



SEVENTH EDITION

PATTY'S INDUSTRIAL HYGIENE

Evaluation and Control
VOLUME 2

EDITED BY
BARBARA COHRSEN

WILEY

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Edited by

BARBARA COHRSEN MS, CIH, FAIHA, MLS
San Francisco, CA, USA

WILEY

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CONTENTS

CONTRIBUTORS	vii
PREFACE	ix
USEFUL EQUIVALENTS AND CONVERSION FACTORS	xi
PART III CHEMICAL EXPOSURE EVALUATION	1
Biological Monitoring of Exposure to Industrial Chemicals	3
<i>Nancy B. Hopf and Silvia Fustinoni</i>	
Real-Time Assessment of Air Contaminants Using Video Exposure Monitoring (VEM) Methods and Techniques	65
<i>James D. McGlothlin, Fan Xu, Sandra S. Cole, and Dave Huizen</i>	
Computed Tomography in Industrial Hygiene	95
<i>Lori A. Todd</i>	
Mathematical Modeling of Indoor Air Contaminant Concentrations	121
<i>Mark Nicas and Thomas W. Armstrong</i>	
Sensors	145
<i>Misti L. Zamora, Christopher Zuidema, and Kirsten Koehler</i>	
PART IV CHEMICAL EXPOSURE CONTROL	161
Characterizing Air Contaminant Emission Sources	163
<i>D. Jeff Burton, Robert L. Harris, and Earl W. Arp</i>	
Engineering Control of Airborne Contaminants: History, Philosophy, and the Development of Primary Approaches	177
<i>D. Jeff Burton and William A. Burgess</i>	

CONTENTS

Industrial Ventilation	199
<i>D. Jeff Burton and Robert D. Soule</i>	
Respiratory Protective Equipment	225
<i>Craig E. Colton</i>	
Chemical Protective Clothing	251
<i>Krister Forsberg and James P. Zeigler</i>	
Control Banding: Background, Evolution, and Application	269
<i>David M. Zalk, Elaine West, and Deborah I. Nelson</i>	
Occupational Safety and Health Law	307
<i>John Howard and Steven Smith</i>	
INDEX	357

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PREFACE

Industrial hygiene is an applied science and a profession. Like other applied sciences such as medicine and engineering, it is founded on basic sciences such as biology, chemistry, mathematics, and physics. In a sense it is a hybrid profession because within its ranks are members of other professions – chemists, engineers, biologists, physicians, nurses, and lawyers. In their professional practice all are dedicated in one way or another to the purposes of industrial hygiene: the anticipation, recognition, evaluation, and control of work-related health hazards. The contributors to these volumes come from these professions.

Although the term “industrial hygiene” used to describe our profession is probably of twentieth century origin, we must go further back in history for the origin of its words. The word “industry,” which has a dictionary meaning, “systematic labor for some useful purpose or the creation of something of value,” has its English origin in the fifteenth century. For “hygiene,” we must look even earlier. Hygieia, a daughter of Asclepius who is god of medicine in Greek mythology, was responsible for the preservation of health and prevention of disease. Thus, Hygieia, when she was dealing with people who were engaged in systematic labor for some useful purpose, was practicing our profession, industrial hygiene.

Industrial Hygiene and Toxicology was originated by Frank A. Patty with publication of the first single volume in 1948. In 1958, an updated and expanded second edition was published with his guidance. A second volume, *Toxicology*, was published in 1963. Frank Patty was a pioneer in industrial hygiene; he was a teacher, practitioner, and manager. In 1946, he served as the eighth president of the American Industrial Hygiene Association. To cap his professional career, he served as director of the Division of Industrial Hygiene for the General Motors Corporation.

At the request of Frank Patty, George and Florence Clayton took over editorship of the ever-expanding *Industrial Hygiene and Toxicology* series for the Third Edition of Volume I, *General Principles*, published in 1978, and Volume II, *Toxicology*, published in 1981–1982. The First Edition of Volume III, *Theory and Rationale of Industrial Hygiene Practice*, edited by Lewis and Lester Cralley, was published in 1979, with its second edition published in 1984. The ten-book, Fourth Edition of *Patty’s Industrial Hygiene and Toxicology*, edited by George and Florence Clayton, was published in 1991–1994, and the Third Edition of Volume III, *Theory and Rationale of Industrial Hygiene Practice*, edited by Robert Harris, Lewis Cralley, and Lester Cralley, was published in 1994. With the agreement and support of George and Florence Clayton, and Lewis and Lester Cralley, Robert Harris edited the fifth edition of *Patty’s Industrial Hygiene*. Vernon Rose and I edited the sixth edition of *Patty’s Industrial Hygiene* with the permission of Robert Harris.

It is now my privilege and honor to follow them and Frank A. Patty as the editor of the seventh edition of the Industrial Hygiene volumes of *Patty’s Industrial Hygiene and Toxicology*. Each of the four volumes and the chapters in the seventh edition are a “stand alone.” Volume 1 covers Chemical Hazard Recognition, Volume 2 addresses Evaluation and Control of Chemical Hazards, Volume 3 considers aspects of Physical and Biological Agents, and Volume 4 considers Management and Specialty Areas of Practice. In addition, Volume 4 contains a complete index covering all four volumes.

Industrial hygiene has been dealt with very broadly in the past editions of *Patty’s Industrial Hygiene and Toxicology*. Chapters have been offered on sampling and analysis, exposure measurement and interpretation, absorption and elimination of toxic materials, instrument calibration,

PREFACE

industrial noise, ionizing and nonionizing radiation, heat and cold stress, pressure, lighting, control of exposures, ergonomics, hazardous wastes, and other vital areas of practice. These traditional areas continue to be covered in this edition. Consistent with the past history of *Patty's*, new areas of industrial hygiene concerns and practices have been addressed: robotics, sensors, social media, nanomaterials, infectious diseases, dermal effects of chemical exposures, mathematical modeling, control banding, product stewardship, construction health and safety issues, cannabis, new energy production, health care work settings, emergency and disaster response, sustainability, and fire safety.

Although industrial hygiene has been practiced in one guise or another for centuries, the most systematic approaches and the most esoteric accomplishments have been made in the past 50 or 60 years – generally in the years since Frank Patty published his first book. This accelerated progress is due primarily to increased public awareness of occupational health and safety issues and need for environmental control as is evidenced by Occupational Safety and Health, Clean Air, and Clean Water legislation at both federal and state levels.

Industrial hygienists know that variability is the key to the measurement and interpretation of workers' exposures. If exposures did not vary, exposure assessment could be limited to a single measurement, the results of which could be acted upon, and the matter filed away as something of no further concern. We know, however, that exposures change, and change is characteristic of the science and practice of our profession as well. We must be alert to recognize new hazards, we must continue to evaluate new and changing stresses, and we must evaluate performance of exposure controls and from time to time upgrade them. These volumes represent the theory and practice of industrial hygiene as they are understood by their chapter authors at the time of their writing. But, as observed by the Greek philosopher Heraclitus about 2500 years ago, "There is nothing permanent except change." Improvements and changes in theory and practice of industrial hygiene take place continuously and are generally reported in the professional literature. Industrial hygienists, the practitioners, the teachers, and the managers must stay abreast of the professional literature. Furthermore, when an industrial hygienist develops new knowledge, he/she has what almost amounts to an ethical obligation to share it with others in the profession.

One cannot ponder the rapid changes and advancements made in recent decades in science and technology, and in our own profession as well, without wondering at what the next two or three decades will bring. Developments in computer technology, information processing, and exchange and communications have greatly influenced workplaces and the general conduct of commerce and business in the past one or two decades. It has also changed the way we now practice the purposes of industrial hygiene. These changes have accelerated. The possibility for continuously monitoring and computer storage of exposures of individual workers is a reality. World population continues to increase geometrically and is expected to be about eight billion in the year 2025; with improvements in preventive health care, there will be an increasingly older population. Genetic engineering and highly effective pesticides are already improving yields of agricultural commodities; if all goes well in this area, feeding the expanding human population may not be a limiting factor. Globalization of manufacturing and commerce has reduced manufacturing employment in the United States and in Europe, and expanded opportunities for populations in some developing nations. The United States and other developed nations are on their way to becoming world centers of information and innovation.

How will all of this affect the future practice of industrial hygiene? In the Preface to the fourth edition of *Patty's*, George and Florence Clayton suggested that the future of industrial hygiene is limited only by the narrowness of vision of its practitioners.

I have relied extensively on the well-written Preface by Robert Harris, Editor of the fifth edition of *Patty's Industrial Hygiene*. In it I saw a sweeping, but still succinct, review not only of Patty's publications but also of the practice of industrial hygiene itself. His writing is as timely in 2021 as it was 20 years ago.

Occupational and environmental hygiene professionals must be aware of the changes likely to take place, and to develop strategies to assure the profession's full participation in protecting the health and safety of workers and the environment of both today and tomorrow. Our participation, locally, nationally, and globally, will continue to be greatly needed in the coming years.

BARBARA COHRSEN
San Francisco, California

USEFUL EQUIVALENTS AND CONVERSION FACTORS

1 kilometer = 0.6214 mile
 1 meter = 3.281 feet
 1 centimeter = 0.3937 inch
 1 micrometer = 1/25,4000 inch = 40 micro inches = 10,000 Angstrom units
 1 foot = 30.48 centimeters
 1 inch = 25.40 millimeters
 1 square kilometer = 0.3861 square mile (U.S.)
 1 square foot = 0.0929 square meter
 1 square inch = 6.452 square centimeters
 1 square mile (U.S.) = 2,589,998 square meters = 640 acres
 1 acre = 43,560 square feet = 4047 square meters
 1 cubic meter = 35.315 cubic feet
 1 cubic centimeter = 0.0610 cubic inch
 1 cubic foot = 28.32 liters = 0.0283 cubic meter = 7.481 gallons (U.S.)
 1 cubic inch = 16.39 cubic centimeters
 1 U.S. gallon = 3,7853 liters = 231 cubic inches = 0.13368 cubic foot
 1 liter = 0.9081 quart (dry), 1.057 quarts (U.S., liquid)
 1 cubic foot of water = 62.43 pounds (4°C)
 1 U.S. gallon of water = 8.345 pounds (4°C)

1 kilogram = 2.205 pounds
 1 gram = 15.43 grains
 1 pound = 453.59 grams
 1 ounce (avoir.) = 28.35 grams
 1 gram mole of a perfect gas $\approx$ 24.45 liters (at 25°C and 760 mm Hg barometric pressure)
 1 atmosphere = 14.7 pounds per square inch
 1 foot of water pressure = 0.4335 pound per square inch
 1 inch of mercury pressure = 0.4912 pound per square inch
 1 dyne per square centimeter = 0.0021 pound per square foot
 1 gram-calorie = 0.00397 Btu
 1 Btu = 778 foot-pounds
 1 Btu per minute = 12.96 foot-pounds per second
 1 hp = 0.707 Btu per second = 550 foot-pounds per second
 1 centimeter per second = 1.97 feet per minute = 0.0224 mile per hour
 1 footcandle = 1 lumen incident per square foot = 10.764 lumens incident per square meter
 1 grain per cubic foot = 2.29 grams per cubic meter
 1 milligram per cubic meter = 0.000437 grain per cubic foot

To convert degrees Celsius to degrees Fahrenheit: $^{\circ}\text{C} (9/5) + 32 = ^{\circ}\text{F}$

To convert degrees Fahrenheit to degrees Celsius: $(5/9) (^{\circ}\text{F} - 32) = ^{\circ}\text{C}$

For solutes in water: 1 mg/liter $\approx$ 1 ppm (by weight)

Atmospheric contamination: 1 mg/liter $\approx$ 1 oz/1000 cu ft (approx)

For gases or vapors in air at 25°C and 760 mm Hg pressure:

To convert mg/liter to ppm (by volume): $\text{mg/liter} (24,450/\text{mol. wt.}) = \text{ppm}$

To convert ppm to mg/liter: $\text{ppm} (\text{mol. wt.}/24,450) = \text{mg/liter}$

Factors for conversion of some units

$\text{Mg/L} \times 28.32 = \text{Mg/cubic foot}$

$\text{Mg/L} \times 1000 = \text{Mg /cubic meter}$

$\text{Mg/cubic foot} \times 35.314 = \text{Mg/cubic meter}$

$\text{Mg/cubic meter} \times 0.2832 = \text{Mg/cubic foot}$

CONVERSION TABLE FOR GASES AND VAPORS^a

(Milligrams per liter to parts per million, and vice versa;
25°C and 760 mm Hg barometric pressure)

Molecular Weight	1 mg/liter ppm	1 ppm mg/liter	Molecular Weight	1 mg/liter ppm	1 ppm mg/liter	Molecular Weight	1 mg/liter ppm	1 ppm mg/liter
1	24,450	0.0000409	39	627	0.001595	77	318	0.00315
2	12,230	0.0000818	40	611	0.001636	78	313	0.00319
3	8,150	0.0001227	41	596	0.001677	79	309	0.00323
4	6,113	0.0001636	42	582	0.001718	80	306	0.00327
5	4,890	0.0002045	43	569	0.001759	81	302	0.00331
6	4,075	0.0002454	44	556	0.001800	82	298	0.00335
7	3,493	0.0002863	45	543	0.001840	83	295	0.00339
8	3,056	0.000327	46	532	0.001881	84	291	0.00344
9	2,717	0.000368	47	520	0.001922	85	288	0.00348
10	2,445	0.000409	48	509	0.001963	86	284	0.00352
11	2,223	0.000450	49	499	0.002004	87	281	0.00356
12	2,038	0.000491	50	489	0.002045	88	278	0.00360
13	1,881	0.000532	51	479	0.002086	89	275	0.00364
14	1,746	0.000573	52	470	0.002127	90	272	0.00368
15	1,630	0.000614	53	461	0.002168	91	269	0.00372
16	1,528	0.000654	54	453	0.002209	92	266	0.00376
17	1,438	0.000695	55	445	0.002250	93	263	0.00380
18	1,358	0.000736	56	437	0.002290	94	260	0.00384
19	1,287	0.000777	57	429	0.002331	95	257	0.00389
20	1,223	0.000818	58	422	0.002372	96	255	0.00393
21	1,164	0.000859	59	414	0.002413	97	252	0.00397
22	1,111	0.000900	60	408	0.002554	98	249.5	0.00401
23	1,063	0.000941	61	401	0.002495	99	247.0	0.00405
24	1,019	0.000982	62	394	0.00254	100	244.5	0.00409
25	978	0.001022	63	388	0.00258	101	242.1	0.00413
26	940	0.001063	64	382	0.00262	102	239.7	0.00417
27	906	0.001104	65	376	0.00266	103	237.4	0.00421
28	873	0.001145	66	370	0.00270	104	235.1	0.00425
29	843	0.001186	67	365	0.00274	105	232.9	0.00429
30	815	0.001227	68	360	0.00278	106	230.7	0.00434
31	789	0.001268	69	354	0.00282	107	228.5	0.00438
32	764	0.001309	70	349	0.00286	108	226.4	0.00442
33	741	0.001350	71	344	0.00290	109	224.3	0.00446
34	719	0.001391	72	340	0.00294	110	222.3	0.00450
35	699	0.001432	73	335	0.00299	111	220.3	0.00454
36	679	0.001472	74	330	0.00303	112	218.3	0.00458

CONVERSION TABLE FOR GASES AND VAPORS *(Continued)*

*(Milligrams per liter to parts per million, and vice versa;
25°C and 760 mm Hg barometric pressure)*

Molecular Weight	1 mg/liter ppm	1 ppm mg/liter	Molecular Weight	1 mg/liter ppm	1 ppm mg/liter	Molecular Weight	1 mg/liter ppm	1 ppm mg/liter
37	661	0.001513	75	326	0.00307	113	216.4	0.00462
38	643	0.001554	76	322	0.00311	114	214.5	0.00466
115	212.6	0.00470	153	159.8	0.00626	191	128.0	0.00781
116	210.8	0.00474	154	158.8	0.00630	192	127.3	0.00785
117	209.0	0.00479	155	157.7	0.00634	193	126.7	0.00789
118	207.2	0.00483	156	156.7	0.00638	194	126.0	0.00793
119	205.5	0.00487	157	155.7	0.00642	195	125.4	0.00798
120	203.8	0.00491	158	154.7	0.00646	196	124.7	0.00802
121	202.1	0.00495	159	153.7	0.00650	197	124.1	0.00806
122	200.4	0.00499	160	152.8	0.00654	198	123.5	0.00810
123	198.8	0.00503	161	151.9	0.00658	199	122.9	0.00814
124	197.2	0.00507	162	150.9	0.00663	200	122.3	0.00818
125	195.6	0.00511	163	150.0	0.00667	201	121.6	0.00822
126	194.0	0.00515	164	149.1	0.00671	202	121.0	0.00826
127	192.5	0.00519	165	148.2	0.00675	203	120.4	0.00830
128	191.0	0.00524	166	147.3	0.00679	204	119.9	0.00834
129	189.5	0.00528	167	146.4	0.00683	205	119.3	0.00838
130	188.1	0.00532	168	145.5	0.00687	206	118.7	0.00843
131	186.6	0.00536	169	144.7	0.00691	207	118.1	0.00847
132	185.2	0.00540	170	143.8	0.00695	208	117.5	0.00851
133	183.8	0.00544	171	143.0	0.00699	209	117.0	0.00855
134	182.5	0.00548	172	142.2	0.00703	210	116.4	0.00859
135	181.1	0.00552	173	141.3	0.00708	211	115.9	0.00863
136	179.8	0.00556	174	140.5	0.00712	212	115.3	0.00867
137	178.5	0.00560	175	139.7	0.00716	213	114.8	0.00871
138	177.2	0.00564	176	138.9	0.00720	214	114.3	0.00875
139	175.9	0.00569	177	138.1	0.00724	215	113.7	0.00879
140	174.6	0.00573	178	137.4	0.00728	216	113.2	0.00883
141	173.4	0.00577	179	136.6	0.00732	217	112.7	0.00888
142	172.2	0.00581	180	135.8	0.00736	218	112.2	0.00892
143	171.0	0.00585	181	135.1	0.00740	219	111.6	0.00896
144	169.8	0.00589	182	134.3	0.00744	220	111.1	0.00900
145	168.6	0.00593	183	133.6	0.00748	221	110.6	0.00904
146	167.5	0.00597	184	132.9	0.00753	222	110.1	0.00908
147	166.3	0.00601	185	132.2	0.00757	223	109.6	0.00912
148	165.2	0.00605	186	131.5	0.00761	224	109.2	0.00916
149	164.1	0.00609	187	130.7	0.00765	225	108.7	0.00920
150	163.0	0.00613	188	130.1	0.00769	226	108.2	0.00924
151	161.9	0.00618	189	129.4	0.00773	227	107.7	0.00928

USEFUL EQUIVALENTS AND CONVERSION FACTORS

CONVERSION TABLE FOR GASES AND VAPORS (Continued)

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25° C and 760 mm Hg barometric pressure)

Molecular Weight	1 mg/liter ppm	1 ppm mg/liter	Molecular Weight	1 mg/liter ppm	1 ppm mg/liter	Molecular Weight	1 mg/liter ppm	1 ppm mg/liter
152	160.9	0.00622	190	128.7	0.00777	228	107.2	0.00933
229	106.8	0.00937	253	96.6	0.01035	277	88.3	0.01133
230	106.3	0.00941	254	96.3	0.01039	278	87.9	0.01137
231	105.8	0.00945	255	95.9	0.01043	279	87.6	0.01141
232	105.4	0.00949	256	95.5	0.01047	280	87.3	0.01145
233	104.9	0.00953	257	95.1	0.01051	281	87.0	0.01149
234	104.5	0.00957	258	94.8	0.01055	282	86.7	0.01153
235	104.0	0.00961	259	94.4	0.01059	283	86.4	0.01157
236	103.6	0.00965	260	94.0	0.01063	284	86.1	0.01162
237	103.2	0.00969	261	93.7	0.01067	285	85.8	0.01166
238	102.7	0.00973	262	93.3	0.01072	286	85.5	0.01170
239	102.3	0.00978	263	93.0	0.01076	287	85.2	0.01174
240	101.9	0.00982	264	92.6	0.01080	288	84.9	0.01178
241	101.5	0.00986	265	92.3	0.01084	289	84.6	0.01182
242	101.0	0.00990	266	91.9	0.01088	290	84.3	0.01186
243	100.6	0.00994	267	91.6	0.01092	291	84.0	0.01190
244	100.2	0.00998	268	91.2	0.01096	292	83.7	0.01194
245	99.8	0.01002	269	90.9	0.01100	293	83.4	0.01198
246	99.4	0.01006	270	90.6	0.01104	294	83.2	0.01202
247	99.0	0.01010	271	90.2	0.01108	295	82.9	0.01207
248	98.6	0.01014	272	89.9	0.01112	296	82.6	0.01211
249	98.2	0.01018	273	89.6	0.01117	297	82.3	0.01215
250	97.8	0.01022	274	89.2	0.01121	298	82.0	0.01219
251	97.4	0.01027	275	88.9	0.01125	299	81.8	0.01223
252	97.0	0.01031	276	88.6	0.01129	300	81.5	0.01227

^aA. C. Fieldner, S. H. Katz, and S. P. Kinney, "Gas Masks for Gases Met in Fighting Fires," *U.S. Bureau of Mines, Technical Paper No. 248*, 1921.

Part III

CHEMICAL EXPOSURE EVALUATION

BIOLOGICAL MONITORING OF EXPOSURE TO INDUSTRIAL CHEMICALS

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1 INTRODUCTION

Occupational health experts began to monitor workers' chemical exposures by measuring the internal dose of a chemical of interest, which gave a more reliable estimate of total exposures such as lead concentrations in urine (1–3). Other human biomonitoring methods sought to measure a chemical's biotransformations in the body, its metabolites. For instance, urinary sulfate was determined in benzene-exposed workers (4). Periodically monitoring industry workers who were exposed to especially benzene was recommended, and the aim was to remove workers from the site before symptoms of acute poisoning (such as anemia) appeared.

Quantifying the parent chemical compound or its metabolites – or *biomarkers of exposure* – in urine and blood is still a widely used biomonitoring approach. The metabolites can, in some instances, be a better measure of toxic exposure than the presence of the compound itself (e.g. quantifying urinary 2,5-hexandione, the toxic metabolite, to determine hexane exposure). Human biomonitoring uses techniques of analytical chemistry to detect the presence of specific chemicals in human bodily fluids and tissues. This kind of biomonitoring relies on the sensitivity of the chemical assays and instruments, which since the 1960s have become able to measure ever-smaller amounts of specific substances (2). For example, these techniques can detect one drop of ink in one of the largest tanker trucks used to haul gasoline, which is about one part per billion. Improvements in laboratory technology are driving the popularity of human

biomonitoring, as specialists can now detect extremely low levels of multiple markers using a relatively small sample. High precision analytical instruments are used to specifically quantify chemicals or their metabolized residues such as inductively coupled plasma mass spectrometry, gas, and liquid chromatography coupled with single or triple quadrupole mass spectrometry, even in the presence of isotopically labeled analogs as internal standards to further improve assay's performance.

Biomarkers that measure bodily alteration such as changes in blood composition to assess a specific disease are known as *biomarkers of effect*. For instance, changes in blood cell composition profiles were used in order to protect hospital workers in radium units from radioactive exposures in the 1920s. Blood cell changes were known to precede radiation-induced diseases such as aplastic anemia. Back then, the British X-ray and Radium Protection Committee recommended that radium units in hospitals adopt in-house blood monitoring programs to reduce the occurrence of aplastic anemia among exposed workers. This biomonitoring approach was later abandoned for a far easier radiation exposure-monitoring program where workers wear dosimeters attached to their clothing. Radiation-induced damage in individuals was later measured using genetic testing or the determination of condensed chromosomes – or karyotyping – by way of microscopy. Extensive data on chromosomal aberrations (CAs) in response to ionizing radiation have been provided from studies in survivors of the atomic bombings at Hiroshima and Nagasaki (5). This chromosome

aberration method was later used to monitor uranium miners and workers in the nuclear industry exposed to radiation (6).

Although a biomarker of effect may be related to exposure to a specific chemical, it is more closely related to the occurrence of an adverse health effect (7). Damage to genetic material (chromosomes or DNA) or other molecular alterations (e.g. adducts) that are chemically induced by exposure are used to survey workers at risk. For instance, occupational exposure to the sterilizing agent ethylene oxide can be monitored with a detectable chemical modification of the hemoglobin molecules in their blood namely the *N*-(2-hydroxyethyl)valine (HEV) hemoglobin adduct. Another example is lead's ability to induce anemia by inhibition of heme synthesis. Lead inhibits delta-Aminolevulinate dehydratase (ALAD), the second enzyme in the heme biosynthesis pathway. ALAD is a zinc metalloenzyme, and its inhibition by lead substitution for zinc is one of the most sensitive indicators of blood-lead accumulation, a measure of recent lead exposure (8). Cytogenetic alterations in cultured peripheral blood lymphocytes, such as CAs and sister chromatid exchanges (SCEs), are used as biomarkers of effects to assess risk from exposures to carcinogens (9). Micronuclei (MN) present in cultured human cells are a measure of genotoxic exposure, and this biomarker of effect is predictive for cancer (10, 11). It is important to note that determining the actual biological damage might potentially be more informative than a simple exposure level but also note that individuals will vary in their susceptibility to such damage.

Biomarkers of exposure generally give a picture of a worker's current exposure while biomarkers of effect reflect chronic exposures. For instance, lead concentration in blood is a measure of current exposure while lead in bone is a reflection of cumulative exposures (12). Exposure biomarkers fluctuate with an individual's exposure. Exposure biomarkers reflect both absorption and the compound's apparent elimination half-life in the body. It is, therefore, pertinent to collect the blood or urine sample at maximum exposure to avoid underestimating the body burden. This is not the case for biomarkers of effect where the sampling time is generally not critical. Exceptions to this general overview exist such as carboxyhemoglobin and methemoglobin.

Exposure biomarkers are used to integrate skin exposure, as measurements of airborne contaminants in the workplace fail to register other routes than inhalation exposure. Skin patches have been used to monitor potential skin exposure but this method does not take into account skin absorption. A biomarker of exposure can assess the bioavailability of the chemical and consequently, the body burden can be determined. Biomonitoring is also used to assess the efficiency of personal protective equipment (PPE). For example, workers wearing PPE to protect themselves from agents that are readily absorbed through the skin might become exposed because of a nonvisible tear in a glove. This breach in protection can only be monitored through biomarkers of exposure.

Human biological monitoring is a powerful tool for assessing human systemic exposure to hazardous substances by inhalation, ingestion, and absorption through the skin. Regular monitoring helps to reassure workers their exposure continues to be well controlled (13). Irreversible biochemical and functional changes are consequently not recommended as biomarkers for exposure monitoring because abnormal values already indicate a health injury that is supposed to be prevented by the monitoring.

At work, reducing exposure to toxic chemicals and their health effects can be implemented with biological monitoring programs and by comparing results to biological limit values (BLVs). The initiative in promulgating BLVs for biomarkers started in the 1970s. In the US, this movement was initiated by the organization for professional industrial hygienists; the American Conference for Governmental Industrial Hygiene (ACGIH), and in Europe, by the German Commission for the Investigation of Health Hazards of Chemical Compounds in the workplace (MAK commission) of the German Research Association (DFG or Deutsche Forschung Gemeinschaft). Since then, both ACGIH and DFG have published their yearly list of BLVs where BLVs are updated and/or new ones added. EU and its Scientific Committee on Occupational Limit values (SCOEL) continued this initiative. In addition, several countries have their own commissions and set country-specific biological exposure limit values such as France, Finland, and Japan.

Expansion of biomonitoring beyond occupational health to the population at large started in the mid-1920s with the health hazards of tetraethyl lead (gasoline additive). Studies showed that blood lead levels measured in healthy babies were above the industry standard, and individuals living in urban areas had higher blood lead concentrations than residents of rural areas (14). This knowledge eventually led environmental protection agency (EPA) to ban tetraethyl lead in automotive fuel. Biological monitoring strategies for population-based studies differ from occupational studies. The exposure source is generally known in the occupational but not in the general population setting. Exposures are during work hours while the exposure time is often unknown for nonoccupationally exposed individuals. Work exposures are generally greater during fixed times while the general population might be exposed to low concentrations over longer periods. This chapter will only include occupational biological monitoring strategies.

This chapter will discuss biomarkers suitable for monitoring of occupational exposures, sampling strategy, how policy makers assess and manage the risk of exposure to chemicals at the workplace. This chapter will also touch upon the ethical issues associated with biomonitoring such as disclosure of data to whom, and with what kind of medical consultation. In addition, different approaches for setting biological monitoring limits will be described.

2 OCCUPATIONAL EXPOSURE ASSESSMENT

The ultimate objective of an occupational exposure assessment is to evaluate the health risk for workers and to implement control measures if the risk is considered unacceptable. Exposure assessment to airborne pollutants is usually performed by measuring the concentration of the studied contaminant preferably in the persons' breathing zone (personal air sampling) but sometimes area air samples are collected.

Sampling strategies depend on the purpose such as compliance (mandated sampling, comparing to existing occupational exposure limits [OELs]) or extensive exposure assessment (characterize the exposure intensity and frequency variability, control measure efficiency) of more or less all workers. Occupational hygiene sampling strategies include sampling workers with the potential for highest exposures, random sampling of a homogenous exposure groups, or selection of workers for periodic exposure monitoring programs. In the occupational environment, strategies for air sampling have been well defined and described in textbooks (15, 16), publications, and standards.

Occupational hygiene assesses workplace exposure by measuring the contaminants in the air or on the surfaces (including skin), and whenever possible, biological monitoring.

2.1 Exposure Monitoring

2.1.1 Air Sampling

The air sampling strategy includes the compounds of interest (what to sample), their OELs, their associated health effects if workers have excessive exposure to the agents, and where and when the compounds are used in the process. Consequently, the key operations and activities are identified. Workers that have the greatest potential for exposure to the agents are targeted and personal air sampling for the identified compounds are collected. Alternatively, stationary samples are used to identify the sources of potential exposures.

Concerns associated with collecting air samples are to take a representative sample of the study population for exposure measurements, account for all possible routes of exposure, select the appropriate sampling methods, and characterize correct exposure times. It is important to understand the basic relationship between factors influencing exposures, and the exposure distribution (often lognormal distribution). This will help understand exposure variability, especially, between- and within-worker variability, exposure correlation in time and space (e.g. time series and spatial analysis), and the methods inherent uncertainties.

Occupational hygienists have to select the appropriate air sampling method for the compounds of interest. Sampling for all agents is impractical. Different media might be required for each agent. It is not convenient for a worker to wear several sampling pumps at the same time. Moreover, it could be that sampling and analytical methods do not exist for the compound of interest. Furthermore, the substance of interest might not be airborne. All these factors need to be considered in the field-sampling plan.

2.1.2 Surface Sampling

Skin exposure is a topic that has been increasingly discussed this last decade since this route of entry is quite relevant for many chemicals. The exposure assessment for the skin route of entry is more challenging than with airborne contaminants. In addition, as air concentrations become lower the relative importance of skin exposure increases.

Skin exposures to chemicals have been evaluated using different methods (17–20). Surface sampling methods include wipe sampling, patch test, hand washing, and the tape stripping method.

Wipe tests consist of wiping a determined surface area with a material (fabrics, filters, etc.). The results are reported as mass of contaminant (in mg or μg) per square centimeter of the treated/body surface. For example, the amount of nicotine contaminating tobacco harvesters' hands at the end of shift were determined with wipe sampling (21).

Patch tests are similar to the surface sampling except they are attached to worker's skin (22). Patches are sampling mediums (fabrics, filters, etc.) placed on different parts of the worker's body where contact with the concerned pollutant is expected. For example, chromic acid skin exposures were measured using patches attached to the hands inside the PPE among electroplaters (23) or polycyclic aromatic hydrocarbons (PAHs) were measured using patches applied to different parts of the body in asphalt workers (24).

Hand washing is a technique applied to assess contamination on hands. It consists of pouring a certain amount of solvent (water or other suitable medium) on the contaminated hands while the worker is rubbing them. The hand wash is collected in a basin underneath. This technique was applied to assess exposure to pesticides in vineyard agricultural workers after re-entry operations (maintenance and cleaning) (25).

The tape stripping method aims to determine the amount of a compound absorbed via skin by quantifying the amount of the compound in the outer layer of the skin (stratum corneum). The upper layers of the stratum corneum (nonliving keratinized layers) are removed by adhesive tapes successively. The total amount of compound absorbed is calculated by adding the compound amount extracted from the cells attached to the adhesive strips sampled from each layer of epidermis. The tape stripping method has been

used to assess skin exposures among chimney sweepers to PAHs (26), among workers employed in the corticosteroid manufacturing industry to budesonide (27), and among jet-fuel exposed workers to naphthalene (28).

No standard exists for occupational skin exposures. Therefore, it is the company or the organization that determines its own reference values for the surface wipes (skin or other surfaces), whole-body clothing, patch, hand wash, or tape stripping methods used. The company needs to decide if the surface is considered “clean” or “contaminated” (29–31). There is no recommended strategy to derive reference values for these sampling methods.

2.1.3 Advantages and Limitations of Environmental Monitoring

Air sampling has several advantages over biomonitoring. There are many more established OELs for airborne contaminants than biomonitoring limit values. Air monitoring can measure peak exposures and very short exposure periods using direct-reading instruments. Peak exposure measurements are not possible with biological monitoring due to pharmacokinetics and technical considerations.

From a legal point of view, the air quality at the workplace is a matter of the employer's responsibility who has to provide a safe occupational environment for the workers. Air sampling is not considered personal while a biological sample is, even if it is related to the air quality at the workplace. This is because the measured exposure quantity is influenced by personal characteristics and worker's behavior. This includes the way the worker operates and protects himself or herself. Biomonitoring might, therefore, be regulated differently than air monitoring depending on the specific country's legislation.

The main limitation of the air sampling is that it only allows the assessment of exposure through inhalation and ignores other routes of entry. This may seriously affect the risk assessment as this is often based on the total dose reaching the target organs. Air monitoring does not take into account the individual respiratory flow rates such as heavy lifting that directly influence the uptake of an airborne compound. Another limitation may be the sampling method: for reactive compounds, adsorption on a solid phase is often impossible and the impractical impingers (or bubblers) remain the only solution (32). Personal air measurements have in general more measurement error than biological measures (33). Although it is probably more feasible and cost-effective to minimize the bias in exposure-response associations by collecting additional airborne measurements than biological measurements.

Air measurements and biological monitoring are two methods of exposure assessment that are complementary. The choice of using air measurements or biomonitoring depends on the sampling purpose. In occupational hygiene

practice, it is useful to start with optimizing working conditions using air sampling before biomonitoring. Another complimentary use of these methods is once biomonitoring programs are in place but the occupational hygienist running the program discovers that workers have elevated biomarker values than expected, then the occupational hygienist uses air monitoring to find the sources. Therefore, biomonitoring has an added value to air measurements where exposure is well managed and the occupational hygienist can use biomonitoring as the ultimate “stress test” to see if everything is placed or check for expected or unexpected contributions from skin absorption, effectiveness of PPE, and exposures after incidents/spills.

2.2 Biological Monitoring Approach

2.2.1 From Exposure to Disease

The value of biological monitoring is that it takes into account all routes of chemical exposure, along with personal characteristics. Biological monitoring of exposure can be used to target intervention and consequently, prevent the progression from exposure to disease because it is in an early step in the continuum of external exposure to health surveillance and disease (Figure 1).

As proposed by Lauwerys and Bernard in 1985 (37), biological monitoring of exposure to an industrial chemical may be defined as the evaluation of the internal dose (internal exposure) by a biological method with the view of assessing the associated health risk. Depending on the biological parameter selected and on the time of sampling, internal dose may mean the amount of chemical recently absorbed, the amount stored in one or several compartments of the organism, or, under ideal conditions, the amount bound to the sites of action. The internal dose estimation has usually relied on two categories of tests: those based on the determination of the chemical and/or its metabolites in various biological media (e.g. blood, urine, and alveolar air) and those based on the quantification of a no adverse biological effect, the intensity of which is related to the internal dose.

The scope of biomarkers has been greatly expanded during the past decades. This is primarily because of the great advances made in both analytical chemistry and molecular biology techniques. The increased biomarker knowledge has also played a significant role, particularly in the area of cancer biomarkers and their potential for predicting health risk in individuals and populations (38–44). For practical applications, biomarkers are generally classified into three categories: *biomarkers of exposure*, *biomarkers of early biological effects*, and *biomarkers of susceptibility* (45–48).

2.2.2 Biomarkers of Exposure

Historically, biomarkers of exposure indicators are the first ones described and still represent the majority of biological

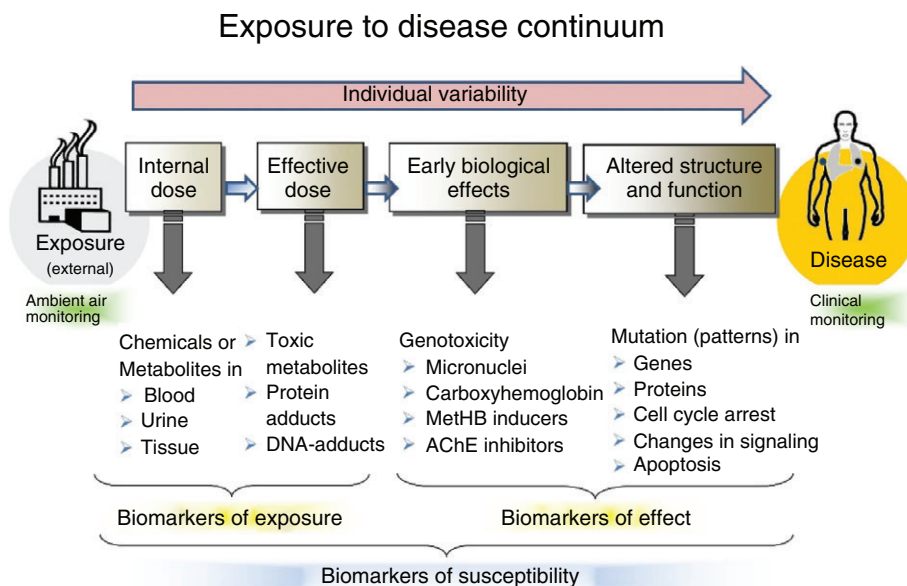


FIGURE 1 Continuum of events between exposure and disease, and use of biomarkers in risk assessment. Source: Adapted from Manini et al. (34); NRC (35); Albertini et al. (36).

parameters validated and used in the assessment of occupational exposure. Generally, biomarkers of exposure give an indication of the compound circulating in the body and/or the amount excreted. Consequently, this is an evaluation of intake or uptake as well as an indication of the body burden. The compound can be the chemical itself (parent compound), some biotransformation products (e.g. metabolites), or some reaction products with macromolecules measured in accessible biological fluids. These exposure biomarkers may reflect the internal dose in various ways. They can be expressed as the quantity of a product:

- Recently absorbed (solvents in the blood, in exhaled air, etc.)
- Absorbed over a few months (metals in the blood or in hair)
- Stored in organs and tissues (dichlorodiphenyl-trichloroethane (DDT) and polychlorinated biphenyls (PCBs) in particular)
- Present on the active site (carboxyhemoglobin, adducts).

2.2.2.1 BIOMARKERS OF INTERNAL DOSE Biological monitoring of occupational exposure to chemicals started in the early 1950s with survey programs for exposure to metals (lead and mercury principally) measuring these metals in blood or in urine. Biomonitoring to organic compounds (organic solvents) came later and was mainly the quantification of urinary metabolites of the solvents.

The validation of these biomarkers of internal dose was the quantitative relationship between biological and air monitoring to a particular chemical. These biological indicators were often validated using controlled experiments with volunteers in an exposure chamber by varying the magnitude of exposure seeking to obtain an external–internal relationship for the chemical of interest. Toxicokinetics of the chemicals is often explored in these controlled human experiments. The better the correlation between internal amount and external amount, the more powerful the biomarker. This approach is still used (49, 50). Validations are also performed by simultaneously assessing biomarkers and personal airborne exposure among occupationally exposed subjects. For example, the correlation between personal air exposures to styrene and styrene-(7,8)-oxide and several urinary biomarkers were investigated among workers. Urinary biomarkers included styrene, mandelic acid, phenylglyoxylic acid, phenylglycine, 4-vinylphenol, the mercapturic acids (*S,R*)-*N*-acetyl-*S*-(1-phenyl-2-hydroxyethyl)-L-cysteine, and (*R,R*)- and (*S,R*)-*N*-acetyl-*S*-(2-phenyl-2-hydroxyethyl)-L-cysteine, and styrene-(7,8)-oxide hemoglobin and albumin adducts. The adopted multiple sampling design allowed for a reduced within subject variability, and very good correlations were obtained between several urinary biomarkers and measured personal styrene air exposures (51, 52).

Biological monitoring helps to better understand the influence of specific exposure determinants such as wearing protective equipment, occurrence of dermal permeation, and influence of exposure to mixtures. If these factors

are not considered important in the occupational hygiene strategy then air monitoring is sufficient. Biological monitoring may be unnecessary in these cases because it may add variability to the alternative of air monitoring (53). Most of the biomarkers and BLVs recommended for risk assessment of exposure to toxic chemicals in the workplace are biomarkers of internal dose (32, 54).

2.2.2.2 BIOMARKERS OF BIOLOGICALLY EFFECTIVE DOSE
Biomarkers of biologically effective dose include the biological indicators of an interaction between the compounds itself or more often one active metabolite and a critical molecular target, mainly proteins and/or DNA.

A large body of evidence demonstrates that DNA adducts are useful markers of carcinogenic exposures. DNA adducts are the results of carcinogen intake, metabolic activation, and delivery to the target macromolecule in target tissues (55). In the past, the ^{32}P -postlabeling technique was used to screen for DNA damage induced by genotoxic agents (56). More robust, specific, and quantitative methods are still being sought to identify and quantify DNA adducts. Specifically, triple quadrupole and ion trap mass spectrometry (57) have shown promise in quantifying DNA adducts, and perhaps high-resolution and accurate-mass spectrometry instruments will play a role in assessing global DNA damage (58). However, the application of this approach in risk assessment is limited to research studies due to the lack of standardized methods and the costly and time-consuming assays.

Among protein adducts, hemoglobin and albumin adducts are estimated to be especially useful for the exposure assessment (reviewed in (59, 60)). In comparison with DNA, they are formed in larger amounts, chemically stable, and not prone to repair mechanisms such as DNA adducts. Because of the long hemoglobin (120 days) and albumin (27 days) lifespan, these adducts cumulate in the human body, making them a very sensitive parameter adapted for the estimation of internal exposure as well as biochemical effects. Their limitations are that they are only surrogates of DNA adducts and their capability to represent the concentration of the reactive intermediate able to react with the target macromolecule is mostly unknown.

Protein adducts were applied to investigate exposure to several electrophilic or electrophilic generating chemicals, such as benzene and styrene/styrene-(7,8)-oxide (61–63). Recently, an adductomic approach taking advantages of high-resolution mass spectrometry was applied to investigate serum albumin adducts of benzene (64).

Carboxyhemoglobin (COHb) is one of the most common biomarkers of target dose. Indeed, carbon monoxide binds rapidly to hemoglobin (Hb) leading to the decrease of the blood capacity to carry oxygen, causing tissue hypoxia. Besides carboxyhemoglobin, limit values for hemoglobin adducts and/or their derivatives, are proposed, mostly by the MAK commission, for several chemicals,

some of which are classified as carcinogenic to humans, including acrylamide, acrylonitrile, 4-aminobiphenyl, aniline, benzidine, 4,4'-diaminodiphenyl-methane, dimethyl sulfate, 1,2-epoxypropane, ethylene, ethylene oxide, methemoglobin-forming substances, 2-naphthylamine, and nitrobenzene (54). Furthermore, the determination of S-methylcysteine albumin is proposed for the assessment of exposure to methyl bromide.

Oxygen-free radicals, reactive metabolites, and peroxides defined as reactive oxygen species (ROS) can induce direct cell injury called oxidative stress that can be the mechanism in the pathogenesis of many diseases. ROS can react with biological macromolecules and produce lipid peroxidation, enzyme inactivation, and DNA damage (reviewed in (65)).

8-*iso*-Prostaglandin F 2α (8-isoprostane) is produced by free-radical lipid peroxidation of arachidonic acid and represents an *in vivo* specific marker of oxidative stress. Lipid peroxides are unstable indicators of oxidative stress in cells that form more complex and reactive compounds, such as malondialdehyde, 4-hydroxy-*trans*-hexenal, and 4-hydroxy-*trans*-nonenal. These can form covalent adducts with biomolecules including DNA and proteins, and thus, are regarded as genotoxic and cytotoxic.

3-Nitrotyrosine and 3-chlorotyrosine are stable products of peroxynitrite and hypochlorous acid, respectively, with tyrosine residues of proteins, which may lead to functional relationship with the neutrophilic inflammation.

Oxidative damage to DNA and RNA may be measured using 8-oxo-7,8-dihydro-2'-deoxyguanosine (8-OHdG) and 8-oxo-7,8-dihydro-guanosine. These oxidative products provide an extensive and growing array of potential biomarkers, although our understanding of their status in cells and tissues, including plasma and urine, remains to be elucidated.

Biomarkers of oxidative stress are increasingly studied with special emphasis on pulmonary diseases resulting from occupational or environmental exposures to asbestos, coal, PAH, welding fumes, nanocomposites, including nanoparticles (66–70). Particularly, 8-OHdG in blood and urine samples was used to assess oxidative stress to DNA following occupational exposure to different chemicals (38, 66, 68, 71). So far, no biomarker of oxidative stress is used for risk assessment.

Biomarkers of epigenetic modifications were recently investigated, mostly in association with occupational and environmental exposures to carcinogens (reviewed in (72)). Epigenetic alterations represent nongenotoxic mechanisms of carcinogenesis, which can alter gene activity without change to the DNA sequence. There are several major types of epigenetic alterations, among which DNA methylation, histones/chromatin structure, and expression of noncoding RNAs. It has been demonstrated that chemically induced epigenetic alterations occur early during exposure and may also have significance as biomarkers of carcinogen

exposure. Benzene, aflatoxins, benzo[*a*]pyrene, and coke oven emissions are among the more investigated chemicals (reviewed in (73)).

2.2.3 Biomarkers of Effects

Biomarkers of effects are measurable biochemical, physiological, or other alterations within an organism that can be recognized as associated with an established or potential health impairment or disease (74).

One of the biomarkers of effect that has received a significant amount of discussion in recent years is the beryllium blood lymphocyte proliferation test (BeLPT). This is a biomarker indicating that the immune system is hyperactive toward Be-antibodies. BeLPT test can identify subjects who have become sensitized and, potentially, with further exposure, may develop disease (75–77).

2.2.3.1 MARKERS OF BIOCHEMICAL CHANGES The initial changes in enzymes and other biological substances or responses affected by the substance are called early effects. Biomarkers of effect are often not specific for a certain substance. If many compounds are used in a workplace, some biomarkers of effect can be applied to understand if a risk exists by looking for effects that may be a result of the mixed exposure. If one or more markers is positive, additional biomarkers of exposure or environmental monitoring can be used to determine the substance responsible for the effect (78). Some examples of the biomarkers of effect will be cited or described under the specific chemical described, but to illustrate this category of indicators, a few examples, that are the best validated and used, are given below.

1. The inhibition of some enzymes in the hemoglobin synthesis pathway caused by lead results in elevated concentrations of free protoporphyrin in blood and an inhibition of D-aminolaevulinic acid dehydratase activity in blood and/or an increased excretion of D-aminolaevulinic acid in urine.
2. The leakage into the urine of certain proteins, such as β 2-microglobulin, D-microglobulin, retinol-binding protein, and albumin, caused by a number of metals and solvents; in addition, inhibition of the activity of certain enzymes in the urine (e.g. *N*-acetyl-D-glycosaminidase) may occur.
3. The inhibition of the enzyme acetylcholinesterase that may occur following exposure to a number of organophosphate and carbamate insecticides (e.g. parathion).

2.2.3.2 MARKERS OF PHYSIOLOGICAL CHANGES The initial biochemical changes may lead to physiological changes. One such example is the occurrence of negative changes in higher cognitive function (e.g. learning and

memory) occurring in workers exposed to metals or solvents. Another example is heat stress and the physiologic responses include increases in heart rate, core body temperature, skin temperature, and sweat production.

2.2.3.3 MARKERS OF CYTOTOXICITY Cytogenetic analysis provides a valuable technique for evaluation of damage to chromosomes based on direct observation and classification of chromosomes in peripheral blood lymphocytes. Among different possibilities, CAs, MN frequencies, SCEs, and comet assays are the most frequently used.

CAs are changes in normal chromosome number or structure that can occur following chemical exposure. Structural CAs in peripheral blood lymphocytes, as assessed by the CA assay, have been used for over 40 years in occupational and environmental settings as a biomarker of early effects from exposures to genotoxic carcinogens. A high frequency of structural CAs in lymphocytes is predictive of increased cancer risk. CA has been investigated in association with several occupational exposures such as ionizing radiation (79) and benzene (80).

Sister chromatid exchange (SCE) frequency represents the interchange of DNA replication products at apparently homologous chromosomal loci. These exchanges presumably involve DNA breakage and reunion. Although the mechanism of SCE formation is not completely elucidated, DNA damage and DNA repair defects play an important role in the formation of SCE (38). SCE has been widely applied as a sensitive DNA damage indicator to evaluate the potential risk associated with exposure to many compounds such as pesticides (78, 81, 82), styrene (83), toluene (84, 85), arsenic (86), PAH (87), and cytostatic drugs (88).

MNs originate from chromosome fragments or whole chromosomes that are not included in the main daughter nuclei during nuclear division. MN induction reflects clastogenic and aneugenic damage and is a predictive biomarker of cancer risk. The cytokinesis-block micronucleus (CBMN) assay is the most extensively used method for measuring MN in human lymphocytes. CBMN assay allows scoring, not only MN frequency but also other genome damages, e.g. nuclear bridge and nuclear buds, cell proliferation, and cell death. The key advantages of the CBMN assay lie in its ability to detect both clastogenic and aneugenic events and to identify cells which divided once in culture. Evaluation of the mechanistic origin of individual MN by centromere and kinetochore identification contributes to the high sensitivity of the method. A number of findings support the hypothesis of a predictive association between the frequency of MN in cytokinesis-blocked lymphocytes and cancer development (reviewed in (89)). Showing the increase in the number of papers published on this focus, this test seems very promising especially in the survey of population exposed to pesticides (90–94), metals (95, 96), formaldehyde (97), asbestos (98) and low doses of ionizing radiation (99).

(See special review issue in Mutation Research Volume 770, Part A, Pages 1–216 (October–December 2016)). MN in lymphocytes could potentially be a biomarker for nanomaterial exposures in the future (100).

Blood is an invasive sampling matrix consequently, methods have been developed to determine MNs in exfoliated buccal cells (101). This minimally invasive Buccal micronucleus cytome (BMCyt) assay is especially useful to understand DNA damage from inhaled genotoxic agents. The popularity of the BMCyt is shown in the increasing number of publications especially among workers exposed to wood dust (102, 103), formaldehyde (104–106), metals (107, 108), and crystalline silica (109–112). A review of occupational exposure and MN frequency in buccal cells concluded that using this tool for monitoring workers exposed to genotoxic agents is useful; however, data regarding exposure (genotoxic agent amount) – response (MN frequencies) is still lacking as exposures were in general poorly measured in these studies (113, 114).

Recent advances in fluorescence in situ hybridization (FISH) and microarray technologies are modifying the nature of cytogenetics, allowing chromosome and gene identification on metaphase as well as in interphase. Automated scoring by flow cytometry and/or image analysis greatly enhanced their applicability.

The measurement of DNA strand breaks by the comet assay in human lymphocytes has become more and more investigated (38). The comet assay or SCGE (single cell gel electrophoresis assay) is a sensitive method of studying DNA damage and repair (115). Usually, lymphocytes are prepared from venous blood. A cell suspension is then embedded in agarose on a microscope slide and lysed to liberate the DNA. During the electrophoresis under alkaline conditions, the DNA fragments migrate to the anode side. The slides are stained with a DNA binding dye. Cells with increased DNA damage display increased migration of DNA fragments from the nucleus toward the anode, which resembles the shape of a comet. A suggestion for a standard protocol of the alkaline comet assay has been published recently in view to improve the predictive value of this assay to assess individual risk of disease (116, 117).

2.2.4 Biomarkers of Individual Susceptibility

Biomarkers of susceptibility are parameters that describe how variability of genetic and constitutional factors may modulate the individual risk developing an adverse effect in association with exposure to a toxicant. Often, susceptibility results from differing rates of enzyme involved in the activation of chemicals (Phase-I enzymes) or mainly in detoxification of chemicals by conjugating them with glutathione, glucuronide or sulfate to produce hydrophilic forms that are readily excreted (Phase-II enzymes). Genetic differences in the regulation, expression, and activity of metabolic genes

might be crucial factors in defining individual susceptibility, as well as in determining the toxic potential of chemicals. From the point of view of occupational medicine (74), these genetic polymorphisms may affect the toxicity of industrial and workplace chemicals and have a considerable influence on biological monitoring strategies and on human risk assessment (118–124) as illustrated in the following examples:

1. People with glucose-6-phosphate dehydrogenase deficiency have more fragile red cells than those with average human levels. They are thus more likely than the average person to develop anemia following exposure to oxidative insults (ROS) (125).
2. People with decreased concentrations of α -1-antitrypsin are more at risk than others of developing emphysema. This protease inhibitor protects the connective tissue of the lung from damage by the proteases that increase in activity when the lung becomes inflamed after exposure to toxicants such as dusts, cigarette smoke, and isocyanates (126, 127). Thus, low α -1-antitrypsin in blood is a biomarker of susceptibility to substances that may damage the lungs (128).
3. Two distinct *N*-acetyl transferase (NAT) enzymes, NAT1 and NAT2, play important roles in the bioactivation and detoxification of certain aromatic and heterocyclic amines. Genes encoding NAT1 and NAT2 are highly polymorphic among human populations, and these polymorphisms result in rapid or slow acetylator phenotypes. Several studies have suggested that variant alleles leading to slow acetylation by the NAT2 enzyme or rapid acetylation by the NAT1 enzyme constitute possible risk factors for bladder cancer (129–131). Adding to the complexity is that some aromatic amines are affected such as 4-aminobiphenyl, while others are not such as benzidine.
4. The glutathione *S*-transferase theta 1 gene (GSTT1) is a particularly attractive candidate for lung cancer susceptibility because of its involvement in the metabolism of PAHs found in tobacco smoke and of other chemicals, pesticides, and industrial solvents (132).
5. The polymorphism in the cytochrome P-450 isozymes might be crucial factors in defining the susceptibility, as well as in determining the toxicity of industrial products such as major solvents and monomers for plastics (133, 134).

Population frequencies of many polymorphic genes of pharmacogenetic interest depend on racial or ethnic characteristics (135). With current biological techniques and rapid development of molecular biology approaches, identification

of genetic polymorphism and screening of workers is not difficult. The most critical challenge; however, is to establish the ethical conditions to identify susceptible cases in the respect of the individual and with the objective of prevention and protection (see Section 3.4.3).

3 BIOLOGICAL MONITORING STRATEGY

3.1 Toxicokinetics

Biological monitoring of occupational exposure is a function of time, exposure, and individuals. The first aspect is illustrated in Figure 2, which shows the behavior of two different biomarkers under various exposure scenarios, that is, constant exposure (Figure 2a), constant occupational exposure (Figure 2b), and varying occupational exposure (Figure 2c). It is evident that biological levels change over time, and that half-life (5 and 50 hours) is a major determinant. In fact, toxicokinetic plays a key role in the relationships between exposure level, time, and biological levels. It is, therefore, important to have some knowledge in this

context in order to use biomarkers of exposure. The same is also true for biomarkers of effects, although their kinetics is much less understood compared to chemicals and their metabolites.

3.1.1 Rate Constant and Half-Life

At low exposure concentrations, the absorption, distribution, and elimination of xenobiotics can be considered as linear. In these conditions, elimination can be characterized by an overall first-order rate constant K , that is, in fact, the sum of k_i constants corresponding to individual elimination processes (renal, biliary, metabolic). Rate constants are proportionality coefficients between excretion rate ($\delta C/\delta t$) and concentration (C) of chemical in the compartment. In a one-compartment system:

$$\frac{\delta C}{\delta t} = KC$$

It is often easier to formalize elimination rate in terms of the half-life $t_{1/2}$. This is the time the chemical takes to reduce the concentration in the compartment by half (or in

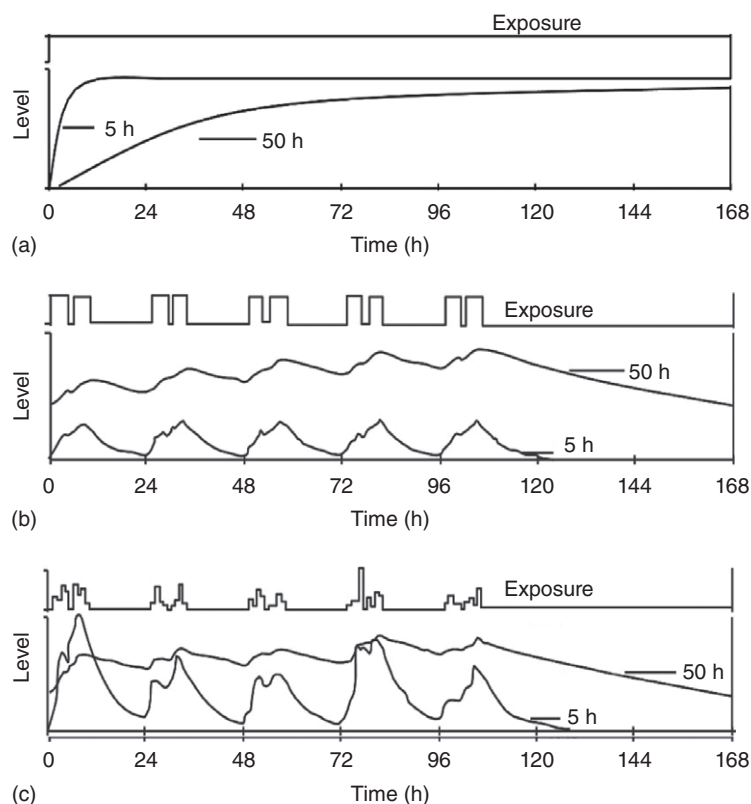


FIGURE 2 Evolution of biomarkers with half-lives of 5 and 50 hours in three exposure situations: (a) continuous exposure, (b) constant occupational exposure, (c) fluctuating occupational exposure (log-normal distribution with GSD 2.0). Source: From Droz and Wu (165). © 1991 Lewis publishers.

other words by a factor of 2). It can be calculated from K by:

$$t_{1/2} = \frac{\ln 2}{K}$$

K can be determined by observation of the decrease in biomarker concentrations over time for one-compartment behavior. This is an important parameter of a biomarker when planning a biological monitoring program. It is notably a key determinant of sampling time.

An apparent first-order rate constant (and its corresponding half-life) for multi-compartment systems can usually be defined at a given post-exposure time range. It is used to obtain experimentally the sampling time for the biomarker. This rate constant is, of course, somewhat dependent on the exposure regimen among others, but its order of magnitude is useful to discuss for the sampling strategy.

Table 1 gives examples of half-lives observed for biological indicators of some occupational toxicants and the consequent sampling time.

TABLE 1 Examples of half-lives of biological indicators of exposure.

Chemical	Biological indicator	Sampling time	Half-life (h)
Aniline	Total <i>p</i> -aminophenol in urine	End of shift	4
Benzene	Phenol in urine	End of shift	5.7
Cadmium	Cadmium in urine	Not critical	20 yr
	Cadmium in blood	Not critical	2400
Carbon disulfide	2-Thiothiazolidine-4-carboxylic acid in urine	End of shift	5
Carbon monoxide	Carboxyhemoglobin	End of shift	5
	CO in expired air	End of shift	5
	<i>N</i> -Methylformamide in urine	End of shift	4
Dimethylformamide	Mandelic acid in urine	End of shift/end of workweek	4
Ethyl benzene	Ethylbenzene in end-exhaled air	Prior to next shift	48
	2,5-Hexanedione in urine	End of shift	15
	<i>n</i> -Hexane in end-exhaled air	During shift	0.25
Lead	Lead in blood	Not critical	900
	Lead in urine	Not critical	700
	Zinc protoporphyrin in blood	After 1 mo exposure	500
	Methyl chloroform in end/exhaled air	Prior to shift/end of workweek	32
Methyl chloroform	Trichloroacetic acid in urine	End of workweek	72
	Total trichloroethanol in urine	End of shift/end of workweek	12
	Total trichloroethanol in blood	End of shift/end of workweek	12
	Methylethylketone in urine	End of shift	4
Methylethylketone	Cholinesterase activity in red cells	Discretionary	700
Organophosphorus cholinesterase	Total <i>p</i> -nitrophenol in urine	End of shift	7
Parathion	Cholinesterase activity in red cells	Discretionary	700
	Total pentachlorophenol in urine	Prior to last shift of the week	700
Pentachlorophenol	Free pentachlorophenol in plasma	End of shift	700
Perchloroethylene	Perchloroethylene in end-exhaled air	Prior to shift/end of workweek	96
	Perchloroethylene in blood	Prior to shift/end of workweek	96
	Trichloroacetic acid in urine	End of workweek	80
	Phenol in urine	End of shift	3.5
Phenol	Mandelic acid in urine	End of shift	4
Styrene		Prior to next shift	20
	Styrene in mixed-exhaled air	During shift	0.25
	Phenylglyoxylic acid in urine	End of shift	7
	Styrene in blood	End of shift	0.5
		Prior to next shift	13
		End of shift	0.5
Toluene	Toluene in venous blood	End of shift	0.5
	Toluene in end-exhaled air	During shift	0.25
Xylene	Methylhippuric acids in urine	End of shift	3.6
Trichloroethylene	Trichloroacetic acid in urine	End of workweek	75
	Trichloroethanol in urine	End of shift/end of workweek	12
	Trichloroethylene in end-exhaled air	Prior to shift/end of workweek	30

3.1.2 Clearance and Volume of Distribution

Clearance (Cl) is the measurement of the volume of plasma from which a substance is completely removed per unit time (e.g. ml min^{-1}) or the flow rate of blood totally cleared of a chemical compound. This can be in a given organ or group of organs, or in the organism as a whole. The total body clearance will be equal to the renal clearance + hepatic clearance + lung clearance. Clearance is a function of the kidney's ability to filter the specific compound; glomerular filtration, secretion from the peritubular capillaries to the nephron, and reabsorption from the nephron back to blood. The clearance is often simply considered as the renal excretion. Associated with the volume of distribution (V_d) of the chemical it permits to calculate the elimination rate constant k or the fraction of a chemical compound that is removed per unit time.

$$k = \frac{\text{Cl}}{V_d}$$

3.1.3 Saturable Kinetics

Toxicokinetics of chemicals of occupational interest can be considered linear in concentration ranges encountered in the workplace in most cases. In some situations, saturation in the kinetics can occur because of limited availability of necessary biological sites. Typically, this involves metabolic enzymes, protein binding, renal tubular secretion, or biliary secretion. These saturation processes can be exacerbated in some cases because of simultaneous exposure to other chemicals, medications, or drugs.

The kinetics of these capacity-limited systems is often described by the Michaelis–Menten equation

$$-\frac{\partial C}{\partial t} = V_m \frac{C}{K_m + C}$$

where $(-\delta C/\delta t)$ is the rate of elimination of a chemical, C is the chemical concentration, V_m is the maximum rate of the process, and K_m is the Michaelis–Menten constant.

In biological monitoring of exposure, an example of product for which saturation can occur is dimethylacetamide (DMAC) that is metabolized to *S*-(acetamidomethyl)mercapturic acid (AMMA) and monomethylacetamide (MMAC) through a saturable process (136) (Figure 3).

3.1.4 Modeling ADME (Absorption, Distribution, Metabolism, and Excretion)

Mathematical models have been developed to quantitatively describe the kinetic behavior of a biomarker (138). The simplest model is a one-compartment model and requires

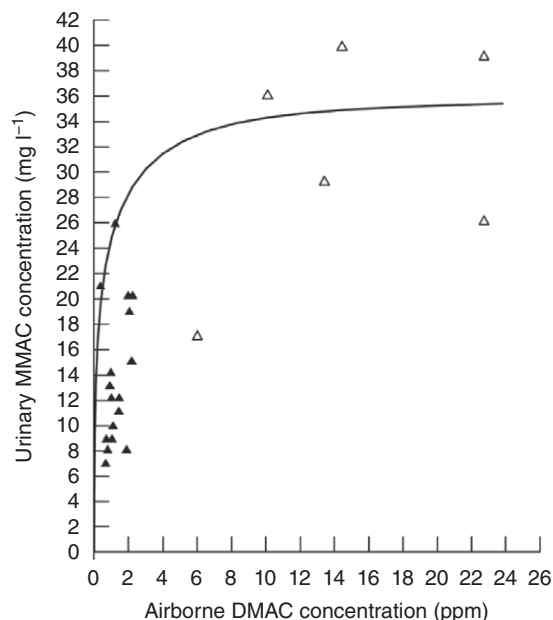


FIGURE 3 Excretion of monomethylacetamide (MMAC) in urine of workers exposed to dimethylacetamide (DMAC). The dependence of end-of-shift MMAC excretion on DMAC concentration in the air shows that MMAC can be used as a biomarker only for exposures lower than 5 ppm. MMAC excretion levels off at higher exposures and is no longer suitable for exposure monitoring. The triangles denote data from two different studies. Source: Adapted from Weber (135).

only a limited number of parameters. The model complexity increases with the number of required compartments added (two compartments, multi-compartments). The kinetic model describes the flow into and out of a central compartment. Adding physiological and metabolic parameters to the kinetic model will give a physiologically based pharmacokinetic (PBPK) model (139).

The simple one-compartment model describes how the chemical concentration varies over time $(\delta C/\delta t)$. The chemical concentration depends on absorption given the initial chemical concentration C_{expo} (rate constant k_a) and elimination (rate constant k_e) of the adsorbed chemical given the chemical concentration C at that time. Both processes; absorption and elimination, are considered first-order, and can be expressed mathematically as

$$\frac{\partial C}{\partial t} = k_a C_{\text{expo}} - k_e C$$

In a two-compartment model, additional compartments are added such as a peripheral compartment or storage compartment. The chemical concentration C_p in these compartments needs to be added, which depends on the transfer rate constants into (k_{cp}) and out of (k_{pc}) the

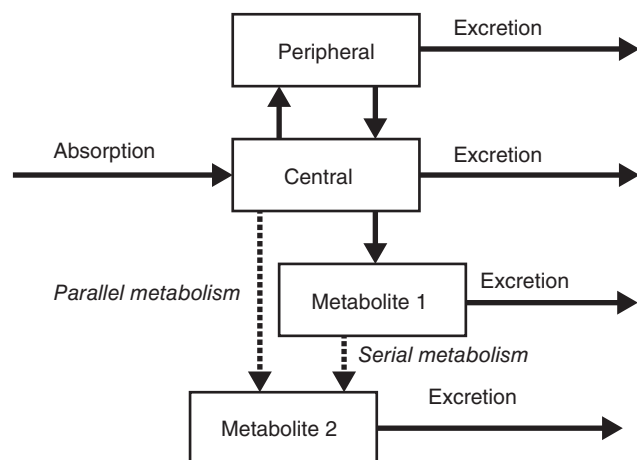


FIGURE 4 Example of a simple multi-compartmental model to describe the parent compound and its metabolites.

compartments. These transfer rates describe the exchange between the central and the peripheral compartment.

$$\frac{\partial C_p}{\partial t} = k_{cp}C - k_{pc}C_p$$

The two-compartment model equation is

$$\frac{\partial C}{\partial t} = k_a C_{\text{expo}} - k_e C - k_{cp}C + k_{pc}C_p$$

Figure 4 presents an example of a two-compartment model. The parent compound is absorbed into the central compartment, where it is excreted or distributed into a peripheral compartment. Here, it either flows back to the central compartment or is excreted. The parent chemical can flow from the central compartment and undergo metabolism. Metabolic transformations are separate compartments with their own rates. The metabolites can be produced in parallel or sequentially before they are excreted. Physiological and metabolic rates are model constants. This model can be considered as a simplified PBPK model. PBPK models can be used to understand the influence individual biological variability has on the exposure biomarkers (140–143).

Numerous validated PBPK models exist for certain chemicals (144–148). PBPK models have been used in risk assessment to extrapolate from animal to man, and between specific exposure scenarios. The mathematical expressions become quite elaborate as compartments are added. PBPK software can be used to build PBPK models. The PBPK software often has available kinetic data from the scientific literature integrated into the model structure such as physiological (air and blood flows, tissue volumes), physico-chemical (tissue affinity, membrane transport mechanisms),

and metabolic (clearance, Michaelis–Menten constants) data. PBPK models can be used to describe individual biological variability as mentioned already, but also to simulate different exposure scenarios (time, concentration, physical workload) (49, 50, 140, 149–153). There is a renewed surge of interest in the application of PBPK models by the regulatory agencies, especially in setting health-based tolerable intake or OELs.

3.2 Sources of Biomonitoring Variability

As shown in Figure 2, biological levels vary over time for a given worker, normally called intra-worker variability. This is, of course, also the case when considering different workers or so-called inter-worker variability. Consequently, an important characteristic of repeated biomarker measurements is variability. This variability can have several origins: analytical variability, biological variability (both inter- and intra-worker), and environmental variability (also inter- and intra-worker) (154). Analytical variability is usually managed and reduced by appropriate quality control programs and will not be addressed here.

3.2.1 Biological Variability

Absorption variability depends on the route of entry. Respiratory adsorption is mainly affected by the solubility of the chemical in the blood and interaction with the surface of the respiratory airways. Pulmonary ventilation will also play a role especially during heavy work. For example, solubility in blood varies from person to person and within a single individual, according to food intake and diet. These factors can thus modify the chemical concentrations in blood and breath. Skin absorption depends on the exposed area, the condition of the skin, and the humidity and temperature of the workplace. Gastrointestinal absorption depends on the stomach content.

Distribution of the chemicals in the body is primarily dependent on body size and composition. For example, lipid-soluble chemicals are distributed differently in slim and obese people. The extent of binding to macromolecules determines the amount of free chemical available for distribution and elimination. Binding varies between workers according to differences in protein concentrations. It can be altered in the presence of other chemicals or drugs competing for the same binding sites. Protein binding is usually capacity limited, therefore, in this case the behavior of biomarkers can show nonlinearities. Cadmium binding to metalloprotein in kidneys is an example of such a saturation (155, 156).

Metabolism is probably the most important source of biological variability. Genetic factors are known to play an important role in the metabolism of several chemicals.

Environmental factors also alter the ability to metabolize chemicals, both within an individual and between individuals. Metabolizing enzymes can be induced by smoking, medication, and absorption of other chemicals present in the environment or diet. Induction is usually a result of continuous or repetitive low exposure.

Simultaneous absorption of chemicals in relatively high doses, as in alcohol consumption, drug intake, or simultaneous occupational exposure to other chemicals can slow down the metabolism by inhibition (usually competitive) of the enzymatic systems. The rate of metabolism also depends on the rate at which the chemical is brought to the enzymatic system. Consequently, blood flow and protein binding can in some cases, induce a significant variability between and within individuals.

For chemicals and metabolites excreted via the lungs, the same parameters as for absorption play a role: pulmonary ventilation and cardiac output. Pulmonary ventilation will increase excretion with exhaled breath. Cardiac output can reduce the internal dose by bringing the chemical to the lung for lung excretion.

Renal excretion is the net result of three mechanisms: glomerular filtration, tubular secretion, and tubular reabsorption. Protein binding slows down excretion of chemicals and their metabolites excreted by glomerular filtration alone. For some chemicals (Cd, Cr), saturation of binding sites in the kidneys can greatly enhance urinary excretion. Tubular reabsorption of weak electrolytes is conditioned by urine pH, which changes their availability for reabsorption. The rate of fluid filtration is also of great importance since it changes the final concentration of the biomarker in urine. The effect of diuresis is partly reduced by relating the biomarker concentration, to urinary creatinine concentration or specific gravity. Finally, fecal excretion is only important for large molecular weight chemicals. This excretion pathway will not influence most biomarkers of exposure significantly.

These sources of variability will influence biological monitoring and make their interpretation challenging in certain cases. It must, however, be stressed that the objective is not to reduce variability but to explain it in a toxicological context (149, 157, 34).

3.2.2 Environmental Variability

Occupational exposures are known to vary, not only between workers but also for a given worker from day to day. Exposures vary within a work shift, depending on work processes and worker activities. Lognormal distributions are usually considered to describe these fluctuations. The effect this exposure variability has on the biological levels for a given worker depends on the kinetic behavior of the chemical in the body (33, 158, 159).

3.3 Consequences of Variability on the Strategy

Biological monitoring is affected by biological variability in factors such as physical workload, skin absorption, a chemical's partition coefficient, and individual anatomical, physiological, and biochemical differences determining the chemical's pharmacokinetics (160, 161). Biologically based mathematical modeling techniques can help in quantitatively accounting for and explaining the underlying biological variability of a biomarker. Consequently, these variabilities must be considered in the strategy for the biological monitoring program. For instance, the within worker variability is considered much smaller than between workers' variability and is simply neglected in calculations.

The most important implication of half-life for biological monitoring is in the selection of the sampling time. Many biomarkers of exposure have absorption, distribution, metabolism, and elimination kinetics following a multi-compartment behavior. Route of absorption will affect sampling time as skin absorption is often slower compared to uptake via the lungs from inhalation. Elimination might be later for workers with skin exposures. Sampling times for metabolites is usually later than if the parent compound is the biomarker because of the extra metabolism step. Elimination by exhaling the substance is very rapid while urinary elimination is slower. Sampling time should represent day or long-term average exposures. Biomarkers with a biological limit value has a specified sampling time while other biomarkers do not necessarily have a set sampling time.

For example, methyl chloroform or 1,1,1-trichloroethane [CAS no 71-55-6] is used as a solvent, a degreasing agent, and an intermediate in industry. Three biomarkers of exposure in urine or breath are available for determining exposures to methyl chloroform. These exposure biomarkers are described below and shown in Figure 5:

1. Methyl chloroform is excreted almost entirely unchanged through the lungs and the elimination process appears to be triphasic with half-lives 1, 5, and 32 hours. The mixed exhaled air concentration after exposure closely follows the venous blood concentrations. Methyl chloroform concentrations measured in exhaled air prior to shift are indicators of integrated exposures on the previous days. It is recommended to sample exhaled breath prior to last shift of workweek.
2. Trichloroethanol (TCOH) is produced by oxidation from a small fraction of methyl chloroform. Urinary excretion of TCOH accounts for 2–5% of total methyl chloroform uptake. TCAA concentrations in urine are indicators of integrated exposures on the monitoring

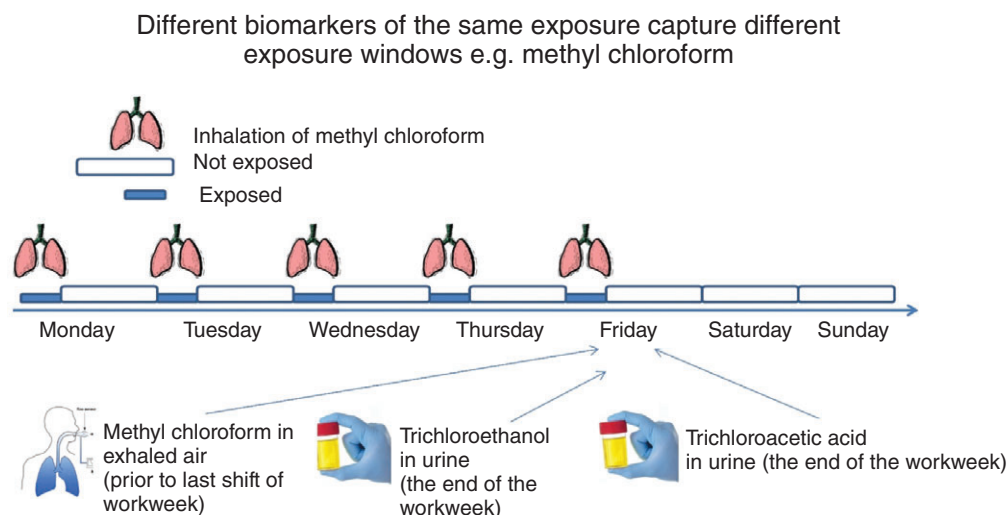


FIGURE 5 Biomonitoring can give you an excellent estimate of workplace exposure if you understand the biology and elimination kinetics of the biomarkers you will measure.

day and previous days. It is recommended to sample at the end of the workweek.

3. Trichloroacetic acid (TCAA) is produced by oxidation of TCOH. Urinary excretion of TCAA accounts for 1–2% of total methyl chloroform uptake. TCOH concentrations in blood and urine are indicators of recent exposure. It is recommended to sample at the end of the workweek.

Both TCOH and TCAA represent only a small fraction of the uptake and are highly variable, therefore, methyl chloroform in exhaled breath is the best indicator of exposure. It is recommended to sample prior to last shift of the workweek. This time is chosen in order to be in a time where the half-life is large enough to make the biomarker representative of chronic exposure time (Figure 6).

The variability observed in biological monitoring results for a given worker is the combination of biological variability (intra) and environmental variability (day-to-day). At a given sampling time, biological monitoring results would indicate a large variability if repeated sampling was collected for the same worker (33, 163). This is apparent in Figure 2. Biomarkers with short half-lives closely follow the environmental concentration and therefore have a larger variability. On the contrary, biomarkers with a long biological half-life fluctuate very little. Biomarkers with a short half-life tend to indicate recent exposures while biomarkers with long half-life integrate exposures over an extended time period.

The number of samples needed to make inferences about a worker population depends on the half-life, the biological variability, and the environmental variability. Air monitoring is largely affected by day-to-day variability in exposure and

the estimation of the long-term average exposure with confidence often requires a large number of samples (164). Using biomarkers with a long half-life in biological monitoring can average these day-to-day fluctuations; however, biological variability induces fluctuations independently of exposure changes. In a simple model, Droz and Wu (165) illustrated the number of samples required to test whether the exposure is below a given value (for example a biological limit value). Comparative results for sampling sizes necessary for air and biological monitoring are shown in Figure 6. The air monitoring values are shown as a horizontal dotted line, which are independent of the biological half-life. Four sets of exposure variables were considered for the input in the model. The number of biological samples required increased with increasing levels of biological variations or the coefficient of variability (CV). An average value with a CV of 0.3, and two extreme values of 0.1 and 0.9 representing an estimated 95% range for the individual variability are shown in Figure 6. The longer the half-life and the smaller the individual variability, the more reliable is the estimate for long-term average exposure. This model is only applicable to stationary exposures meaning when exposures do not change over time. The model illustrates that biological half-life and biological variability impacts the number of samples necessary to obtain a robust value for average exposures. There is a clear advantage of biological monitoring over air monitoring for chemicals with long half-lives. When biological variability is suspected of being linked to health effects, then the above discussion should also include toxicological considerations. There could, therefore, be cases where the indicator with the most residual variability might be a better choice.

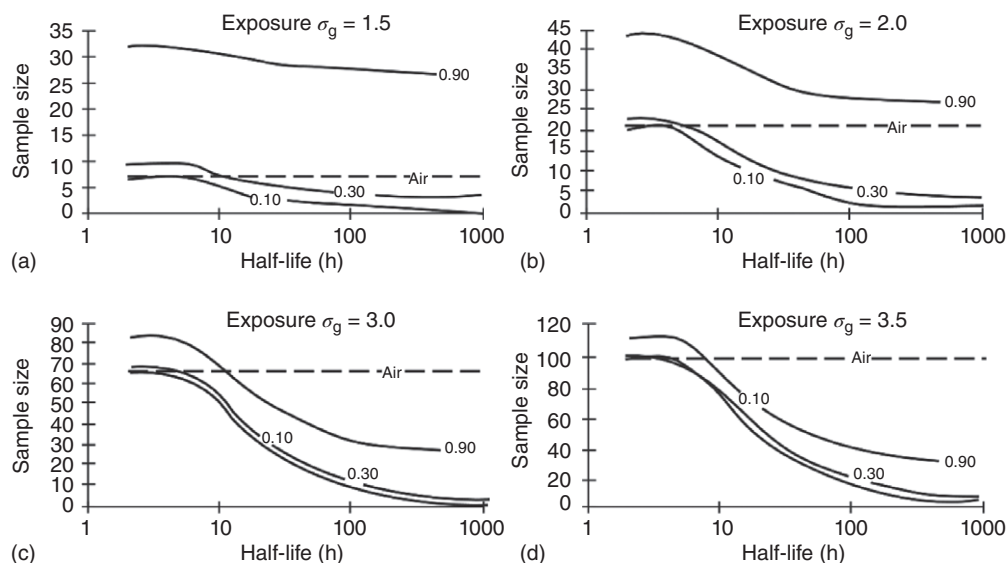


FIGURE 6 Predicted biological sample size as a function of half-life of the biological indicator for a given range of individual variability (CV 0.3, range 0.1–0.9). Broken line indicates predicted sample size for air monitoring (8 h average). Plot (a) is for low exposure variability with a variance (sigmag) of 1.5, plot (b) for medium exposure variability with a variance of 2.0, plot (c) has twice as much variability compared to plot (a) with a variance of 3.0, and plot (d) has high exposure variability with a variance of 3.5 (162). Source: From Droz et al. (162) © 1991 Taylor & Francis.

3.4 Reference Values for Biological Determinants

Already in the nineteenth century, the presence of solvents and their metabolites, as well as the presence of metals, was observed in the urine and blood of individuals exposed to certain industrial pollutants. However, it was not until 1980 that biological monitoring was recognized as a powerful tool for occupational hygiene, and that reference values for biological monitoring of occupational exposure were established and used to protect workers' health.

3.4.1 History and Concepts of Reference Values

Following is a brief history of biological monitoring and reference values of biomarkers for occupational exposure to industrial chemicals in the United States, Europe, particularly Germany, France, Finland, and Japan. These countries were selected because of the crucial differences in their concepts of reference values. Although the concept of reference values varies from country to country, the values are in the same order of magnitude.

Biomonitoring values are often derived within the legal framework of the country. The derivation of these values is, in general, based on the correlation between the air concentration and the biomarker concentration. High correlation signifies that inhalation is the primary route of entry, while low correlation indicates other routes of exposure. Biomonitoring

where correlation coefficients were high, have little added value to air sampling, while moderate to low correlations with air sampling results signify other routes of entry. This especially where biomonitoring is interesting as it takes into account bioavailability and bioactivation and reflects internal dose.

3.4.1.1 THE UNITED STATES The initiative in promulgating reference values for biomarkers was taken by the professional organization ACGIH. The need for BLVs for industrial exposure was first published by ACGIH in its Threshold Limit Value (TLV) booklet in 1973 (ACGIH 1973), but no action was taken to recommend any reference value until 1982, when ACGIH established the Biological Exposure Indices Committee (BEIC). That Committee recommended the first biological exposure indices (BEIs) for six pollutants, which were published in the 1984–1985 TLV/BEI Booklet (ACGIH 1985), and the BEI list has since then been updated and new biomarkers added to it regularly. The 2018 TLV/BEI Booklet (ACGIH 2018) has a BEI recommendation for biomarkers for 51 industrial pollutants (see Table 2). ACGIH also publishes a series of documentations that explain the basis for each BEI. The documentations are updated from time to time and new BEIs are added, updated BEIs are deleted or modified (usually lowered) as new information is available.

TABLE 2 Reference values for biomarkers for ACGIH (2018) and DFG (2017).

Chemical	CAS number	Organization	Biomarker	Sampling time	Biological value	Value	
Acetone	67-64-1	ACGIH	Acetone in urine	End of shift	BEI	25 mg l ⁻¹	
		DFG	Acetone in urine	End of shift	BAT	80 mg l ⁻¹	
Acetylcholine esterase inhibitors		ACGIH	Cholinesterase activity in red cells	Discretionary	BEI	70% of individual's baseline	
		DFG	Acetylcholine esterase in the erythrocyte fraction of whole blood	End of shift/for long-term exposures: at the end of the shift after several shifts	BAT	Reduction of activity to 70% of reference value	
Acrolein	107-02-8	DFG	3-Hydroxypropyl mercapturic acid in urine	End of shift/for long-term exposures: at the end of the shift after several shifts	BAR (NS)	600 µg g ⁻¹ creatinine	
Acrylamide	79-06-1	DFG	<i>N</i> -(2-Carbonamideethyl)-valine in the erythrocyte fraction of whole blood	After exposure for at least 3 mo	EKA	Air (mg m ⁻³)	Biomarker (pmol g ⁻¹ globin)
						0.035	200
						0.07	400
						0.10	550
						0.15	800
						0.30	1600
					BLW	500	
					BAR (NS)	50	
			<i>N</i> -Acetyl- <i>S</i> -(2-carbonamideethyl)cysteine in urine	End of shift	BAR (NS)	100 µg g ⁻¹ creatinine	
Acrylonitrile	107-13-1	DFG	<i>N</i> -(2-cyanoethyl)-valine in the erythrocyte fraction of whole blood	After exposure for at least 3 mo	EKA	Air (mg m ⁻³)	Biomarker (µg l ⁻¹ whole blood)
						0.3	16
						0.5	35
						1	60
						7	420
					BAR (NS)	0.3	
Alkali chromates (CrVI)		DFG	Chromium in the erythrocyte fraction of whole blood	End of shift/for long-term exposures: at the end of the shift after several shifts	EKA (NW)	Air (mg m ⁻³)	Biomarker (µg l ⁻¹ whole blood)
						0.03	9
						0.05	17
						0.08	25
						0.10	32
			Chromium in urine	End of shift/for long-term exposures: at the end of the shift after several shifts	EKA (W)	Air (mg m ⁻³)	Biomarker (µg l ⁻¹)
						0.03	12
						0.05	20
						0.08	30
						0.10	40

BIOLOGICAL MONITORING OF EXPOSURE TO INDUSTRIAL CHEMICALS

Aluminum	7429-90-5	DFG	Aluminum in urine	For long term exposure, at the end of the shift	BAT	50 µg g ⁻¹ creatinine	
4-Aminobiphenyl	92-67-1	DFG	4-Aminobiphenyl released from hemoglobin conjugated in the erythrocyte fraction of whole blood	After exposure for at least 3 mo After exposure for at least 3 mo	BLW BAR (NS)	NA2 15 ng l ⁻¹	
Aniline	62-53-3	ACGIH	Aniline in urine ^a	End of shift	BEI	-	
			Aniline released from Hb in blood	End of shift	BEI	-	
		DFG	<i>p</i> -Aminophenol in urine ^a	End of shift	BEI	50 mg l ⁻¹	
			Aniline in urine after hydrolysis	End of shift	BAT (C)	500 µg l ⁻¹	
			Aniline released from aniline-Hb conjugate in the erythrocyte fraction of whole blood	After exposure for at least 3 mo	BLW	100 µg l ⁻¹	
Antimony and its inorganic compounds	7440-36-0 (antimony)	DFG	Antimony in urine	End of shift/for long-term exposures: at the end of the shift after several shifts	EKA BAT	Not established NA 1	
Arsenic and inorganic compounds	7440-38-2 (arsenic)	ACGIH	Inorganic As plus methylated metabolites in urine	End of workweek	BEI	35 µg As l ⁻¹	
		DFG	Inorganic arsenic and methylated metabolites in urine	End of shift/for long-term exposures: at the end of the shift after several shifts	BLW	50 µg l ⁻¹	
			Arsenic (+III) in urine	End of shift/for long-term exposures: at the end of the shift after several shifts	BAR	0.5 µg l ⁻¹	
			Arsenic (+V) in urine	End of shift/for long-term exposures: at the end of the shift after several shifts	BAR	0.5 µg l ⁻¹	
			Monomethylarsonic in urine	End of shift/for long-term exposures: at the end of the shift after several shifts	BAR	2 µg l ⁻¹	
			Dimethylarsinic in urine	End of shift/for long-term exposures: at the end of the shift after several shifts	BAR	10 µg l ⁻¹	
			Sum Arsenic (+III) + Arsenic (+V) + Monomethylarsonic + Dimethylarsinic in urine	End of shift/for long-term exposures: at the end of the shift after several shifts	EKA	Air (mg m ⁻³) 0.001 0.005 0.01 0.05 0.10	Biomarker (µg l ⁻¹) 15 30 50 90 130

(continued overleaf)

TABLE 2 (continued)

Chemical	CAS number	Organization	Biomarker	Sampling time	Biological value	Value
Barium compounds, soluble	7440-39-3 (barium)	DFG	Barium in urine	End of shift/for long-term exposures: at the end of the shift after several shifts	BAR	10 $\mu\text{g l}^{-1}$
Benzene	71-43-2	ACGIH	<i>S</i> -Phenylmercapturic acid in urine	End of shift	BEI	25 $\mu\text{g g}^{-1}$ creatinine
		DFG	<i>t,t</i> -Muconic acid in urine	End of shift	BEI	500 $\mu\text{g g}^{-1}$ creatinine
			<i>S</i> -Phenylmercapturic acid in urine	End of shift	EKA	Air (mg m ⁻³) Biomarker ($\mu\text{g g}^{-1}$ creatinine)
						0.1 1.5 (NS)
						0.2 3 (NS)
						0.5 5
						1.0 12
						2.0 25
						3.3 45
						6.5 90
					BAR (NS)	0.3
			<i>t,t</i> -Muconic acid in urine	End of shift	EKA	Air (mg m ⁻³) Biomarker ($\mu\text{g g}^{-1}$ creatinine)
						1.0 300
						2.0 500
						3.3 750
						6.5 1200
					BAR (NS)	150
			Benzene in urine	End of shift	EKA	Air (mg m ⁻³) Biomarker ($\mu\text{g l}^{-1}$)
						0.1 0.5 (NS)
						0.2 0.8 (NS)
						0.5 1.5
						1.0 2.75
						2.0 5.0
						3.3 7.5
						6.5 12.5
					BAR (NS)	0.3
Benzidine	92-87-5	DFG	Benzidine adducts in plasma/serum and erythrocyte fraction of whole blood	After exposure for at least 3 mo	EKA	Not established
					BAR	NA1
			Benzidine in urine	End of shift/for long-term exposures: at the end of the shift after several shifts	EKA	Not established
					BAR	NA1

BIOLOGICAL MONITORING OF EXPOSURE TO INDUSTRIAL CHEMICALS

Beryllium and its inorganic compounds	7440-41-7 (beryllium)	DFG	Beryllium in urine	End of shift/for long-term exposures: at the end of the shift after several shifts	EKA BAR	Not established 0.05 µg l ⁻¹	
Bisphenol A	80-05-7	DFG	Bisphenol A after hydrolysis in urine	End of shift	BLW	80 mg l ⁻¹	
Boric acid and tetraborates	10043-35-3 (boric acid)	DFG	Boron in urine	Difference between pre and post shift	BAT	NA 1	
1-Bromopropane	106-94-5	DFG	S(<i>n</i> -propyl)mercapturic acid in urine	for long-term exposures: at the end of the shift after several shifts	EKA	Air (mg m ⁻³)	Biomarker (mg g ⁻¹ creatinine)
						5	2
						10	3.4
						25	7.0
						50	12.0
						101	20.0
1,3-Butadiene	106-99-0	ACGIH	1,2-Dihydroxy-4-(<i>N</i> -acetylcysteinyl)butane in urine	End of shift	BEI	2.5 mg l ⁻¹	
			Mixture of <i>N</i> -1 and <i>N</i> -2-(hydroxybutenyl)valine Hb adducts in blood	Not critical	BEI	2.5 pmol g ⁻¹ Hb	
		DFG	3,4-Dihydroxybutyl mercapturic acid in urine	End of shift/for long-term exposures: at the end of the shift after several shifts	EKA	Air (mg m ⁻³)	Biomarker (µg g ⁻¹ creatinine)
						0.45	600
						1.1	1000
						2.3	1600
						4.5	2900
						6.8	4200
					BAR (NS)		400
			2-Hydroxy-3-(<i>N</i> -butenyl mercapturic acid in urine	End of shift/for long-term exposures: at the end of the shift after several shifts	EKA	Air (mg m ⁻³)	Biomarker (mg g ⁻¹ creatinine)
						0.45	10
						1.1	20
						2.3	40
						4.5	80
						6.8	120
					BAR (NS)		<2
<i>n</i> -Butyl alcohol	71-36-3	DFG	<i>n</i> -Butyl alcohol in urine	At the beginning of the next shift	BAT	2 mg g ⁻¹ creatinine	
				End of shift	BAT	10 mg g ⁻¹ creatinine	

(continued overleaf)

TABLE 2 (continued)

Chemical	CAS number	Organization	Biomarker	Sampling time	Biological value	Value
<i>tert</i> -Butyl methyl ether	1634-04-4	DFG	<i>tert</i> -Butyl methyl ether in blood	End of shift	BAT	NA1
			<i>tert</i> -Butyl methyl ether in urine	End of shift	BAT	NA1
			<i>tert</i> -Butyl alcohol in blood	–	BAT	NA1
			<i>tert</i> -Butyl alcohol in urine	–	BAT	NA1
<i>p</i> - <i>tert</i> -Butylphenol	98-54-4	DFG	<i>p</i> - <i>tert</i> -Butylphenol after hydrolysis in urine	End of shift	BAT	2 mg l ⁻¹
Cadmium and its inorganic compounds	7440-43-9	ACGIH	Cadmium in urine	Not critical	BEI	5 µg g ⁻¹ creatinine
			Cadmium in blood	Not critical	BEI	5 µg l ⁻¹
		DFG	Cadmium in urine	Not fixed	BLW	NA2
			Cadmium in blood	Not fixed	BAR (NS)	0.8 µg l ⁻¹
Carbon disulfide	75-15-0	ACGIH	Cadmium in blood	Not fixed	BAR (NS)	1 µg l ⁻¹
			2-Thiothiazolidine-4-carboxylic acid (TTCA) in urine	End of shift	BEI	0.5 mg/g creatinine
		DFG	2-Thiothiazolidine-4-carboxylic acid (TTCA) in urine	End of shift	BAT	2 mg l ⁻¹
Carbon monoxide	630-08-0	ACGIH	Carboxyhemoglobin in blood	End of shift	BEI	3.5% of hemoglobin
			Carbon monoxide in end-exhaled air	End of shift	BEI	20 ppm
Carbon tetrachloride	56-23-5	DFG	Carboxyhemoglobin in blood	End of shift	BAT (NS, C)	5% of hemoglobin
		DFG	Carbon tetrachloride in blood	for long-term exposures: at the end of the shift after several shifts	BAT	3.5 µg l ⁻¹
Chlorinated biphenyls		DFG	Sum of PCB28, PCB52, PCB 101, PCB 138, PCB 153, PCB 180 in plasma	Not fixed	BAT	15 µg l ⁻¹
			PCB28 in plasma	Not fixed	BAR	0.02 µg l ⁻¹
			PCB52 in plasma	Not fixed	BAR	<0.01 µg l ⁻¹
			PCB101 in plasma	Not fixed	BAR	<0.01 µg l ⁻¹
Chlorobenzene	108-90-7	ACGIH	4-Chlorocatechol in urine ^a	End of shift at end of workweek	BEI	100 mg g ⁻¹ creatinine
			<i>p</i> -Chlorophenol in urine ^a	End of shift at end of workweek	BEI	20 mg g ⁻¹ creatinine
		DFG	4-Chlorocatechol after hydrolysis in urine	At the beginning of the next shift	BAT	25 mg g ⁻¹ creatinine
				End of shift	BAT	150 mg g ⁻¹ creatinine

BIOLOGICAL MONITORING OF EXPOSURE TO INDUSTRIAL CHEMICALS

1-Chloro-2,3-epoxy-propane (epichlorohydrin)	106-89-8	DFG	S-(3-Chloro-2-hydroxy-propyl)mercapturic acid in urine	End of exposure, for long term exposure	EKA	Air (mg m ⁻³)	Biomarker (mg g ⁻¹ creatinine)
						0.23	0.88
						0.5	1.75
						1	3.5
						2.3	8
						8	28
Chloroprene	126-99-8	DFG	3,4-Dihydroxybutyl mercapturic acid in urine	End of exposure, for long term exposure	BAR (NS)	400 µg g ⁻¹ creatinine	
Chromium (VI), water soluble fume	7440-47-3 (chromium)	ACGIH	Total chromium in urine	End of shift at end of workweek	BEI	25 µg l ⁻¹	
Chromium and its compounds		DFG	Total chromium in urine	Increase during shift	BEI	10 µg l ⁻¹	
				End of shift	BAR	0.6 µg l ⁻¹	
Cobalt and cobalt compounds	7440-48-4 (cobalt)	ACGIH	Cobalt in urine	End of shift at end of workweek	BEI	15 µg l ⁻¹	
		DFG	Cobalt in urine	End of exposure, for long term exposure	EKA	Air (mg m ⁻³)	Biomarker (µg l ⁻¹)
						0.010	6
						0.025	15
						0.050	30
						0.100	60
						0.500	300
					BLW		35
					BAR		1.5
Copper and its inorganic compounds	7440-50-8 (copper)	DFG	Copper in urine	–	BAT	NA 1	
				–	BAR	NA 3	
Cresol (all isomers):	1319-77-3	DFG	Cresol, sum of all isomers after hydrolysis in urine	End of shift	BLW	200 mg l ⁻¹	
<i>o</i> -Cresol	95-48-7						
<i>m</i> -Cresol	108-39-4						
<i>p</i> -Cresol	106-44-5						
Cyclohexane	110-82-7	DFG	1,2-Cyclohexanediol after hydrolysis in urine	End of exposure, for long term exposure	BAT	150 mg g ⁻¹ creatinine	
Cyclohexanol	108-93-0	ACGIH	1,2-Cyclohexanediol in urine ^a	End of shift at end of workweek	BEI	–	
			Cyclohexanol in urine ^a	End of shift	BEI	–	

(continued overleaf)

TABLE 2 (continued)

Chemical	CAS number	Organization	Biomarker	Sampling time	Biological value	Value	
Cyclohexanone	108-94-1	ACGIH	1,2-Cyclohexanediol in urine ^a	End of shift at end of workweek	BEI	80 mg l ⁻¹	
			Cyclohexanol in urine ^a	End of shift	BEI	8 mg l ⁻¹	
		DFG	1,2-Cyclohexanediol after hydrolysis in urine	End of exposure, for long term exposure	EKA	Air	Biomarker
						(mg m ⁻³)	(mg l ⁻¹)
						40	50
						80	100
4,4'-Diamino-diphenyl-methane	101-77-9	DFG	4,4'-Diaminodiphenyl-methane after hydrolysis in urine 4,4'-Diaminodiphenyl-methane released from hemoglobin conjugated in the erythrocyte fraction of whole blood	End of shift End of shift After exposure for at least 3 mo	BLW BAR BAR	200	250
						Air	Biomarker
						(mg m ⁻³)	(mg l ⁻¹)
						40	6
						80	12
						200	30
1,2-Dichloro-benzene	95-50-1	DFG	1,2-Dichlorobenzene in blood	Immediately after exposure	BAT	140 µg l ⁻¹	
			3,4- and 4,5-Dichloro-catechol after hydrolysis in urine	End of exposure, for long term exposure	BAT	150 mg g ⁻¹ creatinine	
1,4-Dichloro-benzene	106-46-7	DFG	2,5-Dichlorophenol after hydrolysis in urine	End of exposure, for long term exposure	EKA	Air	Biomarker
						(mg m ⁻³)	(mg g ⁻¹ creatinine)
						61	20
						122	40
Dichloromethane	75-09-2	ACGIH DFG	Dichloromethane in urine	End of shift	BEI	0.3 mg l ⁻¹	
			Dichloromethane in blood	Immediately after exposure	BAT	500 mg l ⁻¹	
				Immediately after exposure	EKA	Air	Biomarker
						(mg m ⁻³)	(mg l ⁻¹)
						35	0.1
						70	0.2
Di-(2-ethylhexyl) phthalate	117-81-7	DFG	Σ(MEHP+5-OH-MEHP + 5-oxo-MEHP + 5-cx-MEPP) after hydrolysis in urine	End of exposure, for long term exposure	BLW	175	0.5
						350	1
						4 mg g ⁻¹ creatinine	

BIOLOGICAL MONITORING OF EXPOSURE TO INDUSTRIAL CHEMICALS

<i>N,N</i> -Dimethyl acetamide	127-19-5	ACGIH DFG	<i>N</i> -Methylacetamide in urine	End of shift at end of workweek	BEI	30 mg g ⁻¹ creatinine	
			<i>N</i> -Methylacetamide + <i>N</i> -hydroxymethyl- <i>N</i> -methyl acetamide in urine	End of exposure, for long term exposure	BAT	30 mg g ⁻¹ creatinine	
<i>N,N</i> -Dimethyl- formamide	68-12-2	ACGIH	Total <i>N</i> -methylformamide in urine	End of shift	BEI	30 mg l ⁻¹	
			<i>N</i> -Acetyl- <i>S</i> -(<i>N</i> -methylcarbonyl) cysteine in urine	End of shift at end of workweek	BEI	30 mg l ⁻¹	
		DFG	<i>N</i> -Methylformamide + <i>N</i> -hydroxymethyl- <i>N</i> -methyl formamide in urine	End of shift	BAT	35 mg l ⁻¹	
Dimethyl sulfate	77-78-1	DFG	<i>N</i> -Methylvaline in the erythrocyte fraction of whole blood	After exposure for at least 3 mo	EKA	Air (mg m ⁻³)	Biomarker (µg l ⁻¹ whole blood)
						0.01	10
						0.03	13
						0.05	17
						0.20	40
1,4-Dioxane	123-91-1	DFG	β-Hydroxyethoxy acetic acid in urine	End of shift	BAT	400 mg g ⁻¹ creatinine	
1,2- Epoxypropane	75-59-9	DFG	<i>N</i> -(2-Hydroxypropyl)-valine in the erythrocyte fraction of whole blood	After exposure for at least 3 mo	EKA	Air (mg m ⁻³)	Biomarker (pmol g ⁻¹ globin)
						1.2	600
						2.4	1300
						4.8	2600
						6.0	3200
2-Ethoxy ethanol and 2-ethoxyethyl acetate	110-80-5 111-15-9	ACGIH	2-Hydroxypropyl mercapturic acid in urine	After exposure for at least 3 mo	BAT	2500	
				After exposure for at least 3 mo	BAR (NS)	10	
				End of exposure, for long term exposure	BAR (NS)	25 µg g ⁻¹ creatinine	
				End of shift at end of workweek	BEI	100 mg g ⁻¹ creatinine	
1-Ethoxy-2- propanol	1569-02-4	DFG	1-Ethoxy-2-propanol in urine	End of shift	BAT	NA1	
1-Ethoxy-2- propyl acetate	54839-24-6	DFG	1-Ethoxy-2-propanol in urine	End of shift	BAT	NA1	

(continued overleaf)

TABLE 2 (continued)

Chemical	CAS number	Organization	Biomarker	Sampling time	Biological value	Value	
Ethylbenzene	100-41-4	ACGIH	Sum of mandelic acid and phenylglyoxylic acid in urine	End of shift	BEI	0.15 g g ⁻¹ creatinine	
		DFG	Mandelic acid + phenylglyoxylic acid in urine	End of shift	EKA	Air (mg m ⁻³)	Biomarker (mg g ⁻¹ creatinine)
						44	130
						88	250
						110	330
						220	670
Ethylene	74-85-1	DFG	<i>N</i> -(2-Hydroxyethyl)valine in the erythrocyte fraction of whole blood	End of shift	BAT		
				After exposure for at least 3 mo	EKA	Air (mg m ⁻³)	Biomarker (µg l ⁻¹ whole blood)
						29	45
						59	90
						117	180
						NA1	
Ethylene glycol dinitrate	628-96-6	DFG	Ethylene glycol dinitrate in blood –		BAT	NA1	
Ethylene glycol mono-butyl ether/2-butoxyethanol	111-76-2	ACGIH	Butoxyacetic acid in urine ^a	End of shift	BEI	200 mg g ⁻¹ creatinine	
		DFG	Butoxyacetic acid after hydrolysis in urine	End of exposure, for long term exposure	BAT	150 mg g ⁻¹ creatinine	
Ethylene glycol mono-butyl ether acetate	112-07-2	DFG	Butoxyacetic acid after hydrolysis in urine	End of exposure, for long term exposure	BAT	150 mg g ⁻¹ creatinine	
Ethylene glycol monoethyl ether	110-80-5	DFG	Ethoxyacetic acid in urine	End of exposure, for long term exposure	BAT	50 mg l ⁻¹	
Ethylene glycol monoethyl ether acetate	111-15-9	DFG	Ethoxyacetic acid in urine	End of exposure, for long term exposure	BAT	50 mg l ⁻¹	
Ethylene glycol monomethyl ether	109-86-4	DFG	Methoxyacetic acid in urine	End of shift	BAT	15 mg g ⁻¹ creatinine	
Ethylene glycol monomethyl ether acetate	110-49-6	DFG	Methoxyacetic acid in urine	End of shift	BAT	15 mg g ⁻¹ creatinine	

BIOLOGICAL MONITORING OF EXPOSURE TO INDUSTRIAL CHEMICALS

Ethylene glycol monomethyl ether and Ethylene glycol monomethyl ether acetate	109-86-4 and 110-49-6	ACGIH	2-Methoxyacetic acid in urine	End of shift at end of workweek	BEI	1 mg g ⁻¹ creatinine	
Ethylene oxide	75-21-8	DFG	<i>N</i> -(2-Hydroxyethyl)valine in the erythrocyte fraction of whole blood	After exposure for at least 3 mo	EKA	Air (mg m ⁻³)	Biomarker (µg l ⁻¹ whole blood)
						0.92	45
						1.83	90
						3.66	180
Formic acid methyl ester	107-31-3	DFG	Methanol in urine	End of exposure, for long term exposure	BAT	NA1	
Fluorides		ACGIH	Formic acid in urine	—	BAT	NA1	
			Fluoride in urine	Prior to shift	BEI	2 mg l ⁻¹	
			Fluoride in urine	End of shift	BEI	3 mg l ⁻¹	
Furfural	98-01-1	ACGIH	Furoic acid in urine ^a	End of shift	BEI	200 mg l ⁻¹	
Halothane	151-67-7	DFG	Trifluoroacetic acid in blood	End of exposure, for long term exposure	BAT	2.5 mg l ⁻¹	
<i>n</i> -Heptane	142-82-5	DFG	<i>n</i> -Heptane in blood	—	BAT	NA1	
			2,5-Heptanedione in urine	—	BAT	NA1	
Hexachlorobenzene	118-74-1	DFG	Hexachlorobenzene in plasma or serum	Not fixed	BAT	150 µg l ⁻¹	
1,6-Hexamethylene diisocyanate	822-06-0	ACGIH	1,6-Hexamethylene diamine in urine ^a	End of shift	BEI	15 µg g ⁻¹ creatinine	
		DFG	1,6-Hexamethylene diamine in urine after hydrolysis	End of shift	BAT	15 µg g ⁻¹ creatinine	
<i>n</i> -Hexane	110-54-3	ACGIH	2,5-Hexanedione in urine ^b	End of shift at end of workweek	BEI	0.4 mg l ⁻¹	
		DFG	2,5-Hexanedione in urine plus 4,5-dihydroxy-2-hexanone in urine after hydrolysis	End of shift/for long-term exposures: at the end of the shift after several shifts	BAT	5 mg l ⁻¹	
2-Hexanone/methyl <i>n</i> -butyl ketone	591-78-6	ACGIH	2,5-Hexanedione in urine ^b	End of shift at end of workweek	BEI	0.4 mg l ⁻¹	
		DFG	2,5-Hexanedione in urine plus 4,5-Dihydroxy-2-hexanone in urine after hydrolysis	End of shift/for long-term exposures: at the end of the shift after several shifts	BAT	5 mg l ⁻¹	

(continued overleaf)

TABLE 2 (continued)

Chemical	CAS number	Organization	Biomarker	Sampling time	Biological value	Value	
Hexone/methyl isobutyl ketone	108-10-1	ACGIH	Hexone/methyl isobutyl ketone in urine	End of shift	BEI	1 mg l ⁻¹	
		DFG	Hexone/methyl isobutyl ketone in urine	End of shift	BAT	0.7 mg l ⁻¹	
Hydrazine	302-01-2	DFG	Hydrazine in urine	End of shift	EKA	Air (mg m ⁻³)	Biomarker (µg g ⁻¹ creatinine)
						0.013	35
						0.026	70
						0.065	200
						0.104	300
			Hydrazine in plasma	End of shift	EKA	0.130	380
						Air (mg m ⁻³)	Biomarker (µg l ⁻¹)
						0.013	27
						0.026	55
						0.065	160
Hydrogen fluoride and inorganic fluorine compounds (fluorides)	766-39-3	ACGIH	Fluoride in urine	Prior to shift	BEI	2 mg l ⁻¹	
		DFG	Fluoride in urine	End of shift	BEI	3 mg l ⁻¹	
				End of shift	BAT	5 mg l ⁻¹	
Iodine and inorganic iodides	7553-56-2 (iodine)	DFG	Iodine in urine	-	BAR	NA1	
Isopropyl alcohol/2-propanol	67-63-0	ACGIH	Acetone in urine	End of shift at end of workweek	BEI	40 mg l ⁻¹	
		DFG	Acetone in urine	End of shift	BAT	25 mg l ⁻¹	
			Acetone in blood	End of shift	BAT	25 mg l ⁻¹	
Lead and inorganic compounds	7439-92-1 (lead)	ACGIH	Lead in blood	Not critical	BEI	200 µg l ^{-1c}	
Lead and its compounds (except lead arsenate, lead chromate, and alkyl lead compounds)		DFG	Lead in blood	Not fixed	BLW	300 µg l ⁻¹ (women > 45 yrs and men)	
					BAR	70 µg l ⁻¹ (women)	

BIOLOGICAL MONITORING OF EXPOSURE TO INDUSTRIAL CHEMICALS

Lindane	58-89-9	DFG	Lindane in plasma/serum	End of shift	BAT	25 µg l ⁻¹
Lithium	7439-93-2	DFG	Lithium in urine	Not fixed	BAR	50 µg l ⁻¹
Manganese and its inorganic compounds	7439-96-5 (manganese)	DFG	Manganese in blood	End of shift/for long-term exposures: at the end of the shift after several shifts	BAT BAR	NA1 15 µg l ⁻¹
Mercury, elemental	7439-97-6 (mercury)	ACGIH	Mercury in urine	Prior to shift	BEI	20 µg g ⁻¹ creatinine
Mercury, and its inorganic compounds		DFG	Mercury in urine	Not fixed	BAT	25 µg g ⁻¹ creatinine
Mercury, organic compounds		DFG	Mercury in blood	Not fixed	EKA	Not established
Methanol	67-56-1	ACGIH DFG	Methanol in urine Methanol in urine	End of shift For long-term exposures: at the end of the shift after several shifts	BEI BAT	15 mg l ⁻¹ 30 mg l ⁻¹
Methemoglobin-forming substances		ACGIH DFG	Methemoglobin in blood Methemoglobin in blood	During or end of shift End of shift	BEI BAT	1.5% of hemoglobin NA1, values ≥1.5% methemoglobin indicate exposure to methemoglobin inducers
Methyl bromide	74-83-9	DFG	Bromide in plasma/serum	End of exposure, for long-term exposures: at the end of the shift after several shifts	BLW	12 mg l ⁻¹
			S-Methylcysteine albumin in serum	Not fixed	EKA	Not established
4,4'-Methylene bis-(2-chloroaniline)	101-14-4	ACGIH DFG	Total MBOCA in urine ^a 4,4'-Methylene bis-(2-chloroaniline) after hydrolysis in urine	End of shift End of shift	BEI BAR	– <1 µg l ⁻¹
4,4'-Methylene diphenyl diisocyanate (MDI), inhalable fraction	101-68-8	DFG	4,4'-Diaminodiphenyl-methane after hydrolysis in urine	End of shift	BLW	10 µg l ⁻¹

(continued overleaf)

TABLE 2 (continued)

Chemical	CAS number	Organization	Biomarker	Sampling time	Biological value	Value	
Methyl ethyl ketone/2-butanone	78-93-3	ACGIH	Methyl ethyl ketone in urine	End of shift	BEI	2 mg l ⁻¹	
		DFG	2-Butanone in urine	End of shift	BAT	2 mg l ⁻¹	
N-Methyl-2-pyrrolidone	872-50-4	ACGIH	5-Hydroxy-N-methyl-2-pyrrolidone in urine	End of shift	BEI	100 mg l ⁻¹	
		DFG	5-Hydroxy-N-methyl-2-pyrrolidone in urine after hydrolysis	End of shift	BAT	150 mg l ⁻¹	
Molybdenum and its compounds except molybdenum trioxide	7439-98-7 (molybdenum)	DFG	Molybdenum in plasma	-	BAT	NA1	
			Molybdenum in urine	-	BAT	NA1	
Naphthalene	91-20-3	ACGIH	1-Naphthol ^a + 2-naphthol in urine ^a	End of shift	BEI	-	
		DFG	1-Naphthol + 2-naphthol after hydrolysis in urine	End of exposure, for long-term exposures: at the end of the shift after several shifts	BAR (NS)	35 µg l ⁻¹	
2-Naphthylamine	91-59-8	DFG	2-Naphthylamine in urine	End of shift	EKA	Not established	
				End of shift	BAR	NA1	
			2-Naphthylamine adducts in the erythrocyte fraction of whole blood	After exposure for at least 3 mo	EKA	Not established	
1,5-Naphthylene diisocyanate	3173-72-6	DFG	1,5-Diaminonaphthalene in urine	After exposure for at least 3 mo	BAR	NA1	
				End of shift	BLW	NA2	
Nickel and its compounds	7440-02-0 (nickel)	DFG	Nickel in urine	For long-term exposures: at the end of the shift after several shifts	BAR	3 µg l ⁻¹	
Nickel (nickel metal, oxide, carbonate, sulfide, sulfidic ores)	7440-02-0 (nickel)	DFG	Nickel in urine	For long-term exposures: at the end of the shift after several shifts	EKA	Air (mg m ⁻³)	Biomarker (µg l ⁻¹)
						0.10	15
						0.30	30
						0.50	45

BIOLOGICAL MONITORING OF EXPOSURE TO INDUSTRIAL CHEMICALS

Nickel (easily soluble nickel compounds) (e.g. nickel acetate and similar soluble salts, nickel chloride, nickel sulfate)		DFG	Nickel in urine	For long-term exposures: at the end of the shift after several shifts	EKA	Air (mg m ⁻³)	Biomarker (µg l ⁻¹)
						0.025	25
						0.050	40
						0.100	70
Nitrobenzene	98-95-3	ACGIH	Methemoglobin in blood	See methemoglobin forming substances BEI	–		
		DFG	Aniline released from hemoglobin conjugated	After exposure for at least 3 mo	BLW	100 µg l ⁻¹	
Nitroglycerin	55-63-0	DFG	1,2-Glyceryl dinitrate in plasma/serum	End of shift	BLW	NA2	
			1,3-Glyceryl dinitrate in plasma/serum	End of shift	BLW	NA2	
Parathion	56-38-2	ACGIH	Total <i>p</i> -nitrophenol in urine	End of shift	BEI	0.5 mg g ⁻¹ creatinine	
			Cholinesterase activity in red cells	Discretionary	BEI	70% of individual's response	
		DFG	<i>p</i> -Nitrophenol after hydrolysis in urine	For long-term exposures: at the end of the shift after several shifts	BAT	500 µg l ⁻¹	
			Acetylcholine esterase activity in the erythrocyte fraction of whole blood	For long-term exposures: at the end of the shift after several shifts	BAT (C)	Reduction of activity to 70% of reference value	
Pentachlorophenol	87-86-5	ACGIH	Pentachlorophenol in urine ^a	Prior to last shift of workweek	BEI	-	
		DFG	Pentachlorophenol in plasma/serum	Not fixed	EKA	Air (mg m ⁻³)	Biomarker (µg l ⁻¹)
						0.01	17 ^d
						0.05	1000
						0.10	1700
			Pentachlorophenol after hydrolysis in urine	Not fixed	EKA	Air (mg m ⁻³)	Biomarker (µg l ⁻¹)
						0.01	6 ^d
						0.05	300
						0.10	600

(continued overleaf)

TABLE 2 (continued)

Chemical	CAS number	Organization	Biomarker	Sampling time	Biological value	Value
Perfluorooctane-sulfonic acid and its salts	1763-23-1	DFG	Perfluorooctanesulfonic acid in serum	Not fixed	BAT	15 mg l ⁻¹
Perfluorooctanoic acid and its inorganic salts	335-67-1	DFG	Perfluorooctanoic acid in serum	Not fixed	BAT	5 mg l ⁻¹
Phenol	108-95-2	ACGIH	Phenol in urine ^a	End of shift	BEI	250 mg g ⁻¹ creatinine
		DFG	Phenol in urine after hydrolysis	End of shift	BLW	200 mg l ⁻¹
Polychlorinated biphenyls		DFG	See chlorinated biphenyls			
Polycyclic aromatic hydrocarbons (PAHs)		ACGIH	1-Hydroxypyrene in urine ^a	End of shift at the end of workweek	BEI	2.5 µg l ⁻¹
			3-Hydroxybenzo(a)pyrene in urine ^a	End of shift at the end of workweek	BEI	—
		DFG	3-Hydroxybenzo(a)pyrene after hydrolysis in urine	At the beginning of the next shift	EKA	Air (mg m ⁻³) 0.07 0.35 0.7 1.0 1.5 0.3 µg g ⁻¹ creatinine
						Biomarker (ng g ⁻¹ creatinine) 0.7 2 3.5 5 7
			1-Hydroxypyrene after hydrolysis in urine	End of exposure, for long-term exposures: at the end of the shift after several shifts	BAR (NS)	
Iso-propyl benzene	98-82-8	DFG	2-Phenyl-2-propanol after hydrolysis in urine	End of shift	BAT	10 mg g ⁻¹ creatinine
Propylene glycol 1-methyl ether	107-98-2	DFG	Propylene glycol 1-methyl ether in urine	End of shift	BAT	15 mg l ⁻¹
Pyrethrum and pyrethroids	8003-34-7	DFG	<i>trans</i> -Chrysanthemumdicarboxylic acid, 4-fluoro-3-phenoxybenzoic acid, <i>cis</i> - and <i>trans</i> -3-(2,2-dichlorovinyl)-2,2-dimethylcyclopropanecarboxylic acid or <i>cis</i> -3-(2,2-dibromovinyl)-2,2-dimethylcyclopropanecarboxylic acid, all parameters after hydrolysis in urine	End of shift	BAT	NA1

BIOLOGICAL MONITORING OF EXPOSURE TO INDUSTRIAL CHEMICALS

Selenium and its inorganic compounds	7782-49-2 (selenium)	DFG	Selenium in serum	Not fixed	BAT	150 µg l ⁻¹	
Styrene	100-42-5	ACGIH	Mandelic plus phenylglyoxylic acid in urine	End of shift	BEI	400 mg g ⁻¹ creatinine	
		DFG	Styrene in urine	End of shift	BEI	y l ⁻¹	
			Mandelic plus phenylglyoxylic acid in urine	End of exposure, for long-term exposures: at the end of the shift after several shifts	BAT	600 /g creatinine	
Tetrachloroethylene	127-18-4	ACGIH	Tetrachloroethylene in exhaled air	Prior to shift	BEI	3 ppm	
		DFG	Tetrachloroethylene in blood	Prior to shift	BEI	0.5 mg l ⁻¹	
			Tetrachloroethylene in blood	16 h after end of exposure	EKA	Air (mg m ⁻³)	Biomarker (µg l ⁻¹)
						21	60
						69	200
						138	400
						206	600
						344	1000
				16 h after end of exposure	BAT		200
Tetra ethyllead	78-00-2	DFG	Diethyllead in urine	End of shift	BAT	25 µg l ⁻¹ , as Pb	
			Total lead, (also applies for mixtures of tetraethyllead with tetramethyllead) in urine	End of shift	BAT	50 µg l ⁻¹	
Tetrahydrofuran	109-99-9	ACGIH	Tetrahydrofuran in urine	End of shift	BEI	2 mg l ⁻¹	
		DFG	Tetrahydrofuran in urine	End of shift	BAT	2 mg l ⁻¹	
Tetramethyllead	75-74-1	DFG	Total lead in urine	End of shift	BAT	50 µg l ⁻¹	
Toluene	108-88-3	ACGIH	Toluene in blood	Prior to last shift of workweek	BEI	0.02 mg l ⁻¹	
			Toluene in urine	End of shift	BEI	0.03 mg l ⁻¹	
			<i>o</i> -Cresol in urine ^a	End of shift	BEI	0.3 mg g ⁻¹ creatinine	
		DFG	Toluene in blood	Immediately after exposure	BAT	600 µg l ⁻¹	
			Toluene in urine	End of shift	BAT	75 µg l ⁻¹	
			<i>o</i> -Cresol in urine after hydrolysis	End of exposure, for long-term exposures: at the end of the shift after several shifts	BAT	1.5 mg l ⁻¹	
Toluene-2,4-diamine	95-80-7	DFG	Toluene-2,4-diamine after hydrolysis in urine	End of shift	EKA	Air (mg m ⁻³)	Biomarker (µg g ⁻¹ creatinine)
						0.0025	6
						0.01	13
						0.017	20
						0.035	37
						0.100 ^d	100 ^d
				End of shift	BAR	NA3	

(continued overleaf)

TABLE 2 (continued)

Chemical	CAS number	Organization	Biomarker	Sampling time	Biological value	Value	
Toluene-2,4-diisocyanate	584-84-9	DFG	Toluene-2,4-diamine after hydrolysis in urine	End of shift	BAR	NA3	
Toluene-2,4-diisocyanate or toluene-2,6-diisocyanate or as mixture of isomers	584-84-9 or 91-08-7	ACGIH	Sum of toluene-2,4-diamine and toluene-2,6-diamine in urine ^a	End of shift	BEI	5 µg g ⁻¹ creatinine	
<i>o</i> -Toluidine	95-53-4	DFG	<i>o</i> -Toluidine after hydrolysis in urine	End of shift	BAR (NS)	0.2 µg l ⁻¹	
Tri- <i>n</i> -butyl phosphate	126-73-8	DFG	Di- <i>n</i> -butyl phosphate in urine	End of shift	BAR	0.5 µg l ⁻¹	
1,1,1-Trichloroethane/methyl chloroform	71-55-6	ACGIH	Methyl chloroform in exhaled air	Prior to last shift of workweek	BEI	40 ppm	
			Trichloroacetic acid in urine	End of workweek	BEI	10 mg l ⁻¹	
			Total trichloroethanol in urine	End of shift at end of workweek	BEI	30 mg l ⁻¹	
			Total trichloroethanol in blood	End of shift at end of workweek	BEI	1 mg l ⁻¹	
		DFG	1,1,1-Trichloroethane in blood	At the beginning of next shift after several shifts	BAT	550 µg l ⁻¹	
Trichloroethylene	79-01-6	ACGIH	Trichloroacetic acid in urine	End of shift at end of workweek	BEI	15 mg l ⁻¹	
			Trichloroethanol in blood ^b	End of shift at end of workweek	BEI	0.5 mg l ⁻¹	
			Trichloroethylene in blood	End of shift at end of workweek	BEI	—	
			Trichloroethylene in exhaled air	End of shift at end of workweek	BEI	—	
		DFG	Trichloroacetic acid in urine	End of exposure, for long-term exposures: at the end of the shift after several shifts	EKA	Air (mg m ⁻³)	Biomarker (mg l ⁻¹)
						3.3	1.2
						33	12
						55	20
						60	22
						82	30
						109	40
						137	50
				End of exposure, for long-term exposures: at the end of the shift after several shifts	BAR		0.07

BIOLOGICAL MONITORING OF EXPOSURE TO INDUSTRIAL CHEMICALS

Trimethylbenzene (all isomers)		DFG	Dimethyl benzoic acid some of all isomers after hydrolysis in urine	End of exposure for long term exposure	BAT	400 mg g ⁻¹ creatinine	
1,2,3-Trimethyl- benzene	526-73-8						
1,2,4-Trimethyl- benzene	95-63-6						
1,3,5-Trimethyl- benzene	108-67-8						
2,4,6-Trinitro- toluene (all isomers and technical mixtures)	118-96-7	DFG	4-Amino-2,6-di-nitrotoluene after hydrolysis in urine	End of shift	BAR	<1 µg l ⁻¹	
			2-Amino-4,6-di-nitrotoluene after hydrolysis in urine	End of shift	BAR	<4 µg l ⁻¹	
Uranium	7440-61-1	ACGIH	Uranium in urine	End of shift	BEI	200 µg l ⁻¹	
Uranium and its hardly soluble inorganic compounds	7440-61-1 (uranium)	DFG	Uranium in urine	Not fixed	BAR	NA3	
Uranium compounds, soluble inorganic		DFG	Uranium in urine	Not fixed	BAR	NA3	
Vanadium and its inorganic compounds including vanadium pentaoxide	7440-62-2 (vanadium)	DFG	Vanadium in urine	End of exposure, for long-term exposures: at the end of the shift after several shifts	EKA	Air (mg m ⁻³)	Biomarker (µg g ⁻¹ creatinine)
						0.025	35
						0.050	70
						0.100	140

(continued overleaf)

TABLE 2 (continued)

Chemical	CAS number	Organization	Biomarker	Sampling time	Biological value	Value
Vinyl chloride	75-01-4	DFG	Thiodiglycolic acid in urine	End of exposure for long term exposure	EKA	Air (mg m ⁻³) 2.6 5.2 10 21 41 Biomarker (mg/24 h) 1.8 2.4 4.5 8.2 10.6 1.5 mg l ⁻¹
Vitamin K antagonists		DFG	Quick value in blood	At the beginning of the next shift Not fixed	BAR BAT (C)	Reduction to not less than 70%
Xylene (all isomers/technical or commercial grade)	1330-20-7 (isomers: 95-47-6, 106-42-3, 108-38-3)	ACGIH DFG	Methylhippuric acid in urine Methylhippuric acids (all isomers) in urine	End of shift End of shift	BEI BAT	1.5 g g ⁻¹ creatinine 2000 mg l ⁻¹

NS, nonsmokers; C, derived as ceiling value because of acute toxic effect; NW, not applicable for exposure to welding fumes; W, applicable for exposure to welding fumes; NA1, For this substance there is at present insufficient data for the derivation of a BAT value; NA2, For this substance there is at present insufficient data for the derivation of a BLW; NA3, For this substance there is at present insufficient data for the derivation of a BAR; BAR, Biologischer Arbeitsstoff-Referenzwerte

^aWith hydrolysis

^bWithout hydrolysis

^cRecommended female workers of child-bearing age to follow CDC reference value

^dValues obtained by extrapolation

Source: ACGIH (32).

BEIs are intended to be guidelines for the evaluation of potential health hazards in the practice of occupational hygiene. BEIs do not indicate a sharp distinction between hazardous and nonhazardous exposures. They are meant to be used for group evaluation rather than for evaluation of individuals, unless the individual is monitored regularly. They are the biological levels of biomarkers that would most likely be reached during occupational inhalation exposure to the TLV, that is, mean values that most likely result from inhalation exposures of eight hours a day five days a week, where it is sure that inhalation is the only route of entry.

The BEI and TLV Committees work together to make BEIs and TLVs compatible. The toxicokinetics provides a powerful tool to achieve this goal (137, 166, 167). This means that, assuming only inhalation exposure, the BEI and its corresponding TLV provide the same protection against systemic adverse effects. Biological monitoring provides earlier warning than air monitoring if skin exposures are likely. Repetitive measurements surpassing the BEI should be taken seriously even if the TLV is not exceeded. The same holds true if ingestion occurs in case of exposure to contaminants in the solid or liquid phase (dust, mist) (168, 169). In both cases, biological monitoring represents a better way to assess the occupational exposure.

Irreversible biochemical and functional changes are not recommended by ACGIH as biomarkers, because the abnormal values associated with such changes indicate a health injury that should be prevented before they occur.

About the time the first reference values were recommended by ACGIH, the governmental agency National Institute for Occupational Safety and Health (NIOSH) began promoting biological monitoring and published their recommendations in 1986. NIOSH's objectives are implementation of biological monitoring in risk assessment, environmental control, and the validation of biological monitoring in epidemiological studies.

NIOSH has drafted a new chapter entitled "Application of Biological Monitoring Methods for Chemical Exposures in Occupational Health" for publication in the NIOSH Manual of Analytical Methods (NMAM) (<https://www.cdc.gov/niosh/docket/review/docket301/pdfs/Revised-DART-NMAM-Biomonitoring-watermark-9-27-17.pdf>). NMAM was first published in 1974. Currently, in its Fifth Edition, the NMAM contains over 60 methods and 11 chapters that can be utilized by the occupational safety and health community to measure worker exposures.

3.4.1.2 EUROPEAN UNION Biological monitoring of occupational exposure has been practiced in Europe since World War II in a number of European countries, most actively in Czechoslovakia, Finland, Italy, Poland, and Sweden. International meetings have been over the years organized to share views and experiences on biological monitoring. The European Community Commission (ECC)

began promoting biological monitoring of environmental and occupational exposures in 1983 with its initial publication of a series of documentations on the toxicity and biological monitoring of seven industrial pollutants (<https://core.ac.uk/download/pdf/16513926.pdf>). The series, originally entitled "Human Biological Monitoring of Industrial Chemicals Series," was renamed in 1984 to "Biological Indicators For Assessment of Human Exposure to Industrial Chemicals". In 1999, it included six volumes containing information on biological monitoring of 40 pollutants (170–175). At that time, the ECC did not recommend any reference values but provided scientific bases on which each country could determine its own reference values (176). In 1995, the Scientific Committee on occupational exposure limits (SCOEL) of the EU was established by the European Commission. SCOEL was composed of experts delegated by member countries, and many of them belong to their National Committees. This favored the construction of a coherent and harmonized approach for setting BLVs. The methodology to develop propositions and recommendations of health-based OELs and BLVs has been published and is periodically revised (177) (online documents from the European Commission <https://circabc.europa.eu/faces/jsp/extension/wai/navigation/container.jsp> accessed 31 October 2018). The methodology is approved by the member states and the employers and employees organizations. The SCOEL advised the European Commission on OELs and presented their recommendations with the critical studies on which the recommendation was based (178). The EU Directorate-General (DG) for Employment, Social Affairs, and Equal Opportunities establishes OELs. EU Member States are obliged to implement national standards for all substances for which an OEL has been established. The proposed OELs and BLVs are based on the best available scientific evidence of potential health effects for the considered pollutant. The recommended BLVs may be health-based or biological guidance values (BGVs).

BLVs are reference values used for evaluating potential health risks in the practice of occupational health. Due to biological variability, an individual's measurement may exceed the BLV without incurring an increased health risk. If, however, the biological levels persistently exceed the BLV, or if the majority of measurements obtained from a group of workers at the same workplace exceed the BLV, the cause of the excessive values must be investigated and proper action taken to reduce the exposure. Exposures equal to the BLV generally do not affect the health adversely, when attained regularly under workplace conditions, except in cases of hypersensitivity. BLVs are the corresponding concentration of a biomarker likely observed in specimens collected from a worker exposed to the chemical in question at the OEL and exclusively by inhalation. BLVs were also developed for OELs that serve as protection against nonsystemic effects

(e.g. irritation or respiratory disorders) or for substances with other routes of absorption, in particular the skin.

BGVs are established where insufficient toxicological data exist and cannot support a health-based BLV. BGVs represent the upper concentration of the substance or a metabolite of the substance in any appropriate biological medium corresponding to a certain percentile (generally 90 or 95 percentile) in a defined reference population. The BGV may be equivalent to the detection limit of the biomonitoring method if background levels cannot be determined. The rationale for the BGVs are specified in the SCOEL documents. A value exceeding the BGV might help in identifying the need for an expert exposure evaluation of the working conditions.

In 2014 (179), the European Commission published the list of BLVs and BGVs, with 22 chemicals, including 5 metals or metal-containing substances (from cadmium, lead, mercury, and nickel), 16 organic chemical or mixture, and hydrogen fluoride, fluoride and its inorganic salts (<http://ec.europa.eu/social/keyDocuments.jsp?type=0&policyArea=82&subCategory=153&country=0&year=0&advSearchKey=recommendation&mode=advancedSubmit&langId=en> accessed 31 October 2018).

3.4.1.2.1 Germany The Commission for the Investigation of Health Hazards of Chemical Compounds in the Work Area is known as the MAK Commission (issued from the German Research Association DFG). This commission provides scientific advice to the DFG Senate, federal and state governments, parliaments and public authorities on health protection issues in connection with exposure to hazardous substances, particularly in the workplace.

In 1979, the MAK commission established a working group on derivation of threshold values in biological materials. The Commission published the first biological tolerance value (BAT) in 1981 (75) and has since updated and added new or corrected values each year. Since 2012, the evaluations have also been available online. Biological values include biological tolerance values (Biologische Arbeitsstoff-Toleranzwerte or BAT), BGV (Biologische Leit-Werte or BLW), biological reference values for workplace substances (BAR), and exposure equivalents for carcinogenic substances (Exposition-säquivalente für krebserzeugende Arbeitsstoffe or EKA) (available at: <https://onlinelibrary.wiley.com/doi/book/10.1002/9783527812127>).

In Germany, biomonitoring is part of a preventive occupational health care. The Commission establishes BATs and BLWs to enable a health risk evaluation for an individual originating from exposures to substances at work. BAT values are intended to protect employees from impairment of health at work. They provide a basis for deciding whether a workers internal dose may be harmful or not.

The BAT value describes the occupational-medical and toxicological derived concentration for a substance, its metabolites, adducts, or an effect parameter in the corresponding biological material at which worker's health is not adversely affected when the individual is repeatedly exposed during long periods. BAT values are based on a relationship between external and internal exposure or between the internal exposure and the resulting effect of the substance.

The BAT value is considered exceeded when the average concentration of the biomarker is greater than the BAT value in several individual examinations. Exceed BAT values prompts an occupational-medical and toxicological data evaluation for the worker. Adverse effects on health cannot necessarily be deduced from one single observation above the BAT value. This is not valid for acute toxicity, which is not be permitted at any time.

BLWs are derived for carcinogenic substances and for substances without sufficient data.

Chemical substances known or suspected to cause cancer in man are not given BAT values because it is not possible to specify safe levels for such substances in biological materials. These substances are, therefore, analyzed for the detection and quantification of an individual's exposure. For this purpose, the relationships between the concentration of the carcinogen in the workplace air and of the substance or its metabolites in biological material are investigated, and the exposure equivalents for carcinogenic substances or EKA are derived.

BARs are biological reference values, i.e. describe the background level of a substance present at the same time in a reference population of working age who are not occupationally exposed to this substance. The BARs are based on the 95th percentile disregarding effects on health.

The full list of DFG biological values (2017), including EKA, has been reported in Table 2.

The MAK Commission established a working group for analytical chemistry. This working group develops, verifies, and publishes analytical methods for the identification of hazardous substances at the workplace, their metabolites, or characteristic parameters of intermediary metabolism in human biological material. The analytical methods developed and validated by the working group are published, at regular intervals. Since 1985 over 200 analytically reliable and verified methods have been published in English as Analyses of Hazardous Substances in Biological Materials; and from 2005, under the title "The MAK Collection Part IV Biomonitoring Methods". Since 2012, the methods have also been available online (<https://onlinelibrary.wiley.com/doi/book/10.1002/3527600418>).

3.4.1.2.2 France In France, the Ministry of Labor determines the list of substances to be evaluated. The BLVs or Indicateurs Biologiques d'Exposition (IBEs) are issued by the French Agency for Food, Environmental and

Occupational Health & Safety (ANSES). A working group made up of selected scientific members to develop IBEs send their recommendations to the committee developing OELs. The OEL committee has to approve the IBE documents produced. Once adopted, the IBE document is sent for a two-month public consultations and comments addressed before final publication by ANSES. The IBE is the concentration of a biomarker that should not to be exceeded in workers. The IBE work group conducts a thorough literature search to identify all potential biomarkers and examine their relationships with health effects and air concentrations of the parent compound. The best biomarker is then selected. If a relationship between a biomarker and a critical effect exists, an IBE based on health effects is developed. If no such relationship exists, a search for a possible relationship between a biomarker and exposure to the parent compound is conducted. If found, then an IBE based on exposure can be developed. If a relationship between a biomarker and exposure does not exist, then no IBE is developed. Instead, a pragmatic IBE is developed, which serves to limit exposure to substances in the workplace. It does not mean, however, that no health effects are associated with exposure to the chemical. The IBE workgroup also develops biological reference values (BRVs). The BRV is the 95th percentile concentration of a biomarker observed in a nonoccupationally exposed adult population.

3.4.1.2.3 Finland The Finish Ministry of Social Affairs and Health's Decree on Concentrations Known to be Harmful (1214/2016: <http://julkaisut.valtioneuvosto.fi/handle/10024/79109>) have issued a list of 16 indicative and one binding (B-Pb) BLVs for chemical agents. Additionally, the Finnish Institute for Occupational Health (FIOH) recommends reference values and biological action limit values for additional chemicals. Reference values and biological action limit values recommended by FIOH are published online (www.ttl.fi/biomonitorointi, under *Analyysit ja näytteenotto-ohjeet*).

3.4.1.3 JAPAN In 1986, Japan established a Society for Research of Biological Monitoring to develop reliable analytical methods, establish reference values, and implement and promote biological monitoring. Since 1993, the Japanese Society for Occupational Health has promoted OELs for mercury, later adding lead, hexane, and 4,4'-methylenebis-(2-chloroaniline) (MBOCA). In 1989, the Ministry of Labor began promoting biological monitoring and accepted reference values recommended by the Society for Occupational Health as guidelines for monitoring exposures to lead and eight solvents. In 2017, Japan Society for Occupational Health updated the OELs and published their 2017–2018 list of OELs (180, 181). Twenty-one chemicals have occupational limits based on biological monitoring (OEL-B) and include four metals

and metal-containing compounds (cobalt, indium, lead, and mercury) and 17 organic chemicals, mostly solvents. In setting OEL-B, considerations are given to the exposure-effect and/or exposure-response relationships between biological monitoring values and health effects, or to the relationship between biological monitoring values and the corresponding airborne concentrations. It is recognized that air concentrations of chemical substances in the workplace will not closely be associated with OEL-B due to various factors, such as intra- and inter-individual variation in metabolism, social and personal habits, and working conditions. Consequently, measured values could exceed OEL-Bs even though exposure to the chemical substance is below the established OEL, and vice versa. Both OEL and OEL-B must be respected in the workplace. OEL-Bs apply when samples are collected at the appropriate sampling time and when workers are exposed to a single substance. For exposure to a mixture of substances, interactions in terms of absorption, metabolism, accumulation, excretion, and health effects must be considered.

According to Japan's Industrial Safety and Health Law, the employers are responsible for the occupational health of their workplace employees, and a physician (serving the workplace on a full-time or part-time basis) selects the biological monitoring program following the legal stipulation. In 2017, the Ministry of Health issued a list of 32 industrial chemicals for which the occupational health regulation in Japan stipulates the application of biological monitoring (Handbook of Industrial Safety and Health Law, 2017). The list contains 14 metals and metal-containing compounds (from arsenic, beryllium, cadmium, cobalt, antimony, indium, lead, manganese, mercury, nickel, and vanadium), 17 organic chemicals, and hydrogen fluoride. The physician can consult the Industrial Health Organization (IHO) when making a judgment regarding biological monitoring programs. More than 120 such IHOs are scattered all over Japan and form the National Federation of Industrial Health Organizations. At each IHO, at least one occupational health physician is present to answer related questions, often in reference to the OEL-B list issued by the Japan Society for Occupational Health, and perform chemical analysis. If a particular IHO cannot perform chemical analysis by themselves, leading IHOs and independent chemical analysis laboratories (some 90 in total) can accept the request for analysis on a commercial basis. Japan has a well-developed quality control program for the analysis of biomarkers in biological specimens and for the implementation of biological monitoring on a regular basis (181).

3.4.1.4 OTHER COUNTRIES A comprehensive survey of all the existing committees or boards in charge of developing biological exposure limits has not been carried out but it is assumed that there are a large number of such bodies throughout the world. In Russia and other countries

of Western Europe, in China and other Asiatic countries, in Australia and New Zealand, in South Africa, in Mexico, and in a few countries of South America there are professional societies related to Occupational Health and most probably, Scientific Committees are also working on OELs and BLVs. Communication and exchange with these countries may be difficult due to the language problem. In many cases, the ACGIH, the German Committee, and the SCOEL values are used as references.

3.4.2 *Quality Control*

Nowadays internal and external quality controls are parts of the total quality management of biological monitoring. A review of external quality assessment schemes (worldwide) has been made by Angerer (38), Jakubowski (177, 182), and Göen (183).

3.4.3 *Ethical Issues*

There are several significant ethical issues related to biological monitoring. Ethical issues should be considered at the preparation stage of any biomonitoring study. The consultations with the workers are of utmost importance as is the ethical review, followed by the quality of the study design, and the selection of noninvasive methods (184, 185). Respect for individuals, confidentiality, privacy, equity, fairness, discrimination, autonomy, nonmaleficence, and self-determination belongs to these ethical issues (186).

In the United States, there is great concern with infringement of confidentiality and possible abuse of information by employers when hiring and firing workers. Therefore, obtaining written consent from the employee is advisable.

In Europe, the protection of the individual "private sphere" has increased during this last decade with the development of the communication and information technology. In many European countries, the occupational hygienists cannot obtain biological samples such as urine to understand exposures because medical doctors are the only ones that can obtain biological samples. Consequently, it is pertinent in many countries for the occupational hygienist to work closely with the occupational physician to obtain the biological samples and their results. The physician and the occupational hygienist should interpret the biomonitoring results together.

Workers have the right to know their own results. It is compulsory in Europe to inform the workers about the health and safety issues related to their individual values. These legal requirements are used to communicate with the workers their own biological monitoring results. In Japan, the Ministry of labor has made it mandatory for workers to be immediately informed of their personal results (187). In Europe, the ethical concerns vary from country to country. The selection of workers on the basis of biomarkers of

individual susceptibility (188–192) is not allowed, and this is probably everywhere in the world. It is unknown, however, how this restriction is followed in different countries. The challenge to determine what information can and should be unveiled to workers, especially in case of exposure to carcinogenic or mutagenic agents should not be underestimated. In addition, the social consequences of human biomonitoring should also be considered (184).

4 BIOLOGICAL MONITORING PRACTICAL APPROACH

4.1 Common Biological Monitoring Media

The choice of a biological matrix depends on the chemical of interest, its persistence, and its half-life in the matrix (193). The most common biomonitoring media are blood, urine, and exhaled air. Biological monitoring programs are implemented with such measurements for screening and, if repeated at timed intervals, for monitoring either an individual or a group.

4.1.1 *Urine*

Urine is generally suitable when monitoring hydrophilic biomarkers of low molecular weight. Urine collects in the bladder before it is voided; hence, the concentration of biomarkers in a urine specimen represents the average excretion during the interval between voids.

Sampling urine for biological monitoring has several advantages. This noninvasive sampling method usually gives sufficiently large samples. Urine samples often require little clean-up before chemical analysis. The main disadvantage is that urine output is highly variable because an individual's water intake and loss (e.g. sweating, diarrhea) influences the urine volume.

4.1.1.1 URINE COMPOSITION Average daily urine output in adults is about 1.2 l (ranging between 0.6 and 2.5 l day⁻¹) and corresponds to a urinary flow rate of about 50 ml h⁻¹. A liter of urine contains about 50 g of solid metabolic end-products and electrolytes. The average specific gravity (density) for urine is 1.020 (ranging between 1.001 and 1.030). Urine is slightly acidic with an average pH of 6.0 (ranging between 4.6 and 8.0). Urine samples with values beyond the ranges of the above parameters indicate abnormal stress on renal function and are not suitable for biological monitoring.

4.1.1.2 RENAL CLEARANCE Kidney is the main organ that removes waste and water from the blood to form urine. The amount the body has cleared or eliminated is the difference of

the chemical's concentration in arterial blood (before it has circulated around the body) and venous blood (after it has passed through the body's organs). The removal efficiency of a compound from the body is measured in liters per time unit (L h^{-1} or ml min^{-1}) and called renal clearance.

4.1.1.3 STANDARDIZATION OF BIOMARKER MEASUREMENTS IN URINE To eliminate the effect of fluctuating urine flow rates, the urine volume and the time between urine voids can be recorded, and the excretion rate of the biomarker can be calculated as amount of biomarker per unit of time. However, collecting such samples, typically 24-hour urine samples, is impractical in field conditions and spot urine samples are generally preferred. Spot urine samples need to be normalized to take into account the diuresis variations that affect the biomarker concentration. A practical solution to normalize the urine results is to relate the excretion of the biomarker to the excretion of solids. Such adjustment can be either specific gravity (density) or creatinine excretion.

Specific gravity is the concentration of solids in urine and is indirectly related to the urine flow rate (194). Specific gravity measurement is simple using a refractometer; however, sedimentation occurring in the urine shortly after voiding makes the measurements in stored urine misleading.

The creatinine excretion rate in urine is more or less constant (about $1.0\text{--}1.6\text{ g d}^{-1}$) and is independent of diet, hydration, and diuresis. Creatinine normalization is used to compensate for variable diuresis for those substances whose urinary biomarker excretion kinetics parallel that of creatinine, i.e. for biomarkers excreted by glomerular filtration (such as phenols, glucuronides, and organic acids (195)). Normalizing with creatinine is unsuitable for biomarkers excreted by passive diffusion (tubular diffusion) or by other means independent of an active transport mechanism, such as for organic solvents and gases (i.e. benzene and glycol ethers). Creatinine concentration can also be used to discriminate between valid or invalid samples. Particularly, a urine sample is considered invalid when its creatinine concentration falls outside the range $0.3\text{--}3\text{ g l}^{-1}$, because is considered "too diluted" or "too concentrated" (195–197).

4.1.2 Blood

Blood concentration of parent compounds is the best indicators of internal exposure. Blood is the only specimen available for measurement altered enzyme activity (i.e. cholinesterase), or macromolecular adducts, such as those resulting from the interaction of the pollutant with hemoglobin (i.e. methemoglobin and carboxyhemoglobin). Blood may also be preferred when monitoring for some metals and chemicals poorly metabolized such as perchloroethylene and polychlorobiphenyls. The disadvantages are that blood sampling is an invasive practice, requires

specialized personnel to draw blood, and often requires a meticulous clean-up procedure complicating the analysis.

Blood distributes the pollutant from the site of entry (respiratory tract, skin, gastrointestinal tract) to other tissues, including to the excretory organs. The process reverses when the exposure ends and blood washes the pollutant and its metabolites from tissues and carries them to the excretory organs. A significant concentration gradient develops when blood passes through the absorption site or through the excretory organs. Thus, the passage of volatile pollutants through the lungs causes a significant concentration gradient between arterial and mixed venous blood. During exposure, the absorption of the pollutant increases its concentration in arterial blood. As the blood passes through the other organs, the pollutant concentration in blood decreases due to retention of the pollutant in the tissues. As a result, the concentration of the pollutant in regional venous blood is lower than in arterial blood. Following the exposure, the pulmonary washout and tissue washout have the opposite effect, the concentrations in venous blood being higher than in arterial blood. This difference has to be kept in mind when sampling for biological monitoring of volatile pollutants. Thus, concentrations of volatile biomarkers in venous blood collected from the vena cubitalis can differ from concentrations in arterial blood collected from the finger.

Skin absorption can induce local differences in biomarker concentration. For example, if one hand is immersed in a solvent, the concentration in blood collected from the arm with the immersed hand can be higher than the concentration in blood collected from the other arm (198, 199).

4.1.2.1 BLOOD COMPOSITION AND SAMPLING Biomarkers can be quantified in whole blood, cellular elements (red cells or lymphocytes), plasma, or serum. To obtain plasma, a tube with anticoagulant such as citrate, oxalate, EDTA, or heparin is used for blood sampling. The choice of anticoagulant depends on the biomarker and on the analytical method. Some biomarkers readily cross the cellular membranes and can be measured in plasma as well as in red cells. For example, solvents such as benzene, toluene, and trichloroethylene distribute evenly in blood, but their hydrophilic metabolites do not readily cross the cellular membranes and there is a concentration difference between plasma and red cells.

4.1.3 Exhaled Air

Biological monitoring based on analysis of exhaled air is limited to gases and vapors of stable, hydrophobic chemicals such as carbon dioxide and volatile organic compounds (VOCs). Exhaled air is not suitable for biological monitoring of unstable pollutants that decompose upon contact with body fluid in the respiratory tract; nor is it suitable for

monitoring of pollutants that dissolve in the mucus covering the walls of respiratory airways.

Inter-individual differences in the metabolic rate introduce variability in the concentration of the parent compounds in blood, and consequently, affect pulmonary excretion. Therefore, biological monitoring in exhaled air is more informative for poorly metabolized chemicals, such as perchloroethylene or methyl chloroform, than for monitoring of extensively metabolized chemicals, such as trichloroethylene. The main advantage of monitoring in exhaled air is the simple analysis requiring no clean-up procedure. VOCs also appear in exhaled air also after skin or gastrointestinal absorption (200, 201); this weakens the correlation between the concentration of pollutants in ambient air and in exhaled air.

4.1.3.1 EXHALED AIR COMPOSITION AND SAMPLING Exhaled breath is a mixture of air coming from the lungs (alveolar air) and of air held in upper respiratory airways (dead space) (202, 203). Because stable, poorly soluble gases and vapors are not absorbed in the upper respiratory tract, their concentration at the beginning of exhalation (i.e. air from respiratory airways) resembles the concentration in the ambient air. In the alveoli, the concentrations of volatile pollutants equilibrate with their concentration in arterial blood. At rest, the air from the upper respiratory tract (dead space) accounts for about one-third of the mixed-exhaled air. The dead space increases as the respiratory rate increases (198).

Precautions are necessary when collecting multi-breath mixed-exhaled air samples in large glass or plastic containers. The sampling container has to have minimal resistance, so that the sample is taken under normal breathing conditions. End-exhaled air samples are representative of alveolar air. The results from monitoring solvent exposure by breath analysis should be corrected for hyperventilation or hypoventilation and for dilution of alveolar air with dead space air. A proportional adjustment of the solvent concentration at the mean normal alveolar partial pressure of carbon dioxide, or P_{CO_2} , is made; alternatively, samples with a P_{CO_2} outside normal range may simply be disregarded (204). Exhaled air samples collected from persons with abnormal pulmonary function are not suitable for exposure monitoring.

4.1.4 Other Matrices

Virtually any tissue or fluid can be used for biomarkers determination. In recent years, several nonconventional matrices have been investigated. The most promising are exhaled breath condensate (EBC), saliva, and hair. Although interesting results have been reported, the current application of biomarkers in nonconventional specimens in occupational health practice requires further developments.

4.1.4.1 EXHALED BREATH CONDENSATE EBC is a matrix where biomarkers may be identified (205–209). EBC may be either thought of as a body fluid or as a fluid formed by cooling exhaled air. EBC has been used to study the pathophysiology of airway diseases and to determine airway inflammation (208, 209). EBC is a suitable matrix for assessing the biomarkers of oxidative stress in exposed workers (202, 203, 210, 211). It is also suitable for quantifying the levels of some pneumotoxic metals in the lung (212, 213), in particular chromium (214), cobalt, and tungsten (205, 215). As related in a recent review on this topic (202, 203), these studies suggest that metals can be measured in EBC from occupationally exposed workers with levels that correlate with biomarkers of lung damage, such as aldehydes derived from lipid peroxidation.

4.1.4.2 SALIVA The use of saliva as a diagnostic fluid is a relatively recent trend in the occupational health studies (216) (reviewed in (217) and (218)). The idea of using saliva is very attractive, as it can be used as a surrogate for blood for some biomarkers with the advantages of being less invasive, autonomous, safe, and simple. Standardized saliva collection uses readily available devices. Biomarkers of stress measured in saliva are associated with both chronic and acute stress. Chronic stress is measured by the salivary cortisol. This cortisol production is associated with the activation of the hypothalamic-pituitary-adrenal axis and by salivary IgA and lysozyme associated with the depression of the immune function. Acute stress is associated with activation of the sympatho-adreno-medullary system, which is reflected by salivary chromogranin A and α -amylase (219). Some studies suggest saliva sampling for exposure biomonitoring to pesticides (220–223); some heavy metals (224) such as arsenic (225), lead (226, 227) but only for elevated blood lead levels (228). Nevertheless, this matrix may be interesting and many compounds present in blood or urine can be detected in salivary samples. Their levels in saliva are usually much lower than in blood, which required sensitive analytical methods (229). The nonoccupational influence on background concentrations (230, 231) and compounds' half-lives in saliva need to be carefully characterized before they can be used in routine biomonitoring of exposed populations.

4.1.4.3 HAIR During past decades, hair analysis has found even broader applications in doping controls and drug abuse studies in forensic toxicology, clinical toxicology, and clinical chemistry and in evaluating environmental exposure to toxicants (232, 233). Hair matrix can be used to gain information on mid- or long-term exposures; considering about 1 cm of growth for month, the length of the hair lock determines the detection window. Hair samples were successfully applied to retrospective monitoring of exposure to heavy metals, in particular for arsenic (234–238). More recently, several studies using hair to assess pesticide exposures have

been published (239) (reviewed in (240)). In agriculture, where several pesticides are typically applied on crops at different times of the growing season, hair sampled before (pre-exposure sample) and after the season (post-exposure sample), can be useful for the evaluation of cumulative and aggregate exposure (238).

4.2 Time of Sampling

4.2.1 Urine

The urinary biomarker concentration rises during exposure and is usually the highest in specimens collected at the end of the exposure. Following exposure, the concentrations of biomarkers decline, with elimination half-lives typically ranging from 3 to 15 hours. For several small organic chemicals, urinary metabolites are indicators of recent exposure. Due to fast decline, the sampling time of the urine void must be carefully chosen to not miss this exposure peak and consequently, underestimate a worker's exposure. This is why the reference values, such as American BEIs or German BATs, usually have sampling times for the urine voids at the end of exposure or end of work shift or prior to the next shift. The sampling time for biomarkers with longer half-lives may be at the end of the workweek (i.e. 1-hydroxypyrene) or discretionary (e.g. metals).

4.2.2 Blood

Blood analysis determines the momentary concentration of the biomarker at the time of the blood collection. Thus, when collecting and analyzing blood for biological exposure monitoring, timing with respect to the exposure, sampling site, and blood specimen used for the analysis is even more critical than for urine and must be carefully chosen. For most organic chemicals, blood biomarker concentration rapidly rises during exposure and declines following the exposure. For biomarkers with a short half-life, the sampling time is critical. For low metabolized solvents, such as methyl chloroform and trichloroethylene, the half-life is longer. The best sampling time for chemicals that tend to accumulate is at the end of the workweek. This will incorporate exposures from previous days. The sampling time for biomarkers with long half-lives (e.g. Pb and other metals, hemoglobin adducts) is discretionary.

4.2.3 Exhaled Air

A pollutant's concentration in exhaled air during exposures fluctuates with the concentration of the pollutant in ambient air. At stable homogeneous exposures, the concentration of the pollutant in exhaled air rises and approaches the steady-state level. Biological monitoring during exposure is unnecessary, because measurements in

breath samples provide approximately the same information as measurements in ambient air collected in the respiratory zone. Immediately after exposure, the pollutant concentration in exhaled air declines very rapidly and it can be too difficult to manage sampling at this time. Conversely, exhaled air samples collected 16 hours after exposure to solvents (prior to the next shift) are preferable, as they contain the pollutants released from the fat and tissue depots, and reflect the average concentration during the previous exposure. However, these concentrations are about 100 times lower than the concentration during exposure and require sensitive chemical analytical methods that can quantify such low levels. Another issue with expired air sampling is contamination. To prevent contamination during sampling, the samples must be collected in an uncontaminated environment, and the worker must be instructed, and possibly trained, in how to exhale into the sampling container.

4.3 Criteria for Selection of a Biomarker

The selection of biomarkers, biological specimens, and the timing of sample collection depends on the purpose of the monitoring. For confirmation of overexposure, measurement in samples collected during or after the exposure is suitable, provided that the biomarker still persists in the body. Samples collected within the period of three half-lives following exposure are usually timely. For retrospective verification of past exposure(s), biomarkers with long half-lives, such as macromolecular adducts, are suitable.

For routine exposure monitoring such as exposure assessment and risk assessment, quantitative data for biological markers are necessary and sampling time must adhere to the indication given with the BLVs.

In selecting a biomarker for biological monitoring, the following factors should be considered:

- Specificity of the biomarker
- Sensitivity and background level of the biomarker
- Availability of an analytical method
- Stability of the sample and of the biomarker during storage and transportation

4.3.1 Specificity of the Biomarker

Specificity is very important for identification of the toxic pollutant (241). Parent compounds are usually the most specific indicators of exposure such as urinary benzene (242–245), although there are exceptions. For example, carbon monoxide in exhaled air may appear to be a specific biomarker of carbon monoxide exposure. However, it has been shown that the solvent methylene chloride is metabolized to carbon monoxide, which is then exhaled, thus both carbon monoxide in exhaled air and carboxyhemoglobin in

blood are not specific biomarkers; of course, this is relevant only in the case of co-exposure to both chemicals. Another example is the sum of mandelic and phenylglyoxylic acids in urine that are biomarkers of exposure to both styrene and ethylbenzene. Their use is recommended when only one of the two chemicals is polluting the workplace. Metabolites are usually less specific biomarkers than the parent compounds. For example, trichloroacetic acid occurs in urine following exposure to trichloroethylene, perchloroethylene, and methyl chloroform.

Nonspecific biomarkers may have an advantage if the exposure to be evaluated is co-exposure to several poorly identified pollutants that have a common biomarker related to the same adverse effect. For example, workers in the rubber industry are often exposed to several unidentified pollutants with similar metabolic mechanisms. Rubber industry pollutants can metabolize to electrophiles, which bind to glutathione. Consequently, total thioether concentrations have been suggested as a biomarker for evaluating exposures to these co-exposures (246). Another example is the nonspecific biomarker, acetylcholinesterase inhibition in erythrocytes, used as a screening test among agricultural workers exposed to mixtures of organophosphate pesticides. Similarly, methemoglobin in blood is a suitable biomarker for exposure to several amines and nitrocompounds that are readily absorbed through the skin.

Metals measured in blood or urine are biomarkers for evaluating exposures to that metal. However, some metals may have different forms/oxidation status affecting their toxicological properties. Therefore, when choosing a biomarker and its acceptable biological level these differences have to be kept in mind; consequently, also the analytical method must be carefully chosen. For example, organic and inorganic mercury have different sources of exposure, different toxicological properties, and different BLVs, and need to be assessed using different analytical methods.

4.3.2 Sensitivity and Background Levels

The biomarker must be present in the biological specimen in a measurable amount. This depends not only on the availability of a sensitive analytical method; it also depends on whether the biological level of the biomarker induced by the pollutant differs from its level in the general population. Deviation of the biological level of the biomarker induced by permissible exposure to the pollutant must be outside the range of its levels in the general population. Occupational exposures are decreasing in the industrialized world. Consequently, the worker population levels are approaching the wide range of exposures observed in the general population. The strength of biomonitoring lies in a sound study design where a worker is followed in time after establishing an individual baseline (which serves as his/her

own control). For industrial exposures, the work pattern offers many opportunities to explore work exposure as a contributing factor.

The dependence of the selection of biomarkers on the permissible exposure in the workplace is illustrated by benzene. The first ACGIH TLV for benzene, published in 1946, was 100 ppm. To monitor benzene exposure at that level, sulfates and phenol in the urine were widely used as biomarkers. Over the years, the TLV was lowered several times, in the 1970s being 10 ppm. To monitor benzene exposure at that level, sulfates were not suitable biomarkers, because the levels of organic sulfates among workers occupationally exposed to benzene were not different from the levels of endogenic sulfates, and urinary phenol was used instead. In 1990, after benzene was confirmed to be a human carcinogen, its TLV was lowered to 0.5 ppm, making phenol in blood and urine an unsuitable biomarker because of its increase in specimens collected from benzene-exposed workers was within the range of normal levels. In 1997, *S*-phenylmercapturic acid (SPMA) in urine was recommended as a suitable biomarker for monitoring of benzene exposures permissible in the workplace (ACGIH – TLV). Likewise, hippuric acid in urine as a biomarker for toluene exposure has been removed from both ACGIH BEI and DFG BAT lists, because the increase of hippuric acid excretion caused by exposure to the new TLV/MAK of 20 ppm is in the range of excretion of endogenic hippuric acid ($0.5\text{--}1.5\text{ g g}^{-1}$ of creatinine). Instead, urinary *o*-cresol and urinary toluene have been recommended as biomarkers of exposure to toluene (247–252).

4.3.3 Availability of Analytical Methods

The importance of selecting a suitable analytical method should not be underestimated. The laboratory should be able to demonstrate recent and frequent experience with the analysis of field samples in addition to participation in external quality assurance schemes. Gas chromatography (GC) and high-performance liquid chromatography (HPLC) interfaced with mass spectrometry (MS) detectors are the best instruments for the measurement of organic biomarkers. Collision cell technology coupled inductively plasma mass spectrometry (CCT-ICP-MS) and atomic absorption spectroscopy are usually the best choice for analysis of metals.

The sampling design includes contacting the laboratory to know if they have the right equipment and methods to analyze the specimen and biomarkers chosen. Nowadays, the assays for biological monitoring should be validated, to ensure adequate quality standards. Assay validation should be performed following international guidelines (for example, the Bioanalytical Method Validation Guidance for the industry of the US FDA, 2018 (253)). Here there are some questions to ask the laboratory:

- How specific is the method? And what can interfere with the measurements?
- Is the method sufficiently sensitive?
- What is the detection limit? What is the quantification limit?
- Is the precision of the method adequate?
- What size sample is required?
- Is the laboratory part in a quality control program?
- How much does the analysis cost?

It is preferable to choose the well-performing laboratory. If this is not possible either because the samples are unstable or there is no suitable place to perform sample clean-up then a laboratory in close proximity to the sampling site should be selected, so the samples can be quickly transported and analyzed in a timely manner.

4.3.4 *Stability of the Biomarker and Specimen*

Biological samples are rarely analyzed in the field; they are usually transported to a laboratory and analyzed a few days later. Preservation of biological specimens, avoidance of contamination, and stability of the samples must be assured. To attain such assurance (assuming that the biomarker is stable and nonreactive), the following questions must be answered:

- Are the sample containers made from material that will not contaminate the sample?
- Are the sample containers made from material that does not absorb the biomarker, or does not react with the biomarker?
- Are the containers adequately sealed to prevent loss of a volatile biomarker?
- Should the samples be transported and stored anaerobically? That is, must the samples occupy the entire volume of the container, or is air space allowed?
- What anticoagulant should be used for blood samples?
- Is the biomarker photosensitive? If it is, the samples should be transported and stored in dark, nontransparent containers.
- At what temperature should the samples be transported and stored?
- Does the analytical method require the samples to be treated immediately after collection (centrifuging of blood or acidifying or alkalizing of urine)?

The answers to the above questions depend on the biomarker, on the biological specimen, and on the analytical method. Advice should be sought from the laboratory on how to collect and transport the samples.

5 BIOLOGICAL MONITORING FOR METALS AND INORGANIC COMPOUNDS

Biomonitoring of metal exposure is usually performed by measuring the total metal content in the biological media, without the distinction of different chemical species. For example, both ACGIH and DFG suggest monitoring lead and its inorganic compounds by measuring lead in whole blood. For cobalt and its compounds, biomonitoring is routinely performed by determination of total cobalt in urine. For several metals, such as chromium (Cr), arsenic (As), and mercury (Hg), it has, however, become clear that different oxidation status/metal binding/organic vs. inorganic species, are associated with different toxicological properties (254). The differentiation of metals in different chemical species or oxidation status is called speciation of metals.

5.1 Some Examples

5.1.1 *Chromium*

Chromium (Cr) is present in the environment in two main oxidation states: Cr(III) and Cr(VI). Cr(III) is an essential element as it is needed for the regulation and metabolism of glucose, sugars, and fats. Cr(III) is thus considered nontoxic, while Cr(VI) has been recognized as a highly toxic elemental species on the basis of experimental and epidemiological evidence. It has been classified as a human carcinogen (255). Occupational exposures to Cr(VI) compounds may occur in the production of chromate pigments and dyes, stainless steel and other chromium alloys, paints used in the aeronautic and maritime industries as well as during electroplating and anodizing, cutting, finishing and welding of chromium alloys and stainless steel, and leather tanning.

The main route of absorption for Cr(VI) is inhalation. Typical exposures are from breathing dust, fumes, and mists. Biological monitoring of Cr(VI) and its salts is performed by quantifying total chromium in urine. Urinary chromium levels reflect both past and recent exposure, with daily accumulation throughout the workweek for the occupationally exposed subjects. This is not, however, an ideal approach to Cr(VI) exposure assessment, as both Cr(VI) and Cr(III) are eliminated in urine. Nevertheless, urine being a noninvasive sampling method that can be easily harvested in large amounts, the determination of urinary chromium is a practical and widely used approach (32, 54, 256). Chromium speciation such as Cr(VI) and Cr(III) has been determined in EBC collected from individuals who worked directly with chromium compounds (such as platers) (257–259).

5.1.2 Arsenic

Arsenic (As) is a metalloid and widely distributed in the environment. Arsenic exists in different chemical forms with different toxicological properties (260). While organic As (mostly arsenobetaine and arsenosugars) is regarded as nontoxic, inorganic As have acute and chronic toxicity in humans. Inorganic As has been classified as a human carcinogen and the target organs are the lungs, skin, and bladder.

Occupational exposures to inorganic As (As(III) and As(V)), occur in the manufacture and/or processing of many As containing products, e.g. nonferrous metal foundries, production of artistic glass, coal-fired power plants, semiconductor manufacturing, the production and use of pesticides and wood preservatives.

Environmental exposures to As occurs mainly through diet, with seafood containing both organic and inorganic As (261, 262). The speciation of As is necessary to separately quantify inorganic As from organic As. Both ACGIH and DFG recommend to quantify inorganic As and methylated metabolites (sum of As(III), As(V), monomethylarsonic and dimethylarsinic) in urine as biomarkers for occupational exposure to arsenic (32, 54). Unambiguous interpretation of biomonitoring results for risk assessment, however, necessitates a controlled dietary intake with exclusion of seafood intake the last days before urinary collection and quantification of As biomarkers (263, 264).

5.1.3 Mercury

Mercury (Hg) can be found in the environment in both organic and inorganic forms. Toxicity and target organs depend on the mercury chemical state. Elemental Hg has many applications in several industries: electrical, chemical, dentistry, to name a few. Inorganic Hg compounds are mainly used as catalysts in plastic manufacturing. Organic Hg compounds are used in medicine, pulp and paper industries, pesticide manufacturing, and for synthesis in chemistry. These compounds are either restricted or not allowed in several countries due to their severe toxicity but are still used in artisanal and small scale gold mining where occupational and environmental exposures to both metallic mercury and methyl mercury occurs in many parts of the world, including South-America, Africa and Indonesia, Philippines.

Monomethyl mercury is the main form of organic Hg. Dietary intake is the main human route of exposures to organic Hg especially from contaminated seafood and rice. Both ACGIH and DFG recommend biological monitoring of exposure to elemental mercury and its inorganic compounds by determining mercury in urine. The reason for selecting this specimen is that inorganic mercury is prevalent in urine. The speciation of mercury in hair for biomonitoring exposure to both inorganic and organic mercury has been recently

proposed. Mercury has a high affinity for hair, and this measurement reflects cumulative exposures (265–268).

5.2 Choice of Specimen and Analytical Method

Binding of metals to proteins can cause large differences between the concentration of the metal in the cellular fraction of the blood and its concentration in plasma or serum. Therefore, urine is usually preferred for biological monitoring of metals such as mercury, chromium, cobalt, cadmium, and vanadium. Inorganic lead is the only metal for which measurement in blood is preferred.

Hair may also be used but the sample preparation is considered as a sensitive step (269). Other specimens such as nails, teeth, and sweat are sometimes used but are not considered routine tools and the interpretation of the results is difficult.

Determining the metal content in biological fluids is a destructive sample process. The metal of interest is determined by eliminating the organic matrix followed by analyzing the free atom in the gaseous state. Atomic absorption spectrometry (AAS), inductively coupled plasma optical emission spectrometry (ICP-OES) and inductively coupled plasma mass spectrometry (ICP-MS) are used. The ICP allows simultaneous determination of most of the relevant metals in occupational settings. Consequently, multi-element biomonitoring studies are now feasible. ICP-MS is more sensitive and allows a more accurate assessment of lower metal concentrations compared to the other techniques (270). This is particularly useful in assessing the metal concentrations in the general population. Double focusing sector field inductively coupled plasma mass spectrometry (SF-ICP-MS) is one of the most selective variants of ICP-MS and can effectively correct for most spectral interferences. These methods allow the determination of the total concentration of metals, irrespectively from metal species. When metal speciation is desired, an additional sample preparation step is required. This step is added to separate the metal species using, for instance, solvent extraction or other chromatographic techniques such as HPLC (271, 272).

5.3 Factors Interfering with Biological Monitoring of Metals

5.3.1 Diet and Environment

The mineral composition of the diet and the source of proteins can affect the biological level of metals. Metals incorporated into the aquatic food chain can increase the metal levels in the human population consuming this food. This happened, for example, in Japan, when mercury was

discarded into Minamata Bay and was absorbed by the local fish population. Consequently, the body burden of Hg was found to be higher in the Japanese population, depending on the local fish diet, than in the population of other countries. Many heavy metals accumulate in seafood, and consequently, eating these increases the biological levels (273).

The mineral composition of drinking water can also affect the biological level of metals. This is the situation in northern Chile, where the soil is rich in arsenic. Arsenic enters the sources of drinking water and increases the body burden of the local occupationally unexposed population. This is also the case for Bangladesh, where there is a severe contamination of the soil (274).

Abnormal dietary and mineral water intake of essential metals, such as calcium, iron, zinc, and copper, can affect the biological levels of toxic metals and interfere with the balance between their intake and excretion. Imbalances of these essential metals may lead to malnutrition. Populations living in highly industrialized areas may have higher levels of some metals in urine or in blood due to a polluted environment (275). Cadmium concentrations in the general population in different countries are available (275–279). Precautions are necessary when assessing occupational exposures with biological monitoring in areas where the general population are also exposed to the metal of interest. This background concentration among the local general population, not expected to have an occupational exposure to the investigated metal, should be measured to properly attribute the metal exposures to occupational or environmental sources. Although, only a part of the total metal exposure can be attributed to occupational exposures, safe biological levels have to be respected regardless of the source of exposure.

5.3.2 *Other Factors Affecting Biological Levels of Metals*

A person's age affects the biological levels of metals. As a person gets older, biological levels tend to accumulate because of the presence of metals in the diet and environment (280). The binding of metals to tissue components usually is a saturable process. After the binding sites are saturated, the plasma concentration and urinary excretion of the metal suddenly rise. An example is the urinary excretion of cadmium, which suddenly rises after the capacity of the binding sites in the renal cortex is saturated and renal dysfunction begins.

The kidneys are the usual target organs of metals. Chronic as well as acute exposure to metals such as cadmium, lead, and mercury can cause kidney damage and alter the urinary excretion of metals and other biomarkers.

Lifestyle factors such as smoking are also known to influence the body burden of cadmium (281, 282). Co-exposure to more than one metal may have a complex effect on their respective concentrations in blood and urine. Competition

for binding sites results in changes in the distribution and excretion of any or all of the metals. Treatment with complex-forming agents, such as EDTA, DMPS, and DMSA, or taking of essential metal supplements, can increase urinary excretion of toxic metals.

5.4 **Current Reference Values for General Population**

Biological monitoring values for populations with occupational exposures are published by different agencies, and among these are ACGIH and DFG (see Section 3.4 and Table 2). Many metals do not have an occupational biomonitoring value. To interpret a worker's biological metal concentration without a biological monitoring reference value, a comparison is often made between the measured values with values obtained from the general population. Within a study, this could be the control group, while some countries are measuring general population values national health and nutrition examination survey (NHANES) that can be used for this purpose. Another calculated value is the Biomonitoring Equivalents (BEs) value. BE is defined as the concentration or range of concentrations of a chemical or its metabolite in a biological medium (blood, urine, or other medium) that is consistent with an existing health-based exposure guideline. These health-based exposure guidelines are derived by integrating available pharmacokinetics data with existing chemical risk assessments. BEs are published in the scientific literature (283–285).

5.5 **Inorganic Gases**

Biological monitoring of inorganic gases is not recommended, except for carbon monoxide. This is because inorganic gases are either irritants, such as chlorine and sulfur dioxide, or their acute toxicity is critical, as with hydrogen cyanide, hydrogen sulfide, nickel carbonyl, and arsine. Air monitoring is preferred, because the acute adverse effect is usually related to peak concentration in the ambient air.

The exception is carbon monoxide, for which sensitive and relatively specific biomarkers are available (Table 2). BEIs are recommended for carboxyhemoglobin in blood and carbon monoxide in exhaled air. A BAT is recommended only for carboxyhemoglobin.

5.6 **Other Inorganic Pollutants**

BEIs and BATs are currently available for fluorides and carbon disulfide. No other inorganic compounds have been considered for biological monitoring.

6 BIOLOGICAL MONITORING OF ORGANIC COMPOUNDS

Organic compound is a generic term to indicate substances containing carbon. Due to carbon's ability to form chains with other carbon atoms, millions of organic compounds are known. A few classes of carbon-containing compounds such as carbonates and cyanides, along with other exceptions such as carbon dioxide, are considered inorganic. Several organic compounds can be found as pollutants in occupational settings, such as VOCs, aromatic and halogenated hydrocarbons, glycol ethers, PAHs, perfluorinated compounds (PFCs), isocyanates, pesticides, and phthalates. The chemical-physical properties of these chemicals, their toxicological behaviors, as well as the biological monitoring strategies adopted to assess exposure and health effect are so diverse that only a global approach will be proposed here without specific details for each group of chemicals.

After exposure to organic compounds, a portion of the intake may be absorbed into the bloodstream, distributed among the organs and tissues, metabolized, and finally excreted. These steps of absorption, distribution, metabolism, and excretion (ADME) determine the toxicokinetic process of the chemicals in the body as illustrated in Figure 7.

In general, absorbed chemicals with short biological half-lives (nonpersistent chemicals) are eliminated in the urine as hydrophilic metabolites or, if they are volatile, are principally eliminated unmodified in the exhaled air (breath). Persistent chemicals, once absorbed and distributed, are stored in deposition sites such as adipose tissue (for organic chemicals) and bone and teeth (e.g. for lead). Their concentrations are in equilibrium with those in blood and are slowly eliminated (193). Hydrophobic pollutants metabolize to water-soluble compounds to facilitate the urinary excretion. The liver is the most efficient metabolizing organ, but other

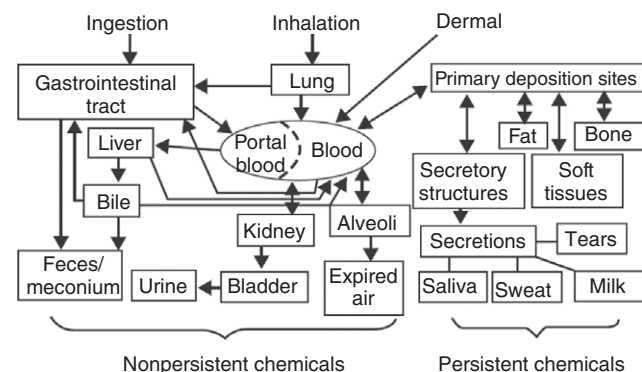


FIGURE 7 Absorption, distribution, metabolism, and elimination (ADME) of chemicals in the body. Source: From Needham et al. (193) © 2005 Springer Nature.

organs, such as the kidneys, skin, and bone marrow, can also mediate the metabolism of xenobiotics. The metabolic products are distributed by the blood throughout the body and are excreted via the kidneys. The metabolic intermediates of some compounds are electrophiles that covalently bind to glutathione (GSH) and to endogenous macromolecules. These metabolic products have to be biodegraded before they can be excreted. The persistence of biomarkers in the body determines whether the measurements in samples collected after the end of exposure are suitable for evaluating recent exposure or retrospective exposure. For example, the hydrophilic metabolites of most organic compounds are excreted within two days after exposure, while metabolic products with macromolecules persist in the body for weeks and even months (286).

6.1 Parent Compound

Measuring unmodified VOCs or solvents in blood or urine have been increasingly investigated with very interesting practical proposals for biological monitoring of exposed workers. Benzene is one example of measuring unmodified VOC in urine (243, 245, 287–293). These biomarkers are characterized by high levels of specificity; they may be justified for the monitoring of exposure to low levels of solvents or to solvent mixtures, and useful for facing ever decreasing limit values in the workplace.

Solvents are excreted via the kidneys by a diffusive process determined by the equilibration of partial pressure in the urine and blood. The steady state being reached rapidly, the concentrations in blood, and consequently in urine can be considered to be representative of the renal blood concentrations and ultimately of environmental levels (294). The bladder collects and holds the urine until voided. Thus, the concentration of a solvent in a urine sample collected at a given time represents an integration of the instantaneous concentration during the urine production and storage period (252, 295).

Quantitative analyses of organic solvents in urine have been performed using headspace with or without solid-phase microextraction headspace-solid phase microextraction (HS-SPME) and gas chromatography coupled with different systems of detection and quantification techniques such as flame ionization, electron capture, or mass spectrometry. The classical method requires no solvents and only a small volume of sample. It is noninvasive and shows high selectivity, sensitivity, repeatability, and linearity (250, 251, 296–298).

6.2 Eliminated Metabolites

Stable, hydrophilic metabolites are readily excreted in urine. Volatile metabolites are also exhaled. Excretion by other

elimination pathways is usually insignificant. Unstable reactive metabolites are either converted into stable metabolites and excreted in urine or detoxified by conjugation with glucuronic acid, sulfuric acid, or glycine. Styrene-(7,8)-oxide is an unstable metabolite from styrene exposure. This metabolite is further oxidized to mandelic acid and phenylglyoxylic acid, before urinary excretion. Conjugation products such as phenylglucuronide and phenylsulfate are often observed in urine from workers exposed to benzene or phenol, and hippuric acid in urine from workers exposed to toluene. Concentrations of stable metabolites in blood and urine rise and decline in parallel, reflecting the exposure of the tissues.

Chromatographic techniques are often used to quantify metabolites. Gas chromatography (GC) in combination with extraction (clean-up procedure) and derivatization of the metabolite(s) of interest are often used. Liquid chromatography (HPLC) is more common as it often avoids the derivatization step. HPLC lends itself particularly to separating highly polar and large molecular weight compounds that have very low volatility and, thus, cannot be separated by GC. The HPLC technique is also used in trace analysis where a concentration procedure is necessary, and the sample is reconstituted in a small volume of a liquid that can be directly injected into the HPLC. HPLC with a triple quadrupole mass spectrometry as the detector is a suitable system for targeted analysis of biomarkers with overall good selectivity and sensitivity.

6.3 Deactivation of Electrophilic Metabolites

Many industrially important organic chemicals entering the body are unstable or undergo biotransformation to highly reactive metabolic intermediates of electrophilic nature. These electrophilic substances covalently bind either to GSH, which are rapidly biodegraded to mercapturic acids (*N*-acetylcysteine conjugates) and excreted in urine or to macromolecules such as albumin, hemoglobin, and DNA to form adducts (299–301).

6.3.1 Glutathione Conjugates

Glutathione (γ -glutamyl-cysteinyl-glycine; GSH) is an endogenous tripeptide consisting of glutamic acid, cysteine, and glycine. It has a high affinity to electrophiles and competes for covalent binding with macromolecules. Conjugation with GSH occurs mainly in the liver, where GSH is produced and where most of the enzymatic activation of xenobiotics occurs. However, some less reactive electrophiles can cross the cell membranes, distribute in the blood through the body, and conjugate with GSH in remote tissues.

The conjugation of electrophiles with the SH-group of cysteine and glutamine cleavage is mediated by

GSH-transferase and gamma-glutamyl transpeptidases, respectively. The conjugated cysteine–glycine dipeptide is further degraded by dipeptidases, leaving cysteinyl residues that are acetylated by *N*-acetyltransferase to produce mercapturic acids. In humans, this mercapturic acid pathway takes place during hepatobiliary cycling. The catabolism of GSH-conjugate is relatively rapid, and the urinary excretion of mercapturic acids is usually completed within 10 hours after the end of exposure. Mercapturic acids are, therefore, indicators of recent exposure. Glutathione *S*-transferases (GSTs) are a supergene family and catalyze the conjugation of GSH to a variety of electrophiles including arene oxides, unsaturated carbonyls, organic halides, and other substrates GST (reviewed in (302)). The GST family is divided into four main mammalian classes: alpha (A), mu (M), pi (P), and theta (T). The classes GSTM1 and GSTT1 have received much attention because of the high prevalence of homozygous deletions resulting in null genotypes and therefore a decreased ability to detoxify carcinogenic/mutagenic compounds. This has been clearly observed in the metabolism of styrene, where the polymorphism of GST weakened the correlation between airborne styrene exposure and the urinary excretion of styrene-(7,8)-oxide mercapturic acids (303). This polymorphism has been supposed to increase the susceptibility to the toxic action of these reactive electrophiles in subjects bearing the null genotypes (304). Although, increasing numbers of studies trying to understand the impact of polymorphism on GSH conjugation have been published (304–309), the importance of the polymorphism for risk assessment is not yet understood.

6.4 Adducts with Macromolecules

Adducts of major interest for biomonitoring occupational exposure are DNA adducts detected in peripheral blood lymphocytes, hemoglobin adducts in peripheral red blood cells and albumin adducts in peripheral blood plasma. The macromolecular adducts persist in the body until the macromolecule is destroyed by catabolism. Because of their long dwelling in the body, macromolecular adducts are indicators of past exposure or of integrated exposure during the last months prior to sampling. Particularly, for peripheral blood lymphocytes, the turnover is more than 180 days; for hemoglobin, the turnover of red blood cells is about 120 days and for albumin about 24 days. It is assumed that adducts have kinetics that mirror that of the tissue. DNA adducts, besides being removed by catabolism, are also removed by the human body's DNA repair system. This system is an enzymatic mechanism to detect and remove the adducted nucleotides from the DNA. This process slows down the accumulation of DNA adducts in the body. The repaired DNA adducts last usually less than 24 hours. The DNA

repair products, that is the DNA base adducted with the electrophile, are excreted in urine.

6.4.1 Adducts with DNA

DNA adducts are indicators of mutagenic and carcinogenic potency of adsorbed pollutants (310–312). Their use in surveying workers is questionable, however, because their appearance signals an adverse effect that exposure monitoring is meant to prevent. Moreover, their level reflects not only the exposure to the pollutant but also the individual's ability to activate the pollutant and to remove the DNA products. Currently, no reference value has been proposed. Reasons for this may be that the laboratory assays to determine DNA adducts are labor-intensive and not yet standardized. Until now, DNA adducts have been used mostly in research protocols and have few applications in the practice of worker surveillance.

The most investigated DNA adducts are those of PAHs, that were used with mixed results for biological monitoring in industry where workers are exposed to mixtures of PAHs (313–317). Given the presence of PAH in tobacco smoke, smoking is likely to interfere with the determination DNA adducts of these chemicals (318).

Recent advancements of sophisticated chemical analytical methods have revived the DNA adducts as a measure of internal exposure to genotoxicants and a biomarker for human risk assessment (319). Ultraperformance liquid chromatography coupled with electrospray ionization ion-trap multistage mass spectrometry (UPLC/ESI-IT-MS) have been used to quantify specific DNA adducts, not only from fresh and frozen tissues but also from formalin-fixed paraffin-embedded tissues. This could potentially be used in analyzing archived pathology samples in molecular epidemiology studies designed to assess the causal role of exposure to hazardous chemicals with cancer risk (320).

6.4.2 Adducts with Proteins

Protein adducts as biomarkers for occupational exposure were first investigated by Osterman-Golkar et al. in 1976 (321). Protein adducts may be considered a surrogate of DNA adducts, as they are similarly produced by alkylation of proteins by electrophilic chemicals, but are much more abundant and do not undergo repair mechanisms. Most investigated proteins are hemoglobin and albumin from peripheral blood samples. Several studies have shown that blood levels of protein adducts reflect the degree of exposure to a specific pollutant (61, 286, 299–301, 310, 311, 322–327).

To bind to hemoglobin, the electrophiles have to penetrate the erythrocyte cell membranes, which the highly reactive electrophiles may be unable to do. Albumin, on the other hand, is present in serum and readily available for binding with the reactive intermediates released from

the metabolizing organs. Therefore, albumin adducts may be more abundant and more sensitive biomarkers than hemoglobin adducts. Furthermore, albumin is synthesized in the liver, where the enzymes mediating the metabolism of xenobiotics are mainly located. In spite of these advantages, hemoglobin adducts have found much wider application in biological monitoring than albumin adducts. The MAK Commission suggested hemoglobin adducts as biomarkers for monitoring of occupational exposure to several carcinogens (See Table 2). Hemoglobin adducts have been also used to monitor workers after accidental exposures to genotoxic agents (328); for example, ethylene oxide produces *N*-(2-hydroxyethyl)valine hemoglobin adducts. These adducts were formed within a day of exposure, based on observations of workers who were monitored following an accidental release (328).

6.5 Genetic Polymorphism in Enzyme Activity

In order to provide a better understanding of the impact of the metabolic polymorphisms on the individual risk to develop adverse effect, biomarkers of susceptibility have been incorporated into cohort studies.

There has been a proliferation of genetic information in the last 25 years resulting in a spectrum of existing and potential uses in the workplace. These uses have different issues and implications that may be more clearly considered in a framework that identifies three distinct uses (research, practice, and regulation/litigation) for inherited genetic factors and acquired genetic effects. While the biomarkers have promise of more refined risk assessments, there is possible dangers in incorporating this into routine biomonitoring concerning various ethical and social issues (186). These include stigmatization, discrimination, and removing a susceptible subject from the exposure without improving the workplace conditions.

Genetic polymorphism of metabolic enzymes has been found to have little impact on the metabolism of organic compounds and to explain only a small percentage of biomarkers variability. Based on these results, these polymorphism are of limited practical interest for risk assessment.

7 BIOLOGICAL MONITORING OF EXPOSURES TO MIXTURES

Although workers are commonly exposed to mixtures of chemicals, most of the studies in toxicology and biological monitoring include only single substances (329–333). In addition to workplace exposures, workers are also exposed from environmental pollution, food, medication, cosmetics,

and chemicals used in hobbies (e.g. pesticides when gardening, solvents in building, particles in woodworking). Potential influences of exposure to mixtures on biological monitoring are *toxicodynamic effects*, which affect the development of toxic endpoints, and *toxicokinetic interactions*, which modify the biological levels of the chemicals and their metabolites, thus changing the relationship between biological levels and exposure. Both of these types of effects should be considered when using biological monitoring.

7.1 Toxicodynamic Effects

By similarity with what is done in air exposure monitoring, four different cases can be distinguished.

No Interaction. Potential health effects are not expected to be different from what is observed for single exposures. Biological monitoring can be carried out as if exposure was for a single substance, and biological monitoring limit value can be applied.

Additivity. When the target site is the same for the different substances in a mixture, then additivity is often assumed. For air monitoring, a simple formula is proposed to combine the concentration (C) for each substance (i): C_i and the occupational exposure level values: TLV_i .

$$\frac{C_1}{TLV_1} + \frac{C_2}{TLV_2} + \dots + \frac{C_i}{TLV_i} \leq 1$$

Using a similar approach, a formula for biological monitoring (334) has been established. It combines the concentration of the biomarker i as MC_i , the background concentration as BC_i , and its reference value BEI_i .

$$\frac{MC_1 - BC_1}{BEI_1 - BC_1} + \frac{MC_2 - BC_2}{BEI_2 - BC_2} + \dots + \frac{MC_n - BC_n}{BEI_n - BC_n} \leq 1$$

This equation could be used for chemical biomarkers having similar health effects. However, it should not be used in the case of a metabolite common to several mixture components as in the case for trichloroacetic acid that is a metabolite of both trichloroethylene and methyl chloroform.

Synergism. When the likelihood of a health effect is increased by other components of the mixture, then the above equation does not apply and the situation should be left to professional judgment.

Antagonism. Similarly, when the likelihood of health effects is reduced by the presence of other component(s), no general rule can be established. Decisions should be taken on a case-by-case bases (professional judgment).

The most suitable biomarker is the most toxic, but this is sometimes not feasible. Take, for example, the biomarker for the carcinogenic mixture of PAHs. Although this is a carcinogenic exposure yet the commonly used biomarker is the metabolite 1-hydroxy pyrene, which is the metabolite of

pyrene, a non toxic PAH. The most toxic component of PAHs is benzo[a]pyrene (BAP) and its urinary metabolite is 3-hydroxy-BAP. Nevertheless, this is not normally measured, as it is excreted in very low quantities and laboratory methods cannot quantify these low levels. 1OHP is the most abundant urinary metabolite and pyrene exists in most PAH exposures which makes it a more suitable biomarker.

7.2 Metabolic Interactions

Exposure to mixtures of chemicals can also lead to toxicokinetic interactions, that is, quantitative modifications of the ADME processes. Competition between two or more substances for the same biotransformation enzymes might influence the relationship between the absorbed dose and the value of the relevant biomarker, although, this often occurs after a particular concentration threshold (329). The extent of the interaction between chemicals also depends on the extent of biotransformation of each compound. This might change an established association between the biomarker concentration in a given biological medium and the airborne concentration of the parent compound, which is often the basis for a BLV. Consequently, the BLV might not yield an appropriate value for monitoring exposure to a mixture (329).

At low exposures in well-controlled work environments, significant modification of lung absorption is unlikely. Exceptions, however, do exist for instance when a direct interaction between the contaminants in the air occur. Exposure to mixtures can modify the rate of skin absorption, and consequently, the biological levels. Elimination can be affected by exposure to mixtures, either via saturation of binding sites or by interaction in the biotransformation process.

7.2.1 Metabolic Interactions Among Pollutants

Exposure to mixtures are often encountered, especially to mixtures of organic substances. Organic substances in a mixture can, in some cases, be metabolized by the same enzymes and may saturate every active site. At saturation, the reaction rate reaches its maximum and no further rate increase occurs. This leads to inhibition of further metabolism is of course dependent on the exposure concentrations and is usually negligible at low exposures. Such inhibitions have been demonstrated in several cases under experimental conditions, for example, for xylene and ethylbenzene, for xylene and methylethylketone, and for benzene and toluene (334, 335). When combined exposures occur, it is important to investigate the specific case in detail.

Enzymes can be induced, meaning the metabolic activity of an enzyme increases either by binding to the enzyme and activating it, or by increasing the expression of the gene coding for the enzyme. Enzyme induction is a possible

bias in biological monitoring and can occur when exposure is combined with intake of inducers such as alcoholic beverages and medications, chlorinated insecticides, aniline, and some ketones.

7.2.2 *Competition for Binding Sites*

Chemicals or their metabolites may bind to proteins. As with enzymes, protein-binding sites are capacity limited. Therefore, at high concentrations saturation is possible, and consequently, the free protein fraction available for distribution and elimination is reduced.

Chemicals or their metabolites might compete for the same binding sites during exposure to mixtures, thus potentially increasing the unbound fraction of the chemical or their metabolites making either more available for distribution and excretion. Binding interactions for several metals including lead, cadmium, zinc, copper, and some essential metals have been studied (334).

7.2.3 *Effects of Alcohol Consumption*

Interaction with ethanol in workplaces is important to consider, as it is usually ingested in large quantities compared to other pollutants. At high doses, ethanol induces some enzymes, specifically the mixed ethanol oxidizing system (MEOS) that includes cytochrome P-450. Alcohol intake during or just after exposure will inhibit solvents' metabolism, producing an increase in solvents' concentrations in blood and a decrease in the metabolites formation. This has been studied for many chemicals under controlled conditions (153, 336): alcohols, aromatic hydrocarbons, glycol ethers, ketones. Inhibition of solvent metabolism decreases progressively when ethanol blood concentration decreases (337).

Ethanol can increase the enzymatic biotransformation of solvents; however, this is only expected to occur at high solvent exposure, since in most cases metabolism is blood flow limited.

7.2.4 *Effect of Medications*

Treatment with pharmacologic agents and simultaneous occupational exposure to chemicals is a largely unexplored field, probably because these two aspects relate to two different specialty areas. Many drugs of various structures are known to induce their own metabolism or the metabolism of chemicals. In certain cases, inhibition of biotransformation also occur. Both of these processes could lead to changes in biological monitoring results. Few data from studies among workers or with controlled volunteers are available to discuss the importance of medication on biomarkers. In the absence of such data, simulations using toxicokinetic models can be used (153, 338). An

application to four different organic solvents with realistic values has shown that biomonitoring results are sometimes quite sensitive to medication, either through changes in V_m (maximum rate achieved at saturating substrate concentration), K_m (substrate concentration at which the reaction rate is half of V_m) or liver blood flow. For example, hormonal contraceptives had an effect on the urinary levels of several biomarkers among women with an increase of more than 50% in metabolites concentrations and a decrease of up to 50% in unchanged substances concentrations, suggesting an increase in their metabolic rate (50). It is presently not possible to take into account quantitatively the influence of medication on biological monitoring results, but this should be recorded when sampling for biomarkers.

8 TRENDS AND CONCLUSIONS

During the last years, several meetings' reports or reviews on biomonitoring have been published with relevant information concerning current tendencies in this topic. A few relevant aspects are reported here to conclude this chapter. Biomonitoring was initially developed for the assessment of the health risks from exposure to chemicals at work, and the approaches and concepts of biomonitoring are derived from such occupational exposures. Nowadays, biomonitoring is also increasingly used to assess nonoccupational exposure from the environment for the general population (38, 337, 339). One of the major challenges is the reconsideration of the basis of biomonitoring action limits: until today, they have mostly been developed as point estimates of the highest concentration likely not to induce serious health effects for most of the workers (healthy adult population). In the modern risk assessment practices, a no-effect level is developed for the general population including children and sensitive individuals. The major difference between the worker health protection and the public health protection is that the first is based on scientific evidence (evidence-based medicine) and the latter on the precautionary principle (prevention when a doubt does exist before the absolute scientific evidence).

This actual emphasis on biomonitoring for assessing the general population's exposure to chemicals in the outdoor and indoor environments promotes the development of analytical techniques allowing increasingly lower concentrations of chemicals in biological fluids or tissues to be detected and quantified (184, 340, 341). However, if measuring chemicals in the human body becomes relatively easy, the interpretation and the communication of the results of the biomonitoring studies, represent a serious challenge (44, 340, 342–346). Recognizing this difficulty, the International Life Sciences Institute (ILSI) and the Health and Environmental Sciences Institute (HESI) established a Biomonitoring Technical Committee in 2002 to:

1. delineate the appropriate scientific uses of biomonitoring tools and/or biomonitoring data needed to characterize exposure to chemicals and
2. define the criteria needed for integration of biomonitoring and toxicology data into a robust risk assessment process (342, 347).

In the same perspective, European expert task force on biomonitoring has been setup at the request of the European Chemicals Industry Council (CEFIC) and the European Center for Ecology and Toxicology (ECETOC) to develop criteria for the consistent use of biomonitoring data and a risk-based framework and guidance on the interpretation of biomonitoring data for exposure and risk assessment purposes. In the report published in 2005 (348), a number of considerations are made that enable the relevance of any biomonitoring result to be interpreted reliably. The following four keys are required for any biomonitoring information used to evaluate health risks:

1. Analytical integrity including validated protocols, quality assurance, and control, adequate sample size.
2. Toxicokinetics including the timing of the samples, the knowledge of kinetics, and the related knowledge of exposure parameters (route of entry).
3. Health effects including the (in)ability to relate to effects (dose–response), and knowledge about mechanisms, potential confounders, and co-exposure.
4. Weight of evidence including the shape of the dose–response curve, and the nature of related findings, plausibility to the cause–effect relation.

The development and application of molecular genetic methodologies and other “omic” technologies in toxicology allowed the discovery of new biomarkers of exposure, susceptibility, and response as have been illustrated for benzene (e.g., see <http://omics.org>) (349). The OMICS field ranges from genomics (focused on the genome) to proteomics (focused on large sets of proteins, the proteome) and metabolomics (focused on large sets of small molecules, the metabolome). The field of genomics is divided into genotyping (focused on the genome sequence), transcriptomics (focused on genomic expression), and epigenomics (focused on epigenetic regulation of genome expression). In the future, contribution of the OMICS techniques to occupational and environmental health will help the field progress towards an integrated view of the interaction between environment and human health (350).

In the specific field of occupational exposure, the decreasing trend in exposure levels requires the research and the development of “novel” biomarkers as presented in previous sections. All these biomarkers require validation including the characterization of the background level. To

this regard, the production of reference values for the general population (with no occupational exposure) will be very useful to assess the health risk arising from occupational exposure (34).

One of the main goals of the field of “Occupational Health” is to protect the workers’ health and to promote their wellbeing. Biological monitoring is consolidating its value and usefulness to progress in this direction for the benefit not only of the workers and the companies but also for the whole community.

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REAL-TIME ASSESSMENT OF AIR CONTAMINANTS USING VIDEO EXPOSURE MONITORING (VEM) METHODS AND TECHNIQUES

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1 INTRODUCTION

1.1 Historical Development of Real-Time Assessment of Air Contaminants and Video Exposure Monitoring (VEM)

In 1985, three researchers from the National Institute for Occupational Safety and Health conducted an exposure assessment and control evaluation of the B.F. Goodrich Tire Plant, in Marietta, Ohio. What made this study unique was that it was the first time that a portable computer, a video camera video home system (VHS), and a real-time aerosol photometer were used, as a system, to gather second-by-second exposure data. In this instance, the evaluation of dust generated from a manual scooping task to make a wide range of customized products such as insulated wire for Trident submarines to wallpaper for hotels. This system required synchronization of time for all three pieces of technology: the computer to collect the second-by-second stream of airborne particle data, the video camera to link visualization of work tasks with the generation of airborne particles, and the data logger for the real-time aerosol photometer (1). The system was called video exposure monitoring (VEM).

The results presented a unique picture of exposure that could not be seen using traditional time-weighted average (TWA) sampling protocols for hazardous airborne agents. Figure 1a is a video screenshot showing the relative airborne dust levels from a drum scooping task when the drum was full. Figure 1b is a video screenshot showing higher airborne dust levels when the drum is half-full. The data were modeled to show that when the job was organized into work tasks of scooping, weighing the power, and turning away to put the filled bag of powder in a receiving drum the exposure to dust became a major hazard after half the drum was emptied of powder (Figure 2). Based on this information, the drum was cut in half, and the job streamlined to improve work flow and productivity, resulting in approximately 90% reduction in dust exposure and a work cycle that was reduced from approximately 90–30 seconds (see Figure 3a and b). This was the genesis case study in the United States that kick started VEM.

About the same time, and unknown to the National Institute for Occupational Safety and Health (NIOSH) team, another group in Europe was conducting similar research (Rosen et al.). They called their system picture mix (PIMEX). It took about two years for the two groups of

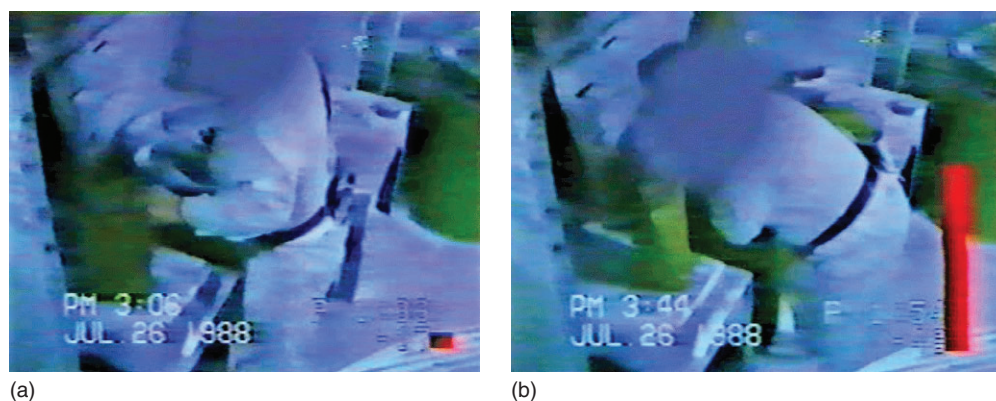


FIGURE 1 (a) Screen shot of drum scooping task: drum is full of powder at the beginning of the scooping task. (b) Screenshot of drum scooping task: drum is half-full of powder at the beginning of the scooping task.

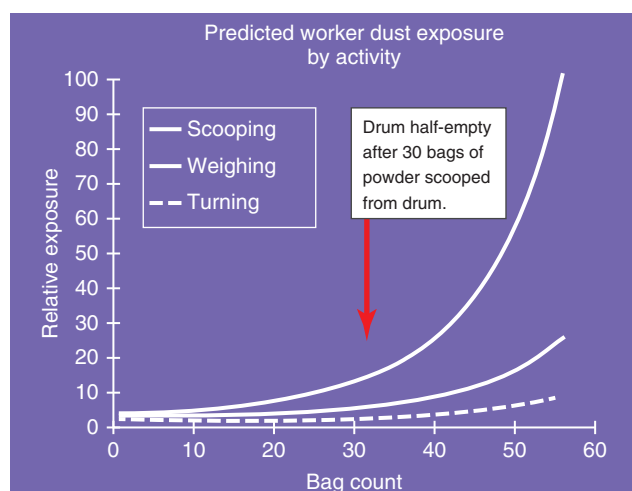


FIGURE 2 Work tasks: scooping, weighing, turning (to put filled bag in receiving drum), and dust exposure as a function of number of bags filled. After 30 bags of powder are scooped from the drum, dust exposure significantly increases.

researchers to discover each other through their respective publications.

Occupational VEM is one of the improvements in this field. McGlothlin et al. recorded workers handling powdered materials in order to identify the effects of dust exposure (1). Rosen et al. used this technique to identify causal factors such as working habits and workplace settings (2). This technique provides industrial hygienists deeper insight into the causes of worker exposure compared to conventional sampling with pumps, sampling media, and real-time sampling. Basically, occupational VEM includes video data in the assessment process and aims to establish an association between exposure levels and workplace events and to identify the causal factors.

NIOSH researchers applied VEM to a number of case studies and found utility in this method, especially in targeting exposure sources and developing controls that were unique based on using this technology (3).

Since that time, researchers in the United States and Europe have had slow but steady progress in the area of exposure assessment. In the 1980s and 1990s VEM and picture mix exposure (PIMEX) showed great promise but failed to develop to its full potential. There are a number of reasons that this technology did not take off including: (i) it was a research and development tool that was customized based on needs; (ii) it was somewhat complex to operate requiring an elaborate protocol to collect the data; (iii) lots of data to analyze; (iv) expensive to purchase equipment, link the system, and make it operational; (v) required development of software to collect the data and software to analyze and playback the data; (vi) real-time sensor companies developing their own proprietary software to capture and play back data (no video, just real-time sensor data); (vii) industry and government (until recently) not interested in developing this technology as a platform for exposure assessment and control; (viii) vision for exposure assessment and control is limited to worker health and safety and not combined with process engineering. VEM has been shown to protect worker safety and health and also shows value in process improvement, quality control, residual product recovery, and recycling; (ix) the occupational hygiene culture is focused on traditional sampling protocols (i.e. sampling pumps, sampling trains, filter cassettes, and charcoal/silica get tubes) and acting on these results rather than using VEM to augment traditional sampling, pinpoint exposure sources, and identify cost-effective controls; (x) expensive and cumbersome storage devices to capture and store sensor and video data. Until recently, storing video on portable storage devices was challenging and very expensive.

In 1999, one of the original NIOSH researchers for VEM retired from the U.S. Public Health Service and became

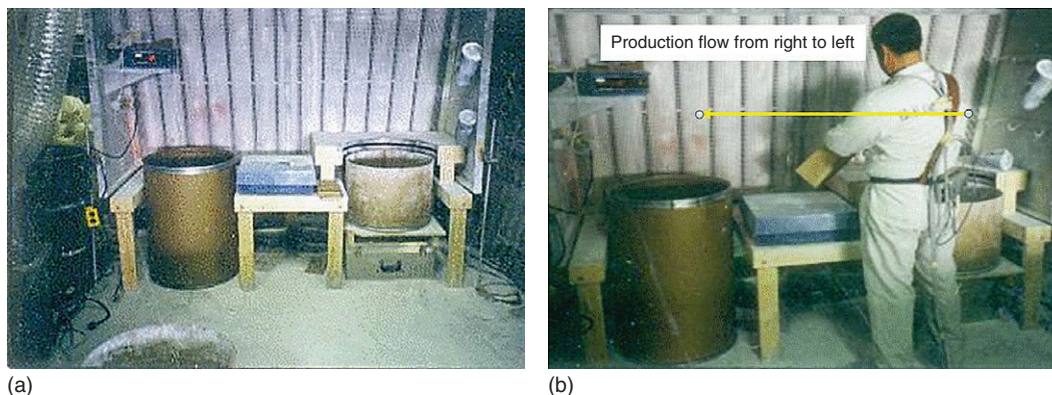


FIGURE 3 (a) Based on VEM results showing scooping task after bag 30 significantly increases dust exposure, the drum was cut in half and all work organized in the ventilated hood area. (b) Ergonomics applications to workstation to improve workflow. Work cycle time reduced from approximately 90–30 seconds. Biomechanical stress reduced because of reduced reaching and bending.

a tenured professor at Purdue University to advance this research. Purdue's Exposure Assessment Research Laboratory (P.E.A.R.L.), headed by Dr. James D. McGlothlin, focused on industry and university case studies to advance this technology. From 1999 to 2015, several case studies had been conducted, particularly in the pharmaceutical industry. The goal for each case study was to identify exposure sources and the impact of cost-effective controls, including best practices and engineering controls. Most important was advancing the ease and use of VEM to provide insight on exposure and control that could not be gained from traditional air-sampling techniques (i.e. sampling pump, sampling train, and sampling medium), which most often provided average exposure data over time. Traditional sampling cannot be replaced by VEM, as the TWA data are compared to occupational safety and health standards. However, VEM can point to exposure sources, and when controls are applied, before and after traditional sampling can be used to verify outcomes.

In many of the case studies conducted at Purdue University, 80% of the exposures occurred during 20% of the work cycle. In some instances, 90% of the exposure occurred during 10% of the work cycle. Because it was obvious what work task or engineering control was causing exposure, it was easy to apply controls. The outcomes were very cost-effective.

In Europe, PIMEX has worked to advance its system and marketed it to industry. At Purdue University, while VEM was primarily a research and development tool, it did apply for and was approved for two patents (Patent: 7,126,121. Real-Time Video Radiation Exposure Monitoring System and Patent: 7,205,891 Real-Time Wireless Video Exposure Monitoring System).

In 2015, NIOSH's Pittsburgh lab introduced its system titled: enhanced video analysis of dust exposures (EVADE). While the initial version was clunky and required some

training for users, the software was free and could be downloaded for use. Since the first release, a newer version (EVADE 2.0) is now available for free download and use. To date, the NIOSH's Pittsburgh lab's mandate is to focus on exposure assessment and control of mining operations. As such, it has developed tools to evaluate particulate and noise exposures. Additional sensors outside this area may be adapted by the software. However, additional sensors outside dust and noise are not tested and validated by the Pittsburgh lab. Unfortunately, many of the same challenges to VEM and PIMEX noted above also plague NIOSH's EVADE initiative. The good news is that the government has spent significant taxpayer money to advance this as a viable and valuable tool to protect worker safety and health. It may be beneficial, given NIOSH's role, to work with sensor manufacturers to encourage open source code to connect to third-party software developers. The current practice is for some sensor manufacturers to link their own proprietary software to the real-time sensors, limiting applications such as VEM. Fortunately, there are many sensor manufacturers that focus on what they do best, make high-quality sensors, and that allow plug-and-play protocols that link to VEM-like systems. This benefits the sensor manufacturers and the occupational hygiene community.

While advances in real-time technology have advanced, especially in the area of personal wearable devices, it has not advanced in occupational and environmental safety and health. The chapter describes the occupational exposure characteristics that are related to work activities and presents the strategy for occupational VEM. The current application and development of each part of the assessment system are discussed. New ideas for further improvement of the VEM system are suggested.

Four short case studies are presented in this chapter to show advances in VEM. The objective is to show how VEM has advanced from a complex, cumbersome, and expensive

system to an easy, affordable, portable, and powerful system that anyone can operate to conduct effective exposure and control assessments.

2 OCCUPATIONAL EXPOSURE

2.1 Exposure Agents

There are three kinds of hazards that workers are potentially exposed to in the workplace: chemical, biological, and physical. Workers may be exposed to chemical agents, such as vapor, gas, or dust, by inhalation, dermal uptake, or ingestion. Among these, inhalation is the predominant exposure route. Biological factors can include viruses and bacteria. Physical factors can be noise, vibration, electromagnetic fields, and radiation.

2.2 Exposure Types

Worker activities can directly produce these agents and cause personal exposure. Workers can also be exposed incidentally to agents that exist in the background, are not generated by workers, or are generated by nearby workers. That is, workers may be exposed to agents that are not related to their work. Figure 4 illustrates the relationship between workers, tasks, and agents. Direct or indirect exposure can occur individually or simultaneously.

2.3 Exposure Variability

For a given worker, exposure levels can vary from day to day due to changes in the weather and within the day because of changes in work tasks. Also, variations exist between

workers. If the studied workers are in the same job, the variation may be due to the difference in working habits. If the studied workers are not in the same job, the variation may be due to the differences in the type of work. Talking to the workers and their supervisors is helpful in determining what is routine in their job and what is not. When analyzing the data, patterns of exposure will emerge more quickly with less job variability.

2.4 Exposure Effects

Exposure to the agents previously mentioned can cause acute or/and chronic effects on the health of workers. In occupational hygiene work, average exposure levels on a daily basis are often used and are considered to be related to chronic effects. Peak exposure is a serious problem and can cause acute health effects. There is concern that high short-term exposures could also result in chronic ill health (4). However, it is often ignored when average exposure levels are below the relevant occupational exposure limit. It is important to note that exposure levels three times the standard exposure limit for an eight-hour day should be controlled. However, when traditional sampling is done over an eight-hour day, identifying peak exposures three times the limit is not known. This leads to a false sense of security of no immediate health hazard when there may be long-term harm leading to illness, disease, and premature death. Real-time sensors for hazardous agents can help identify excursions of over three times the standard exposure and provide better insight into short-term, high-exposure, and long-term health effects.

3 DESCRIPTION OF OCCUPATIONAL VIDEO EXPOSURE MONITORING

3.1 Why Video Exposure Monitoring?

It is important to have a profile of the worker's exposure instead of average exposure levels because of at least two reasons that have been mentioned: exposure variability and peak exposure effect on health. Direct-reading instruments make it possible to collect a large amount of real-time data with short intervals and to form a profile of exposure concentrations for a period of work time. To interpret the variation of exposure level, records of workers' activities are needed. Recording worker performance on video provides the detailed information required to analyze later the workplace events as opposed to notes taken during monitoring, which typically do not include the same level of detail (5).

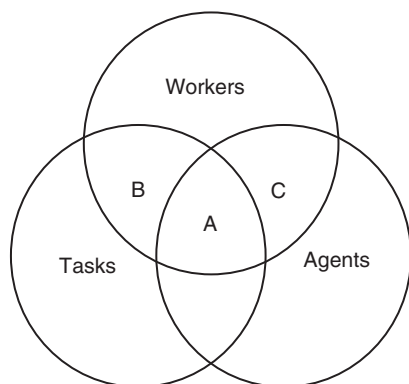


FIGURE 4 Workplace exposure factors. A: Task-related exposures, B: incidental exposure from nearby tasks, and C: incidental exposure from background.

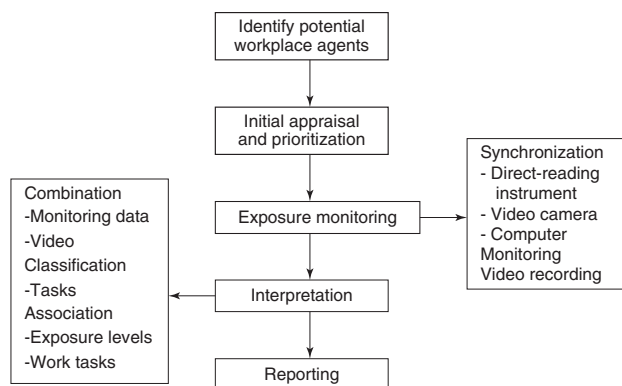


FIGURE 5 Schema of occupational video exposure monitoring.

3.2 Assessment Strategy

The strategy of occupational VEM is similar to that of conventional assessment, as shown in Figure 5. However, some additional steps are required. During exposure monitoring, VEM requires that all equipment be synchronized for accuracy and validation of later data analysis. During data interpretation, worker activities are sorted according to task type, tool use, or other factors, and then each measurement is ascribed to the corresponding descriptive category. The relationship between measurements and worker activities can then be established by statistical methods.

3.3 Monitoring and Mixed Systems

Several different kinds of VEM systems have been developed. The main difference between the systems lies in the technique of inputting monitoring data and mixing the data with video. A typical system that was developed and applied by McGlothlin et al. (6) includes the following:

- A personal, direct-reading sampling instrument (sensor) used to gather worker exposure data. Note, some sensors can be equipped with a data logging device to capture and store the data. Later, this data can be uploaded to a computer and synchronized with video taken of the worker.
- Wireless communications, either Bluetooth, or similar technology, or the internet to achieve the wireless transmission between the instrument and the computer.
- Video equipment to record worker activities.
- Computer software to capture, synchronize, and store video and sensor(s) data.
- Playback software to show the synchronized video and sensor data.

Recent advances in smaller, less expensive, and more portable computers, such as the Raspberry Pi, have made it easier to attach it to directly connect the sensors and a camera to this unit and attach it to the worker or place in an area-for-area monitoring. The synchronized data are then uploaded from the Raspberry Pi storage device to a portable or desktop computer for playback and analyses. A detailed description is given later in one of the case studies.

Rosen et al. have used a custom-built video mixer for merging the sampling signal with the camera's video output signal and used a video tape recorder for storing results (2, 5). The overall improvement in the VEM system is attributed to the technical improvement of each component. This is described later.

3.4 Uses

Generally, occupational VEM techniques can be used in the following three categories:

- Exposure assessment that includes determining compliance with occupational exposure levels, investigating task/source, and so on.
- Research on topics such as ventilation system effectiveness assessment.
- Evaluation of best practices to determine what work tasks may be causing high exposures and what can be modified to control them.
- Industrial hygiene and Safety training programs.

4 SELECTED DIRECT-READING INSTRUMENTS

VEM systems use direct-reading instruments to gather exposure data. Direct-reading instruments combine sampling and analytical functions and typically rapidly display monitoring results. Most systems are capable of storing continuous readings and displaying averages for determined time intervals (6). Examples of direct-reading instruments include a photoionization detector (PID) for organic vapors and a light-scattering detector for aerosols. Instruments that detect radiation are also being utilized in VEM (7). The recent book by American Industrial Hygiene Association (AIHA) titled *Important Instrumentation and Methods for the Detection of Chemicals in the Field* (8) provides details on various instruments that detect chemicals in (near) real time for exposure assessment and worker health protection. More important, this book provides examples of how real-time exposure assessment systems are becoming more portable and powerful (computing power, memory, response time, and accuracy) to identify and quantify chemicals, thus making real-time sensors a very useful exposure assessment tool for

industrial hygienists and safety specialists, production engineering, and health professionals.

4.1 Photoionization Detector

PIDs utilize the principle of photoionization as the primary means of detection (9). Ultraviolet (UV) light is used as a means of ionizing compounds that enter the detection compartment. The ions produced in this process are then collected by electrodes. The current generated is therefore a measure of the ionized compound concentration. Since PIDs are based on ionization, PIDs will analyze and produce a total concentration of everything that can be ionized in the atmosphere and will not distinguish among the species present. When there is only one contaminant of interest in the atmosphere, the readings can be the true concentrations. When more than one contaminant can be detected by the PID, the ratio of the mixture should be obtained and used as response coefficients for the contaminant of interest as long as the ratio of the mixture remains unchanged.

4.2 Aerosol Measurement Instrument

Portable and personal instruments for direct-reading measurements of particulate matter are based on the principle of light scattering. The instrument continuously senses the intensity of light scattered from the particles in the sensing volume at a given angle relative to the incident light beam as they pass through a sensor cell of defined volume (10). The instrument updates and displays the aerosol mass concentration every given time interval.

4.3 Response Delay of Direct-Reading Instruments

VEM requires that instruments respond quickly so they can reflect the real relationship between workplace events and exposure levels. However, readings of some real-time instruments do not represent the events taking place at the same time. Instead, they lag behind that time. When the instrument's inlet concentration changes quicker than the instrument's response, the instrument will miss the actual concentration at that time and provide a distorted concentration picture (11). To limit the distortion, the response time of the instrument should be shorter than the events of interest so that the analysis result can provide an actual association between exposure concentrations and workplace events. When the response time is significant and can be measured, it should be factored in during data processing.

5 WIRELESS DATA COMMUNICATIONS

5.1 Radio Telemetry

When exposure monitoring was first introduced, the monitoring instrument carried by the worker was connected to a data logger with a long cable to allow instant access to data. This kind of connection affected and limited the activities of the worker. The development of a radio telemetry instrument suitable for personal exposure monitoring enabled remote acquisition of data in the VEM system. The radio telemetry instrument consists of data terminal equipment (DTE) and data communications equipment (DCE). DTE is connected to the output port of the monitoring instrument, and data are continuously transmitted to DCE. The DCE then loads the data into the computer. Information on exposure levels can then be simultaneously displayed on a video monitor in a graphic format. Kovein and Hentz (12) applied a radio telemetry system with a modified commercial frequency scanner to monitor personal exposure to methylene chloride in a furniture-refinishing facility. McGlothlin (13) used SATEL-3ASd in VEM of airborne organic vapor exposures in a pharmaceutical manufacturing facility (see Figure 6). In this monitoring project, the worker carried only two instruments: MiniRAE™ and SATEL™. Alternatively, if instant data are not necessary and telemetry is not possible, the response from the instrument can be data logged and then mixed after the video has been recorded (14). An example where the use of radio telemetry equipment is not allowed is in hazardous areas, such as areas where flammable gas may be present, which require electrical equipment to be intrinsically safe or otherwise protected.

5.2 Bluetooth and Wireless Internet Communications

Bluetooth communications was invented in 1994 by Ericson, a Swedish telecom manufacturer. As known by anyone streaming music from their smartphones to their wireless headphones, or from their personal training devices (Fitbit, Garmin, etc.) to their smartphones, this communications protocol has become commonplace in recent years. With



FIGURE 6 Radio telemetry diagram.

applications to VEM, Bluetooth is especially valuable for streaming health hazard sensor data to a portable computer.

Basically, Bluetooth is a wireless communication specification operating on the unlicensed 2.4 GHz band. It is the much smaller cousin of wireless fidelity (Wi-Fi) because of its short-range communications (about 32 ft (10 m)); further-range communications is for Class I industrial applications (about ~330 ft (100 m)). Because Bluetooth communications is unlicensed, it can be used by anybody who wants to transmit and receive data. Bluetooth communication kits come with a transmitter, receiver, and control chips to modulate and demodulate digital signals. Bluetooth communication operates either as a short-range continuous data transfer (data streaming) or in small packets of data over longer distances. Bluetooth communications is not perfect. For example, physical obstructions (especially metal), battery life, and other devices in the same band frequency can hamper communications. In spite of these limitations, advances in next-generation Bluetooth technology, ease of operation, ubiquitous availability of Bluetooth systems, and low cost make it go-to communications protocol for VEM.

5.3 Internet (Wi-Fi)

Internet Wireless Communications known as Wi-Fi stands for wireless fidelity. This technology is for local area networking with devices and is based on IEEE 802.11 standards. Real-time sensors that can detect Wi-Fi compatible devices can connect to the internet via a wireless local area network (WLAN) and a wireless access point (AP). When a unique internet protocol number is identified between the sensor and computer, communication is established. The main advantages of Wi-Fi-enabled sensors are speed (up to and over 24 megabits per second) and distance (anywhere in the world). The disadvantage is if the computer cannot connect to the Wi-Fi. This can be due to not having a connection, radio transmission interference, and costs (from telephone wireless internet plans), among others. In spite of this, the coming implementation of 5G wireless communications will be a game changer for nearly everything we do in life and work.

6 VIDEO EQUIPMENT

Consumer-quality video equipment can often be used to record worker's activities. The digital camcorder is preferable for computer processing; otherwise, analog-to-digital conversion will be required for analog video. Special video-editing programs can directly control the digital camcorder on the computer and capture video clips from the recorded video in the camcorder. It is important to make sure that

the on-screen clock or timer is captured by the computer. Normally, time displayed on the digital camcorder as a subcode will not be captured when the computer and the camcorder are directly connected. A compressor must be connected between them to transmit the time code to the computer at the same time as the video was recorded. The captured video can be stored on the computer in various formats including moving picture experts group (MPEG) and audio video interleave (AVI), depending on the requirement of the video-sensor mixer software. Recent advances in video camera equipment have made it more portable, more affordable, and more field rugged. This includes portable sports cameras such as the GoPro camera line (<http://GoPro.com>), proprietary playback software, and the Garmin camera line (<http://Garmin.com>) nonproprietary playback software. The challenge is when the camera companies develop proprietary software to playback the pictures and video. This becomes a hindrance to using such cameras for VEM applications. Some camera companies, like many health sensor companies who develop software that only communicates to their devices, restrict access to markets where products, such as VEM, can be used.

7 RASPBERRY Pi – DISRUPTOR INNOVATION FOR VEM

The Raspberry Pi was created in February 2012 by the Raspberry Pi Foundation (<http://novadigitalmedia.com/history-raspberry-pi>). This very small (the size of a deck of playing cards) and inexpensive computer (approximately \$50) was set up to promote and teach basic computer science in schools and colleges in the United Kingdom (UK). The Raspberry Pi Foundation initially released two computers: the Model A and the Model B. Both computers had different specifications and capabilities. Because the Raspberry Pi encouraged open source software programming, a community of hardware and software enthusiasts formed to purchase thousands of these kits to develop their own projects. In this instance, VEM has been using the Raspberry Pi since 2015 with great success because of the many plug and play universal serial bus (USB) connections of nonproprietary sensors and cameras. Thanks to the increasing capacity of the micro-SD storage cards (that also run the VEM software), embedded in the Raspberry Pi and the increasing storage capacity of thumb storage drives, the data recording and storage are not issues as they were in the past.

8 MIXING SOFTWARE/INSTRUMENT

Video and monitoring data can be mixed with a special mixing instrument or by a computer with special software.

The output can then be recorded on video media or stored on the computer. Recent advances in the development of this software are in two distinct packages: (i) simultaneously recording and storing video and sensor data on a portable computer (VEM capture) and (ii) playing the video and sensor data back on a laptop computer (VEM playback). Both systems are shown in the last case study presented in this chapter.

8.1 Overlay Technique from NIOSH

As mentioned in the introduction, NIOSH researchers developed the initial VEM platform. At that time, researchers from NIOSH developed a VEM overlay technique (15). A special computer program was developed to generate a graphical representation of worker exposures. A colored bar with a black background can be generated to show the magnitude of exposure, or curves with different colors for start-till-current exposure trend and overall exposure trend can be generated. Using a video overlay board in the computer, one or two exposure data graphs can be then overlaid onto the video that has recorded the worker's activities. Before overlaying, the computer's graphical signal should be converted to a National Television System Committee (NTSC) signal. To synchronize the exposure data with the video, the graph-generating program is first set up. When the time on the video's clock reaches the time of the first reading in the data set, the program's display is started. With practice, this will synchronize the exposure data and video recording of the work activities to within less than a second, which is

sufficient for most applications. In those days, the process of synchronizing the video with the sensor signal was very simple: Manually and simultaneously activating both the video and sensor activation buttons to collect the data. The overlaid video signal can be displayed on a video monitor and recorded on a second video recorder.

8.2 PIMEX – The European Experience

At the same time that NIOSH began this research, Gunnar Rosen et al. from the National Institute for Working Life in Sweden also worked on a PIMEX system for the same purpose (16). Video mixer AVM 2000 was used to mix the signals from video and the direct-reading instrument instead of using an overlay card on a computer. The mixed signals were then transmitted to videotape recorders to be recorded on tape. The mixed video displayed the exposure measurement in the same way as the NIOSH technique. With the development of computer technology, several research groups have been improving PIMEX. Up to now, picture-mix personal computer (PIMEX-PC) from the National Institute for Working Life in Sweden, Finnish-picture-mix (FINN-PIMEX) from video text tracks (VTT) in Finland, and Exposure Video Visualization (PIMEX) from the Health and Safety Laboratory (HSL) in England are available (5, 17, 18). Overall, as the result of processes by these systems, the following data can be demonstrated on the screen: a video recording of worker activities and graphs of exposure levels and concentration values (see Figures 7–9). All these systems also have the capability to control the progress of video. In

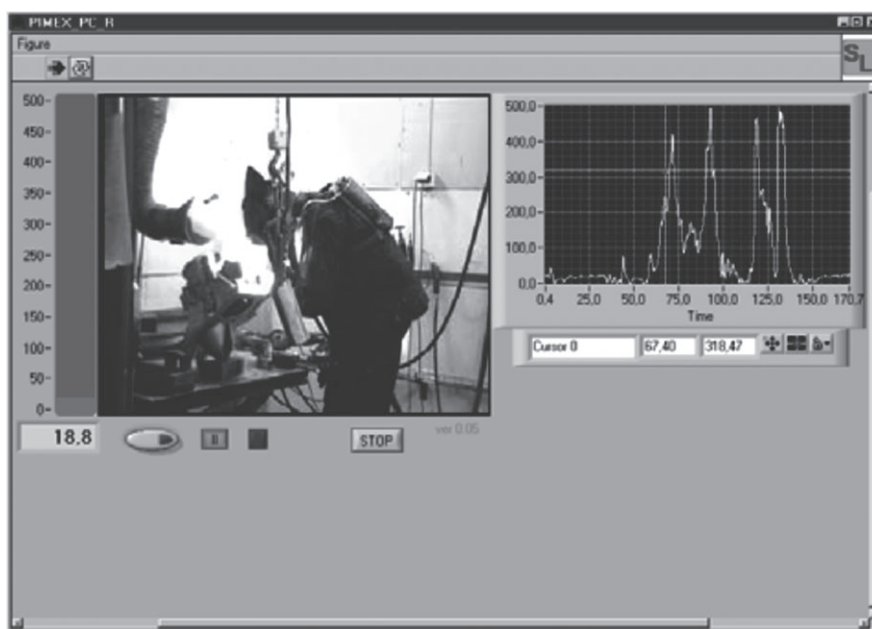


FIGURE 7 PIMEX-PC computer interface.

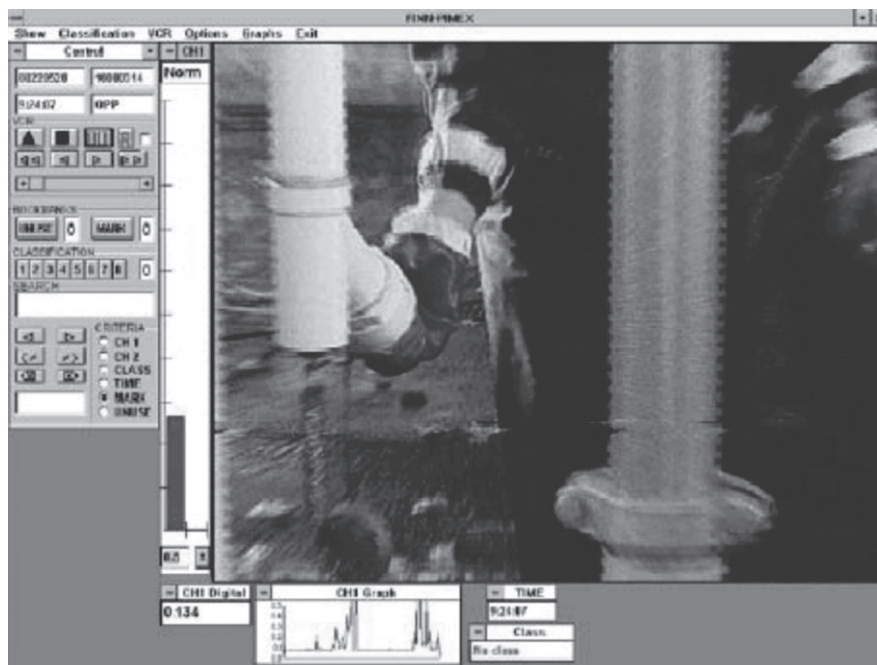


FIGURE 8 FINN-PIMEX computer interface.



FIGURE 9 PIMEX-HSL computer interface.

PIMEX-PC, the analyst can drag the cursor on the graph of the overall exposure levels to a point of interest, and then the video will start from that point. PIMEX-HSL can label tasks or activities in a hierarchy, which provides a convenient way for the analyst to identify the high-exposure reason.

8.3 MVTA – Multimedia Video Task Analysis (University of Wisconsin)

Multimedia video task analysis (MVTA) was originally developed to assess ergonomic conditions and their effects on biological reactions, such as pulse and respiration. It also can work as combination and analysis software for VEM. Its special motion analysis window allows the analyst to break the whole work period into several parts representing different events (see Figure 10). McGlothlin (13) used this feature in VEM of airborne particulate and organic vapor exposures in a pharmaceutical manufacturing facility. In this application, biomechanical data have been replaced by exposure data.

8.4 EVADE – NIOSH Updates Its 1985 Roots in VEM

In 2014, researchers from NIOSH's Mining Research Division, in Pittsburgh, PA, launched a website that promoted its version of VEM titled The EVADE software program (<http://cdc.gov/niosh/mining/works/coverSheet1867.html>). Basically, it used updated computer, video, and sensor

technology to do what the original NIOSH researchers, from the Engineering Control Technology Branch (ECTB), did in 1985. However, the launch of EVADE was welcome news among occupational hygienists-promoted real-time exposure assessments as a tried and proven technology for pinpointing exposure sources and then applying cost-effective controls. EVADE merges video files and logged data files, which allows the user to view them to help identify exposure sources. NIOSH has updated its original version of EVADE to make it more functional and user-friendly. EVADE has many challenges in advancing this initiative including (i) the slow pace of updating the program and verifying results; limited applications: only dust and noise sensors have been validated so far. This makes sense as EVADE's main purpose for applications in the mining industry, a congressional mandate; (ii) video and sensor data are stitched together after the fact. This can result in errors in demonstrating what is really happening. For example, you can stitch your vacation video of Hawaii with airborne particulate levels during a mining operation. While this is not the intent of NIOSH's EVADE program, it is possible. As such, the results from using this program could not be admissible in a court of law. That said there are many advantages from the release of EVADE including (i) validation of this technology as a viable exposure assessment tool to help occupational hygienists determine exposure sources and devise more effective controls; (ii) they are working with stake holders outside of NIOSH to improve the tool for future applications; and (iii) it is free. While patented technology from Purdue University rivals EVADE (US



FIGURE 10 MVTA computer interface.

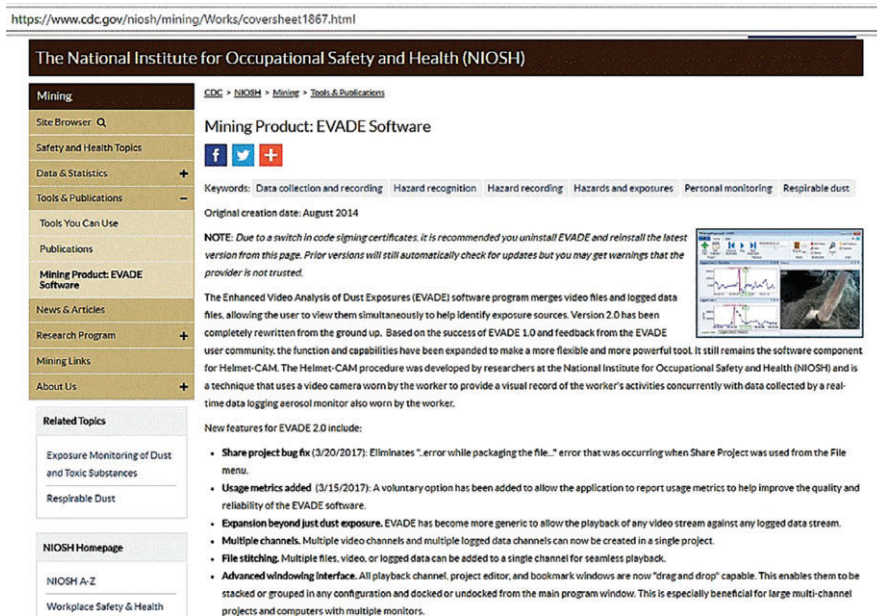


FIGURE 11 Screenshot of NIOSH EVADE website showing video and sensor data during a mining operation.

Patent No. 7,126,121; US Patent No. 7,205,891), VEM will move forward as a very effective instrument to prevent and control disease, injury, and premature death in the workplace. Figure 11 shows a screenshot of the NIOSH webpage showing the features of EVADE on a computer screen.

8.5 Mixing Software Functions

Developing computer programs is the trend of the combination technique of video and monitoring data. Much information can be displayed on the screen, and many options can be chosen by analysts. Computer-aided VEM systems have provided industrial hygienists a handy way to analyze the data and present their findings. Generally, video and monitoring data mixer software should have the following basic functions:

- A video recording of worker activities and graphical exposure monitoring data can be displayed, synchronized in separate windows.
- The contaminant name, contaminant unit, instant concentration readings, and exposure time can be displayed, and short-term exposure level (STEL), TWA, and peak exposure reading can be calculated and displayed.
- The scale of the sensor data graph can be adjusted.
- The video can be controlled using a control panel on the interface.
- More than one sensor and video output can be shown on the control panel interface.

9 DATA INTERPRETATION

The exposure variation and its association with work activities can be better addressed in VEM than in other conventional exposure assessment processes. Two analysis methods are being used to interpret the correlation between worker activities and exposure levels: the ratio method and the regression method.

9.1 Worker Activities Classification

Worker activities are one of the main factors that affect the exposure levels of workers. Worker activities can be classified based on the task types. For example, dry cleaning worker activities are classified as loading and unloading the dry cleaning machines. When exposure levels fluctuate, detailed classification of activities is recommended. Working location, ventilation conditions, and surrounding environmental conditions also play a role in exposure levels and should be considered as factors when applicable.

9.2 Ratio Method

The ratio method is used to identify the relative importance of the work activities to total exposure. Two variables are used to represent this importance: relative exposure dose d_i and relative exposure level $e_{rel,i}$ (19). Exposure data are sorted according to each work activity to which they are ascribable. The relative exposure dose d_i for the work activity

i is calculated from

$$d_i = \frac{\sum_{j=1}^{n_i} e_{ij}}{\sum_{j=1}^k \sum_{i=1}^{n_i} e_{ij}}$$

where e_{ij} is the momentary exposure measure j associated with work activity i , n_i is the number of data associated with work activity i , and k is the number of work activities.

Relative exposure dose does not clearly point out which activity causes higher exposure(s). For example, a certain activity with long duration may have high relative exposure dose. But this high value of exposure dose does not necessarily mean that the corresponding activity is serious. Relative exposure level $e_{\text{rel},i}$ for a certain work activity, which is calculated as follows, can be used to explain which activity may cause high exposures:

$$e_{\text{rel},i} = \frac{\bar{e}_i}{\bar{e}}$$

in which

$$\bar{e}_i = \frac{\sum_{j=1}^{n_i} e_{ij}}{n_i} \quad \text{and} \quad \bar{e} = \frac{\sum_{j=1}^k \sum_{i=1}^{n_i} e_{ij}}{N}$$

where N is the total number of measurements.

9.3 Regression Functions

Building a multiple regression function is a way to evaluate whether the dependent variable of exposure concentration is a function of the explanatory variables. The explanatory variables are usually qualitative and have a value of one or zero to indicate whether the event has occurred. Sometimes, quantitative explanatory variables, such as production rate, can also be used. Statistical tests of whether the regression coefficients differ significantly from zero can be used to explain whether the corresponding factor contributes to the variation of exposure levels. A representative model is

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \cdots + \beta_n X_n + \varepsilon$$

where Y is the exposure concentration, X_i is the explanatory variables ($i = 1 - n$), β_i is the regression coefficient ($i = 0 - n$), and ε is the residue.

In many cases, each real-time measurement may be some function of the preceding measurements. This phenomenon, called autocorrelation, can cause an overstatement of the significant effects of explanatory variables (20). Autocorrelation tests should be conducted, and some data that correlate to previous data should be eliminated in this situation.

10 DISCUSSION

10.1 Monitoring Subject Selection

As mentioned earlier, there is variation in exposure levels between workers. It is recommended that more than one worker be monitored for a given job position, and it is recommended that this monitoring be conducted simultaneously. By comparing the data from more than one worker, subjective factors such as work habits and objective factors such as ventilation rate can be more easily identified.

10.2 Monitoring Instrument

The occupational VEM technique has a broad application field. Even though the most common application is to assess chemical exposure, some researchers are beginning to expand its application into new areas, such as to assess exposure to radiation and biological agents. The main challenge of the application of occupational video monitoring is the applicability of monitoring instruments. Portability is also critical. Instruments currently available for vapor are PIDs that are not specific to one chemical. This limitation leads to fewer applications in complex environments where more than one contaminant is present. This limitation can be addressed when there is a spike in vapor exposures as measured by the PID, and then using an air-sampling canister, under negative pressure, to capture the vapor and analyze using a gas chromatograph/mass spectrometer (GC/MS).

10.3 Future of the VEM Systems

The advancement of the VEM has seen significant advancements in this technology just within the past few years. Within the next five years, VEM will likely be a common device worn not only by workers but also by individuals who are concerned about exposure to harmful agents in their environment. Examples include those who are health compromised, such as having asthma, and want to be alerted by changes in airborne particle levels that may set off an asthma attack. Another example would be for those who have allergies, or sensitivity to trace chemicals, and VEM units will alert them in real time about hazard levels.

While VEM has had slow but steady advances in this technology over the past few decades, it has largely stayed as a research and development tool rather than one that is available in the marketplace. The reasons are easy to understand: (i) VEM was relatively expensive, costing approximately \$5000–\$7000 to procure equipment for sampling. This includes a laptop computer that has adequate random access memory (RAM), graphics display, sensors, data transmitters, data-storage devices, and software to run both capture and playback of the video and sensor data;

(ii) Requires reliable and easy-to-use software that works across several computer platforms; (iii) VEM is not plug and play. It requires training, skill, and awareness of the strengths and limitations; (iv) It can be bulky and hard to transport, requiring special handling instructions if traveling by air; (v) It is not foolproof, you do not know if you have reliably captured the data you want until playing it back; (vi) VEM is not the gold standard for determining compliance to standards, traditional TWA sampling is; (vii) Instrument manufacturers of sensors develop their own proprietary software, making it less adaptable to use with VEM.

Until now, VEM has been beyond the easy reach of the practicing industrial hygienist, production engineers, safety professionals, and allied health science practitioners. In the past few years a disrupter technology has been introduced that may eliminate many of the challenges noted above. This disrupter technology is the Raspberry Pi; introduced just a few years ago, it has caught not only the attention of hobbyists' and hardware and software engineers but also with occupational safety and health practitioners. The Raspberry Pi computer starter kit begins at \$35.00, and a camera and cable to attach to the Raspberry Pi can be purchased for under \$20. There is an endless array of off-the-shelf sensors (humidity, air temperature, barometric pressure, etc.) that can be purchased in a bundle for under \$15. The Raspberry Pi computer features a micro-SD card that can be inserted to the mother board and have it perform to specifications. Also, the Raspberry Pi can be ordered with a touch screen for approximately \$70.00. All that is needed to complete the package is a real-time sensor (usually \$200–\$500), to evaluate hazardous airborne agents, and a \$10–\$20 storage device to capture and store VEM data. The only other device needed is a \$1000 laptop computer to play back the VEM data and video. Because the Raspberry Pi system cost several thousand dollars less than the original system, is portable, easy to use, reliable, and always links the video with sensor software, it may be the go-to device for VEM in the future. Some may be wondering why not the smartphone to perform the same function? For example, the smartphone has a built-in camera, a built-in computer, and software in the form of an App, such as the noise program developed by NIOSH, that can be downloaded for easy use. So, why not the smartphone instead of Raspberry Pi? The answer is that the smartphone, at this time, can only handle one sensor at a time, while the Raspberry Pi can handle several sensors and video inputs at the same time. Also, smartphones require development of an App for each sensor, needs to be vetted and approved by the smartphone management companies, and the companies take a cut of every App downloaded by users.

Regarding software, most of the available software has a limited capacity for capturing, storing, and playing long videos, resulting in poor performance of data analysis. The software should operate on several platforms (Windows, iOS, Android, Linux, etc.) and be user-friendly and robust.

For convenience of training and storage, dynamic displays, including video, graphs, and other information, it should be easy to store the information on a protected server or cloud service where the data can be encrypted and only accessed by two-factor authentication by an authorized user. Finally, use of artificial intelligence (AI) using algorithms from big data can help identify common exposure sources in similar industries and to catalog what controls are most effective.

11 FOUR CASE STUDIES

The following case studies have been selected to show significant advances in VEM technology, the variety of applications, and the utility of VEM to identify and control hazardous exposure sources.

11.1 Airborne Particulates and Solvents in an Industrial Facility

Frequently, in an industrial setting it is desired to know what factors such as work practices, exposure sources, and engineering controls affect the exposure of workers to airborne particulates and/or solvents. VEM has the ability to specifically define these factors when combined with the appropriate detector and data analysis method. This case study examines the process of developing, assembling, and testing a video-monitoring system by assessing the exposure of workers as a function of work activity under different engineering controls using three methods of data analysis.

11.1.1 Purpose

The purpose of this study had several objectives. The first objective was to build a video-monitoring system that could monitor a worker's activities and worker's exposure to airborne particulates and solvents. The second objective was to test the system in an industrial facility and specifically identify exposure sources as a function of the tasks performed by the worker. The third objective was to evaluate the effectiveness of engineering controls. The final objective was to compare three different data analysis techniques to determine exposure as a function of the task performed by the worker.

11.1.2 Materials and Methods

This study was performed in a solute-charging (addition) room in an industrial facility. The solutes added to the solvent, methylene chloride (MeCl_2), were a sodium bicarbonate (NaHCO_3) powder and dimethylaminothioacetamide hydrochloride (DMATA). At the time of this study, NaHCO_3 and DMATA were regulated as nuisance dusts. By the



FIGURE 12 Process tank with sealed manway.

American Conference of Governmental Hygienists (ACGIH) eight-hour threshold limit value (TLV) and Occupational Safety and Health Administration (OSHA) permissible exposure limit (PEL) for nuisance dusts, the limit for these substances is 5 mg m^{-3} . MeCl_2 , however, is recognized as an acute eye and skin irritant. In addition, it has been classified by the ACGIH as a potential occupational carcinogen. The eight-hour ACGIH TLV for MeCl_2 is 50 ppm (21), while the eight-hour OSHA PEL is 25 ppm (22, 23) with a STEL of 125 ppm.

Exposure assessment of workers consisted of six sampling sessions for personal dust and MeCl_2 exposure at the time of addition of each of the solutes to the solvent. Three of the sampling sessions occurred prior to using an engineering control. During these three sessions, the parts of a task based on exposure levels were identified that could be the best possibilities for changing to better control exposure. After modifying the elements of the tasks in order to reduce personal exposure, three additional sampling sessions were conducted to evaluate how successful the controls were in reducing the personal exposure to workers. The main modification in control made was changing the charging adapter on the manway (see Figure 12) to a ventilated manway charging adapter (Figures 13 and 14).

The job performed at the facility was divided into two tasks. The first task consisted of the addition of NaHCO_3 to the processing tank, and the second task consisted of the addition of DMATA to the processing tank. Each of these tasks was divided into four distinct work elements. The first task consisted of the elements bag positioning, tie clipping, bag charging, and bag disposal. The second task consisted of the elements drum lifting with hoist, drum charging, drum removal with hoist, and intermediate phase (one drum removed and another drum positioned under hoist).

These activities were recorded using two methods. One method entailed using a video camera to document workers activities while having the worker monitored for MeCl_2 and particulate exposure at the same time. The other method

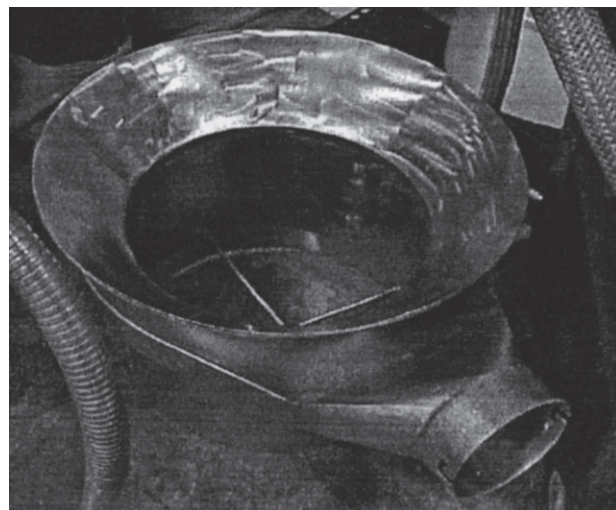


FIGURE 13 Ventilated manway charging adapter.

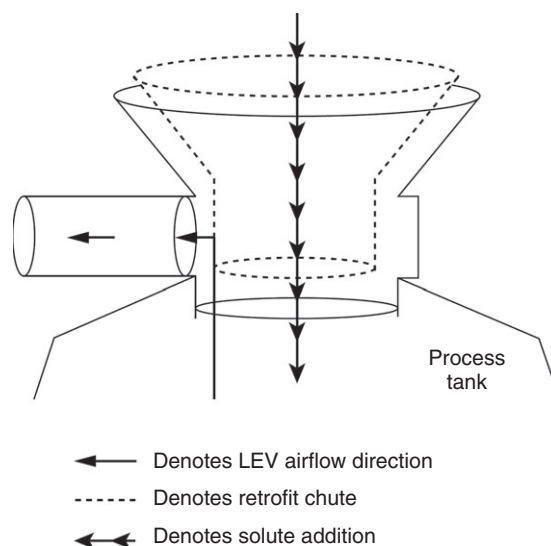


FIGURE 14 Diagram of ventilated manway adapter retrofit (postcontrol).

entailed using a watch synchronized to the video camera and the monitoring instruments and then using handwritten notes to document the start and stop times for each element within each task.

MeCl_2 exposure to the workers, who were wearing personal protective equipment (PPE) consisting of a Dover™ full-body air suit, was monitored by a Foxboro TVA 1000B flame ionization detector (FID). The FID sampling inlet was attached near the worker's breathing zone with data stored in three-second intervals.

The Haz-Dust II real-time personal dust monitor was used to monitor worker's exposure to particulates. This

monitor's inlet was attached in the worker's breathing zone, and particulate data was formatted into three-second intervals.

The video equipment consisted of video camera (SONY CCD-TRV66 analog handycam), two 8-mm videocassette recorders (videocassette recorder (VCR): SONY EV-S5000 and SONY EV-S3000), VHS VCR (Panasonic model NV 8950), and a video monitor (Panasonic CT 20104 color video monitor).

The computer hardware and software consisted of a 500-MHz processor PC with 128 of RAM, 13 GB hard drive, and an analog video capture card. The software applied in this case study included MS Excel for data analysis, VEM, and MVTA. VEM software enabled exposure data to be graphically represented against time so that worker's activities could be correlated with exposure. The MVTA software was used to examine the overlaid video simultaneously with exposure and discrete job elements. This software allows coding to be performed that determined which job elements contributed the most to worker exposure. One final piece of hardware necessary for combining the video and exposure was the overlay board. The overlay board used in this study was the Magni Systems MagniCoder Pro.

The experimental design of the case study was such that three real-time exposure assessment techniques were evaluated. Each of these methodologies was evaluated prior to the control intervention of the ventilated manway charger adapter and then again evaluated postinstallation of the control. The data analysis techniques were as follows.

Data analysis technique 1 consisted of time coding the real-time exposure data for the tasks and elements of the job using notes taken during the additions of NaHCO_3 and DMATA to the MeCl_2 solvent. The data was then used to determine average particulate and MeCl_2 concentrations as well as peak 15-minutes average concentrations during each of the runs. In addition, the average particulate and MeCl_2 concentrations as well as peak 15-minutes average concentrations were determined for each job element within each task.

Data analysis technique 2 was a nonstatistical method used to evaluate the concentration during each work element. This method rather than relying on notes taken instead used the technique of overlaying the real-time exposure data onto the video of the worker's activities. The analysis consisted of observing the video with the exposure data and determining the concentration of particulate and MeCl_2 during each work element. Then the elements were ranked from most to least contributory to exposure. In this method, the eight-hour TWA, STEL, or quantitative concentration averages were not calculated.

Data analysis technique 3 was similar to data analysis technique 1; however, instead of using manual time coding of the work elements, the software program MVTA was used to code the work tasks and elements from the video.

Following the data analysis, each of the data analysis techniques was evaluated for their ability to perform the following jobs:

- Quantitative calculation of exposure for each work element.
- Ranking of work elements with regard to worker exposure.
- Estimation of exposure throughout the run, the eight-hour TWA and STEL concentrations of MeCl_2 , and particulates within each task element
- Cost, setup, and analysis time necessary to use each data analysis technique.

11.1.3 Results and Discussion

Prior to using the engineering control of the ventilated manway (Figures 13 and 14), the results from using each of the three data analysis techniques showed that techniques 1 and 3 gave nearly identical output in particulate and MeCl_2 concentrations following coding for time for the work elements within the tasks. Using these techniques, the run average, the eight-hour TWA, peak STEL, and average concentration during work elements could be calculated. The resulting particulate levels varied between runs but were less than the PEL. The resulting concentrations of MeCl_2 had two out of three runs where the exposure was greater than the PEL of 25 ppm. For all the runs, the peak STEL of MeCl_2 was significantly greater than the allowable STEL for the addition of both NaHCO_3 and DMATA. These techniques revealed that no specific work element consistently contributed the most to exposure in all runs. Technique 2 was useful in showing that exposure could be viewed as work is performed. But this technique was not able to determine the exposure effect of each work element due to the large number of data points collected, which made it difficult to see graphical changes in concentration versus time. However, the technique was useful in identifying time points within a work element where a high concentration of MeCl_2 occurred. Since the work elements and correlation with high MeCl_2 concentration were not consistent, it was difficult to determine any exposure trends during specific work elements. Technique 2 did show as did techniques 1 and 3 that during the NaHCO_3 bag-charging element that several peak exposures for MeCl_2 occurred.

Following the use of the engineering control and applying data analysis techniques 1 and 3, the particulate exposure levels were found to be less than the PEL for all the runs. The MeCl_2 concentration results showed that only one run of the three runs produced a peak STEL concentration (181.0 ppm) greater than the OSHA STEL. The work element that produced the highest average concentration throughout all the runs was the NaHCO_3 bag-charging

element, which suggests that this is the work element that is the greatest factor in contributing to MeCl_2 exposure. As in the precontrol situation, during postcontrol (use of engineering control), technique 2 of data analysis was unable to define the exposure effect of each work element. However, it was apparent that MeCl_2 concentration levels were less than prior to the use of the control. In addition, a tendency was noted that exposures during NaHCO_3 bag-charging element were higher than during other elements of the addition of NaHCO_3 to MeCl_2 task.

Comparison of before the engineering control installed and afterward shows that during addition of both NaHCO_3 and DMATA the particulate concentration was significantly reduced following the use of the ventilated manway adapter. In addition, the average MeCl_2 concentration was reduced to levels below the OSHA STEL and PEL levels in both NaHCO_3 and DMATA addition procedures following the use of the ventilated manway adapter.

Evaluation of the three techniques with each other shows the advantages and disadvantages of each data analysis technique. Technique 1 was able to determine the exposure based on the work element, rank the contribution of each work element to exposure, give values for total exposure, eight-hour TWA, and STEL at a minimal cost. However, the time required for data analysis following each run was extensive. In addition, the use of manpower to manually record notes regarding worker's activities increases the cost that may offset the cost of equipment. Another disadvantage with technique 1 is the limitation on the speed of manually recording the worker's activities that could cause some element times to be missed. Technique 2 has the advantage of giving insight on exposure, particularly peak exposures and the correlation to work elements of a task. However, at the time of this study, the great numbers of data points collected made it difficult to examine any exposure tendencies due to a work element. In addition, due to variations between runs this technique was difficult to use. This technique cost significantly more than technique 1 due to the large amount of hardware and software needed to overlay the exposure data into the video from observations of the worker's activities. However, the time to perform the data analysis was less for technique 2 than for technique 1. Technique 3 had the advantages of technique 1 of being able to calculate total exposure, eight-hour TWA, and STEL while taking approximately the same time as technique 2 to perform the data analysis. The capital investment of this technique is higher than technique 1 or 2 due to the additional MVTA software in addition to the equipment used in technique 2. However, in the long term, this cost may be recouped due to a reduction in manpower needed to analyze the data. That is, instead of needing an environmental, health, and safety professional to code manually the data during the procedure, a technician could videotape the procedure during monitoring and then the professional could later perform the data analysis with the MVTA.

11.1.4 Conclusions

Data analysis techniques 1, 2, and 3 allowed the determination of variations in exposure due to the element of a task being performed. Data analysis techniques 1 and 3 were qualitatively determined to be the most useful methods for determining concentration as a function of work elements. Methods were most successful for work element exposure determination, ranking of element exposure within each task, and determination of total exposure, eight-hour TWA, and STEL exposure. In terms of using time most efficiently, technique 1 required the least capital investment, but the cost savings over the long term would be negligible relative to the other two techniques due to the high operational costs involved. Techniques 2 and 3 require the least time for data analysis due to the video being overlaid over the real-time exposure data. Thus, the analysis for these techniques just requires the time to watch the sampling session video.

The use of VEM in this industrial facility identified real-time specific tasks that correlated with higher exposures. In addition, VEM showed its effectiveness for control measures to reduce the exposure of workers to these hazardous.

11.2 Gases – Nitrous Oxide Exposure in a Dental Office Setting

Nitrous oxide gas is used as an anesthetic in dental offices during oral surgeries such as wisdom teeth extraction. Nitrous oxide has been used for over 100 years in dentistry because of its ability to relieve pain while having minimal side effects. However, due to greater exposure of an occupationally exposed worker such as a dentist or dental assistant, adverse health effects arising from exposure to concentration as low as 50 ppm to nitrous oxide have been documented. The effects involve the reproductive, hematological, nervous, and audiovisual systems (24–26). Both the ACGIH and NIOSH have established guidelines for allowable levels of exposure. The ACGIH has established a threshold limit value of 50 ppm eight-hour TWA (27). The NIOSH-recommended exposure limit (REL), which was established in 1992, is 25 ppm TWA during the time of administration of nitrous oxide (28).

Due to these effects, waste gas-scavenging systems are recommended to be used in dental offices to reduce exposure to nitrous oxide to dental office workers. Under ideal testing conditions, a geometric mean of 25 ppm was achieved in the breathing zone of the dentist when using one type of scavenging system (29). In this study, no actual patients were involved. However, when patients are actually involved in the examination of the scavenging systems, other factors such as other engineering controls, work practices, and patient behavior may affect waste anesthetic gases and may cause the actual levels to be higher.

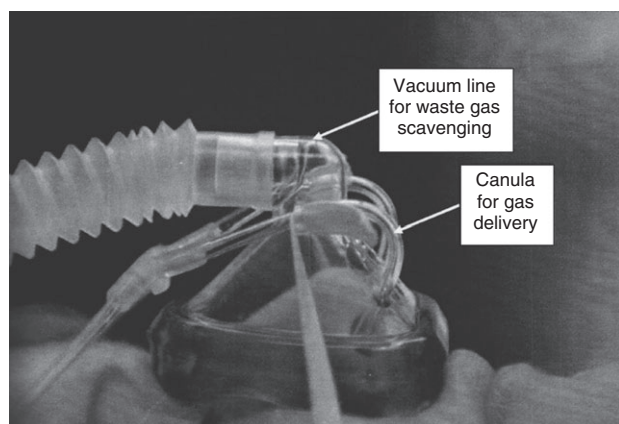


FIGURE 15 System 1 (Safe Sedate Dental Nasal Mask™).

11.2.1 Purpose

This study, which applied the techniques of video monitoring, real-time exposure monitoring of nitrous oxide, and infrared (IR) thermography to two types of scavenging gas systems in dental offices during oral surgery, had three main objectives. The first objective was to assess and compare the efficacy of two different designs of waste gas-scavenging systems used in a dental office. The second objective was to compare the performance of the systems to the relevant occupational exposure limits. The third objective was to use one of the scavenger systems and evaluate the effect of work practices in two dental offices based on experience using the system, work practices, and nitrous oxide exposure.

11.2.2 Materials and Methods

The overall design of this study involved three phases: Phase 1 consisted of using new scavenging system design, called System 1 (Safe Sedate Dental Nasal Mask™) shown in Figures 15 and 16, in a dental office (Office 1) performing typical wisdom teeth extractions. This office had a dentist (Dentist 1) who was experienced with System 1. Phase 2 was performed in Office 1 with a different waste gas-scavenging system, called System 2 (PORTER-scavenging System: PORTER Instrument Company, Inc., Hatfield, PA), shown in Figure 17. Phase 3 involved System 1 in a different office, Office 2, with a dentist (Dentist 2) inexperienced with System 1. All phases were performed during typical wisdom teeth extraction surgeries in which at least two wisdom teeth were extracted. No other additional procedures were performed at the time of the wisdom teeth extraction for any of the patients.

Phases 1 and 2 were used to assess and compare the efficacy of two different designs of waste gas-scavenging systems used in a dental office. In addition, Phases 1 and

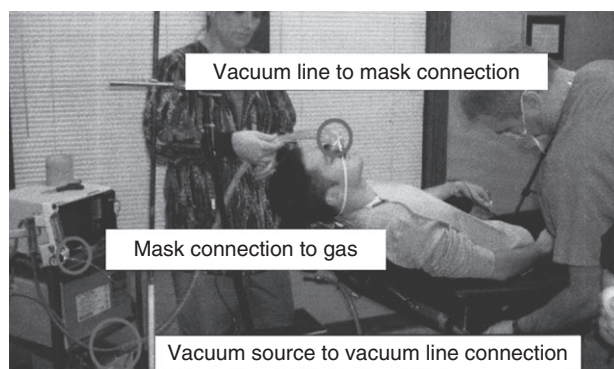


FIGURE 16 Typical setup for System 1.

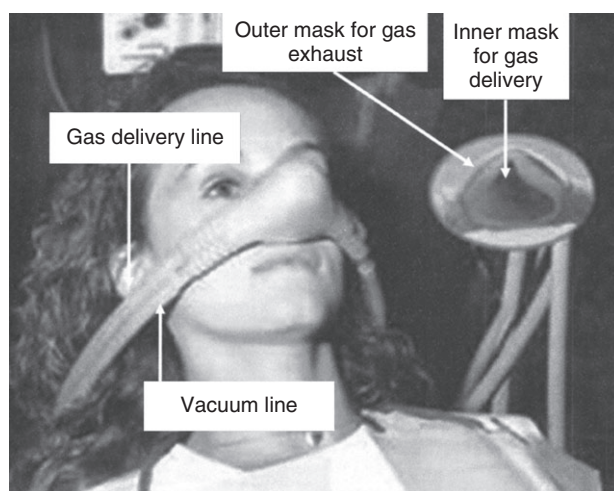


FIGURE 17 System 2 (PORTER™) design.

2 were used to compare the performance of the systems to the relevant occupational exposure limits of the NIOSH REL. Finally, Phases 1 and 3 were used to compare the effects of work practices (MVTA used for comparison) in office 1 versus office 2 using System 1. In other words, part of the comparison would involve the difference in actual work practices due to the differences in experience using System 1.

The main equipment required for the performance of each of these phases required for monitoring of exposure the use of a digital video camera, a waste gas-scavenging system, an IR camera, and a real-time ambient air analyzer for nitrous oxide. Other required equipment were external hard drives for data storage, a laptop computer for operation and image storage from the IR camera, and a digital camera for photographic records of events occurring during the study. The overall camera setup for the digital video camera and IR camera is shown in Figure 18.

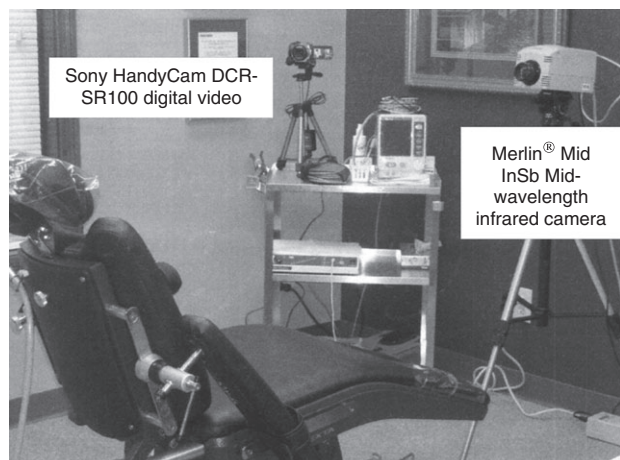


FIGURE 18 Example of camera setup.

The digital video camera used to film the activities of the dentist and staff while performing the wisdom teeth procedure was a SONY HandyCam® DCR-SR100. The video images saved to the camera were then uploaded to a computer where then Image-Mixer software was used to edit the video and prepare it for synchronization to the IR thermography images and to the data concerning nitrous oxide exposure to the dentist and staff obtained in real time by the ambient air analyzer.

The IR camera was used to detect IR radiation in the 3–5 μm wavelength range. The system used was a Flir Systems Merlin® Mid InSb mid-wavelength infrared (MWIR) camera. Flir System's ThermaCAM Researcher Pro 2.8 Sr-3 software was used to view the thermographic images. A typical image obtained from this camera is shown in Figure 19. This camera is able to detect nitrous oxide in the environment and convert it to an image able to be seen by humans. The white circles show where nitrous oxide was detected around the subject's head as it was being administered and the surgery was proceeding. The variations in color reflect the concentration of nitrous oxide, with higher concentration (nearer the source) being more opaque.

The air concentration of nitrous oxide in real time was measured by the Miran SapphIRe Ambient Air Analyzer (ThermoFisher Scientific). During each subject's procedure, this instrument was attached to the dentist's shoulder of the dominant arm when he was in the room to measure the concentration within the dentist's breathing; otherwise, when the dentist left the room, the instrument's probe was placed on a surrogate stand as near to the typical breathing zone for the dentist. This was to indicate the airborne exposure to nitrous oxide for an individual remaining in the area for the entire time of the nitrous oxide administration. The data obtained from these procedures were then uploaded to a computer for further data analysis.

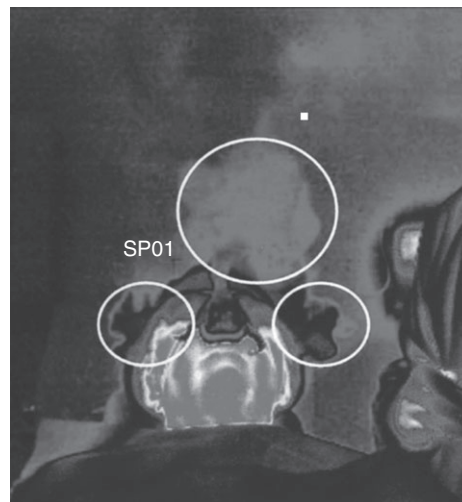


FIGURE 19 Typical image of nitrous oxide (shown by circles) from infrared camera.

The software used to combine the nitrous oxide air concentration data with the digital videos and IR thermography videos was MTVA software that was used in Case Study 1. The combination of these three types of data allowed the researchers to determine a relevant exposure value of nitrous oxide for a specific time point or interval of time. Therefore, an evaluation of the best work practices using System 1 could be performed by comparing the work practices and occupational exposures to nitrous oxide of the dentists in Phase 1 and Phase 3.

11.2.3 Results and Discussion

The results as shown in Table 1 and analysis of variance (ANOVA) demonstrated that System 1 when used by an experienced user was significantly better than System 2 at controlling occupational exposure to nitrous oxide. System 1, which was used in Phase 3 by inexperienced user, did not achieve the same levels as the experienced user and was not significantly different from System 2. Neither system achieved the NIOSH REL of 25-ppm TWA for the time of exposure. Other studies have shown that it is possible for System 2 to achieve levels less than 50 ppm (30, 31), but this study did not show this. This may be due to previous studies evaluated the system in mock surgeries not using actual patients. Therefore, variables that are controlled in mock surgeries, such as patient talking and breathing rates, may be difficult to control in actual practice. The use of VEM with real-time detection of nitrous oxide allows the researcher to observe the effect of these variables.

While neither scavenging system demonstrated the ability to control occupational exposure to nitrous oxide below the

TABLE 1 Summary of descriptive statistics for each study phase of nitrous oxide case study.

	Phase 1: System 1 – Experienced user	Phase 2: System 2 – Experienced user	Phase 1: System 1 – Inexperienced user
<i>n</i>	16	14	13
Mean air concentration of nitrous oxide/surgery (ppm) (S.D.)	61.6 (35.8)	225.6 (71.1)	166.5 (68.9)
Minimum, maximum (ppm)	25.5, 155.8	80.2, 363.8	64.5, 332.8
Confidence interval (95%)	42.5, 80.6	184.6, 266.6	124.9, 208.1

NIOSH REL, System 1 performed better at this task than System 2. Use of System 1 achieves maximal efficiency when combined with consistent best work practices. This study demonstrates that not only is control of occupational exposure to nitrous oxide in the oral surgery environment dependent on system design, it is also heavily influenced by experience and motivation for proper system utilization, work practices, patient, and surgical variables that are less easily controlled.

The combination of IR thermography, digital videos, and real-time ambient air monitoring of nitrous oxide concentration allows the comparison of occupational exposure to nitrous oxide between two scavenging systems for waste gas while examining the best work practices to use while performing wisdom teeth extractions such as ensuring that the mask of the scavenging system is fitted properly for either System 1 or System 2. The comparison between the two dentists' offices showed from the combination of these three data analysis that the use of best practices by the experienced dentist was significantly less than the less-experienced dentist. The evaluation of IR thermography and air concentration data using MTVA suggests that key work practices and patient and surgical variables affect waste gas emissions.

11.2.4 Conclusions

VEM using a real-time detector of nitrous oxide together with digital videography and IR thermography allowed the evaluation of the efficacy of two different types of waste gas-scavenging systems. In addition, it allows the examination of the work practices of two different dentists with different levels of experience with a specific scavenging system. These work practices were then able to be examined in detail using VEM and MTVA to determine specific times/intervals of time when exposure was highest and determine how the differences in work practices resulted in different exposures for the same task. These examinations then could lead to recommendations for improvements in work practices, leading to lower occupational exposure to nitrous oxide.

11.3 Radiological – University Laboratory Using Radioactive Materials

The training of nuclear pharmacists in the handling of radioactive materials occurs in university laboratories. In this setting, nuclear pharmacy students learn about the regulations concerning annual limits to radiation exposure, safe work practices, and also begin to see the potential for musculoskeletal disorders due to the layout of the workstation. The annual limit to the extremities, which is of particular concern to nuclear pharmacists due to manipulations of radioactive materials and equipment with the hands allowed by the Nuclear Regulatory Commission (NRC), is 500 mSv (32). Nuclear pharmacists generally stay below the limits but are still at risk for acute high exposures when accidents occur, so there is a need to work to lower the potential daily exposures. In addition, the type of workstation used causes the risk of musculoskeletal injury to be not minimal and needs to be examined for ways to lower the risk of musculoskeletal injury. Therefore, radiation workers in the workplace face two conflicting challenges: minimizing radiation exposure and minimizing the risk of injury to the musculoskeletal system resulting in the principles of radiation protection: minimization of exposure time, maximization of distance from the radiation source, and shielding techniques being in direct conflict with minimizing musculoskeletal disorders of the upper extremities and lower back. The interplay between the principles of reducing radiation exposure and the ergonomic stresses to the body is complex and often involves a conflict between best ergonomic practices and the best way to protect the worker from radiation exposure. Therefore, implementation of efficient, ergonomically friendly, and safe procedures has the potential to protect the nuclear pharmacist from musculoskeletal injury while minimizing radiation exposure to the hand and fingers.

Traditionally, in the nuclear pharmacy, film badges and thermoluminescent dosimeters (TLDs) have been used to monitor alpha, beta, neutron, and gamma radiation exposure for individuals. These dosimeters are worn as badges on the chest and as a ring on the finger(s). These monitoring methods give accumulated dose, and the dosimeter and/or badges are processed before the dose received by the worker

is known. Recently, real-time monitoring systems that monitor the instantaneous dose rate and the total dose of gamma radiation of the fingers obtained by an individual have been developed (33–35). These video-monitoring systems can simultaneously monitor radiation exposure and body postures of the worker while performing typical tasks of the nuclear pharmacist, thus allowing an ergonomic assessment and assessment of radiation exposure for individuals based on anthropometric variations in individuals and workstation design and layout. In addition, because the video is combined with the recorded exposure data, the task performed can be correlated with the instantaneous dose rate and total dose, warning a worker when he/she has reached a dangerous level of exposure.

Real-time video monitoring together with real-time detectors has been previously used for the assessment of chemical exposure and ergonomic evaluations of workers (36–40). In addition, the feasibility of the use of real-time video monitoring of radiation exposure has been shown by some work performed in the United Kingdom using the early advanced exposure gamma instrument system (AEGIS) as well as a system developed in the United States by Wang and McGlothlin (7, 33–35). The main disadvantages of some of these systems are that they only detect gamma radiation and rely on the worker to record his/her activities. The AEGIS (34, 35, 41) uses up to two cameras together with two dosimeter probes worn on a finger on each hand to assess both exposure and worker posture. The dosimeter is wireless and connects the video and exposure data to the laptop computer through Bluetooth technology. One camera focuses on the hands and one focuses on the body. The advantages of the new system and software are that assessment of radiation exposure and worker posture occurs simultaneously in conjunction with tasks being performed and identification of unintended procedures or actions that may increase exposure and risk. In addition, because the video is combined with the recorded exposure data, the task performed can be correlated with the instantaneous dose rate and total dose, warning a worker when he/she has reached a dangerous level of exposure. This preliminary study used the AEGIS video-monitoring system and dosimeter and observed two students of different heights.

11.3.1 Purpose

Using real-time VEM of radiation exposure and ergonomics, the objectives in the preliminary study were as follows. The first objective of this study was to identify specific tasks where anthropometric variations in individuals can cause increased radiation exposure to the extremities. A second objective to this study was to identify worker tasks that cause stress to the body. A third objective of this study was to identify ways to make the workstation have a more ergonomic design and layout.

11.3.2 Materials and Methods

The main equipment and supplies used in this project were a small nuclear pharmacy teaching lab containing ^{99}Mo – $^{99\text{m}}\text{Tc}$ generator(s), laminar flow hoods, L-blocks, syringe shields, vials containing radioactive materials, lead containers, syringes, tongs, dose calibrators, Geiger–Muller counters, microscopes, materials for product quality assurance, a heat source, single-channel analyzers for wipe tests, and waste containers. Some of the equipment are shown in Figure 20.

In addition, Web cameras and the advanced extremity gamma instrumentation system, which consists of an ED2 Personal Extremity Dosimeter and software that can capture and synchronize video and radiation exposure measurements via Bluetooth technology to a computer, are shown in Figure 21.

The study involved recording tasks of a typical nuclear pharmacist's duties. The system used two Web cams to record video on a laptop computer. One camera was used for recording the worker's body position, while the second camera was used to record the AEGIS dosimeter measurements and the worker's activities being performed by the hands. Still pictures were taken of the task of interest for radiation exposure and ergonomic concerns. Both Web cameras were started simultaneously and were synchronized to the AEGIS dosimeter measurements. In addition, activities were observed to see if the worker has an awkward posture with the shoulders abducted, whether the elbow is in neutral posture, static loading on the neck, glare/visual interferences from the screen, and the barrier height for different physical differences between the workers.

Ergonomic evaluations consisted of measurements of the height of the participants, the arm reach of participants, workstation height, dimensions of L-block used for radiation protection while preparing radiopharmaceuticals, and the distance to the dose calibrator from the front of the workbench. In addition to these measurements, participants were observed while in the lab and on video preparing radiopharmaceuticals. The observations documented body positions and activities performed.

The measurements of radiation exposure (mSv h^{-1}) to the hands and fingers were obtained in real time using an ED2 dosimeter while simultaneously video recording the tasks performed by the hands. The ED2 dosimeter has two probes that were attached to the fingertips on each hand. Then, the AEGIS software, which connects to the dosimeter, permits wireless capture of radiation exposure to the computer with/without video recording. The dosimeter is able to measure instantaneous dose rate and cumulative dose of exposure and sets off an alarm if above a preset threshold level for accumulated dose and dose rate. The actual tasks observed and recorded by the (radiation exposure measurements recorded by AEGIS software at sampling

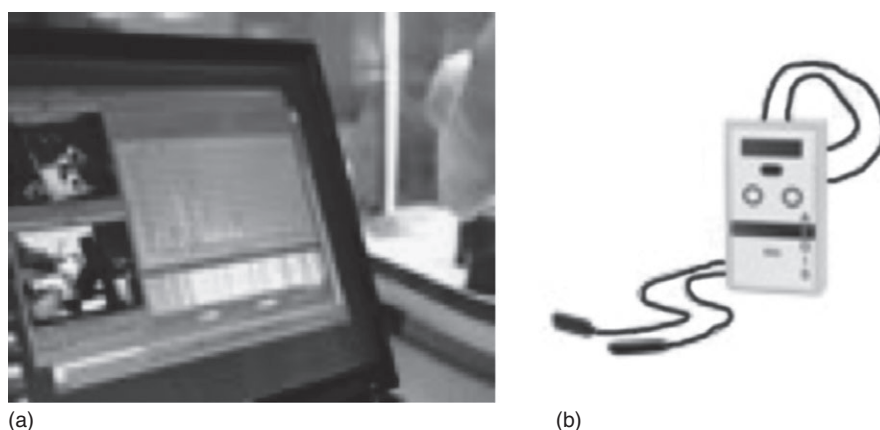


FIGURE 21 Advanced extremity gamma instrumentation system. (a) Computer with AEGIS software, shows graphical output of radiation exposure with video monitoring. (b) ED2 personal extremity dosimeter: probes are attached to fingers.

TABLE 2 Summary of the results of radiation exposure to the hands in two trials by two relatively moderately experienced nuclear pharmacy students.

Trial length (mm:ss)	Trial 1		Total dose to both hands	Trial 2		Total dose to both hands
	1:44			1:51		
	Right hand	Left hand		Right hand	Left hand	
Max dose rate ($\mu\text{Sv h}^{-1}$)	3766.078	333.281		816.539	1633.078	
Total dose (μSv)	5.920	0.606	6.526	1.750	1.407	3.157
Annual dose (at 6 h d^{-1} for 250 d yr^{-1}) (mSv)	307.385	31.465	338.85	85.135	68.449	153.584



FIGURE 20 Typical equipment found in a nuclear pharmacy lab: L-block. Vials with radioactive materials, dose calibrator, syringe, and lead containers.

rate of 1/s): (i) draw up radionuclide, saline solution using syringe shield, needle cap removed with left hand, (ii) assay of radiopharmaceutical kit by tong manipulation into dose calibrator, (iii) Repeat steps a–b w/o tongs or syringe shield.

11.3.3 Results and Discussion

To obtain the radiation data shown in Table 2, Figures 22–24, the following procedures were followed for each trial:

Trial 1 (Student 1):

0–55 seconds. Radionuclide drawn into syringe using syringe shield, needle recapped while in syringe shield, syringe removed from syringe shield with tongs, syringe placed in dose calibrator using tongs, dose measured, syringe removed from dose calibrator, syringe replaced back into syringe shield, needle cap removed, draw up saline, cap replaced.

55–104 seconds. Process repeated w/o using syringe shield or tongs to manipulate syringe. Syringe manipulated with right hand, left hand removed needle cap.

Trial 2 (Student 2):

0–74 seconds. Radionuclide drawn into syringe using syringe shield, needle recapped while in syringe shield, syringe removed from syringe shield with tongs, syringe placed in dose calibrator using tongs, dose measured, syringe removed from dose calibrator, syringe replaced back into syringe shield, needle cap removed, draw up saline, cap replaced.

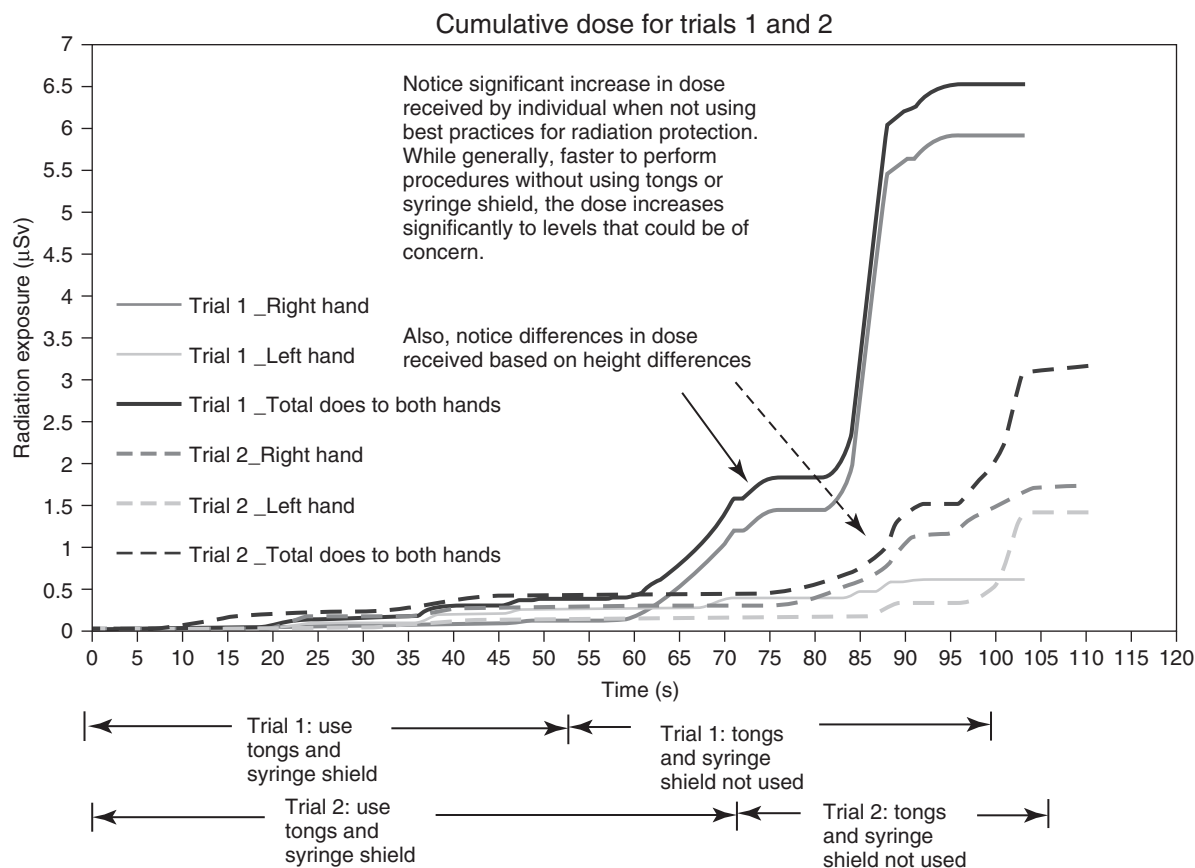


FIGURE 22 Cumulative dose for two students: Trial 1: Student 1 of height ~64 in. and Trial 2: Student 2 of height ~72 in.

74–110 seconds. Process repeated w/o using syringe shield or tongs to manipulate syringe. Syringe manipulated with right hand, left hand removed needle cap.

This study, by Table 2 and Figure 22, then shows that it is possible for a nuclear pharmacist to achieve a dose that is about 2/3 (338.85 mSv) of the annual dose limit of 500 mSv. In the event of spills or other incidents, the potential to be above the annual dose limit is plausible. However, performing the same tasks at the same workstation, another taller participant received a dose that was about 45% of participant 1. In addition, by the video recording and synchronized radiation exposure data, Figures 23 and 24 show in real time how specific work practices along with height differences may play a role in radiation exposure as the figures show specific time points when exposure varies depending on the task being performed. The ability to determine the correlation between task performed and exposure was aided greatly by the use of the real-time dosimeter data results which were synchronized by the AEGIS software to the video recording. Based on these two

trials, anthropometric differences, such as height, may play a significant role in radiation exposure. In addition, this study identified possible ways to lessen the radiation exposure and stress to the body by modifying the workstation.

In addition to the radiation exposure, video observations of the students indicated that stresses to the student's bodies differed according to height. Table 3 shows some of the observed ergonomic risks to students working in the nuclear pharmacy lab. Furthermore, changes to the layout of the workstation and tools used also were observed to have the potential to lessen musculoskeletal stresses to the body, such as using tongs that are angled while maintaining distance between the source and the worker. Some further findings and recommendations are demonstrated in Table 4.

This may indicate that not only are work practices in the nuclear pharmacy but also workstation design and layout, anthropometric variability in individuals, and work experience of nuclear pharmacist may all play a significant role in radiation exposure in the nuclear pharmacy. Using the anthropometric variations in nuclear pharmacists to modify a workstation so that it is more user-friendly for each nuclear pharmacist has the potential not only to reduce the radiation

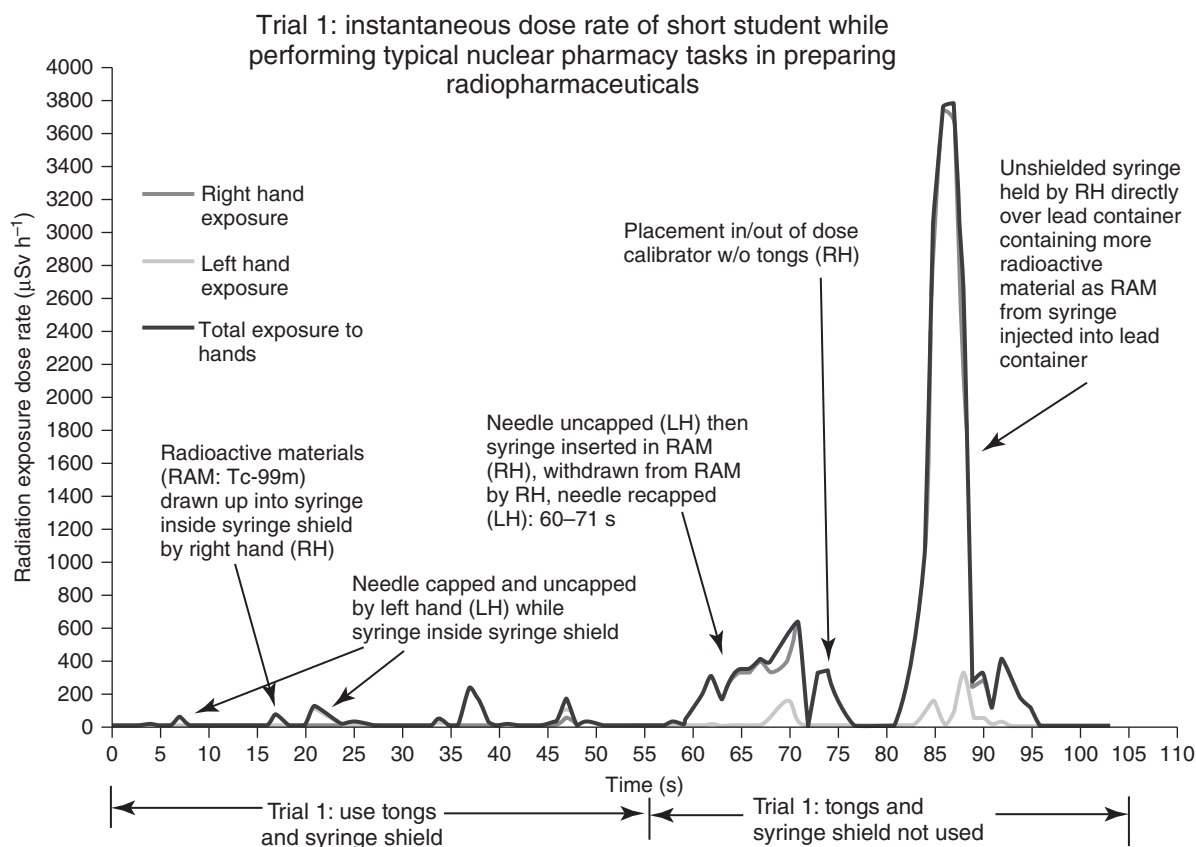


FIGURE 23 Instantaneous dose rate in $\mu\text{Sv/h}$ for shorter individual (~ 64 in.).

exposure but also to increase the efficiency and productivity of the nuclear pharmacist.

11.3.4 Conclusions

VEM appears to have a future role in nuclear pharmacy for both reducing radiation exposure and reducing musculoskeletal disorders using better work practices redesigning the layout and design of the workstation. In this study VEM showed that accommodations must be made for varying population sizes to avoid musculoskeletal disorders while still considering radiation safety in a nuclear pharmacy workstation. Furthermore, it showed that anthropometric variations in individuals could significantly affect the dose received as the short participant received a total dose of 338.85 mSv (2/3 of annual limit of 500 mSv), while the tall participant received a total dose of 153.58 mSv (45% of short participant). These doses obtained by these student participants show the potential for annual dose 500 mSv that is the annual limit allowed by the NRC. The AEGIS system has the potential to be a tool for training nuclear pharmacists in correct work practices as well as being a real-time monitor of work practices in actual nuclear pharmacy.

11.4 Carbon Dioxide and Heart Rate Monitoring in a Craft Beer Brewing Company

For the past 20+ years, the craft beer industry has experienced rapid growth, increasing in numbers from 1000 in 1996 to over 5000 in 2016. One of the by-products from brewing beer is carbon dioxide (CO_2) from the fermentation process. In addition, CO_2 is added to beer bottles, and to fermentation tanks, to purge the air against oxidation, thereby protecting the taste. While the popularity of brewing beer has grown, there has been little emphasis on occupational and safety hazards associated with carbon dioxide exposures during the brewing process.

11.4.1 Purpose

The purpose of this study was to use the Raspberry Pi with VEM software to monitor CO_2 exposure and heart rate while workers were performing selected work tasks during the beer brewing processes (42).

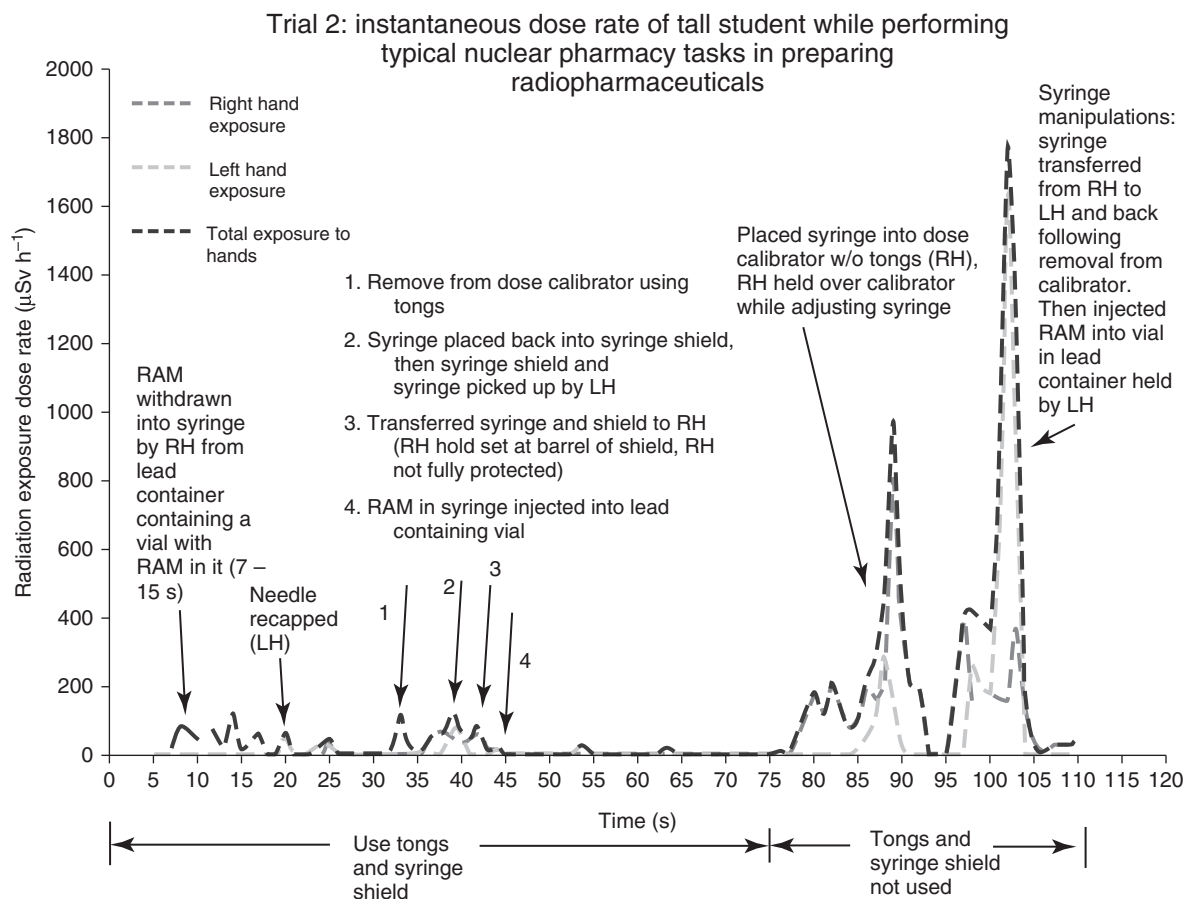


FIGURE 24 Instantaneous dose rate in $\mu\text{Sv/h}$ for taller individual (~ 72 in.).

11.4.2 Materials and Methods

VEM capture software was copied to a micro-SD card and plugged into the Raspberry Pi with a touch screen (Figures 25 and 26). A portable battery was connected to the Raspberry Pi to give it power. A CO_2 sensor was plugged into a USB port on the Raspberry Pi, and a small camera was connected to an internal slot on the Raspberry Pi. The heart rate monitor (Garmin: Vivosmart Heart Rate Tracker wrist watch) was connected via Bluetooth to the Raspberry Pi. A portable thumb drive was connected to a second USB port on the Raspberry Pi to render the video, sensor, and heart rate data from the test run. The Raspberry Pi was put into a backpack and put on the worker. The CO_2 nondispersive infrared (NDIR) sensor was tethered to the worker's lapel, the camera attached to the worker's cap (Cap-Cam), and the heart rate monitor was on the workers wrist (see Figures 27 and 28 for set up). A portable sports camera (Garmin-Virb X) was connected to a chest harness and fastened to the worker to capture high-quality wide-angle video (Figure 27). The sports camera clock was synchronized with the Raspberry Pi clock.

After the test run was completed, the backpack was removed, sensors detached from the worker, and recording stopped. The thumb media storage drive was removed from the Raspberry Pi and connected to a laptop computer containing VEM playback software. A screenshot of the playback software is shown in Figure 29. One of the most convenient features of the playback software is that parameters of exposure can be set so the program can fast forward to video and sensor data of interest. For example, if CO_2 data went over 5000 ppm, then conditions can be set on the playback software to a given time, for example 10 seconds before and after the peak event of 5000 ppm to see what was happening and what may have caused the high exposure. This time-saving feature serves to show patterns of exposure that could lead to effective interventions and controls.

11.4.3 Results and Discussion

The Raspberry Pi performed to expectations. Video, CO_2 , and heart rate data were collected on the VEM capture program and uploaded to VEM playback program. Figure 29

TABLE 3 Observations of ergonomic risk factors.

Ergonomic risk factor	Laboratory task
Repetitive motion	- Microscopy - Forceps holding/manipulation - Syringe use - Geiger counter use - Unsupported wrist rotation during manipulations of vials and lead containers
Awkward postures	- Shield heights - Finding writing space - Reaching around shields
Contact stress	- Leaning on countertops
Static postures	- Forward bending at trunk and neck in front of L-blocks - Unsupported arms held above waist - Standing in one place for extended time periods

is a screenshot showing the output from the test run. Preliminary results show that there is a correlation between increases in CO₂ and increase in heart rate (one of the symptoms from CO₂ exposure). Additional studies are needed to determine the interactive effects between physical activity during work, CO₂ exposure, and changes in heart rate.

11.4.4 Conclusions

The Raspberry Pi shows promise as an inexpensive VEM tool to capture multiple sources of data at one time. In this pilot case study, video, CO₂, and heart rate data were captured from a representative worker performing a routine work task.

TABLE 4 Ergonomic findings and recommendations.

Findings	Recommendations
#1: Dose calibrator: located in hood behind the L-block. Student had to reach far into hood to use and had to bend over to read	Move position of readout screen
#2: Shield size: shield not adjustable, but variety of student sizes	- Make shield heights adjustable - Make shield easier to put arms around - Make shield angle adjustable (fixed 15° angle hourglass shields, \$130, Topac, Inc.)
#3: Shield transparency: limited view angles, so students must strain their necks to see what they are doing	Provide completely transparent, adjustable shields equivalent to L-block shielding
#4: Workspace: students unable to have optimal 90° angle of the elbow when performing tasks	Use wooden blocks under preparation tray to reduce arm strain
Wrist in awkward positions when drawing up radionuclide and saline	Change angle of shield
Unsupported elbows when holding lead vials or syringe shields with syringe containing radioactive materials	
#5: Forceps/tongs: wrists with repetitive use could suffer injury. Also, an exposure peak seen when tongs are not used	Supply angled tongs that still maximize distance for radiation protection while being more comfortable for the wrists

**FIGURE 25** Raspberry Pi with touchscreen. Front view – software opening VEM program.

The methods used to collect the data by a worker putting on, using, and taking off a backpack were easy and did not influence the work process. Set up of the Raspberry Pi data collection system and putting on the worker took approximately one to two minutes. Taking the backpack and sensors off the worker took less than one minute.

While this system was far more efficient than previous data collection systems using VEM, the biggest advantage was the reduction in the overall cost of the system, nearly 90% less expensive than previous VEM systems tested. Additional studies are being conducted in this industry, and in other industries, to improve the operation and function of VEM using the Raspberry Pi.



FIGURE 26 Raspberry Pi with touchscreen set for recording video and sensor data and put into worker's backpack.



FIGURE 28 VEM set up for video, sensor, and heart rate collection using the Raspberry Pi. Side view.



FIGURE 27 VEM set up for video, sensor, and heart rate collection using the Raspberry Pi. Front view.

12 SUMMARY

The evolution and utility of VEM is presented in four different settings. Assessments of occupational exposure to different types of hazards while performing specific tasks have demonstrated the utility of VEM. In all four case studies the exposure could be correlated with specific work elements of tasks. The occurrence of high as well as low exposures and what was being done in each instance showed the value of combining video with sensor data. This was particularly valuable when peak exposures occurred and could be linked to specific work tasks. Showing these links provide means for improving work practices and/or engineering controls.

These four case studies show the progression in the development of real-time monitoring of exposure to different types of occupational hazards. The first case study showed the tedious nature of manually taking notes at the start and stop times of job elements to quantify exposure.

In the second case study, the MTVA software was adapted to use with chemical hazards rather than ergonomic assessments of task elements. This software was used in combination with IR thermography, the real-time detector of nitrous oxide, and digital videos for analysis of exposure. Both of the first two case studies required the user to download the data

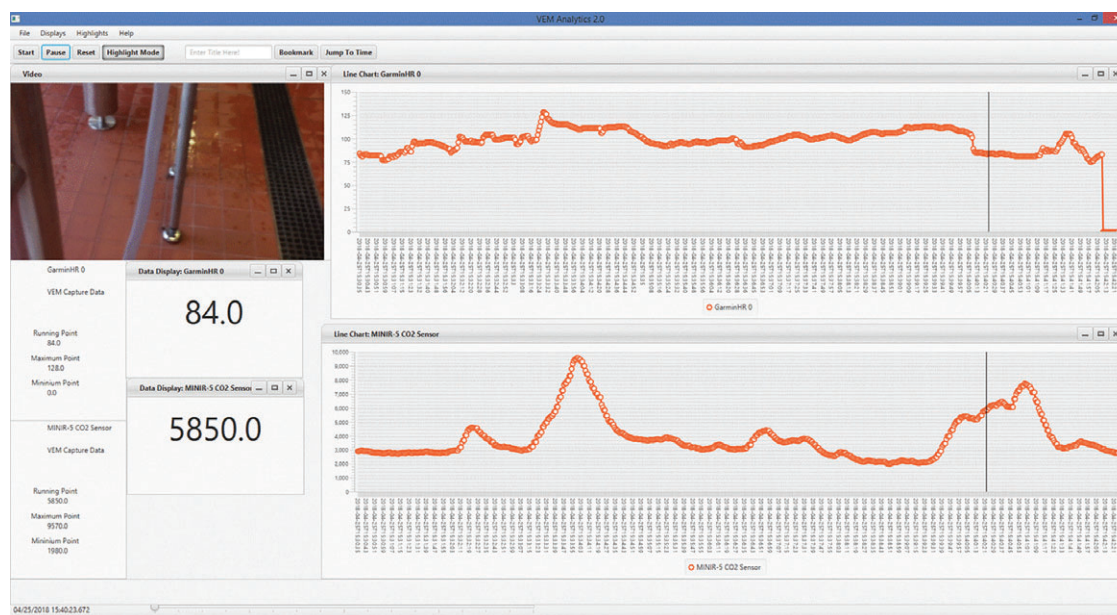


FIGURE 29 Screenshot of VEM playback program showing heart rate and carbon dioxide exposures on laptop computer.



FIGURE 30 Raspberry Pi zero with carbon dioxide (CO₂) sensor-attached DJI drone – for occupational and environmental sampling. Drone camera synchronized with CO₂ sensor. Use of GPS and artificial intelligence to determine flight path and sampling areas.

from the exposure detector to a computer before performing further data analysis.

The third case study showed how an integrated system (AEGIS) that has the software which synchronized video and exposure monitoring can be used to track exposure to radiation while obtaining visual information concerning the tasks performed, and thus the exposure can be readily correlated to task elements. In addition, because the detector (ED2 dosimeter) can be connected to the computer by wireless technology, the data does not have to be downloaded to the computer as the data goes directly to the computer and the exposure can actually be graphically seen as it occurs.

In addition, both exposure data and video can be observed later.

The fourth case study showed significant progress using VEM with the Raspberry Pi. Not only was it easy to use and playback for determining exposures, it was by far the least expensive system developed to date. Raspberry Pi, or something like it, may gain momentum among occupational hygienists. This is because many of the barriers (i.e. cost, complexity, and confusion) have been removed, and the value of determining specific exposure sources and cost-effective controls will be a valuable asset in protecting the health and safety of workers.

13 FUTURE APPLICATIONS OF VEM

Future applications for VEM will see more portable, powerful, and ubiquitous personalized systems that may link biosensing with monitoring hazards in the environment and at work. Storage, maintenance, and management of VEM will be Cloud based, using 5G internet platforms, where applications to assist workers and the environment will be more efficient and without limits. Automation will be a fact of life for the workplace. VEM will help industrial hygienists and manufacturing engineers decide where and when robots replace workers who perform routine, repetitive, and hazardous operations. This will leave workers to do higher skilled jobs robots cannot do (i.e. inspection and quality control). Preventive maintenance by workers will be automatic as tools will be brought to work stations by robots

that need calibration or need parts replaced, thus leaving workers to focus on problem solving that computers cannot do. In addition, environmental exposures may be linked with medical records showing changes in blood chemistry as indicators of hazard exposure. AI, aided by big data analytics, may be the next big enabler – helping the individual make smart decisions to improve their lives at home and at work. While there are many warnings about loss of privacy, it will be humans driving this process not machines. VEM likely will evolve from industrial and environmental applications to a personalized health assessment tool that simultaneously monitors our personal health and can visualize and quantify dangerous levels of chemical, biological, and physical hazards. For example, Figure 30 shows a drone equipped with a Raspberry Pi zero connected to a carbon dioxide sensor. The drone camera is synchronized to the internal clock of the Raspberry Pi, allowing it to sample the air without restrictions. Using global positioning system (GPS) coordinates, the video, carbon dioxide levels, time of day, and location can be recorded and used for a variety of purposes. Self-driving automobiles seemed like a generation away from reality but is now taking hold worldwide. For VEM and all its potential as an exposure assessment tool for the workplace and environment that time is now.

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COMPUTED TOMOGRAPHY IN INDUSTRIAL HYGIENE

LORI A. TODD, PH.D.

1 INTRODUCTION

A variety of air monitoring methods are used by industrial hygienists and occupational health professionals to evaluate indoor and outdoor human exposures to contaminants, evaluate effectiveness of controls, monitor process emissions, locate leaks, and determine the effectiveness of ventilation systems. Most sampling methods are either placed directly on an individual or in fixed locations in an area. These methods are essentially point samplers, thus the results are spatially limited to the discrete locations of the sampling devices. When the concentrations are integrated over time, the results are temporally limited to the length of the sample time. Limited spatial and temporal resolution is important because it reduces an industrial hygienist's ability to effectively evaluate and control exposures to contaminants.

When sampling devices are placed in a worker's breathing zone, the results relate only to the physical location of the specific worker or to the paths that they travel during the sampling period. Industrial hygienists take these spatially limited results from a subset of workers and assume they are representative of the larger unsampled workforce. This assumption may not always be valid; in practice, it is difficult to select a representative subset of individuals to sample because the concentration distributions in a room are unknown. Before choosing a subset of workers to sample, a larger homogenous group is usually created based upon similarities in the tasks they perform and in the local environments in the rooms where they work (1). The local environment is important because contaminant flow patterns are

strong determinants of exposure; however, environmental similarity is difficult to predict. Data on ventilation systems and airflow patterns are usually lacking and individuals selected for sampling may not be truly representative.

If a device is placed in a fixed location of a room to obtain an area sample, or a direct reading instrument is carried throughout an area to attempt to characterize flows, the results relate only to the physical location or path of the sampling device. Strategies for placing area samplers assume that locations with the highest or most relevant concentrations are represented and that the areas between the samplers are of less importance. In practice, this assumption is difficult to support; however, industrial hygienists use this information to guess the dispersion patterns of chemicals for the regions in the room between the area samplers. The assumptions and decisions currently made using spatially and temporally limited air sampling may not be valid; air concentrations are quite variable during the day due to changing ventilation patterns, the movement of people in a space, fluctuations in source emissions, and differences in work practices among people.

Temporal resolution is important for understanding and effectively controlling the generation and transport of contaminants in air, for identifying chemical intermediates produced during a process, for locating leaks, and for monitoring chemicals that are acutely toxic. Ideally, sample results would enable us to construct a complete spatial and temporal profile of the flow of air contaminant concentrations for an entire day, week, or season. This would require an enormous number of real-time measurements to

be concurrently obtained throughout an area. This is rarely performed. While real-time instruments can be used to provide good temporal resolution of concentration fluctuations, the number of chemicals that an instrument can accurately measure at one time is usually limited.

It can be particularly challenging to evaluate exposures and the flow of contaminants in outdoor environments such as animal facilities, landfills, oil refineries, and neighborhoods adjacent to factories. In these situations, exposure variability will be high and will be impacted by meteorological conditions.

In addition to the above limitations, air sampling is usually performed infrequently, and information about daily, weekly, or monthly variability is lost. Most industrial hygiene investigations involve short campaigns of one or two days. Thus, insufficient data are currently being used to evaluate the impact of industrial emissions and indoor air contaminants on the health of workers and residents in the community.

Computed tomography (CT) also called computer assisted tomography (CAT) is a promising method for both the occupational and environmental field and has the potential to provide both spatially and temporally resolved estimates of contaminant concentrations noninvasively (does not pump air out of a space through collection media), and in real-time, over large areas. This technique combines the real-time chemical detection methods of optical remote sensing (ORS), such as an open-path Fourier transform infrared (OP-FTIR) spectrometer, with the mapping capabilities of CT (2–17). This environmental CT system generates near real-time spatially and temporally resolved two-dimensional concentration maps of chemicals at low limits of detection (ppb–low ppm) for an entire area. Not just another nifty tool, this technology represents a major departure from conventional industrial hygiene air sampling methods and could allow researchers to understand and evaluate human exposures, source emissions, chemical dispersion indoors, airflow patterns, and chemical transport in ways that are unavailable using conventional methods. This technique provides a powerful tool for visualizing air contaminant species, concentrations, and flows in industry and outdoors in the community (see Figure 1).

CT is best known for its use in medical X-ray absorption imaging where it is a well-established diagnostic technique. With traditional X-rays, a person is placed between an X-ray machine and the photographic film. The X-ray machine sends radiation through the body at a single angle which results in a two-dimensional image on the film. The resulting image appears as if you are looking through the body and the structures of the body are superimposed making it difficult to distinguish individual organs.

In contrast, for CT scanning, the scanner looks like a large box with a tunnel in the center. The patient lies on a table that slides them in and out of the tunnel (see Figure 2). What makes CT scanning unique is that the scanner rotates around

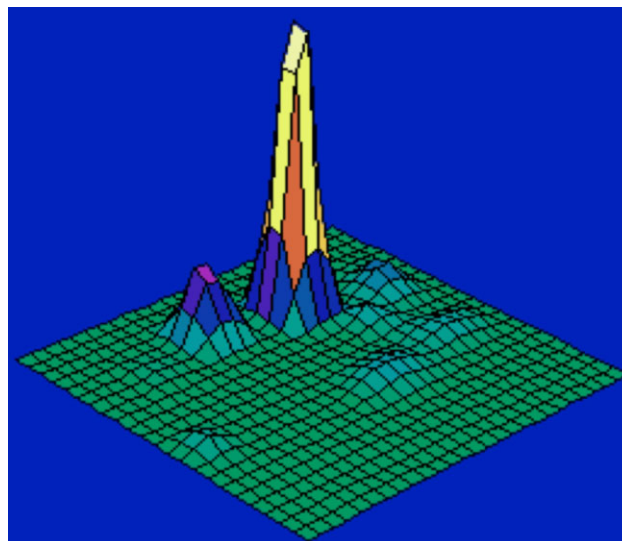


FIGURE 1 Example of a two-dimensional concentration map of a chemical at one height in a room. The peak heights represent the concentrations of the chemical at specific locations in the room. The diameters of the peaks represent dispersion of the chemical.



FIGURE 2 An example of a commercial medical CT scanner.

the patient and thousands of X-rays are sent through the body at many angles resulting in a 360° image (see Figure 3). To reconstruct a three-dimensional image, the ring of X-rays around the body is sequentially moved to adjacent planes of the body. In essence, adjacent wafer-thin cross-sectional slices are obtained through a body, like slices through bread. The resulting images reveal body structures in great detail. The origin of the word “tomography” is from the Greek word “tomos” meaning “slice” or “section” and “graphe” meaning “drawing.”

The first commercial clinical X-ray CT scanner was introduced in 1972 by EMI Ltd. under the leadership of Hounsfield (17). In the beginning, it took several hours to

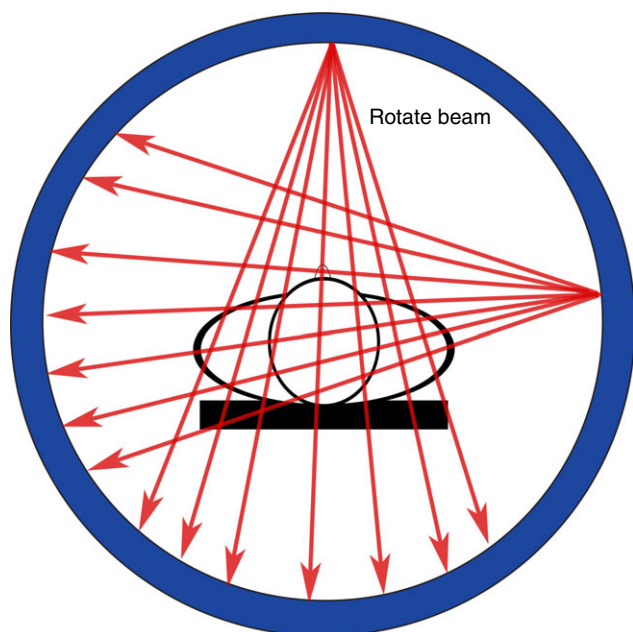


FIGURE 3 The medical CT scanner takes X-rays, as a fan beam, and then rotates around the body to obtain measurements at many angles. The outer ring holds the detectors.

acquire the raw data for a single scan or “slice” and then it took days to reconstruct a single image from this raw data. Over the years, scan time has significantly decreased and the technique has evolved to become one of the most essential methods of radiological diagnosis. CT systems can now collect up to four slices of data in about 350 ms and reconstruct images from millions of data points in less than a second.

In medicine, tomography is usually used to find small abnormal features, such as tumors, within the known features of the human anatomy. Therefore, to achieve high spatial resolution, a large number of rays must be used.

The principles behind medical CT scanning are applicable to many other fields. While the overall concept is the same, the CT systems differ in layout and design, due to the different application types and requirements. CT for environmental air sampling of chemicals involves using a remote sensing system that can obtain a network of concentration measurements at different angles across a space, usually through one plane. Instead of sending rays through a body to reconstruct organs and anomalies, rays are sent through the air to measure contaminants. The network of measurements is then processed using a tomographic reconstruction algorithm to generate a tomographic concentration map of a slice through the air.

Each tomographic concentration map provides a snapshot, which represents a short time period (minutes), of the concentration and location of contaminant plumes in a

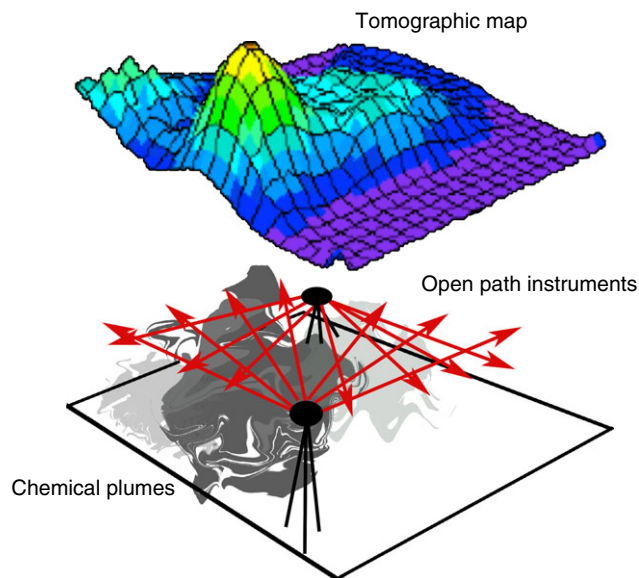


FIGURE 4 An environmental CT scanner taking a slice of open-path measurements of chemicals in air through a room. The measurements are processed using a specific algorithm to produce a tomographic concentration map.

slice or plane through the air (see Figure 4). As measurements are obtained over the day, the reconstructed concentration maps can be linked together to provide a powerful tool for visualizing the flow of air contaminants over space and time. Thus, a video of concentration fluctuations, for single or multiple chemicals, can be created for a room or area. Using a CT system for industrial hygiene monitoring, multiple locations throughout a room are quantified simultaneously, reducing the need to first determine the few important hot spots to sample. For example, Figure 5 shows a series of tomographic concentration maps of a tracer gas released over time, in one location, in an exposure chamber (18). If this was a workplace, and an integrated sampler was placed in the assumed highest concentration area, the industrial hygienist would have missed significant concentrations accumulating in other areas. The concentration maps generated with this CT system provide a powerful way to track the rapid movement of chemicals in the room. When maps are combined with ventilation measurements, tracer gas releases, information on process changes and workload, meteorological data, or information on the movement and location of workers in a room, the combined information can be used to quantify chemical emission rates, evaluate the effectiveness of ventilation systems, and track human exposures. With this environmental CT system, concentrations can be resolved in near real-time for an entire area with far fewer measurements than would be necessary, to obtain the same level of detail, using conventional point samplers.

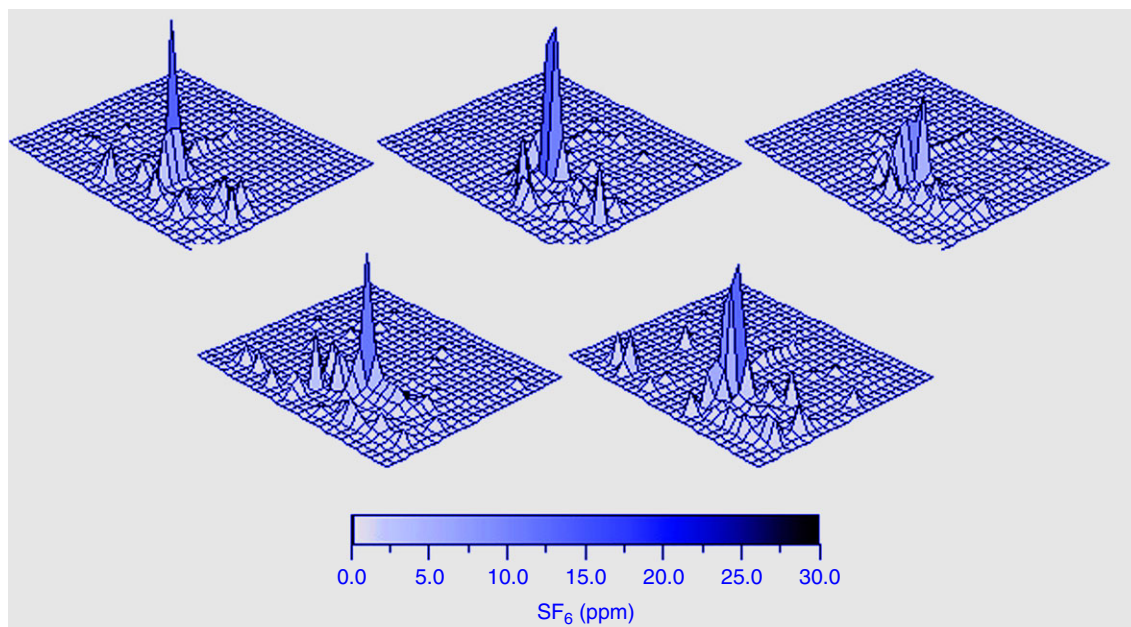


FIGURE 5 A series of five tomographic concentration maps reconstructed for sulfur hexafluoride in an exposure chamber. Each map represents a seven-minute snapshot.

1.1 History of Applying Tomography to Environmental Sampling

The use of tomographic techniques dates to 1917 with a paper by mathematician Radon (19). He proved that a three-dimensional object could be reconstructed uniquely from the infinite set of all its projections (line integrals along the particular measurement path). CT has been used in astronomy for producing maps of microwave radiation emitted from the sun (20, 21), imaging of nuclear fuel pin bundles (22), optics (23, 24), and electron microscopy for complex biomolecules (25–28). However, its greatest achievement and progress has been in the field of medicine, where cross-sections of the human body are reconstructed from a large number of X-ray attenuation measurements through the section of the body of interest (28–31).

In industrial hygiene or environmental air sampling, CT reconstructs chemical concentrations, and plume shapes. This could be an advantage because occupational and environmental scientists are interested in large structures (plumes) rather than small structures within the large structures (tumors in the body). However, there are some challenging differences when applying CT to air sampling:

1. Instead of using X-rays, optical rays must be used that can safely, noninvasively, and in near real-time monitor chemical concentrations across a space.
2. In medical CT a person can easily be placed inside a device that houses the X-rays; however, in air sampling, a large area, a room, or outdoor space cannot as easily be encircled by remote sensing instruments.
3. Appropriate ORS instrumentation must be available for indoor monitoring of chemicals across an open space.
4. People, equipment, or building structures all restrict the number and symmetry of available line-of-sight measurements.
5. In contrast to most organs in the body, chemical concentrations are constantly fluctuating in both time and space.
6. The signal-to-noise ratio of available ORS instrumentation limits data acquisition speed.
7. The current cost of ORS equipment limits the number of instruments and associated hardware that can be used. To be feasible, the use of CT in air sampling must use minimal hardware and still achieve acceptable results.
8. In indoor applications, often only a very limited number of path-integrated measurements can be obtained. When a limited number of beams from a few projection angles are used, artifacts such as streaking and distortion can be encountered in the reconstructed gas concentration map. Reconstruction errors that arise due to insufficient data are usually called aliasing distortions. It is important to use a reconstruction algorithm that minimizes aliasing distortions when a limited amount of data is available.

The first investigations applying CT to air pollution were in 1979 and 1982, when Byer et al. (32, 33), and Wolfe and Byer (34), described a theoretical laser-based system for measuring air pollution on an urban scale. Artificial concentration profiles were generated on a computer, and a simulated CT system was evaluated which used a circularly symmetrical set-up of laser fan beams. A circle of mirrors was used to reflect the laser fan beams across kilometer distances to detectors; thus, the mirrors created multiple virtual laser sources. These studies suggested rather complex virtual source beam set-ups (geometries) that required many mirrors and detectors. Consequently, the optical systems proposed in these studies would be difficult to align or maintain. The use of multiple detectors made the system costly, hardware intensive, and posed calibration and equipment maintenance difficulties. To date, these and other practical considerations have prevented the application of CT to large-scale (>1 km) ambient air pollution monitoring.

The first investigation of the application of CT to industrial hygiene was in 1990 when Todd and Leith (8, 9) performed a theoretical study using computer-generated static chemical profiles and a simulated CT system. This study showed the feasibility of applying CT to industrial hygiene by successfully reconstructing concentration profiles composed of overlapping bivariate Gaussians, using a simulated CT system with as few as four projection angles. An equal angle parallel projection geometry was used in these initial studies that had optical sources and detectors on three sides of a square room (see Figure 6). For a 40 by 40 foot room, this geometry placed one detector per foot along the side of the room. This geometry was chosen for its simplicity and applicability to various workplace layouts. As shown in Figure 6, the acute angle that the light beam makes with the room width is called the projection angle. A projection is defined as all the parallel, equally spaced light beams with the same projection angle. For every positive acute angle, its negative counterpart is used. From 4 to 12 projection angles were evaluated using stationary test data. In these initial computer simulation studies, the mean percent errors for reconstructing the highest concentrations of plumes decreased (from 9% to 0.3%) as the number of projection angles increased (from 4 to 12), respectively. In addition to the relatively low quantitative errors, the reconstructed concentration maps were visually similar to the original concentration maps. Although this geometry is not practical given the current remote sensing instrumentation, these studies were important for showing that CT is a feasible technology to apply to reconstructing chemical concentrations. The number of projections used was orders of magnitude fewer than required in other applications. Considerable progress has been made in this application of CT for measuring chemicals in indoor and outdoor air. There have been many theoretical and experimental studies, and a few field studies (2–15, 35–41). Progress in using CT to

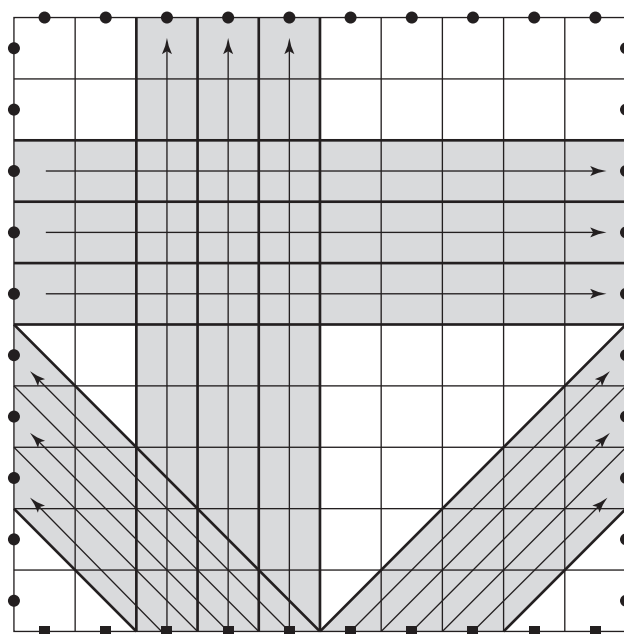


FIGURE 6 An equal-angle parallel-projection geometry. Representation of a 10 by 10 room with four projection angles, 0, 90, -45 , and $+45$.

measure aerosol distributions in air has been slower (42–44). Outdoors, this technology is being applied to measuring emission rates of chemicals, such as ammonia, off of waste lagoons from intensive swine facilities, emissions from landfills, emission from volcanoes, and industrial chimneys (5, 17, 39, 45–47).

2 DESIGNING COMPUTED TOMOGRAPHY SYSTEMS

As applied to air monitoring for chemicals, CT is the process of measuring a spatial concentration profile of a plane through a room using a network of line-integrated concentration data. The plane could be horizontal or vertical; the horizontal plane would primarily be used for the industrial hygiene application (see Figure 7). In theory, one or more rotating ORS instruments, such as a tunable diode laser or an OP-FTIR spectrometer can be placed in an area, along with mirrors, detectors, and/or retroreflectors, to create a network of remote sensing optical beams. Retroreflectors return an optical beam directly back to its origin. As the ORS instrument scans the area, it measures the integrated concentrations of contaminants present in the volume of each scanned beam path. Using a tomographic algorithm, a computer takes all of the one-dimensional path-averaged measurements and produces a two-dimensional estimate (map) of the concentrations and locations of the chemicals in the sampled

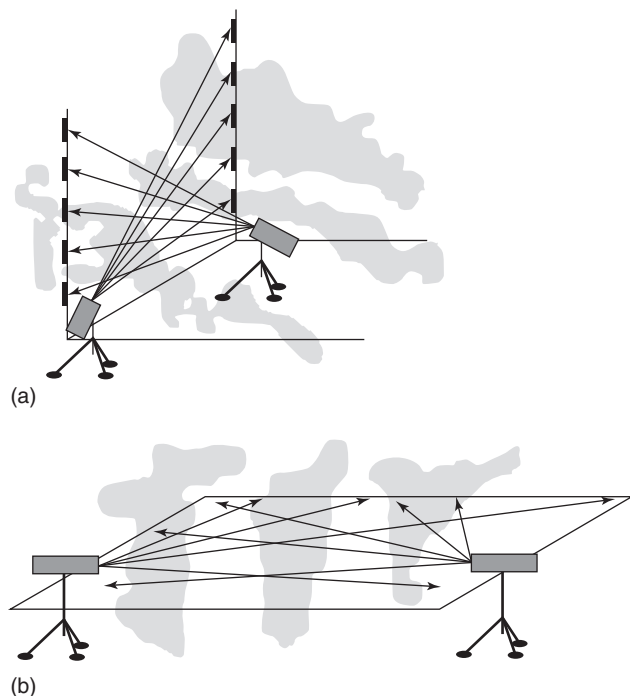


FIGURE 7 Horizontal and vertical planes for using CT to map chemicals in air. (a) Two ORS instruments monitoring a vertical plane to capture plumes coming off of an area. (b) Two ORS instruments monitoring a horizontal plane to capture plumes through a room.

plane (31). The tomographic map can be generated in a matter of minutes on a personal computer. The strategy is to obtain reconstructed concentration maps whose ray sums are similar to the measured ray sum data. The degree of spatial resolution (ability to differentiate between peaks) that can be reconstructed using the maps depends upon the number and orthogonality of the ORS beam paths for a given size area. The number and spatial placement of beams are partially determined by the type of ORS hardware. Constraints placed on the geometry of the CT system can translate into insufficient measurements, a limited number and range of angles and, ultimately, into artifacts in the reconstructed maps. To obtain a network of open-path measurements, with the currently available instrumentation, each ORS instrument sequentially scans the air; thus, each open-path measurement is taken at a different point in time.

Therefore, if geometries use a high density of rays, the overall time required to scan an area can be very long. Given that concentrations are in flux, this introduces inconsistencies in the data that adversely affects reconstruction accuracy. The degree of temporal resolution that can be obtained depends upon the ORS instrument measurement time for each individual beam, and the time required to completely sample an area. To map concentration profiles in flux, accurately, the time required to sample the entire room (due to ray density

and measurement time) must be balanced with the movement of air contaminants. Each complete set of ray measurements must be obtained very quickly to minimize data inconsistencies and to capture short-term fluctuations in concentrations and peak exposures. Using a given geometry, the choice of reconstruction algorithm can impact the spatial and temporal resolution of concentrations and the overall accuracy of the reconstructed maps.

Some of the decisions faced when using CT in industrial hygiene include:

1. Selecting appropriate reconstruction algorithms.
2. Designing and testing optimum remote sensing geometries.
3. Generating test concentration data to evaluate the CT system.
4. Selecting appropriate image quality measurements to evaluate the reconstructed concentration maps.
5. Selecting appropriate remote sensing instrumentation. The quality of the reconstructed concentration maps determines the ability of scientists to use the maps for exposure assessment, source monitoring, and leak detection.

Scientists need to be able to use the reconstructed maps to answer specific questions such as:

1. What are the quantities of chemicals leaking from an industrial process or emitted from an industry?
2. Where are the chemicals leaking from?
3. What quantities of chemicals do people potentially inhale?
4. What are the chemical dispersion patterns in air?

In general, when developing a measurement system using CT, both the geometry of the ORS equipment and the reconstruction algorithm must be tailored to the specific application and evaluated using computer simulations and laboratory experiments before they are deployed in the field.

Computer simulation studies are an efficient way to design and evaluate potential ORS algorithms and geometries for a specific industrial hygiene application. This is accomplished by using a computer simulation program and a battery of appropriate test concentration maps to simulate the entire CT process from data acquisition to reconstruction of concentration maps. Test maps are high-resolution grids that represent a room or area; each cell in the grid is assigned a concentration. Test concentration data should model reality, test the limits of the system, and include as many potential sources of error as possible. Although static concentration maps can be used, time-varying images provide a more rigorous evaluation of an algorithm or geometry. Time-varying images are sets of multiple maps that represent spatial and temporal

changes in concentrations of single or multiple chemicals in air. These test maps are usually computer generated because temporally and spatially resolved field data do not usually exist. It is important to use a variety of test concentration profiles to evaluate how well the reconstructed maps can perform specified tasks relevant to the application (48–50).

2.1 Test Concentration Maps

The test concentration profiles should be generated on a grid, which represents the sample site; the resolution of the test map grid (number of cells) should be a minimum of two to four times the density of the resolution of the final reconstructed map. The level of spatial detail needed for the application determines the resolution of the final grid. Test maps are then fed into a simulation program and synthetic open-path data are created by back calculating the measurements from the maps. Test maps that have been used in simulation studies include: (i) Kriged experimental point sample data from studies using an exposure chamber (static maps); (ii) CT maps reconstructed from chamber studies using a prototype CT system (static or time-series maps), and (iii) static and spatially and temporally varying data generated using dispersion models (3, 4, 51, 52). Static maps can be used for preliminary tests; however, they should include a range of peak numbers, peak concentrations, and plume diameters. Static maps cannot reveal the impacts of temporally changing concentration profiles. Time-series maps can be created with varying source generation and decay rates, diffusion coefficients, air velocities, source locations, and source intensities for single and multiple contaminants. Figure 8 shows time-series maps, which model the movement and decay of a single contaminant source.

2.2 Image Quality Parameters

To evaluate CT geometries and algorithms, it is necessary to quantitatively and qualitatively (by visual assessment) compare the reconstructed concentration distributions with the true (test maps) concentration distributions. Quantitative measures that can be used in computer simulation studies include nearness, peak exposure error, peak height error,

peak location error, and projection data distance. It is important to use a variety of quantitative measures because they evaluate different uses for the maps, and geometries and algorithms may not be ranked the same by all the measures. For example, nearness measures overall reconstruction accuracy and could reflect the presence or absence of artifacts. In contrast, exposure error measures how well the highest concentrations are reconstructed and would not necessarily be related to how well the shape of the peaks are reconstructed.

2.2.1 Nearness

Nearness describes the discrepancy between the true and the reconstructed concentration map on a cell-by-cell basis and is a global measure of the errors over all the cells in the map (53–56). Nearness is a dimensionless number; the smaller the nearness the better the agreement (see Eq. (1)). Nearness should only be compared between maps with the same number of grid cells. Nearness can only be used on experimental data where the true concentration distribution is known.

$$\text{Nearness} = \sqrt{\frac{\sum_{j=1}^{N^2} (c_j^* - c_j)^2}{\sum_{j=1}^{N^2} (c_j^* - c_{\text{avg}}^*)^2}} \quad (1)$$

where, c_j^* is the concentration of the j th grid cells on the “true” map, c_j is the concentration of the j th grid cells in the reconstructed map, c_{avg}^* is the mean concentration of all the grid cells in the “true” map, and N^2 is the total number of grid cells in the map.

2.2.2 Peak Location Error

“Peak location error” was developed to reflect how accurately a reconstructed map pinpoints the location of a chemical leak or emission source (9). It is the root mean square (RMS) difference in the location of the peaks in the original and reconstructed maps (see Eq. (2)). For example, for a 40 by 40 m area, reconstructed on a 40 by 40 grid, a location

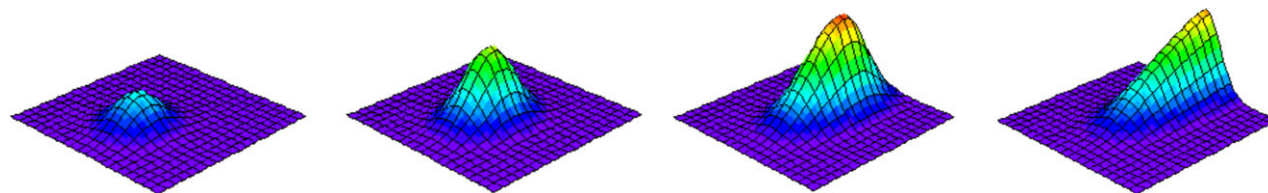


FIGURE 8 Example of time-series maps showing the movement of contaminants over time. The peak height represents the concentration of the chemical and the area represents the spread of the plume.

error of two would be equivalent to a distance of 2 m. The significance of this error is related to the level of accuracy required to pinpoint the plume. For example, if one were only interested in locating the general area of a leak, a coarse approximation would be required.

$$\text{Peak Location Error} = \sqrt{(x - x^*)^2 + (y - y^*)^2} \quad (2)$$

where, x is the x coordinate of the location of the peak in the reconstructed map, x^* is the x coordinate of the location of the peak in the test map, y is the y coordinate of the location of the peak in the reconstructed map, and y^* is the y coordinate of the location of the peak in the test map.

2.2.3 Peak Exposure and Peak Height Error

A measure of peak exposure error was developed to reflect the error in estimating the average concentration of a chemical inhaled by a person (2). Most occupational exposure limits for chronic toxicants are based upon averages of concentrations over time. Therefore, using time-series maps, concentrations can be averaged over an extended time frame (see Eq. (3)). In addition, the spatial movement of the worker can be simulated and the appropriate size footprint can be factored into the equation.

$$\text{Peak Exposure Error} = - \frac{\sum_{\text{time space}} \sum c_j^* - \sum_{\text{time space}} \sum c_j}{\sum_{\text{time space}} \sum c_j^*} \times 100 \quad (3)$$

where, time varies from the first time series map to the last map in the series, space represents a window around the exact location of the peak or through the path that the worker travels, c_j^* is the concentration of the j th cell in the test map, and c_j is the concentration in the j th cell in the reconstructed map.

Peak height error uses Eq. (3); however, space would represent a small window only around the location where the peak is at its highest. For static maps, the time factor would be removed.

2.2.4 Projection Data Distance

Projection data distance, Eq. (4), is a measure of how closely the reconstructed ray sums match the original ray sums (55). A data distance value of zero implies a perfect match.

$$\text{Projection Data Distance} = \sqrt{\frac{\sum_{i=1}^M \left(p_i - \sum_{j=1}^{N^2} a_{ij} c_j \right)^2}{M}} \quad (4)$$

where, p_i is the true i th ray sum, $\sum_{j=1}^{N^2} a_{ij} c_j$ is the calculated i th ray sum, a_{ij} is the contribution of the j th cell to the i th ray and, M is the total number of rays.

2.2.5 Visual Assessment

Visual evaluation of the reconstructed maps is the most useful method for evaluating CT geometries and algorithms. Although it is time consuming and subjective, it allows the finest distinctions to be made between geometries and algorithms, and it models what the industrial hygienist will be using in the field. Visually comparing surface plots of the reconstructed two-dimensional maps with the original maps is the most direct way to discern differences in peak location, peak shape, and peak resolution, and document the generation of artifacts. Artifacts can include unpredictable irregularities that look like noise, patterns such as streaking, and false concentration peaks. Artifacts and streaks can result in underestimation or overestimation of concentrations in the maps. By understanding artifact generation, industrial hygienists can determine the situations where geometries and algorithms might fail in the field and can use the information to design more robust geometries and algorithms. False peaks and streaking could be due to an uneven placement of rays and sparse sampling. The video of reconstructed concentration maps can be evaluated as to how well dispersion, concentrations, and plume contours are reconstructed.

3 CT ALGORITHMS FOR THE INDUSTRIAL HYGIENE APPLICATION

Many different tomographic reconstruction algorithms have been proposed for CT applications: the three main types are analytic (30, 57), back-projection (58–60), and iterative methods (20, 28, 56, 61). Analytic techniques are used in most commercial medical CT scanners; however, they may not be the best algorithms to use for reconstructing chemical concentrations where data is sparse and angular coverage is limited. Iterative methods, for example, may yield better performance in industrial hygiene applications where there are incomplete data, nonsymmetric ray geometries, limited angular coverage, and noise due to nonstationary chemical profiles. Iterative methods allow flexibility in the placement of remote sensing equipment in a room and allow constraints to be imposed on reconstructed measurements (60, 62). Some of the algorithms that have been used when applying CT to reconstructing concentrations include algebraic reconstruction (4, 9) smooth basis function minimization (13, 14) and non-iterative LTD (63) techniques.

Bayesian approaches may be particularly suited for reconstructing chemicals in air because they allow investigators to incorporate a priori knowledge about the source being

measured. When the data is limited and noisy, prior information can be of as much importance as the data. Many chemical gas concentrations and fluid flows are controlled by turbulent diffusion and thus characterized by smooth shapes. Including a prior information can force the solution to have smooth shapes implicitly which makes the algorithm less sensitive to measurement noise. These methods make a trade-off between matching the measured data and regularizing the solution, by prior information, resulting in smooth images. These include smooth basis function minimization (SBFM) (13, 14, 64), the low third derivative (LTD) (65), and the modified low third derivative (LTDm) (63, 66, 67).

A single algorithm may not be appropriate for all air contaminant applications. An algorithm that can accurately pinpoint leaks might not provide the most accurate estimates of overall environmental concentrations. An algorithm used to reconstruct rapidly changing concentration distributions may not be applicable for a region with near steady-state concentrations. Therefore, it is important to evaluate and refine an algorithm for a given application. Some of the algorithms that have been used in industrial hygiene applications will be described below.

3.1 Iterative Methods

Iterative methods can be considered as brute force methods to solve image equations. Using iterative methods, an idealized measurement space, such as a room, is broken into an N by N grid of cells. Figure 9 shows a 10 by 10 grid of 100 cells. Each cell, j , is assigned a concentration c_j , which is assumed to be uniform and nonnegative. Ray sums are line integrals (path-integrated concentrations) of c_j along various paths through the room. The rays have a finite width and, therefore, are

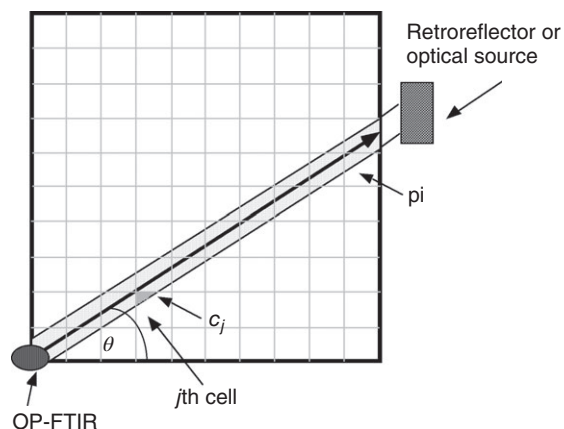


FIGURE 9 An idealized room is represented by 10 by 10 grid of 100 cells. The projected ray sum is p_i , with a projection angle of h . The concentration of the contaminant in the j th cell is c_j . The ray only covers a portion of the cell.

approximated by strip sums. The relationship between cell concentrations and ray sums can be expressed as Eq. (5),

$$p_i = \sum a_{ij}c_j, i = 1 \dots M, j = 1 \dots N^2 \quad (5)$$

where, p_i is the ray sum at projection angle Θ , a_{ij} is the weighting factor representing the contribution of j th cell to the i th raysum, c_j is the density function for the j th cell, M is the total number of rays, and N^2 is the total number of cells in an N by N grid.

Equation (5) represents an array of M equations and N^2 unknowns. For reconstructing chemical concentrations, typically a sparse geometry is used and the number of equations is far fewer than the number of unknowns. In addition, time constraints are placed on the sampling that generate inconsistent data. Therefore, iterative approaches have been used to solve these equations rather than using matrix inversions.

3.1.1 Algebraic Reconstruction Techniques (ART)

For ART1, an initial guess is made of the values in all the cells in the grid; based on this guess, the first path-integrated ray concentration is calculated. The values of all the cells that the ray passes through are then corrected so that the calculated ray sum equals the measured ray sum. The correction procedure is shown in Eq. (6) and is repeated sequentially for each ray. With this algorithm, the weights of all cells through which the ray passes are assigned a value of one, and the weights of all cells through which the ray does not pass are assigned a value of zero. One iteration is completed when all the ray sums have been corrected. The ART1 algorithm is terminated after a fixed number of iterations, such as 10, or by using a stopping criterion, such as the fractional change in the variance of the reconstructed concentration map, from one iteration to the next (54, 55).

$$c_j^{(q+1)} = c_j^{(q)} + \frac{\left(p_i - \sum_{j=1}^{N^2} a_{ij}c_j\right) a_{ij}}{\sum_{j=1}^{N^2} a_{ij}^2} \quad (6)$$

where, q is the iteration number.

The ART3 algorithm is based on the premise that a precise solution to Eq. (5) is generally impossible because the p_i s are physical measurements that contain measurement error (68). Therefore, ART3 finds a solution to the inequalities shown in Eq. (7) and uses the same correction scheme as in Eq. (6). However, the equations have to be satisfied only within a tolerance, which is estimated from prior knowledge of the experimental conditions and errors.

$$p_i - \epsilon_i \leq \sum_{j=1}^{N^2} a_{ij}c_j \leq p_i + \epsilon_i, i = 1, 2, 3, \dots M, \quad (7)$$

where, ϵ_i is an allowed tolerance.

For ARTW, the initial guess and correction procedure is the same as ART1; however, the weights of each cell, for a given ray, are proportional to the average length of the ray through the cell. The average length of a ray in a cell is calculated by estimating the area of the cell covered by a ray and dividing it by the width of the ray, which can be assumed to be one-cell width wide.

SIRT (simultaneous iterative reconstruction technique) uses Eq. (6) to determine the change in the j th cell; however, the value of the j th cell is not changed until all of the differences in the ray sums are calculated. At the end of each iteration, the cell concentrations are then changed once using an average value of all the corrections that would be made to that cell.

SART (simultaneous algebraic reconstruction techniques) (69–71) makes cell corrections similar to SIRT; however, average corrections are applied to each cell after calculations are made for all ray sums in one projection. Therefore, when four projection angles are used, four averages are applied to each cell in an iteration.

MART (multiplicative algebraic reconstruction techniques) is similar to ARTW; however, cell corrections are updated by a multiplicative adjustment scheme that maximizes an entropy function (72). The correction in the cell estimate is equal to a relaxation factor raised to the power of the ratio of the measured raysum and the back-projected raysum. In MART, like ART, the cell estimates are corrected one ray at a time.

3.1.2 Maximum Likelihood Expectation Maximization (MLEM) Algorithm

Maximum likelihood expectation maximization (MLEM) is a simultaneous iteration technique that corrects all the cells at once after an entire set of ray sum data is obtained in each iteration (73, 74) (see Eq. (8)). The correction factor for a cell is equal to the sum of the ratios of the reprojected values of the cells and the backprojected values of the cell. In MLEM, the cell estimates are corrected taking into consideration all the projections simultaneously. MLEM is usually allowed to iterate longer than the ART algorithms.

$$C_j(n+1) = \left(c_{jn} / \sum t_{ij} \right) * \sum \left(t_{ij} p_i / \sum t_{ij} c_{jn} \right) \quad (8)$$

where, $C_j(n)$ is the concentration in j th cell after the n th iteration, $\sum t_{ij} c_{jn}$ is the reprojected value of the image estimate c_{jn} , and $\sum t_{ij} p_i$ is the backprojection of the projection array.

The concentration distribution is estimated by using the maximum likelihood criterion, which is given by Eq. (9),

$$\ln L(C) = \sum \left\{ - \sum t_{ij} c_j + p_i \ln \left(\sum t_{ij} c_j \right) - \ln(p_i) \right\} \quad (9)$$

where, $L(C)$ is the likelihood of generating the image C , t_{ij} is the transfer matrix from image cell j to set of parallel

projections i , c_j is the concentration at cell j , p_i is the raysum for the i th set of projections, i is the number of rays, 1 to M , and j is the number of cell, 1 to N^2 .

The likelihood strictly increases at each step unless it is at a maximum; therefore, all the cells have positive values of concentration.

3.1.3 MLEM and Grid Translation

In the above iterative methods, the reconstruction grid has a fixed, single basis resolution (N by M). The concentration in each cell is assumed to be homogeneous, nonnegative, and is updated with each iteration. One limitation of choosing a fixed single reconstruction grid resolution is that the location of the edges of each of the grid cells in relation to a particular peak position and shape could adversely impact reconstruction accuracy. For example, if a peak in the original high-resolution map is distributed across multiple grid cells, the highest value that is reconstructed in these cells can severely underestimate the actual peak value. A grid translation (GT) method has been developed to be used with MLEM to improve upon this limitation (75). In the GT method, this problem is overcome by not just using the (single) basis grid for reconstruction, but an additional number of translated grids as well.

With the GT method, reconstructions are performed on a number of different grids rather than on a fixed single grid. The basis grid is the same as used in the single grid methods and the additional grids are formed by translating, in both the horizontal and vertical direction, over distances equal to a fraction of a basis grid cell size. After the determined number of MLEM iterations on each of the translated grids, the resulting “interim” concentration maps of each of the grids are combined into one final map of higher resolution.

3.1.4 MLEM: Grid Translation-Multigrid (GT-MG)

The grid translation-multigrid (GT-MG) method improves upon the previous GT method. The GT-MG method starts with a very coarse resolution 2 by 2 basis grid. GT is then used to generate additional grids starting with this 2 by 2 grid. After the determined number of translations are performed using MLEM, a final combined higher resolution map is obtained.

Next, the basis grid resolution is increased to 3 by 3 cells. The initial concentration values used in the 3 by 3 grid are calculated from the final combined map generated from the 2 by 2 basis grid. Iterations are then performed on the new set of grids, resulting in a new final combined map. The method proceeds by incrementally increasing the basis grid resolution, applying the GT method and then using the final map of the previous (lower) basis grid resolution to set the initial concentration values in the new grids (76).

3.2 Smooth Basic Function Minimization (SBFM)

The previous algorithms did not assume anything about the underlying concentration profile except that it is nonnegative and the concentrations are homogeneous in discrete grid cells. SBFM does not artificially create a grid of cells and assumes *a priori* information about the underlying concentration profile by modeling the data with smooth basis functions (bi-variate Gaussians defined in the x - y plane) (13, 14).

3.3 Non-iterative Low Third Derivative (LTD) Method

The LTD method was developed for indoor applications and reconstructs the concentration field by trading off matching the measured data and regularizing the solution, by prior information, to result in smooth images. In this approach, the estimate is the most probable image given the measured path integrals, prior information of the image solution and a statistical model of the data acquisition. In the LTD algorithms, one prior information is that the third spatial derivative of concentration is assumed to be close to zero, resulting in locally quadratic concentration profiles (65–67). For example, the third-derivative (change per pixel) between two adjacent pixels $c(r, k)$ and $c(r, k + 1)$ is described by Eq. (10).

$$\left. \frac{\partial^3 c}{\partial k^3} \right|_{r, k \rightarrow r, k+1} = c(r, k + 2) - 3c(r, k + 1) - 3c(r, k) - c(r, k - 1) = 0 \quad (10)$$

In a modification of this method, called LTDm (63), an extra constraint is placed on the reconstructed concentration field. It states that pixels contained within beams whose path integral is under a certain cut-off limit (e.g. under the detection limit of the system) are forced to assign a concentration value of zero or close to zero.

4 SIMULATION STUDIES OF RECONSTRUCTION ALGORITHMS

Rigorous testing should be performed when developing or modifying algorithms because they are based on different mathematical foundations which could make them sensitive to different types of ORS geometries and concentration profiles.

Todd (4, 9) has studied iterative algorithms using both simulated concentration data and data obtained from prototype CT systems placed in an exposure chamber. In general, MART and MLEM performed the best, followed by ARTW,

ART1, ART3 and then SIRT and SART. For the ART algorithms, reconstructions were improved by using a more accurate weighting scheme to allocate the concentration corrections (ARTW). While MLEM and MART were similar, MART performed better when the concentration profiles had broad peaks, and MLEM performed better for rapidly changing concentration profiles. Regardless of the type of algorithm, most peaks were reconstructed within one foot of their true position using both static and time-series test maps. With these traditional iterative methods, peak exposure errors ranged from 25% to 50% using time-series maps and 8% to 15% using static maps.

Using the newer GT and GT-MG methods, visually, reconstructions of the peaks were significantly improved over single grid reconstructions, see Figure 10. In addition, the peak exposure errors were reduced by as much as 40% and 85% over using the traditional MLEM reconstruction algorithm. These methods provide a significant improvement over traditional methods for reconstructing chemical plumes in air. In particular, this improvement is important for coarse resolutions. Given the sparse remote sensing configurations that must be used in industrial hygiene applications, the ability to produce high-resolution maps with few measurements is significant. This improvement is achieved without artificially interpolating additional optical rays and without using any assumptions about the underlying resolution or the number of peaks in the map.

Comparison of algorithms performed in numerical simulations by different researchers can be tricky because results depend not only on the algorithm but also on the beam set-up and the test distributions. Keeping this in mind, studies by Cehlin (63) using LTDm show promise for reconstructing chemical distributions in air. Using LTDm, the agreement between tomographic reconstructions and test maps were similar to the performance using the GT-MG algorithm developed by Verkruysse and Todd (75, 76). The LTDm showed excellent reconstruction quality for single-peak profiles; for maps with three peaks or sharp gradients, the quality was reduced.

5 ORS GEOMETRIES FOR CT IMAGING OF CHEMICALS IN AIR

The geometry of a CT system involves the placement of the open-path instrumentation (optical sources, detectors, mirrors, or retroreflectors) in or around a room. In theory, because concentrations in a room are really not discretized into cells, an ideal geometry would be symmetrical and would completely flood the room with an infinite number of optical rays that span a wide range of angles. Sampling each cell identically (number and orientation) means that the reconstruction result is more or less independent of the locations of the gas sources and peaks. However, this is may not

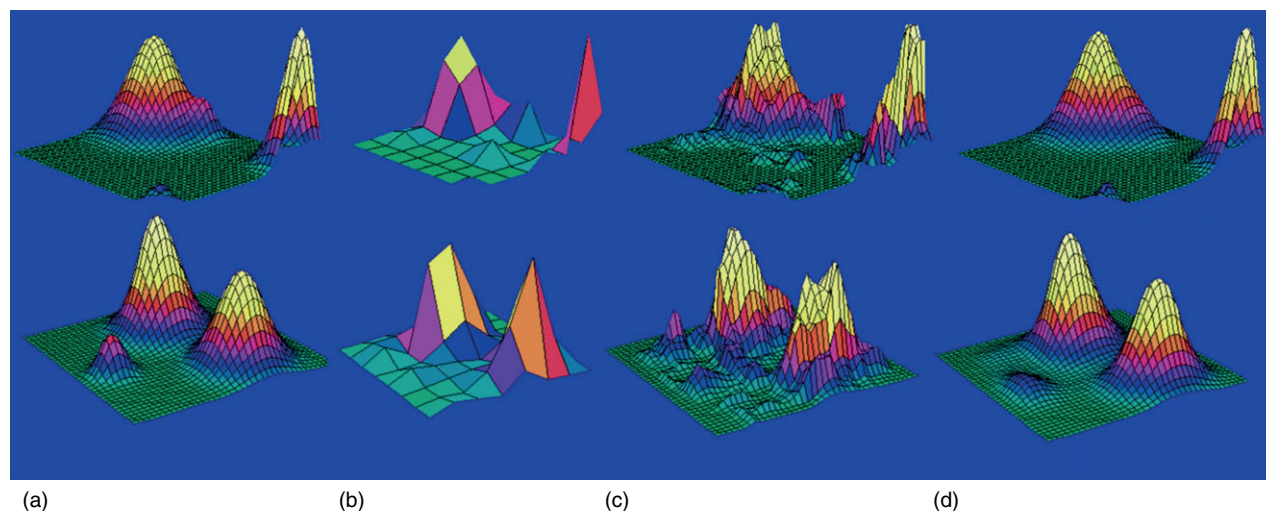


FIGURE 10 (a) Original test maps with three peaks are shown in the left column. Corresponding reconstructions using the single grid (b), grid translation method (c), and grid translation multigrid method (d) are shown in columns 2–4, respectively.

always be realistic. In practice, limitations are placed on the geometry due to the layout of rooms or area, purpose of the sampling, ORS instrumentation, monetary resources, and the need to quickly measure spatially changing concentration profiles. Estimates of how many equally spaced angles are needed for good resolution vary, and are specific to the application (24, 77).

Symmetry is important to ensure that all areas of the room are sampled equally; symmetrical geometries yield better quality reconstructions than asymmetric geometries. Unequal sampling can result in artifacts, streaking, and distortions of the images. Unlike medicine, reflected rays can be used in the application of CT to industrial hygiene. Reflected rays can improve reconstruction accuracy by adding orthogonal rays to the geometry and increase coverage. Reflected rays are created by using mirrors to reflect rays across a space to a retroreflector that returns the beam directly back to its point of origin. However, mirrors are difficult to align quickly and to maintain alignment in the field. In contrast, retroreflectors are easy to align and maintain alignment; but, they are currently very expensive.

As a rule of thumb, increasing the number of remote sensing instruments results in better reconstruction quality because the angular coverage of the beams is increased, and multiple measurements can be taken within a short period of time. The most critical factor in designing geometries is the independence of the optical beams; by maximizing the angular separation between the different ray projections or rays, independence is maximized. With only a few remote sensing instruments, independence can be maximized by creating parallel reflections at many angles.

The higher the density of rays in a geometry, the higher the reconstruction resolution. However, when reconstructing

nonsteady state plumes of contaminants, a trade-off exists between the ray density and the rate at which the rays are obtained. When using CT for industrial hygiene sampling, the airflow and contaminant generation conditions determines the point at which increasing the density of rays deteriorates reconstruction quality because of the increase in the overall sample rate.

5.1 Simulation Studies of Geometries

To use a traditional equal angle parallel projection geometry (ideal) in a room, hundreds of detectors would be placed along a wall. With the currently available ORS instrumentation, this set-up would be very expensive. A more feasible set-up involves the use of a scanning, fan-like beam geometry. For example, an entire OP-FTIR spectrometer or a portion of the optics is placed on a 360° rotating base. One or more of these spectrometers are placed in a room, and they sequentially scan the room shooting light at retroreflectors or receiving light from optical sources. When there is only one spectrometer, multiple mirrors are used to reflect light across the room to create a network of intersecting rays.

Todd (10, 16, 78) has extensively studied many different CT geometries designed with from one to four scanning remote sensing instruments (see Figure 11). Some of the geometries had optical beams with only straight lines of sight, others also used mirrors to reflect the beams across the room to retroreflectors in order to increase spatial coverage. When two or more scanning instruments were used, they were placed along the walls of the rooms and scanned a range of 0°–180°. When one instrument was used, it was placed in the center of the room and it scanned a range of 360°. Simulations were performed using both static and time-series

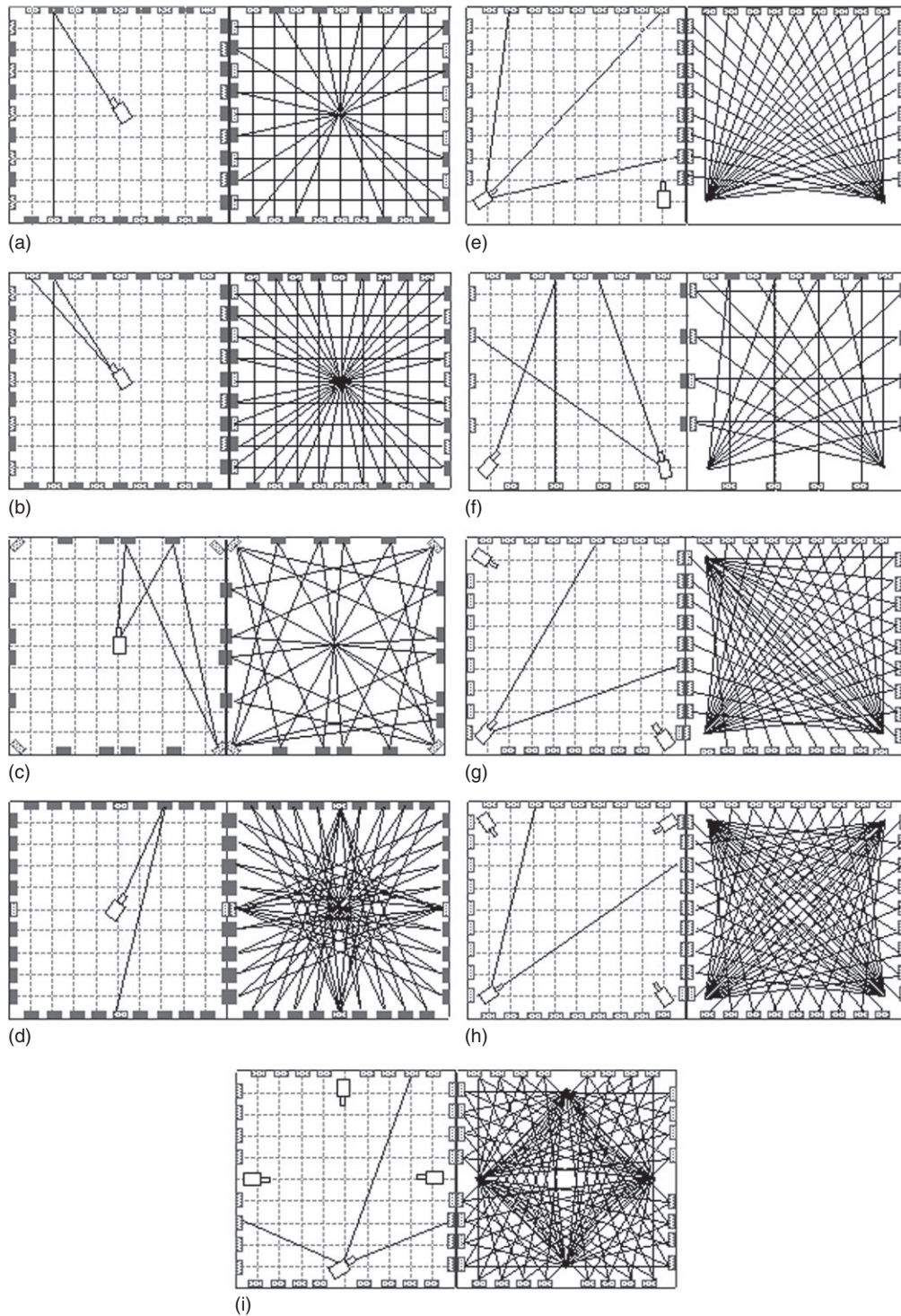


FIGURE 11 Each CT geometry is illustrated with a pair of diagrams. The left diagram shows a few rays and the diagram on the right shows the overall pattern of the rays. A dark box represents a mirror and a light box represents a retroreflector (a–d), single instruments are placed in the center of a room. Mirrors are used to create virtual equal angle parallel projections (a, b), with (b) using additional straight rays. Mirrors are used to create fan-like beams (c, d). Fan beams are represented using two instruments (e, f), three instruments (g), and four instruments (h–i).

test concentration maps; each time-series map represented changes in concentrations every 15 seconds over simulated three-hour time periods.

Geometries were designed on a 20 by 20 grid and used a total of 120 rays. Therefore, one, two, three, and four ORS instruments used 120, 60, 40, and 30 rays per instrument, respectively. It was assumed that the time required to take each ray was equivalent regardless of the geometry. Therefore, the greater the number of instruments, the shorter the time required to sample an entire room.

Using the time-series maps, geometries with four instruments were superior and reconstructed maps that were quantitatively more accurate, visually smoother, and had fewer artifacts, than geometries with fewer instruments. The geometries using a single instrument in the center of the room with reflected rays gave very poor reconstructions with the time-series maps that simulated a high airflow. Large streaks were present in the reconstructions, radiating from the grid center where the instruments and the peaks were co-located. Peaks appeared jagged, there was streaking along some of the ray paths, peaks were poorly located and concentrations were significantly overestimated. One of the single instrument geometries both simulated parallel projections with reflected rays and used additional straight rays (see Figure 11b). Even with this geometry, reconstructions were poor using maps that simulated high airflow in the room. However, for low airflow simulations, this geometry reconstructed the maps very well and equivalent to the four-instrument geometry. The importance of using a variety of time-series maps is illuminated by the results using a single instrument. When the static maps were used, several of the single instrument geometries had quantitative and qualitative results equivalent to the three and four instrument geometries. Park et al. (36) also tested similar single instrument geometries. In their studies, they only used static test maps generated from a bivariate normal distribution model and from experimental chamber data. Their results were similar to the Todd and Bhattacharyya (3) study using static maps.

When using time series maps, differences in the reconstruction quality can occur because of the difference in the times required to scan an area completely. For example, if 120 rays in total are used, and if it takes 15 seconds for each ray measurement, the four, three, two, and one instrument geometry could require 7.5, 10, 15, and 30 minutes to sample the room once, respectively. The difficulty that the single instrument geometries had with reconstructing the time series maps was due in part to the increased time required to obtain a complete set of rays relative to the spatial and temporal changes in concentrations. If the overall sample times are made equivalent, then the geometries which have a higher density of orthogonal rays will produce better reconstructions. In practice, there is a limitation to the speed that each ray measurement can be taken. The faster the

measurement of the chemicals, the lower the signal-to-noise ratios, and higher the chemical limits of detection.

An alternative to decreasing measurement time by reducing instrument measurement time is to use fewer optical rays. For a four-instrument geometry, when 30, 40, or 80 rays per instrument were used to scan a room, the smaller the number density of rays, the lower (better) the nearness, data distance, and exposure errors (2). When using 30 rays, exposure error improved over using 40 rays. The reconstructed maps using 30, 40, and 80 rays were visually very similar to each other; however, peak heights for reconstructed maps using 30 rays were closer to the original map than reconstructed maps using 40 or 80 rays. These simulations indicate that coarser sampling may be a better means of tracking changing concentration profiles over time than using finer sampling.

In general, most of the geometries tested could locate the highest concentration points in the peaks within a few grid cells. As the ventilation rates increased, nearness and peak location errors increased (worse). As the number of detectors increased, peak location and exposure errors decreased; the four-instrument geometry had mean location errors of two grid cells and mean exposure errors of 12–15%. The number of concentration plumes had a greater adverse impact on reconstruction quality than the diameter and concentration of the peaks. The diameter of the concentration peaks will be a limitation when the density of rays is so sparse that the rays miss the peaks.

5.2 Chamber Studies of Geometries

Several research groups have evaluated CT for industrial hygiene by using pilot CT systems in exposure chambers and comparing tomographic map concentrations with concentrations obtained from point samples taken in the chamber.

Samanta and Todd (7, 37) tested a prototype CT system that used a single Midac open-path FTIR spectrometer (MIDAC Corporation, Irvine, CA) on a translatable table that was placed on a track along the periphery of the chamber. With this set-up, one instrument was used to simulate four instruments; a single OP-FTIR spectrometer scanned the chamber from many different angles to create a network of open-path measurements. Two configurations were tested, one with two instruments on each of two sides of the chamber (136 rays) and one with one instrument on each of four sides of the chamber (100 rays). The chamber was divided into a grid of 120 cells, with each cell being one square foot. The chamber was equipped with a point sampling system that collected tracer gas samples from specific points in the chamber directly above the beam.

Single and multiple plumes of sulfur hexafluoride were generated vertically up from the floor of the chamber. During the experiments, open-path measurements and

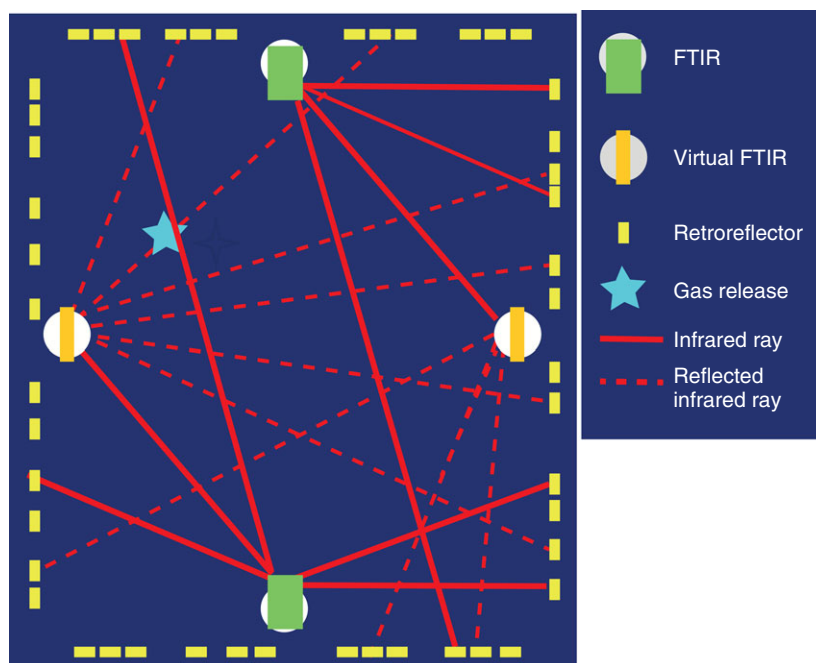


FIGURE 12 Rapid scanning set-up in the chamber studies using virtual spectrometers (two rotating OP-FTIR spectrometers and two rotating mirrors; virtual spectrometers.)

point samples were obtained over approximately 1.5 hours. Recently, a rapid scanning system was developed which uses two rotating monostatic Midac spectrometers and two rotating mirrors, to obtain a total of 48 rays. The rotating mirrors act as virtual spectrometers to create four OP-FTIR spectrometers. However, only two instruments are operating at a given time (see Figure 12). Using this set-up, a complete set of open-path measurements was obtained every seven minutes.

For the chamber experiments, the tomographic reconstructed concentration maps were compared with the point sample maps created by kriging the point samples. Reconstructions were performed using MART and MLEM. In almost all of the experiments, regardless of the geometry, the CT system reconstructed the location of the plumes within one foot. The geometry using 136 rays reconstructed multiple peaks better than the geometry using 100 rays. This may be due to the fact that the 136-ray geometry has a greater angular range of coverage than the 100-ray geometry. The rapid scanning system was successful at mapping rapidly changing plume concentrations. Using the rapid scanning system, the peak concentrations in the tomographic maps were within 14% of the concentrations in the point sample maps (79, 80). Figure 13 shows reconstructions of single and multiple source experiments. In these figures, the time-averaged point sample map is compared with the seven-minute CT reconstruction. The reconstructions agreed closely with the point sample maps.

Yost et al. (12) performed chamber studies using a single OP-FTIR spectrometer (Nicolet Instrument Corp, Wisconsin) mounted on a translatable table, to simulate a parallel projection geometry with four projection angles (36 rays). Acetone was released in the chamber and three hours were required to complete the CT scans and obtain the point samples. Maps were reconstructed using an ART algorithm. While the peaks were located correctly, there was a large discrepancy between the concentration of the peaks reconstructed with the tomographic and point sample maps. This may have been due to fluctuating concentrations and airflow patterns in the chamber, and a very sparse geometry. Additional studies by Drescher et al. (14, 15) used a rapidly scanning system that had a single scanning OP-FTIR spectrometer in the center of a chamber, one retroreflector in each of the four corners of the room, and 52 flat mirrors on the walls. This geometry had 56 optical rays with an overall sampling time of six minutes. Using this geometry and the SBFM algorithm, the tomographic maps were very similar to the point sample maps and quantitatively agreed to within 50%. More recently a single OP-FTIR spectrometer was placed on a turntable to generate a set of rays of different lengths. In chamber studies using a robot to simulate a person, personal exposures were estimated using the OP-FTIR spectrometer (81, 82).

Bingham et al. (83) designed a multi-spectral infrared CT system incorporating quantum cascade laser modules using a modified MLEM reconstruction algorithm. The goal is to

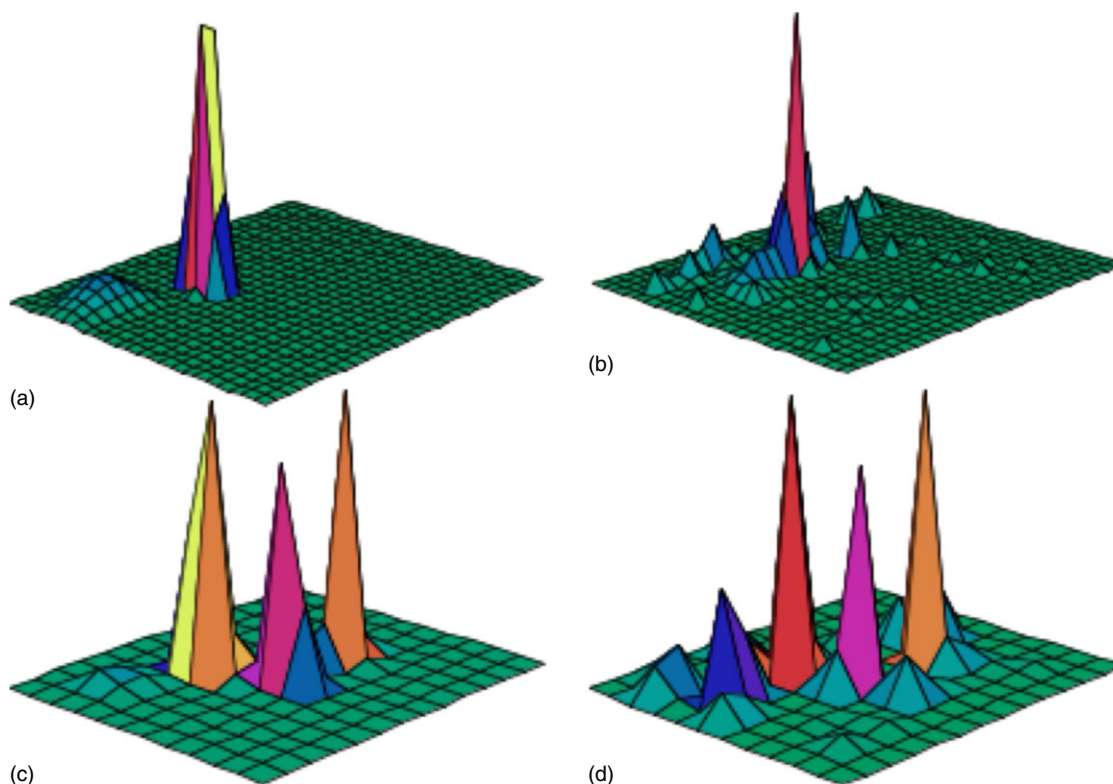


FIGURE 13 (a) Point sample map of the entire 45-minute period for a single plume experiment. (b) Reconstruction of a seven-minute scan of the chamber. (c) Point sample map of the entire 56-minute period for a three-plume experiment. (d) Reconstruction of a seven-minute scan of the chamber.

eventually provide an efficient, deployable system that will provide long-term spatial information about gasses present in air. This research provided an initial proof-of-principle small scale laboratory test of the system using methane as the tracer gas. In these qualitative experiments, they were able to reconstruct plume shapes. They are now working on follow-up fieldwork.

Grauer et al. (84) developed a CT system that uses broadband transmittance measurements. Broadband systems may provide chemical reconstructions *via* low-cost, commercially available OP detectors. Many of these devices are also intrinsically safe, and could, therefore, be used at industrial facilities without modification. However, broadband transmittances are a nonlinear function of the gas burden. Therefore, to apply CST reconstruction techniques to broadband transmittances, new methods are required to process the measurement data. This research tested the system in a small-scale laboratory experiment using propane as the test gas and a 35-beam, four-projection orthogonal measurement grid. The CT reconstructed propane concentrations were broadly consistent with the FID point sample measurements.

One of the problems encountered in laboratory validation studies is that a noninvasive, real-time, spatially resolved technique is compared to invasive point samples taken at a

different height and time frame than the optical beams. In addition, the point samples must be processed, such as by kriging, to obtain spatial concentration maps. This can introduce errors. Thus, differences in concentrations between the methods may be due in part to technical problems associated with differences in the sampling methods.

6 FIELD STUDIES

A small-scale CT system was used in an outdoor study to compare tomographic results with dispersion models and to calculate chemical emission rates (5). This pilot environmental CT system used two scanning OP-FTIR spectrometers and eight retroreflectors and was deployed on a 70 by 70 m field. Sulfur hexafluoride was released at known rates from a simulated volume source and was measured at various points in the study field with the use of a network of Tedlar® bag point samples.

This highly underdetermined system was used to reconstruct concentration maps in near real-time for the entire field site. The concentration maps were compared with model maps with respect to plume location and plume shape. For many of the reconstructed time periods, the shapes,

locations, and directions of the plumes in the reconstructed tomographic maps compared fairly well with the model predictions. For almost all of the time periods, the concentrations in the tomographic maps were higher than the concentrations in the model-generated maps. For the periods where the maps did not agree, the wind direction was found to be rapidly and repeatedly shifting. One of the reasons for this could be the fact that the model used average wind conditions to generate concentrations, whereas the CT system took measurements sequentially and in real-time. The CT system may have more accurately captured real-time variability.

The first large-scale field implementation of a CT system was performed at an intensive swine confinement operation to measure ammonia and other contaminants generated from a waste lagoon (47). The CT system operated every day for up to 24 hours a day for several weeks over three seasons. Two monostatic OP-FTIR spectrometers were placed on 360° rotating platforms, on opposite sides of a six-acre swine waste lagoon, each within 1 m of the surface of the lagoon. This created a horizontal network of infrared rays. Twelve metal retroreflectors were positioned around the periphery of the lagoon, see Figure 14. The OP-FTIR spectrometers sequentially scanned the retroreflectors, and both spectrometers operated simultaneously. Total path lengths ranged from 132 to 426 m. A sulfur hexafluoride tracer gas was released from the center of the lagoon at a known emission rate and the network of rays simultaneously monitored ammonia, other waste gases, and the tracer gas, sulfur hexafluoride, every two minutes. Concentration maps of the gases were generated for the entire lagoon surface. The system was operated remotely from computers that were located in a van; the

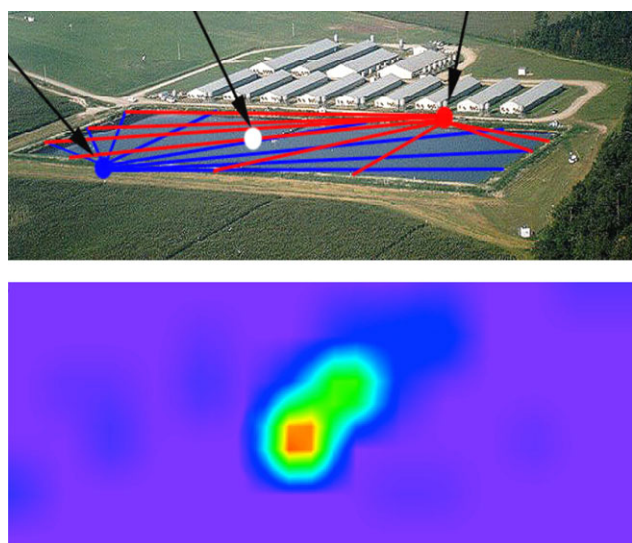


FIGURE 14 Top image is the open-path FTIR configuration over the swine waste lagoon. Bottom image is a map of a reconstructed sulfur hexafluoride plume.

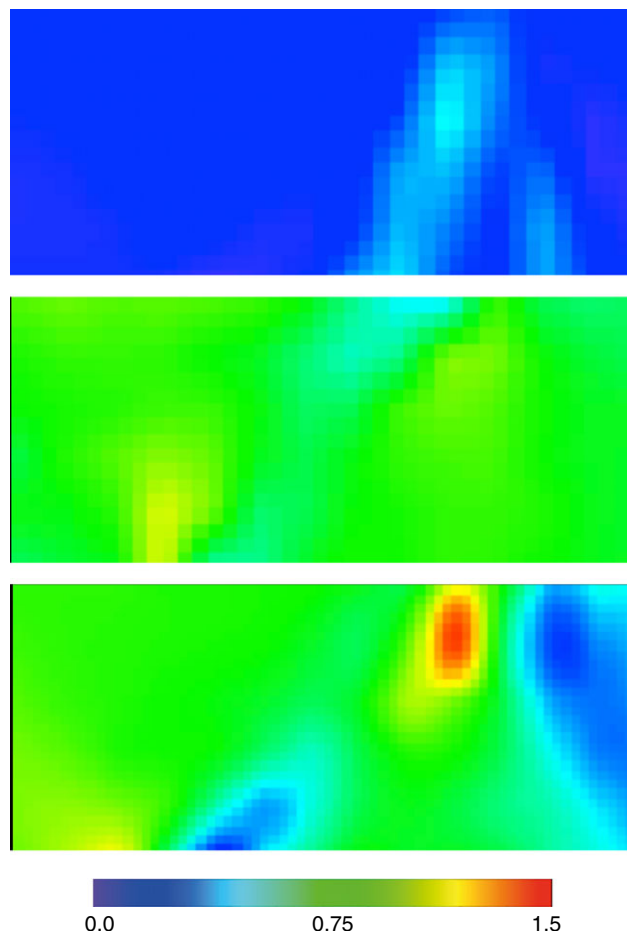


FIGURE 15 Three CT concentration maps of ammonia over the waste lagoon. Each map represents a 15-minute period.

entire system was connected using fiber optic cables. Except for replenishing the liquid nitrogen during the day to cool the detectors, the spectrometers were operated without supervision. The tomographic maps revealed that the concentration of ammonia varied widely over the surface of the lagoon, and was not homogeneous as is the assumption when using point-sampling devices for these types of sources. This was an ideal application of CT. Using conventional point sampling equipment only a few locations can be easily sampled on a lagoon. In comparison, the CT system can measure a relatively large area. Figure 15 shows CT concentration maps for ammonia for three seasons.

Gases and aerosols released to the atmosphere by eruptive and noneruptive volcanic activity can affect both the environment and human health. Among the major components of volcanic emissions, sulfur dioxide (SO_2) can cause severe damage to vegetation and is harmful to humans, especially those who are prone to respiratory illnesses. Remote sensing techniques combined with CT may be a viable substitute for conventional point sampling measurements which can

be dangerous to obtain because they are taken from within the volcanic plume where there are toxic gases. In addition, while in situ methods allow for accurate estimation of concentrations, they are spatially limited to the vicinity of the specific measurement points.

Measuring volcanic carbon dioxide (CO_2) emission rates, as a tracer for other gases, is one pathway towards forecasting increased volcanic activity, such as seismicity or eruptions. Field studies were performed of volcanic gas plumes at the Campi Flegrei volcano in Italy, to measure emissions (85) using computed tomographic as a way to predict volcanic activity. These studies used a portable hard-target differential absorption lidar (DIAL) system to obtain the path integrated concentrations of CO_2 . The resulting tomographic maps were found to be in satisfactory agreement with independent measurements of CO_2 . Carbon dioxide fluxes retrieved from the 2-D maps were comparable but modestly higher than emission rates found from previous studies.

CT was used to reconstruct SO_2 concentration distributions in the volcanic plume of Miyakejima, Japan, using an airborne traverse technique (86). In this study, three compact UV spectrometers were mounted on a helicopter. The helicopter flew under the volcanic plume about 10 km downwind from the caldera of Miyakejima volcano. The instruments were aimed at three different zenith angles, enabling simultaneous measurements of SO_2 path integrated concentrations in three different directions. The LTD algorithm was used to reconstruct the plumes from the remote sensing measurements. The SO_2 path-integrated concentration data obtained by the three spectrometers were interpolated and formatted evenly at spatial intervals of 100 m. Each set of measurements took two minutes to obtain and maps were reconstructed that were five minutes apart. The horizontal and vertical widths of the maps were 6 and 3 km, respectively. The horizontal and vertical widths of the reconstructed plumes were about 3 and 1–1.5 km, respectively. The reconstructed concentration data was found to match observed data. The shapes of the plumes reconstructed after each traverse were quite different from each other in spite of the short time intervals between traverses (five minutes).

Burton et al. (87) reconstructed two-dimensional cross-sections of SO_2 in the volcanic gas plume of Mt. Etna in Sicily. The data for the projections were generated using a network of five scanning ultraviolet spectrometers, positioned on the flanks of the volcano. The maps were reconstructed using the SART algorithm. A month-long sample data set collected in June 2008 was selected for testing the tomographic reconstruction algorithms. The volcanic SO_2 flux was determined from each tomographic reconstruction by multiplying the sum of all the pixel concentrations, the cross-sectional area of a pixel and the component of the measured wind speed. This was compared with the SO_2 flux obtained directly from the network. The results showed a

good agreement between the tomographic maps and the raw network data.

Communities that live next to major industries such as refineries and petrochemical plants can be exposed to emissions of hazardous air pollutants. Many of these communities may already have compromised health problems because they may be economically disadvantaged. Adequately monitoring community exposure from these emissions is important for protecting health and can pose challenges when using conventional air sampling methods.

The combination of remote sensing using the long-path differential optical absorption spectroscopy (DOAS) technique and CT was used during a 2015 Benzene and other Toxics Exposure (BEE-TEX) field study. The goal of BEE-TEX was to establish cost-effective, state-of-the-art, neighborhood-scale monitoring networks in the Houston Ship Channel and other areas of high toxic emissions around the country (88–90). The tomography was performed in the Manchester neighborhood beside the Ship Channel of Houston, Texas for an entire month. Two geographically separated sets of LED sources were used to generate overlapping light beams that were reflected back by an array of mirrors encircling the community of interest toward detectors co-located with the light sources. The multiple overlapping light paths made it possible to generate CT concentration maps using the ART reconstruction algorithm.

The LED light sources and DOAS detectors were mounted on scaffolding towers across the main entrance of a refinery. Reflectors were mounted on a scaffolding tower, on guard rails of a Bridge, and on telescopic towers along the southern end of Manchester between 15 and 25 m above ground level. DOAS light paths were sampled sequentially, with a total measurement cycle time for all light paths of roughly 30 minutes.

The CAT scan network detected large nocturnal plumes of toluene and xylenes most likely associated with railcar loading and unloading operations at the petrochemical facilities. The presence of such plumes during railcar operations was confirmed by a mobile laboratory equipped with a proton transfer reaction-mass spectrometer (PTR-MS), which measured transient peaks of toluene and benzenes of 50 and 57 ppb, respectively. Plume reconstruction and source attribution results derived from DOAS CAT scans compared reasonably well with corresponding results derived from mobile PTR-MS measurements despite the low number of light paths that were operational during the campaign.

7 BACKGROUND OPTICAL REMOTE SENSING INSTRUMENTATION

In theory, any remote sensing instrument can be used to perform CT in industrial hygiene as long as it can quickly

and safely measure path-integrated concentrations of chemicals in air along an open-path. Lasers, such as tunable diode lasers, have high scanning rates and offer the ability to sample the air over very long pathlengths (kilometers); however, they are usually limited to one or a few gases and may present an eye safety hazard (91–96). OP-FTIR spectrometers have primarily been used outdoors, in fenceline, air pollution, and hazardous waste applications, where one instrument with a long pathlength is needed (97–100). For indoor air monitoring, OP-FTIR spectrometers have advantages over lasers in that they can measure a wide range of multiple chemicals at low limits of detection (ppb–ppm) and they pose a low eye-safety hazard (101–111). OP-FTIR spectrometers, and DOAS are the main instruments that have been used thus far for applying CT to industrial hygiene and environmental (17, 39, 90) monitoring. For industrial hygiene, OP-FTIR is most commonly used, so they will be described here.

7.1 OP-FTIR Spectrometer Design

OP-FTIR spectrometers typically use a remotely placed optical source to transmit an infrared (IR) beam across the open air to a detector. Chemicals present in the optical path are measured in near real time, and concentrations are integrated over the entire length of the optical path, to obtain path-averaged concentrations.

The OP-FTIR spectrometers are operated in two different configurations: bistatic and monostatic (see Figure 16). These configurations differ in the transfer optics and the number of times that the IR beam passes through the air. In the bistatic mode, the IR source is placed at the opposite

end of the optical path from the detector (can be greater than 500 m apart), and the IR beam passes through the air once. In the monostatic mode, the IR source and detector are co-located at one end of the path, and the beam is sent out to a reflector placed at the other end of the path. In the monostatic mode, the reflector (flat mirror, corner cube, or cat's eye retroreflector) sends the light directly back to the detector, and the IR light passes through the air twice. Telescopes can be used to collimate, send and receive the IR beam to and from the spectrometer to the retroreflector (monostatic systems) or to receive the IR light at the detector (bistatic systems). Telescopes may not be necessary when short path lengths are used for indoor workplace or exposure chamber applications.

7.2 Theory of Operation

OP-FTIR spectrometers use IR absorption to identify and quantify hundreds of chemicals in air. IR absorption techniques are based on the principle that compounds selectively absorb energy in the IR region of the electromagnetic spectrum. When molecules absorb incident electromagnetic radiation at specific wavelengths, the energy can boost electrons from their ground state to an excited state, or cause the molecules to stretch, bend, or rotate (112, 113). With the exception of elements, inorganic salts, and diatomic molecules (oxygen, nitrogen, chlorine), most substances absorb in the IR region.

In the mid-infrared region of the electromagnetic spectrum (4000 to 400 cm^{-1}), absorption usually occurs at several different wavelengths of IR light, which results in patterns or bands. This pattern of energy absorption, called the absorption spectrum, creates a unique fingerprint for each molecule and can be used to identify the chemical. Figure 17 shows an absorption spectrum for ammonia. Small differences in chemical structure can result in large differences in absorption spectrum. To identify a compound, the number, location, and shape of absorption bands in a spectrum are compared to a reference spectrum for the same chemical. A reference spectrum is created using known concentrations of the chemical of interest under controlled conditions of temperature and pressure. The pattern of absorption is used for identification of compounds and the intensity of the spectral bands is used for quantification.

Quantification is performed by selecting a wave number region in the absorption spectrum of the gas that ideally is free from interferences from other contaminants. Within constraints, there is a linear relationship between the intensity of the spectral bands and the concentration of the compound. This relationship is based on Beer's Law which states that at a constant path length, the intensity of the IR energy diminishes exponentially with the concentration of

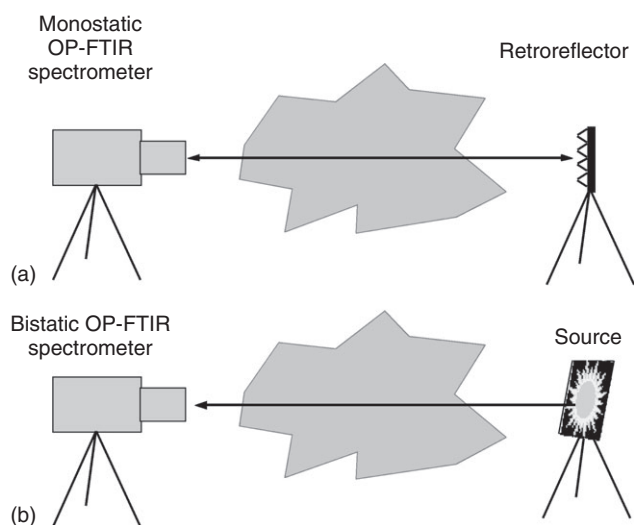


FIGURE 16 Two configurations of an OP-FTIR spectrometer. (a) Monostatic spectrometer. (b) Bistatic spectrometer.

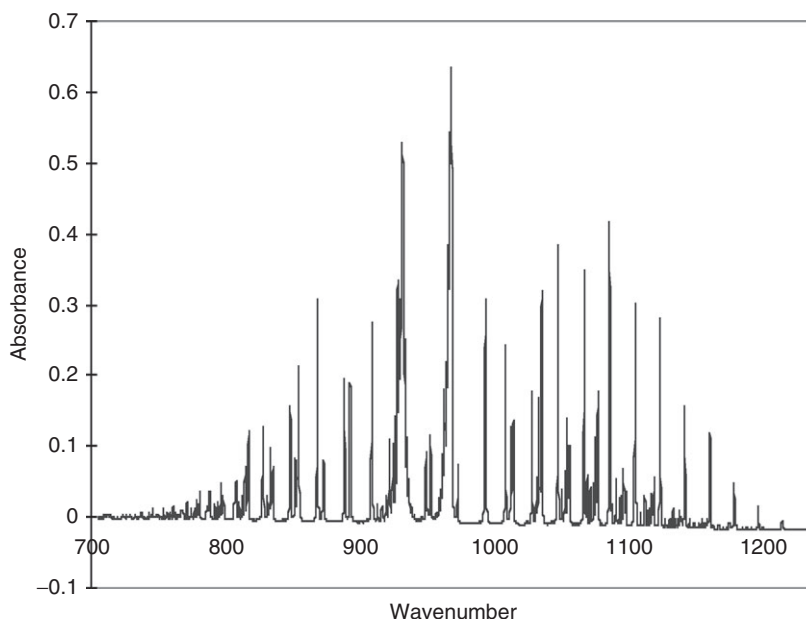


FIGURE 17 Absorption spectrum for ammonia.

chemicals in the path (see Eq. (11)).

$$I = I_o \exp -aCL \quad (11)$$

$$\text{Transmission} = I/I_o \quad (12)$$

$$\text{Absorption} = -\log(I/I_o) \quad (13)$$

$$\text{Absorption} = aCL \quad (14)$$

where, I is the intensity of IR light when the absorbing chemical is present, I_o is the intensity of IR light without the absorbing chemical present, a is the molecular absorption coefficient of the chemical, C is the concentration of the chemical and, L is the path length of the IR radiation through the chemical.

To measure concentration, the intensity of the IR light with and without contaminants must be obtained and converted to an absorption spectra (see Eqs. (11)–(14)). Background spectra (I_o) are generated either using ambient air that does not contain target contaminants or are generated synthetically. The primary challenge facing users of open-path FTIR spectrometers is the acquisition of a clean background spectrum (105, 114).

An interferometer is the optical device used in OP-FTIR spectrometers to scan simultaneously and rapidly (seconds) the entire mid-IR region. An interferometer can achieve high spectral resolution (the ability to distinguish between absorption bands of compounds), high specificity, high signal-to-noise ratios, and low limits of detection (ppb)

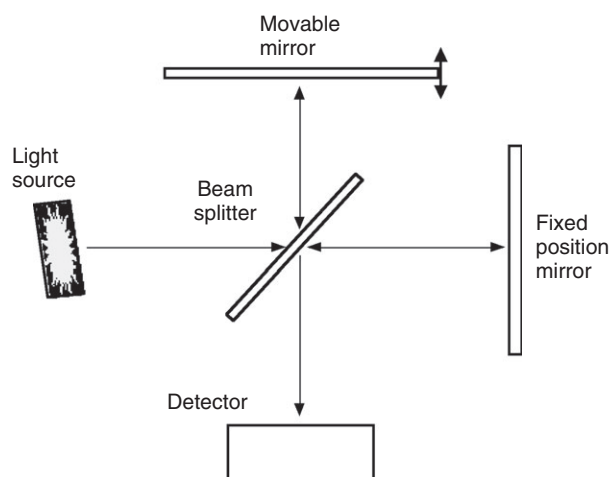


FIGURE 18 Schematic of a Michelson interferometer.

(115, 116). One type of interferometer is the Michelson interferometer (see Figure 18) (113). An interferometer consists of a beam splitter, a stationary mirror, and a moveable mirror. They are orthogonal to each other. A Nernst glower, which emits broadband electromagnetic radiation, is used to generate IR light. The IR light travels to the beam splitter which divides the light into two beams of equal intensity; one half of the light is sent to the moveable mirror and one half is sent to the fixed mirror. After hitting the mirrors, the

beams recombine at the beam splitter and exit to the detector. When the moving mirror and the fixed mirror are at the same distance from the beamsplitter, the IR light beams reflected off the mirrors are in phase with each other, and all the wavelengths of light constructively interfere in the recombined beam. This results in the highest intensity of light for all possible mirror positions. When the moving mirror moves along the optic axis, the half of the optical beam which hits the moving mirror travels a shorter distance than the optical beam which hits the fixed mirror. At any mirror position, the intensity of light is governed by constructive and destructive interferences in the recombined beam. When the light recombines it hits the detector and a signal is recorded; the pattern of constructive and destructive interference is called the interferogram, and depends upon the wavelengths of light present in the beam. Using an IR broadband radiation source, the incident IR radiation contains many wavelengths. Therefore, at each position of the moving mirror, the signal recorded by the detector is an integral of the intensities of all the wavelengths of light. The interferogram is a plot of light intensity vs. optical path difference (mirror position) and is used in all subsequent analyses.

To create absorption spectra, first the interferogram is converted to a single beam spectrum by using appropriate software to perform a fast Fourier transform. Two single beam spectra (sample and background) are then ratioed to get a transmission spectrum (see Eq. (12)), and an absorption spectrum is generated by taking the negative logarithm of the transmission spectra (see Eq. (13)). Absorption (Eq. (14)), is proportional to the concentration of the chemical and the distance (path length) that the light travels through the chemical. Therefore, the longer the path length that the IR light travels through the air containing the compound of interest before it reaches the detector, the greater the sensitivity and the lower the limits of detection.

7.3 Quantification

Quantitative analysis can be performed using a variety of methods including measuring peak height, measuring peak area, spectral subtraction, partial least squares, iterative least squares, and classical least squares (CLS). CLS is most commonly used to match the measured spectra to a library of calibration reference spectra for the chemicals of interest (115–118). When the concentrations of chemicals are measured, they are integrated over the entire length of the optical path and are reported as the product of concentration and path length (ppm–meters). The ppm–meter concentration is then divided by the path length to obtain a path-averaged concentration (ppm).

The resolution of an OP-FTIR spectrometer refers to the minimum separation in wave numbers that two absorption features can have and still be distinguished from one

another. Typical OP-FTIR spectrometers used for environmental CAT scanning have minimum resolutions of 0.5 and 1.0 wave numbers; the higher the resolution, the lower the wave number. At any resolution, the OP-FTIR spectrometer can average individual measurements (scans) over time to decrease the SNR (signal-to-noise ratio). For tomographic imaging spectrometer measurement rates should be minimized to reconstruct concentration profiles with multiple peaks or with rapidly changing concentration profiles. Therefore, measurements should be made at the lowest possible wavenumber resolution that adequately resolves spectral features of chemicals in the air because as resolution increases, scan time increases. In general, the SNR is directly proportional to the resolution, and to the square root of the measurement time; doubling the resolution doubles the noise.

8 CHALLENGES AND FUTURE DIRECTIONS

An innovative measurement technology for environmental air sampling has emerged to allow visualization of the spatial distribution of chemical concentrations over time. By combining ORS technologies with CT, spatially and temporally resolved two-dimensional concentration maps would be produced for a room or area. These maps could be used to evaluate pollutant dispersion in a workplace, characterize human exposures, support fundamental modeling research, and locate fugitive emissions (75). There may always be limitations to this method due to sparse sampling in a room or outdoor area, and lack of symmetry in beam geometries due to available lines of sight for the optics. This could translate into concentration measurement errors. For example, how can CT maps be used if the measurements are taken above the breathing zones of workers? However, the ability to use a tomographic system over hours, days, and weeks in one workplace, might result in more accurate estimates of human exposures than currently available technology using limited numbers of point samples taken sporadically over time. Once installed, a CT system could run continuously at low cost.

This method has great potential monitoring exposures outdoors as well. Chemical concentrations and flux measurements can be obtained over large areas or areas which are hazardous to measure by other methods. Tomographic networks may be a viable way to increase the spatial and temporal coverage of air pollution monitoring networks for both regulatory and scientific applications, especially in industrial fenceline communities. With miniaturization of instrumentation, they may be able to be placed on unmanned aerial vehicles for obtaining measurements.

In order to implement and improve this technology, several opportunities remain. These include extensive field validation studies, development of robust reconstruction

algorithms, development of improved geometries for a variety of workplace designs, miniaturization and increased ruggedness of open-path instrumentation, and expansion of the technique to three three-dimensional tomography. With less expensive and smaller instrumentation, the number of beam paths can be increased considerably resulting in better reconstructions.

For three-dimensional tomography, networks of intersecting path integrated concentration measurements would be obtained through the air at several heights and angles over an area using the ORS system. CT algorithms process the measurements as they are obtained in real-time to reconstruct three-dimensional chemical concentration maps. These maps are a set of concentration values on a series of cross-sectional 2D grids or sets of horizontal and diagonal rays to represent the 3D grid. These maps would reconstruct the volume of air contaminants not just a single slice. Ultimately, reconstructed concentration maps need to be evaluated in user studies in the field with industrial hygienists.

A major improvement to current reconstruction algorithms is the multigrid reconstruction technique described before as well as Bayesian methods. These methods could be further developed to alter the size of the reconstruction of grid cells in real-time to address peaks of different sizes and at different positions in a room. Therefore, in areas of low concentration, where information is not important, or there is high uncertainty, larger cells can be used. A fine grid of cells can be used in areas near people, sources, or high concentration gradients.

To date, researchers have worked with fixed CT geometries. Another improvement is a dynamic geometry. A technique is being developed which, in real-time, pinpoints the regions of high concentrations and adapts the density of the rays to follow the movement of the plume. The use of adaptive ray sampling could improve reconstructions by optimizing the position of the rays. Researchers have used adaptive techniques in signal processing (119), image processing (120, 121), and CT (122), to achieve improved sampling of sharp spatial changes in objects. An adaptive sampling technique is being developed that selectively acquires ray measurements from the highest concentration regions in a room at finer intervals compared to the lower concentration regions. For example, retroreflectors could be evenly spaced along the walls of the room. The CT system would generate an initial tomographic map, and this map would be used to alter the geometry in real-time to reposition the rays. Thus, the density of rays would be increased where there is high information content and would be reduced in places of low concentrations. Reconstruction accuracy can improve when only a few additional optical rays are placed through the areas of highest concentration (8).

With improved and less expensive ORS instrumentation, it will be possible to increase the accuracy of reconstructions as well as move to three-dimensional tomography in indoor

air. This will greatly enhance the usefulness of this technique for industrial hygiene. One improvement to OP-FTIR spectrometers is the development of multichannel systems that use segmented open-path beams. With segmented beams, a single fan beam would actually be comprised of many individual beams that would simultaneously hit an array of retroreflectors. Therefore, multiple ray sum measurements would be obtained simultaneously rather than sequentially when using a scanning OP-FTIR spectrometer. This could reduce sampling times from minutes to seconds. In addition to ORS instrumentation refinements, low-cost retroreflector arrays need to be developed to allow flexibility in geometry design. The use of segmented fan beams and low-cost retroreflector arrays will enable three-dimensional mapping of an area quickly.

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MATHEMATICAL MODELING OF INDOOR AIR CONTAMINANT CONCENTRATIONS

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1 INTRODUCTION

In the past decades, physical–chemical mathematical models have gained acceptance as an exposure estimation method for occupational indoor air contaminants (1–3). Although direct air sampling is preferred traditionally, there are situations in which monitoring is not feasible, that is where the interest concerns: (i) past exposure levels generated by a process that has been discontinued, (ii) future exposure levels for an operation under consideration, and (iii) future exposure levels during an accidental release. Mathematical modeling, given appropriate input information, can be used to estimate exposures in the past, present, or future. Mathematical modeling fits well at multiple stages of the industrial hygienists' mission to anticipate, recognize, evaluate, control, and confirm exposures, including helping prioritize our monitoring activities (the highest predicted exposures are monitored first) or deciding whether monitoring a particular operation is warranted. In such cases, mathematical modeling can be used to estimate exposure intensity.

Because mathematical modeling is theoretical and based on explicit assumptions, some occupational hygienists may believe that modeled exposure estimates are too uncertain to be reliable. However, due to the substantial variability in air contaminant exposure that can pertain across time and across individuals performing the same type of work, exposure estimates made via air sampling are also uncertain. In fact, air sampling should involve a statistical approach such that one collects numerous air samples over time and/or

individuals, where the time periods and/or individuals are chosen according to a random selection process that eliminates investigator bias. In practice, few measurements are obtained, and the periods/subjects chosen for monitoring usually are often based on convenience. The latter circumstance violates an explicit assumption underlying the statistical analysis of air monitoring data, namely, that the periods/subjects monitored are chosen by a random selection process. The relative accuracy of exposure estimates made by modeling versus monitoring has been discussed elsewhere (4). The purpose of this chapter is not to explore the pros and cons of different exposure estimation methods, but to present some useful physical–chemical mathematical models.

The three elements of a physical–chemical model are (i) the instantaneous chemical mass emission rate function; (ii) the pattern of chemical dispersion in air; and (iii) the location of the worker (receptor) relative to the point(s) of contaminant emission. Depending on the dispersion pattern assumed (item (ii)), the location of the worker (item (iii)) may not be relevant. These three items are discussed below.

2 CHEMICAL EMISSION RATE FUNCTIONS

The instantaneous emission or generation rate is often denoted $G(t)$ and has the units of mass time^{-1} . When a constant rate is assumed, the notation $G(t) = G$ is used.

2.1 Constant Rates

Although emission rates usually vary with time, assuming a constant emission rate is reasonable if we want to estimate an eight-hour time-weighted average (TWA) exposure level and are not concerned with short-term exposure intensity and variability. In some cases, a material mass balance can be used to estimate a constant emission rate. For example, if we know the solvent mass that evaporates during a time interval T , the “constant” emission rate is

$$G \text{ (mg min}^{-1}\text{)} = \frac{\text{Mass emitted (mg) into air in the interval}}{T \text{ (min)}} \quad (1)$$

A problem studied by several investigators is the vapor emission rate from a pure liquid with a fixed surface area and temperature, as would apply to an open surface tank or a large pool of liquid (5–8). An algorithm developed by Hummel et al. (6) for predicting a constant emission rate in this scenario is

$$G \text{ (mg min}^{-1}\text{)} = \frac{165.6 \times \text{MW}^{0.833} \times P_v \times \left(0.0345 + \frac{1}{\text{MW}}\right)^{0.25} \times A}{T^{0.05}} \sqrt{\frac{U}{L \times P_{\text{atm}}}} \quad (2)$$

where MW is the molecular weight of the chemical (g mol^{-1}), P_v is the vapor pressure of evaporating chemical (Pascal, Pa), P_{atm} is the atmospheric pressure (Pa) ($1 \text{ atm} = 101\,325 \text{ Pa}$), A is the surface area of the liquid pool (m^2), L is the surface length of the liquid pool (m), U is the airspeed over the liquid pool (m s^{-1}), and T is the temperature of the liquid (K) ($\text{K} = 273.15 + ^\circ\text{C}$).

The length of the liquid pool, L , is the longest dimension of the surface. For example, if an open tank has surface dimensions $2 \text{ m} \times 1 \text{ m}$, then $L = 2 \text{ m}$. Air is presumed to move in the same direction as the longest length aspect.

A third scenario involving constant emission is molecular diffusion from an open bottle. The neck of the bottle is a diffusion path of length δ (m) not subject to turbulent air motion and has cross-sectional area A (m^2). For a pure chemical, the chemical concentration in the bottle headspace (at the start of the diffusion path) is assumed to equal the chemical's saturation concentration in air, C_{sat} (mg m^{-3}). The latter concentration is computed based on the ideal gas law as follows:

$$C_{\text{sat}} \text{ (mg m}^{-3}\text{)} = \frac{1.605 \times 10^4 \times P_v \times \text{MW}}{T} \quad (3)$$

where P_v is the chemical's vapor pressure (mmHg) at temperature T (K), and MW is the chemical's molecular weight (g mol^{-1}).

It is assumed that once molecules reach the top of the bottle's neck (at the end of the diffusion path), they are immediately dispersed into room air such that the chemical concentration at the end of the pathway is essentially zero. The presumed constant emission rate from the bottle is

$$G \text{ (mg min}^{-1}\text{)} = \frac{A \times D_M \times C_{\text{sat}}}{\delta} \quad (4)$$

where D_M ($\text{m}^2 \text{ min}^{-1}$) is the chemical's molecular diffusion coefficient in air. If a published D_M value is not available, it may be estimated using the Fuller equation (9):

$$D_M \text{ (m}^2 \text{ min}^{-1}\text{)} = \frac{0.6 \times T^{1.75}}{P_{\text{atm}}} \times \frac{\sqrt{0.0345 + \frac{1}{\text{MW}}}}{\left[2.70 + \left(\sum V_{\text{chem}}\right)^{1/3}\right]^2} \quad (5)$$

where $\sum V_{\text{chem}} = \sum_{i=1}^k n_i \times v_i$, k is the number of different elements in the molecule, n_i is the number of atoms of the i th element in the molecule, v_i is the atomic diffusion volume ($\text{cm}^3 \text{ mol}^{-1}$) of the i th element, T is the air temperature (K), MW is the molecular weight of the chemical (g mol^{-1}), and P_{atm} is the atmospheric pressure (Pa).

Atomic diffusion volumes for some common elements are as follows: carbon, 15.9; hydrogen, 2.31; oxygen, 6.11; chlorine, 21.0; fluorine, 14.7; bromine, 21.9; iodine, 29.8; sulfur, 22.9; nitrogen, 4.54.

2.2 A Variable Rate

There are numerous variable emission rate functions that might be considered (10–12). This chapter presents one such function that has a broad application, namely, the exponentially decreasing emission rate:

$$G(t) \text{ (mg min}^{-1}\text{)} = G_0 \times \exp(-\alpha \times t) \quad (6)$$

where G_0 (mg min^{-1}) is the initial rate at time zero, and α is a first-order rate constant with the unit min^{-1} . The mass rate of emission decreases over time. This function is often appropriate for organic solvent evaporation due to small spills and application onto surfaces (13), and due to off-gassing of sorbed chemicals (14). It has been used frequently in indoor air quality modeling (15–17). The exponential function applies when there is a finite chemical mass in the source that is not replenished as mass is lost. If M_0 (mg) denotes the chemical mass in the source at time zero, the initial emission rate is $G_0 = \alpha \times M_0$.

3 DISPERSION PATTERNS AND WORKER (RECEPTOR) LOCATION

Three patterns of contaminant dispersion in room air are considered. Because the idea of worker (receptor) location relative to the source is intimately involved in the first two constructs, the issue of worker location is discussed at the same time.

3.1 Well-Mixed Room

In a well-mixed room (WMR), the contaminant instantaneously and perfectly mixes throughout room air, such that the contaminant's airborne concentration is uniform throughout the room. Worker (receptor) location relative to the source is not an issue because the exposure level is assumed the same at all locations. The room parameters are the volume V (m^3) and the supply/exhaust air rate Q ($\text{m}^3 \text{min}^{-1}$). Strictly, we should consider only the nonoccluded air volume, which is the total room volume minus the volume of the solid objects in the room. Because the occluded volume is usually a small portion (approximately 5%) of the total room volume, this fine point is often ignored. In addition, if Q is fixed, the effect of increasing the concentration due to emitting contaminant into a smaller volume tends to be balanced by increasing the contaminant's exhaust removal rate from that same smaller volume.

Perfect mixing is physically unrealistic in finite time and can lead to seriously underestimating exposure intensity for a worker close to a point source of chemical emission. Still, the WMR construct provides reasonable exposure estimates in four situations given somewhat typical air movement for mixing: (i) for room occupants at some distance from a point source, say, at greater than 2 m; (ii) for all room occupants about two minutes after emission from a point source ceases; (iii) for all room occupants if the emissions are from numerous dispersed point sources or from a large surface area such as painted walls; or (iv) there is significant mixing turbulence such as from floor fans used for comfort in the workbook.

In the WMR construct, one approach involves using a mixing factor m to account for imperfect air mixing. The room supply/exhaust air rate Q is multiplied by m to give an "effective" supply/exhaust air rate Q_{EFF} , or $Q_{\text{EFF}} = m \times Q$, where $0 < m \leq 1$. The value $m = 1$ is perfect mixing, whereas $m < 1$ is imperfect mixing. Some texts express m in terms of a safety factor K , where $K = 1/m$. In a ventilation application, if one requires a certain Q value, the design airflow rate is recommended to be increased K -fold, or $Q_{\text{DESIGN}} = K \times Q$.

Although the mixing factor is widely used, in the authors' view, it should *not* be used for three reasons. First, the

mixing factor violates the conservation of mass principle for the chemical in room air and for the airflows in the room (18). Second, assigning a value for m essentially involves guessing (19). Third, estimating a value for m based on measurements of concentration decay over time can still lead to gross errors (20). Where it is important to account for imperfect mixing, as in estimating worker exposure near an emission source, the near-field (NF)/far-field (FF) construct or a turbulent eddy diffusion construct should be used.

3.2 Near Field/Far Field

The room is treated as containing two adjacent zones – the NF zone surrounds the emission source and contains the breathing zone of the worker whose exposure is to be estimated, and the FF zone is the rest of the room. The respective NF and FF volumes, V_{NF} and V_{FF} (m^3), sum to the room volume. Air within each zone is perfectly mixed, but there is a limited airflow between the two zones. Room supply/exhaust air flows into and out of the FF at rate Q ($\text{m}^3 \text{min}^{-1}$). The interzonal airflow rate β ($\text{m}^3 \text{min}^{-1}$) depends on the conceptual NF geometry (which involves the worker's distance from the source) and a random airspeed s (m min^{-1}) near the source. One study reported that indoor airspeeds are log-normally distributed with a geometric mean of 3.7 m min^{-1} (12 fpm) and a geometric standard deviation (GSD) of 2 (21).

Figure 1 depicts a hemispherical NF zone centered on an emission source on a table. The hemisphere's radius r (m) is set to include the breathing zone of the worker. The free surface area, FSA (m^2), of the NF is that conceptual surface

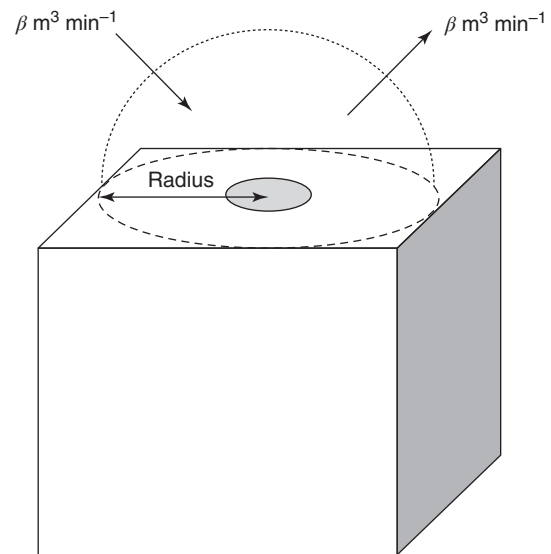


FIGURE 1 Hemispherical near-field zone centered on an emission source on a table.

through which air can flow. For a hemisphere with its base on a solid surface, $FSA = 2 \times \pi \times r^2$. The interzonal airflow rate is

$$\beta (\text{m}^3 \text{ min}^{-1}) = \frac{1}{2} \times FSA \times s \quad (7)$$

The factor 1/2 is used because in a small section of the FSA, air cannot simultaneously flow into and out of the NF zone. Assuming equality of airflow into and out of the NF also maintains a mass or volume balance of air in this zone. This balance is analogous to the equality in the airflow rates Q into and out of the larger room.

The NF/FF construct leads to predicting a higher chemical concentration in the NF than in the FF, which is the phenomenon we want to describe. However, a drawback is that the NF/FF construct predicts a discontinuity in the concentration across the NF boundary. If predicting a series of concentrations at different distances from a point source is important, a turbulent eddy diffusion construct is preferred because it produces a continuous concentration gradient with increasing distance from the source.

The NF/FF dispersion construct for exposure estimation was first described by W.C. Hemeon about half a century ago (22). Several investigators subsequently developed the same dispersion construct while apparently unaware of Hemeon's earlier work. Note that room air can be divided into more than two conceptual zones such that we create a multizone model. The need to consider more than two zones depends on the scenario being modeled and the purpose of our modeling. Several publications have demonstrated the utility of the two-zone model (23, 24).

3.3 Turbulent Eddy Diffusion

Turbulent eddy diffusion involves the random motion of eddies of air that carry chemical molecules (or particles) away from the source. This dispersion mechanism is distinct from molecular diffusion that involves the random motion of individual molecules due to their kinetic energy. Turbulent diffusion is characterized by a diffusion coefficient D_T ($\text{m}^2 \text{ min}^{-1}$). Although D_T has the same $\text{m}^2 \text{ min}^{-1}$ unit as the molecular diffusion coefficient D_M , turbulent diffusion coefficients are greater than molecular diffusion coefficients. D_M values are on the order of $0.001 \text{ m}^2 \text{ min}^{-1}$, while D_T values are on the order of $0.1\text{--}10 \text{ m}^2 \text{ min}^{-1}$ (1).

Applying this dispersion construct requires specifying the worker's location relative to the source. That location can be expressed as a Cartesian coordinate position (x, y, z) relative to the emission point which is taken to be at the origin (0,0,0). However, if there is no advective airflow (the bulk movement of air in a given direction, on average), an equal concentration surface is predicted at a fixed distance from the emission point, and the worker's location can be expressed as a radial distance r (m) from the source, where $r = \sqrt{x^2 + y^2 + z^2}$.

Turbulent eddy diffusion is akin to a three-dimensional random walk. Consider that time proceeds in small discrete steps, and that a set of molecules (or particles) is at the origin at time zero. In one time step, each molecule flips three coins. The outcome of the first coin flip (heads or tails) decides which direction to move on the x -axis; the outcome of the second coin flip decides which direction to move on the y -axis; and the outcome of the third coin flip decides which direction to move on the z -axis. The molecules move in a mutually independent fashion. As time proceeds, the molecules become dispersed in a symmetrical three-dimensional pattern relative to the origin. Of course, molecules do not flip coins in discrete time steps, but the mathematical description of the three-dimensional random walk is the same description applied to turbulent eddy diffusion.

Now, consider that an advective airflow pattern does exist in the vicinity of the emission source, which signifies that air is moving in a certain direction and at a certain speed, on average; in different terms, there is an average airflow velocity (vector). For example, the average movement might be left to right along the x -axis. The result is that the molecules (particles) tend to move to the right (in the direction of the vector), but turbulent eddy diffusion is superimposed on this movement. With reference to the three-dimensional random walk, there is a bias in the coin that determines the direction of movement along the x -axis. If heads mean "go right" and tails mean "go left," there is a greater probability of heads than tails. However, there is still some chance of moving to the left on the x -axis, and there is still completely random movement along the y -axis and z -axis. In the lexicon of random walk theory, the contaminant undergoes a random walk with drift.

Given turbulent eddy diffusion with advection, contaminant dispersion is characterized by a turbulent diffusion coefficient D_T and by a mean airspeed U (m min^{-1}) in a specified direction (usually along the room's x -axis). Note that the average airflow vector need not be along the room's x -axis and that an average airflow vector can be decomposed into components along each of the three room axes. The worker's location must be expressed as a Cartesian coordinate position (x, y, z) relative to the emission source taken to be at the origin (0,0,0).

4 SPECIFIC MODELS

In general, any emission rate function can be combined with any dispersion pattern in room air to produce a mathematical model. The models most commonly used in occupational hygiene have analytical solutions, which means there are closed-form equations by which the contaminant concentrations are computed. For a model without an analytical solution, the contaminant concentration is found

using a numerical method implemented by a computer program. Some important models with closed-form solutions are presented below. A numerical method for models lacking closed-form solutions is available in the literature (25). Note that the examples used to illustrate the behavior of the models are hypothetical, and no justification is offered for the specified input values (V , Q , $G(t)$, etc.). Of course, in a real-world application, the occupational hygienist must select model input values that apply to the specific exposure scenario.

4.1 WMR with a Constant Emission Rate

Consider a room with volume V (m^3) and supply/exhaust air rate Q ($\text{m}^3 \text{min}^{-1}$) that contains a source emitting a chemical at constant rate G (mg min^{-1}). If there are two different sources emitting contaminant into room air at the constant rates G_1 and G_2 , respectively, the overall emission rate is $G = G_1 + G_2$. The same principle applies to three or more sources. In some presentations of the WMR model, an in-room source emits at rate G_1 , and the contaminant concentration in the supply air, C_{IN} (mg m^{-3}), provides a second source at rate $G_2 = Q \times C_{\text{IN}}$. The first-order rate of contaminant removal from room air via exhaust ventilation is Q/V (min^{-1}), which is the number of air changes per minute. Let α_L (min^{-1}) denote a possible first-order rate of elimination by some other mechanism, where $\alpha_L \geq 0$. For example, a chemical vapor may adsorb onto room surfaces, and contaminant particles can settle onto the floor and room surfaces due to gravity. Let C_0 (mg m^{-3}) denote the contaminant concentration in room air at time zero, where $C_0 \geq 0$. The equation that predicts the time-dependent airborne contaminant concentration, $C(t)$ (mg m^{-3}), for $t \geq 0$, is the following:

$$C(t) \text{ (mg m}^{-3}\text{)} = \frac{G}{Q + \alpha_L V} \times \left[1 - \exp\left(-\frac{Q + \alpha_L V}{V} \times t\right) \right] + C_0 \times \exp\left(-\frac{Q + \alpha_L V}{V} \times t\right) \quad (8)$$

If the emission process continues for a long time such that $t \rightarrow \infty$, the contaminant concentration reaches a steady-state value C_{SS} given by

$$C_{\text{SS}} \text{ (mg m}^{-3}\text{)} = \frac{G}{Q + \alpha_L V} \quad (9)$$

Note that the initial concentration C_0 does not affect the steady-state concentration C_{SS} . If we let $G=0$ in Eq. (8), we obtain the classical expression for the decrease in the contaminant concentration starting from some initial value C_0 :

$$C(t) \text{ (mg m}^{-3}\text{)} = C_0 \times \exp\left(-\frac{Q + \alpha_L V}{V} \times t\right) \quad (10)$$

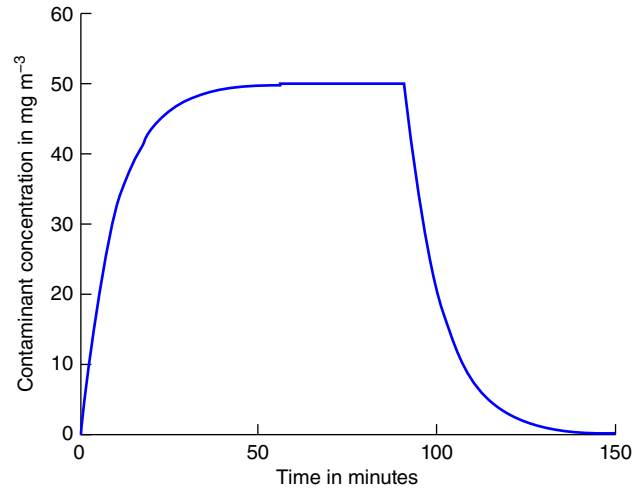


FIGURE 2 The well-mixed room dispersion construct with a constant contaminant emission rate followed by exponential purging. The input values are $V = 200 \text{ m}^3$, $Q = 20 \text{ m}^3 \text{min}^{-1}$, $k_L = 0$, $C_0 = 0$, and $G = 1000 \text{ mg min}^{-1}$ for $0 \leq t \leq 90 \text{ min}$. Subsequent to $t = 90 \text{ min}$, $G = 0$, and $C_0 = 50 \text{ mg m}^{-3}$.

This is often termed the exponential purging or decay equation.

Example. Figure 2 depicts the $C(t)$ time series for a scenario in which $V = 200 \text{ m}^3$ and $Q = 20 \text{ m}^3 \text{min}^{-1}$, such that $Q/V = 0.1$ air changes per minute (= 6 air changes per hour (ACH)). Over the interval $0 \leq t \leq 90 \text{ min}$, $G = 1000 \text{ mg min}^{-1}$ for some contaminant, but for $t > 90 \text{ min}$, $G = 0$. The only loss mechanism of the contaminant from room air is the exhaust airflow, in which case $\alpha_L = 0$, and $C_0 = 0$. According to Eq. (8), the expression for $C(t)$ when $G = 1000 \text{ mg min}^{-1}$ is

$$C(t) \text{ (mg m}^{-3}\text{)} = 50 \times [1 - \exp(-0.1 \times t)]$$

Figure 2 shows that by $t = 90 \text{ min}$, the concentration has reached the predicted steady-state value of 50 mg m^{-3} . When emission ceases and $G = 0$, Eq. (8) pertains with $C_0 = 50 \text{ mg m}^{-3}$, and the concentration exponentially decreases toward zero. According to Eq. (10), the expression for $C(t)$ for $t > 90 \text{ min}$ is

$$C(t) \text{ (mg m}^{-3}\text{)} = 50 \times \exp(-0.1 \times [t - 90])$$

The reason that 90 min is subtracted from t in the argument of the exponent function is to maintain the same zero starting time for the process.

A Note About First-Order Loss Rates. A first-order loss rate α operates in the following manner. If $[t, t + \Delta t]$ denotes a small time interval, the product $\alpha \times \Delta t$ is the fraction of the quantity (say, contaminant mass) present at time t that is lost in the interval $[t, t + \Delta t]$. The absolute amount of

contaminant lost in the interval depends on the mass present at the start of the interval, but the fraction of mass lost is always $\alpha \times \Delta t$. First-order loss rates that simultaneously act on the same contaminant are treated as independent and additive. For example in Eq. (8), the argument of the exponent term contains the quotient $(Q + \alpha_L V) \div V$. Dividing by V , we obtain

$$\text{Overall loss rate} = \frac{Q}{V} + \alpha_L \quad (11)$$

The first-order loss rate of contaminant due to airflow out of the room, Q/V , is added to the first-order loss rate of contaminant due to a second mechanism, α_L (for example adsorption onto a surface). Related to this additive property is proportionality. That is, the fraction of contaminant that is removed from room air due to one mechanism is the first-order loss rate due to that mechanism divided by the overall first-order loss rate. For example, if first-order loss rates due to ventilation (Q/V) and a second mechanism (α_L) act on the contaminant, then

$$\begin{aligned} &\text{fraction of contaminant removed by ventilation} \\ &= \frac{Q/V}{Q/V + \alpha_L} \end{aligned} \quad (12)$$

$$\begin{aligned} &\text{fraction of contaminant removed by second mechanism} \\ &= \frac{\alpha_L}{Q/V + \alpha_L} \end{aligned} \quad (13)$$

In some scenarios, we are interested in the amount of contaminant lost from room air via a particular mechanism/pathway. For example, consider that particles containing inorganic lead (Pb) are emitted into the air of a room for which $Q/V = 0.05 \text{ min}^{-1}$ (or 3 ACH). The Pb-containing particles have aerodynamic diameter $d_a = 5 \mu\text{m}$. A total of 10 mg Pb is emitted into room air. We want to estimate the Pb mass that settles onto the floor and other horizontal room surfaces. We proceed by estimating a first-order loss rate due to gravitational settling from stirred (well-mixed) room air, denoted α_{grav} , based on the expression (24)

$$\alpha_{\text{grav}} = \frac{V_{\text{TS}}}{H} \quad (14)$$

where V_{TS} is the particle terminal settling velocity (m min^{-1}) and H is the room height (m). An approximate expression for a particle's terminal settling velocity is (24)

$$V_{\text{TS}} = 0.0018 d_a^2 \left[1 + \frac{0.166}{d_a} \right] \quad (15)$$

where d_a is expressed in μm . For $d_a = 5 \mu\text{m}$, $V_{\text{TS}} = 0.0465 \text{ m min}^{-1}$. Consider that the room height is

$H = 3 \text{ m}$, in which case $\alpha_{\text{grav}} = (0.0465 \text{ m min}^{-1}) \div (3 \text{ m}) = 0.015 \text{ min}^{-1}$. The overall first-order loss rate from room air is

$$\frac{Q}{V} + \alpha_{\text{grav}} = 0.050 + 0.015 \text{ min}^{-1} = 0.065 \text{ min}^{-1}$$

The fraction of Pb mass estimated to be lost by gravitational settling is

$$\frac{0.015 \text{ min}^{-1}}{0.065 \text{ min}^{-1}} = 0.23$$

Thus, we estimate that $0.23 \times 10 \text{ mg} = 2.3 \text{ mg}$ Pb settles onto the floor and/or horizontal room surfaces.

4.2 Well Mixed Room Constant Generation with Backpressure

A variant of the WMR with constant generation rate can account for the limitation of generation as the concentration approaches saturation (11) and does not allow prediction of concentrations above saturation. This aspect called backpressure has been incorporated in modeling software discussed later in this chapter (Section 7).

$$\begin{aligned} C(t) &= \frac{G}{Q + \frac{G}{C_{\text{sat}}}} \left[1 - \exp \left(-\frac{G + Q \cdot C_{\text{sat}}}{V \cdot C_{\text{sat}}} \cdot t \right) \right] \\ &\quad + C_0 \cdot \exp \left(-\frac{G + Q \cdot C_{\text{sat}}}{V \cdot C_{\text{sat}}} \cdot t \right) \\ \text{and } C_{\text{sat}} &= \frac{VP_{\text{sat}}}{760} \cdot 10^6 \end{aligned} \quad (16)$$

where:

- C_{sat} = the saturated vapor concentration (mg M^{-3}) for the substance modeled
- C_0 = an initial concentration if not zero
- V = room volume
- G = the initial contaminant mass emission rate
- Q = room exhaust flow
- VP_{sat} = saturation vapor pressure of the modeled substance in Torr or mm Hg

4.3 WMR with Constant Emission Rate and Local Exhaust Ventilation Removal and Recirculation of Air

Explicit consideration of local exhaust ventilation (LEV) removal of the contaminant and recirculation of treated room air has been developed (26) and described in detail for a

series of conditions, covering the contaminant generation phase and purge phase after generation cessation. The formulations include consideration of a cyclic process where the generation rate operates for less than the full cycle. The most detailed of the one box steady state equations developed is as follows:

$$\begin{aligned}\bar{C} &= \frac{\gamma G(1-\epsilon_L\epsilon_{LF})}{(Q+\epsilon_{RF}Q_R)+\epsilon_{LF}Q_L} \quad \bar{C}_{LE} = \bar{C} + \frac{\epsilon_L\gamma G}{Q_L} \\ \bar{C}_{LR} &= \bar{C}_{LE}(1-\epsilon_{LF}) \quad \bar{C}_{RF} = \bar{C}(1-\epsilon_{RF})\end{aligned}\quad (17)$$

where:

- $\bar{C}$ = A “pseudo-steady state” concentration averaged over the process cycle
- $\bar{C}_{LE}$ = concentration inside the local exhaust (mg m^{-3})
- $\bar{C}_{LR}$ = concentration downstream of the local exhaust filtration unit of the LEV system (mg m^{-3})
- $\bar{C}_{RF}$ = recirculation concentration; concentration downstream of the filtration unit of the general ventilation return system (mg m^{-3})
- G = generation rate (mg min^{-1})
- Q = room ventilation rate ($\text{m}^3 \text{min}^{-1}$)
- Q_L = local exhaust ventilation rate ($\text{m}^3 \text{min}^{-1}$)
- Q_R = room recirculation system ventilation rate ($\text{m}^3 \text{min}^{-1}$)
- t = current time (min) or task duration
- t_g = time of generation for each task (min)
- T = task duration; sum of task durations (min)
- V = room volume (m^3)
- ϵ_L = fraction of the source emissions immediately captured by the local exhaust
- ϵ_{LF} = local exhaust return filtration efficiency
- ϵ_{RF} = general ventilation recirculation filtration efficiency
- γ = fraction of time that the source produces the contaminant for a task or a series of tasks

The reader is referred to the appendices of the cited publication (Hewett) for additional details and for the time-varying concentration equations.

4.4 WMR with a Distribution of Particle Sizes

The preceding discussion on the WMR segues to estimating the particulate mass concentration when particles are present as a distribution of d_a values, as is normally the case, and not present in just one size. The distinction is important because larger particles have greater V_{TS} values and greater first-order loss rates due to settling. For example, given $H=3$ m, a

particle with $d_a = 1 \mu\text{m}$ has $\alpha_{\text{grav}} = 0.0007 \text{ min}^{-1}$, whereas a particle with $d_a = 10 \mu\text{m}$ has $\alpha_{\text{grav}} = 0.06 \text{ min}^{-1}$. Therefore, a single gravitational loss rate cannot be assigned to all the particles. The solution approach is essentially divide and conquer. That is, we divide the particle mass distribution into narrow d_a intervals (bins) of equal mass, use a representative d_a value for each interval, compute the particle mass concentration for each interval, and combine these concentrations across the intervals to get the overall particle mass concentration.

For simplicity, assume that the count distribution of particle d_a values is log normal with a count median aerodynamic diameter (CMAD) and a GSD. The mass median aerodynamic diameter (MMAD) is a function of the CMAD and GSD as follows:

$$\text{MMAD} = \text{CMAD} \times \exp[3 \times (\ln \text{GSD})^2] \quad (18)$$

The d_a value corresponding to a given percentile of the cumulative particle mass distribution, denoted here as $d_{a,P\%}$, is found by the equation

$$d_{a,P\%} = \text{MMAD} \times \text{GSD}^{Z_{P\%}} \quad (19)$$

where $Z_{P\%}$ is the standard normal deviate (or z value) corresponding to that percentile. For the tenth percentile, $Z_{10\%} = -1.282$; for the twentieth percentile, $Z_{20\%} = -0.842$; and so forth. Standard normal deviate values are available in every statistics text and statistical software program.

Example. Consider a log-normal distribution of particle d_a values with $\text{MMAD} = 4 \mu\text{m}$ and $\text{GSD} = 2$. We divide the distribution into, say, 10 d_a intervals of equal particle mass (more intervals can easily be used). Table 1 shows the lower and upper limits of the d_a values (in μm) for the 10 equal mass intervals. The first interval is bracketed by the zero and the tenth percentiles, the second interval is bracketed by the tenth and the twentieth percentiles, and so forth. The upper limit of the 10th interval is equated with the theoretical 99th percentile (for which $Z_{99\%} = 2.326$). The interval's representative value is taken as the interval midpoint. Although it would be better to derive the representative value by a mass-weighting approach within the interval, using the midpoint is adequate for intervals of small width, as in this example. Table 1 shows the first-order loss rate due to gravitational settling for each representative d_a value given a room height $H=3$ m. Across the 10 intervals, there is an 18-fold range in the representative d_a value ($14.9 \mu\text{m} \div 0.83 \mu\text{m}$), but a 260-fold range in the α_{grav} value ($0.13 \text{ min}^{-1} \div 0.0005 \text{ min}^{-1}$).

Next, consider that particulate contaminant conforming to this d_a distribution is emitted at the constant rate $G = 2000 \mu\text{g min}^{-1}$ into a WMR with $V = 200 \text{ m}^3$ and $Q = 10 \text{ m}^3 \text{min}^{-1}$. For each of the 10 d_a intervals of

TABLE 1 Lower and upper limits for aerodynamic diameter d_a .

bin	Lower d_a limit (μm)	Upper d_a limit (μm)	Representative d_a value (μm)	α_{grav} (min^{-1})	C_{ss} ($\mu\text{g m}^{-3}$)
1	0	1.65	0.83	0.0005	19.8
2	1.65	2.23	1.94	0.0025	19.0
3	2.23	2.78	2.51	0.0040	18.5
	2.78	3.36	3.07	0.0060	17.9
5	3.36	4.0	3.68	0.0085	17.1
6	4.0	4.77	4.39	0.012	16.1
7	4.77	5.75	5.26	0.017	14.9
8	5.75	7.12	6.44	0.026	13.2
9	7.12	9.72	8.42	0.043	10.8
10	9.72	20.1	14.9	0.13	5.56
					$\Sigma = 153 \mu\text{g m}^{-3}$

Emitted particles with initial MMAD = $4 \mu\text{m}$ and GSD = 2 are divided into 10 bins (ranges) of aerodynamic diameters d_a with equal mass. Note for these particles, CMAD = $0.946 \mu\text{m}$. For each bin, the table lists the upper and lower d_a limits, a representative d_a value within the range, the first-order loss rate due to settling for a particle with the representative d_a value, and the predicted steady-state mass concentration in room air. The predicted steady-state aerosol mass concentration is the sum of the concentrations for the 10 bins.

equal mass in Table 1, the emission rate by definition is $200 \mu\text{g min}^{-1}$. Because we know α_{grav} for each interval, and because Q is the same for all the intervals, we can use Eq. (9) to compute the steady-state particle mass concentration in each interval. These concentrations are listed in the last column in Table 1. The overall steady-state particle mass concentration is the sum of these 10 steady-state concentrations, equal to $153 \mu\text{g m}^{-3}$.

There are two important limitations of this method for estimating particulate contaminant concentrations. First, some aerosols change their size distribution after emission due to condensation or particle agglomeration, such that it is difficult to specify a fixed size distribution. Second, and perhaps more important, relatively large particles (say, $d_a > 10 \mu\text{m}$) do not disperse uniformly throughout room air but tend to gravitationally settle near their point of emission. The consequence is that using the WMR dispersion construct leads to overestimating the airborne concentrations of particles with high d_a values at receptor locations distant from the emission source. To handle this circumstance, the author and collaborators have developed a modeling technique based on Markov chain probability theory, although implementation of the technique requires computer coding (27, 28). The basics of the technique are outlined later in this chapter.

4.5 WMR with an Exponentially Decreasing Emission Rate

Consider a room with volume V (m^3) and supply/exhaust air rate Q ($\text{m}^3 \text{min}^{-1}$) that contains a source emitting a chemical at an exponentially decreasing rate $G(t) = G_0 \times \exp(-\alpha \times t)$

in mg min^{-1} . To simplify the calculations, the terms C_0 and α_L are not included, although they could be. The equation that predicts the time-dependent airborne contaminant concentration, $C(t)$ in mg m^{-3} , for $t \geq 0$, is the following:

$$C(t) (\text{mg m}^{-3}) = \frac{\alpha M_0}{\alpha V - Q} \times \left[\exp\left(-\frac{Q}{V} \times t\right) - \exp(\alpha \times t) \right] \quad (20)$$

As time passes, the chemical concentration increases to a peak value and then decreases to zero. The time at which the peak concentration occurs, t_{peak} (min), is given by

$$t_{\text{peak}} (\text{min}) = \frac{V \times \ln\left(\frac{\alpha V}{Q}\right)}{\alpha V - Q} \quad (21)$$

To compute the peak concentration, we use t_{peak} in the $C(t)$ equation.

Example. Figure 3 depicts the $C(t)$ time series for a scenario in which $V = 200 \text{ m}^3$, $Q = 20 \text{ m}^3 \text{min}^{-1}$, $M_0 = 40\,000 \text{ mg}$, and $\alpha = 0.15 \text{ min}^{-1}$, over the interval $0 \leq t \leq 60 \text{ min}$. According to Eq. (20), the expression for the time series is

$$C(t)(\text{mg m}^{-3}) = 600 \times [\exp(-0.10 \times t) - \exp(-0.15 \times t)]$$

According to Eq. (21), the peak concentration occurs at

$$t_{\text{peak}} = \frac{200 \times \ln\left(\frac{0.15 \times 200}{20}\right)}{0.15 \times 200 - 20} = 8.1 \text{ min}$$

Inserting this time into the $C(t)$ equation yields a peak value of 89 mg m^{-3} .

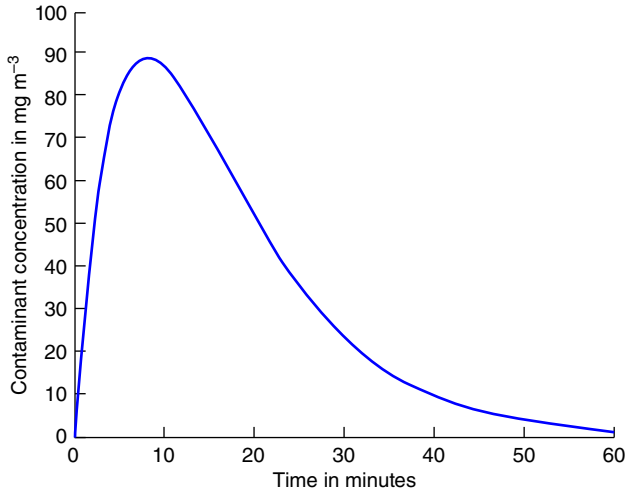


FIGURE 3 The well-mixed room dispersion construct with an exponentially decreasing contaminant emission rate. The input values are $V = 200 \text{ m}^3$, $Q = 20 \text{ m}^3 \text{ min}^{-1}$, and $G(t) = 6000 \times \exp(-0.15 \times t) \text{ mg min}^{-1}$.

4.6 NF/FF with a Constant Emission Rate

Consider a room with volume $V \text{ (m}^3\text{)}$ and supply/exhaust air rate $Q \text{ (m}^3 \text{ min}^{-1}\text{)}$ that contains a point source emitting a contaminant at constant rate $G \text{ (mg min}^{-1}\text{)}$. The NF zone surrounding the source has volume $V_{\text{NF}} \text{ (m}^3\text{)}$, such that $V_{\text{FF}} = V - V_{\text{NF}}$. The airflow rate between the NF and the FF zones is $\beta \text{ (m}^3 \text{ min}^{-1}\text{)}$. To simplify the calculations, the initial contaminant concentrations in the two zones and a second loss rate α_L are not included, although they could be. The equation that predicts the time-dependent airborne contaminant concentration in the NF zone, $C_{\text{NF}}(t) \text{ in mg m}^{-3}$, for $t \geq 0$, is the following:

$$C_{\text{NF}}(t) \text{ (mg m}^{-3}\text{)} = \frac{G}{Q} + \frac{G}{\beta} + G \left(\frac{\beta Q + \lambda_2 V_{\text{NF}}(\beta + Q)}{\beta Q V_{\text{NF}}(\lambda_1 - \lambda_2)} \right) \times \exp(\lambda_1 \times t) \left(\frac{\beta Q + \lambda_1 V_{\text{NF}}(\beta + Q)}{\beta Q V_{\text{NF}}(\lambda_1 - \lambda_2)} \right) \times \exp(\lambda_2 \times t) \quad (22)$$

where

$$\lambda_1 \text{ (min}^{-1}\text{)} = 0.5 \left[- \left(\frac{\beta V_{\text{FF}} + V_{\text{NF}}(\beta + Q)}{V_{\text{NF}} V_{\text{FF}}} \right) + \sqrt{\left(\frac{\beta V_{\text{FF}} + V_{\text{NF}}(\beta + Q)}{V_{\text{NF}} V_{\text{FF}}} \right)^2 - 4 \left(\frac{\beta Q}{V_{\text{NF}} V_{\text{FF}}} \right)} \right]$$

$$\lambda_2 \text{ (min}^{-1}\text{)} = 0.5 \left[- \left(\frac{\beta V_{\text{FF}} + V_{\text{NF}}(\beta + Q)}{V_{\text{NF}} V_{\text{FF}}} \right) - \sqrt{\left(\frac{\beta V_{\text{FF}} + V_{\text{NF}}(\beta + Q)}{V_{\text{NF}} V_{\text{FF}}} \right)^2 - 4 \left(\frac{\beta Q}{V_{\text{NF}} V_{\text{FF}}} \right)} \right]$$

The terms λ_1 and λ_2 are ventilation removal rate constants. The absolute value of λ_1 pertains to contaminant

removal from the FF zone, and the absolute value of λ_2 pertains to contaminant removal from the NF zone. Because $|\lambda_2|$ is usually greater than $|\lambda_1|$, removal from the NF zone proceeds more quickly than removal from FF zone (or the general room).

There is an analogous equation for airborne contaminant concentration in the FF zone, denoted $C_{\text{FF}}(t)$. The latter expression is not given here because the values predicted by the $C_{\text{FF}}(t)$ equation are nearly identical to those predicted by the WMR equation for the same values of G , Q , and V . The $C_{\text{FF}}(t)$ equation is available in the literature (1, 20).

If the emission process continues for a long time such that $t \rightarrow \infty$, the contaminant concentrations in the NF and FF zones reach steady-state values given by

$$C_{\text{NF,SS}} \text{ (mg m}^{-3}\text{)} = \frac{G}{Q} + \frac{G}{\beta} \quad (23)$$

$$C_{\text{FF,SS}} \text{ (mg m}^{-3}\text{)} = \frac{G}{Q} \quad (24)$$

$C_{\text{FF,SS}}$ is the same value predicted using the WMR model with a constant emission rate. If $\beta \leq Q$, then $C_{\text{NF,SS}} \geq 2 C_{\text{FF,SS}}$, which signifies the NF steady-state concentration is at least twofold the FF steady-state concentration (and twofold the steady-state value predicted by the WMR model). This condition pertains in a room with a low airspeed near the source, or in a large room with a large Q value. In general, as the room size increases, Q increases but β need be little affected, in which event $\beta \ll Q$. In that circumstance, the NF/FF model predicts a much higher contaminant concentration near the emission source compared to the WMR model. On the other hand, if $\beta \gg Q$ because there is high airspeed near the source, then $C_{\text{NF,SS}} \geq C_{\text{FF,SS}}$. In this case, the rapid dispersion of chemical away from the source makes the room behave as if it were well mixed.

Example. Figure 4 depicts the $C_{\text{NF}}(t)$ time series for the following scenario. A room with $V = 200 \text{ m}^3$ and $Q = 20 \text{ m}^3 \text{ min}^{-1}$ contains a point source emitting contaminant at $G = 1000 \text{ mg min}^{-1}$. The source is on a flat surface, and a worker is positioned near the source such that the breathing zone is always within a radius of 1.0 m of the source. Thus, the NF zone can be modeled as a hemisphere

with $r = 1.0 \text{ m}$, $\text{FSA} = 6.28 \text{ m}^2$, and $V_{\text{NF}} = 2.1 \text{ m}^3$. The random airspeed at the NF/FF boundary is 3.7 m min^{-1} , such

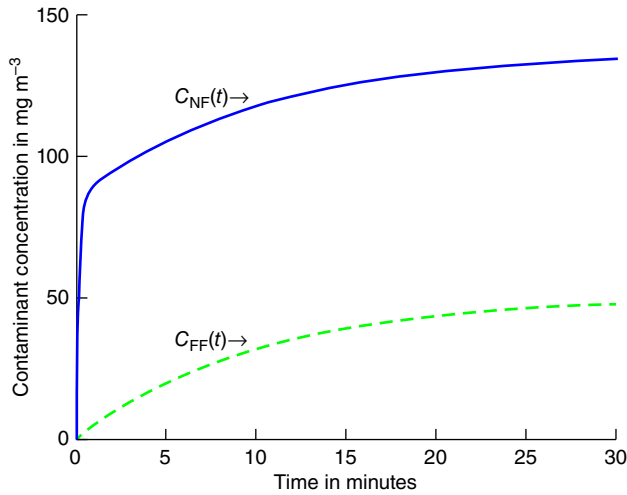


FIGURE 4 The near-field/far-field dispersion construct with a constant contaminant emission rate. The input values are $V_{NF} = 2.1 \text{ m}^3$, $V_{FF} = 197.9 \text{ m}^3$, $Q = 20 \text{ m}^3 \text{ min}^{-1}$, $\beta = 11.6 \text{ m}^3 \text{ min}^{-1}$, and $G = 1000 \text{ mg min}^{-1}$.

that $\beta = 1/2 \times (6.28 \text{ m}^2) \times (3.7 \text{ m min}^{-1}) = 11.6 \text{ m}^3 \text{ min}^{-1}$. According to Eq. (20), the expression for the time series is

$$C_{NF}(t) \text{ (mg m}^{-3}\text{)} = 50 + 86 - 51.8 \times \exp(-0.10 \times t) - 84.2 \times \exp(-5.61 \times t)$$

Note that $|\lambda_1| = 0.10$ and approximately equals Q/V_{FF} (the air exchange rate in the FF zone), whereas $|\lambda_2| = 5.61$ and approximately equals β/V_{NF} (the air exchange rate in the NF zone).

For comparison, Figure 4 also shows the time series for the FF contaminant concentration that, again, is essentially the same as that predicted for a WMR concentration time series. In Figure 4, the NF concentration rapidly increases to approximately 90 mg m^{-3} in the first minute and thereafter increases more slowly toward the steady-state value of 136 mg m^{-3} (as provided by the above equation for $t \rightarrow \infty$). The latter slow increase in the NF concentration mimics the shape of the slow increase in the FF concentration. The explanation of the NF concentration behavior is as follows. The high air exchange rate in the NF zone ($\beta/V_{NF} = 5.5 \text{ min}^{-1}$), combined with direct contaminant emission into the NF zone at $G = 1000 \text{ mg min}^{-1}$, causes rapid buildup to the value $G/\beta = 86 \text{ mg m}^{-3}$. Thereafter, incremental increases in the NF concentration are due to the flow of contaminated air from the FF zone into the NF zone, and the contaminant concentration in the FF zone increases slowly due to the relatively low air exchange rate in the FF zone ($Q/V_{FF} = 0.10 \text{ min}^{-1}$). The steady-state FF concentration is $G/Q = 50 \text{ mg m}^{-3}$.

Appropriate parameter values are essential for any reliable modeling. For the two-zone model, β is arguably difficult

for modelers to comfortably value. Since β is $1/2 \text{ FSA} \times S$, it depends on the NF size and geometry to calculate the FSA. Studies evaluating the utility of the two-zone model contain information on the NF size and geometry utilized (23, 24). Although actual estimates of S for the specific conditions being modeled may be preferable, some reported values may be useful. Random airspeeds appear to span a similar broad range, although a geometric mean airspeed of 3.7 m min^{-1} with a GSD of 1.96 had been reported (21) for a broad range of work area types. Recently, chamber study evaluation and verification in five workplaces (29) giving median air velocities of $3\text{--}30 \text{ m min}^{-1}$ and another study (30) yielded a mean airspeed of 4 m min^{-1} with a standard deviation of 3.0 for measurements in 12 rooms with volumes from 79 to 1137 m^3 and air change rates of $3.3\text{--}8.6$ per hour.

In applications of the NF/FF dispersion model, the first author of this chapter recommends using the observed median value of 3.7 m min^{-1} as the random air velocity if the operation takes place on an open shop floor with no strong sources of air motion near the NF zone boundary (for example air cooling fans, drafts from supply air ducts or open windows). A lower airspeed is appropriate if the individual is working within an enclosed space that does not receive mechanical ventilation. WC Hemeon (the originator of the NF/FF dispersion construct) recommended using an airspeed of 15 m min^{-1} given operation of a fan or air jet close to the NF zone (22).

4.7 NF/FF with Local Exhaust Removal and Recirculation of Treated Air

A version on the NF/FF model accounting for local exhaust removal from the NF and recirculation of treated air to the FF has been published (31). The “pseudo steady state” version is as follows. See Eq. (17) above for the definition of terms.

$$\begin{aligned} \bar{C}_F &= \frac{\gamma G [1 - \epsilon_L \epsilon_{LF} - \epsilon_L \epsilon_{LF} (1 - \epsilon_N)]}{Q + \epsilon_{RF} Q_R + \epsilon_{LF} Q_L} \text{ where } \epsilon_N = \frac{Q_L}{Q_L + \beta} \\ \bar{C}_N &= \bar{C}_F + \frac{\gamma G (1 - \epsilon_L) \epsilon_N}{Q_L} \end{aligned} \quad (25)$$

Refer to the publication (31) for the time-varying solution and suggested model calibration procedures.

4.8 NF/FF with an Exponentially Decreasing Emission Rate

Consider a room with volume $V \text{ (m}^3\text{)}$ and supply/exhaust air rate $Q \text{ (m}^3 \text{ min}^{-1}\text{)}$ that contains a source emitting a chemical at the exponentially decreasing rate $G(t) = G_0 \times \exp(-\alpha \times t)$ in mg min^{-1} . There is a NF zone surrounding the source with volume $V_{NF} \text{ (m}^3\text{)}$, such that $V_{FF} = V - V_{NF}$. The airflow

rate between the NF and the FF zones is β ($\text{m}^3 \text{min}^{-1}$). To simplify the calculations, the initial concentrations in each zone and a second loss rate α_L are not included, although they could be included. The equation that predicts the time-dependent airborne contaminant concentration in the NF zone, $C_{\text{NF}}(t)$ in mg m^{-3} , for $t \geq 0$, is the following

$$C_{\text{NF}}(t) \text{ (mg m}^{-3}\text{)} = \frac{\alpha M_0 \left[\left(\frac{\beta+Q}{V_{\text{FF}}} - \alpha \right) \left(\frac{\beta}{V_{\text{NF}}} + \lambda_2 \right) - \frac{\beta^2}{V_{\text{NF}} V_{\text{FF}}} \right]}{(\lambda_1 - \lambda_2) \times V_{\text{NF}} \times \left[\left(\frac{\beta+Q}{V_{\text{FF}}} - \alpha \right) - \frac{\beta^2}{V_{\text{NF}} V_{\text{FF}}} \right]} \times \exp(\lambda_1 \times t) - \frac{\alpha M_0 \left[\left(\frac{\beta+Q}{V_{\text{FF}}} - \alpha \right) \left(\frac{\beta}{V_{\text{N}}} + \lambda_2 \right) - \frac{\beta^2}{V_{\text{NF}} V_{\text{FF}}} + (\lambda_1 - \lambda_2) \left(\frac{\beta+Q}{V_{\text{FF}}} - \alpha \right) \right]}{(\lambda_1 - \lambda_2) \times V_{\text{NF}} \times \left[\left(\frac{\beta+Q}{V_{\text{FF}}} - \alpha \right) - \frac{\beta^2}{V_{\text{NF}} V_{\text{FF}}} - \frac{\beta^2}{V_{\text{NF}} V_{\text{FF}}} \right]} \times \exp(\lambda_1 \times t) + \frac{\alpha M_0 \times \left(\frac{\beta+Q}{V_{\text{FF}}} - \alpha \right)}{V_{\text{NF}} \times \left[\left(\frac{\beta+Q}{V_{\text{FF}}} - \alpha \right) \left(\frac{\beta}{V_{\text{NF}}} - \alpha \right) - \frac{\beta^2}{V_{\text{NF}} V_{\text{FF}}} \right]} \times \exp(-\alpha \times t) \quad (26)$$

where λ_1 and λ_2 are computed by the previous expressions in Eq. (22).

The contaminant concentration in the NF zone increases to a peak value and then decreases toward zero. The time at which the peak concentration occurs cannot be analytically determined but can be found by examining the time series of $C_{\text{NF}}(t)$ values. There is an analogous equation for airborne contaminant concentration in the FF zone, denoted $C_{\text{FF}}(t)$. The latter expression is not given here because the values predicted by the $C_{\text{FF}}(t)$ equation are close to those predicted by the WMR equation with an exponentially decreasing emission rate given the same Q and V values and the same $G(t)$ function. The $C_{\text{FF}}(t)$ equation is available in the literature (13).

Example. Figure 5 depicts the $C_{\text{NF}}(t)$ time series over the interval $0 \leq t \leq 30$ min for the following scenario. A room with $V=200 \text{ m}^3$ and $Q=20 \text{ m}^3 \text{min}^{-1}$ contains a point source on a flat surface, and a worker is positioned near the source such that the breathing zone is always within a radius of 1.0 m of the source. Thus, the NF zone can be modeled as a hemisphere with $r=1.0$ m, $\text{FSA}=6.28 \text{ m}^2$, and $V_{\text{NF}}=2.1 \text{ m}^3$. The random airspeed at the NF/FF boundary is 3.7 m min^{-1} , such that $\beta = 1/2 \times (6.28 \text{ m}^2) \times (3.7 \text{ m min}^{-1}) = 11.6 \text{ m}^3 \text{min}^{-1}$. At time zero, there is $M_0 = 40\,000 \text{ mg}$ in the source, and the evaporation rate constant is $\alpha = 0.15 \text{ min}^{-1}$. According to Eq. (23), the expression for the time series is

$$C_{\text{NF}}(t) \text{ (mg m}^{-3}\text{)} = 621.7 \times \exp(-0.10 \times t) - 519.0 \times \exp(-5.61 \times t) - 102.7 \times \exp(-0.15 \times t)$$

For comparison, Figure 5 also shows the time series for the FF contaminant concentration which, again, is similar to

that predicted for a WMR concentration time series given the same Q and V values and $G(t)$ function, as seen in Figure 2. In Figure 5, the NF concentration rapidly increases to a peak value of 477 mg m^{-3} that occurs at 0.75 min after emission begins and then decreases toward zero. The FF

concentration increases more slowly to a peak value of 89 mg m^{-3} that occurs at 8.3 min after emission begins, and then decreases toward zero. Note that in Figure 3 for a WMR with the same Q and V values and the same $G(t)$ function, the peak concentration is also 89 mg m^{-3} , but occurs slightly earlier at 8.1 min after emission begins. The NF/FF dispersion construct predicts a peak exposure concentration near the source that is 5.4-fold greater ($477 \div 89 \text{ mg m}^{-3}$) than the peak exposure predicted by the WMR dispersion construct. In addition, the initial 15-min TWA exposure concentrations predicted by the NF/FF dispersion construct versus the WMR

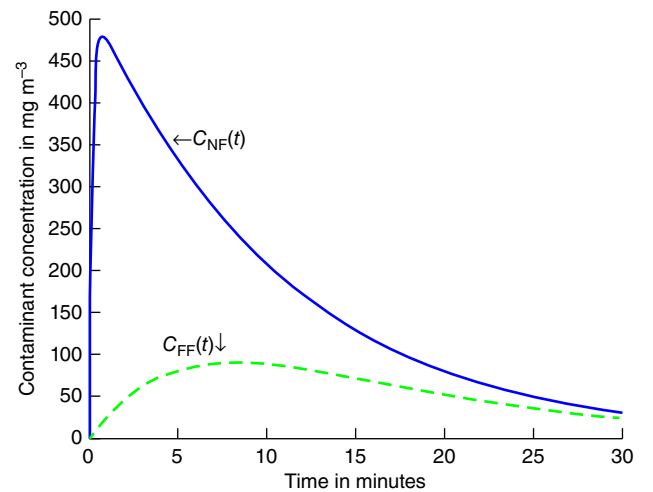


FIGURE 5 The near-field/far-field dispersion construct with an exponentially decreasing contaminant emission rate. The input values are $V_{\text{NF}} = 2.1 \text{ m}^3$, $V_{\text{FF}} = 197.9 \text{ m}^3$, $Q = 20 \text{ m}^3 \text{min}^{-1}$, $\beta = 11.6 \text{ m}^3 \text{min}^{-1}$, and $G(t) = 6000 \times \exp(-0.15 \times t) \text{ mg min}^{-1}$.

dispersion construct are, respectively, 275 and 72 mg m⁻³; the former TWA value is 3.8-fold greater than the latter (275 mg m⁻³ ÷ 72 mg m⁻³). If the $C_{NF}(t)$ equation above is a good descriptor of the actual contaminant concentrations that would develop, then relying on the traditional WMR dispersion construct would lead to substantially underestimating exposure intensity near the source.

4.9 Hemispherical Turbulent Eddy Diffusion Without Advection and with a Constant Emission Rate

Consider a room that contains a source emitting a contaminant at constant rate G (mg min⁻¹). The source sits on a flat surface such as the floor. The release position is set at the origin (0,0,0) in a three-dimensional coordinate system. Contaminant disperses away from the origin in a radially symmetric pattern via turbulent eddy diffusion with coefficient D_T (m² min⁻¹). Assume there is no advective airflow near the source, so $U=0$. Let $C(x,y,z,t)$ in mg m⁻³ denote the chemical concentration at position (x,y,z) relative to the source at the origin at time t . Because the source is on a flat surface for which $z=0$, we assume that the z coordinate for the worker's position is greater than or equal to zero. The equation which predicts $C(x,y,z,t)$, for $t \geq 0$, is the following:

$$C(x,y,z,t) \text{ (mg m}^{-3}\text{)} = \frac{G}{2\pi D_T \sqrt{x^2 + y^2 + z^2}} \times \left(1 - \operatorname{erf} \frac{\sqrt{x^2 + y^2 + z^2}}{4D_T t} \right) \quad (27)$$

The term $\operatorname{erf}(a)$ in the brackets denotes the *error function*, which is an integral expression. In Eq. (24), a time value close to zero corresponds to $\operatorname{erf}(a) \approx 1$ and a concentration close to zero, while a large time value corresponds to $\operatorname{erf}(a) \approx 0$ and a concentration close to the steady-state value. Many mathematical software packages compute $\operatorname{erf}(a)$ values. If software is not available, one can use the following approximation:

$$C(x,y,z,t) \text{ (mg m}^{-3}\text{)} \times \frac{G}{2\pi D_T \sqrt{x^2 + y^2 + z^2}} \times \left[1 - \sqrt{1 - \exp \left(-\frac{\sqrt{x^2 + y^2 + z^2}}{4D_T t} \right)} \right] \quad (28)$$

If contaminant emission continues such that $t \rightarrow \infty$, the contaminant concentration reaches a steady-state value given by

$$C(x,y,z)_{SS} \text{ (mg m}^{-3}\text{)} = \frac{G}{2\pi D_T \sqrt{x^2 + y^2 + z^2}} \quad (29)$$

Again, due to the radial symmetry in dispersion, the radial distance r from the emission point can be substituted for the quantity $\sqrt{x^2 + y^2 + z^2}$ in Eqs. (27) and (28).

A Technical Note. Four problems with Eq. (27) are that (i) it does not maintain a mass balance of chemical in room air; (ii) it does not account for removal of contaminant from room air by exhaust ventilation and other mechanisms such as sorption or deposition onto surfaces; (iii) it does not account for “reflection” of molecules from room surfaces (other than from the surface on which the source sits); and (iv) as the distance from the source decreases such that $r \rightarrow 0$, the predicted concentration tends toward infinity. These problems can be resolved by modeling turbulent eddy diffusion via a Markov chain method, which is outlined in a later section of this chapter (28, 32).

Example. The solid line curve in Figure 6 depicts the $C(t)$ time series for the following scenario. A point source on the floor emits contaminant at $G = 1000$ mg min⁻¹. The source location is at the origin (0,0,0) in a three-dimensional coordinate system. A worker kneels near the source and is positioned at $x = 0.577$ m, $y = 0.577$ m, and $z = 0.577$ m, such that the breathing zone is at a radial distance of 1.0 m. The turbulent eddy diffusion coefficient is $D_T = 1.0$ m² min⁻¹. According to Eq. (24), the expression for the time series is

$$C(t) = 159 \times \left[1 - \operatorname{erf} \left(\sqrt{\frac{1}{4 \times t}} \right) \right]$$

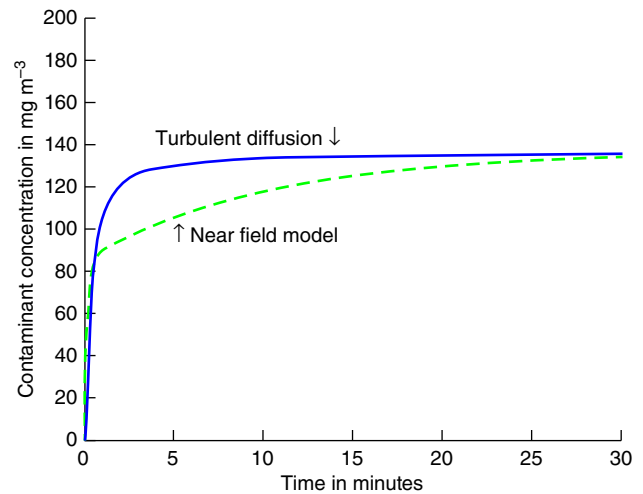


FIGURE 6 The hemispherical turbulent eddy diffusion dispersion constructs with a constant contaminant emission rate. The worker is at $r = 1.0$ m from the source, with $D_T = 1.0$ m² min⁻¹ and $G = 1000$ mg min⁻¹. The solid line curve is the hemispherical turbulent diffusion model. The dashed line curve is the concentration time series for the NF/FF dispersion construct using a hemispherical NF zone with $r = 1.0$ m, $G = 1000$ mg min⁻¹, $V_{NF} = 2.1$ m³, $V_{FF} = 197.9$ m³, $Q = 20$ m³ min⁻¹, and $\beta = 11.6$ m³ min⁻¹.

In Figure 6, the concentration rapidly increases to approximately 150 mg m^{-3} in the first five minutes and thereafter increases slowly toward the steady-state value of 159 mg m^{-3} (as provided by the above equation for $t \rightarrow \infty$). For comparison, the dashed line curve shows the NF zone concentration time series for a hemispherical NF with radius = 1.0 m, $G = 1000 \text{ mg min}^{-1}$, and the other NF/FF model parameter values used in Figure 4 ($V_{\text{NF}} = 2.1 \text{ m}^3$, $V_{\text{FF}} = 97.9 \text{ m}^3$, $Q = 20 \text{ m}^3 \text{ min}^{-1}$, $\beta = 11.6 \text{ m}^3 \text{ min}^{-1}$). The overall shapes of the two curves are similar (a rapid buildup followed by a gradual increase), although the NF zone concentration tends toward a lower steady-state value of 136 mg m^{-3} . The two curves would be more similar if $D_T = 1.17 \text{ m}^2 \text{ min}^{-1}$ and $\beta = 11.6 \text{ m}^3 \text{ min}^{-1}$ because both would reach the same steady-state value of 136 mg m^{-3} . The two curves would also be more similar if $D_T = 1.0 \text{ m}^2 \text{ min}^{-1}$ and $\beta = 9.17 \text{ m}^3 \text{ min}^{-1}$, because both would reach the same steady-state value of 159 mg m^{-3} .

The correspondence (or apparent lack thereof) between the hemispherical turbulent eddy diffusion and the hemispherical NF/FF dispersion constructs raises the issue of how D_T and β values (which both depend on random airspeeds) are assigned and related.

The algebraic relationship between D_T and β has not yet been fully determined but would seem to involve the following concepts. At any point in a room, one expects to find a distribution of air velocity vectors over time. Each vector is decomposed into respective components along the x -axis, y -axis, and z -axis. In the ensemble of these vectors, there is a mean vector along each axis – denoted by $\bar{X}$, $\bar{Y}$, and $\bar{Z}$ – and a variance of the magnitude of the vectors along each axis. For the x -axis, this variance of the magnitude of the vectors, denoted σ_X^2 in $\text{m}^2 \text{ min}^{-2}$ is computed as follows:

$$\sigma_X^2 = \frac{\sum_{i=1}^n (|X| - |\bar{X}|)^2}{n}$$

where n is the number of vectors in the ensemble. There is an analogous variance for the vectors along the y -axis and z -axis. A measure of turbulence intensity is a combination of these variances designated as K (m min^{-1}):

$$K = \sqrt{\sigma_X^2 + \sigma_Y^2 + \sigma_Z^2}$$

The product of the K value (m min^{-1}) and a length aspect ΔL (m) produces a quantity with the unit $\text{m}^2 \text{ min}^{-1}$ and would seem related to the turbulent eddy diffusion coefficient D_T with the same unit. If the K value (m min^{-1}) were also used as the random airspeed s in the NF/FF dispersion construct, the interzonal airflow rate β and D_T would be algebraically related.

Some progress in determining D_T , β and their relationship has been achieved. A hypothesized relationship

between mechanical energy from ventilation flow and any thermal stratification (33) led to a predictive equation for D_T , albeit one not widely validated. Recent controlled chamber studies (29) also suggest a relationship between D_T and ACH, with the data covering ACH range of 0.43–2.89 and D_T roughly covarying over the range of 0.067–0.55, for values averaged at each reported ACH. This generally agrees with an earlier finding for such a relationship in a residential environment (34). As previously noted, D_T values estimated in different indoor settings span a 100-fold range from 0.1 to $10 \text{ m}^2 \text{ min}^{-1}$ (1). The D_T value of $1.0 \text{ m}^2 \text{ min}^{-1}$ used for Figure 6 was the geometric mean of the reported range limits, or $\sqrt{0.1 \times 10}$ and, if lacking more specific information, is a reasonable default for environments with moderately mixed air. In modeling, one may consider lower values for quiescent air environments (e.g. a nonventilated closet) and higher for very well mixed conditions, such as when mixing fans are present. Envision D_T in meters squared per minute as the planar area in meters squared that a molecule in a “random walk” could cover in that time due to the random air velocity in the space modeled.

As noted above in the two-zone model discussion, random airspeeds appear to span a broad range, although a geometric mean airspeed of 3.7 m min^{-1} with a GSD of 1.96 had been reported (21) for a diverse range of work area types. Recent chamber study evaluation and verification in five workplaces (29) give median air velocities of $3\text{--}30 \text{ m min}^{-1}$, and another study (30) yielded a mean airspeed of 4 m min^{-1} with a standard deviation of 3.0 for measurements in 12 rooms with volumes from 79 to 1137 m^3 and air change rates of $3.3\text{--}8.6$ per hour.

4.10 WMR with a Reversible Sink

When the WMR model was introduced in this chapter, a loss rate constant α_L (min^{-1}) was used to denote contaminant removal from air by a nonventilatory mechanism such as adsorption onto room surfaces or sorption into construction materials and furnishings. These surfaces and materials are often termed “sinks.” If the flow is one-way only from room air to the sink, Eq. (1) applies. However, if the flow is two-way (reversible) such that the contaminant can move from the sink back into room air, a different equation must be used. A conceptual diagram is Figure 7. The hatched area at the bottom of the room represents a sink, which need not be physically located on the floor (although carpeting could be a sink). The factor α_2 is a first-order rate of transfer for contaminant mass in room air to the sink, and the factor α_3 is a first-order rate of transfer for contaminant mass in the sink back into room air. Exhaust ventilation is converted to a first-order loss rate from room air, α_1 (min^{-1}), by dividing Q ($\text{m}^3 \text{ min}^{-1}$) by the room volume V_{room} (m^3). The volume of the sink is V_{sink} (m^3).

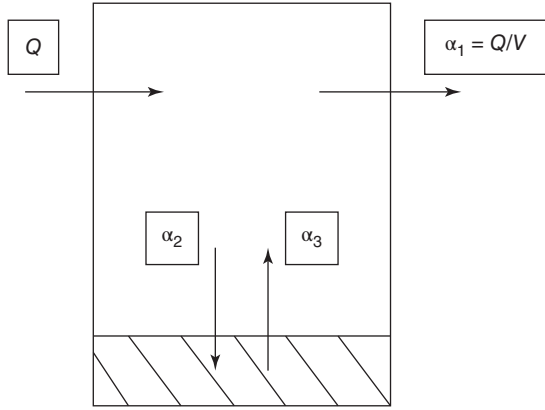


FIGURE 7 A well-mixed room with a reversible sink (the hatched area). The first-order loss rate of contaminant from room air due to exhaust airflow is $\alpha_1 = Q/V \text{ min}^{-1}$. The first-order rate of contaminant mass transfer from room air to the sink is $\alpha_2 \text{ min}^{-1}$. The first-order rate of contaminant mass transfer from the sink to room air is $\alpha_3 \text{ min}^{-1}$.

Consider that at time zero, the contaminant concentration in room air is $C_{\text{room},0}$, the contaminant concentration in the sink is $C_{\text{sink},0}$, and emission into room air begins at constant rate $G \text{ (mg min}^{-1}\text{)}$. The equation that predicts $C_{\text{room}}(t)$ in mg m^{-3} , for $t \geq 0$, is the following:

$$C_{\text{room}}(t) = \frac{G}{Q} + \left[C_{\text{room},0} - \frac{G}{Q} \right] \exp(-\lambda_2 \times t) + \Psi [\exp(-\lambda_3 \times t) - \exp(-\lambda_2 \times t)] \quad (30)$$

where

$$\Psi = \left[C_{\text{sink},0} - \frac{G\alpha_2}{V_{\text{sink}}\alpha_1\alpha_3} + \frac{G\alpha_2}{V_{\text{sink}}\alpha_1(\lambda_2 + \alpha_3)} - \frac{C_{\text{room},0}V_{\text{room}}\alpha_2}{V_{\text{sink}}(\lambda_2 + \alpha_3)} \right] \times \left[\frac{1}{\frac{V_{\text{room}}\alpha_2}{V_{\text{sink}}(\lambda_3 + \alpha_3)} - \frac{V_{\text{room}}\alpha_2}{V_{\text{sink}}(\lambda_2 + \alpha_3)}} \right]$$

$$\lambda_1 = \frac{-(\alpha_1 + \alpha_2 + \alpha_3) + \sqrt{(\alpha_1 + \alpha_2 + \alpha_3)^2 - 4\alpha_1\alpha_3}}{2} \lambda_3$$

$$\lambda_2 = \frac{-(\alpha_1 + \alpha_2 + \alpha_3) - \sqrt{(\alpha_1 + \alpha_2 + \alpha_3)^2 - 4\alpha_1\alpha_3}}{2}$$

The reversible sink also affects the decay in the room air contaminant concentration once *de novo* emission ceases. The concentration decreases less rapidly when the reversible sink is present because contaminant is released from the sink into room air. Consider that at some reference time zero, the contaminant concentration in room air is $C_{\text{room},0}$, the contaminant concentration in the sink is $C_{\text{sink},0}$, and there is no emission into room air other than from the sink. The

equation that predicts $C_{\text{room}}(t)$ in mg m^{-3} , for $t \geq 0$, is the following:

$$C_{\text{room}}(t) = \Omega [\exp(-\lambda_2 \times t) - \exp(-\lambda_3 \times t)] + C_{\text{room},0} \exp(-\lambda_3 \times t) \quad (31)$$

$$\text{where } \Omega = \left[C_{\text{sink},0} - \frac{C_{\text{room},0}V_{\text{room}}\alpha_2}{V_{\text{sink}}(\lambda_3 + \alpha_3)} \right] \times \left[\frac{1}{\frac{V_{\text{room}}\alpha_2}{V_{\text{sink}}(\lambda_2 + \alpha_3)} - \frac{V_{\text{room}}\alpha_2}{V_{\text{sink}}(\lambda_3 + \alpha_3)}} \right]$$

and λ_2 and λ_3 are the same parameters as computed for Eq. (27).

Example. Figure 8 depicts the $C_{\text{room}}(t)$ series (the solid line curve) over the time period $0 \leq t \leq 24 \text{ h}$ for the input values $G = 1000 \text{ mg min}^{-1}$, $V_{\text{room}} = 200 \text{ m}^3$, $V_{\text{sink}} = 1 \text{ m}^3$, $Q = 3.33 \text{ m}^3 \text{ min}^{-1}$, α_2 and $\alpha_3 = 0.0017 \text{ min}^{-1}$, and $C_{\text{room},0}$ and $C_{\text{sink},0} = 0$. For comparison, the dashed line curve shows the concentration time series for a WMR with $G = 1000 \text{ mg min}^{-1}$, $V_{\text{room}} = 200 \text{ m}^3$, and $Q = 3.33 \text{ m}^3 \text{ min}^{-1}$, but absent the sink. The effect of the reversible sink is to delay the buildup of the contaminant concentration to the same steady-state value. At $t = 1440 \text{ min}$ (24 h), C_{room} with the reversible sink is 296 mg m^{-3} , while C_{room} without the sink is 300 mg m^{-3} . At 24 h, the concentration in the sink is $52\,500 \text{ mg m}^{-3}$. According to Eq. (27), the expression for $C_{\text{room}}(t)$ for $0 \leq t \leq 1440 \text{ min}$ (24 h) is given by

$$C_{\text{room}}(t) (\text{mg m}^{-3}) = 300 - 267.7 \times \exp(-0.0015 \times t) - 32.3 \times \exp(-0.0185 \times t)$$

Figure 8 also depicts the $C_{\text{room}}(t)$ series (the solid line curve) over a 16 h period subsequent to cessation of the original emission source; that is $G = 0$ for $t > 1440 \text{ min}$ (24 h). The input values V_{room} , V_{sink} , Q , α_2 , and α_3 are the same as in the buildup scenario, but the new starting concentrations are $C_{\text{room},0} = 296 \text{ mg m}^{-3}$ and $C_{\text{sink},0} = 52\,500 \text{ mg m}^{-3}$. The latter values were attained by the end of the 24 h buildup period when $G = 1000 \text{ mg min}^{-1}$. For comparison, the dashed line curve shows the concentration time series for a WMR room with the same V_{room} and Q values, and with a starting concentration of 300 mg m^{-3} but absent the sink. Again, the reversible sink decreases the rate of contaminant removal from room air because contaminant enters room air from the sink. After 16 h of concentration decay (at $t = 40 \text{ h}$ referenced to the original time zero), C_{room} with the reversible sink is 0.54 mg m^{-3} , while C_{room} without the sink is essentially zero. According to Eq. (28), the expression for $C_{\text{room}}(t)$ for $1440 \text{ min} < t \leq 2400 \text{ min}$ is given by

$$C_{\text{room}}(t) (\text{mg m}^{-3}) = 28.6 \times \exp(-0.0015 \times [t - 1440]) + 267.7 \times \exp(-0.0185 \times [t - 1440])$$

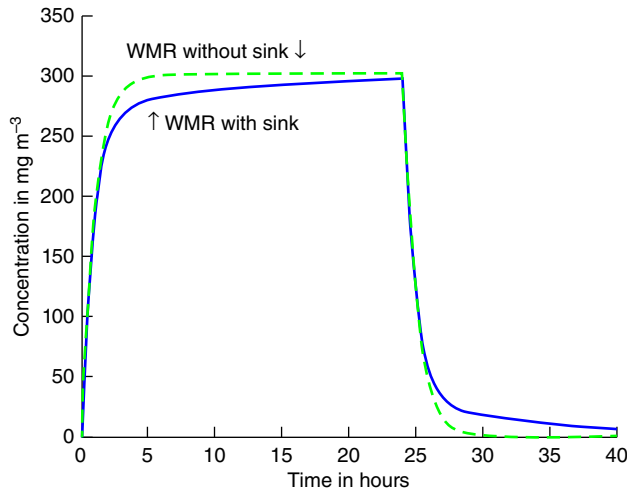


FIGURE 8 The well-mixed room dispersion constructs with a constant contaminant emission rate and with a reversible sink. The input values are $V = 200 \text{ m}^3$, $V_{\text{sink}} = 1 \text{ m}^3$, $Q = 3.33 \text{ m}^3 \text{ min}^{-1}$, $\alpha_2 = 0.0017 \text{ min}^{-1}$, $\alpha_3 = 0.0017 \text{ min}^{-1}$, $C_{\text{room},0} = 0$, $C_{\text{sink},0} = 0$, and $G = 1000 \text{ mg min}^{-1}$. The solid line curve is the WMR model with a reversible sink. The dashed line curve is the WMR model without a sink.

The reason that the 1440 min (24 h) is subtracted from t in the argument of the exponent function is to maintain the same zero starting time for the process.

A reversible sink can lead to the undesirable buildup of contaminant in room air once a room is vacated and the ventilation system is turned off. Upon subsequent entry, the occupants can be exposed to a contaminant level that is annoying or overtly harmful. One such scenario that was investigated involved the off-gassing of methyl bromide subsequent to home fumigation for termites (35). At the end of an aeration period following methyl bromide treatment, the methyl bromide concentration decreased to a level deemed acceptable. However, when the house was closed back up, the methyl bromide concentration increased to unacceptable levels due to off-gassing from construction materials and furnishings (the sinks) and an inadequate dilution air exchange rate.

The reader may have noticed that the structure of the WMR model with a reversible sink is similar to the NF/FF model. In both constructs, the room contains two compartments that can undergo an exchange of contaminant mass. In the NF/FF model, airflow into and out of the NF zone causes the exchange. In the reversible sink model, sorption into the sink and off-gassing from the sink mediate the exchange. The analytical solution equation for two compartments is more complicated than for one compartment, and if there were three or more compartments in the room, the corresponding equations would be decidedly more complex. A relatively simple method for modeling mass exchanges

between multiple compartments is a Markov chain, which is described in the next section.

5 THE MARKOV CHAIN METHOD

5.1 Basic Ideas

To explain the method, we consider a WMR with a reversible sink. Designate room air as “state 1,” designate the sink as “state 2,” and designate exhausted out of the room as “state 3.” There are two first-order loss rates acting on a contaminant molecule in state 1 (room air) – α_1 for removal by exhaust ventilation and α_2 for removal by sorption into the sink – so the overall rate is $\alpha_1 + \alpha_2$. Next, consider an incremental time step Δt equal to, say, 0.01 min. The probability that a contaminant molecule present in room air at time t remains in room air at time $t + \Delta t$ is given as follows:

$$\begin{aligned} \text{Probability molecule remains in room air} \\ = \exp(-(\alpha_1 + \alpha_2) \times \Delta t) \end{aligned} \quad (32)$$

This probability does not depend on the actual time t , only on the length of the time step Δt . The probability that the molecule leaves room air in the interval Δt is the complement:

$$\begin{aligned} \text{Probability particle leaves room air} \\ = 1 - \exp(-(\alpha_1 + \alpha_2) \times \Delta t) \end{aligned} \quad (33)$$

Given that the molecule leaves room air in interval Δt , the *conditional* probability that it leaves via exhaust ventilation versus sorption into the sink is, respectively, as follows:

$$\begin{aligned} \text{Conditional probability molecule leaves} \\ \text{via exhaust ventilation} = \frac{\alpha_1}{\alpha_1 + \alpha_2} \end{aligned} \quad (34)$$

$$\begin{aligned} \text{Conditional probability molecule leaves via sorption} \\ = \frac{\alpha_2}{\alpha_1 + \alpha_2} \end{aligned} \quad (35)$$

In turn, the *unconditional* probability that in interval Δt the molecule leaves room air via exhaust ventilation versus sorption into the sink is the product of the corresponding conditional probability and the probability that the molecule leaves room air in the first place:

$$= \frac{\alpha_1}{\alpha_1 + \alpha_2} \times [1 - \exp(-(\alpha_1 + \alpha_2) \times \Delta t)] \quad (36)$$

$$= \frac{\alpha_2}{\alpha_1 + \alpha_2} \times [1 - \exp(-(\alpha_1 + \alpha_2) \times \Delta t)] \quad (37)$$

Let the quantity p_{ij} denote the probability that a molecule in state i at the start of the interval Δt is in state j at the end of the interval. The quantity p_{ij} is termed a "single-step transition probability." The probability that a molecule present in room air at the start of the interval remains in room air is denoted p_{11} , equal to the right-hand side of Eq. (32). The probability that a molecule in room air at the start of the interval is exhausted out of the room is denoted p_{13} , equal to the right-hand side of Eq. (36). The probability that a molecule in room air at the start of the interval sorbs into the sink is denoted p_{12} , equal to the right-hand side of Eq. (37). These three probabilities sum to one: $p_{11} + p_{12} + p_{13} = 1$. Thus, for a molecule present in room air at the start of the interval, we have accounted for all the places the molecule can be at the end of the interval.

The single-step transition probabilities are based on the properties of first-order loss rates discussed earlier in this chapter. The overall first-order rate by which a molecule leaves state 1 is the sum of the first-order rates associated with the independent removal mechanisms of exhaust ventilation (α_1) and sorption into the sink (α_2). Given that a molecule leaves state 1, the probability that it leaves via exhaust ventilation is the first-order loss rate due to ventilation divided by the total first-order loss rate, and the probability that it leaves via sorption is the first-order loss rate due to sorption divided by the total first-order loss rate.

Next, we consider a molecule in the sink. The probability that a contaminant molecule present in the sink at time t still remains in the sink at time $t + \Delta t$ is given as follows:

$$\text{Probability molecule remains in sink} = \exp(-\alpha_3 \times \Delta t) \quad (38)$$

where α_3 denotes the first-order rate at which the molecule leaves the sink and enters room air.

In this case, there is only one removal mechanism (off-gassing) and one first-order loss rate. The probability that the molecule leaves the sink in the interval Δt is the complement:

$$\text{Probability molecule leaves sink} = 1 - \exp(-\alpha_3 \times \Delta t) \quad (39)$$

The probability that a molecule present in the sink at the start of the interval remains in the sink is denoted p_{22} , equal to the right-hand side of Eq. (38). The probability that a molecule in the sink leaves the sink and enters room air is denoted p_{21} , equal to the right-hand side of Eq. (39). The probability that a molecule in the sink directly moves to the exhausted out of the room state 3 is zero, because only molecules in room air can be exhausted, in which case $p_{23} = 0$. The sum of the three probabilities is one: $p_{21} + p_{22} + p_{23} = 1$. For a molecule present in the sink at the start of the interval, we have accounted for all the places the molecule can be at the end of the interval.

What if a molecule had already been exhausted out of the room (in state 3) at the start of the interval? If we

do not permit reentry into room air via the supply airflow, then molecules that enter state 3 never leave. For exhausted particles, this signifies that $p_{31} = 0$, $p_{32} = 0$, and $p_{33} = 1$.

Next, we create a matrix $\mathbf{P}$ with three rows and three columns. Each row represents a state (where the row number equals the state number), and each column represents a state (where the column number equals the state number). The cell entries are

$$\mathbf{P} = \begin{bmatrix} p_{11} & p_{12} & p_{13} \\ p_{21} & p_{22} & p_{23} \\ p_{31} & p_{32} & p_{33} \end{bmatrix} \quad (40)$$

A square matrix $\mathbf{P}$ in which the sum of the entries in each row equals one is termed a Markov matrix. $\mathbf{P}$ is also termed a single-step transition probability matrix because it contains the probabilities of moving between states in one time step. The time course of molecular movement is tracked via matrix multiplication. After n time steps (for which $t = n \times \Delta t$), the expected proportion of molecules starting in state 1 (room air) that are present in state 1 is the entry in the first cell and first row of the matrix $\mathbf{P}^n$, which is the matrix $\mathbf{P}$ multiplied by itself n times. This proportion is denoted by $P_{11}^{(n)}$. In general, $P_{ij}^{(n)}$ denotes the probability that a molecule starting in state i is in state j after n time steps. In each row of $\mathbf{P}^n$, the row entries sum to one. For example, in our 3×3 $\mathbf{P}^n$ matrix, $P_{11}^{(n)} + P_{12}^{(n)} + P_{13}^{(n)} = 1$. This condition signifies that we have accounted for the fate of all the molecules that were present in room air at a specified starting time ($n \times \Delta t$ time steps in the past).

Consider that at the starting time, there are $M_{1,t=0}$ contaminant molecules in room air and $M_{2,t=0}$ contaminant molecules in the sink. If no new contaminant molecules are added to the system, then at $t = n \times \Delta t$, the expected contaminant molecule concentration in room air (state 1) with volume V_{room} (m^3) is

$$C_{\text{room}}(t = n \times \Delta t) (\#/\text{m}^3) = \frac{M_{1,t=0} \times P_{11}^{(n)} + M_{2,t=0} \times P_{21}^{(n)}}{V_{\text{room}}} \quad (41)$$

The molecular number concentration ($\#/\text{m}^3$) is easily converted to a mass concentration (mg m^{-3}) via multiplying the number concentration by the mass (mg) per molecule. The easier alternative is to define $M_{1,t=0}$ and $M_{2,t=0}$ as the starting contaminant mass (mg) in, respectively, room air (state 1) and the sink (state 2). The relative simplicity of the Markov chain method is seen by comparing Eq. (41) with Eq. (31) for the time-dependent contaminant concentration in room air given initial concentrations in room air ($C_{\text{room},0}$) and the sink ($C_{\text{sink},0}$), and no further emission (other than from the sink). As if by magic, matrix multiplication (via a computer code) supplies the values for $P_{11}^{(n)}$ and $P_{21}^{(n)}$. If we define $M_{1,t=0}$ and $M_{2,t=0}$ as starting contaminant masses, then $M_{1,t=0} = C_{\text{room},0} \times V_{\text{room}}$ and $M_{2,t=0} = C_{\text{sink},0} \times V_{\text{sink}}$.

Note that the NF/FF model can be implemented with a similar 3×3 $\mathbf{P}$ matrix structure. In this case, state 1 is the FF, state 2 is the NF, and state 3 is exhausted out of the room. The first-order loss rates are $\alpha_1 = Q/V_{\text{FF}}$, $\alpha_2 = \beta/V_{\text{FF}}$, $\alpha_3 = \beta/V_{\text{NF}}$. Moreover, multiple compartments within the room (different air spaces and/or different sinks) can be considered in a relatively compact fashion; in the $\mathbf{P}$ matrix, each row and column correspond to one of the compartments. For example, with regard to the WMR with a reversible sink, some sinks are better modeled as having two parts – a “fast sink” and a “slow sink” – such that contaminant release from the former is more rapid than from the latter. In this scenario, we can define four states – room air (state 1), the fast sink (state 2) physically contiguous with room air, the slow sink (state 3) physically contiguous with the fast sink and exhausted out of the room (state 4) from state 1. We can form a 4×4 $\mathbf{P}$ matrix and proceed in the same manner as outlined earlier.

5.2 Accounting for Ongoing Emission

Equation (41) applies to a scenario in which there is starting contaminant mass in one or more compartments, but no new mass is emitted into the system such that $G(t) = 0$. Incorporating ongoing contaminant emission is more a matter of bookkeeping than mathematical analysis. The explanation again uses a WMR with a reversible sink with no starting contaminant mass in room air or the sink. Consider that in each time step subsequent to $t = 0$, a certain mass of contaminant is emitted into room air (state 1). The contaminant mass (mg) emitted in the k th time step is denoted $M_{1,k}$, and is treated as being emitted at the beginning of the time step. At time $t = n \times \Delta t$, where $k \leq n$ and where we are at the end of the n th time step, a number $n - k + 1$ time steps have elapsed. For example, if $n = 3$ and $k = 1$, three time steps ($3 - 1 + 1$) have elapsed between the release of mass $M_{1,1}$ and time $t = 3 \times \Delta t$. The proportion of mass $M_{1,1}$ that remains in room air (state 1) is $P_{11}^{(3)}$. In general, for mass $M_{1,k}$ released into room air (state 1) at the start of the k th time step, the proportion that remains in room air (state 1) at time $t = n \times \Delta t$ is $P_{11}^{(n-k+1)}$, the entry in the first row and first column of the matrix $\mathbf{P}^{(n-k+1)}$.

The total contaminant mass in room air (state 1) at $t = n \times \Delta t$ is the sum of the remainders of the individual masses released in time steps $k = 1, 2, \dots, n$, or

$$\text{Total mass in room air at } n \times \Delta t = \sum_{k=1}^n M_{1,k} \times P_{11}^{(n-k+1)} \quad (42)$$

By definition, $P_{11}^{(1)} = p_{11}$. The contaminant concentration in room air is this total mass divided by the room volume V_{room} :

$$C_{\text{room}}(t = n \times \Delta t) (\text{mg m}^{-3}) = \frac{\sum_{k=1}^n M_{1,k} \times P_{11}^{(n-k+1)}}{V_{\text{room}}} \quad (43)$$

Now, what if there were contaminant masses in room air and/or the sink at time zero? The answer is that the right-hand side of Eq. (38) concerning the fate of these initial contaminant masses (in which case $M_{1,t=0}$ and $M_{2,t=0}$ are defined as masses) is added to the right-hand side of Eq. (43).

The final question is – how do we find the $M_{1,k}$ values? If we have a constant emission rate G (mg min^{-1}), the mass released in each time step is $G \div (1 \div \Delta t)$, where Δt is in minutes. For example, if $\Delta t = 0.01$ min and $G = 1000 \text{ mg min}^{-1}$, then $M_{1,k} = (1000 \text{ mg min}^{-1}) \div (1 \div 0.01 \text{ min}) = 10 \text{ mg}$ for all k . If the emission rate function $G(t)$ is variable and continuous, we need to integrate $G(t)$ over each time step. Where $t = n \times \Delta t$, define the time (referenced to time zero) at the start of the k th interval as $t_{\text{start}} = (k \div n) \times t$, and define the time (referenced to time zero) at the end of the k th interval as $t_{\text{end}} = t_{\text{start}} + \Delta t$. It follows that

$$M_{1,k} = \int_{t_{\text{start}}}^{t_{\text{end}}} G(t) dt \quad (44)$$

6 MODELING TURBULENT EDDY DIFFUSION AND ADVECTION

The Markov chain method can be applied to within-room contaminant dispersion by turbulent eddy diffusion and advection (28, 32). A complete discussion is beyond the scope of this chapter, but the basic elements of the method are provided. Consider that we divide room air into cubic cells with length aspect ΔL (m) and volume $V_{\text{cell}} = (\Delta L)^3$ (m^3), where the cells are aligned along the x -axis, y -axis, and z -axis. The air within each cell is assumed well mixed, although room air overall need not be well mixed. We focus on the behavior of a contaminant molecule in an interior room cell (one not bordering a room surface). The molecule can leave the cell due to turbulent eddy diffusion or due to advective airflow (flow in a given direction, on average). Assume the advective flow is left to right along the x -axis. The interior cell has six neighbor cells that each shares a face with the interior cell – to the left and to the right on the x -axis, to the front and to the rear on the y -axis, and above and below on the z -axis. In one time step, the molecule can remain (hold) in the interior cell, or move to one of its adjacent neighbor cells.

The advective airflow with speed S (m min^{-1}) is orthogonal to the left-hand face of the cubic cell with area $(\Delta L)^2$. The first-order loss rate for advective transport from the cell, α_1 (min^{-1}), is the quotient of the volumetric airflow through the cell and the cell volume:

$$\alpha_1 = \frac{S \times (\Delta L)^2}{(\Delta L)^3} = \frac{S}{\Delta L} \quad (45)$$

If the molecule leaves the interior cell due to advection, it travels to the neighboring cell to the right. The turbulent eddy diffusion coefficient D_T has the unit $\text{m}^2 \text{min}^{-1}$. D_T reflects a rate of dispersion and can be converted to a first-order loss rate with the unit min^{-1} according to the following expression:

$$\alpha_2 = \frac{6D_T}{(\Delta L)^2} \quad (46)$$

The rate α_2 pertains to removal from the interior cell by turbulent diffusion regardless of the direction of movement. For movement by turbulent eddy diffusion to each individual neighboring cell, the rate constant is $\alpha_2/6$. The total first-order loss rate of the molecule from the interior cell is $\alpha_1 + \alpha_2$. In one time step Δt , the probability that the molecule remains in the interior cell (denote p_{hold}) is

$$p_{\text{hold}} = \exp(-[\alpha_1 + \alpha_2] \times \Delta t) \quad (47)$$

In one time step Δt , the probability that the molecule leaves the interior cell and moves to the neighboring cell to the right (denoted by p_{right}) is

$$p_{\text{right}} = \frac{\alpha_1 + (\alpha_2/6)}{\alpha_1 + \alpha_2} \times [1 - p_{\text{hold}}] \quad (48)$$

In one time step Δt , the probability that the molecule leaves the interior cell and moves to any of the other neighboring cells is

$$p_{\text{left}} = p_{\text{forward}} = p_{\text{back}} = p_{\text{up}} = p_{\text{down}} = \frac{\alpha_2/6}{\alpha_1 + \alpha_2} \times [1 - p_{\text{hold}}] \quad (49)$$

Equations (47)–(49) provide the single-step transition probabilities for a molecule in the interior cell, where these probabilities sum to one. Given that p_{right} is greater than the other probabilities of movement, molecules tend to move to the right (due to advective airflow) but also randomly disperse (due to turbulent eddy diffusion). If a similar set of single-step transition probabilities is assigned for each room air cell, one can form a Markov matrix $\mathbf{P}$ that describes molecular movement within the room, where each row and column of $\mathbf{P}$ represents a room air cell. We can also account for reflection of molecules by room surfaces, and the removal of molecules from room air via the exhaust airflow and sorption into sinks, but those details are not covered here.

An advantage of the Markov chain method for modeling turbulent eddy diffusion is that it limits the contaminant concentration to a finite value, unlike analytical Eq. (27) for hemispherical turbulent eddy diffusion when $r \rightarrow 0$. In the Markov chain method, contaminant molecules from a point source are released into one (or several) receiving air cell with a defined volume and are dispersed from this receiving cell(s) by turbulent eddy diffusion and advective airflow. The contaminant concentration may build up to a high value in

the receiving air cell(s), but it does not increase to an infinite value.

6.1 Modeling Particle Settling

For particulate contaminants, the Markov chain method can also incorporate gravitational settling. In the case of molecules, we considered the loss of contaminant molecules from an interior room cell due to advective airflow (with loss rate α_1) and turbulent eddy diffusion (with loss rate α_2). A third loss rate α_{grav} operates for particles. To assign this rate, the particle's terminal settling velocity V_{TS} is divided by the height of the cell ΔL :

$$\alpha_{\text{grav}} = \alpha_3 = \frac{V_{\text{TS}}}{\Delta L} \quad (50)$$

For a particle in an interior room cell, the total first-order loss rate is $\alpha_1 + \alpha_2 + \alpha_3$. In one time step Δt , the probability that the particle remains in the interior cell is

$$p_{\text{hold}} = \exp(-[\alpha_1 + \alpha_2 + \alpha_3] \times \Delta t) \quad (51)$$

In one time step Δt , the probability that the molecule leaves the interior cell and moves to the neighboring cell below is

$$p_{\text{below}} = \frac{\alpha_3 + (\alpha_2/6)}{\alpha_1 + \alpha_2 + \alpha_3} \times [1 - p_{\text{hold}}] \quad (52)$$

In one time step Δt , the probability that the molecule leaves the interior cell and moves to the neighboring cell to the right is

$$p_{\text{right}} = \frac{\alpha_1 + (\alpha_2/6)}{\alpha_1 + \alpha_2 + \alpha_3} \times [1 - p_{\text{hold}}] \quad (53)$$

In one time step Δt , the probability that the molecule leaves the interior cell and moves to any of the other neighboring cells is

$$p_{\text{left}} = p_{\text{forward}} = p_{\text{back}} = p_{\text{up}} = \frac{\alpha_2/6}{\alpha_1 + \alpha_2 + \alpha_3} \times [1 - p_{\text{hold}}] \quad (54)$$

Equations (51)–(54) provide the single-step transition probabilities for a particle in the interior cell and sum to one. If a similar set of single-step transition probabilities is assigned for each room air cell, one can form a Markov matrix $\mathbf{P}$ that describes particle movement within the room, where each row and column represents a room air cell. We can also account for the settling of particles onto the floor and other horizontal surfaces, and the removal of particles from room air via the exhaust airflow and deposition onto vertical surfaces, but those details are not covered here. Note that for large particles with α_3 much greater than α_1 and α_2 , the particles will travel downward to the floor relatively

quickly and will not disperse throughout the room. Thus, the Markov chain method for a particulate contaminant overcomes the limitation of the WMR construct that assumes uniform dispersion in the room.

7 IMPLEMENTATION OF MATHEMATICAL MODELS IN MICROSOFT EXCEL

Occupational hygiene practitioners wishing to use the mathematical models face the issue of implementing the equations in suitable software and verifying the computational integrity of that setup. Symbolic mathematical software (e.g. Mathematica, MatLab or MathCad) or general scientific packages including open source versions such as R or SciLab are possibilities. These generally require investment in time to learn the software sufficiently to set up and run the equations, and some require licensing fees. For some of that software, already available scripts to run a given model may be available for download, but these can be difficult to find and edit to specific needs. Numeric calculation packages, i.e. spreadsheets are widely available and used in occupational hygiene in numerous ways. Use of spreadsheets to implement selected equations (25) was described. Currently, a Microsoft Excel suite of the mathematical models improving and expanding on the prior work (25) plus a General Help file are available for download on the AIHA website (36). The spreadsheet runs in all versions of Excel for Windows PCs since Excel 2000 and in Apple computers in recent versions of Excel for Mac. The 11 models implemented in that Visual Basic enhanced spreadsheet called IH Mod are listed below. Most but not all are described in this chapter.

- The Well-Mixed Room Model
 - with a Constant Emission Rate
 - with Backpressure
- The Well-Mixed Room Purging Equation
- The Well-Mixed Room Model with an Exponentially Decreasing Emission Rate
- The Two-zone model: Near Field Far Field Constant Mass Emission Rate
- The Two-zone model: Near Field Far Field Decreasing Mass Emission Rate
- Turbulent Eddy Diffusion
 - without Advection following a Pulse Release
 - without Advection given a Constant Mass Emission Rate
 - with Advection following Pulse Release
 - with Advection and a Constant Contaminant Emission
- Estimating Contaminant Generation Rate from Small Spills (Hummel equation)
- Near and Mid – Field Gaussian Plume Models

A brief narrated and illustrated tutorial on using IH Mod is included in a YouTube video (37). For each model, IH Mod includes a brief help section (accessed via the green question mark (?) icon on the top left of the model pages) which provides the main aspects and constraints of the model, definitions of terms, and selected references. The spreadsheet is currently constructed to work in five languages, English, French, German, Korean, Italian, with more to be added. The user may select the language at the opening screen. Each model has sections for input variables, graphs of results, controls for printing, specification of the maximum time to cover in the calculation, the time course for the contaminant release for the continuous generation rate models, and a time of interest for the user between the start and maximum time specified. The continuous generation rate models include a calculation of the mass emitted to time t (time of interest specified by the user) to check that mass emitted is not greater than the available contaminant mass. The current IH Mod typically divides the user-specified simulation time into 100 increments for calculation and graphing. However, a higher resolution mode of 5000 intervals is available by user choice if needed for a specific problem.

7.1 Stochastic (Monte Carlo Simulation) Approaches

The spreadsheet suite of models IH Mod discussed above can be used with certain commercial or “freeware” Monte Carlo Simulation (MCS) packages to use statistical distributions of parameters and inputs and yield statistical distributions of predicted concentrations. To conduct MCS in IH Mod, the user must “unprotect” the model sheet, which does not require a password. However, such use is somewhat cumbersome and restrictive. Thus, an update IH Mod 2.0 is available (36) and uses the capability of MS Excel and Visual Basic to provide MCS in Excel and requires no other software. Version 2.0 also retains the prior deterministic modeling option. See Figure 9 for an example of the IH Mod 2.0 implementation of the two-zone constant generation rate model with Monte Carlos Simulation options.

8 MODEL VALIDATION

Validation of mathematical models used for exposure assessment can cover several aspects of the models. First, are the mathematical equations for the model correctly derived and described? Are the models’ assumptions and approximations clearly stated? Second, if the model is presented in software, does the software accurately and reliably calculate the underlying equations? Third, are there any checks that entered parameter values are in appropriate value ranges for the model’s assumptions? Fourth, do the results hold

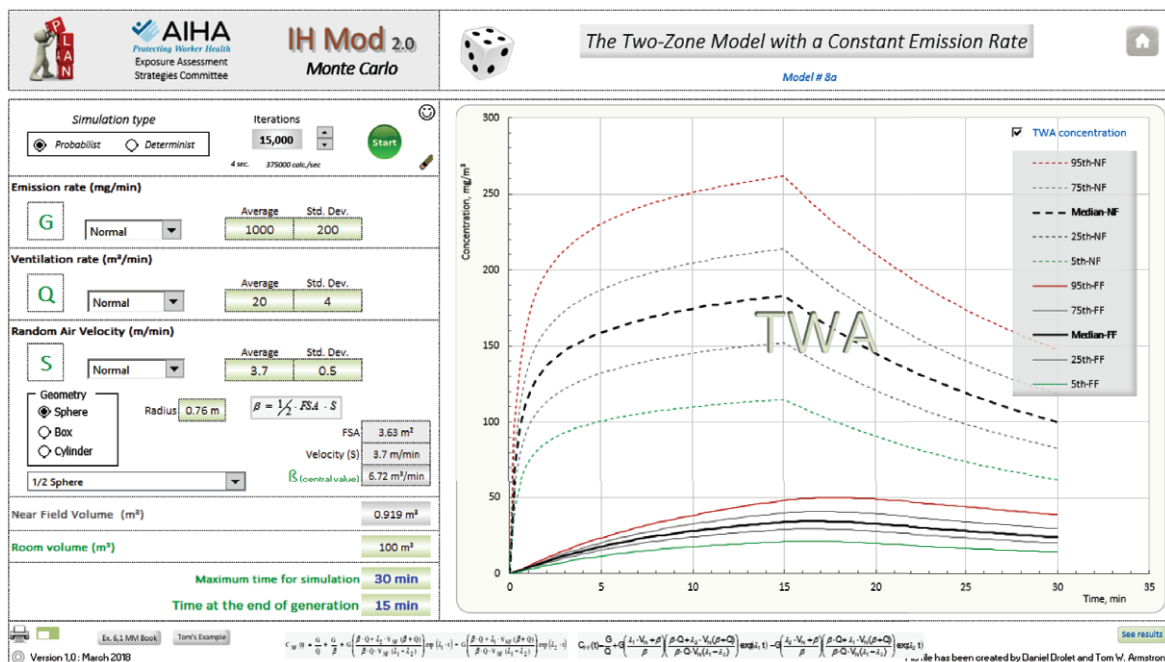


FIGURE 9 Implemented in MS Excel, IH Mod 2.0 (36) provides Monte Carlo Simulation capability for a suite of models of utility for indoor air exposure assessments. This example shows the Near Field and Far Field TWA results on the graph. The user can choose deterministic (fixed parameter values) or stochastic (parameter values as uniform, triangular, normal or log-normal distributions) modes.

up against a reality check, such as against some available measurements? This last point is often difficult to complete because the model is being used to assess exposures sometime in the past or predict results for a possible future scenario, or scenario that is not available for any measurements of parameters of resulting concentrations. Published proposed approaches for model calibration (26, 31, 38) covered variants of the well mix box and two-zone models but are actually more generalizable with little modification to many models. The proposal gives a structured, systematic approach applied to both steady state and varying condition estimates. The calibration procedure involves the estimation of the model parameters for a specific exposure scenario. It utilizes one to several concentration measurements at relevant locations in the modeled space but not proximate to the source, from within the local control exhaust system and in the recirculated air stream. For the model described in Section 4.1 the V (room volume), Q (room ventilation rate), and Q_L (LEV rate) should be known or can be otherwise reliably obtained. The often more difficult to determine model variables – G (mass emission rate) and the collection and filtration efficiencies (ϵ_L , ϵ_{LF} , and ϵ_{RF}) – are estimated using the calibration measurements and the algebraic rearrangements of the steady state equations.

For the two-zone model, the concepts are similar but more details and more parameters are unknown and need to be measured for the calibration (31, 38).

9 ADDITIONAL MODELS AND RESOURCES

The focus of this chapter has been on indoor air concentration models, their development and to some extent their use. The physical–chemical models discussed earlier consider the source, dispersal, and removal of the contaminant in the estimation approaches. There are many more models for indoor air described in the literature and available for use than can be covered in this chapter. More evolve each year, either in the physical–chemical family or with other approaches, including a combination of measured exposure data and structured scenario evaluation to search the database and report back the potential exposures. The US Environmental Protection Agency (US EPA) has developed models to estimate indoor concentrations and/or exposures to contaminants. Additional models have been developed in Europe, Canada, and elsewhere. A few but seemingly key models from these groups are mentioned in the following section, as are some additional resources related to mathematical model use. Note that some of the models discussed in the following section are directed at residential and consumer exposure issues but may be relevant to other scenarios, including primary manufacturing and downstream use situations.

9.1 Primarily European Union Developed Tools

Several of the following models are directed at consumer and general populations exposures, or environmental exposures. Several have notable utility though for occupational assessments since consumer and occupational tasks may have significant similarities after considering the differences in frequency, duration, quantity of agent, and the environmental conditions.

The Consumer Exposure model ConsExpo (39) uses a series of standard scenarios for consumer exposure assessments to a wide variety of products in a wide variety of circumstances. It utilizes models varying in complexity, from simple screening models to more advanced, physical-chemical principle models.

The European Centre for Ecotoxicology and Toxicology of Chemicals (ECETOC) Targeted Risk Assessment (TRA) (40) model is considered a Tier 1 (screening level) model that calculates the risk of exposure from chemicals to workers, consumers, and the environment. It has been identified by the European Commission's Regulation on Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH) as a preferred approach for evaluating consumer and worker health risks.

Stoffenmanager (42, 43) is also considered a Tier 2 model for more detailed than screening evaluation but with control banding decisions its main objective. Stoffenmanager shares some developmental aspects with Advanced REACH Tool (ART; see the following discussion) and may also be affected by internal multiplier errors.

The ART (44, 45) is considered a Tier 2 model for more detailed than screening evaluation in the EU REACH program. ART utilizes a structured subjective evaluation of a scenario and comparison to available data. Its developer used multipliers to modify two-zone model results as part of the ART and Stoffenmanager (see the earlier discussion) procedures. Recent research (41) suggests ART's current multipliers appear to be incorrect and may be producing somewhat erroneous results. Suggestions for correction (41) include more transparency in the model routines and possible inclusion directly of two-zone model calculations.

9.2 Selected US EPA Models

The Multi-Chamber Chemical Exposure Model (MCCEM) (42) provides multiple zone exposure estimates as average and peak indoor air concentrations of chemicals released from products or materials in homes and other residences. The data libraries included cover residential settings, but the model can be used for other indoor environments if the user provides applicable input values for the model parameters such as room volume and ventilation.

MCCEM estimates inhalation exposures to chemicals, as potential single day doses, or chronic doses, but does not account for actual absorption into the body.

The Wall Paint Exposure Model (WPEM) (43) evaluates applicator and bystander exposures during and following paint application.

The Exposure and Fate Assessment Screening Tool (E-FAST) (44) is considered an environmental screening-level tool. E-FAST provides estimates of the concentrations of chemicals released to air, surface water, landfills, and consumer products. Estimates provided are potential inhalation, dermal, and ingestion dose rates resulting from releases of chemicals. Modeled estimates of concentrations and doses are designed to reasonably overestimate exposures, for use in an exposure assessment in the absence of or with reliable monitoring data.

The Chemical Exposure Model (CEM) (45) is a software tool that estimates inhalation, oral, and dermal exposures based on the chemical, consumer product, receptor, and environment of interest. It estimates acute and chronic exposures and provides a variety of exposure metrics.

The Stochastic Human Exposure and Dose Simulation (SHEDS) (46) models are probabilistic models that can estimate exposures people face from chemicals encountered in everyday activities. The models generate predictions of aggregate and cumulative exposures over time to inform risk assessments that protect human health. SHEDS can estimate the range of total chemical exposures in a population from different exposure pathways over different time periods given a set of demographic characteristics. SHEDS can also help identify critical exposure pathways, factors, and uncertainties.

The Indoor Environmental Concentrations in Buildings with Conditioned and Unconditioned Zones model (IECCU) (47) is (i) a general-purpose indoor exposure model in buildings with multiple zones, multiple chemicals, and multiple sources and sinks and (ii) a special-purpose concentration model for simulating the effects of sources in unconditioned zones on the indoor environmental concentrations in conditioned zones.

These US EPA models MCCEM and WPEM have not yet been updated to run in Windows versions after Windows 95 and Windows XP but do run in more recent versions of Windows after installing "Virtual Box" software to emulate Windows 7 XP mode. Instructions (48) are available.

9.3 Additional Resources and Information

The European Exposure Factors Sourcebook (49) includes European exposure factors for exposure analysis and risk assessment. The ExpoFacts Sourcebook has three parts: a database, a reference guide, and a document library. All of these are free to use, and available through the site. Important exposure factors are housing conditions, consumption of

food and beverages, and time use in different microenvironments. The European exposure factor data have traditionally been scattered around national and international institutes, in scientific articles and reports. This data has now been compiled to the extent possible into this ExpoFacts database so that it would be accessible for all of those who need it.

The Consumer Product Information Database provides primarily US consumer product composition information (50) by category of uses, such as automotive, landscaping and yard, home maintenance, hobby and craft, personal care, and more. The website provides composition information with Chemical Abstract Service (CAS) numbers to use in finding additional information with links to the Hazardous Substances Data Bank (HSDB). The Household Products Database (51) of the National Library of Medicine links over 18 000 consumer brands to health effects from Safety Data Sheets (formerly Material Safety Data Sheets), provided by manufacturers and allows scientists and consumers to research products based on chemical ingredients. The database is designed to provide information on (i) the chemical ingredients and their percentage in specific brands, (ii) products that contain specific chemical ingredients, (iii) the manufacturer for a specific brand, (iv) contact information for the manufacturer, (v) the acute and chronic effects of chemical ingredients in a specific brand, and (vi) Other information available about the chemicals in the toxicology-related databases of the National Library of Medicine.

The Exposure and Risk Screening Methods for Consumer Product Ingredients document (52) presents methodologies and specific consumer exposure information that can be used for screening-level risk assessments of environmental and repeated human exposures to High Production Volume chemicals through the manufacturing and use of consumer products, mainly laundry, cleaning, and personal care products. However, the approach can be applied to other consumer products when information on how consumers use the products is available. These methodologies allow hazard information to be put into context by using exposure information to characterize risk. Screening-level risk assessments are useful for prioritizing the need for further work.

The US EPA document, *Methods for Assessing Exposure to Chemicals. Volume 7. Methods for Assessing Consumer Exposure to Chemical Substances* (53) provides relevant guidance outlining the factors to consider in consumer exposure assessments.

The Consolidated Human Activity Database (CHAD) (54) is a compilation of detailed data on human behavior from 22 separate exposure and time-use studies. The database includes more than 54 000 individual study days of detailed human behavior, with each day broken down into individual hours and activity types. The data include demographic information, including age, sex, employment, and education level, which allows researchers to examine

specific groups within the general population and how their unique behavior patterns influence their exposures to chemicals. The data in CHAD can help researchers understand the patterns of human behavior that influence their exposure to chemicals in their environment. Product for use in human exposure and health studies with predictive models.

The ECETOC developed the Human Exposure Assessment Tools Database (heatDB) (55) as a compendium for risk assessors to search and locate human exposure tools and data available that is in the public domain. Available sources of exposure data have been gathered, structured and categorized into a harmonized system. Available tools for exposure assessment were also gathered and categorized. The database allows risk assessors to quickly review what data sources and tools are available for given purposes and to have guidance on their appropriate use using a tiered approach. There are hundreds of identified sources of human exposure data and tools in heatDB. Users can register for free, login and use the database as required. There is a search box for searches on all covered data fields. There is also a message board where users can leave suggestions for improvements to the database or identify new data sources and tools to include in future versions.

The book *Residential Exposure Assessment: a Sourcebook* (56) contains information and resources to assess and manage potential exposures occurring in and around the home, addressing such issues as US legislation relevant to products used in and around the residence, methods for measuring and modeling exposures across multiple pathways and routes, and distributional data available for key residential exposure factors.

The US EPA publication, *Exposure Factors Handbook: 2011 Edition* (57) provided a compilation General US exposure factors such as: drinking water consumption, soil ingestion, inhalation rates, dermal factors including skin area and soil adherence factors, consumption of fruits and vegetables, fish, meats, dairy products, homegrown foods, human milk intake, human activity factors, consumer product use, and building characteristics. Recommended values are for the general population and for various segments of the population who may have characteristics different from the general population.

10 MODEL SELECTION

The emphasis of this chapter has been on indoor air modeling of air concentrations of contaminants. For this use, the models and tools discussed provide foundation in the principles. There are many additional models to estimate air concentrations of contaminants available, as briefly discussed in Section 9. Given the diversity of the models, how does one decide on the appropriate one to use? The answer is one that is simple enough to use but adequate to

provide a relevant answer that can support an appropriate decision. The model needs to answer the question at hand and should be relevant to the exposure scenario and your substance of interest. For example, many models do not work well for particulates. Other models are specific to worker or consumer exposures. Some models are based on established tasks or activities that may not be relevant to the scenario to assess. Often it makes sense to start simple and go more complex if necessary. That is, if a very simple and probably biased high model gives a “no problem” answer the process may end. However, more sophistication may be required, so a “tiered” approach advocated for occupational modeling applies (58). Modelers may also conduct a literature search to find if others have modeled air concentrations for similar scenarios to the one at hand, and if so, which models were considered and used.

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SENSORS

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1 INTRODUCTION

Sensors are devices designed to detect changes in the environment. They are incorporated into direct-reading instruments (DRIs), in which sampling and analysis of the sensor signal are carried out. They typically provide a high temporal resolution output (that may include multiple measurements per second) and are increasingly available for a variety of agents relevant to occupational exposures. The term “sensor” has been informally used as a catch-all that includes instruments spanning a wide range of costs and capabilities. As such, “sensors” can include benchtop devices which provide high accuracy and precision measurements costing over \$100 000, down to single or multi-gas instruments and safety alarms costing \$50 or less. More commonly the term “sensors” refers to DRIs appropriate for initial site surveys and personal exposure monitoring or assessment (typically in the \$500–\$5000 price range). Recently, a multitude of low-cost sensors have entered the market with applications for a variety of physical and chemical hazards (typically less than \$1000). Both low-cost sensors and traditionally used DRIs are generally small, lightweight, and often run on battery power, making them ideal for occupational uses. Although DRIs have been used in occupational exposure assessments for decades, their cost and complexity have presented barriers for their widespread use. Low-cost sensors represent an opportunity for new exposure assessment strategies in occupational health.

Low-cost sensors often rely on indirect sensing techniques, but in many cases, sensors use the same principles of operation as more expensive equipment. Some manufacturers have reduced costs by using less expensive

components, which can result in reduced data accuracy and precision. Users of sensors must have a clear understanding of the principles of operation and biases for each sensor to evaluate if it is fit for the purpose under the desired conditions and to ensure data are interpreted with maximum reliability. An advantage of the increased accessibility presented by low-cost sensors as compared to integrated sampling methods, is that they increase the number of samples for which a practitioner may measure on-site with immediate results. This approach reduces some concern over physical loss of sampling media (though loss of digital data is still possible) and can reduce sampling costs by eliminating consumables and analysis costs. However, most sensors require periodic calibration of varying complexity, sometimes as often as daily. Failure to appreciate the importance of calibration can result in data with unacceptable accuracy, precision, or integrity. Finally, sensors can produce a data stream with many more points than integrated methods. This can be both an advantage and a disadvantage. The high temporal resolution information can allow for unique exposure assessment opportunities (see Section 5), but the large amount of data can result in highly spatially and temporally correlated data, which can complicate data analyses for statistical approaches that assume independence of individual measurements and poses important challenges for data management beyond the typical expertise of industrial hygienists.

When evaluating sensors for use in occupational exposure assessment, there can be many competing instruments to choose from for any specific application. Determining which is best and how data from different devices compare can be difficult. Several performance characteristics should

be evaluated prior to purchasing a sensor. **Sensitivity** is the change in the measured signal per a unit change in the agent intensity. **Resolution** is the smallest change in agent intensity that can be detected by the sensor. **Dynamic range** is the analyte range for which the sensor's response is linear. **Selectivity**, also referred to as specificity, relates to the ability of the sensor to respond to, and only to, the agent of interest. A sensor's **limit of detection** (LOD) is the lowest detectable agent level at which the sensor response is statistically greater than in the absence of the agent. A sensor's **limit of quantification** (LOQ) is the lowest detectible agent level at which a sensor can quantitatively respond with a stated accuracy and precision. **Response time** is the amount of time it takes for a sensor to respond to a change in intensity. Sensors can also be subject to a **dead band**, wherein a sensor is unresponsive to a range of hazard levels resulting in an output equal to zero. These metrics can vary substantially for different sensors. For example, the lower the cost of a sensor, typically the higher the LOD, which can pose a challenge for sampling in relatively low concentration environments (1).

This chapter explores low-cost sensors with some comparisons to traditional sampling and commonly used DRIs, where appropriate. This chapter will focus on three categories of sensors: particulate matter (PM) (Section 2), gases (Section 3), and physical agents (Section 4). The types of sensors, their operating principles, and advantages and disadvantages are described in the sections below and summarized in Table 1. Throughout the chapter, specific instruments are listed as examples, but do not constitute an endorsement of any particular instrument or device.

2 PARTICULATE MATTER (PM) SENSORS

PM hazards in the workplace come from a variety of sources, such as combustion engine exhaust, silica dust, and welding fume (2, 3). Exposure to PM has been associated with cardiovascular events and disease, lung cancer, and a variety of adverse health effects, such as inflammation, oxidative stress, decreased lung function, increased respiratory disease, and infection (4–8). Although there are many PM metrics that may have health relevance (e.g. particle number or surface area), regulatory standards for PM specify the use of gravimetric, filter-based samples to measure PM mass concentrations for compliance measurements (9). Many DRIs directly or indirectly provide measurements of PM mass concentration. Industrial hygienists use DRIs as screening tools and to supplement time-weighted average measurements with higher temporal resolution information (2). In some cases, gravimetric filter samples are taken alongside the direct-reading measurements.

2.1 Direct Measures of PM Mass Concentration

While most PM DRIs rely on light-scattering principles to provide indirect measurements of PM concentration (Section 2.2), one instrument that provides direct mass measurements is the tapered element oscillating microbalance (TEOM). The principle of operation of the TEOM relies on detecting the change in frequency of a filter mounted on an oscillating element as it loads with PM. This instrument's response is

TABLE 1 Summary of low-cost sensor technologies, advantages, and disadvantages by hazard type.

Type of hazard	Types of sensors	Advantages	Disadvantages
Particulate matter	Photometers, OPCs	• High time resolution • Portable • Battery-operated	• Calibrations are aerosol composition specific • Poor size resolution • Subject to drift as components get dirty • Subject to humidity artifacts
Gases	Electrochemical and heated metal oxide	• High time resolution • Broad range of analyte gases • Portable • Small footprint	• Short lifetime • Low selectivity • Influenced by environment (temperature, humidity, etc.) • Cross-sensitivities to interfering gases
Physical hazards	Temperature, humidity, noise, vibration, radiation	• High time resolution • Portable • Battery-operated	

independent of the size, shape, composition or other particle characteristics. Benchtop TEOMs are commonly found in stationary ambient air quality monitoring sites, but the technology has been miniaturized in a package for portable or personal measurements (e.g. Personal Dust Monitor, “PDM” Thermo Scientific, Franklin, MA) (10). With a cost of over \$15 000, this instrument falls somewhere between typical portable DRIs and high-grade, stationary benchtop instruments. The PDM instrument shows very good agreement with established filter-based personal sampling methods for coal dust and has been approved by the National Institute of Occupational Safety and Health (NIOSH) and Mine Safety and Health Administration (MSHA) for continuous and integrated measurement of respirable dust in mines, including for compliance purposes (11). Currently, there are no low-cost sensors with a similar principle of operation.

2.2 Indirect Measures of PM Mass Concentration

Aerosol photometers measure the amount of light scattered by many particles in an air sample volume, and the amount of scattered light is linearly related to the aerosol mass concentration (12). A light source is placed on one side of a sensing volume, through which air will flow, and a detector is placed on an angle from the light source. Some of the light scattered by particles in the sensing volume reaches the detector. The amount of light incident on the detector is linearly related to the mass concentration (Figure 1a). The wavelength of light and angle of the detector are selected to minimize the effect of particle size, shape, and refractive index (12). Particles must be large enough to scatter enough light to contribute to the signal, so only particles larger than approximately $0.2\ \mu\text{m}$ are detected by photometers. Photometers are factory-calibrated to a known aerosol type, often road dust,

that may have characteristics that are different than particles encountered in workplaces. The concentrations reported by the photometer using the factory calibration can be useful to compare concentrations over time or between locations, but may be substantially different than the true mass concentration because the sample PM composition may be different than the calibration PM composition; errors up to a factor of five are not uncommon (13). To produce more precise estimates of mass concentration, it is common to correct the photometer with a gravimetric correction factor. To produce the gravimetric correction factor, the photometer is co-located with a filter over the same duration. The ratio of the filter-based gravimetric mass concentration to the time-weighted average photometric-based mass concentration provides a multiplicative correction factor that can be applied to each photometric measurement. This correction factor assumes that the properties of the aerosol are constant during the duration of the filter sample.

Optical particle counters (OPCs) measure light scattered from each particle individually (Figure 1b) (14). If the composition of the particle is known, the scattered light intensity can be used to size the particle (12, 15). Calibrations are developed by manufacturers to determine sensors’ response to particles of a known size with relevant chemical compositions. Then a sampled particle is assigned to a size bin based on these calibrations (12). Commercially available instruments typically size particles into 5–16 size channels and cover the range from 0.1 to $5.0\ \mu\text{m}$, though some instruments can detect smaller and/or larger particles (12). OPCs are also limited by the maximum number concentration that can be accurately sampled due to the need to have a single particle in the illumination path at a time. When particle number concentrations are very high (actual concentration is highly instrument-specific; typically, greater than $10^4\ \text{cm}^{-3}$), more than one particle will be illuminated at a time which will lead to erroneous measures.

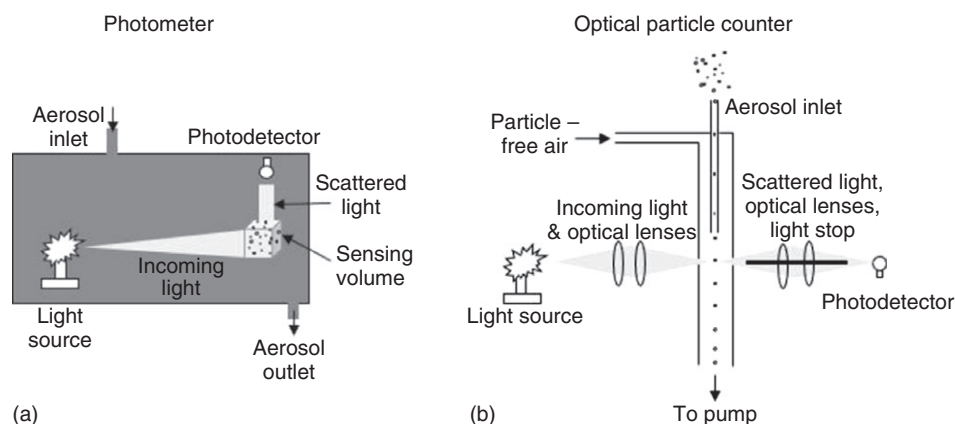


FIGURE 1 Principles of operation for common light-scattering PM sensors. (a) Photometers detect many particles in a volume of air at once. (b) Optical particle counters detect and size single particles at a time. Source: (b) Adapted from Hinds (12).

If the particle density and shape are known or assumed, the measured particle size distribution can be used to estimate the particle mass concentration. Gravimetric correction factors (as described for photometers) may also be useful to calculate mass concentration.

Particles may be hygroscopic, meaning they absorb water vapor from the air which increases their size. Larger particles will scatter more light resulting in increased response by the light-scattering devices (16, 17). However, this deposited water is not particle mass and leads to an overestimation of the true mass concentration. As such, relative humidity (RH) is an important factor affecting these measurements. RH artifact corrections have been reported in the literature for some devices (18, 19).

Industrial hygienists have used instruments which rely on light scattering for at least three decades to provide time-resolved measurements of aerosol mass concentration (e.g. Personal Data Rams, "pDRs" Thermo Scientific, Franklin, MA; DustTrak TSI Inc., Shoreview MN; Portable Aerosol Spectrometers, "PASs" Grimm Technologies Inc., Douglasville, GA). These portable photometers and OPCs currently cost from \$3000 to \$10 000 and from \$7000 to \$15 000, respectively (20).

2.2.1 Devices That Incorporate Light Scattering and Gravimetric Elements

There are a limited number of devices that integrate both direct-reading photometry and gravimetric capabilities. These devices address the challenges related to the refractive indices of aerosols and variations in size distribution by including an in-line filter for gravimetric correction of the direct-reading optical measurements. Two examples are the pDR-1500 (Thermo Scientific, Franklin, MA) and the microPEM (RTI International, Research Triangle Park, NC). Both instruments are portable/wearable and can be used for personal exposure measurements. As with many low-cost sensors, baseline drift is a problem (21) that requires correction (22), but the gravimetric measurement provides a way to correct the data.

2.2.2 Commodity Sensors for Commercial Customers, Researchers, and Hobbyists

Recently, technological advances have resulted in a large number of low-cost "commodity" sensors, some of which are geared towards commercial customers that manufacture their own equipment or instruments, while others were designed for integration into heating, ventilation, and air conditioning (HVAC) and air filtration systems to detect dust. Commodity sensors have also gained popularity with researchers and hobbyists. Inexpensive commodity sensors (\$10–\$500) are produced by many manufacturers including Beijing Plan-tower Co., Ltd. (Beijing, ROC), Alphasense Ltd. (Essex,

UK), and Shinyei Corporation of America (New York, NY). These low-cost commodity sensors may have fans that draw in air or may be passive, relying on room airflow to introduce air into the sensor. Sensors with fan-powered airflow may have virtual impactors that provide coarse size selectivity, whereas, passive sensors cannot provide any specific information on size-fractionated PM.

Commodity sensors must be integrated with microcontrollers into larger hardware assemblies, such as monitors or networks before they can provide aerosol concentration measurements, which can pose a substantial burden for the casual user (23). These PM sensors generally operate on photometric or OPC principles of light scattering, requiring calibration to translate sensor signal to concentration by end users. Many academic groups have undertaken efforts to calibrate these sensors, characterize their performance, and evaluate their suitability for providing aerosol mass concentration measurements (24–26). In these evaluations, different types of commodity sensors generally exhibited a linear response over application-specific concentration ranges, but responded differently to different types of aerosol, different aerosol size distributions, and required individual calibration curves (24–27). Similar to higher-grade instruments, low-cost commodity PM sensors are also subject to the effects of RH (25).

Recently, several manufacturers have developed commercialized low-cost, consumer aerosol monitors (CAMs, <\$500) (28). These monitors are built with the inexpensive commodity sensors described above and may be equipped with features such as a fan to provide airflow, digital display, datalogging capabilities, internet connectivity, and computer and smartphone interfaces. Examples of sensor manufacturers include the Dylos Corporation (Riverside, CA), Airvis ("Speck" Pittsburgh, PA), PurpleAir (Wilmington, DE), and Airboxlab ("foobot" San Francisco, CA); however, new firms and products are continually entering the market. Laboratory and field evaluations of CAMs have shown generally strong correlations with reference instruments. However, variable degrees of bias among CAMs have been observed for different types of PM sources (28–30). Furthermore, poor performance for concentrations above $200 \mu\text{g m}^{-3}$ has been reported and these concentrations are often exceeded in the workplace (28, 30). CAMs are initially factory calibrated, but details on these calibrations are often not provided to the users. Instead, for best performance, end-users of these devices should make the necessary gravimetric corrections to yield accurate PM measurements. Current CAMs do not meet the accuracy and reliability requirements for compliance-based industrial hygiene applications and are typically capable only of total particle number concentration or environmentally relevant particulate metrics including mass concentrations of PM with diameter less than 2.5 or $10 \mu\text{m}$ ($\text{PM}_{2.5}$ and PM_{10}). One drawback of some CAMs for industrial hygiene applications is that many have been

designed for monitoring indoor air; they are not portable nor wearable and may require Wi-Fi networking for data collection, limiting their use for personal occupational exposure assessment.

2.3 Novel Aerosol Metrics Unrelated to Regulatory Standards

Novel sensors are entering the market that capture potentially health-relevant information through metrics other than aerosol mass concentration. For example, ultrafine particles (UFPs) are particles with diameter less than $0.1\ \mu\text{m}$ which contribute little to the total mass concentration despite the fact that they typically dominate the particle number concentration (12). A major source of UFPs is combustion, including diesel-powered vehicles (31), but they have been measured at a variety of work environments (32). In addition, UFPs that have been engineered to have useful properties, sometimes called engineered nanoparticles, have seen wide application in industry, medicine, and consumer goods over the last decade. UFPs are small enough to pass through the respiratory system, cross the blood–brain barrier, and disperse in body tissues and organs (33). The independent health effects of UFPs are not well established, but an expert panel that reviewed current evidence concluded that UFPs likely cause increased all-cause mortality, hospital admissions for cardiovascular and respiratory diseases, aggravation of asthma symptoms, and decreases in lung function (34–36).

UFPs pose a challenge to measure because they have diameters smaller than the wavelengths of light used in optical-light scattering devices, so they are not detected by photometers or OPCs. Wearable diffusion classifiers (e.g. DiscMini, Matter Aerosol, Switzerland; Partector, Naneos, Switzerland; and Nano Tracer, Phillips Aerasense, Netherlands) charge particles and draw them into an electrometer that converts the signal to particle surface area, number concentration, and mean diameter (37, 38). Diffusion classifiers have been used to characterize personal exposure to UFPs in urban microenvironments (39) and among highway maintenance workers (40). Miniaturized condensation particle counters (MiniCPCs) increase the size of UFPs by condensing water vapor onto them so that they can be measured optically by light-scattering instruments. MiniCPCs are small enough to be worn and have been used to assess UFP exposure in children (41) and respirator efficacy (42). Wearable electrothermal piezoresistive cantilever resonators have been piloted in workplaces to provide direct-reading nanoparticle measurements (43), and miniaturized silicon resonant microcantilever mass balances and miniaturized electrostatic precipitators have been incorporated into a pocket-sized instrument (44). Nanoparticle sensor development is still in the early stages and the electronics are more expensive than photometers (nanoparticle sensors

generally cost \$8000 or more). However, demand from the environmental and industrial hygiene fields is driving research and development (2).

Black carbon particles are emitted during combustion and may have a stronger deleterious effect on health compared to PM generally (45). Aethalometers measure black carbon concentration through light-absorbing characteristics, in contrast to light scattering characteristics. Particles from an air stream are collected on a spot of filter tape within the aethalometer. The instrument's light source is directed onto the spot where carbonaceous particles absorb and attenuate the amount of light that passes through the filter to the detector. The increased light attenuation between two sequential measurements is proportional to the increase in the mass of light-absorbing material collected on the filter (which can be converted to the concentration in air). The filter tape advances to a “clean” spot when the density of light-absorbing material reaches a pre-determined limit. Pocket-sized Aethalometers (e.g. MicroAeth, AethLabs, San Francisco, CA) that measure black carbon agree well with full-size benchtop aethalometers (46) and have been used in personal exposure assessment in transport microenvironments (47).

3 GAS SENSORS

Many gases in industrial settings can adversely affect worker health. The species, duration, and concentration of an exposure will determine the severity of the health effects, which can range from an irritating cough to premature death. For example, acute exposures to hazardous welding gases can result in irritation of the nasal passages, throat, and lungs, but chronic exposures can result in cancer, emphysema, or damage to the kidneys (48). More than 700 chemical substances for which the American Conference of Governmental Industrial Hygienists (ACGIH) has established industry-wide exposure limits are gases. Thus, it is not surprising that no single instrument or even class of sensors is able to quantify concentrations of all hazardous gases. For many industrial hygienists, a common practice is the use of single or multi-gas instruments, which may be comprised of several types of sensors such as electrochemical (EC) and metal–oxide–semiconductor (MOX) sensors. Each of these types of sensors has specific advantages, lifetimes, limits of detection, and calibration requirements, so it is important to be knowledgeable about the type of sensor that is being utilized (Figure 2).

3.1 Electrochemical Sensors

EC sensors were first used in the 1960s, when semiconductor sensors were shown to detect low concentrations of reducing

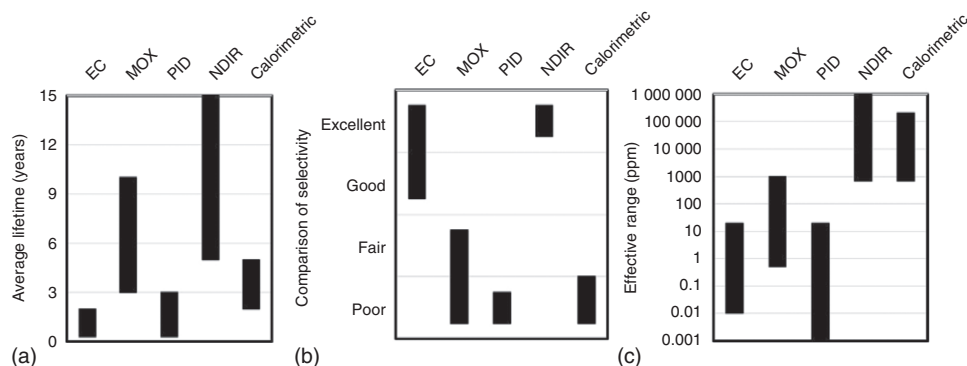


FIGURE 2 Comparison of the (a) average lifetime, (b) selectivity, and (c) appropriate measurement ranges of the electrochemical (EC), metal-oxide-semiconductor (MOX), photoionization detector (PID), nondispersive infrared (NDIR, an optical gas sensor), and calorimetric gas sensors. Source: Korotcenkov et al. (49), Spinelle et al. (50), and Szulczyński and Gębicki (51).

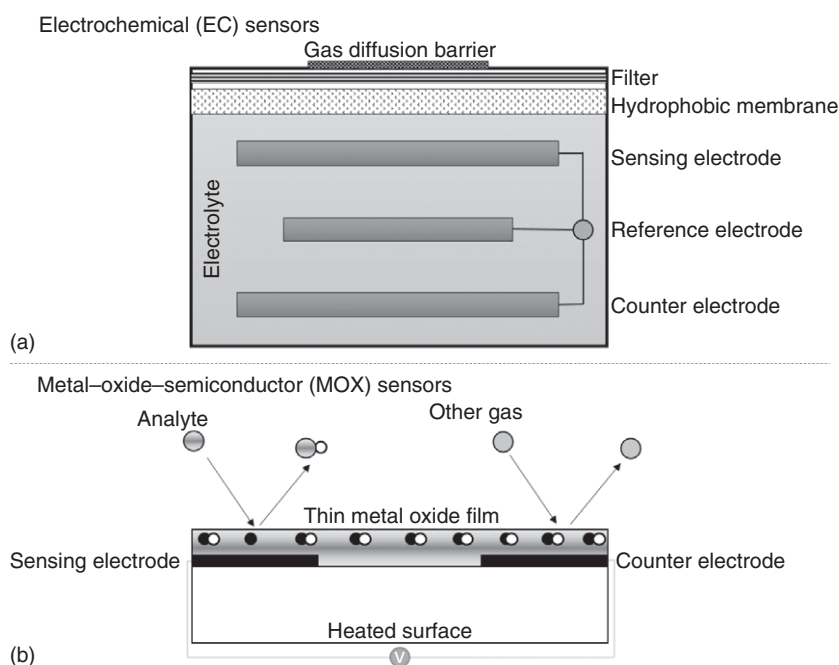


FIGURE 3 Schematic of (a) electrochemical (EC) and (b) metal-oxide-semiconductor (MOX) sensors.

and combustible gases when exposed to a simple electrical circuit (52, 53). Since then, EC sensor technology has been developed for both oxidizing and reducing gases. The detection mechanism requires oxidation or reduction of the analyte resulting in the generation of an electric current (54). EC sensors typically contain a gas-permeable hydrophobic barrier, an electrolyte, a sensing electrode (or working electrode), a counter electrode (or auxiliary electrode), and sometimes a third reference electrode (55) (Figure 3a). After entering the sensor through the gas-permeable hydrophobic barrier, the sample air contacts the sensing electrode, which

is bathed in the electrolyte and it is either oxidized or reduced, depending on the analyte (Figure 3a). When the analyte is oxidized (e.g. CO), the counter electrode functions as a cathode and the sensing electrode operates as an anode for the purpose of completing the circuit to allow the charge to flow. Conversely, when the analyte is reduced by the chemical reaction of the sensor (e.g. O_3), the sensing electrode functions as the cathode, and the counter electrode functions as the anode. The electrodes work as catalysts in these reactions, and the electrolyte provides the electron that is consumed.

Example Oxidation: $\text{CO} + \text{H}_2\text{O} \rightarrow \text{CO}_2 + 2\text{H}^+ + 2\text{e}^-$

Example Reduction: $\text{O}_3 + 2\text{H}^+ + 2\text{e}^- \rightarrow \text{O}_2 + \text{H}_2\text{O}$

The reference electrode is an electrode that is not exposed to the resultant current from the reaction. Since the sensing electrode will degrade over time, a reference electrode is introduced to assess the sensor's performance. There are some EC sensors that have more electrodes, but the working principle is consistent with a three-electrode system.

Most EC sensors are designed so that the gas concentration in the sensing compartment is limited by diffusion, which results in an output that is linearly proportional to the ambient gas concentration (54). This is one strength of EC sensors because a linear response allows for more precise measurement at low concentrations and fewer calibration points needed. The hydrophobic barrier also prevents the electrolyte from leaking out of the sensor (56). The sensor's signal will deteriorate if the electrolyte evaporates too quickly. In some sensors, a filter is installed in front of the barrier to increase sensitivity and selectivity by filtering out unwanted gases or particulates. The material of the electrodes and electrolyte are key factors since sensitivity and selectivity are strongly influenced by the type and the structure of the electrode material and the electrolyte must facilitate the desired reaction efficiently (57–59). The electrodes are typically fabricated by fixing metal with large surface area on a porous hydrophobic membrane (55).

EC sensors can be divided into three quantification methods: amperometry, voltammetry, and coulometry (60, 61). In amperometric EC sensors, a resistor is connected across the electrodes. A fixed potential is applied to the sensing electrode, and when a current from the oxidation or reduction reaction occurs, the resultant current is measured, which is proportional to the gas concentration (60). Potentiometric EC sensors (i.e. voltammetry) measure the potential difference (in volts) between the sensing electrode and the reference electrode (62). The sensing electrode's potential is governed by the concentration of the analyte in the gas phase, and the reference electrode provides a stable reference potential. Conductometric EC sensors (i.e. coulometry) measure the conductivity change in the presence of a given solute concentration (60, 63). Amperometric and Potentiometric EC sensors are the most common for gas detection and generally have similar response times, dynamic ranges, and sensitivities (62).

EC sensors can facilitate sensitive and selective analyses of numerous gas-phase species at a high time resolution (typically on the order of seconds) and at a low cost (<\$100 each). In addition, EC sensors have low power requirements to operate. In fact, the power requirement is the lowest among all sensor types currently available for gas monitoring (64). Their small size (e.g. Alphasense Ltd. EC sensors are

round with diameter of either 20 or 32 mm) also permits measurements in a broad range of locations.

However, there are also two notable limitations of EC sensors. First, their life expectancy is highly dependent on the desired analyte and environmental conditions (54, 55, 61, 65, 66). When operated and stored in recommended conditions, EC sensors generally have a lifetime of 1–3 years, but actual lifetimes can be on the order of months when concentrations are high or extremes in temperature or RH are encountered. It can be difficult to predict when a sensor will begin to lose sensitivity, so frequent calibration of EC sensors may be needed to ensure accurate data are produced. EC sensors frequently degrade at a faster rate when exposed to heavily polluted conditions. For example, the lifetime of ammonia EC sensors is directly related to its exposure to ammonia because the electrolyte is consumed as the reaction occurs, so doubling the concentration will halve the life expectancy (67). Temperature and RH extremes can also notably affect sensor lifetimes. The ideal storing and operating conditions for EC sensors is 20 °C and 60% RH. Exposures to high temperatures can enhance the evaporation of the electrolyte, thus reducing sensitivity and lifetimes. Repeated exposures to temperatures outside of the suggested operating temperatures have been observed to shift the baseline (i.e. the response measured when no gas is present or present below the LOD), which can introduce additional complications during data analyses (66). In addition, exposures to very low temperatures can reduce sensitivity by as much as 80% and decrease response times (66). Even if EC sensors are operated within the suggested temperature range, the predicted value for a constant concentration may vary as a function of temperature. For this purpose, it is useful to expose the sensors to a known concentration over a broad range of temperatures and humidities to evaluate the influence of these parameters on the predicted concentrations prior to their use. These influences can often be corrected for during post-processing if the EC sensors were co-located with temperature sensors during the measurement period. The most important factor governing sensor lifetime is RH (66). When the RH increases beyond 60% RH, water can be absorbed into the electrolyte causing dilution or leaking, and when the ambient air is below 60% RH, the electrolyte solution will begin to evaporate, concentrating the electrolyte. Dilution and concentration of the electrolyte solution can be reversible if the sensor is exposed to RH levels of the opposite extreme (66). EC sensors are minimally affected by pressure changes (65).

The second important limitation of EC sensors is cross-sensitivity to interfering gases, or non-targeted gases, that will also be detected by the sensor resulting in inaccurate estimates of the desired analyte. It is vital to understand the effects of potential interferants on each type of EC sensor in operation. In some reactions, the interfering effect is positive, resulting in values that are higher than

the actual concentrations; whereas in other sensors, the interference is negative, resulting in values that are lower than the actual concentrations. The addition of a chemical filter or compensator may be able to increase specificity of the sensor. For example, CO and H₂S EC sensors use similar measurement designs, but in order to reduce the interferant effect, most CO EC sensors include an internal activated carbon filter to remove the H₂S before it reaches the sensing electrode (67).

3.2 Metal–Oxide–Semiconductor Sensors

MOX sensors were also developed in the 1960s when it was found that certain chemicals react rapidly with the surface of thin semiconductor films (e.g. a transition or heavy metal oxide film) at high temperatures (68). When a semiconductor film is heated to a high temperature (typically between 150 and 400 °C), oxygen adsorbs onto the film by capturing electrons in the semiconductor film (69). This reaction will either increase the resistance, referred to as n-type MOX sensors, or decrease the resistance of the sensor, p-type, depending on the sensor design. When the target analyte is present, it will react with the oxygen or metal oxide film, allowing a current to flow freely through the sensor and producing a measurable change in the conductivity (or resistivity) of the metal oxide. The change in conductivity (or resistivity) is logarithmically proportional to the analyte gas concentration. The magnitude of the change is also dependent on the resistance of the film and whether the analyte is an oxidizing or reducing gas.

MOX sensors are typically composed of sensing and counter electrodes connected by a thin metal oxide film over a heating element (Figure 3b). The metal oxide film is mounted on sintered ceramic inside a flame arrestor, a device that permits gas to flow through while blocking a flame. While this method was first demonstrated with zinc oxide (ZnO), many other metal oxides have been found to be suitable for detecting combustible, reducing, or oxidizing gases (70–72). Tungsten trioxide (WO₃) and tin dioxide (SnO₂) are the most widely used metal oxides for gas sensing applications (73). Since the metal oxides films have a large surface area, the sensitivity can be as low as parts per billion (ppb) (71). The sensitivity may be altered by changing the temperature of the heating element. Heating the metal oxide film above 100 °C reduces effects of ambient conditions and improves selectivity. Doping the primary metal oxide with a secondary metal oxide, called binary oxides, can also enhance the selectivity and sensitivity of a sensor (70). For example, SnO₂ doped with 0.5% strontium oxide (SrO) increased the sensor's ability to measure nitrous oxide (N₂O) by a factor of four (70). MOX sensors may also be referred to as heated metal oxide sensors (HMOSs) or chemiresistors.

MOX sensors also have a high time resolution (typically on the order of seconds to minutes), a low price point

(\$10–\$500 per sensor), and a small footprint. Although both EC and MOX sensors are constrained by cross-sensitivities, the interferant may be different for each type of sensor. For example, a MOX ozone sensor exhibits a cross-sensitivity to volatile organic compounds (VOCs); whereas, EC ozone sensors can be highly sensitive to NO₂. These distinctions allow users to pick which sensor is best suited for their measurement environment. MOX sensors typically have longer operational lifetimes of about three to five years, and when stored in proper conditions, the time spent in storage will not reduce the operational lifetime of the sensor. There are also several limitations of this sensing method. MOX sensors are sensitive to a broad range of gases, but selectivity can be a major concern (63, 71). The presence of other gases reacting with the metal oxide may increase or decrease charge carrier concentration, making sensor readings inaccurate. For example, VOCs have been shown to strongly react with SnO₂. VOCs are ubiquitous in the ambient air since there are numerous anthropogenic and natural sources, and they exhibit a broad range of properties, which make them difficult to completely filter. This is a major limitation since nearly all environments have some type of VOC source, thus the impact of this interferant, as well as others, should be considered when using MOX sensors. MOX sensors are also particularly affected by RH since water interacts with metal oxides and alters the conductivity of the film (49). For example, SnO₂ exhibits decreased response time and larger responses in the presence of high RH (49). MOX sensors may also exhibit **hysteresis** in humid environments (74, 75). Signal hysteresis is a difference between two measurements obtained at the same concentration because the sensor was in different conditions prior to the measurements. For example, a sensor may yield a different value for 50 ppb if the prior concentration was 25 ppb when compared to measurements with a prior concentration of 75 ppb (i.e. depending on if the concentration was increasing or decreasing).

MOX sensors also need relatively frequent calibrations. Two major factors influence the longevity of a MOX sensor's calibration. First, the heat output may increase after protracted use, which results in baseline drift over time, and second, the sensor may become "poisoned" by interferant gases irreversibly bonding to the metal oxide film (74, 75). Some research suggests that a calibration is valid for about two to three months (75). MOX sensors may also exhibit a non-linear response requiring more calibration points (71).

3.3 Other Gas Sensing Technologies

In addition to EC and MOX sensors, there are several other gas sensing methodologies. A common instrument is

a photoionization detector (PID), often used for measuring VOCs. PID sensors use ultraviolet (UV) light to ionize gas molecules, decomposing neutral molecules into positive and negative ions. These ions are passed through two polarized electrodes and as the ions move towards the electrodes, an electric current is produced which is converted to a voltage by the sensor (76). This voltage is proportional to concentration. The lamp in a PID will typically function for between 5000 and 10 000 operational hours (approximately 208–417 days), but the output will decline as the lamp ages. Routine re-calibration is needed to compensate for this effect (76). PID sensors have high temporal resolution and a wide range of prices depending on electronics and detection limits (\$500–10 000), but they can exhibit signal drift and are not selective (50). PID sensors are not selective because they ionize any molecule with an ionization energy less than or equal to the lamp output, typically about 10 eV. However, the biggest drawback may be the high detection limits (in the parts per million range) (76, 77). High concentrations of methane, temperature fluctuations, strong electrical fields, and high RH can also affect the accuracy of the sensor.

Calorimetric gas sensors detect the presence and concentration of combustible gases (e.g. ammonia) by measuring heat produced from a gas on the sensor surface. Response time of calorimetric gas sensors is in the range of milliseconds and the output is linear, but the major drawback is low selectivity. The most widely utilized sensors using the method is known as the pellistor (78–80).

Optical gas sensors determine analyte gas concentration by leveraging the characteristic optical absorption in the UV, visible, near-infrared, or mid-infrared regions of the electromagnetic spectrum of a given gas species. A nondispersive infrared (NDIR) sensor is one of the more commonly used optical sensors and is frequently used to measure CO₂. These sensors are compact, low-cost, exhibit long operational and storage lifetime, and have less frequent recalibration needs. However, optical sensors are not able to discriminate between gas species if their absorption lines overlap, and they are sensitive to temperature and pressure changes (81).

4 PHYSICAL AGENTS

In addition to PM and gases, there are many other environmental factors that support a safe environment in industrial settings that may need to be monitored, such as ionizing and nonionizing electromagnetic radiation, noise, vibration, air flow, and temperature (2, 82). Similar to the evolution of sensors designed for chemical exposures, the trend for these types of sensors is toward producing small wearable sensors that can generate real-time quantitative data.

4.1 Sound Levels and Noise Exposure

Occupational noise exposure leads to hearing impairment, hypertension, annoyance, and may be associated with biochemical effects, immune effects, and changes in absentee rate and performance (83). Noise monitoring has been conducted for decades, and it is the most common type of physical agent monitoring. Noise dosimeters can function as area or personal noise monitors (84, 85). Typically, personal noise measurement is conducted with noise dosimeters worn by workers, and advancements have led to dosimeters that can be fitted inside earplugs or earmuffs to obtain an “in-ear” noise exposure (84). Modern dosimeters are designed to provide the user with parameters such as instantaneous sound pressure level (the local pressure deviation from atmospheric pressure caused by a sound wave), maximum, minimum, and time-weighted average, such as an eight-hour average. A noise dosimeter is comprised of a transducer (the microphone), an electronic amplifier, and a calibrated attenuator for gain control (86). A transducer measures sound pressure and transforms it into an electric signal that is converted into the sound level. There are several type of microphones available (i.e. condenser, piezoelectric, electret, or dynamic) so it is important to ensure that the instrument selected will be accurate in the expected conditions (86). Briefly, piezoelectric microphones, often used in sound survey meters, are stable, robust, and not substantially influenced by ambient conditions. Condenser microphones, often used in precision sound level meters, are more accurate than the other types, but they are more prone to being affected by dirt and RH. The electret is a condenser microphone that has been modified to be less sensitive to dirt and humidity. Some lower-cost noise sensors have been described using this type of microphone (87). The dynamic microphone is more mechanically resistant than the other three, but its poor frequency response severely limits its use. Novel smartphone technology also allows workers to collect personal noise measurements. The “NIOSH Sound Level Meter” mobile application is a tool that measures sound levels in the workplace using the built-in cell phone microphone and reports the instantaneous sound level (88). Users should be aware that the accuracy may depend on the quality of the built-in microphone. Alternatively, the application also allows users to collect measurements with an external microphone connected through the headset jack and to calibrate it with a known source. Microphones need to be individually calibrated before and after each measurement by applying a known sound pressure level at a fixed frequency (such as 1 KHz at 114 dB) to the microphone. The dosimeter and calibrator should also be factory calibrated every two years. Noise dosimetry measurements are sensitive to changes in atmospheric pressure (85). Additional information about noise and hearing conservation can be found in **Noise and Hearing Conservation**.

4.2 Temperature

Excessive exposure to heat can cause a range of health effects, from heat rash to heat exhaustion and heat stroke (89). Temperature sensors can be used to determine whether a working environment maintains a satisfactory temperature. This can be achieved by installing a series of thermocouple sensors to identify thermal gradients within a room. A thermocouple is a sensor made of two electrical conductors (called thermoelements or legs) joined at one end, called the junction or measuring end. The measuring end is installed in the area to be characterized, while the control end is held at ambient temperature. A thermocouple generates a voltage as a result of the thermoelectric effect, which is used to determine the temperature. Another option is to employ temperature-sensitive paints (TSPs) (90–93). TSPs are paints that contain nanothermometers with thermally sensitive molecules that fluoresce as a function of temperature. TSPs permit comprehensive assessments of temperature in a given environment and can be used to identify temperatures as low as 25 °C up to greater than 500 °C. Recent advancements have produced paints that are sensitive to both pressure and temperature changes at resolutions of 22 mbar and 4.3 °C, respectively (94). Temperature sensors have also been used to monitor tool condition. For example, metal cutting generates a substantial amount of heat in room, which may increase as the tool ages. An online method for thermocoupled tool temperature measurements has been available since the late 1980s, but research indicates the most effective sensing option is with non-contact measurement techniques, such as infrared thermal imaging (95–97). It is also possible to monitor worker core body temperatures in real-time over several days using new ingestible capsules (98). This sensor consists of a receiver and an ingestible capsule whose resistance is dependent on temperature. Additional information about the effects of temperature on heat stress can be found in **Heat Stress**.

4.3 Vibration

Workplace vibration is generally categorized into local vibration and whole-body vibration (WBV) (99). Local vibration, experienced by machine operators in their hand/arms, for example, can lead to injuries or chronic disorders, such as hand-arm vibration syndrome (100). Vibration sensors can be used to monitor the condition of industrial tools (96, 101). Tool vibration can be indicative of its condition. For example, an aged drill will vibrate more and increase exposures for tool users. This vibration can be sensed using a miniature highly sensitive 3-D accelerometer (101, 102). An accelerometer acts as a damped mass on a spring. When the mass is moved due to vibration, the displacement is converted into an electrical signal that is measured to determine the acceleration.

Additional information about the effects of vibration can be found in **Hand-Arm Vibration**.

In contrast, WBV is often experienced by workers that operate trucks, trains, tractors, and heavy machinery, and is associated with degraded comfort, interference with work activities, motion sickness, and cardiovascular, respiratory, endocrine, central nervous system, and musculoskeletal (particularly low-back pain and injuries) health effects (99, 103). The important characteristics of WBV include vibration frequency, magnitude (displacement, velocity, or acceleration), direction, and duration (99, 104, 105), which have recently been measured using consumer-grade sensors (105) and sensor networks (104) with the aim of quantifying and controlling worker exposure.

4.4 Radiation

Non-ionizing radiation refers to any type of electromagnetic radiation that only has enough energy to excite a molecule; whereas ionizing radiation (i.e. alpha, beta, gamma, or X-ray radiation) has a higher energy and can modify a molecule (106, 107). Exposure to non-ionizing radiation can lead to non-mutagenic biological effects, such as burns, but exposure to ionizing radiation can cause much more serious effects, such as radiation sickness, cancer, and genetic damage. There are three main categories of radiation detectors: gas-filled detectors, which are the most commonly used, scintillators, and solid-state detectors (108). The basic operation of a gas-filled detector is the collection of charges created by direct ionization of a sample. Gas-filled detectors are filled with a gas that characteristically does not interact with electrons, typically a noble gas such as argon or helium, so any produced charges are due to the presence of radiation in the sample (108). Gas-filled detectors are divided into three subcategories based on the method of applied voltage: ionization chambers, proportional counters, and Geiger–Mueller (G–M) tubes. G–M tubes, often simply referred to as “Geiger Counters”, are one of the oldest versions of radiation detectors and are still commonly used because of their handheld size, low cost, and ease of use. One drawback of this method is that the detector cannot differentiate between radiation types. Scintillation detectors use photomultiplier tubes and photodiodes to measure the characteristic flash of light that a photon of radiation produces when it interacts with the scintillator material (108). Scintillation detectors are highly sensitive and can differentiate between radioactive materials. The operational principal of a solid-state semiconductor is similar to a simple gas-filled detector but at a much smaller scale. A solid-state semiconductor detector uses a semiconductor, such a silicon or germanium crystal, to measure the effect of incident charged particles or photons (109, 110). The absorption of ionizing radiation generates electrons and electron-deficient

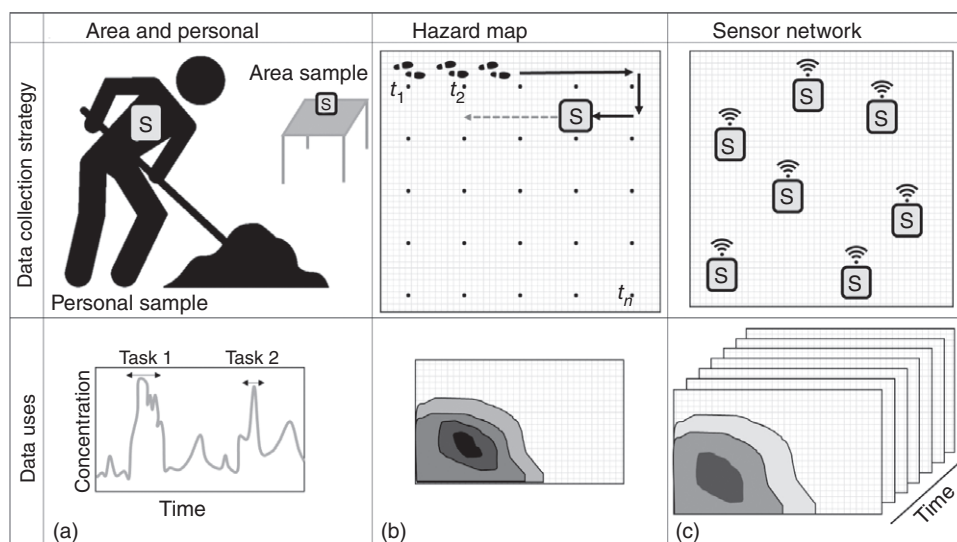


FIGURE 4 Use strategies for sensors (denoted by the boxed “S”). Top panels depict the data collection strategy and bottom panels depict possible data uses. (a) Area and personal samples could be collected at high-temporal resolution. Sensors provide a time series of data during tasks or work-shifts. (b) Hazard mapping can be conducted as a sensor is carried around a facility following a pre-defined grid by sampling one grid for each time interval. Sensor data can be linked with known locations to produce a hazard map with dark shading indicating higher concentrations. (c) Sensors can be distributed in a sensor network, possibly using wireless data connectivity (denoted by the Wi-Fi symbol above the sensor box). Sensor data can be linked with known locations to produce hazard maps at all times.

sites, called holes, in the semiconducting material. The movement of these electrons creates a pulse of current that is amplified and analyzed. Solid-state semiconductor detectors are highly sensitive devices that exhibit a response to single photons and have been used to accurately measure occupational radiation dose rates in real-time (109). Additional information about ionizing radiation measurements can be found in **Ionizing Radiation**.

5 APPROACHES FOR SENSOR USE

Traditional industrial hygiene sampling has focused on compliance monitoring (111, 112), that is, to evaluate if a workplace is in compliance with regulatory occupational exposure limits (OELs). Most regulatory OELs are specified for time-weighted averages and, as such, most compliance monitoring relies on time-integrated sampling that may fail to capture short-duration, high-level exposures. Sensors provide an opportunity to go beyond compliance monitoring to better quantify variability in worker exposures, which may have important implications for health risk. The time and cost of conducting compliance monitoring have meant that the available dataset is often limited by practicality, resulting in few measures collected and that professional judgment is heavily relied on to determine when, where, and on whom samples should be collected and whether workers are adequately protected from agents (113). Sensors may provide a cost-effective means to dramatically increase the

amount of quantitative data available to industrial hygienists and design sampling campaigns that best use available resources for compliance monitoring.

A summary of possible approaches is shown graphically in Figure 4. The top row shows data collection strategies and the bottom row shows how that data could be used by an industrial hygienist. Sensors can be used to: (i) provide high-temporal resolution area and personal sampling, (ii) collect data needed to produce hazard maps, and (iii) distribute sensor networks that can generate hazard maps at high-temporal resolution. For area and personal sampling, a time-series of measurements could be examined to identify high agent intensity tasks. For hazard map and sensors networks, the sensor data can be paired with known measurement locations to produce contour plots of measured agents to identify areas of concern. Sensor networks can also provide the industrial hygienist with information about how the agents vary over time and space, which may help identify processes leading to high intensities and higher risks for workers. These approaches are described in more detail in the following sections.

5.1 Short Duration Sampling and Video Exposure Monitoring

As described above, traditional sampling approaches often rely on cumulative measures, which may pose a challenge to meet method limits of detection for sampling durations

substantially shorter than an eight-hour shift. As such, it may not be feasible to evaluate the exposures during a single, short-duration task. Sensors may be better suited to evaluate short-duration exposures (Figure 4a). Such information may be useful for determining when to conduct compliance monitoring, evaluating whether some workers generate higher intensities while doing similar tasks, and rapidly evaluating the efficacy of an intervention to reduce exposure.

Some researchers have also paired sensor data with a video of the worker to help visualize tasks that create high intensities using a method called video exposure monitoring (114). Software has been developed that links the video and sensor data by the time stamp to allow both the industrial hygienist and the worker to view the tasks that resulted in higher exposures, including one developed by NIOSH (115). This can be an important training tool for workers to see how changes to their work practices or techniques can result in reductions in exposures.

5.2 Personal Exposure Assessment

DRIs have been used for personal monitoring for more than a decade (116). Low-cost sensors are gaining attention for personal monitoring for both occupational and environmental applications (Figure 4a). Using low-cost sensors for personal exposure assessment requires that sensors' packages include battery power and data storage capabilities. These devices have been designed for personal sampling purposes for PM (117, 118), gas (119, 120), and physical agents (121). Most sensors are not considered reliable enough for compliance monitoring but can be useful for evaluating exposure variability, prioritizing workers for compliance monitoring, to evaluate how activities and behaviors impact exposure, and identifying locations of high exposure.

5.3 Hazard Maps

Hazard maps, or depictions of hazard or agent intensity on a floor plan, provide a visual, easy to understand way to show risk (122–124). Hazard maps facilitate rapid dissemination of hazard information between employees, management, and regulators. The data needed to generate a hazard map can be produced efficiently using sensors. Typically, a sensor is moved on a pre-defined grid around a facility to collect high spatial-resolution data on agent intensity (124, 125) (Figure 4b). A spatial interpolation method is then used to predict intensities at unsampled locations so that a surface can be produced. Hazard maps can be used to identify "hot spots" of potential exposure and are useful for determining where interventions can be targeted to reduce exposures. However, hazard maps can be biased because it takes a period of time to map the facility, so the map does not truly represent a single time (122). In the presence of variable exposures,

hazard maps can conflate spatial and temporal variability and care should be taken when interpreting the data (126).

5.4 Low-Cost Sensor Networks

As sensor technology continues to decrease in price, it is increasingly feasible to distribute sensors in a network (Figure 4c) to produce hazard maps with both high temporal and spatial resolution (127), without the need for staff to be physically present at each location to collect the data. Such networks could be useful for identification of the determinants of exposure (e.g. tasks, processes, and control measures), understand air quality to avoid fouling of products and machines, and assessment of systemic hazards, such as dust explosions. Such a network could also function as a surveillance system to notify workers and health and safety professionals when user-defined exposure thresholds are exceeded (128) or to trigger additional sampling (including other agents or detailed chemical speciation) when these levels are reached. Networks could also be used as part of the decision-making process to determine if the use of personal protective equipment (PPE) is advisable (129). Ultimately, pairing sensor network estimates of agent intensity with worker location information (possibly done with indoor positioning sensors) could be used to estimate worker exposures for all workers on all days (130). This would represent a huge increase in quantitative personal exposure data, reduce the need for workers to carry sampling equipment, and further maximize resources for compliance monitoring.

6 CONCLUSIONS AND OPPORTUNITIES FOR FUTURE DEVELOPMENTS

Despite great improvements in sensor technology, many analytes will still require filter-, adsorption-, or absorption-based sampling and laboratory analysis. Comparatively few analytes can be measured with sensors compared to the wide range of hazardous agents encountered in modern workplaces. However, the field of sensor technology is continually growing. Sensors for new agents, and those with higher accuracy and lower limits of detection for existing agents, are rapidly entering the marketplace. Sensors provide exciting opportunities to better assess exposures for workers and identify control strategies to reduce those exposures. Furthermore, internet and mobile interfaces are currently increasing in functionality and adoption, including capabilities for data collection, analysis, and display. In the near future, it may also become more common for devices to broadcast data wirelessly so that industrial hygienists can monitor sensor readings in near real-time. New techniques with sensor networks can provide information for building management of indoor conditions (131) and multi-hazard sensor networks

can map multiple workplace agents with high temporal and spatial resolution (127).

Much of the development of sensor technology has been towards reducing cost and increasing the portability and wearability of sensors. Among industrial hygiene professionals, there is desire for smaller, easier-to-use monitors compared to legacy equipment that may require pumps, sampling media, suspension liquids, or large batteries (2). Researchers with interest in both occupational and environmental exposures are continuing efforts to determine the best calibration strategies for these sensors to improve data accuracy and precision. Efforts will likely also continue to increase the types of measurements that can be made with a sensor (e.g. PM speciation, additional gases, biological hazards, and health sensors). Health sensors, for example, are becoming more common, especially among elite athletes and military personnel, and are capable of measuring physiological processes, such as cardiac rhythm, blood chemistry, activity levels, and lung function, in a non-invasive manner. Although these types of sensors have not seen substantial use in industrial hygiene, applications may exist in the future to better link exposures with subclinical measures of health.

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Part IV

CHEMICAL EXPOSURE CONTROL

CHARACTERIZING AIR CONTAMINANT EMISSION SOURCES

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1 THE EMISSION INVENTORY

An emission inventory for an industrial process is a compilation of information from which one can identify emission sources and estimate the rates (quantity per unit time) at which pollutants are released to the environment. For purposes of this chapter, only the emissions that contaminate workroom air are considered; emissions to surface or groundwater, to soil, or to other environmental receptors are only treated as they may, in turn, result directly in emissions to the workplace.

An emission inventory may be simple or complex. A rudimentary inventory may consist of source location, date, identification of process, a qualitative listing of materials used, and an index of size (e.g. annual production rate) for the subject enterprise. Such an inventory, along with emission factors generated by studies of similar processes, will permit the making of an estimate of annual emissions. A comprehensive emission inventory, on the other hand, may contain sufficient detail to permit quantification of emissions, including temporal variations, for a number of specific materials from each point of release in a complex industrial process.

An inventory of emissions allows for the making of estimates of emission rates, the nature and intensity of exposures to airborne contaminants, and the appropriate dilution ventilation flowrates. The level of detail needed and achievable for the emission inventory depends both on the purposes for which it is to be used and the data available.

2 ELEMENTS OF THE EMISSION INVENTORY

The compilation of emission inventories is a well-established specifically identifiable activity in the field of air pollution control. Practices and procedures have been highly developed and descriptions of the technology are available (1–6). Emission inventory has been practiced in industrial hygiene for many years but has not been identified as a categorical work area in this field to the extent that it has been in the field of air pollution control. Although the types of data used and the techniques for obtaining them vary somewhat, the same basic elements appear in emission inventories in both fields of work.

2.1 Identification of Agents

Anticipation, recognition, evaluation, and control of hazards are the four basic steps in the practice of industrial hygiene. An emission inventory, regardless of whether it is specifically identified as such, is necessary for all four steps and is particularly important in the first three, anticipation, recognition, and evaluation. It is clear that if a hazard is to be controlled, it must first be anticipated and/or recognized; this recognition, and the identification of an emission, is a rudimentary emission inventory. Evaluation requires more than identification. In situations involving release of chemical agents to the air, evaluation may include obtaining

additional information such as quantity, character, and temporal variations of emissions, all of which are part of the emission inventory. The design and implementation of emission control require detailed information about the emission source that goes beyond the level of detail usually required for an emission inventory. The identification, by means of an emission inventory, of materials that are released from a process or operation, however, is a fundamental step in the recognition of those that represent a potential hazard in the workplace or the community.

For manufacturing processes, preliminary identification of potentially hazardous agents can often be based upon the identification of process raw materials, intermediate and by-product materials, and the process end products. In commercial enterprises, the identification of materials that are handled permits the singling out of those that may represent potential hazards. For combustion sources, information on the composition of fuel and the type of combustion equipment used permits qualitative identification of pollutant components.

The evaluation phase of an industrial hygiene or community air pollution problem requires, in addition to identification of the agents of concern, a number of other kinds of information that can be obtained in an emission inventory. Among the most fundamental of these is the identification and description of the site or location at which the contaminant is released to the air.

2.2 Identification of Emission Sites

The most cursory emission inventory identifies the site or location of an emission source at a particular process, piece of equipment, or operation. Such location information is generally useful for indicating the need for more thorough workplace exposure evaluation. Any emission inventory use other than agent identification alone requires more specific emissions location information. For example, in air pollution control, the identification of specific stacks, vents, and other points of emission is necessary for diffusion modeling and for most impact evaluations and emission regulatory activities. For industrial hygiene purposes, the location of a specific workplace, process point, and perhaps even a particular process equipment opening (e.g. a mixer charging port) or work practice (e.g. the handling of shipping bags after use) may be needed. Such location information is vital to the hazard assessment process. It is necessary for identifying the workers subject to exposure from the particular source and for identifying alternatives from which to select the means for control of any hazard caused by the emission. An emission inventory that identifies both the materials emitted from a process and the specific locations at which these materials are released can serve as the first step, and occasionally the only step necessary, in the evaluation of a hazard and initiation of a control effort.

2.3 Time Factors in Emissions

Time resolution in emission inventories may be yearly, seasonal, monthly, weekly, daily, hourly, or even less than hourly, depending on specific needs and the availability of data. The assessment of emissions to workplaces that involve cyclic or intermittent operations may require use of time intervals of 15 min or less. For short time or intermittent operations – for example, the taking of materials samples at process sampling ports – the actual time interval of emission and the frequency with which the operation occurs should be recorded in the inventory.

In some cases, the interval of record for the quantity of material released is relatively long – for example, a monthly record of solvent use – even though actual release may be cyclic or may occur over short intervals. In such cases, the emission inventory record should contain a sufficiently detailed description of the process or operation to permit estimation of actual emission intervals and the quantities of materials released during these intervals.

It is important that the emission inventory record includes both the date on which the inventory was done and the calendar interval for which it applies. When a change in process or operation occurs that materially affects the composition, quantity, or condition of an emission, the emission inventory record should be updated to reflect the change. In the absence of any substantial change, the inventory should be revalidated at convenient intervals. When an emission inventory record is updated or revalidated, the old record should be retained; a sequential inventory file over a long period may be invaluable in future retrospective epidemiological studies.

3 QUANTIFYING EMISSIONS

Emissions can be quantified either by direct measurement, such as source testing, or by indirect means. Indirect means includes techniques such as *process materials balance* or the *determination of an index parameter* – for example, a production rate – that can be related empirically to emissions.

3.1 Source Sampling

Source sampling is ordinarily associated with measurement of air pollutant emissions. Under some circumstances, the techniques can be applied to industrial hygiene investigations as well. The techniques of air pollutant source testing have been described in detail by Paulus and Thron (3, 7) and others. The Environmental Protection Agency (EPA) has published stepwise procedures on source sampling for particulates (8). This chapter contains a number of data recording

forms that are useful in sampling not only for particulates but also for other agents as well.

Source sampling ordinarily consists of withdrawing a representative sample from a contaminant-bearing gas stream in a duct or stack. Analysis of the sample yields data on concentration of the contaminant in the gas stream. Concentration data, combined with companion data on gas flow rates in the ducts or stacks, yield values for contaminant emission rates for gas streams released to the atmosphere.

The critical concern in source sampling is the representativeness of the sample. Both composition and flow rate of a contaminated gas stream may vary as the processes and operations that generate it vary. Thus, representativeness of a source sample depends very much on the representativeness of processes and operations at the time of sampling.

As mentioned earlier, the techniques of source sampling were mostly developed for use in air pollution emission measurements. They can, in some circumstances, be applied to in-plant industrial hygiene purposes as well. When a workplace is served by general dilution ventilation in the exhaust mode, the techniques of source sampling can be applied to the exhausted airstreams to determine the rate at which contaminants are released to the workplace air. The calculation methods described in **Engineering Control of Airborne Contaminants: History, Philosophy, and the Development of Primary Approaches** on industrial ventilation can be used to estimate emissions when the concentrations of contaminant in the supply and exhaust air and the ventilation rate are known with the system at equilibrium. The contaminant generation rate is the sum of the generation rates calculated for all exhaust discharges. The procedure is most applicable when general dilution ventilation in the exhaust mode is the sole, and controlling, ventilation regimen for the workplace, that is, when there is no mechanical local exhaust ventilation. If local exhaust ventilation is used in the workplace, its influence as general dilution ventilation must be taken into account when using this technique to estimate workplace emissions.

Source sampling techniques may also be used to quantify emissions from individual points of release in a workplace. The emissions may be captured using a temporary exhaust ventilation setup, and the amount of material released may be determined by sampling from that exhaust stream. Application of this technique to a single source or emission point in a space that contains several sources of the air contaminant requires either elimination of the influence of the other sources or correction for them. A mechanical arrangement can be provided to supply contaminant-free outside air to the test source. The exhaust stream from the test source will then contain only contaminant from that source and will be unbiased by contaminant from other sources.

Alternatively, monitoring of the concentration of contaminant in room air that supplies the source test exhaust system permits correction for other sources; emissions from the test

source can be determined by the difference in contaminant concentration in supply and exhaust air of the test system.

3.2 Materials Balance

In some cases, knowledge of processes and operations permits determination of the amount of material released to the air of a workplace without emission measurements. If it is known that a gas or vapor is generated by chemical reaction or otherwise and is released to workplace air in proportion to the use of a raw material or a production rate, that index of generation can be used to determine the release rate. Examples include the generation of products of combustion by unvented open flames, as is the case with direct fired unit heaters. Here, fuel composition and use rate are indices of contaminant emissions. Uses of volatile solvents in which the solvents do not become part of a product, but evaporate completely into the workplace air, are common in industry. Solvent use rate, in such cases, is also an emission rate. When exhaust ventilation is applied to some operations in a workplace and not to others, distinction must be made between the portion of the material captured by exhaust ventilation and the portion released in the occupied workplace; only the portion that is released directly to the workplace air is used to estimate workplace exposures.

When complete evaporation of a volatile material does not take place, some index other than total use is needed for quantifying emissions. In the simple case, when the amount used and the amount remaining can be determined, the amount released as vapor can be obtained by difference. When this is not possible, more sophisticated means such as exhaust air sampling must be employed. With complete evaporation of a mixture of volatile materials, the quantity of each component that vaporizes is merely the quantity of that material in the mixture. Partial evaporation of a mixture, however, does not necessarily yield vapor quantity of each component in proportion to the quantity of that component in the liquid mixture.

Applications of materials balance concepts for the determination of emissions require engineering analysis on a case-by-case basis. Procedures and equations for estimating emission rates from multiple indoor sources have been reported (9–11).

3.3 Emission Factors

The need exists for emissions estimates for large numbers of sources in community air pollution studies. The impracticability of source-by-source emissions tests has led to the development of emission factors. An emission factor is a pollutant emission rate for a particular type of emission source expressed as a quantity of pollutant released per unit of activity of that type source. The unit of activity chosen in each case is one that can be determined and can be related

quantitatively to emissions; it may be by “ton of product,” “million Btu of heat produced,” “mile of vehicle travel,” or other such index units. Emission factors represent typical emissions from a class of sources and ordinarily cannot be applied with confidence to individual sources. In the absence of other information, however, emission factors for a particular source type can give useful insights into the character and general levels of emissions from individual sources of that type.

The most reliable emission factors are those based on a combination of emission measurements, process data, and engineering analysis for a large number of sources. Those that do not have a theoretical basis and are derived from only one type of data, or from data from only a few sources, should be used with caution. In some cases, sufficient knowledge or information is available to permit development of empirical or analytic relationships between emission rate and some process parameter such as material composition or stream temperature. Such factors are generally the most reliable of all and can even be applied to individual sources with reasonable confidence.

Air pollutant emission factors for a large number of source types have been tabulated and reported by the EPA's Office of Air and Waste Management (12). Process descriptions and emission control practices, along with typical collection performance for various types of control, are presented for most of the source types covered. Table 1 lists major source types for which emission factors appear in the current publication. In a separate document, the EPA has published emission factors for arsenic, asbestos, beryllium, cadmium, manganese, mercury, nickel, and vanadium for processes involving these materials (13).

Emission factors in the EPA tabulation generally apply to identifiable point sources in processes or operations from which pollutants are released to the atmosphere through vents or stacks. As such, they have limited applicability to in-plant industrial hygiene assessments. They do, however, identify some of the air contaminants that are generated by these processes; the same contaminants may represent potential in-plant exposures.

3.4 Fugitive Sources

Contaminant emissions from point sources such as tank vents or transfer points, processes and operations, or manufacturing equipment that clearly involve release of a process material – for example, release of volatile components in cementing or painting operations – are ordinarily capable of identification and quantification. There are other types of fugitive emission sources not so easily accommodated and sometimes neglected in emission inventories. Such sources, like poorly functioning exhaust hoods, may be intermittent, temporary, or unpredictable; many are unrecognized

TABLE 1 Major source types for which air pollution emissions factors have been adopted by EPA and others over the past 40 years.

1. External combustion sources
Bituminous and subbituminous coal combustion
Anthracite coal combustion
Fuel oil combustion
Natural gas combustion
Liquefied petroleum gas combustion
Wood waste combustion in boilers
Lignite combustion
Bagasse combustion in sugar mills
Residential fireplaces
Residential wood stoves
Waste oil combustion
2. Solid waste disposal
Refuse combustion
Sewage sludge incineration
Medical waste incineration
Municipal solid waste landfills
Open burning
Automobile body incineration
Conical burners
3. Stationary internal combustion sources
Stationary gas turbines for electricity generation
Heavy-duty natural gas-fired pipeline compressor engines
Gasoline and diesel industrial engines
Large stationary diesel and all stationary dual-fuel engines
4. Evaporation loss sources
Dry cleaning
Surface coating
Nonindustrial surface coating
Industrial surface coating
General industrial surface coating
Can coating
Magnet wire coating
Other metal coating
Flatwood interior panel coating
Paper coating
Polymeric coating of supporting substrates
Automobile and light-duty truck surface coating operations
Pressure-sensitive tapes and labels
Metal coil surface coating
Large appliance surface coating
Metal furniture surface coating
Magnetic tape manufacturing
Surface coating of plastic parts for business machines
Wastewater collection, treatment, and storage
Polyester resin plastic products fabrication
Asphalt paving operations
Solvent degreasing
Waste solvent reclamation
Tank and drum cleaning
Graphic arts
General graphic printing
Publication gravure printing
Commercial/consumer solvent use
Textile fabric printing

TABLE 1 (continued)

5. Petroleum industry	Sodium carbonate
Petroleum refining	Hydrogen cyanide
Transportation and marketing of petroleum liquids	9. Food and agricultural industries
Natural gas processing	Tilling operations
6. Organic chemical process industry	Growing operations
Carbon slack	Fertilizer applications
Adipic acid	Pesticide applications
Explosives	Orchard heaters
Paint and varnish	Harvesting operations
Phthalic anhydride	Cotton harvesting
Plastics	Grain harvesting
Poly(vinyl chloride)	Rice harvesting
Poly(ethylene terephthalate)	Cane sugar harvesting
Polystyrene	Livestock and poultry feed operations
Polypropylene	Cattle feedlots
Printing ink	Swine feedlots
Soap and detergents	Poultry house
Synthetic fibers	Dairy farms
Synthetic rubber	Animal and meat products preparation
Terephthalic acid	Meatpacking plants
Lead alkyl	Meat smokehouses
Pharmaceuticals production	Meat rendering plants
Maleic anhydride	Manure processing
Methanol	Poultry slaughtering
Acetone and phenol	Dairy products
Propylene	Natural and processed cheese
Benzene, toluene, and xylenes	Cotton ginning
Butadiene	Preserved fruits and vegetables
Cumene	Canned fruits and vegetables
Ethanol	Dehydrated fruits and vegetables
Ethylbenzene	Pickles, sauces, and salad dressings
Ethylene	Grain processing
Ethylene dichloride and vinyl chloride	Grain elevators and processes
Ethylene glycol	Cereal breakfast food
Ethylene oxide	Pet food
Formaldehyde	Alfalfa dehydrating
Glycerine	Pasta manufacturing
Isopropyl alcohol	Bread baking
7. Liquid storage tanks	Corn wet milling
Organic liquid storage tanks	Confectionery products
8. Inorganic chemical industry	Sugar processing
Synthetic ammonia	Sugarcane processing
Urea	Sugar beet processing
Ammonium nitrate	Salted and roasted nuts and seeds
Ammonium sulfate	Almond processing
Phosphate fertilizers	Peanut processing
Normal superphosphate	Fats and oils
Triple superphosphate	Vegetable oil processing
Ammonium phosphate	Beverages
Hydrochloric acid	Malt beverages
Hydrofluoric acid	Wines and brandy
Nitric acid	Distilled spirits
Phosphoric acid	Miscellaneous food and kindred products
Paint and varnish	Fish processing
Phosphoric acid	Coffee roasting
Sulfuric acid	Snack chip deep-fat frying
Chlor-alkali	Yeast production
	Tobacco products

TABLE 1 (continued)

Leather tanning
Agriculture wind erosion
10. Wood products industry
Lumber
Chemical wood pulping
Pulp bleaching
Papermaking
Plywood manufacturing
Reconstituted wood products
Waferboard and oriented strand manufacturing
Particleboard manufacturing
Medium-density fiberboard
Charcoal
Wood preserving
11. Mineral products industry
Hot mix asphalt plants
Asphalt roofing
Bricks and related clay products
Calcium carbide manufacturing
Refractory manufacturing
Portland cement manufacturing
Ceramic products manufacturing
Clay and fly ash sintering
Western surface coal mining
Coal cleaning
Coal conversion
Concrete batching
Glass fiber manufacturing
Fruit manufacturing
Glass manufacturing
Gypsum manufacturing
Lime manufacturing
Mineral wool manufacturing
Construction aggregate processing
Sand and gravel processing
Crushed stone processing
Lightweight aggregate manufacturing
Phosphate rock processing
Diatomite processing
Taconite ore processing
Metallic minerals processing
Clay processing
Talc processing
Feldspar processing
Vermiculite processing
Alumina manufacturing
Perlite manufacturing
Abrasives manufacturing
12. Metallurgical industry
Primary aluminum production
Coke production
Primary copper smelting
Ferroalloy production
Iron and steel production
Primary lead smelting
Zinc smelting
Secondary aluminum operations

Secondary copper smelting and alloying
Gray iron foundries
Secondary lead processing
Secondary magnesium smelting
Steel foundries
Secondary zinc processing
Storage battery production
Lead oxide and pigment production
Miscellaneous lead products
Leadbearing ore crushing and grinding
Electric arc welding
Electroplating
13. Miscellaneous sources
Wildfires and prescribed burning
Fugitive dust sources
Paved roads
Unpaved roads
Heavy construction operations
Aggregate handling and storage piles
Industrial wind erosion
Abrasive blasting
Explosives detonation
Wet cooling towers
Industrial flares
14. Greenhouse gas biogenic sources
Emission from soils – greenhouse gases
Termites – greenhouse gases
Lightning emissions – greenhouse gases
Icteric fermentation – greenhouse gases

Source: Adapted from EPA. <https://www.epa.gov/air-emissions-factors-and-quantification/ap-42-compilation-air-emission-factors>.

or ignored in emission inventories. Fugitive sources and the generation of secondary pollutants deserve attention in IH emission inventories, however, all of them may not be capable of quantification or prediction.

Fugitive sources that are of consequence primarily in the field of air pollution, and for which emission factors have been developed, include unpaved roads, aggregate handling and storage piles, heavy construction operations, and paved roads (12). Other sources that are consequential from the standpoints of both air pollution and industrial hygiene include the following:

1. LEV hoods and systems that do not completely control the contaminant
2. Structural and industrial process fires
3. Off-gassing from recently manufactured products
4. Materials spills (accidents, equipment failure, or malfunction)
5. Sample collection and analysis
6. Process leaks (flanges and piping, valves, packing glands, conveyors, pumps, compressors, tanks, bins, etc.)
7. Relief valves and control device bypasses

8. Maintenance and housekeeping activities (tank and vessel cleaning, filter cleaning, replacing piping, pumps, sweeping, etc.)
9. Emissions from waste streams and reemissions of collected materials
10. Secondary reactions (nonproduct process reactions, extraprocess reactions)

Virtually all exhaust hoods have fugitive emissions that must be taken into account during the emission inventory process. Sometimes, these emissions are trivial, but in other cases, they can be significant. See, for example, the case study in Section 5.4.

Structural fires are intermittent phenomena predictable only in the aggregate and not as individual events; they are considered to be emission sources primarily in the air pollution sense. An industrial hygiene consequence of urban fires, however, is the exposure to toxic materials of firefighters and others who may be involved in rescue or control activities. A number of toxic atmospheric contaminants are generated by structural fires; these tend to vary from one fire to another. Of concern in all structural fires, however, is emission of carbon monoxide. Burgess et al. (14) have described exposures of emergency personnel to carbon monoxide emissions in real fire situations; the maximum sustained air concentrations of carbon monoxide to which these persons were exposed in the events in which it was measured was about 2%. Materials balance using pyrolysis and oxidation processes offer one means of estimating the quantities of pollutants that may be generated in any particular case.

Estimates of emissions from industrial fires require individual analysis. The quantities and characteristics of combustion products depend on the nature of the materials that burn or are present in the fire and on the circumstances of combustion (e.g. whether open or confined). Again, consideration of pyrolysis and oxidation phenomena may permit estimation of the nature and quantities of air contaminants generated by any particular event. The likelihood and consequences of accidental fires is an appropriate consideration in industrial emission inventories.

Material spills in manufacturing, transporting, and uses of industrial materials are not infrequent occurrences. Studies of processes and operations with specific attention to spills can reveal the frequencies and magnitudes of spills if they are usual occurrences (15). Such spills can then become part of an emissions inventory. When spills are not a usual occurrence, an emission inventory can do little more than trigger consideration of the possibilities and consequences of such events. Guidance for protection of workers when a spill of a hazardous substance occurs, developed as a joint project of the National Institute for Occupational Safety and Health (NIOSH), the Occupational Safety and Health Administration (OSHA), the U.S. Coast Guard, and the U.S. Environmental Protection Agency, has been published (16).

Process leaks are sometimes of major consequence from the standpoint of industrial hygiene. Control of process leaks, for example, has been a major factor in achieving acceptable working conditions in vinyl chloride monomer and polymerization plants. Process leaks can be identified by inspection or instrumental methods; timely repair may obviate quantifying for an emission inventory. Should quantification be necessary, use the techniques of source testing or materials balance.

Predicting and quantifying emissions of particulate material from industrial sources is generally more difficult and more technically demanding than is assessment of emissions of gases and vapors. Quantifying emissions of fugitive dusts is described in Refs (17–24) and (6).

4 EMISSION ESTIMATES FROM PLANT AND COMPANY RECORDS AND REPORTS

In the absence of in-plant measurements of emissions, estimates derived from *secondary sources* of information can be used for inventory purposes. In some cases, data are available from similar processes and plants elsewhere, and estimates by analogy may prove to be sufficient for a given purpose.

In other cases, unique features of a process or operation may make estimates by analogy inappropriate. An alternative to measurement data or analogy makes use of records and reports whose basic purposes were other than for industrial hygiene, but whose content may be extracted, combined, or otherwise manipulated into usable estimate of emissions and potential exposure. Vital information may be recorded in a variety of business documents, including engineering, accounting, production, quality control, personnel, and governmental records. Although these records represent a rich source of information for emission inventory purposes, they can serve other purposes in the practice of industrial hygiene and occupational health research as well. Some of these purposes are mentioned from time to time in the following discussions of specific types of records.

4.1 Research and Development Records

Industrial research and development units often issue a variety of reports to producing units as aids in bringing a new product on stream, to ensure a required level of uniformity in a given item produced by different plants, or to make changes or improvements in operating equipment, materials, or techniques. Valuable insight with respect to materials and work practices employed in the past may be gleaned from several of these records. Among such records are the following:

- *Product specification.* Final product and intermediate component data included in a product specification often give dimensions, weight, materials of construction, processing aids, processing conditions, tools and fabricating equipment, and special notes.
- *Standard operating procedure.* This record may exist under a variety of names: standard operating procedure (SOP), Standard Practice, Uniform Methods, and (Company Name) Manual of Operations appear among the myriad of titles. Many, however, share fairly specific operational instructions, usually in a step-by-step approach by processing sequence. Vital data from this record can include the following:
 - Fabrication equipment
 - Authorized materials of construction
 - Acceptable processing aids
 - Processing conditions
 - Alternate materials for cyclic operations (e.g. summer versus winter stocks)
 - Change notices affecting materials or techniques
 - Instructions regarding protective equipment
- *Formulations and raw materials.* Detailed data concerning the qualitative aspects of potential exposures can be derived from the study of information describing the raw materials employed in a process.
 - Raw material specifications may contain composition data, restrictions on contaminants, and acceptance testing schedules
 - A listing of authorized vendors can offer clues to potential contaminants based on knowledge of a vendor's source of supply or processing methods
 - Formulation records often contain information on the composition of mixtures as well as the methods, equipment, quantity, and conditions of processing

4.2 Analytical Laboratory Records

Quality control considerations often dictate that incoming raw materials be monitored for selected chemical and physical properties, that supplies from prospective vendors be subjected to acceptance testing, and that production quality be assayed by sampling at intermediate stages of the process. A single journal entry of analytical results may include a wealth of intelligence applicable to an emissions inventory. Analytical laboratory records may include some of the following:

- *Raw material test results.* Recorded in either the analyst's journal or on prepared forms will be entries such as follows:
 - Analytical results vis-à-vis specifications

- Date of analysis, and perhaps date of receipt
- Quantity of the shipment
- Vendor
- Method of analysis
- Analyst
- *Authorized vendors.* Quality control laboratories often maintain vendor-supplied information regarding purchased materials. Material safety data sheets, product specifications, production methods, and quality control statements all offer bits of useful data.

4.3 Process and Production Records

Records generated by production units relate to such matters as scheduling, quality control, cost control, and to a lesser extent, training exercises. Depending on the product and process, production-type records can be of considerable value in generating an emissions inventory.

- *Flowcharts.* A detailed diagram of a process is particularly useful in identifying points and potential for the release of air contaminants.
- *Operating conditions.* Time, temperature, and pressure data are useful in assessing possible release of reaction products, by-products, degradation products, and unreacted raw materials.
- *Scheduling.* Shift, cyclic, and seasonal variations may influence the emissions of contaminants. Such variations can often be ascertained through production scheduling records. Included under this heading are records of batch versus continuous production modes. Gantt chart records offer a particularly attractive systematic source of scheduled activities that can be both precise and detailed.

4.4 Plant Engineering Records

Virtually all industrial organizations include an engineering component that is responsible for the physical plant and supporting facilities. This responsibility has been known to result in a plant archive that is particularly useful in emissions inventory activity and in research that requires reconstruction of past environmental conditions.

- *Plant layout.* The plant floor plan, coupled with elevation drawings, affords a visualization of the process, materials flow, occupied areas, and possibly insights relating to contaminant generation and control. Furthermore, many engineering drawings are cross-referenced to other drawings of equipment, emissions control features, and adjacent work areas. Useful characteristics of plant engineering files include the following:

- Processing equipment type, extent, and location on layouts.
- Department floor space showing geographic boundaries and physical barriers.
- Engineering controls, especially industrial ventilation systems, are depicted in mechanical equipment layouts, which normally show the location, site, type, and rating of air-moving equipment, as well as a reference to the detailed drawings covering the system.
- Dates of change or modification are often included in drawings, either by direct entry or by reference to a new set of plates.
- *Equipment specifications.* Files on processing equipment installed by or under the supervision of plant engineers often include specifications that supply clues to potential problems such as process emissions, sound power rating and directivity data, or emission control features incorporated in the equipment.
- *Project records.* Each major project of construction, modification, or installation normally proceeds as an integral project with an individual(s) assigned as coordinator. Usually, this project officer accumulates records that include data on the following:
 - Equipment specifications
 - Performance checks and acceptance test results
 - Prime contractor and subcontractors
- *Material balance.* A detailed accounting of materials, products, and side streams, either measured or theoretical, can serve as a basis for a quantitative estimate of emissions.

4.5 Industrial Engineering Records

The practice of industrial engineering includes the analysis of work procedures to improve either work conditions or productivity or both. Typical industrial engineering records contain information on work methods and standards that are useful for compiling emission inventories and for estimating past emissions and exposures that may have resulted from them. Such records often include the following:

- *Job descriptions.*
 - Description numbers, department listings, and simple descriptive job titles can provide the link between the tasks performed and the work history recorded in an individual's personnel file.
 - Job location within a plant, thus, the potential for various exposures may be ascertained from the geographic area, processing equipment, or department listing contained in a job description.
- The listing in a job description of tools, equipment, and processing aids can help establish the nature of emissions and characteristics of potential exposures (e.g. inhalation, skin absorption).
- Task evaluations often include judgments concerning such health-related items as work conditions, safety requirements, hazards, skills, effort, and responsibility.
- *Time and motion studies.* Task breakdowns are useful to establish contact with materials of interest, and the fraction of time spent on certain tasks coupled with cycle time can afford an estimate of the extent of exposure.
- *Process analysis.* Evaluations of an entire process focus on tasks performed by all the members of a crew rather than those of individual workers. Particularly useful in process analysis reports are listings of fractions of a workday spent at different workstations by members of the operating crew, including break time and sequencing of tasks.

4.6 Accounting Records

Accounting records cover virtually all phases of an operation for both outside reporting and internal control purposes. Major areas of interest for emission inventory purposes include records on incoming materials, internal use of these raw materials, and plant production factors (25).

- *Purchasing.* Raw materials for both production and support operations, as well as processing equipment, are ordinarily obtained from outside the company, resulting in some acquisition record. Even when raw materials are drawn from captive sources, records of resource depletion may be available.
 - Listings of materials, quantities, and supplier may be available through the purchasing ledger, often found in the accounts payable portion.
 - Capital equipment is normally amortized by a recognized accounting procedure, the evaluation of which can be employed to determine the date of acquisition. Alternatively, many organizations maintain a property book that contains similar information.
- *In-plant issues of materials.*
 - Data on raw materials consumption often can be developed through accumulation of issues to departments, cost centers, or plants, or through collected expense or work-in-process accounts.
 - Material variance accounts may serve as surrogates for material balance data if the latter are unavailable. The absolute variance value between actual and standard material usages may be of marginal value, but changes in this quantity can be important in establishing trends.

- Nonproduction supplies are often issued to maintenance and other support departments through a “general store” account, with the receipt listing the item and quantities issued.
- *Inventory*. Inventory control may be maintained through stock records that list material, vendor, date, and quantity received, date and quantity of issue, department to which issued, and location and quantity on hand.
- *Production*. Finished goods and work-in-process production accounts may include an identification of the work schedule, days operated, and average production level.

4.7 Personnel Records

Personnel records per se can provide insights into the nature and locations of contaminant releases applicable to emission inventories. In addition, they are vital to other industrial hygiene and occupational health research activities. In any study of causal association between conditions of work and health experience, the work experience of each individual is an integral component. Thus, accurate and reliable personnel-type records are vital. Organizational units that normally can develop, or assist in developing, useful records include the personnel, payroll, industrial relations, safety, and medical departments. The IH might check records related to personnel, industrial relations, safety, medical, insurance surveys, and union activities.

4.8 Government-Mandated Records and Reports

During the past five decades OSHA, EPA, and state agencies have promulgated numerous regulations intended to ensure that employees, customers, the general public, and government agencies would have the necessary information with which to evaluate potential exposures resulting from chemical releases to the workplace and ambient environments. The resultant records and reports can provide valuable information to compiling the emission inventory, and will sometimes afford insights into potential exposure conditions. Copies of past reports of this type are likely to be filed in the plant or corporate office(s) that deal(s) with environmental affairs and/or that deals with government regulatory agencies.

Some government requirements and activities that might have insights into potential exposure conditions and emission sources include the following:

- OSHA Hazard Communication Rules
- OSHA Access to Medical (and Exposure) Records
- OSHA Standards Governing Specific Chemicals
- The Toxic Substances Control Act

- SARA Title III Rules
- The Resource Conservation and Recovery Act
- Other Governmental Records and Reports (e.g. nationwide statistics and industrywide data)

4.9 Record Locations

Within many corporate industrial organizations, records of major additions or changes, as well as events affecting the entire operating units, are likely to be available at a central location, such as the division or corporate offices. Examples of these types of records are overall production levels, descriptions of uniform practices, and product specifications. More specific records, or those dealing with minor plant alterations, are ordinarily available only at the local plant level. Historical records may be at a central plant storage facility. At the plant level, project officers often retain personal copies of papers related to their projects; if a plant record has been discarded, such personal records may provide valuable historical data.

4.10 Quality of Secondary Data and Records

Information derivable from secondary sources of data is limited by the nature and detail of the record content. In general, the more distant the time of interest, the less complete will be the record, and the lower will be the confidence in its accuracy. When data are sparse and only plantwide data are available, estimated measures such as gallons per cubic foot of plant building volume per month, or pounds used per employee per day, may be the limit of detail for emission estimates, but this may serve for plant-to-plant contrasts. More detailed data such as quantities of materials used in specific departments and descriptions of controls for specific work areas permit more detailed estimates. Material generation rates coupled with general area ventilation rates may enable one to estimate an area average concentration. Such data may be particularly useful for within-plant contrasts or for plant-to-plant studies of particular areas or processes.

Records pertaining to the detailed nature of tasks, such as standard operating procedures or job descriptions, make possible a ranking of jobs – thus, a ranking of increments of time in individuals’ work histories – by potential for exposure to any particular agent or combination of agents of interest. In this fashion, personnel with increments of time in their work histories having similar exposures, for example, homogeneous exposure groups (HEGs) (26), can be grouped for comparison of health experience with other workers who share different common exposure profiles, that is, who have histories of work in other HEGs.

As an example of the use of secondary information, an illustration of the type of emissions output that has been

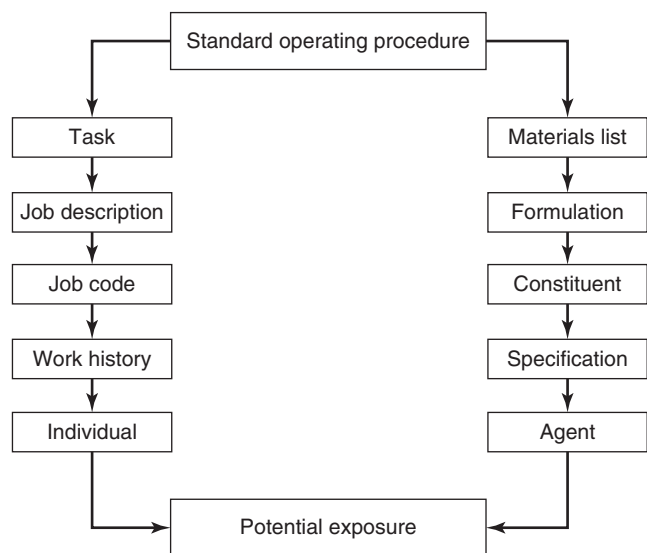


FIGURE 1 Synthesis of potential exposures associated with a manufacturing step for which a standard operating procedure is available.

accomplished for retrospective research purposes through the use of such sources of information follows.

In Figure 1, the SOP is the pivotal document that identifies both tasks and materials for a step in manufacturing. A formulation record, or series of records, for each material used in that particular manufacturing step identifies each raw material constituent of each material. Examination of the raw material specification for each constituent then permits identification of agents (e.g. coal tar naphtha) that may be emitted in the workplace, often with additional compositional detail (e.g. aromatic content or benzene content). Because formulations, constituents, and specifications change from time to time, the listing of potential emissions thus identified must show inclusive dates on an agent-by-agent basis.

The tasks portion of the SOP includes a job description, which in turn has a specific job code. The job code is listed in the personnel record of each person who has held that particular job. Examination of the personnel records of the plant's current and past workers identifies complete work history, including dates and duration of each job code assignment for each individual who has held the specific job of interest.

In this way, the potential for contact with a particular chemical agent by an identified individual, including dates and duration of the contact, can be developed, even to events that occurred in the distant past.

4.11 Records Retention

Emissions records, or records from which emissions estimates can be made, should be retained. A single specific

age at which a record no longer has value cannot be stated. For research purposes, exposure records have value equal to, or greater than, that of medical examination records. Because long latent periods are associated with health effects of some agents, early exposure records may be invaluable in the search for causal associations. Exposure records, or emission records, that identify contact with agents or from which exposure estimates can be made, should be retained long enough to be used in studies of the mortality experiences of the worker populations to which they apply.

The need for long-term retention of environmental records is recognized in the record-keeping provisions of the OSHA regulation of toxic and hazardous substances (27). Time periods for which employee exposure records must be retained vary with the substance being regulated. For example, records of exposures to asbestos must be retained for at least 20 years, those for vinyl chloride must be retained for not less than 30 years, and those for coke oven emissions must be retained for the duration of employment plus 20 years, or for 40 years, whichever is longer. Emission data are pertinent to these records. Such retention is appropriate for all records of emissions of air pollutants or of chemical agents released in places of work.

5 USE OF THE EMISSION INVENTORY

Emission inventories are fundamental to the identification, evaluation, and control of industrial hygiene hazards associated with airborne chemical contaminants. Not all uses for inventory information can be examined here, but a few are presented, as well as a case study that demonstrates its use.

5.1 Regulatory Requirements

Various governmental regulatory programs in occupational safety and health, air pollution, and toxic substances control have reporting requirements that involve emission inventory information. Regulations regarding the nature and content of these reports, the agents covered, and the types of establishment with reporting obligations change periodically. Persons responsible for industrial or commercial enterprises that involve emissions to community air, or the handling or production of agents that may be covered in occupational health or toxic substances regulatory programs should keep abreast of the specific requirements imposed by state and federal regulations. Emission inventory programs can then be so designed and operated that the emissions data necessary to satisfy reporting requirements are obtained.

5.2 Determination of Emission Rates

Knowing the quantities of a chemical material used in a process can lead to an estimate of the amounts emitted into

the work environment. Dilution ventilation rates, to be cost-effective, must be based on the amount of material to be diluted. Dilution ventilation and the determination of appropriate dilution ventilation rates are covered in **Engineering Control of Airborne Contaminants: History, Philosophy, and the Development of Primary Approaches**.

5.3 Workplace Exposure Estimates

Qualitative estimates of the potential for emissions and consequent exposures of workers can be made when agents have been identified and conditions of their use are known. Even the most rudimentary emission inventory – the identification of agent, process, and location of use – permits a useful kind of exposure potential assessment. An operating program in which the industrial hygiene department of a large research facility systematically obtains descriptions of all uses of the many hundreds of chemical agents available at the facility has been described (28). The system includes a hazard rating for each agent based on its toxicity, flammability, reactivity, and special properties such as may be found in the agent's material safety data sheet. Use information does not identify emissions per se, but retrieval of use information for a particular agent permits rapid subjective assessment of its emissions potential throughout the facility. Quantitative information on emissions, either measured, calculated, or estimated, can be combined with data on workplace ventilation to estimate workroom concentrations of an agent. Such estimates may occasionally be of use in validating sampling data, but are more likely to have value in such applications as assessing growth or decay of concentrations in nonequilibrium situations, in predicting the consequences of new processes or changes in operations, or in estimating retrospectively the levels of a contaminant to which particular groups of workers may have been exposed. The latter use is of particular interest in reconstructing emergency or accident episodes, or in retrospective epidemiological studies of worker populations.

5.4 Case Study: Sample Calculations Demonstrating the Use of an Emission Inventory and Characterization

An IH has been informed about a planned mild steel welding operation in a confined space at the plant. The IH is asked to assist in developing a suitable emission and exposure control plan.

Data and Information gathered by the IH included an emission inventory, drawings of the confined space, and a full description of the work practices to be used. These sources of information are summarized below:

- The operation is to employ two welders (plus a helper) in a confined underground space, as shown in Figure 2,

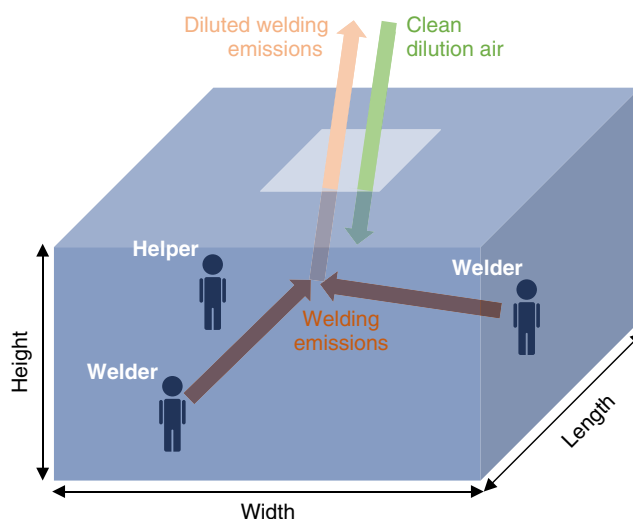


FIGURE 2 Planned welding operation in a confined space with exhaust hoods.

with appropriate safety measures in place (e.g. observer outside, communications established).

- Primary emission and exposure controls include both local exhaust and dilution ventilation; management desires both to be employed. (See **Engineering Control of Airborne Contaminants: History, Philosophy, and the Development of Primary Approaches** and Ref. (6) for more information on industrial ventilation.)
- An entry hatch, 2 ft × 2 ft, is located on top of the confined space where air can enter and an 8 in. exhaust duct will be located. Each welder will be provided with a portable exhaust hood attached to the exhaust flex ductwork.
- The operation is located near sea level and at room air temperature, so ventilation design can assume standard conditions, STP, with $d = 1$. (See **Engineering Control of Airborne Contaminants: History, Philosophy, and the Development of Primary Approaches** and Ref. (6) for more information on design and standard conditions.)
- Dilution air can originate from a clean, pollution-free location.
- Exhaust air volume flowrates can be chosen to provide sufficient makeup air to the space to also serve as sufficient dilution air for welding operation fugitive emissions.

The emission inventory includes the following information:

- There will be two major emission sources (two welders).
- The surface to be welded is clean, uncoated, and uncontaminated.

- The major air contaminants emitted during welding are ozone and iron fume.
- Adequate control of the iron fume will also provide control of ozone.
- An emission factor for total fume, $R = 0.1 \text{ g min}^{-1}$ of total iron fume per welder (during the actual arc), has been derived from EPA's AP 42 publication (12) for the type of welding to be performed.
- Each welder actually welds ("strikes an arc") about 20% of the time (ratio of time welding = 0.20).
- The efficiency of capture for the welding exhaust hoods is at least 0.90 (90%) by prior testing. Employees have been trained to use the hoods correctly and are experienced in their use. (This means that up to 10% of fume generated during welding must be diluted to an acceptable exposure concentration by the general makeup air that will replace air exhausted by the hoods. The exhaust air volume flow rate will be selected to ensure sufficient dilution air is provided to control fugitive emissions for the worst-case scenario of 10% fugitive emissions.)
- Air mixing factor, $K_{\text{mix}} = 1.0$ (free-standing air-mixing fans in the space will be used to ensure complete turbulent air mixing, if necessary.)
- The IH chooses an acceptable exposure concentration of total fume, $C_a = 0.3 \text{ mg m}^{-3}$ (TWA, BZ exposure). Source and justification: $C_a = 2 \times$ the EPA NAAQS PM-10 standard for 24 h and/or 10% of the ACGIH recommendation for "NEC" respirable particles.
- Dimensions of the confined space: $H = 14 \text{ ft}$, $W = 16 \text{ ft}$, $L = 18 \text{ ft}$.
- Main exhaust duct diameter = 8 in. (ductwork through the entry hatch).
- The following calculations were performed by the IH and forwarded to the engineering group for their use in designing the system and for procuring equipment:

Estimation of the dilution ventilation required if 10% of welding fume become fugitive emissions (worst case):

$$\begin{aligned}
 Q_d &= [R \times K_{\text{mix}} \times (1 - \text{capture efficiency}) \\
 &\quad \times (\text{time ratio}) \times 2 \text{ welders}] / C_a \\
 &= [0.1 \text{ g min}^{-1} / \text{welder} \times 1000 \text{ mg g}^{-1} \\
 &\quad \times 0.10 \times 0.2 \times 2 \text{ welders}] (K_{\text{mix}}) / 0.3 \text{ mg m}^{-3} \\
 &= 13.3 \text{ m}^3 \text{ min}^{-1} = 470 \text{ ft}^3 \text{ min}^{-1} \\
 &\quad (\text{Note: } 1 \text{ m}^3 \text{ min}^{-1} = 35.3 \text{ ft}^3 \text{ min}^{-1})
 \end{aligned}$$

- Exhaust volume flow rate at each hood:
 - Exhaust volume = supply volume = $470/2 = 235 \text{ ft}^3 \text{ min}$ per exhaust hood, well within the design and operational requirements of the proposed exhaust

hoods. (See **Engineering Control of Airborne Contaminants: History, Philosophy, and the Development of Primary Approaches** and Ref. (6) for more information on hood design and selection for specific processes like welding.)

- Volume of the confined space:

$$\text{Volume} = L \times W \times H = 18 \times 16 \times 14 = 4032 \text{ ft}^3$$

- Number of air exchanges in the confined space per hour:

$$N = Q \times 60 / \text{volume} = 470 \times 60 / 4032 = 7 \text{ ac h}^{-1}$$

- Area of the exhaust duct:

$$A_{\text{duct}} = \pi D^2 / 4 = 0.3491 \text{ ft}^2$$

- Velocity of air in the exhaust duct:

$$V_{\text{in,duct}} = Q / A = 470 / 0.3491 = 1350 \text{ fpm}$$

- Open area of the entrance hatch:

$$\begin{aligned}
 A_{\text{hatch open space}} &= 2 \text{ ft} \times 2 \text{ ft} - \text{area of duct} \\
 &= 4.0 \text{ ft}^2 - 0.3491 \text{ ft}^2 = 3.65 \text{ ft}^2
 \end{aligned}$$

- Velocity of air into the confined space through the entry hatch:

$$V_{\text{hatch opening}} = Q / A = 470 / 3.65 = 130 \text{ fpm}$$

- All design parameters appear feasible and within normal design criteria.

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ENGINEERING CONTROL OF AIRBORNE CONTAMINANTS: HISTORY, PHILOSOPHY, AND THE DEVELOPMENT OF PRIMARY APPROACHES

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1 INTRODUCTION

There are many approaches available for the control of air contaminant emissions and worker exposures. These include administrative and preventive controls (education, training, risk assessment, work practices, worker rotation, and job timing), personal protective controls (respirators, protective clothing, personal hygiene, and immunization), and engineering controls, the topic of this chapter and Industrial Ventilation.

Although attention is given in this chapter to the control of *chemical* airborne contaminants, many of the control principles are also applicable to biological and physical hazards. Brief historical case studies are used to illustrate applications of engineering control techniques and approaches. The target for control may be a hand tool, a piece of equipment, an operation, an integrated manufacturing process such as electroplating line, or a complete manufacturing facility in a dedicated building such as a foundry.

One model of the three critical zones of (I) contaminant generation, (II) release, emission, and dispersion, and (III) employee exposure is shown in Figure 1. Ideally, the goal is to engineer and operate the process or operation to eliminate air contaminant generation and emissions (e.g. using processes that have no generation or emissions). If

it is not possible to achieve this goal and a contaminant is emitted, the second defense is to prevent its dispersal in the workplace (e.g. using barriers, enclosures, and local exhaust ventilation). Finally, if these approaches are not feasible and emissions at the operation can result in worker exposure, control of the contaminated air is required (e.g. by dilution of the air contaminant to some safe, acceptable exposure concentration).

While this chapter covers the process and equipment design and materials selection, Industrial Ventilation covers the widely used engineering control topic industrial ventilation and Characterizing Air Contaminant Emission Sources covers techniques for characterizing emissions that cannot be controlled at the source.

The Occupational Safety and Health Administration (OSHA) considers engineering controls as any modification of plant, equipment, processes, or materials to reduce employees' exposure to toxic materials and harmful physical agents. As noted in Table 1, industrial hygiene authors have used a variety of terms to classify the various engineering control approaches (1–4). These are usually used in appropriate combinations. For example, to control a welding operation, the industrial hygienist (IH) may employ local exhaust ventilation, good work practices, and dilution ventilation for fugitive emissions (5).

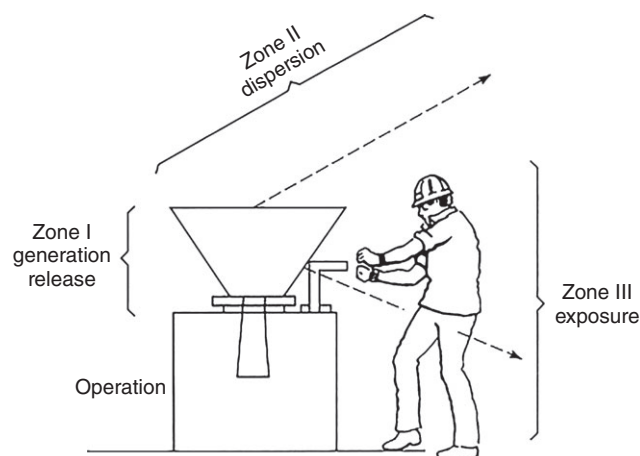


FIGURE 1 Contaminant generation, release, and exposure model.

TABLE 1 Classifications of methods for control of air contaminants.

<i>First (1)</i>	<i>Burgess (2)</i>
Material substitution	Toxic materials
Processing change	Eliminate
Equipment change	Replace
Local exhaust ventilation	Dust control
General (dilution) ventilation	Reduce impurities
Equipment enclosure	Equipment and process modification
Employee enclosure	Task modification
	Facility layout
<i>Gideon et al. (3)</i>	Ventilation
Control at source, material substitution	Local exhaust and dilution ventilation
Process or equipment change, Isolation	<i>Sherwood and Alsbury (4)</i>
Local exhaust ventilation	Automation, alternative methods
Work practice	Substitute materials, methods
Control at workplace	Plan layout, enclosures, remote
General exhaust ventilation	Local exhaust ventilation
Housekeeping	Dilution ventilation
Control at worker	
Isolation	

2 ENGINEERING CONTROL TYPES

The most widely used engineering control approaches include process change, substitution, elimination, isolation, enclosure and ventilation, both general and localized. In a technological sense, an appropriate combination of these approaches can usually be brought to bear on any industrial hygiene control problem to achieve satisfactory quality of

the work environment. A thorough analysis of the control problem must be made in order to ensure that cost-effective choices are made from among these methods. Controls must be compatible with the technical process, acceptable to the workers in terms of day-to-day operation, and be accomplished with optimal balance of installation and operating costs.

With the tendency for acceptable occupational exposure limits (OEL) to become increasingly more stringent, the duties of the IH must also include an ongoing analysis of installed control measures. Apart from problems associated with operation and maintenance of these provisions, the concept of the control provision itself might become outdated by changes in processes or regulations. The IH then must be able to develop and suggest effective control methods and must have the capability to continue to evaluate the effectiveness of these methods regularly.

2.1 Substitution and Elimination

Substitution frequently offers the most cost-effective solution to an industrial hygiene problem. There is a tendency to choose correction rather than elimination. For example, the first inclination for some in considering a vapor exposure problem in a degreasing operation is to provide or increase ventilation rather than substitute a solvent that has a lower degree of hazard associated with its use. In its broadest sense, substitution includes replacing hazardous substances, changing from one type of process equipment to another, or in some cases even changing the process itself.

Some examples of substituting materials of lower toxicity are classics in the history of emission and exposure control. Most IHS are familiar with the substitution of red phosphorus for white in the manufacture of matches, for example. Although this was done primarily in reaction to a tax law, the result was a markedly reduced potential hazard. The sequence of substitutions of degreasing solvents is, however, illustrative of a problem associated with substitution. Industry moved from petroleum naphtha to carbon tetrachloride to chlorinated hydrocarbons to fluorinated hydrocarbons. Each of these substitutions alleviated a problem but resulted in new problems. When using substitution as a control method, one hazard can be replaced by another if the substitution is not carefully considered.

Many industrial processes provide only limited opportunities to substitute less hazardous materials. However, it might be possible to substitute, or at least modify, process equipment. This approach is almost always used with physical hazards, for example, substituting safety glass for regular glass in enclosures, replacing unguarded equipment with properly guarded machines, and replacing safety gloves or aprons with garments made of materials more impervious to chemicals being handled. It can be every bit as effective with chemical exposures and chronic IH hazards.

In general, a change in any process from a batch to a continuous type of operation carries with it an inherent reduction in potential hazard. This is true primarily because the frequency and duration of potential contact of workers with the process materials are reduced when the overall process approach becomes one of the continuous operations. The substitution of processes can be applied on a fundamental basis. For example, substitution of airless spray for conventional spray equipment can reduce the exposure of a painter to solvent vapors. Substitution of a paint-dipping operation for the paint-spray operation can reduce the potential hazard even further. In any of such cases, the automation of the process can further reduce the potential hazard.

2.2 Isolation and Enclosure

The principle of isolation is frequently envisioned as being limited to installation of a physical barrier between a hazardous operation and the workers. Fundamentally, however, this isolation can be provided without a physical barrier by appropriate use of distance and time. Perhaps the most common example of isolation as a control measure is associated with storage and use of flammable solvents. Large tank farms with dikes around tanks, underground storage of some solvents, detached solvent sheds, and fireproof solvent-storage rooms within buildings all are commonplace in industry. Although the primary reason for the isolation of solvents is the risk of fire and explosion, the principle is no less valid as an engineering control of employee exposures.

Typically, application of the principle of isolation maximizes the benefits of other engineering controls such as local exhaust ventilation. For example, the charging of mixers is the most significant operation in many processes that use formulated ingredients. When one of the ingredients in the formulation is relatively high in toxicity, it is worthwhile to isolate the mixing operation, that is, construct a separate mixing room, thereby confining the airborne contaminants potentially generated by the operation to a small area rather than having them influence a larger portion of the plant. Using isolation also makes the application of industrial ventilation more cost-effective. (*Note:* Industrial Ventilation covers the important engineering control topic of industrial ventilation.)

2.3 Scope and Other Issues

Strategies used to implement engineering controls depend on the plant, process, and operation. The control problem may involve a single piece of equipment, a process, or an entire integrated manufacturing plant. In a simple situation faced by IHS, a shop repairing electric motors may, for example, consider a change in solvents in a parts cleaner. The number of persons participating in the control strategy review is

small, the decision will be made in a short time, and it will probably rely heavily on vendor information.

A far more complex situation, as another example, involves the scale-up of a chemical process, say, to manufacture a photographic dye. The research to develop the new molecule and synthesize a small quantity for initial tests is completed by a research chemist at a laboratory bench. At this stage, little is known about the chemical or its toxicity, however, since gram quantities are handled in a well-controlled laboratory hood, the risk is negligible. The next step involves a scale-up of the operation in a pilot plant facility designed to manufacture kilogram quantities of the material for testing purposes. This testing will provide limited data on the physical properties of the new chemical, its product potential, and toxicity data. If the results are encouraging, production scale-up is considered. A premanufacturing notification may be submitted to the Environmental Protection Agency (EPA) and/or to other air pollution control authorities prior to production. These submissions, which typically require a description of air contaminant control technology and an estimation of worker exposure, may involve a comprehensive review of the operation, as described in Table 2. Suppose it is decided to manufacture the chemical at an existing plant using conventional chemical processing equipment. If the IH has been involved in the pilot plant operation, he or she is well placed to participate in a review of the control technology necessary for the full-scale plant. As demonstrated in Table 2, the range of talent necessary to define the engineering controls may be extensive and the time frame well extended.

Step-by-step review to identify the appropriate engineering controls will minimize worker exposure. If appropriate exposures are not installed during initial construction, then controls will be retrofitted at significant increased cost. Early integration of controls are most easily accepted and economically implemented.

The most complex engineering controls are encountered in the design and construction of a large and complex production facility. The project is complex due to the range of issues that are encountered; however, the design process is started with a clean design sheet and state-of-the-art controls can be included in the design. In the example in Table 2, a large number of specialists are included in the review team. If the design is done in-house, the IH should be a key participant. If the design work is contracted to a design and construction firm, plant personnel are one-step removed from the design process. The company will usually have a project engineer to interface between the outside team and company engineering group. In this case, clear communication must be established by the IH to ensure involvement in the design review.

For the IH facing his or her first process hazard review, the job may seem daunting. An initial step is to identify your responsibility. Does it include merely health issues at the workplace or are environmental and fire protection problems

TABLE 2 Specialists participating in risk assessment of new chemical manufacture.

	Administrative	Legal	Sales	Marketing	Chemists	Engineers	Toxicologists	Occupational hygienists	Environmental scientists	Statisticians	Risk analyst	Transportation systems analysis	Economists	Information specialists
<i>Part I: general information</i>														
A. Manufacturer identification	X	X												
B. Chemical identity					X									X
C. Marketing data			X	X						X			X	
D. <i>Federal Register</i> notice	X	X		X	X	X	X	X	X					
E. Schematic flow diagram					X	X		X	X					
<i>Part II: risk assessment data</i>														
A. Test data		X			X		X		X	X	X			
B. Exposure from manufacture														
1. Worker exposure					X	X	X	X		X	X			
2. Environmental release					X	X			X	X	X			
3. Disposal					X	X	X	X	X		X			
4. By-products, etc.					X	X					X			X
5. Transportation		X		X		X					X	X		
C. Exposure from process operations														
1. Worker exposure					X	X	X	X		X	X			
2. Environmental release					X	X			X	X	X			
3. Disposal					X	X	X	X	X		X			
D. Exposure from consumer use	X	X	X	X		X			X		X			
<i>Part III: risk analysis and optional data</i>														
A. Risk analysis and optional data	X	X			X		X		X		X			
B. Structure–activity relationships					X		X				X			
C. Industrial hygiene	X	X			X	X	X	X			X			
D. Engineered safeguards					X	X	X	X	X		X			
E. Industrial process and use restriction data					X	X								
F. Process chemistry					X	X								
G. Nonrisk factors: Economic and noneconomic benefits	X	X	X	X	X	X					X		X	

to be included in your review? Once your responsibility has been defined, the issues of concern for the project should be identified. Mature industries such as metallurgical, glass, and ceramics have been studied and extensive information is available on standard operations and sources of contamination. As noted in *Characterizing Air Contaminant Emission Sources*, the EPA has published emission factors for many processes that are useful in process hazard reviews. Other sources of information on control technology for mature industries include numerous technical reports published by the National Institute for Occupational Safety and Health (NIOSH). Search for specific topics at: www.2a.cdc.gov/nioshtic; www.cdc.gov/niosh/surveyreports/default.html.

If the employer or company has similar operations elsewhere, obtain material and process data, industrial hygiene survey data, and air sampling information from that plant to assist in the review. A step-by-step review of the operations can then be undertaken. This health and safety review should be as rigorous as the review of percent yield on the process and produce a detailed process flow diagram showing the locations of contaminant emissions in addition to the major physical stresses such as noise, heat, and ergonomics. It is also important to consider ancillary systems such as compressed air, refrigeration, cooling towers, and water treatment. Bulk handling of chemicals and granular minerals frequently presents a major industrial hygiene problem and should be given special attention. Finally, a detailed description of the workers' tasks, including required emergency response actions, is required since work location and movement have a major effect on contaminant control. A comprehensive checklist for review of environmental and occupational health and safety issues in planning major plant construction was provided by Whitehead (6).

An element that is frequently overlooked in the design of engineering controls is the worker. A review of a specific operation conducted by several workers frequently will identify subtle differences in the way the task is performed. A worker inspired by a wish to reduce lifting or reduce dust exposures may modify the tasks to accomplish these ends. Workers frequently have insight into details of the operation that the design engineer will overlook. The real-time video monitoring approach discussed in Section 3.2.1 is useful in defining these modifications in tasks.

It is sometimes difficult to find standard engineering controls for emerging technologies. In some cases, industrial groups develop and publish their own engineering controls. Such is the case, for example, with advanced composite manufacturing, a technology that was developed in recent years in the manufacture of aircraft. An association of companies involved in this work has published a volume describing the major hazards and the controls that should be applied (7).

The best control is often developed in the field, working with plant employees. In the 1970s, for example, a number of

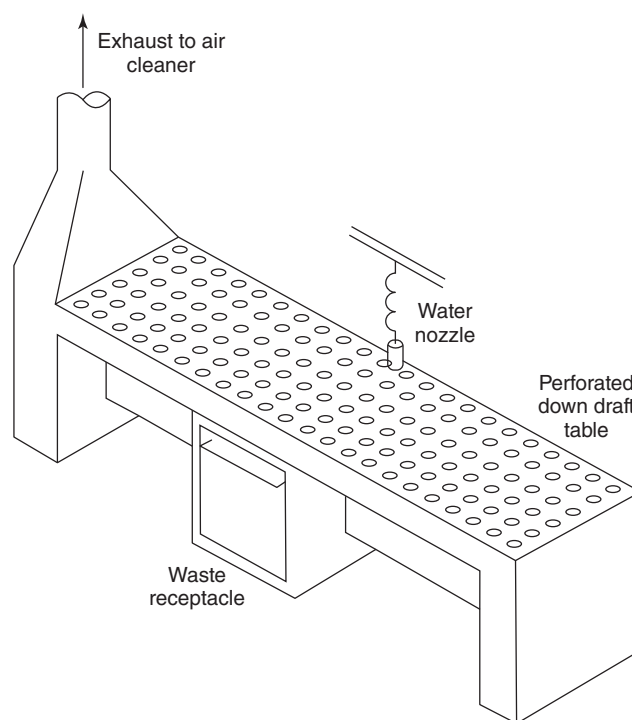


FIGURE 2 Integrated controls on an asbestos insulation fabrication workbench.

cases of asbestosis in shipyard workers fabricating asbestos insulating pads for steam propulsion plants prompted the plant to develop an integrated workstation incorporating a number of control features. Initial designs of the down-draft work table were fabricated and evaluated by workers resulting in a number of recommendations that were incorporated in the final table, improving its acceptance and performance (Figure 2).

3 ENGINEERING CONTROL STRATEGIES

As noted earlier, engineering controls attempt first to eliminate air contaminant generation and emission; second, prevent dispersal in the workplace; and third, control contaminated air concentrations in the breathing zones of employees. This stepped strategy is impacted by the influence of toxic materials present in the process, plant equipment, process type, operational factors, job tasks, work practices, plant layout, and other factors discussed below.

3.1 Control of Toxic Materials

The use of toxic materials ranges in complexity from simple wet degreasing to the synthesis of new chemicals as noted

above. In degreasing, the exposure is associated with the use of the cleaning agent or handling of its wastes. In synthesis of a new chemical, exposure may occur to raw materials, intermediates, by-products, and the new chemical and/or waste streams. To minimize worker exposure to such chemicals, it is necessary to consider the following engineering control options.

3.1.1 *Eliminate the Toxic Material*

This option refers to elimination without replacement. Toxic chemicals are often used in a process to improve yield or to improve function or appearance. After careful review, it may be possible to eliminate the chemical. The pressure to do so may come from potential health effects, the cost of workplace, and environmental controls to introduce the toxic chemical into the plant, or it may arise from pressure from the marketplace. An example of the latter resulted from legislation in Switzerland requiring precautionary labeling of batteries containing mercury. The conventional dry cell battery utilized electrodes of manganese dioxide and zinc with an electrolyte of ammonium chloride. A characteristic of the cell was zinc corrosion with subsequent power loss. A mercury compound was added to inhibit this corrosion and resulting performance degradation. At least one manufacturer determined the performance enhancement from mercury was not necessary and the mercury compound was removed from the battery formulation (8). This change eliminated exposure to mercury for several hundred workers in this company.

3.1.2 *Replace with Alternative Material: Substitution*

This control approach has the greatest potential for significant reduction in worker exposure to toxic chemicals. One famous example involved the cooperative action taken by the U.S. Public Health Service, the State of Connecticut Department of Public Health, industry, and labor unions in 1941 to prevent mercurialism by replacing mercuric nitrate with

nonmercury compounds in the carroting process in felt hat manufacture.

In another example, amendments to the Safe Drinking Water Act effectively banned the use of lead-based solder. The acceptable alternative solders are alloys of tin in the range of 90–95% and the balance is copper, silver, zinc, or antimony (9). The introduction of the alternative solder minimized exposure of manufacturing, construction, and maintenance personnel to lead. The banning of mercury in hat manufacture was an action taken specifically for occupational health reasons; the action on lead-based solder was prompted by environmental concerns but had a positive impact on the health of plant workers.

3.1.2.1 HISTORICAL TOXIC CHEMICALS USE REDUCTION AND REPLACEMENT APPROACHES It is useful for the IH to understand and incorporate into IH engineering control strategies the toxic materials management nomenclatures, approaches, and programs that have developed over the past three decades in the broader EH & S field (see Table 3).

The Pollution Prevention Act of 1990, for example, described a national U.S. policy toxic waste management hierarchy as follows: first, source reduction as the most desirable approach; second, recycling and reuse; third, treatment; and finally, disposal as the least desirable approach (11).

To initiate this strategy the EPA established the Waste Reduction Innovative Technology Evaluation (WRITE) program. This program funded programs in six states and one county over a three-year period to (i) provide engineering and economically feasible solutions to industry on specific pollution prevention problems, (ii) provide performance and cost information on these techniques, and (iii) promote early introduction of these pollution prevention programs into commerce and industry. A review of completed WRITE programs that demonstrated the usefulness and importance of replacement technology is shown in Table 4 (12). Although initiated for environmental quality reasons, each of these changes had a positive impact on worker health in the facilities using these chemicals.

TABLE 3 Environmental control approaches.

Form of control	Emphasis	End rule
Pollution control	"End-of-pipe" control	Does not eliminate pollution, but merely transfers contaminant from one media to another. Incurs an environmental risk from transporting toxic chemicals
Pollution prevention Toxic use reduction	Reduction in the production of contaminants Reduction in pollutants generated in manufacturing by changes in plant operation procedures, production processes, materials, or end products. Focus on a target list of chemicals	Direct waste reduction, covers all pollutants Priority setting permits control of high potential risk chemicals

Source: Adapted from Ref. (10).

TABLE 4 Examples of material replacement from EPA WRITE program.

Operation	Original material	Replacement
Anodizing aluminum parts	Chromic acid anodizing, hexavalent chromium exposure	Sulfuric acid anodizing, eliminates exposure to chromium
Removal of paint on defective parts	Methylene chloride-based paint stripper	Abrasive blasting with plastic beads, no vapor exposure
Flexograph printing	Application of alcohol-based ink labels	Water-based inks eliminate vapor exposure
Cleaning and deburring small metal parts	Vapor degreasing and alkaline tumbling	Automatic aqueous rotary washer. Eliminates vapor and caustic mist exposure
Cleaning flexographic plates	Solvent cleaning with Stoddard solvent, acetone, toluene, and alcohol	Cleaning with terpenes and aqueous cleaners

Source: Adapted from Ref. (12).

TABLE 5 Step model for the substitution process.

Operation	
1	Problem identification
2	Identification and development of a range of alternatives
3	Identification of consequences of the alternatives
4	Comparison of the alternatives
5	Decision
6	Implementation
7	Evaluation of the result

Source: Adapted from G. Goldschmidt, "Improvement of the Chemical Working Environment by Substitution of Harmful Substances: An Iterative Model and Tools," personal communication, 1991.

Historically, EPA has kept and maintained extensive statistics about toxic materials in its Toxics Release Inventory (TRI) database. The TRI tracks hundreds of chemicals found in over thousands of facilities that manufacture, use, process, or dispose of them. Such facilities are required to provide annual reports on release, disposal, and management of these 650 chemicals. See https://iaspub.epa.gov/triexplorer/tri_release.chemical to find more information.

Denmark, one of many European countries to embark on a national toxic use reduction program, based their work on the simple step model shown in Table 5 (G. Goldschmidt, personal communication).

The simplicity of this approach suggested that replacement technology can be done on an ad hoc basis, however, Goldschmidt (G. Goldschmidt, personal communication) warned that chemical replacement for occupational health reasons is a complex task and requires a systematic review of both the existing conditions and those prevailing after the replacement action. A review of 162 individual replacement actions by the Danish Occupational Health Services confirmed that replacement was successful if done in a rational manner following the step model shown in Table 5. Among the impressive examples of this program was the replacement with water-based systems of the solvent-based paints in all indoor paints and most outdoor paints.

3.1.2.2 STATE TOXIC USE REDUCTION PROGRAMS The Massachusetts Toxic Use Reduction Act of 1989 was a good example of state efforts to control toxic materials in that it focused on toxic use reduction and excluded off-site recycling, off-site nonproduction unit recycling, transfer, or treatment. The five toxic use reduction techniques acceptable under the Massachusetts act were as follows:

- *In-Process Recycling or Reuse.* Recycling, reuse, or extended use of toxins by using equipment or methods that become an integral part of the production unit of concern, including, but not limited to, filtration and other closed-loop methods.
- *Improved Operations and Maintenance.* Modification or addition to existing equipment or methods, including, but not limited to, such techniques as improved house-keeping practices, system adjustments, product and process inspections, or production unit control equipment or methods.
- *Changes in the Production Process.* Includes both the modernization of production equipment by replacement or upgrade based on the same technology or the introduction of a new production equipment of an entirely new design.
- *Input Design.* Replacement of a chemical used in production with a chemical of a lower toxicity.
- *Product Reformulation.* Redesign of the product to produce a product that is nontoxic or less toxic on use, release, or disposal.

Rossi et al. (10) proposed two divergent routes a manufacturer could take. The route for ease of implementation included first, recycling and improved operations and maintenance, then production process changes, and finally replacement of toxic chemicals and product reformulation. However, for effective toxic use reduction, the first step was to eliminate or replace the toxic chemical in the process

or reformulate the product, then initiate production process changes, and finally, recycle and apply operations and maintenance control techniques.

3.1.2.3 INDUSTRY-BASED PROGRAMS One company's program to reduce toxic materials use is instructive for the IH and is summarized here. The company had multiple goals to reduce the use of toxic chemicals, minimize toxic emissions to all environmental media, encourage recycling of chemicals, and reduce all wastes (8). In the design of this program, the company followed many of the recommendations of the Office of Technology Assessment report on the reduction of hazardous waste. In this company program, specific goals for toxic use and waste reduction are set for all production managers and their annual performance reviews included this issue.

Each chemical used in the company was assigned to one of five environmental risk categories (ERC). (The materials in ERC I posed the greatest risk to the environment and ERC II–ERC IV represented progressively less risk. A fifth category included plastic, steel, paper, and other waste identified as rubbish, rubble, and trash.) A critical issue in the design of the program was the decision logic for assigning categories. A number of options were considered, including ranking chemicals based on workplace exposure guidelines such as threshold limit values (TLVs) or permissible exposure limits (PELs), label signal words (13), regulatory lists published by OSHA and EPA, and the mathematical weighting of a range of risk factors, including toxicity and chemical and physical properties (E. Karger, personal communication).

The company chose to assign the ERCs based on a "wise person" approach based on a battery of risk factors reflecting the materials' total occupational and environmental impact from release both as an isolated incident such as a spill or the chronic release of small amounts of the chemical to air, water, and soil. The majority of risk factors were toxicity based and chosen to identify significant adverse health and environmental impact. Included in the group of risk factors were acute and chronic toxicity based on animal studies or structural analysis, human case history, and epidemiological studies, carcinogenicity, mutagenicity, teratogenicity, and reproductivity effects. A limited number of physical and chemical properties associated with the "releasability" of the chemicals were also included in a second group of risk factors. The third group of risk factors reflected broad environmental impacts. The specific criteria for assignment to the five categories are shown in Table 6.

This company had a major chemical production facility involved in the manufacture of photographic dyes that required frequent changes in processes. Ahearn et al. (8) state that in the design of new processes and products, the evaluation of toxic use and waste minimization technology should be given equal importance to considerations of cost and performance of a new process or product. The

TABLE 6 Categories for a corporate toxic use reduction program.

Categories I and II: use to be reduced
Human or animal carcinogens, teratogens, or reproductive agents
Highly toxic chemicals
Chemicals with human chronic toxicity
Chemicals for which there are adverse environmental impacts
Category III: transportation off-site to be reduced via source reduction or recovery and reuse on-site
Suspected animal carcinogens
Moderately toxic materials
Chemicals that cause severe irritation of eyes and respiratory tract at low concentrations
Chemicals with limited chronic toxicity
Corrosive chemicals
Chemicals for which there are environmental considerations
Category IV: disposal volume to be reduced via waste reduction or reuse following onsite recycling
All other chemicals not included in Category V
Category V: any material such as paper, metal parts, and so on that is identified as rubbish, rubble, or trash

Source: Adapted from E. Karger, personal communication, 1992.

engineering group developing the new processes rigorously reviewed all materials and process alternatives to ensure that the target reductions were met. In this company, the "end of pipe" abatement strategy was given secondary attention relative to optimization of process and product design for toxic use reduction.

An important part of the program was the goal of a 10% reduction in the use of toxic materials per unit of production each year for the first five years following the general strategy of elimination of use, replacement with a material of lower risk, reduction in quantity used, and a hierarchical program of waste handling. The goal was to eliminate, replace, or reduce the use of categories I and II materials and ensure the maximum reuse of categories III and IV materials.

In describing the success of the program, the authors (8) presented an example of a process in which a change resulted in elimination of a carcinogenic material. The original process required an aqueous oxidation step using a hexavalent chromium compound; the new process was based on a catalyzed air oxidation step that did not require the chromium compound (Figure 3). As a result of this change, worker exposure to hexavalent chromium was eliminated and this process change saved the company over one million dollars. It was the conclusion of this company that the process that used the least quantity of toxic chemicals was usually the most economical.

As active participants in the global market, manufacturers in the U.S. have been implementing international management consensus standards. The most widely sought approval continues to be that of the ISO 14000 Environmental

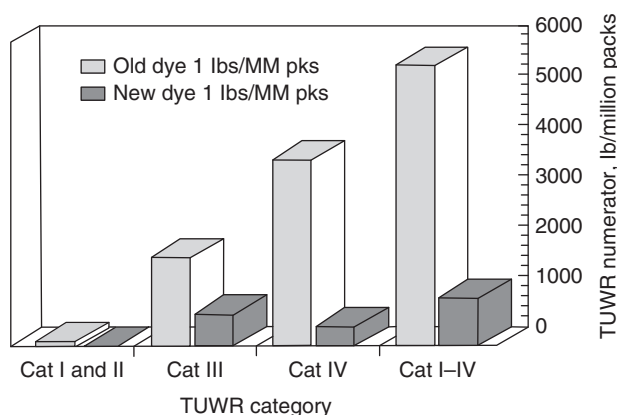


FIGURE 3 Impact of replacement technology on a chemical process resulting in the elimination of hexavalent chromium from the workplace and its impact on toxic use and waste reduction (TUWR) categories. Source: Courtesy of Polaroid Corp.

Management Systems Standard (14). To gain registration under this standard, a firm is audited to ensure that the company has an effective management system in place so that appropriate decisions can be made regarding their impact on the environment (and as a consequence, a positive impact on employee health).

3.1.2.4 OUTCOME OF REPLACEMENT TECHNOLOGY Although the replacement of toxic chemicals may provide impressive gains, the replacement of a target material must be done with great caution. If the replacement technique is to be used successfully, it must be carefully reviewed to define its impact on worker health and environmental impact, product yield, and product quality (Figure 3). It is important that the impact be evaluated in both pilot plant operation and field trials before making the change.

Historically, IHs have devoted more attention to solvent replacement for metal cleaning than any other control problem. It is useful to expand on the history of such cleaning agents because it demonstrates the complexity of the replacement technology approach and suggests pitfalls that may arise in using this technique. Wolf et al. (15) review the major decisions on general degreasing solvents during this period as follows:

In the 1960s and 1970s in particular, chlorinated solvents were widely substituted for flammable solvents because they better protected workers from flammability. As smog regulations were promulgated in the late 1960s and early 1970s, users moved from the photochemically reactive flammable solvents and TCE to the other “exempt” chlorinated solvents. In the 1980s, there was increased scrutiny of the chlorinated solvents: TCE, PERC, and METH were considered undesirable because of their suspect carcinogenicity,

and TCE and CFC-113 were being examined for their contribution to stratospheric ozone depletion.

Each change starting in the 1950s, progressing from flammable solvents to chlorinated solvents to nonphotochemical reactive materials to chlorofluorocarbon (CFC) solvents, introduced a new set of problems. The six major classes of solvents were used in 1999 and there was pressure for replacement due to the array of human toxicity and environmental effects. The increased use of CFCs in the 1970s and 1980s, rising to a level of 180×10^3 metric tons per year, was based on performance and reduced chronic toxicity. However, the impact of these chemicals on ozone depletion resulted in the ban on manufacturing of CFC-113 and 1,1,1-trichloroethane (TCA) worldwide in 1996. The hydrochlorofluorocarbons were considered interim candidates for industrial degreasing, but are now considered for banning in 2020 and 2040. The hydrofluorocarbons and the other candidate solvents not containing chlorine do not present an ozone depletion risk but may present unacceptable toxicity concerns.

A vigorous research effort was pursued by dozens of companies to develop alternatives to the cleaning agents listed in Table 7. It is doubtful that a single agent will ever be found that will have the broad application of the chlorinated solvents, however, good progress has been made in nonozone-depleting, hydrocarbon-based systems. Again, all these efforts have indirectly put positively impacted employee exposure, health, and well-being. As such, it is useful for the IH to be involved in and aware of all forms of environmental actions.

3.1.3 Dust Control

A number of techniques are used to minimize worker exposure to pneumoconiosis-producing and toxic dusts based on changes in the physical form or state of the material. The common techniques to reduce “dustiness” in this manner are presented below.

3.1.3.1 MOISTURE CONTENT OF MATERIAL The relationship between moisture content of granular materials and worker exposure to dust is well known. The use of water as a dust suppressant has been of great interest to the mining, mineral processing, and foundry industries. Research by the British Cast Iron Research Association demonstrated that silica in air concentrations in foundries was maintained below the then existing exposure standards when the moisture content of foundry sand was kept above 30% (16). A sand handling technique that involves direct blending of new moist sand directly from the mixer with shakeout sand to add moisture to cool the shakeout sand and reduce dustiness was described by Schumacher (17). The author also demonstrated

TABLE 7 Characteristics of historic generic solvent categories.

Generic solvent category	ODP ^a	Photochemical reactivity	GWP ^b	Flash point ^c	Tested for chronic toxicity
Flammable solvents	—	Yes	—	F	
Isopropyl alcohol					Rule issued
Mineral spirits					No
Combustible solvent ^d	—	Yes	—	C	
Terpenes					Limited ^e
DBE					No
NMP					Rule issued
Alkyl acetates					No
Chlorinated solvents					
TCE	—	Yes	—	—	Yes
PERC	—	Yes ^f	—	—	Yes
METH	—	No	—	—	Yes
TCA	0.1	No	0.02	—	Yes
Chlorofluorocarbons (CFCs)		No			
CFC-11	1.0		1.0	—	Yes
CFC-113	0.8		1.4	—	Yes
Hydrochlorofluorocarbons (HCFCs)		No			
HCFC-123	0.02		0.02	—	In testing
HCFC-141b	0.1–0.18		0.09	—	In testing
HCFC-225	NA		NA	—	In testing
Hydrofluorocarbons (HFCs) and fluorocarbons (FCs)					
Pentafluoropropanol	—	NA ^g	NA ^g	NA ^g	No

^aODP: The oxygen depletion potential is the potential for ozone depletion of 1 kg of a chemical relative to the potential of 1 kg of CFC-11, which has a defined ozone depletion potential of 1.0.

^bGWP: The global warming potential of a chemical is the potential of 1 kg of the chemical to cause global warming relative to the potential of 1 kg of CFC-11 to cause global warming. CFC-11 has a GWP of 1.0.

^cF, flammable; C, combustible.

^dDBE, dibasic esters; NMP, *N*-methyl-2-pyrrolidone.

^eOne of the terpenes, D-limonene, has been tested.

^fAlthough PERC is not photochemically reactive, it is not exempt under the Clean Air Act.

^gNA means not available.

Source: Adapted from Ref. (15).

a correlation between results of a simple laboratory dustiness test and in-plant dust exposure.

The Bureau of Mines and the National Industrial Sand Association investigated the use of foams, steam, and water sprays for dust control in mineral processing plants (18). Foam was found to be approximately 20% more effective than water alone or water with a surfactant. Steam also produced impressive reductions in dust concentrations of 65%, however, as is the case with foam, it is more expensive to apply than water.

The British Occupational Hygiene Society (19) explored various dustiness estimation methods that could be useful in design of control systems. In chemical processing, a solid product is often isolated in cake form that is wet with solvent or water. Frequently this material must be dried to ensure product quality and shelf life and to permit packing and shipping. However, if the product is to be used “in-house,” one should determine if the drying operation can be omitted permitting direct handling of the wet cake thereby saving money and reducing dustiness.

3.1.3.2 PARTICLE SIZE In general, the more extensive the grinding or comminution of a granular material, the greater the dust hazard the material will present during transport, handling, and processing. When possible, purchase the most coarse form of the chemical that is suitable for the process. There are production implications that may override considerations of worker exposure. As an example, if the material must be placed in solution, the large particle size will slow this process.

3.1.3.3 DUST CONTROLLED FORMS In the last three decades, the rubber, pharmaceutical, pigments, and dyestuff industries have given attention to the dustiness of the raw materials they produce and use. Dustiness testing has been extended and significant product design changes have been adopted to minimize dustiness, worker exposure, and product acceptance. In tire manufacture at least a dozen chemicals in granular form are added in small quantities to the batch mix. In an effort to minimize worker exposure to dust from these chemicals, The British Rubber Manufacturing Association

TABLE 8 Dust-controlled forms of rubber production chemicals: comparative performance.^a

Property	Untreated powder	Wax or otherwise bound			Polymer bound		
		Soft paste	Putty	Prills	Pellets/granules	Slab	Pellets/granules
Active content	5	3	4	5	4	4	4
Convenience of handling	3	1	2	4	5	2	5
Freedom from dust	1	5	5	4	4	5	5
General cleanliness and safety	1	1	2	3	3	5	5
Suitability for automatic weighing	3	1	1	4	4	1	5
Wastage	3	2	4	4	4	5	5
Ease of disposal of containers	3	1	3	3	4	4	4
Identification	—	—	—	—	—	—	—
Mill mixing behavior	3	1	3	3	3	5	4
Internal mixing behavior	5	2	3	5	5	5	5
Dispersion in rubber	5	5	4	3	4	4	4
Total	32	22	31	38	40	40	46

^a5 = excellent; 4 = good; 3 = average, 2 = below average; 1 = poor.

Source: Adapted from Ref. (20).

sponsored design of low dusting forms of these common chemicals. The properties of seven dust-controlled forms of rubber chemicals were reviewed by Hammond (20), shown in Table 8. The author notes that the disadvantages of the most effective approach, coating the chemical with a polymer, included the variability in active chemical content based on bulk weight, the reduced chemical content, and the unsuitability of the polymer in the formulation.

3.1.3.4 SLURRY FORM This application has limited application, but in those cases where it can be used, it does have great impact on dust concentrations. In the tire industry, for example, “masterbatch” rubber, rubber processed with all chemicals except the vulcanizing agent, was processed from the Banbury to the drop mill where it was “sheeted off” for storage. Until 1960, dry talc or limestone was dusted on the slabs of “masterbatch” material to keep it from sticking. This operation resulted in poor housekeeping and a significant exposure to talc. A more protective technique, adopted in the 1960s, involved dipping the stock in a slurry of talc-in-water before racking for storage. This simple change resulted in a significant reduction in worker exposure to talc.

3.1.4 Impurities in Production Chemicals

Even in low concentrations, impurities or unreacted chemicals in a raw or final product may create exposures that warrant control.

3.1.4.1 RESIDUAL MONOMER IN POLYMER In polymer manufacture, there is frequently unreacted monomer in the final product. Residual monomer had not been given much attention until the early 1970s when angiosarcoma, a rare liver cancer, noted in workers manufacturing the vinyl chloride polymer was attributed to the monomer exposure.

Investigation showed that the polymer used in subsequent fabricating operations had unreacted monomer present in concentrations as high as 0.4% (21). This level of contamination prompted concern about the monomer exposure of workers handling the bulk polymer in plastic fabrication operations such as injection molding. As a result of this concern, the vinyl chloride manufacturers modified the manufacturing process to reduce the monomer concentration to less than 1 ppm (22), thereby eliminating significant worker exposure. Residual monomer is frequently present in concentrations up to 1% in many of the common polymers and may warrant control. If significant air concentrations are noted when handling the polymer, engineering control should be first based on the removal or reduction of the monomer content in the polymer, with other controls considered next if this is not possible.

3.1.4.2 SOLVENT IMPURITIES Impurities may pose an unrecognized risk, especially in solvents of high volatility. In the manufacturing of automobile tires, for example, the various rubber components were “laid up” on a tire-building machine. To effect good bonding between the components, the rubber was made tacky by applying a small amount of solvent to the surface with a pad. For several decades, this solvent was benzene. Worker exposure, probably in the range of 1–10 ppm, may be responsible for the excess leukemia seen in older tire builders. Starting in the 1950s, the industry began to replace benzene with white gasoline, a safer solvent. However, in studies completed in the 1970s by the Harvard School of Public Health Joint Rubber Studies Group, the residual benzene content in white gasoline was 4–7% and air sampling indicated that 1/3 of the air samples on tire builders exceeded 1 ppm (R.L. Treitman, personal communication). As shown by this historic example, technical-grade chemicals can have

significant impurities. The level of contamination should be identified by the IH and if sufficiently high, worker exposure should be evaluated. The necessity for the reduction in the impurity level can then be determined.

3.2 Equipment and Processes

In Section 3.1, the engineering control options focused on the choice of materials to minimize the generation and emission of airborne contaminants. An equally important step is a review of the various alternatives in the choice of equipment and processes. A number of operational insights should be considered when choosing a facility and its equipment. Wolfson (23) emphasized the importance of this effort and suggested that the removal of dispersal mechanisms should be a major objective of the design and selection of facilities and equipment.

3.2.1 Diagnostic Air Sampling

Contaminant control cannot be achieved until the significant operational elements of the process that generate and release the contaminant are identified. Occasionally, this can be done simply by a critical review of the operations but usually, diagnostic air sampling is necessary.

The value of short-interval, task-oriented air sampling using conventional integrated sampling with subsequent analysis has been clearly stated by Caplan (24). In describing this approach, illustrated in Table 9, Caplan states,

For the job analyzed in Table 9 presumably a single sample would have shown a concentration of 0.21 mg m^{-3} . The task-oriented sampling, however, reveals several interesting things.

Column 5 shows that tasks B and C are the major contributors to the day's exposures and that a significant reduction in the concentration at either of those tasks would be adequate to bring the eight-hour exposure well below the TLV. This is true even though task C in itself is below the TLV. In addition,

it shows that task F, well above the TLV concentration, is of such short duration that significant improvement in that part of the exposure would not have a large effect on the eight-hour exposure.

The difficulty in this approach is that it is not possible to frequently measure the air concentrations during brief individual tasks and activities due to the low air sampling rate and the limited sensitivity of the analytical procedures. To reveal important generation points in the job, it is necessary to resolve the air concentration profile in a time frame of seconds. The advent of real-time, direct-reading air sampling instruments for particles, gases, and vapors with response times of less one second now permit the investigator to identify these critical contaminant elements in process events and work practices. In recent years, this air sampling technique has seen expanded application with coincidental videotaping of the worker during a work cycle. In its most sophisticated form, the time-coupled, real-time contaminant concentration at the workers breathing zone is superimposed on the video display permitting the viewer to analyze the data display to identify the specific time and location of release. Control technology can then be applied to those tasks or incidents.

The video display approach may also be used to identify work practices that may either positively or adversely affect worker exposure. In a talc bagging operation, for example, one individual consistently had the lowest dust exposure although visual inspection did not reveal any differences in equipment or work practice. If the real-time technique were available, the worker's "secret" could have been identified and applied to the other workers. When a "correct way of doing the job" can be identified, the video concentration format is an excellent educational tool for workers.

A series of studies by NIOSH investigators described the application of this technique to a range of in-plant tasks (25,26). The air sampling instrument was a real-time monitor with a response time much shorter than the period of the shortest worker activity or movement. The instrument was equipped with a data logger with a clock "locked-in" or synchronized with the video. The data logger was

TABLE 9 Task-oriented air sampling.

Task	GA/BZ ^a	Minutes/day	Concentration (mg m^{-3})	Minutes/day $\times$ concentration
A. Charge pot	BZ	40	0.12	4.8
B. Unload pot	BZ	80	0.50	40.0
C. General survey	GA	250	0.16	40.0
D. Lab: sample trips	GA	20	0.05	1.0
E. Change room	GA	30	0.08	2.4
F. Pump room: repack	BZ	30	0.32	9.6
G. Lunch room	GA	30	0.07	2.1
		480		99.9
TLV = 0.2 mg m^{-3}	Wt. avg. = $99.9/480 = 0.21 \text{ mg m}^{-3}$			

^aGA, general air; BZ, breathing zone.

Source: Adapted from Ref. (24).

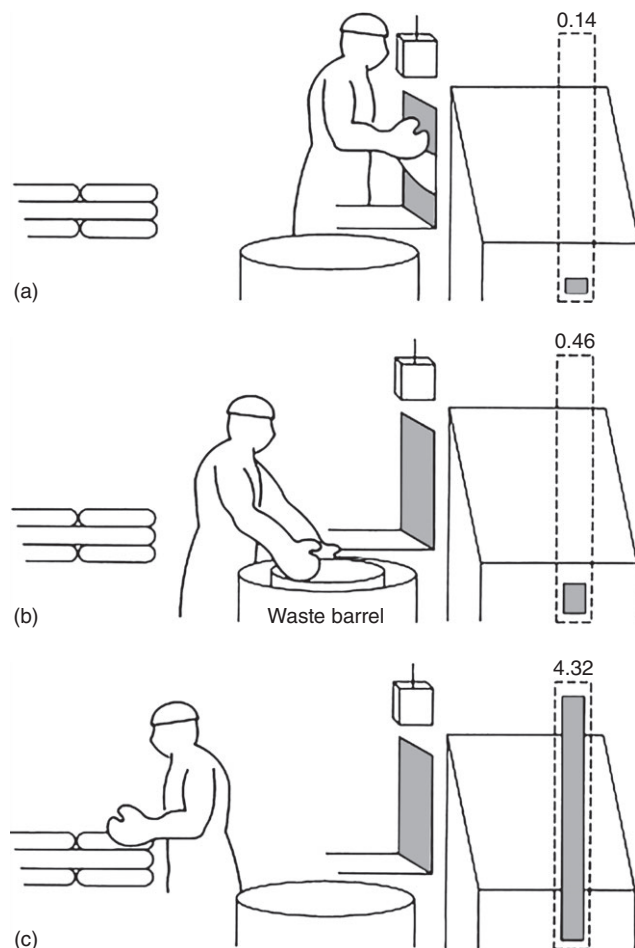


FIGURE 4 Relative dust exposure during bag dumping as determined by video air sampling technique. (a) Operator slits bag and dumps the granular material into a hopper equipped with an exhaust hood with minor dust exposure. (b) Operator drops the bag into the waste barrel; there is a significant increase in dust concentration. (c) As the operator pushes the bag into the waste barrel, a cloud of dust is released and the relative dust concentration increases to 4.32. Source: From Ref. (28). Reprinted with permission from Applied Occupational and Environmental Hygiene, 7(4), 1992.

downloaded to a computer and the data file was analyzed permitting a graphical overlay of air contamination data on the videotape. In Figure 4, the video display from a study of a bag dumping operation is re-created in a line drawing for clarity to show the time-coupled concentration on the video screen display (28). Graphical representation of the air sampling data for three jobs with the concentration from the video overlay is shown in Figure 5 (30).

The application of this technique to control technology was shown (31) at a chemical weighing and transfer station. The information obtained permitted the investigators to redesign the workstation controls based on a perimeter exhaust hood and an air shower to eliminate eddies induced

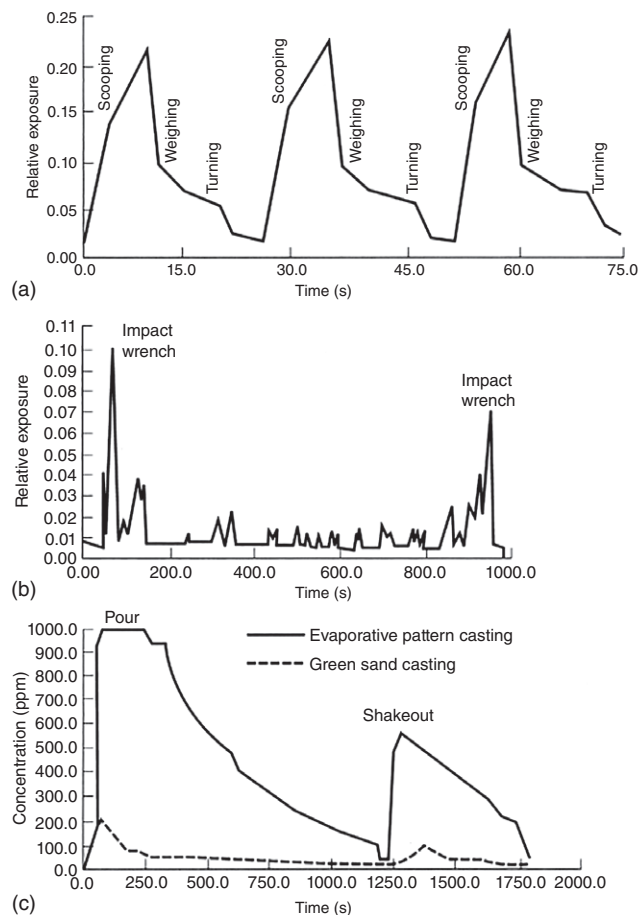


FIGURE 5 Peak dust exposures identified by video real-time monitoring. (a) Relative exposure versus time for three bags during manual weigh out of powders. (b) Relative dust exposure during automotive brake servicing. (c) Carbon monoxide emissions from evaporative pattern casting and green sand processes. Source: From Ref. (30). Reprinted with permission of Applied Occupational and Environmental Hygiene. Taylor & Francis.

by the worker's body. Effective control of the dust exposure was obtained with one-third of the airflow of the original system. In addition to improved worker protection, the cost savings of the new system resulted in a payback period of 4.5 years.

The Swedish National Institute of Occupational Health adapted this technique to allow real-time mixing of the concentration and video portions by radio telemetry (27). The intermediate datalogging of exposure information was eliminated; the direct reading instrument data signal was converted to a radio frequency and broadcast with a transmitter to a receiver for processing by a microcomputer. The investigator received immediate feedback on the effects of engineering controls and work practices. In the United States, investigators at the NIOSH modified this system for a series of controlled technology studies.

Such diagnostic tools may see even more expanded applications to workstation designs in the coming years because it permits the engineer to identify the specific tasks, equipment function, or worker movements that contribute to worker exposure.

3.2.2 Equipment

3.2.2.1 ANCILLARY EQUIPMENT The stepwise review of the dispersal potential noted above should include all equipment, not only the major machinery. The importance of this approach is highlighted when one looks at the history of the use of simple air nozzles in the industry. For most of the 1900s, the widespread application of the air nozzle operating at line pressure (100 psi) was used to remove chips and cutting oil from machined parts and to dry parts after cleaning with solvent. In the 1970s, OSHA required that the operating pressure for these nozzles for cleaning purposes be dropped from 100 to 30 psi. This change had many positive effects, including a reduction in noise, eye injuries, solvent mist, and vapor exposures.

Another common piece of equipment, albeit much more complex, is the centrifugal pump. The difficulty of equipment selection is typified by the experience of a chemical engineering team designing a modern chemical plant having hundreds of centrifugal pumps. A major issue in such plants is the impact of fugitive losses from rotating machinery such as pumps on the workplace and general environment (29). The total loss percentage from rotating machinery varies from 8% to 24% with overall uncontrolled emissions ranging from 31 to 3231 ton year⁻¹ for a model chemical plant or a large refinery (32). The authors describe two possible control programs for pump fugitive losses – either a monitoring and maintenance program or engineering control by installation of dual seal pumps, sealless pumps, and a closed exhaust hood with air cleaning.

The historic phaseout of TCA and trichlorotrifluoroethane solvents in vapor phase degreasers accelerated the search for alternative solvents, as described in Ref. (32). Initial steps to reduce emissions from this common equipment included the use of covers, increased freeboard height, refrigerated condenser fluids, and lower hoist speeds. Although these changes did reduce fugitive emissions and therefore worker exposures, the survival of this type of equipment was also made possible through the availability of vapor tight degreasers (33). In the past, such closed system technology has been associated with major processing facilities.

3.2.2.2 MAJOR PROCESSING EQUIPMENT The complexity of the control technology problem becomes apparent when one moves from choices of ancillary equipment to decisions on major pieces of processing equipment. As an example, a small chemical processing plant for organic synthesis is a

multifloor plant with a series of major operations staffed by six chemical technicians. The condensed version reviewed in this chapter (Figure 6) permits discussion of equipment alternatives to minimize the generation and release of air contaminants. The three-step process includes, first, a reaction step to form a solid in suspension, conducted in a pressure vessel. In this case, there is no alternative equipment. The reaction must be conducted in a closed pressure vessel equipped with the safety controls shown in Figure 6 to minimize the possibility of a chemical accident.

The second step, the isolation of the solid reaction product, can be done by at least three different techniques. The environmental contaminant potential of these processes varies considerably. However, the choice cannot be made on this basis alone, since these techniques do have specific production capabilities that may be the major determinant in the choice. Finally, the reaction product is dried and drummed for sale or use in a subsequent operation. Again, there are several ways to accomplish the drying. The ranking of these isolation and drying operations based on their environmental impact is shown in Figure 6.

The responsibility for the choice of specific equipment in the processing plant will rest with the project design group and will be based on production capacity, ancillary services required, maintenance history, and cost and delivery in addition to health and safety considerations. It is not expected that the IH will have complete operational and application data on all chemical unit operations, but the environmental and worker health impacts must be understood and made known to the engineering group.

3.2.3 Processes

A review of the production engineering literature shows a range of processes that can be considered for a manufacturing facility. The choice is usually made based on production output and cost data. Industrial processes designed to accomplish a given task have one other parameter, their ability to contaminate the workplace; this characteristic of a process should be given equal weight to production criteria (34).

The development of technology in a given area such as welding has historically been pushed by production needs, not by worker health concerns. Over time, welding technology has become more complex and sometimes more environmentally challenging. Studies have also been conducted to influence the process design to minimize air contamination. This was the case with Gray and Hewitt (35) who defined the welding operating parameters that influence fume generation and proposed operational configurations that minimize fume formation rate and the chemical composition of the fume, thereby permitting improved efficiency of controls.

An exercise that demonstrates the value of a ranking approach for process environmental impacts is shown in the

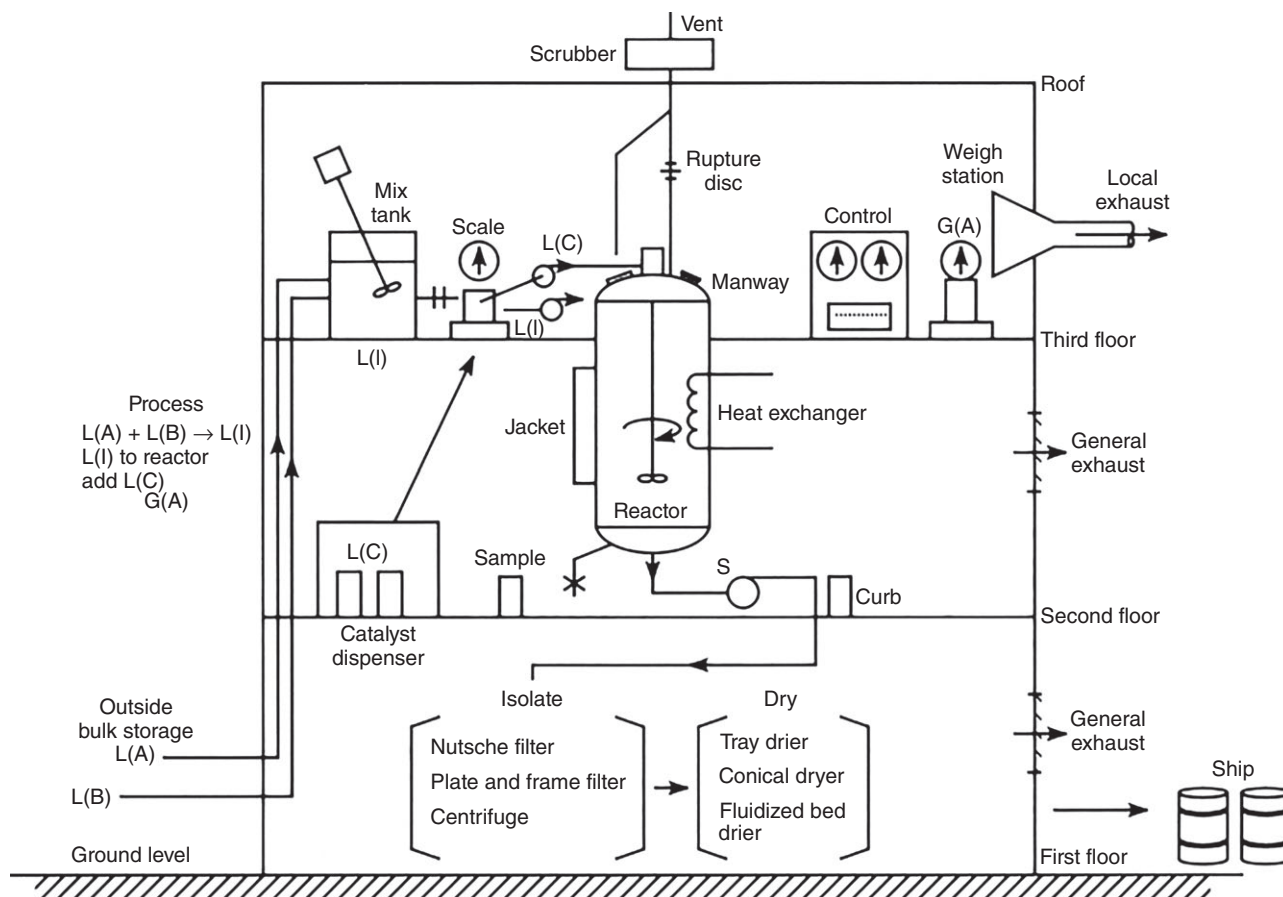


FIGURE 6 Chemical processing facility. Liquid reagents L(A) and L(B) are transferred to a mixing vessel. After mixing, the resulting liquid L(C) is transferred to the reactor by vacuum. Granular chemical G(A) is weighed under local exhaust ventilation (LEV) and dumped into the reactor through a charge port also equipped with LEV. A catalyst L(C) is transferred to the reactor by a positive displacement pump. After the reaction is complete, the new chemical is isolated by one of three techniques – nutsche filter, plate and frame filter, or centrifuge. The resulting wet cake is then dried by one of three methods – tray drier, conical drier, or fluidized bed drier. The isolation and drying techniques are ranked by environmental impact with the worst process noted first.

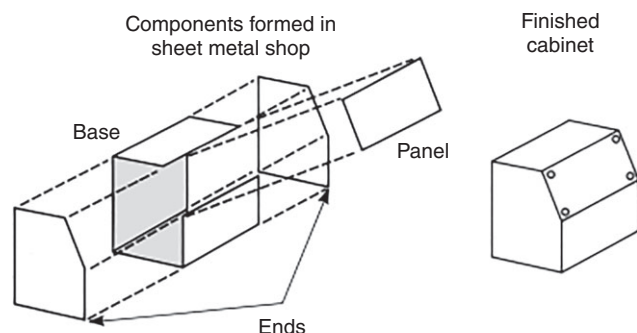
manufacture of an electronic cabinet (Figure 7). As in the case of the chemical process shown above, the fabrication steps are simplified for ease of discussion. The four enclosure components are fabricated from lightweight aluminum stock using sheet metal shear, brake, and punch. These operations may present a noise hazard but do not generate air contaminants and will not be included here. The enclosure can be assembled and painted by a number of techniques; the processes are ranked from worst to best in terms of adverse effect from air contamination.

Another general approach that applies to many processes is the use of containment. This control approach was considered by an engineering control panel sponsored by the Environmental Protection Agency, and the following containment ranking was proposed (36):

Standard control measures may often be categorized for each process: a sealed and isolated system where

airborne contaminant levels are very low (ppb range for vapors); a substantially closed system where airborne contaminant levels are still relatively low (fraction of ppm or low ppm range for vapors); a semi-closed system which is typical of nondedicated equipment used in job shop chemical processing facilities; and an open system.

An example of a sealed and isolated system is the modern refinery where such an approach is required both for production reasons and health and safety. A substantially closed system is typified by a semiconductor manufacturing facility and a semiclosed system by the chemical processing plant in Figure 6. In such fine chemical processing plants, it is common for the product to be made by an elaborate chain of separate reaction steps with a number of intermediates formed. In many cases, the intermediate chemical must be



Finishing options		
Metal cleaning	Welding	Painting
Wet degreasing with chlorinated HC	Torch welding	Air atomization
Vapor with chlorinated HC	Inert gas-shielded arc welding	Airless spraying
Wet degreasing with terpenes	Submerged arc	Hot paint
Water with detergent	Resistance	Electrostatic
		Powder
		Dipping

FIGURE 7 Manufacture of an electronic cabinet. The operational options for cleaning, abrasive blasting, and painting are ranked in terms of environmental acceptance with the worst process noted first.

isolated and removed from the vessel. Each transfer of the intermediate poses a potential for release of contaminants. Since the reaction train may include dozens of steps and take weeks to complete, a method that would streamline the process and reduce the number of transfers would reduce the exposure of the worker.

With the introduction of the pressure nutsche (a type of vessel), it is now possible for chemical plants with relatively simple reaction trains to convert to a closed system. This reaction vessel permits the chemical engineer to design a reaction sequence, including formation of the new molecule, cleaning of the product, and drying and packaging all without removing the chemical from the vessel at each step with its resulting exposure to the chemical processing worker.

Even more impressive as a control technique was the introduction of a process called cascade chemistry (37). In this approach, the organic synthesis reactions are conducted at room temperature and atmospheric pressure with carefully selected initial charging chemicals. Properly designed, one reaction cascades into another without the addition of new chemicals. In this system, hazards are minimized by

TABLE 10 Examples of process change technology from EPA WRITE program.

Operation	Process change
Hand mixing of paint	Proportional mixer blends paint at the gun, thereby eliminating handling paint and solvent at a mix operation
Conventional manual air spray painting	Computer-controlled robotic painting with an electrostatic spray to reduce worker exposure to paint mist and solvent vapors
Performance testing of electronic parts with CFC-based cooling system	Installed compressed air cooling system

Source: Adapted from Ref. (12).

operating at low temperature and pressure while eliminating the isolation and transfer steps.

Most common industrial facilities, that is, foundries, electroplating, painting, welding, and machining are examples of open systems. The contaminant released as a mist from electrolytic plating operations can be trapped by a layer of plastic chips or a persistent foam blanket on the surface of the bath. Surfactants may be added to the electrolyte to reduce mist escape. The plate-and-frame filter in the chemical processing industry is difficult to handle with local exhaust ventilation. Often a solvent wash of the cake with a highly toxic material results in high exposure when the filter is broken and the solvent-wet cake is removed. In some cases, after the initial wash, the cake can be washed with isopropanol to strip out the toxic solvent. It is then washed with water so that the exposure when the filter is broken and the product is removed is nil.

Other examples of process changes (developed in the EPA WRITE program) are shown in Table 10.

3.3 Work Task Modification, Automation, and Robotics

It is well known that simple changes in work tasks and work practices can have significant impacts on worker exposures. In the 1900s, workplace time and motion studies were used to improve productivity. Later a job placement technique (38) based on a detailed analysis of the time and effort of the job tasks was effective in reducing on the job injuries. More recently, the analytical tools of the ergonomic specialist permit identifying difficult tasks contributing to occupational injuries and illness.

As suggested in Section 3.2.1, the IH has techniques to investigate the source of contaminants, the generation

mechanism, and to make a semiquantitative assessment of the generation rate. This approach has tremendous value in analyzing not only the critical generation points on the machine but also in viewing the impact of specific worker actions and movement on air concentrations. Preliminary studies reveal that minor changes in work position and movement may offer significant reductions in exposure.

Occasionally, the specific modification in work practice is dictated by knowledge of the mechanisms of generation and release of the contaminant. Such is the case with the flow of granular material at material transfer points. The generation mechanism is the airflow induced by the falling granular material (39). The induced airflow can be minimized by restricting the open area of the upstream face, reducing the free fall distance, and reducing the material flow rate.

Automation is a general technique that separates the worker from the individual process. A good example of this technique is the manufacture of asphalt roof shingles. In the 1970s, competition resulted in the automation of all parts of the process from the dipping of the stock to the bundling of the package.

Another example of a simple automation process that reduces worker exposure is tire curing. In the early plants, the worker lifted the tire out of a curing press at the end of the curing cycle and placed another tire in the mold for curing. During this period, he was directly exposed to the emissions released from the press. By 1970, most plants had automated this process. The worker now places the uncured tire on a holding rack in front of the curing press line. When the curing cycle is completed, the tire is ejected from the press to a belt conveyor and the next tire to be cured is transferred from the rack to the press without exposure of the worker.

The spread of robotic techniques has permitted almost all industrial procedures to be good candidates for automation. The movement of the worker who buffs rubber boots can now be captured by a robotic system as shown in Figure 8. Another application of robotic techniques is spray painting where the robotic system reproduces the movement of a skilled painter. Although ventilation is still required on this job, the worker overseeing the operation is separated from the point of release of the paint mist and solvent.

3.4 Facility Layout and Equipment Placement

As stated earlier, the most efficient way to do a job is the one that is most environment-friendly. Certainly, this is true insofar as overall plant layout is concerned (40).

In the shop fabricating the enclosure in Figure 7, the desired flow of materials is from the incoming truck dock or railroad siding to sheet metal fabrication and then to assembly, finishing, inspection, and finally shipping. In a

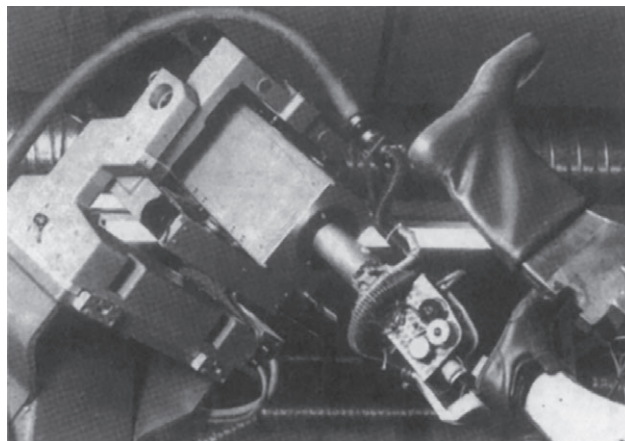


FIGURE 8 Robotic buffing of rubber boots. Source: Reproduced with permission of Matti koivumaki.

facility manufacturing pharmaceuticals, the input chemicals are transported to bulk storage and then to chemical processing, packaging, inspection, and shipping. In all manufacturing processes from handling metal to fine chemicals, it is important to minimize the distance the material is moved and the number of times it is picked up and transferred. When this rule is followed, worker exposure to air contaminants is usually minimized.

3.4.1 Material Transport

This issue is given major attention in industry where large quantities of raw material, intermediates, and final products are handled. Examples are injection molding of children's toys, manufacture of automobile tires, and paint manufacture. In some cases, material handling alone defines the plant layout. Bulk storage is often in large silos located outside the plant with delivery to the workstations by mechanical or pneumatic conveyors. This was true in the manufacture of plastic tape where tons of PVC granules were used each day (Figure 9). This plant also required large quantities of solvent delivered from bulk storage by piping to mix tanks and then directly to the coating heads. The intent of this system was to have all material handling to the individual coaters done in closed systems.

In organic synthesis, it is common practice to have outside bulk storage of at least a dozen solvents. The solvents are transferred to an inside reaction vessel by piping to a reactor manifold with necessary valving and meters. Granular materials used in small quantities are stored in adjoining storage areas and delivered to the reactor and charged by manual dumping, with a dumping fixture, or occasionally with a transfer lock. When a large number of drums must be dumped, a bulk handling system can be used with direct delivery to the reactor vessel.

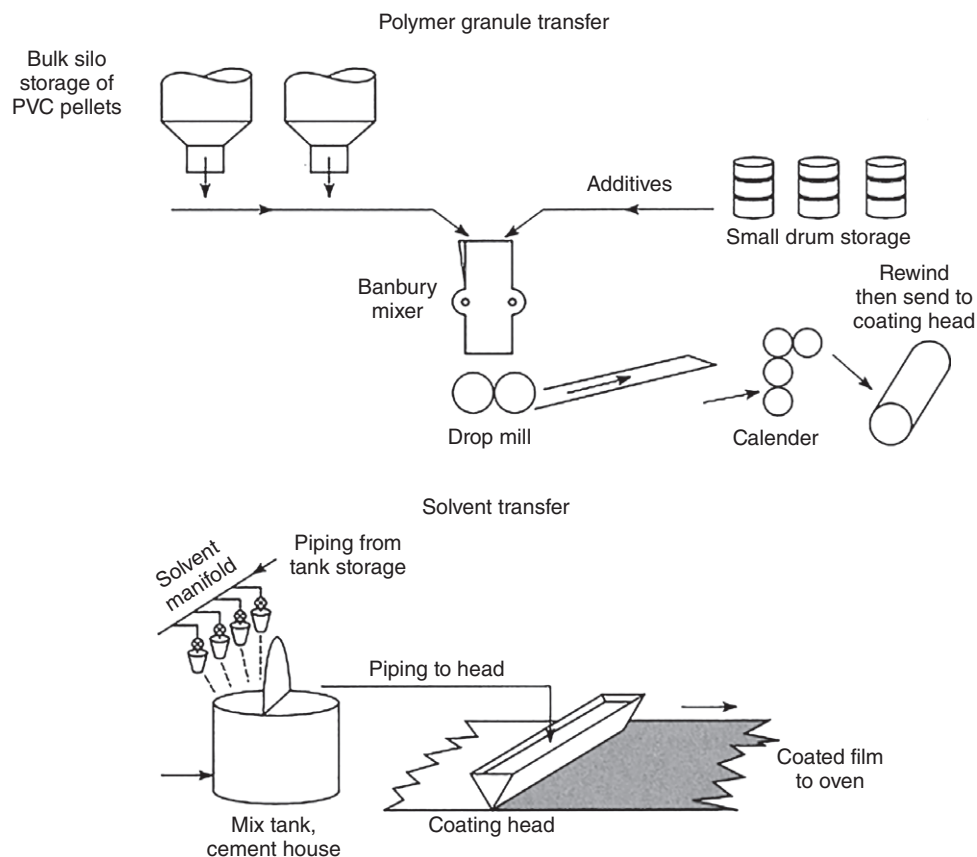


FIGURE 9 Manufacture of electrical tape showing the closed bulk transport of granular plastic and the piping of solvents to the mix tank.

3.4.2 General Considerations

The location of the process within the facility can greatly influence a worker's exposure. This is true of operations such as foundries where jobs may be easily classed as clean or dirty and where exposures vary greatly. The conventional iron foundry provides a good example of the importance of plant layout. It is common practice to define the optimal plant layout as one with airflow from the cleanest to the dirtiest operations with the exhaust focal point establishing this gradient (see Figure 10a). The layout of a similar foundry that does not follow this guideline is shown in Figure 10b. In the latter case, the relatively clean molding line is positioned adjacent to the shakeout, an area where the control of airborne foundry dust and thermal degradation products is difficult. This poor layout results in *silica* and other contaminants released by shakeout moving into the molding area and exposing this work population. If the desired concentration gradient cannot be achieved by ventilation or distance, then structural walls or plastic barriers are a possibility. Although such barriers define the space, compartmentalizing complicates the design and application of local exhaust ventilation, replacement air, HVAC, and other important services.

3.4.3 Workstations

A foundry in Finland faced problems not only of airborne contaminants but also heat, noise, and housekeeping in casting cleaning. The problems were resolved by redesigning the open workspace to provide individual workstations designed with integrated services positioned for ease of work (Figure 11). This layout resulted in improved material flow, better housekeeping, reduced air contamination, better ergonomics, and improved productivity. The success of the installation was due, in part, to close employee-employer involvement in the design.

3.4.4 Service and Maintenance

Close attention is often given to production area layout as noted in the above example, but rarely given to the working environment of the maintenance group. An example of an area where maintenance was not considered was tire-curing presses in the plants of the 1970s. The presses were arranged in double rows back-to-back with limited space between rows for steam, water, and electrical services. While this layout and density represented optimal use of space, repairs

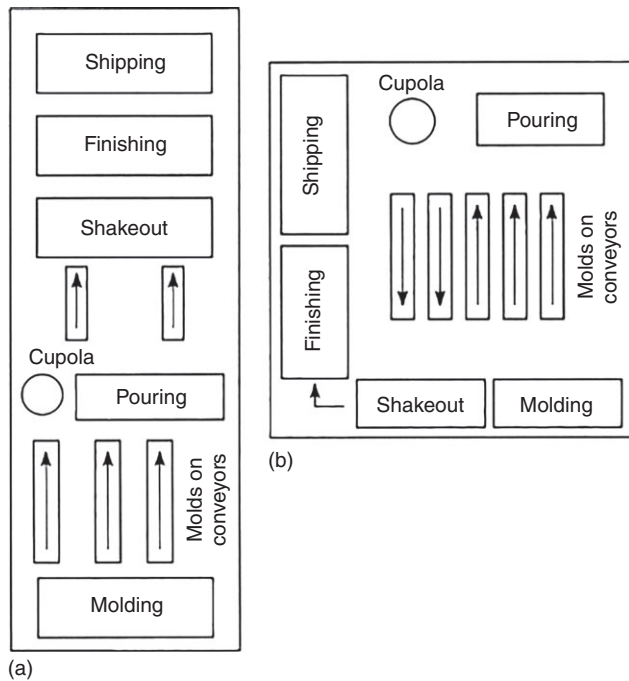


FIGURE 10 Layout of two gray iron foundries. (a) Foundry is designed for straight process flow and gradual transition from activities that represent limited contamination to those of greater contamination. (b) In foundry, the process flow reverses and the dirty shakeout ends up adjacent to the molding line.

of steam and water piping were done in an extremely tight space and controls for the worker were difficult to set up.

The best example of a planned layout that provides proper workspace for the trades is noted in the semiconductor industry (Figure 12). In this layout, all transfer pumps, distribution lines, and vacuum pumps are located in a service alley separated from the fabrication bay. This design reflects principal concern, not for the comfort of the maintenance worker, but rather to protect the fabrication area against contamination. Notwithstanding, it does result in adequate space for the trades to carry out their work in a safe manner (M. Horowitz, personal communication).

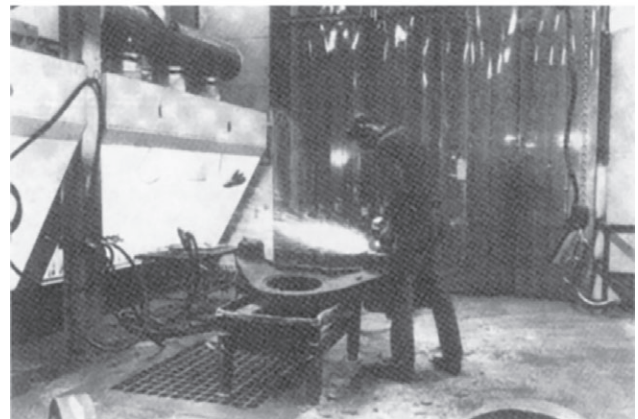
An extension of this concern is the installation of a small field service bench with necessary tools and equipment in plant production areas where maintenance is frequently done. This arrangement permits the maintenance person to do many repairs at the site and not transport equipment back to a main facility with the potential for chemical spills.

3.4.5 Segregation of Operation

It is often necessary to segregate or remove an operation from the main production area as an engineering control measure. In the semiconductor and fiber optics industry, each time a new facility is designed, engineers must choose



(a)



(b)

FIGURE 11 Well-integrated workstation in a foundry. (a) Overall layout of foundry finishing area. (b) Individual workstation with exhaust hood. Source: Reproduced with permission of Matti koivumaki.

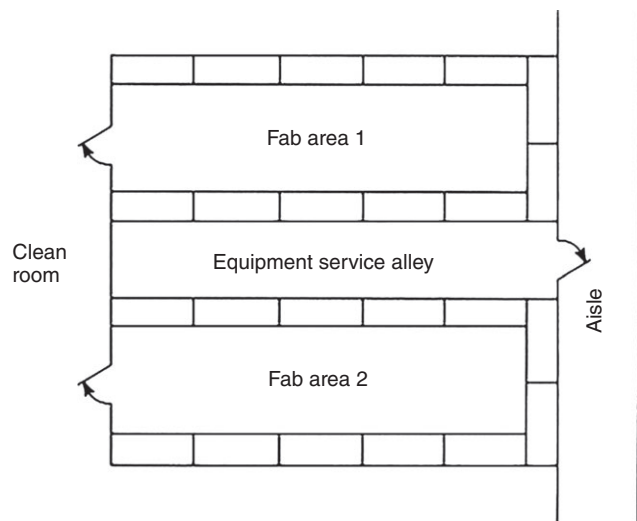


FIGURE 12 Layout of semiconductor facility showing service aisle isolated from, but adjoining the fabrication bays.

whether to store small amounts of highly toxic gases close to the production tool or store large quantities at a segregated position some distance from the plant to be distributed by double-walled piping to the production tools. This latter segregation technique permits the plant to reduce the number of persons at risk while providing extensive controls at the work site. This option must be weighed against storing small quantities of gas directly at the tool, thereby minimizing failures in the transfer systems but requiring frequent change of gas cylinders with the entailed risks.

3.4.6 Isolation of the Worker

The practice of isolating the worker as a control measure is placed under this section since it should be considered in conjunction with the layout of the major equipment. This widely used technique was mandated by OSHA coke oven regulations that require enclosures with clean, conditioned air. The larry car and pusher cars had controlled environment cab enclosures; the lidsmen had enclosures designed to remove them from the hostile coke oven environment during available rest periods.

In other industries, this approach has been chosen to eliminate worker exposure to air contaminants while providing a comfortable working environment. These applications include enclosed booths on a variety of construction equipment, front end loaders in smelters, crane cabs in metallurgical industries, operator cabs in steel rolling mills, and pouring stations in foundries.

3.5 Ventilation

In the introduction to this chapter, it was stated that ventilation is an important component of engineering controls. (In fact, ventilation of some form is required at every human occupancy.) If air contaminants are emitted, they can be collected at the source – with various degrees of success – using local exhaust ventilation; or, if disseminated, air contaminants can be diluted to some acceptable, safe concentration with dilution ventilation. These important engineering controls have traditionally been called industrial ventilation. (“Industrial” as in “Industrial Hygiene.”) Industrial Ventilation covers the application of these two engineering control approaches.

4 STANDARDS AND GUIDELINES

Engineering controls should always be built to current standards of good engineering practice. These include international and local building codes, OSHA, EPA, and other government codes and regulations, ANSI (American National Standards Institute) and ASTM standards, and

various “standard of practice” guidelines published by organizations such as NIOSH, DOT, AIHA, ACGIH, ASSE, and others.

Similarly, professional IH activities should always be guided by standards and guidelines of good practice. Industrial hygiene and occupational health standards fall into two basic classes: mandatory standards (e.g. OSHA regulations) and recommended or consensus standards (e.g. ACGIH TLV®, AIHA WEEL, ISO 14000 standard on environmental management, ANSI/ASSE Z910 standard on dilution ventilation, ANSI/ASSE Z.10 standard on occupational health and safety management systems, and ASHRAE 62 standard on indoor air quality).

Important mandatory standards and codes (e.g. PELs) have been developed by the federal government in accordance with provisions of the Occupational Safety and Health Act (OSH Act) of 1970. The Mine Safety and Health Act of 1977 also provided for codes and standards development related to mining health and safety. Types of OSHA standards include design standards (e.g. ventilation standards of 1910.94) and performance standards (e.g. PEL standards of 1910.1000). Within these are the so-called vertical standards (e.g. standards that apply to only one industry, such as 1910.261 related to the pulp and paper industry) and horizontal standards (e.g. standards that cover one topic but apply to all industries, such as 1910.141 related to walking and working surfaces).

Other standards-writing organizations of interest to the IH and that could impact engineering controls include the ANSI, the Nuclear Regulatory Commission, the Department of Defense and its components, the National Fire Protection Association, the National Safety Council, the American Public Health Association, and ISO (International Standards Organization).

Perhaps the most important standard related to industrial ventilation is ANSI Z9.2-2018, *Fundamentals Governing the Design and Operation of Local Exhaust Systems* (41). The American Society of Safety Engineers is the Secretariat of the Z9 Committee. The Z9 Committee oversees the development and publication of 14 industrial ventilation standards (41, 42).

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INDUSTRIAL VENTILATION

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1 INTRODUCTION

There are many approaches available for controlling air contaminant sources, emissions and worker exposures. These include the various administrative, preventive, and (generally preferred) engineering controls covered in **Characterizing Air Contaminant Emission Sources**. Industrial ventilation (IV) is the most widely used engineering control. In fact, ventilation is required in every human occupancy. “Industrial” in this case is used in the same sense it is used in “Industrial Hygiene” (IH).

Because virtually all emission and exposure control projects involve the use of ventilation in some fashion, every IH receives training in the selection, operation, testing, and troubleshooting of IV systems. This chapter provides a review of the subject and is intended for practicing IHs.

At its most fundamental level, industrial ventilation provides control of an environment by strategic use of airflow. The flow of air may be used to control thermal stresses (e.g. overheating of a workspace, high humidity), to remove an air contaminant near its source of emission using local exhaust ventilation (LEV) (e.g. welding exhaust hood, duct, fan, and stack), to dilute the airborne concentration of a contaminant to acceptable exposure levels using natural or mechanical dilution ventilation (e.g. dilution ventilation used to control fugitive emissions during welding), and to replace air exhausted from the workplace (e.g. providing “makeup” air to replace that exhausted at a welding operation). Applied either as a general or local control, industrial ventilation also has the objectives of

preventing fires and explosions, and most important to the industrial hygienist, preserving employee health, safety, comfort, and productivity.

Principles and applications of LEV and dilution ventilation are presented in subsequent sections of this chapter. Use of these principles in solving exposure problems requires a basic understanding of the fundamental relationships that describe airflow. These are presented briefly in the following section; more elaborate discussions and derivations of these relationships are given in several of the references provided at the end of this chapter (1–3).

2 FUNDAMENTAL DEFINITIONS AND PHYSICAL RELATIONSHIPS

STP is the standard temperature and barometric pressure (Re: American Conf of Governmental Industrial Hygienist (ACGIH)) for most industrial ventilation systems:

$T = 70^{\circ}\text{F}$, $\text{BP} = 29.92 \text{ in.Hg}$, dry air (US units)

$T = 21^{\circ}\text{C}$, $\text{BP} = 760 \text{ mmHg}$, dry air (SI units)

Properties of air at STP: $\text{MW} \approx 29$;

weight density $= 0.075 \text{ ft}^{-3} = 1.2 \text{ kg m}^{-3}$

2.1 Airflow Rate

The fundamental equation describing airflow rate is referred to as the “continuity equation” or principle of “conservation

*Retired.

of mass.” This relationship states that the mass rate of airflow remains constant along the path taken by the air. For any two points in the airstream we can express the relationship as

$$A_1 V_1 \rho_1 = A_2 V_2 \rho_2 \quad (1)$$

where A is the cross-sectional area through which the air moves (ft^2 or m^2), V is the average linear velocity of air (fpm or m s^{-1}), and ρ is the air weight density (lb ft^{-3} or g m^{-3}).

For most industrial applications, ρ is relatively constant because absolute (or barometric) pressures and temperatures within a ventilation system vary over a narrow range (usually less than a few percent of ambient barometric pressures and temperatures) so the air remains essentially “incompressible.” (Exceptions exist where air is heated in the system.) Therefore, in most cases:

$$A_1 V_1 = A_2 V_2$$

Note that the units, $\text{ft min}^{-1} \times \text{ft}^2 = \text{ft}^3 \text{ min}^{-1}$ = a unit of flow rate, designated in this chapter as Q . So,

$$Q = VA \quad (\text{ft}^3 \text{ min}^{-1} \text{ or } \text{m}^3 \text{ s}^{-1});$$

these are often written as “cfm” and “cms”) (2)

Sample Calculation. The cross-sectional area of a round 12 in. diameter duct is $A = 0.7854 \text{ ft}^2$. The average velocity of air flowing in the duct is $V = 2250$ feet per minute (fpm). What is the air flowrate, Q ? Assume STP.

$$\begin{aligned} Q &= V \cdot A \\ &= 2250 \text{ fpm} \cdot 0.7854 \text{ ft}^2 = 1770 \text{ scfm} \end{aligned}$$

Note: “scfm” suggests a flow rate at STP; a flow rate for non-STP air is often designated as “acfm,” flow corrected for actual conditions.

2.2 Density Correction for Air at Non-STP

To correct for nonstandard air, ventilation engineers estimate a density correction factor, d (or df). d is derived from the Ideal Gas equations and is used to correct air density for temperatures and barometric pressures different from STP. *Note:* the ACGIH definition of STP is used in this chapter.

In the following equation, BP is the absolute barometric pressure.

$$d = \frac{T_{\text{STP}} (\text{absolute})}{T_{\text{actual}} (\text{absolute})} \cdot \frac{\text{BP}_{\text{actual}}}{\text{BP}_{\text{STM}}} \quad (3)$$

R is the degrees Rankine, $R = ^\circ\text{F} + 460$; absolute temperature.

K is the degrees Kelvin, $K = ^\circ\text{C} + 273$; absolute temperature.

Sample Calculation. The air temperature is 90°F and the barometric pressure is 27.50 in.Hg. What is the density correction factor, d ?

$$\begin{aligned} d &= \frac{460 + 70^\circ}{460 + 90^\circ} \cdot \frac{\text{BP}}{29.92 \text{ in.Hg}} \\ d &= \frac{530}{550} \cdot \frac{27.50 \text{ in.Hg}}{29.92 \text{ in.}} = 0.886 \end{aligned}$$

2.3 Velocity Pressure and Velocity

Velocity pressure (VP) is pressure exerted by air in motion. (Wind creates force and pressure; think of a hurricane.) If SP is analogous to potential energy (Section 2.4), then VP is analogous to kinetic energy and is directly related to air velocity. It exists only when air is in motion, acts in the direction of airflow, and is always positive in sign. The relationship between the velocity of air and VP is given by Bernoulli's equation:

$$\begin{aligned} V &= 4005 \sqrt{\text{VP}/d} \quad (\text{US}) \\ V &= 4.043 \sqrt{\text{VP}/d} \quad (\text{SI}) \end{aligned} \quad (4)$$

where V is the velocity (fpm or m s^{-1}), 4005 is the US units factor, 4.043 is the SI units factor, VP is the velocity pressure (in.w.g. or mmw.g.), w.g. is the “water gauge,” the pressure given in height of water column on a manometer, and d is the air density correction factor, unitless (at STP, $d = 1$).

Sample Calculation. The average VP of an airstream in a duct is $\text{VP} = 0.33 \text{ in.w.g.}$ What is the average velocity? (assume STP, $d = 1$).

$$V = 4005(\text{VP}/d)^{1/2} = 4005(0.33/1)^{1/2} = 2300 \text{ fpm}$$

2.4 Static Pressure (SP)

Static pressure (SP), created by gravity (as barometric pressure or atmospheric SP) and modified by fans in a ventilation system, produces the energy required to initiate air movement and create VP at the hood, overcomes the resistance in a system caused by friction of the air against the duct walls, and overcomes turbulence and shock losses caused by a change in direction or velocity of air movement. SP is analogous to potential energy, and it exists even where there is no air motion. It acts equally in all directions and tends either to collapse the walls of the duct upstream from the fan or to expand the walls of the duct on the downstream side. SP usually is negative in sign upstream from a fan and positive downstream. It is measured as the difference between duct and atmospheric pressures. The most common unit of

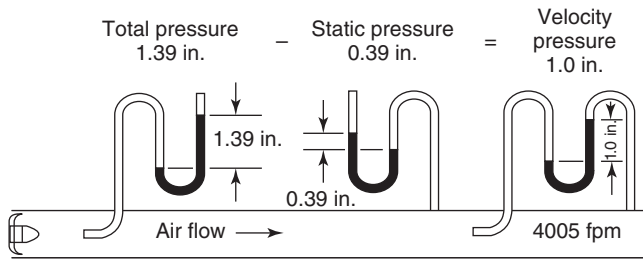


FIGURE 1 Relationships among velocity pressure, static pressure, and total pressure.

SP in the USA is “inches of water” (“in.w.g. H_2O ”). The standard barometric pressure (or atmospheric SP) is about 407 in.w.g.

2.5 Total Pressure

The driving force for the airflow is a pressure difference that is required to start and maintain flow. This pressure is called total pressure (TP) and has two components, VP and SP; the relationship among the three is simply

$$TP = SP + VP \text{ or } SP = TP - VP \text{ or } VP = TP - SP \quad (5)$$

Normal Sign Convention: Upstream of the fan, TP and SP are negative, VP is positive; downstream of fan, all pressures are considered positive.

Figure 1 shows the relationships between SP, VP, and TP at different points in a duct system. Note that the manometer measurements are downstream of the fan.

If air flowing through a duct system undergoes an increase in velocity, a part of the available SP is used to create the additional VP necessary to accelerate the flowing air. Conversely, if the velocity is reduced at some point in a duct system, a portion of the kinetic energy or VP at that point can be converted into potential energy or SP. SP and VP are therefore mutually convertible. However, this conversion is always accompanied by a loss of SP due to turbulence and shock; the conversion is never 100% efficient.

2.6 Static Pressure (Energy) Losses

Air in motion encounters resistance at all surfaces encountered by the flowing volume of air. Consequently, some of the SP (energy) of the air is given up in overcoming this friction and is transformed into heat. The rougher the surface confining the flow or the higher the flow rate, the higher the frictional losses.

Frictional loss in a duct varies directly with the length, inversely with the diameter, and directly with the square of the velocity of air flowing through the duct. This loss can be

estimate from charts using the Fanning friction factor, which is an empirical function of Reynolds number, duct material, and type of construction (4).

SP also is lost due to turbulence caused by a change in direction or velocity within a duct. The “pressure drop” in a duct system due to dynamic losses increases with the number of elbows or angles and the number of velocity changes within the system.

Acceleration and hood-entrance loss is a drop in (or loss of) SP caused by turbulence when air is accelerated from rest to enter a duct or opening. Turbulence losses of this type vary with the type of opening.

The SP loss is most often estimated by its relationship to VP:

$$SP_{\text{loss}} = K \cdot VP \cdot d \quad (6)$$

where SP_{loss} is the loss of SP (in.w.g. or mmw.g.), K is a unitless loss factor determined experimentally for every type of fitting in a system, VP is the average velocity pressure in duct (in.w.g. or mmw.g.), and d is the density correction factor, unitless.

Sample Calculation. Suppose air is flowing in a duct system at an average VP of $VP = 0.90$ in.w.g. at STP. The air moves through an elbow with a published loss factor, $K = 0.28$. What is the approximate loss of SP through the elbow?

$$SP_{\text{loss}} = K \cdot VP \cdot d = 0.28 \times 0.90 \text{ in.w.g.} \times 1.0 = 0.25 \text{ in.w.g.}$$

3 LOCAL EXHAUST VENTILATION

LEV controls an emitted air contaminant by capturing it at or near the place where it is generated and removing it from the workspace. The intent is to capture or contain as much of the emitted contaminant as possible but no hood is completely effective in practice. “Fugitive emissions” (those that escape capture at the hood) are controlled using dilution ventilation or some other means of control, as warranted. The makeup air for the hood exhaust often serves this purpose when designed to do so.

An LEV system usually includes all of the following components: a hood or enclosure, ductwork, an air-cleaning device (where necessary for air pollution abatement purposes), an air-moving device (usually an exhaust fan), and a stack to safely disperse any contaminants in the airstream (Figure 2). In general, LEV systems consist of more individual components than do dilution ventilation systems, and because they also offer more operational parameters that must be controlled within acceptable ranges, they require more maintenance and involve higher operating expenses as well.

When the primary purpose of ventilation is to provide control of airborne contaminants, LEV systems are generally

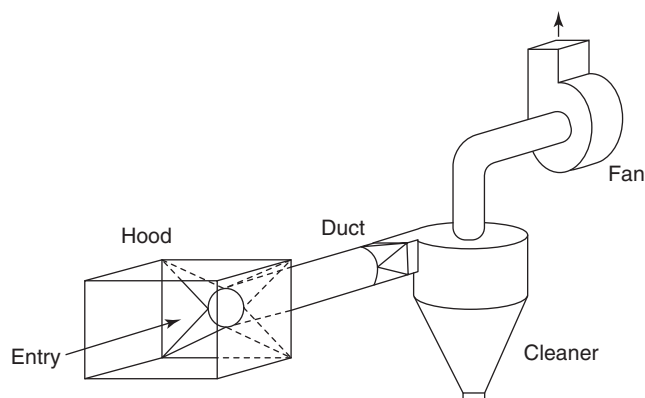


FIGURE 2 Interrelated components of a local exhaust system.

superior to dilution ventilation. The advantages of the LEV system over a dilution system for any particular application will include many of the following:

- Capture and control of a contaminant can be very effect, given proper design and operation of the system. Consequently, the exposure of workers to contaminants at the sources exhausted can be prevented. With dilution ventilation the contaminant is controlled at the breathing zone (BZ), and at any given location in the workplace this dilution may be highly variable and therefore inadequate at times.
- Volumetric rates of required LEV exhaust air are less with local ventilation; as a result, the volume of makeup air is less. LEV control offers savings in both capital investment and heating costs.
- The contaminant is contained in a smaller exhausted volume of air. Therefore if air pollution control is needed, it is less expensive because the cost of air pollution control is approximately proportional to the volume of air handled.
- With particulate contaminants, LEV systems can be designed to capture large, settleable particles or at least confine them within the hood, and thus reduce the effort needed for good housekeeping.
- Equipment and exposed surfaces in the workroom are better protected from such deleterious effects of the contaminant as corrosion and abrasion.
- Fans used with LEV systems usually have fairly high pressure characteristics to overcome pressure losses in the system. Therefore, the performance of the fan system is not likely to be affected adversely by such influences as wind direction or velocity or inadequate makeup air. This is in contrast to dilution ventilation, which can be affected greatly by seasonal factors.

3.1 Individual Components of an LEV System

3.1.1 Hoods

A hood is a structure designed to partially enclose a contaminant-producing operation or to guide airflow in an efficient manner to capture and contain the contaminant. The design and location of the hood is one of the most critical aspects in the successful operation of a local exhaust system.

3.1.2 Ductwork

The ductwork in an exhaust system provides a path for flow of the contaminated air exhausted from the hood to the point of discharge. It also carries SP from the fan to the hood where airflow is generated. The following points are important in design and operation of the ductwork:

- All duct velocities in industrial ventilation systems must be high enough to prevent any particles or dust in the airstream in each duct from settling out and plugging the duct.
- When the airstream is dust free, e.g. consisting only of dust or particles naturally found in the air, the duct velocity can strike an economic balance between ductwork cost and fan, motor, and power costs. Many users have found a duct velocity of 1500–2000 fpm is optimal.
- Recommended duct “dust transport” velocities for various dust conditions can be found in (1–3, 5). For example, air in a duct contaminated with “fine powder coal dust” should be maintained at a velocity of 4000 fpm, or more (2).
- Location and construction of the ductwork must furnish sufficient protection against external damage, corrosion, and erosion to maximize the useful life of the local exhaust system.

3.1.3 Air Cleaners

Most exhaust systems installed for contaminant control require an air cleaner. Occasionally the collected material has some economic reuse value. Much of the time, obtaining an emissions permit from the local air pollution control authority will require installing an air cleaner.

3.1.4 Fans

The fan, usually of a centrifugal type, is the heart of the LEV system. Wherever practicable, a fan should be placed downstream from the air cleaner so that it will handle uncontaminated air. When chips and other particulate matter must pass through the impeller, the straight blade or paddlewheel-type

fan is best because it is least likely to clog. Fans and motors should be mounted on substantial platforms or bases and isolated by antivibration mounts. At the fan inlet and outlet, the main duct should attach through a vibration isolator, that is a sleeve or band of very flexible material, such as rubber or fabric. The vibration isolator at the fan inlet should be mounted on the outside of the duct.

The importance and interaction of the various components of the exhaust system will become evident in the discussion on design of a ventilation system later in this chapter. Because of the importance of the role played by the exhaust hood in the overall success of the ventilation system, and because it is the component of the system that typically permits most innovation in concept, specific discussion of the application of the various types of hood follows below.

3.1.5 Stacks

The stack should be tall enough (usually about 10 ft above the highest ridge of the roof line or air intakes) and far enough away from air intakes (usually 50 ft or more) to minimize re-entrainment of contaminated air into the building.

3.2 LEV Hood Types

The “hood” is the point at which air first enters the LEV system. As such, the term can be used to apply to any opening in the exhaust system regardless of its shape or physical disposition. An open-ended section of ductwork, a canopy-type hood situated above a hot process, and a conventional laboratory booth-type hood all could be called hoods in the context of this discussion.

The hood captures or contains the contaminant generated by a process or operation and causes it to be carried through the ductwork to a convenient discharge point. The quantity of air required to contain or capture the air contaminants depends on the size and shape of the hood, its position relative to the point of generation of the contaminant, and the nature and quantity of the air contaminant itself. It should be emphasized that there is not necessarily a standard hood that is correct for all applications of a particular operation because the methods of processing are unique to each operating plant. On the other hand, standard concepts for exhaust hoods have been developed and recommended for many types of operations (1–3).

Hoods can be classified conveniently into four categories, based on the concept of contaminant capture/control: enclosures, booth-type hoods, receiving hoods, and capture or exterior hoods.

3.2.1 Enclosure Hoods

Enclosure hoods normally surround the points of emission or generation of contaminant as much as practicable. In essence,

they surround the contaminant source to such a degree that all contaminant-dispersal action takes place within the confines of the hood itself. Because of this, enclosure hoods generally require the lowest rates of exhaust ventilation, and therefore are economical and quite efficient. They should be used whenever possible, and they deserve primary consideration when a moderately or highly toxic contaminant is involved. Capture hoods can often be made closer to enclosing hoods by the judicious use of flanges.

3.2.2 Booth-Type Hoods

The laboratory hood and spray-painting booths are special cases of enclosure type hoods where the worker is located at or in the hood itself. Air contamination takes place within the enclosure, and air is exhausted from it in such a way, and at such a rate, that an average velocity is induced across the hood openings sufficient to overcome the tendency of the contaminant to escape from within the hood. The five (or more) walls of the booth reduce the exhaust air requirements, although not to the extent of a total enclosure.

3.2.3 Capture or Exterior Hoods

Exterior hoods must capture air contaminants generated from a point outside the hood itself. Exterior hoods therefore differ from enclosure or receiving hoods in that their sphere of influence must extend beyond their own dimensions in capturing contaminants without the aid of natural forces such as natural drafts, buoyancy, and inertia. In other words, directional air currents must be established adjacent to the suction opening of the hood to provide adequate capture at the emission source. Thus, they are quite sensitive to external sources of air disturbance and may be rendered completely ineffective by even competing lateral movements of air. They also require more air to control a given process and are the more difficult of the various hoods to design. Examples of exterior hoods include the exhaust slots on the edges of liquid tanks, the tapered capture hood at a welding station, and exhaust grilles in the floor or workbench below a air-contaminated process.

3.2.4 Receiving Hoods

The term “receiving” refers to a hood in which a stream of contaminated air from a process is exhausted by a hood located near the source of generation of the contaminants specifically for purposes of control. Two examples of this type of hood are canopies situated above hot processes and hoods attached to grinders, positioned to take advantage of centrifugal and gravitational forces to maximize control of the dust generated by the process. Canopy hoods, frequently located above hot processes, are similar to exterior hoods in that the contaminated air originates beyond the physical

boundaries of the hood. The fundamental difference between receiving and exterior hoods is that in the former, the hood takes advantage of the natural movement of the released contaminant, whereas in the latter, air is induced to move toward the exterior hood. Receiving hoods are not considered capture hoods.

Receiving hoods are designed to be in the natural pathway of the contaminant as it is normally released by the operation. If space is limited, baffles or shields may be placed across the line of throw of the particles to remove their kinetic energy. Then the particles may be captured and carried into the hood by lower air velocities. Additional examples of receiving hoods include those associated with many hand-tool operations (surface grinders, metal polishers, stone cutters, and sanding machines).

3.3 Factors Influencing the Performance of LEV Systems

Control of air contaminants through LEV will be more effective if the following basic factors and principles are understood and followed.

3.3.1 Capture/Control Velocities

Hoods perform their function in one of two ways: capture or control. With the capture approach, air movement is created to draw the contaminant into the hood. When the air velocity that accomplishes this objective is created at a point outside a nonenclosing hood, it is called capture velocity. Some exhaust hoods essentially enclose the contaminant source and create an air movement that prevents the contaminant from escaping from the enclosure. The air velocity created at the openings of such hoods is called the control velocity.

Successful design of any exhaust hood is based on correct determination of the two quantities, control velocity and capture velocity. The air velocity, which must be developed by the exhaust hood at the point of emission or in the area of desired control, is based on the magnitude and direction of the air motion to be. Some empirical ventilation standards, especially concerning dusty equipment such as screens and conveyor belt crossovers, are based on parameters such as "cubic feet per minute per foot of belt width." These so-called exhaust-rate standards are usually based on successful experience, are easily applied, and usually give satisfactory results if not extrapolated too far. In addition, they minimize the effort and uncertainty involved in calculating the fan action of falling material, thermal forces within hoods, and external-air currents. However, such standards have three major pitfalls:

- They are not of a fundamental nature; that is they do not follow directly from basic "laws."

- They presuppose a certain minimum quality of hood or enclosure design, although it may not be possible or practical to achieve the same quality of hood design in a new installation.
- They are valid only for circumstances similar to those that led to their development and use. It should be clear that the nature of the process generating the contaminant will be an important determinant of the required capture velocity.

3.3.2 Airflow Characteristics at a Capture Hood

The flow characteristics at a hood opening are much different from the flow pattern at a supply or discharge opening. Air blown from an opening maintains its directional effect in a fashion similar to water squirting from a hose and, in fact, is so pronounced that it is often called "throw." However, if the flow of air through the same opening is changed so that the opening operates as an exhaust or intake with the same volumetric rate of airflow, the flow becomes almost completely nondirectional, and its range of influence is greatly reduced. As a first approximation, when air is blown from a small opening, the velocity 30 diameters in front of the plane of the opening is about 10% of the velocity at the discharge. The same reduction in velocity is achieved at a much smaller distance in the case of exhausted openings, such that the velocity equals 10% of the face velocity at a distance of as little as 1 diameter from the exhaust opening (Figure 3 illustrates this point). Therefore, local exhaust hoods should not be applied to any operation that cannot be conducted in the immediate vicinity of the capture hood.

Required airflows into a hood are described by a theoretical "area" approach (Section 3.3.3), and by empirical approaches not covered here (see American Conference of Governmental Industrial Hygienists and Committee on Industrial Ventilation (1) for more information on empirical approaches).

3.3.3 Determining Airflow Rates into Hoods Using $Q = VA$

Required airflow rates into hoods have been well described by Hemeon (3). His theoretical "area" approach to airflow into hoods is based on the fundamental equation $Q = VA$. To determine the appropriate airflow rate, Q , one needs to determine the appropriate capture or control velocity along some area of approach to the hood. See Figure 4 for typical areas. For an enclosing, booth-type hood, for example the area is a plane and the velocity is the average desired face velocity through the plane. For an ideal round capture hood with the emission source located in front of the hood, such as the end of a flex duct placed over a box, there is a point source of "suction" just inside the duct that "draws" air from

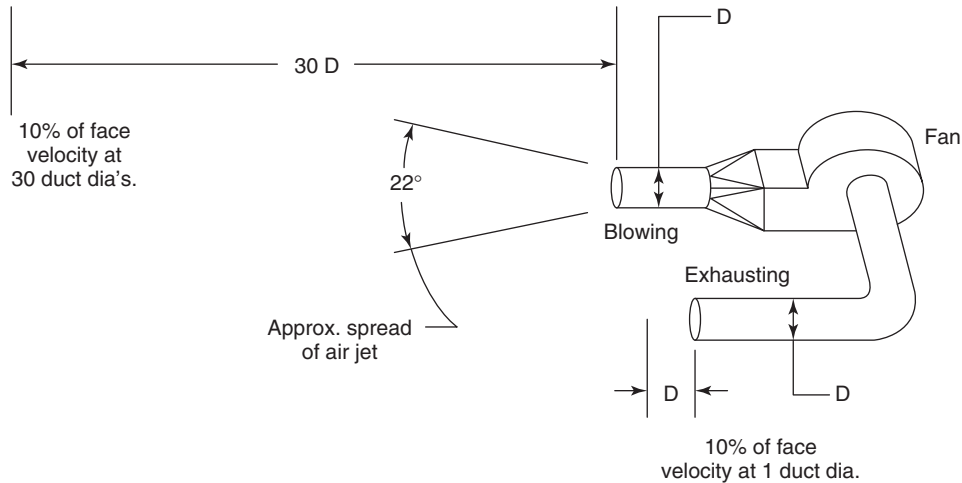


FIGURE 3 Airflow characteristics of blowing and exhausting.

all directions equidistant from the point. The approach area is approximately a sphere and the velocity is the average desired capture velocity along the surface area of the sphere. In this case,

$$Q = VA$$

where $A = 4\pi X^2$ and

$$Q = V(12.57X^2)$$

where Q is the airflow ($\text{ft}^3 \text{min}^{-1}$ or $\text{m}^3 \text{s}^{-1}$), V is the desired capture velocity at point X (fpm or m s^{-1}), and X is the centerline distance to emission source (ft or m).

Similar areas can be determined for almost all hoods, as shown in Figure 4. When the width-to-length ratio (aspect ratio) of an exhaust opening approaches 0.1, the opening behaves like a slot, for example. The approach area to a free-standing slot is like a cylinder.

Note also that if Q is known, an estimate of the capture velocity at a free-standing slot can be made by solving for V :

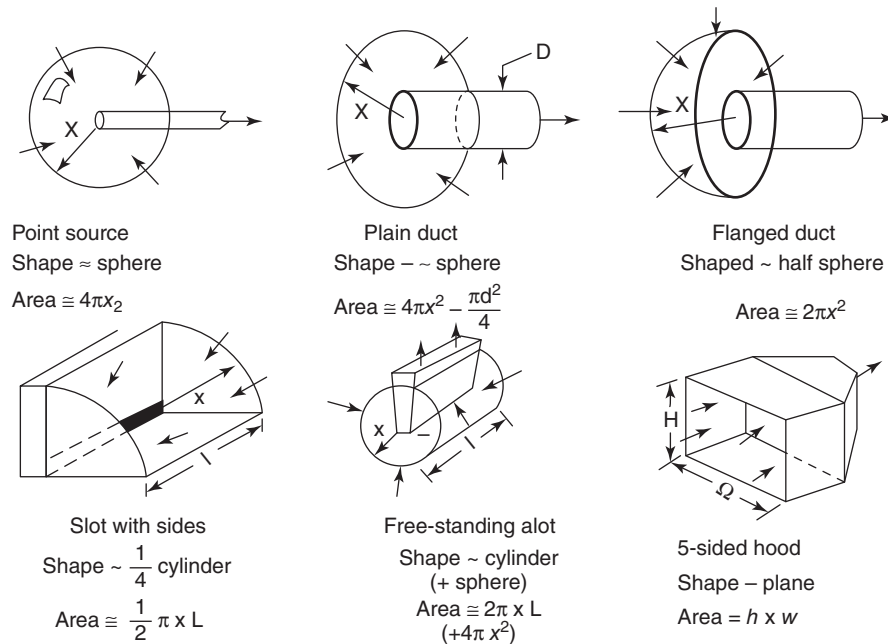


FIGURE 4 Areas of Approach for use in $Q = VA$.

$$V = \frac{Q}{2\pi XL}$$

where L is the length of slot (ft or m) and X is the centerline distance (ft or m).

3.3.4 Hood-Related Equations

Like all fittings, there is a SP loss as air flows through a hood and into the duct. This "hood entry loss" is given by

$$h_e = SP_{\text{loss}} = K_h \cdot VP \cdot d \quad (7)$$

where " $h_e = SP_{\text{loss}}$ " is the loss of SP at the hood (entering the duct from the hood) (in.w.g. or mmw.g.), K_h is a loss factor determined experimentally for every type of hood, VP is the average velocity pressure in duct serving hood (in.w.g. or mmw.g.), and d is the density correction factor, unitless.

The entry loss plus the acceleration energy required to move the air at a given velocity (1 VP) make up the hood-SP SP_h , which is expressed algebraically as

$$SP_h = h_e + VP \text{ and } h_e = SP_h - VP \quad (8)$$

where h_e is hood-entry loss. SP_h is often measured a short distance downstream from the hood entrance using a pitot tube. The calculation (or measurement) of SP_h is often the first step in the design (or evaluation) of a LEV system, which will be discussed later. When using this equation, let SP_h be the absolute value (let the sign of SP_h be +).

The coefficient of entry, C_e , is a measure of how efficiently a hood is able to convert SP to VP as the air moves through the hood into and down the duct. The coefficient of entry is the ratio of rate of flow by the hood-SP to the theoretical flow if the hood-SP were completely converted to VP. C_e ranges from 0 to 1 and is unitless.

$$C_e = \sqrt{\frac{VP}{SP_h}} \quad (9)$$

where C_e is the coefficient of entry, unitless, VP is the average velocity pressure in duct serving hood (in.w.g. or mmw.g.), and SP_h is the absolute value (sign = +) of the SP in the duct serving hood (in.w.g. or mmw.g.).

Combining several equations, the airflow rate can be determined from the duct diameter, hood SP, and the coefficient of entry:

$$Q = 4005AC_e\sqrt{SP_h/d} \text{ for US} \\ Q = 4.043AC_e\sqrt{SP_h/d} \text{ for SI} \quad (10)$$

where C_e is the coefficient of entry, unitless; A is the cross-sectional area of duct (ft² or m²); Q is the air volume flow

rate (acfm or acms); SP_h is the absolute value (sign = +) SP in duct serving hood (in.w.g. or mmw.g.); and d is the density correction factor, unitless.

Sample Calculation Using Hood Equations. Suppose an IH measures the average VP and SP using a pitot tube and manometer just downstream in the duct from a welding hood.

These are data: $VP = 0.75$ in.w.g., $SP = -1.40$ in.w.g., duct diameter = 12 in., duct area = 0.7854 ft², air at STP, and $d = 1.0$.

In this case

$SP_h = 1.40$ in.w.g. (The absolute value of the static pressure near the hood in the duct.)

$$h_e = SP_h - VP = 1.40 - 0.75 = 0.65 \text{ in.w.g.}$$

$$C_e = \sqrt{\frac{VP}{SP_h}} = \sqrt{\frac{0.75}{1.40}} = 0.73$$

$$Q = 4005AC_e\sqrt{SP_h/d}$$

$$= Q = 4005 \times 0.7854 \times 0.73 \sqrt{1.40/1.0} = 2700 \text{ scfm}$$

3.3.5 Effects of Flanging

Flanges surrounding a capture hood opening force air to flow mostly from the zone directly in front of the hood. Thus, the addition of a flange to a capture hood improves the efficiency of capture and control, as shown in Figures 4 and 5.

3.3.6 Air Distribution in the Face of Enclosing Hoods

To provide adequate control of emissions in an enclosing hood, the airflow across the face of a hood should be fairly uniform throughout its cross section. One method to assure uniformity is to provide slots at the back of the hood with a low velocity plenum behind the slots, or large-area chamber behind it, for example in large, shallow hoods, such as paint-spray booths, laboratory hoods, and draft-shakeout hoods. These are called compound hoods because they require two accelerations (one at the slot, another at the duct) and two losses (one at the slot and one at the duct entry).

As mentioned in Section 3.3.4, the hood SP, SP_h , represents the energy needed to accelerate the air from ambient velocity (often near zero) outside the hood, through the hood, and to the duct velocity, and also to overcome the frictional SP losses resulting from turbulence of the air upon entering the hood and ductwork. Equations (6) and (7) described this action.

However, for slotted, plenum, or compound hoods there are two entry losses, one through the slot and the other into the duct. There are two accelerations, one at the slot and one into the duct from the plenum. For a slotted compound hood,

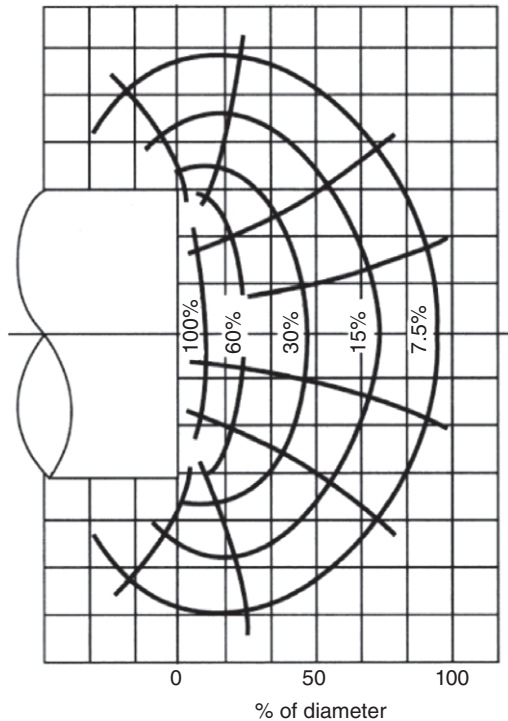


FIGURE 5 Velocity contours for unflanged circular opening.

Eqs. (6) and (7) can be combined to form:

$$SP_h = K_{slot} \cdot VP_{slot} \cdot d + K_h \cdot VP_{duct} \cdot d + VP_{slot} + VP_{duct} \quad (11)$$

In some rare cases, the VP resulting from acceleration through the slot is not all lost in the plenum but it is best not to assume this. In most cases the slot VP is lost (crashing against the back wall of the plenum). Velocities in the plenum are usually so low that the velocity in the plenum can be ignored.

3.3.7 Enclosure of the Emission Source

Any operation to be exhausted by local ventilation should be enclosed as much as possible. This generally provides better control per unit volume of air exhausted. Nevertheless, the requirements the process and of adequate access to the process must always be considered. An enclosed process may be costly in terms of operating efficiency or capital expenditure, but the savings gained by exhausting smaller air volumes may make the enclosure worthwhile.

Where materials flow into an air exhausted enclosure (like a bin equipped with an exhaust duct that is being filled with falling sand), one must take into account the induced airflow into the bin by the moving materials. Design and actual exhaust pressures and airflow rates should be adjusted, as needed (3).

3.3.8 Capture of Contaminants

The velocity of air through all openings must be high enough not only to contain the contaminant but also to remove the contaminant from the hood. The importance of optimal capture and control velocity was discussed in the preceding sections.

3.3.9 Keeping Contaminants Out of Breathing Zone

Hoods that do not completely enclose the process should be located as near to the point of contaminant generation as possible. Airflow should be provided in a direction away from the worker toward the contaminant source.

3.3.10 Providing Makeup Air

In order to keep the building from operating under negative pressure, all air exhausted from a building or enclosure must be replaced. This applies to local exhaust systems as well as dilution systems. Additionally, the incoming air must be tempered by a makeup-air system before being distributed inside the process area. Without sufficient makeup air, exhaust-ventilation systems cannot work as efficiently as intended. Makeup-air requirements are discussed below.

3.3.11 Low Volume High Velocity Exhaust Systems

A unique application of the fundamentals of the LEV fundamentals discussed in this chapter have been applied in a unique way in what is referred to as low volume high velocity (LVHV) exhaust ventilation. With typical application of this approach, small volumes of air at relatively high velocities are used to control dust generated by portable hand tools and machining operations. Control is achieved by exhausting the air essentially at the point of generation by means of close-fitting, custom-designed hoods. To maximize the flexibility required by operators of the equipment, flexible, small-diameter, lightweight plastic hoses are used, being built into the overall design of the tool. Figure 6 illustrates a typical application for control of dust generated by a disk sander. The capture velocities in these situations are high; slot velocities typically are in excess of 20 000 linear fpm. However, because of the short distances required for capture of the dust and the small-diameter tubing (ductwork) associated with the system, the total airflow rate is low.

Although this technique does not have widespread applicability, there are situations for which it has optimized control of dust. Successful use of LVHV exhaust ventilation has been made in such diverse activities as rock drilling, conventional machining, machining of beryllium, wood sanding, metal-surface grinding, pneumatic chipping, internal-surface grinding, and chiseling. Development of these exhaust systems has been somewhat empirical.

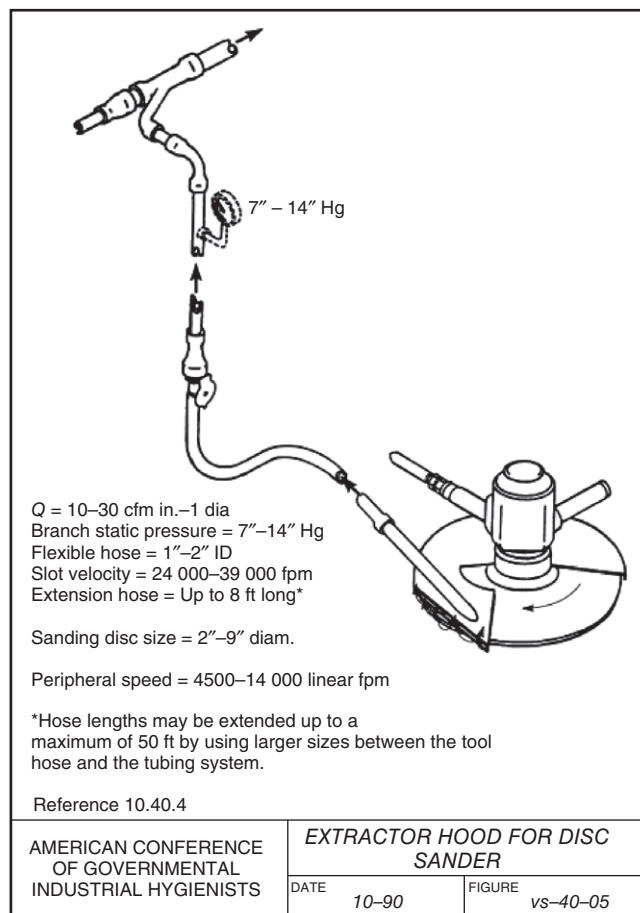


FIGURE 6 Typical arrangement for low volume high velocity hood.

However, proper design of such systems requires the same careful, deliberate consideration of ventilation principles as more conventional-exhaust systems.

3.3.12 Duct Velocities

As discussed in Section 3.1.2, in order to prevent particles of dust and fumes from settling and plugging ductwork, air velocities for transporting these materials must be relatively high. The minimum velocity, called transport or scrubbing velocity, typically is $3500\text{--}4500$ linear fpm. At these velocities, frictional loss from air moving along the surface of the ducts becomes significant; therefore, all fittings, such as elbows and branches, should be wide-swept and gradual, having smooth interior surfaces.

Local exhaust systems used exclusively for clean air, gases and vapors may have lower duct velocities (e.g. 2000 fpm) because there is likely to be nothing to settle and plug the ducts. Lower velocities markedly reduce the frictional and pressure losses against which the fan must

operate, thereby realizing a saving in power cost for the same airflow.

If there is (or there is a chance of) condensation (of water or chemical vapors) in the ductwork, or if the air carries small liquid particles, the ductwork can be sloped to drain any condensed and settled fluid.

If condensable vapors and solid particles are both present in the exhaust air, the ductwork can be heated or insulated to prevent condensation and the mixing of settled particles and fluid to create "mud." If these conditions exist or could exist, always provide cleanout ports on the top for ducts and provide for periodic duct cleaning.

4 FACTORS INFLUENCING THE DESIGN OF NEW LEV SYSTEMS

Specific design methods for LEV systems are presented in a number of texts (1-3, 5-7). An important predesign phase, known as problem characterization, is frequently given little attention (Table 1). This is a topic that can be best addressed by an industrial hygienist who can provide data on emissions, air patterns, and worker movement and actions.

If the process is new, information from a similar operation with the same unit operations may be available. If the facility is a duplicate of one in the company the industrial hygienist should visit the operation with the ventilation designer. Frequently, the designer is an outside contractor.

TABLE 1 Information needs for problem characterization.

Emission source behavior

Location of all emission sources or potential emission sources

Which emission sources actually contribute to exposure?

What is the relative contribution of each source to exposure?

Characterization of each contributor:

Chemical composition, temperature, rate of emission, direction of emission, initial emission velocity, continuous or intermittent, time intervals of emission

Air behavior

Air temperature

Air movement

Mixing potential

Supply and return flow conditions

Air changes per hour

Effects of wind speed and direction

Effects of weather and season

Worker behavior

Worker interaction with emission source

Worker location

Work practice

Worker education, training, cooperation

Source: Reprinted with permission of Burton (2).

In this case it is important that the problem characterization approach be followed, and an information package be provided the designer.

A few cautions are appropriate for the use of available design data. The ACGIH *Industrial Ventilation Manual* provides the most comprehensive selection of design criteria for general industry (1). Each of the “VS Prints” found in Chapter 13 (29th Edition) provides four specific design elements: hood geometry, airflow rate, minimum duct velocity, and entry loss. A missing element is the performance of the hood in terms of percent containment or capture efficiency, which varies with the application and usage.

LEV system design approaches include manual designs, computer-aided designs (CAD), and computational fluid mechanics (CFD). CAD programs for LEV systems can help provide detailed engineering design of LEV systems. CFD is a branch of fluid mechanics that uses numerical analysis to solve and analyze problems that involve fluid flows. Computers are used to perform calculations to simulate the interaction of air and its components with surfaces associated by boundary conditions. Unfortunately, CAD and CFD programs dedicated specifically to LEV system design are few and sometimes not suitable for the functions and intents of unique tailored LEV systems. In this chapter, we explore the manual or traditional approaches, which help the designer and the LEV system owner to better understand what is actually occurring in the system and to better tailor the system to the actual environmental conditions.

As noted, several different traditional approaches to the design of the LEV system are available to the IH and engineer. However, they all consist of a series of similar steps. The following paragraphs briefly summarize the typical sequential procedure used in the initial design of LEV systems. The example provides a typical procedure for the design at STP of a two-hooded duct system into a fan.

1. Prepare a sketch of the layout of the workroom and the operations within it. This will facilitate preparation plans and specifications for the layout of the contemplated exhaust system. Although it is helpful if the layout is approximately to scale, subsequent steps in the procedure, such as calculating proper duct sizes, can be accomplished from even a very simple drawing. For purposes of illustration, consider the design of an LEV system serving a manual grinding station and a welding operation within the same general work area. The concept sketch for the ventilation system to provide control of contaminants at these operations is illustrated in Figure 7.
2. Find in the literature or design a hood for each operation. The type of hood should be selected with the idea of performing the job with the least amount of exhaust air. This requires some ingenuity in designing

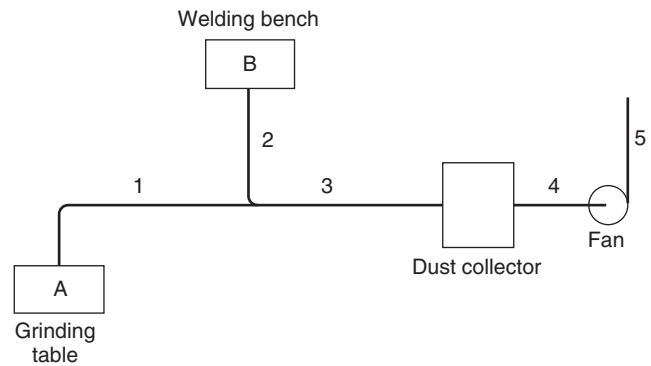


FIGURE 7 Simple sketch of local exhaust system.

enclosures that will not interfere with production; they may be equipped with movable sections. There may be a standard hood available for a particular application, such as found in (1). For convenience, we will use the hoods shown in Figures 8 and 9, respectively, which depict the configuration and design parameters for these hoods (1). Figure 10 shows the proposed layout.

3. Estimate the required control or capture velocity for each operation and type of hood. This part of the process involves some judgment, particularly with hoods of nonstandard design. For this illustration, the information presented in Figures 8 and 9 can be used in making preliminary estimates of appropriate velocities and volumetric-flow rates. Accordingly, an airflow rate of 200 cfm per square foot of bench area for the grinding table and a slot velocity of 1000 (linear) fpm for the welding bench is selected.
4. Estimate or compute the sphere of influence over which the selected capture velocities must function. It will be advantageous to consider the hood arrangements in three dimensions. In the sample calculation, assume that work at both the grinding table and the welding bench will be conducted on a flat surface 2×4 ft and that most of the work will be conducted within 2 in. of the table surface.
5. Determine the total volumetric airflow needed for each hood. From the information supplied in Figures 8 and 9, the required volumetric airflows for the two hoods can be calculated. For this example, a volumetric-flow rate of $200 \text{ ft}^3 (\text{min ft}^2)^{-1}$ of work surface and a bench area of 8 ft^2 have been assumed. Thus, a volumetric-flow rate of $1600 \text{ ft}^3 \text{ min}^{-1}$ will be required for hood A, the grinding table. For the welding bench, the required volumetric rate will be $350 \text{ ft}^3 \text{ min}^{-1}$ per linear foot of hood times 4 ft (the length of the hood), or a total of $1400 \text{ ft}^3 \text{ min}^{-1}$.

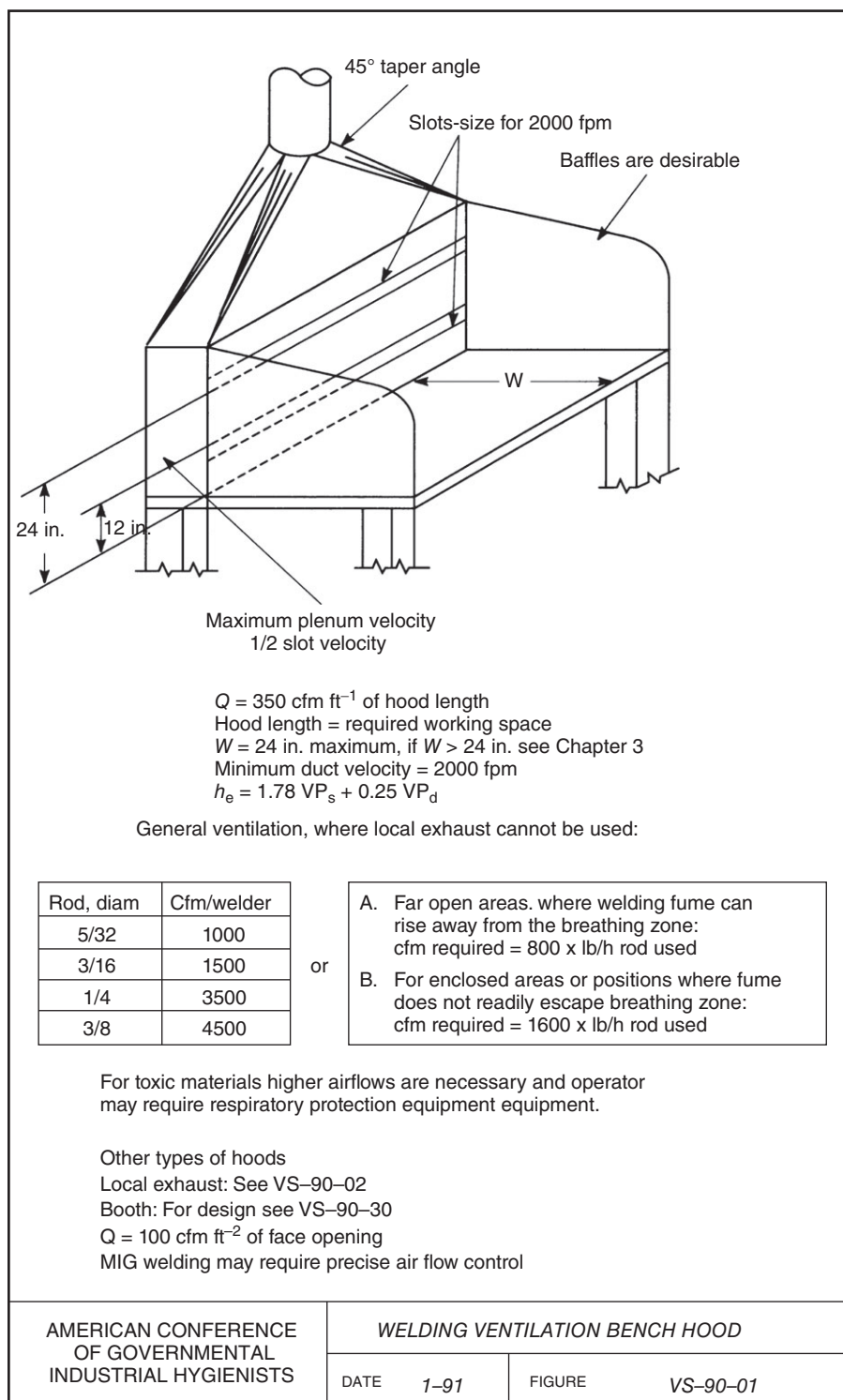


FIGURE 8 ACGIH-recommended hood for portable hand grinding.

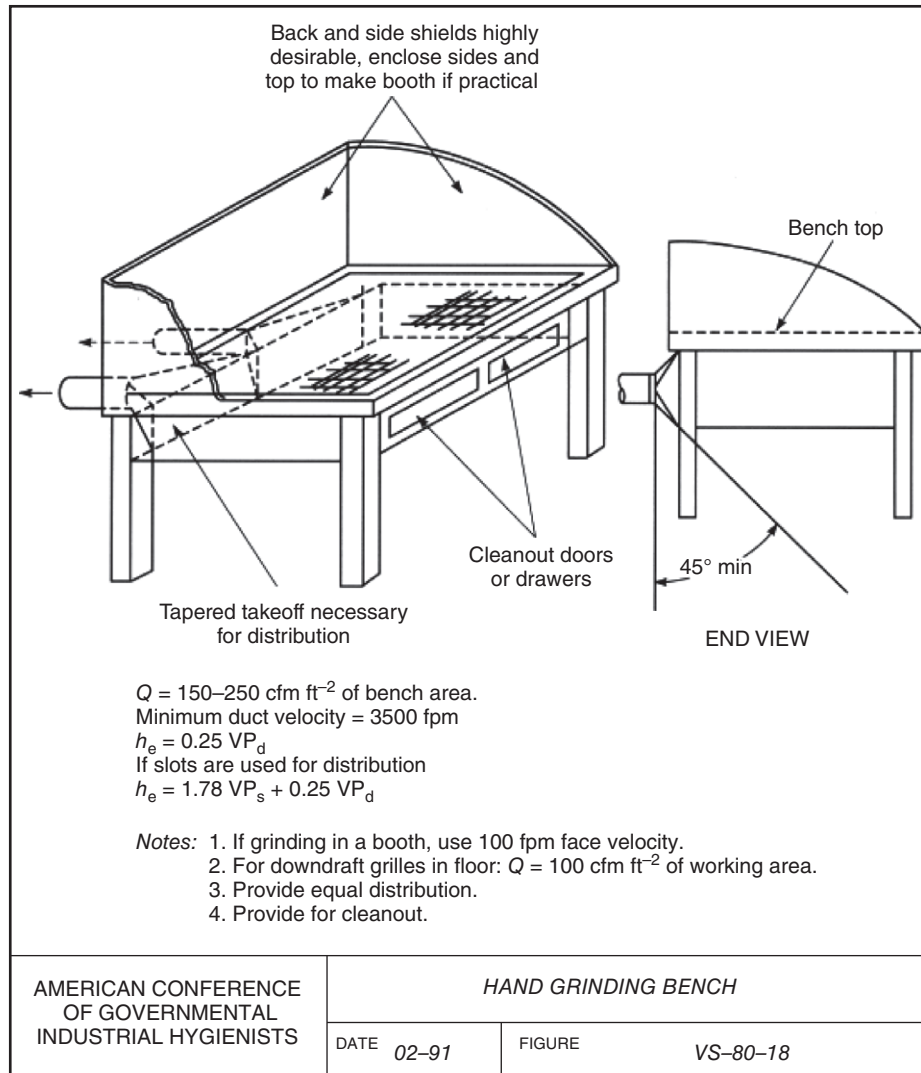


FIGURE 9 ACGIH-recommended for welding bench.

6. Select the minimum transport velocities for the contaminant-laden air being moved through the ductwork. Velocities in the range of 2000–2500 linear fpm are commonly used for gases and vapors (although keep in mind that no air is “dust free”). The recommended transport velocities of Figures 8 and 9 suggest minimum values of 3500 and 2000 linear fpm for ductwork servicing the grinding table and welding bench hoods, respectively. This is a designer choice, however, and transport velocities should be selected based on the conditions at the operation. In our case, let us assume that the transport velocity in the duct serving the welding hood should be about 3500 fpm; for the grinding hood, 4000 fpm.
7. Determine the nearest practical duct diameter necessary to carry the required volumetric rate of air at

the proper velocity. It is usual to choose standard sizes of ducts available from the fabricator to avoid the unnecessary expense of special fabrication. The actual transport velocity should be computed for use in subsequent design steps. In the example problem, using Eq. (2), and assuming that standard ductwork is available in full-inch diameter increments only, the duct diameter nearest to the calculated necessary diameters is 8 in. for both the grinding table and the welding bench. Using 8 in. diameter ductwork for these hoods would produce transport velocities of 4580 and 4010 linear fpm for the grinding hood and welding hood, for example.

8. Compute the VPs corresponding to air velocities in each duct connected to a hood. VPs can be calculated

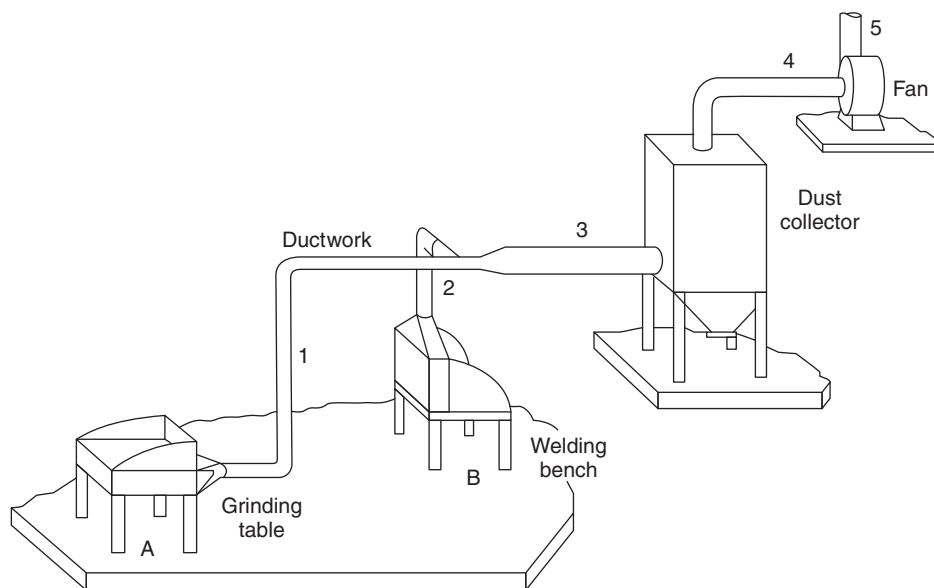


FIGURE 10 Representation of ventilation system.

- using Eq. (4). In this case, $VP_{\text{grinder duct}} = 1.30 \text{ in.w.g.}$ and $VP_{\text{welder}} = 1.00 \text{ in.w.g.}$
- Estimate the entry loss for each hood using Eq. (7). In the example problem, these equations are also given in Figures 8 and 9. Hood entry loss factors (K_h) are also available in other references. In this case, $h_e = 0.25 \times 1.30 \text{ in.} = 0.335 \text{ in.w.g.}$ and $SP_h = 1.30 \times 0.335 \text{ in.} = 1.63 \text{ in.w.g.}$
 - Estimate the hood SP, SP_h , for both hoods, using information developed in steps 8 and 9, and using Eqs. (8) and (11).
 - Estimate SP losses in elbows, branch-to-main junctions, and all other fittings in the duct system using Eq. (6). Loss factors (K) are available for a wide range of ducts and duct fittings (1–3). For this sample problem, refer again to Figure 10 for the relative arrangement of equipment in the exhaust system. Note that Branches 1 and 2 contain two 90° elbows, the centerline radius of the elbow turns is twice the duct diameter, Branch 2 merges with the main duct on a 45° angle of entry, and Duct section 4 contains one 90° elbow also with a centerline radius of 2 diameters.
 - Obtain the duct-friction losses from an appropriate chart, table, or formula. A friction chart like the one illustrated in Figure 11 can be used. For the various sections of ductwork associated with the example problem, the following friction losses can be derived by referring to Figure 9:
- | | |
|----------------|--------------------------------|
| Duct section 1 | 4.0 in.w.g. per 100 ft of duct |
| Duct section 2 | 2.9 in.w.g. per 100 ft of duct |
- Sum the accelerations and the losses for each branch up to the junction. The total SP demand from each hood to the junction should be about the same if cost-effective balance is to be achieved. Increase or decrease duct sizes to make the SP demand in both duct runs about equal at the junction. Now estimate the actual flow rate in each duct for the SP at the junction for the larger (the “governing”) of the two SP demands. For the illustration, let us assume that the governing $SP = -1.90 \text{ in.w.g.}$
 - Moving from the junction to the fan, add the SP losses of all additional fittings and accessory equipment such as air cleaners. In many cases, this information can be obtained directly from the manufacturers. For this example, assume that the pressure drop across the dust collector is $2.0 \text{ in H}_2\text{O}$.
 - Follow the same procedure for the stack or ductwork downstream of the fan. Then add all the SP losses into and out of the fan. Assume for this sample calculation that $SP_{\text{in}} = 5.50 \text{ in.w.g.}$ and $SP_{\text{out}} = 0.5 \text{ in.w.g.}$ and that the VPs in and out of the fan are equal.
 - Select a fan of proper type, size, and speed to produce the highest operating efficiency, or lowest horsepower, consistent with other considerations. Use the calculated total airflow in cubic feet per minute (Q ; about 3000 cfm) and the total system SP required (SP ; about 6.0 w.g.) for fan selection purposes. When selecting a fan, it is necessary to be familiar with the fan laws and system curves, that is how the SP and volumetric airflow are related. A fan curve or system curve shows graphically the possible combinations of volumetric

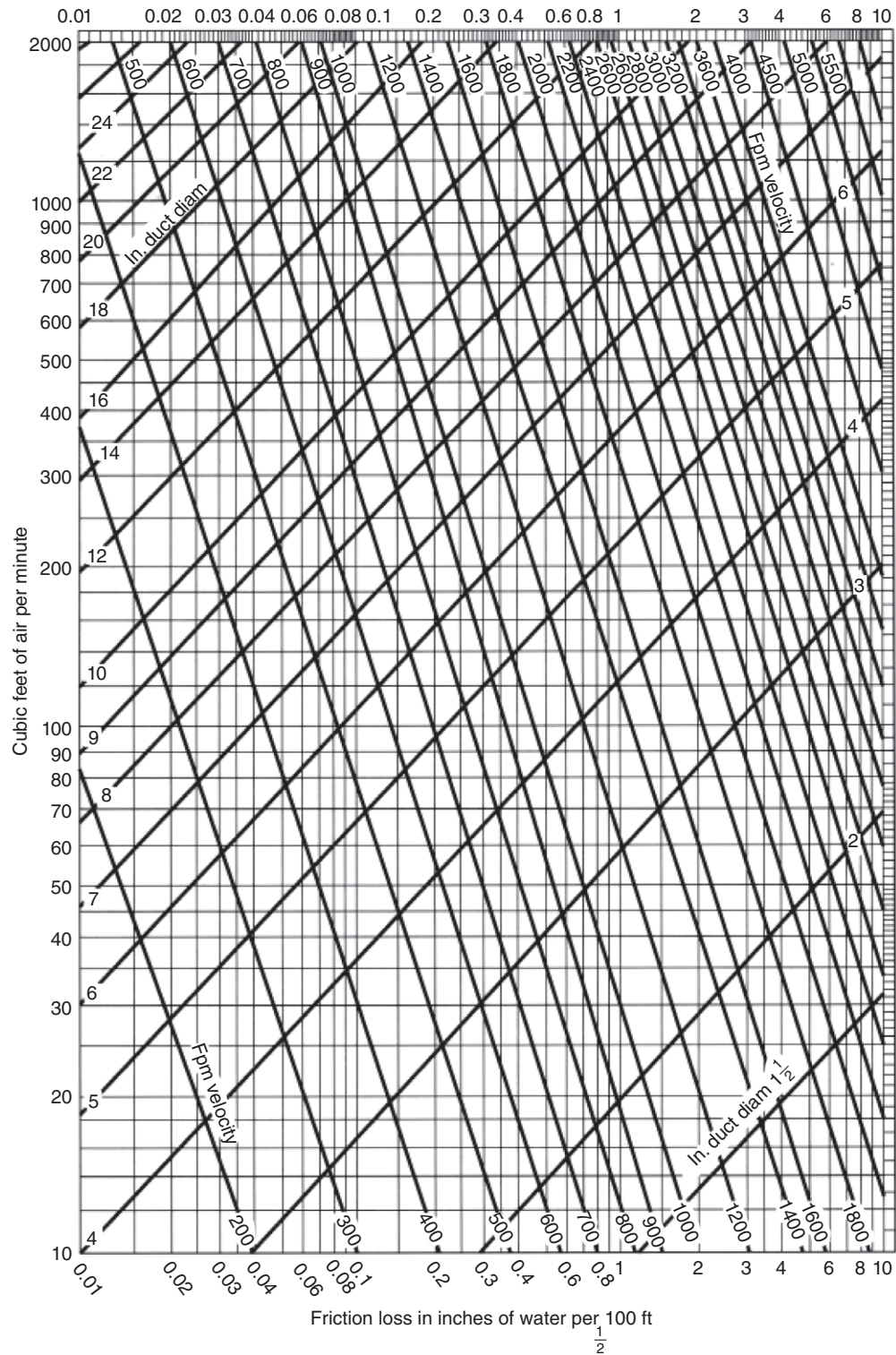


FIGURE 11 Typical friction loss of air in straight duct.

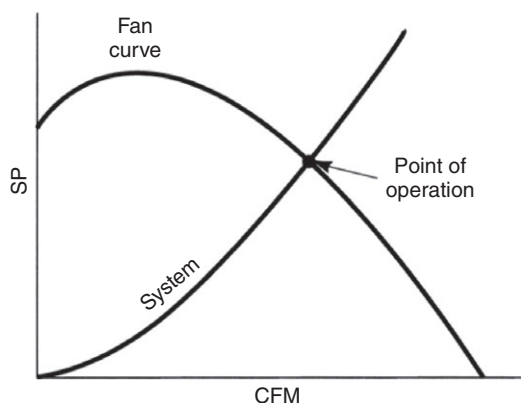


FIGURE 12 Fan and system curve.

flow and SP for a given application. Because the fan and system each can operate only at a single point on its own curve, the combination can operate only where these curves intersect (Figure 12). Thus, a fan must be chosen on the basis of its characteristics and the requirements of the system in which it will be applied. Each fan is characterized by the volume of air flow, the pressure at which the flow is produced, the speed of rotation, the power required, and the efficiency. These quantities are measured by manufacturers with standard testing methods, and the results are plotted to furnish characteristic “fan curves” or “fan tables” (2). During design, one must consider potential leakage of air into the LEV system. (Leakage robs air from the hood where emission sources must be controlled.) Sometimes even “sealed ducts” can leak up to 5% of the total airflow and air cleaners might leak as much as 10–15% of the total air reaching the fan if they are not well maintained. Check with your duct and air cleaner suppliers for estimates of air leakage in their equipment when selecting the fan and motor operating specifications.

All LEV system design approaches essentially follow these 16 steps, with simplifications or complexity added, depending on the system (1–3, 5, 6).

4.1 Ventilation Regulations and Standards

4.1.1 OSHA Codes

Some types of ventilation, both dilution and local exhaust, are covered by occupational safety and health regulations. Older federal standards, e.g. those established by the Occupational Safety and Health Administration (OSHA), include specific ventilation requirements for the major applications identified in Table 2.

TABLE 2 Major industrial activities covered by OSHA standards which include ventilation requirements.

Industrial application	Standard reference
Abrasive blasting	29 CFR 1910.94(a)
Asbestos	29 CFR 1910.1001(c)
Bulk gas plants	29 CFR 1910.106(f)
Confined spaces	29 CFR 1910.146
Dip tanks containing combustible or flammable liquids	29 CFR 1910.108(b)
Electrostatic spraying	29 CFR 1910.107(i)
Flammable or combustible liquids in storage rooms and enclosures	29 CFR 1910.106(d)
Grinding, polishing, and buffing	29 CFR 1910.94(b)
Hydrogen	29 CFR 1910.103(b)
Laundries	29 CFR 1910.262(c)
Open surface tanks	29 CFR 1910.94(d)
Oxygen	29 CFR 1910.104(b)
Powder coatings	29 CFR 1910.107(i)
Sawmills	29 CFR 1910.265(c)
Spray-finishing operations (general)	29 CFR 1910.107(d)
Surface coating	29 CFR 1910.94(c)
Textiles	29 CFR 1910.262(rr)
Welding, cutting, and brazing	29 CFR 1910.252(f)

In addition to the references to ventilation requirements in these codes, many occupational health standards for specific substances, for example benzene, ethylene oxide, formaldehyde, and lead, incorporate language clearly meant to include ventilation considerations. In many OSHA health standards there is a section titled “Methods of Compliance,” which contains a statement implying that the employer must institute engineering controls and work practices to reduce and maintain employee exposure to or below the Permissible Exposure Limit (PEL)-Time-Weighted Average (TWA), except to the extent that such controls are not feasible. It is inconceivable that such engineering controls would not rely heavily on ventilation.

For the most part, the ventilation requirements incorporated into OSHA standards are based on consensus-type standards developed by organizations such as the American National Standards Institute (ANSI) and the National Fire Protection Association (NFPA). Although the past few decades have not seen much regulatory activity regarding ventilation requirements, the number and degree of specificity of ventilation standards may increase in the future.

Many of the occupational health standards being developed by OSHA are couched in language that makes it clear that engineering control of the specific contaminants covered by the standard is the primary responsibility of the employer. In fact, engineering controls (chiefly ventilation in the case of airborne contaminants) should be applied to the

extent feasible even if they are not sufficient by themselves to reduce the airborne concentration of the contaminant to the specified acceptable level. Thus, in addition to the occupational health standards dealing with specific aspects of ventilation, there are indirect references to the requirement for installation of ventilation systems to maintain the work environment within stated acceptable limits. Accordingly, the need for application of sound engineering in the control of workplace contaminants undoubtedly will continue to increase.

4.2 ANSI Z9 Standards

Perhaps the most important standard related to industrial ventilation is ANSI Z9.2-2018, *Fundamentals Governing the Design and Operation of Local Exhaust Systems* (8). The American Society of Safety Engineers (ASSE) is the Secretariat of the Z9 Committee. The Z9 Committee develops, manages and publishes 14 industrial ventilation standards and guidelines covering open surface tanks, spray finishing, abrasive blasting, lab ventilation, recirculation of exhaust ventilation, confined spaces, dilution ventilation, O&M maintenance, and others (9–11).

5 DILUTION VENTILATION

As suggested in **Characterizing Air Contaminant Emission Sources**, when enclosure or other forms of isolation or substitution are not appropriate or have been used to the practicable extent, the IH looks to LEV as the primary-control measure. And if that is not feasible or cost-effective, the IH will apply dilution ventilation. It should be kept in mind that LEV systems are not necessarily 100% efficient in capturing and controlling contaminants released by a process. It is because of this residual or background level of contamination that dilution ventilation provisions are always included as a complementary aspect of the total ventilation within a plant.

As used in this chapter, the term dilution (or, general) ventilation refers to the practice of supplying and exhausting large volumes of air throughout a workspace. It is used typically in industry to achieve comfortable work conditions (temperature and humidity control) and to dilute concentrations of airborne contaminants to acceptable concentrations throughout the workspace. When properly used, dilution ventilation can be effective in removing large volumes of heated air or relatively low concentrations of low toxicity contaminants from several decentralized sources. Dilution ventilation can be provided by either natural or mechanical means; often the best overall result is obtained with a combination of mechanical- and natural-air supply and exhaust.

5.1 Natural Ventilation

Natural ventilation can be provided either by gravitational forces, using thermal forces of convection primarily, or by anemotive forces, created by differences in “wind pressure.” These two natural forces operate together in most cases, resulting in the natural displacement and infiltration of air through windows, doors, walls, floors, and other openings in an industrial building. Unfortunately, the wind currents and thermal-convection profiles on which natural ventilation depends are erratic and frequently unpredictable. Thus, it is perhaps a misnomer to refer to natural ventilation as a “control” method, because to employ this technique requires dependence on, rather than control of, natural forces.

There are some good applications for natural ventilation. The pressure exerted on the upwind side and concurrent suction exerted on the downwind side of a building as a result of wind movement can be predicted for flat terrain fairly reliably. Thus, the wind forces exerted on an isolated building in a relatively flat area permit the prediction of natural ventilation forces. In the more common complex industrial building, however, the effects of the presence of one building on the others normally cannot be calculated; thus, the use of wind-pressure models in the development of general ventilation systems is not feasible.

The impact and effectiveness of natural ventilation provided to a building depend both on the wind pressure profiles and on the thermal effects occurring within the structure. The warmer inside air tends to rise and leave the building through any available openings in the upper structure; cooler air tends to infiltrate the building by the reverse process in the lower structure. These thermal effects, which are much more predictable than the external wind forces, can be useful in design of a general ventilation scheme (5).

5.2 Mechanically Controlled Ventilation

A modern industrial complex characterized by a low profile building structure (i.e. large floor space, low height) as well as multistory buildings of masonry and glass construction present ventilation problems that were not found among older industrial plants. For the most part industrial facilities constructed 40–50 years ago incorporated by design many features that relied upon natural ventilation of the workspace. By contrast, modern buildings generally avoid natural-ventilation and mechanical ventilation must be relied upon almost completely. Mechanical-ventilation systems exhaust contaminated air by mechanical means (exhaust fans) with the concomitant use of appropriate air supply to replace the exhausted air. The best method of achieving this in modern closed buildings is to supply air through a system of ductwork, distributing the air into the work areas in a manner that will provide optimal benefit to the workers for both comfort and control of contaminants.

5.3 Dilution Ventilation for Contaminant Control

Dilution ventilation has as its primary function the maintenance of concentrations of airborne contaminants at or below acceptable exposure limits, in terms of either potential fire and explosion or occupational health considerations. If enough clean air is mixed with contaminated air, the concentration of the contaminant can be diluted to any reasonable level. Of course, dilution ventilation for purposes of fire and explosion control should not be employed in areas occupied by workers because the concentrations of concern from an occupational health standpoint invariably are orders of magnitude below those of concern for explosive limits. Exposures to atmospheres controlled to concentrations below the lower explosive limit or even a fraction thereof could cause narcosis, severe illness, or even death. Therefore, it is extremely important not to confuse dilution-ventilation requirements for health-hazard control with those for fire and explosion prevention.

When considering whether dilution ventilation is appropriate for health-hazard control, it should be remembered that dilution ventilation has four limiting factors:

- The quantity of contaminant generated must not be excessive, or the air volume necessary for dilution would be prohibitively large.
- Workers should be far enough away from evolution of the contaminant or the contaminant should be of sufficiently low concentration, so the workers will not be exposed to excessive levels.
- The toxicity of the contaminant should be relatively low.
- The evolution or generation of the contaminant should be reasonable, uniform, and consistent.

In practice, dilution ventilation for control of health hazards is used to best advantage in controlling the concentration of vapors from organic solvents of relatively low toxicity. To apply the principle of dilution successfully to such a problem, data must be available on the rate of vapor generation or on the rate of liquid evaporation. Usually such data can be obtained from the plant records on material consumption.

5.4 Estimating Dilution Ventilation Volume Flow Rates

The concentration of a gas or vapor at any time can be expressed by a differential-material balance that, when integrated, provides a rational basis for relating ventilation to the

generation and removal rates of a contaminant under various conditions. Starting with a fundamental material balance, and assuming no contaminant in the air supply, the following relationship applies:

Rate of accumulation = rate of generation – rate of removal

This basic relationship can be applied in various ways. For a specific concentration C , and uniform generation rate G ,

$$G(t_2 - t_1) = Q'C(t_2 - t_1)$$

$$Q' = \frac{G}{C}$$

$$Q = \frac{KG}{C}$$

where G is the rate of generation of contaminant, Q is the rate of ventilation, K is the design distribution constant, allowing for incomplete mixing, C is the concentration under steady-state conditions, V is the volume of room or enclosure, and t is the time.

Therefore, the rate of flow of uncontaminated dilution air required to reduce the atmospheric concentration of a hazardous material to an acceptable level can be estimated if the generation rate can be determined. For liquid solvents the steady-state dilution ventilation requirement can be conveniently expressed as

$$Q = \frac{387 \times \text{ER} \times K \times 10^6}{\text{MW} \times \text{Ca} \times d} \quad (12)$$

where Q is the actual ventilation rate ($\text{ft}^3 \text{min}^{-1}$), ER is the evaporation rate of liquid (lb min^{-1}), MW is the molecular weight of liquid, K is the design factor for incomplete air mixing at some location in the workspace, Ca is the acceptable exposure concentration, usually some fraction of the appropriate Occupational Exposure Level (OEL) (ppm), and d is the air density correction factor.

Sample Calculation. What air volume flow rate is required to dilute 0.5 gallons of toluene uniformly evaporated into the workroom air in paint shop located in Salt Lake City, Utah, during a painting process that takes 8 h? (MW = 92.1; SG = 0.866, Ca = 10 ppm; $d = 0.85$; $K = 1.5$).

Note: $\text{lb} = \text{gallon} \times 8.33 \times \text{SG} = 0.5 \times 8.33 \times 0.866 = 3.607 \text{ lb}$ and $8 \text{ h} = 480 \text{ min}$. $\text{ER} = 3.607 \text{ lb (480 min)}^{-1} = 0.00751 \text{ lb min}^{-1}$.

$$Q = \frac{387 \times \text{ER} \times K \times 10^6}{\text{MW} \times \text{Ca} \times d} = \frac{387 \times 0.00751 \times 1.5 \times 10^6}{92.1 \times 10 \times 0.85} = 5600 \text{ acfm (rounded)}$$

See Ref. (2) for additional sample calculations and applications.

5.5 Dilution Ventilation Airflow Patterns

Dilution ventilation presents some disadvantages, the most significant one being that it can permit the occupied space to become, in effect, a large settling chamber for dusty contaminants, even though the exposure concentration may be within acceptable limits as far as potential health hazard is concerned. In some rare cases, the settling or separation of contaminants from the air may represent condensation of materials that were vaporized by high temperature processes and accumulated on surfaces after condensation. The undesirability of the settling of contamination onto surfaces within the plant has been dramatically demonstrated in plants handling highly combustible dusts in which, although the dust concentrations at any one time were not sufficient to constitute a hazard, accumulation over many months resulted in explosions. It is therefore necessary to maintain an effective ongoing good-housekeeping program in conjunction with any broad-based engineering control such as general ventilation.

The routes by which the air will enter and leave the workspace are important considerations in the design of general ventilation systems for a plant. The routes are of critical concern not only to the occupants of the building but potentially to the neighbors and the community at large. In general, the relative locations of air inlets and outlets should be considered in the implementation of a dilution ventilation system.

5.5.1 Air Inlets

Sufficient combined or total-inlet area should be planned to accommodate the required volume of makeup air. This will prevent excessive inlet velocities that consume power, create drafts on workers, stir up dust, and interfere with performance of local exhaust systems. The chosen inlet velocity is likely to represent an engineering compromise between low velocities, which require large inlet areas, and higher rates, which may facilitate rapid dilution of contaminants.

When widespread hazardous operations are controlled by dilution ventilation, inlets should be well distributed around the building to provide uniform circulation. If contaminants are controlled by localized dilution or by forceful diffusion into the general room-air reservoir, inlets may be purposely located to give nonuniform air-supply distribution.

When using natural ventilation, any thermal or convection effects within the building should be taken advantage of in locating air inlets. For this purpose, the designer must avoid the location of inlets (and outlets) near the neutral zone of inside-outside pressure differentials, which is approximately midway between the floor and roof. Inlets should also be located remote from stacks or ventilators discharging contaminants from the same or neighboring structures.

5.5.2 Air Exhausts and Outlets

Outlets should be located as far as possible from air inlets to prevent short-circuiting. This advice holds for both natural- and mechanical-ventilation systems.

If widely scattered operations are controlled by dilution ventilation, outlets should be uniformly distributed around the building. Similarly, if contaminants are controlled by localized dilution, air outlets may be purposely located to short-circuit a corner of a large room, with the intent of creating a high rate of air change there without involving the atmosphere of the entire space. This method of localized-space ventilation requires a higher rate of exhaust air than supply air within the area to be controlled to prevent the spread of contaminants throughout the room.

Outlets, like inlets, should be placed to take full advantage of thermal effects. They should be protected against the direct force of prevailing winds, which reduce the capacity of any exhaust fans or destroy the anticipated airflow route planned based on thermal effects inside the building.

Preferably, dilution air should enter the workspace at approximate breathing zone height, pass through the workers' breathing zone, then through the zone of contamination; afterward, if it is not exhausted, it should enter a space of higher relative contamination. A useful concept in the interest of air-handling economy is progressive ventilation. The air removed from an industrial plant frequently may be directed in a way that will provide both local and dilution ventilation. In fact, the air may be routed through several areas in succession, always in the direction of increasing air contamination, as long as the exhaust from one area is acceptable as the supply for the next. Progressive ventilation saves energy in the form of airborne heat and horsepower to move the air.

5.6 Which is More Appropriate, LEV or Dilution Ventilation as a Primary Control?

Table 3 shows a hierarchy of desired ventilation controls. When technically feasible and cost-effective, approaches higher in the table should be employed. Table 4 shows ventilation type selection criteria traditionally used by the IH.

6 TESTING AND MONITORING

6.1 Acceptance and Start-Up Testing

It is important that new ventilation systems be inspected and tested on completion of the installation to ensure the system conforms to the design specifications, flow rates and velocities have been met, and that worker exposure goals have been achieved.

TABLE 3 Ventilation control hierarchy.

Type of ventilation	Hood type	Example
LEV	Total enclosure	Glove box
LEV	Partial enclosure	Laboratory hood
LEV	Low volume high velocity, tool integrated	Portable grinder
LEV	Exterior, capture or receiving hood	Welding hood
DV	Mechanical exhaust and supply	Roof ventilators
DV	Natural ventilation	Wind induced

LEV, local exhaust ventilation; GEV, general exhaust (dilution) ventilation.
Source: Adapted from Ref. (12).

6.2 Checking Preconstruction Details

Ventilation system design should use standard fittings and equipment for hardware such as hoods, elbows, entries, expansions, contractions, stacks, and so on. If the hardware elements provided for installation are standard, SP losses will be approximately those estimated during design. If the system is large it may be worthwhile to test for losses.

Hoods warrant special attention. The entry losses on standard hood designs as noted in the ACGIH Ventilation Manual are quite reliable, however, if the hood design is not typical it may be difficult to estimate entry loss. In such a case the best solution is to have a single hood fabricated and tested to define the entry loss. This is especially important when a large number of hoods are to be installed. With a sample hood the coefficient of entry can be defined for use in routine hood static suction measurements to calculate airflow using Eq. (10).

An initial physical inspection of the completed system should be conducted to determine if the system is built according to the design plans and specifications. The size and type of fittings should be checked and the hood construction reviewed. The fan type and size should be as specified and the direction of rotation, speed, and current usage should be noted. A detailed inspection sheet should be completed.

Air cleaning equipment should be inspected to determine if it is installed according to specifications. If ancillary equipment such as pressure sensing or velocity measuring equipment is included in the systems, it should also be inspected and calibrated. Be sure all local and national codes are being complied with. For example, EPA and local air pollution authorities sometimes require differential pressure monitoring at baghouses and wet scrubbers to assure that cleaning effectiveness is being maintained.

Air cleaning equipment should normally be mounted on the suction side of the fan, especially if the equipment is located inside a building. If this is not done air contaminants may leak into occupied spaces.

6.3 Airflow

The general format for testing a new LEV system balanced without blast gates is shown in Figure 13. The airflow rate through each branch servicing a hood should be determined using, for example a pitot tube and manometer to conduct

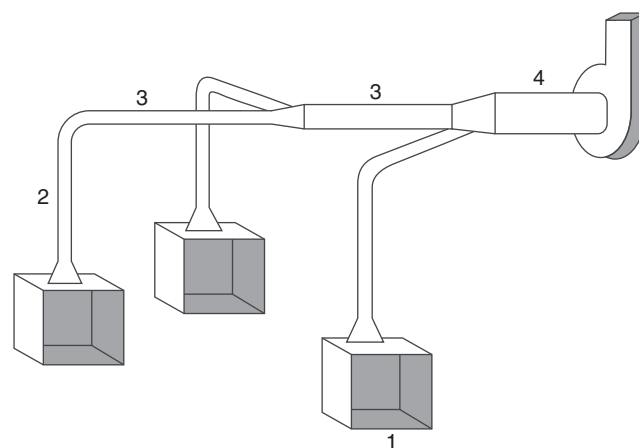


FIGURE 13 Typical locations for ventilation measurements: (1) at the face of booth-type hoods, (2) just downstream of a hood to measure VP and SPh, (3) in the main duct to define exhaust rates by differences before and after junctions, and (4) in the main to define total system airflow at the fan.

TABLE 4 Application of local exhaust and general exhaust ventilation.

Local exhaust ventilation better when	General exhaust ventilation better when
Contaminant is toxic, hazardous	Contaminant has low order of toxicity and hazard
BZ is close to contaminant release	BZ remote from emission sources
Contaminant generation rates varies over shift	Contaminants are gases and vapors not particles
Contaminant generation rate is high with few sources	Uniform contaminant release rate
	Cost-effective and technically feasible
Contaminant source is fixed	Multiple generation sources, widely spaced
Cost-effective and technically feasible	Generation sites not close to breathing zone
	Plant located in moderate climate; clean dilution air

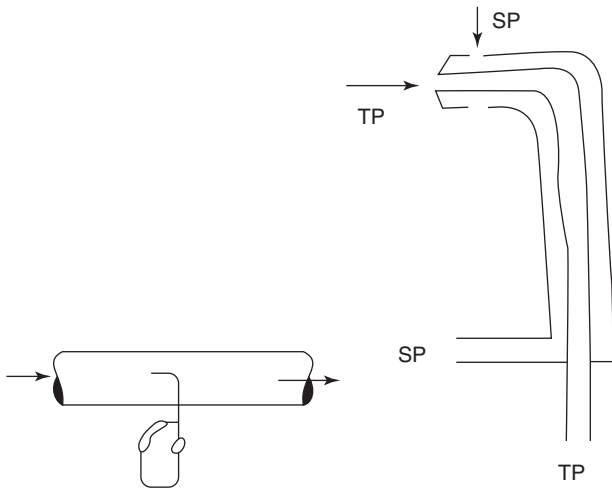


FIGURE 14 Pitot tube used for determining TP, SP, and VP in ductwork.

a pitot traverse in the ductwork (see Refs. (1–3, 5, 6) for details on ventilation testing). Figure 14 shows a typical pitot tube that can measure TP, SP, and VP in ductwork.

Electronic manometers with microprocessor-based instruments are available for direct reading of pressure and velocity. When used in conjunction with a small portable recorder, the pitot traverse can be conducted by one person.

One of two critical design velocities should be measured, depending on the hood type. A partial enclosure such as a paint spray hood has a design velocity or control velocity at the plane of the hood face. Exterior hoods such as a simple welding hood will have a capture velocity specified at a certain working distance. The control and capture velocities may be calculated from the airflow rate and the hood dimensions. Frequently, the actual velocities must be measured to satisfy plant or regulatory requirements. Face velocities at partial enclosures are usually evaluated using a velometer. These instruments have a wide range of applications but care should be taken to observe their limitations as described in the manufacturer's literature.

The measurement of hood SP, SP_h , is also of value in periodic inspections and should be measured at the acceptance tests. A permanent manometer should be installed to provide a real-time monitor of SP_h because it is directly related to airflow. The measurement, made 2–4 diameters downstream of the hood, provides a simple method of calculating airflow using Eq. (10). The data collected in the acceptance tests also become important baseline information for subsequent periodic inspections described in Section 5.

6.4 Performance

The term performance, as used in here, describes the ability of the LEV to minimize the release of air contaminants

from equipment serviced by the system. This measurement can be done by qualitative, semiquantitative, and quantitative methods.

6.4.1 Qualitative Methods

The use of smoke tracers released at the generation point, if done properly, provides an excellent qualitative method of checking the performance of the hood. The control boundary can be established with this technique. In addition, it can be an excellent teaching tool for the worker who can view the impact of his own body and actions and that of external disturbances such as drafts from windows, doors, and traffic on the ventilation. Corrosive smoke cannot be used in semiconductor facilities; both dry ice and ultrasonic streams have been evaluated for this purpose. In Europe another qualitative technique, light scatter with back lighting, is widely used to identify the source and generation mode of particle contamination. Exquisite photographs of dust release based on this technique have been used as a design input for ceramic industry dust control.

6.4.2 Semiquantitative

One approach is described here. The LEV system is first assessed to determine if it meets good practice in terms of general design and airflow rates. If those are acceptable the system is checked qualitatively by smoke and then semiquantitatively using a tracer gas, as shown in Figure 15. A series of release grids are designed that model the actual release area. An oil mist generator operating with corn oil is used to generate a submicronized aerosol. The generator is positioned to release the mist deep in the hood so that all mist is collected. The probe of a forward light scatter photometer samples the duct stream laden with the mist and the reading is defined as 100% containment. The grid is then positioned at the actual work release point and a new reading is taken in the duct. If all the mist is collected the reading will be 100%; if only 1/2 the oil mist is collected the reading of containment is 50%.

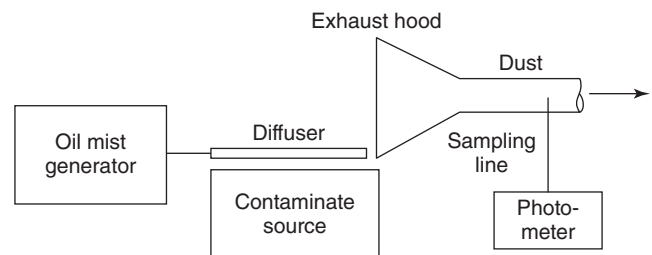


FIGURE 15 Containment fraction for a hood can be determined in the field using a tracer introduced first inside the hood to establish the 100% benchmark and then at the normal contaminant release point. Source: Ref. (13). Reproduced with permission of Taylor & Francis.

Case Study. In one series of studies using this technique, M. Ellenbecker (personal communication) evaluated the capture efficiency of a series of LEV hoods in a chemical processing plant. The test aerosol was mineral oil with a count median diameter of 0.3–0.4 μm . In each operation the area source of contamination, such as a reactor charge port or the wet surface of the cake on a plate and frame filter, was simulated with a grid network of nozzles that could be varied from a point source to an area source several meters square. In this system, the contaminant release for the grid was relatively passive and therefore one cannot duplicate the dynamics of the source such as the “throw.” Nor can one duplicate the generation rate or other physical parameters such as temperature. For these reasons it must be identified as a semiquantitative procedure and extensive laboratory validation would be needed to upgrade the test to a quantitative procedure.

The performance of 10 local exhaust hoods chosen for evaluation in this well maintained chemical plant were highly variable. Four hoods (two reactor and two weigh scale hoods) with a capture efficiency of 100% were obviously operating satisfactorily. However, in one case the exhaust rate was too high. The exhaust rate was reduced by a factor of four and a capture efficiency of 100% was still maintained. Such excessive flow rates will result in high operating costs to exhaust the air and bring in tempered replacement air. Another four hoods achieving capture efficiencies of 90–100% (reactor, drum vent, centrifuge, and a weigh scale hood) were adequate for many operations but the investigator felt they might not be acceptable for highly toxic air contaminants. A single Neutsche filter hood had a capture efficiencies of 85%. Ellenbecker felt the design was unsatisfactory and the maintenance program should be reviewed and upgraded. A single bung hole exhaust hood with a capture efficiency below 70% was felt due to an inferior design.

This evaluation system and others now available using tracers such as sulfur hexafluoride are semiquantitative. They do not attempt to closely model the specific chemical or its generation rate. Although the tests are semiquantitative, the procedure is simple, the equipment suitable for in-plant tests, and the procedure can be done in 20–30 min. It can be effectively used by a technician to explore the effects in changes in hood geometry and placement, airflow rate, and baffle design. It is also an excellent training aid for chemical processors who must learn to use the exhaust system as a valuable tool.

6.4.3 Quantitative

The capture efficiency of a LEV system is usually difficult to establish in a plant using the process-generated contaminant. To conduct such a test, the system must be enclosed temporarily so that all the contaminant enters the hood to

establish the 100% capture efficiency concentration. If that cannot be done both the fraction of the contaminant collected by the hood and that fraction lost from the hood must be independently determined. The fraction of the contaminant lost to the room is especially difficult to measure.

Case Study. Conroy (14) used a quantitative approach in the evaluation of capture efficiency on a degreaser hood. In her work both the local and general exhaust airflow rates were measured as was the volume of the workspace. Solvent concentration at several locations in the general workplace and in the duct servicing the exhaust hood were measured periodically as was the velocity of the cross drafts in the workspace. Using mass balance models, the rate of solvent emission to the workspace was calculated based on the workspace concentrations and the ventilation characteristics of the workspace. The hood exhaust rate and the concentration in the duct determined the local exhaust emission rate. The ratio of the LEV emission rate to the total rate of solvent emission, that is the sum of the loss to the room and that removed by the hood is the hood capture efficiency.

In most cases quantitative measurement of hood performance is made by air sampling on the worker. This procedure obviously does not measure capture efficiency but rather the ability of the LEV system to achieve a certain air concentration at the breathing zone of the worker. In such a case, the most realistic test involves the operator using the actual chemical.

6.5 Periodic Maintenance Testing

The LEV system should be inspected periodically to ensure that the system continues to meet performance and design standards and complies with various regulations. The motor-fan components are inspected to determine the condition of the fan blades, direction of rotation, belt tension, guarding, and lubrication. The hoods and ductwork are inspected for corrosion damage, plugging, leaks, and any local modification by the plant.

The importance of well-qualified personnel to design, install, operate, and inspect LEV systems is of paramount importance to the IH.

7 MAKEUP AIR AND RECIRCULATION OF EXHAUST AIR

Adequate supplies of outside air are necessary to ensure proper operation of ventilation systems. Properly designed exhaust systems will remove toxic contaminants by themselves; however, they should not be relied upon to draw air into the building to replace that which is exhausted, because this can result in excessive negative pressures within the building, leading to undesirable effects. Mechanically

controlled systems for supplying the air to the workspace are preferred and in most modern industrial facilities are necessary to achieve the overall desired ventilation. Most outside air-supply systems currently installed in industrial plants have been placed in operation only to replace the exhausted air, with little or no regard to the overall positive effects that can be achieved by the air-supply system in the total environmental-control system.

7.1 Need for Adequate Makeup Air

Air enters a workspace in an amount equal to the volume actually exhausted, regardless of whether mechanical provisions are made for replacement of the air. Of course in some cases, particularly when the total-exhaust volume is small, the replacement air enters the building with no adverse effects, even in the absence of a mechanical makeup-air system. When the exhaust volumes are relatively large in comparison to the size of free inlet area of the building, however, undesirable effects will be experienced. Older industrial buildings with large void spaces in the enclosing walls may provide significant openings, and air leakage into the building can be quite pronounced. Modern windowless plants of masonry construction, however, can be essentially airtight, with the result that the building is starved for air if there is a significant volume of exhaust ventilation. In a building that is relatively open, an influx of outside air is particularly undesirable in northern climates, where the incoming air cools the perimeter of the building, workers exposed to the incoming air are subjected to drafts, temperature gradients are produced within the building, and the internal heating system is usually overtaxed. Although the incoming air eventually may be tempered to acceptable conditions by mixing with interior air, it is an ineffective heat-transfer process, usually resulting in wasted energy.

Reasons for considering an adequate supply of makeup air in conjunction with a total ventilation system include the following:

1. Lack of adequate makeup air creates a negative pressure within the building; this increases the SP that must be overcome by the exhaust fans if they are to function properly. This effect can result in a reduction of the total volume of air exhausted from the enclosure, and it is particularly serious with low pressure fans such as the common wall fans and roof exhausters of the propeller type.
2. Cross drafts created by the infiltration of uncontrolled makeup air interfere with proper operation of exhaust hoods and also may disperse contaminated air from one area of the building to another; moreover, they can seriously interfere with proper operation of process equipment. The relatively high velocity cross drafts

through windows and doors created by the infiltration of air can even dislodge settled material on beams and other horizontal surfaces, resulting in resuspension of solid contaminants in the workroom.

3. If the negative pressure created within the building is significant enough, there may be actual backdraft on flues and other natural draft stacks, posing a potential health hazard from release of combustion products into the workroom. Such backdrafting can occur in natural-draft stacks at very low negative pressures. Secondary problems associated with the backdraft phenomenon include difficulty in maintaining pilot lights in burners, erratic operation of temperature controls, and potential corrosion damage in stacks and heat exchangers due to condensation of water vapor from the flue gases.
4. The cold drafts resulting from infiltration of uncontrolled makeup air can produce worker discomfort, leading to reduced work efficiency attributable to lower ambient temperatures and the drafts impinging on the workers.
5. The differential pressures created across internal partitions may make doors difficult to open or close if the amount of infiltrated makeup air is high enough. In some extreme cases, this can pose a safety hazard when doors are moved by the force of the pressure gradient itself in an uncontrolled manner.
6. The conditions of cooler ambient temperatures near the building perimeter often lead to decisions to correct the problem by installing more heating equipment in those areas when installation of a proper makeup-air system would eliminate the problem. The heaters warm the air only after it has entered the building, usually too late to be of benefit to the workers at the perimeter. Then the overheated air moves toward the building interior, making those areas often uncomfortably warm. Often attempts are then made to alleviate this problem by installing more exhaust fans to remove the excess heat, but this further aggravates the problem of temperature gradients within the building. The net result is the unnecessary wasting of heat without solving the problem. The fuel consumption associated with attempts to achieve comfortable temperatures within the building by this approach is much higher than it would be with a properly installed system for providing makeup air.

7.2 Principles of Supplying Air

The volume of makeup air provided to a workspace generally should equal the total volume of air removed from the building by exhaust-ventilation systems, process venting, and combustion processes. The determination of the actual amount of air removed from the building usually requires

no more than a simple inventory of air-exhaust locations, with measurements of the amount of air being exhausted and compilation of the exhaust volumes. It frequently is desirable to incorporate any reasonable projections for additional exhaust requirements in the near future, certainly if process changes or additions or modifications to the plant are being contemplated. Often it is desirable to install an air-supply system of a capacity slightly larger than actually needed to allow for future needs. In most cases the drive mechanism on the air-supply system can be modified to supply only the desired quantity of air.

The locations of the makeup-air units, with the consequent distribution of air and creation of airflow patterns within the building, often do not receive sufficient thought before installation, and in many instances this aspect of the system is neglected altogether. However, successful operation of the total-ventilation system depends upon proper distribution of makeup air. The following principles for supplying makeup air should be incorporated into the design of an air-supply system:

1. Locate the inlet for the fresh air away from any sources of contamination, such as exhaust stacks or furnace exhausts. It is advisable to filter the fresh air, in order to protect equipment and to ensure maximum efficiency of heat exchange in the tempering systems.
2. Incorporate a mechanically operated air mover, that is a fan or blower, in the air-supply system to prevent the development of negative pressure within the room or building.
3. Design the locations of the makeup-air entries so as to maximize utilization of the air within the workspace. Properly located makeup-air-supply inlets can be used to provide general dilution-ventilation first, after which the air provides makeup for exhaust systems operated within the building. Obviously, this concept does not apply for specialized types of makeup air such as those installed for spot-cooling purposes, where the air is introduced at temperatures significantly below room temperature, and at specific workstations. In general, the air distribution pattern created by the combination of makeup-air supply and process exhaust must be engineered carefully to provide effective coverage within the building without creating excessive drafts, which could interfere with process operations or compromise the comfort of workers.
4. Introduce the makeup air into the plant at a height of approximately 8–10 ft wherever practicable. In this way, the air is used first by the workers, maximizing the results of general ventilation. Such an arrangement for distribution of the incoming air also permits closer control of the ambient workplace temperature.
5. Heat or cool the makeup air, as necessary, to approximately the desired inside temperature. Accordingly,

the temperature range for incoming air typically varies between 65 and 80°F, depending on the geographic location of the building and the climatological and meteorological conditions characteristic of the location and time of year.

7.3 Recirculation of Exhaust Air

Typical application of LEV includes discharge of the contaminated air to the atmosphere, with or without benefit of an air cleaning device. In recent years, some industries have actively investigated exhaust systems that will clean the air of contaminants to a degree sufficient to permit discharge of the air directly back into the workplace. This approach is desirable because air cleaning or pollution control devices have been employed to substantial degrees to meet air quality or emission standards. Additionally, the heating and/or cooling of makeup air needed to replace exhausted air can be an expensive item, particularly because costs of energy are increasing and in some cases energy to operate new installations is not readily available.

The acceptability of recirculating air systems obviously depends to a great extent on the health hazard associated with the contaminant being exhausted. It has been a fairly consistent policy of official occupational health agencies not to condone the recirculation of exhausted air if the contaminant could have an adverse effect on the health of workers in the event of system failure. Even if the air cleaner is efficient enough to sufficiently clean the air for health protection, incorrect operation, or poor maintenance of the system could result in the return of hazardous contaminated air, for example operations using lead. Recirculation systems should comply with ANSI/ASSE – Z9.7 Recirculation of Air from Industrial Process Exhaust Systems. (Use latest version.)

7.3.1 Circumstances Permitting Recirculation of Air

Recirculation of exhausted air is sometimes a feasible method of supplementing ventilation within the workplace. In some situations, the economic and energy-conservation factors may be important enough to warrant the additional capital and operating expenditures of assuring the safe provision of recirculated air. In general, recirculation of exhausted air may be permitted under the following circumstances:

1. The ventilation system should be furnished with a primary air-cleaner system efficient enough to provide an exit concentration, that is concentration of contaminant in the air recirculated to the workroom, not exceeding an allowable value, which may be calculated for equilibrium conditions using the following equation:

$$C_R = \frac{(PEL - C_o)Q_T}{2Q_R K} \quad (13)$$

where C_R is the concentration of contaminant in exit air from the collector before mixing, Q_T is the total ventilation flow through the affected workspace ($\text{ft}^3 \text{min}^{-1}$), Q_R is the recirculated airflow (fpm), K is a mixing factor, usually varying between 3 and 10 (3 = good mixing conditions), PEL is the acceptable or permissible exposure concentration; usually some fraction of the OEL, C_O is the concentration of contaminant in workers' breathing zone with local exhaust discharged outside.

2. A secondary air cleaning system of efficiency equal to or greater than the primary system should be installed in series with the primary cleaner. As an alternative to this approach, a reliable monitoring device may be installed to furnish a representative sample of the recirculated air. This monitoring system must be fail-safe with respect to failure of the power supply, environmental contamination, or the obvious results of poor maintenance.
3. A warning signal should be provided to indicate the need for attention to the secondary air cleaning system, or the air monitor should indicate when the concentrations have exceeded predetermined allowable limits.
4. There should be a mechanism for either immediate bypass of the recirculated air to the outdoors or complete shutdown of the contaminant-generating process to become operative under conditions that activate the system's warning device.
5. The system meets the requirements of ANSI Z9.7 (latest version), Recirculation of Air from Industrial Process Exhaust Systems (11).

7.4 Additional Design Safeguards for Recirculated Air

With the full expectation that interest in and development of refined recirculated air systems will continue, the following factors and considerations should be incorporated into analysis of the appropriateness of recirculated air systems in any exhaust air setting.

1. Usually it is necessary to provide dilution ventilation air in addition to that recirculated to ensure continual dilution of the contaminants in the recirculated airstream.
2. When it is proposed or possible that all the supplied ventilation air be that recirculated from exhaust systems, all possible contaminants in the airstream should be evaluated, not just the most significant. Of particular concern would be minor contaminants in the airstream that might pass through the primary and secondary air cleaning devices. For example, a fabric

filter-high efficiency particulate filter combination, although providing essentially complete collection of particulate contaminants, could allow the concentration of gases and vapors to build up during the course of operation from relatively insignificant to potentially hazardous levels.

3. Wherever practicable, the recirculating air system should be designed to permit bypass to the outdoors when weather conditions permit. For example, if the system is intended to conserve heat during winter months, it can discharge outdoors in warmer weather if windows and doors are designed to permit sufficient makeup air when opened.
4. Air recirculated through wet collectors may pose a problem in that the humid air from such equipment usually causes uncomfortably high humidity within the workplace and possible condensation problems. Excessive humidity may be prevented through the use of auxiliary ventilation equipment.
5. Design data and testing programs preceding installation of recirculating air systems should consider all operational time periods of the system because it can be reasonably expected that the concentration of contaminants exiting typical collectors will vary over time.
6. As with design and layout of any air-supply system, the ductwork from the recirculating air system should provide adequate mixing with other air supplies to avoid uncomfortable drafts on workers or air currents that could adversely affect the performance of local exhaust hoods.
7. In general, even when a monitoring device is available, the installation of a secondary air-cleaner system is preferable because it usually lends a greater degree of reliability to the system and requires a less sophisticated maintenance program.
8. Although the primary concern for the quality of the recirculated air centers on acceptable exposure limits, odors or nuisance values for contaminants should be considered as well. In fact, in some locations, adequately cleaned recirculated air, provided by a system with appropriate safeguards, can be of better quality than the makeup-air supply entering the building from outside.
9. Routine testing, maintenance procedures, and records should be developed for the circulating air system. In addition, the workroom air should be tested periodically.

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RESPIRATORY PROTECTIVE EQUIPMENT

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1 HISTORICAL REVIEW

The respirator is historically one of the oldest types of equipment used for personal protection in the occupational setting. It is uncertain when the use of primitive forms of respiratory protection began. However, Pliny the Elder recorded the first known use of such a device early in the first century AD. Although respirators have been used for almost 2000 years, the genesis of their technical development is the mid-nineteenth century. During that century, respiratory technology advanced rapidly as evidenced by the

- Appearance of the first early ancestors of modern atmosphere-supplying respirators.
- Recognition that a different type of respiratory equipment was needed for protection against particulate hazards than was needed for protection against gaseous or vaporous hazards.
- Rapid advancement of particulate filter technology after the discovery of Brownian motion (first observed 1827).
- Discovery of the adsorptive properties of activated charcoal for many types of organic vapors.

Chemical warfare agents, introduced in World War I, focused attention on the need for adequate respirators. In the United States, the Bureau of Mines (BM) successfully carried out this work for the Army. The BM in 1919 initiated the first respirator certification program in the United States and certified their first respirator, a self-contained breathing apparatus (SCBA), in 1920 (1). Manufacturers voluntarily submitted their devices for testing, which, if satisfactory, could be sold as BM-certified devices. The term “certified

respirator” has become a part of the language of industrial hygiene. In 1920, the BM began to publish “Approval Schedules” for specific types of respirators. However, it had no statutory authority to regulate the use of respirators in the United States. The use of respirators continued unregulated until the Federal Coal Mine Health and Safety Act was enacted in 1969. As a result of this legislation, regulations were promulgated in Title 30 of the *Code of Federal Regulations Part 11* (30 *CFR* Part 11) governing the certification and use of respirators in the mining industry (2). In 1972, the testing and certification program was assumed by the National Institute for Occupational Safety and Health (NIOSH).

This document also established procedures and prescribed requirements for joint approval by the BM and NIOSH. As a result, NIOSH shared a joint certification function with the BM, and certification labels carried the designation of both agencies. Later, the BM responsibility was passed to the Mine Enforcement and Safety Administration (MESA) and then went to Mine Safety and Health Administration (MSHA) (e.g. NIOSH/BM, NIOSH/MESA, or NIOSH/MSHA approved for ...).

In 1995, NIOSH promulgated new certification regulations, Title 42 *Code of Federal Regulations* Part 84 (42 *CFR* 84) to replace 30 *CFR* Part 11 (3). Except for the particulate filter requirements, most requirements of the existing regulations (30 *CFR* 11) were incorporated into the new regulation (42 *CFR* 84) without change. This rule also gave NIOSH the sole responsibility for certifying most respirators. Currently, respirators are tested and certified by the National Personal Protective Technology Laboratory (NPPTL). NPPTL is a division of NIOSH. MSHA and NIOSH continue to jointly

review and approve respirators tested by NPPTL for mine emergencies, mine rescue, and the associated service life plans, user manuals, and other documentation.

Closely following the passage of the 1969 Federal Coal Mine Health and Safety Act was the 1970 enactment of the Occupational Safety and Health Act. This legislation established the Occupational Safety and Health Administration (OSHA) and NIOSH. OSHA has the regulatory authority to require and monitor the use of respirators in general industry under Title 29 *Code of Federal Regulations* Part 1910.134 (29 *CFR* 1910.134) and in construction under 29 *CFR* 1926.103 (4, 5). OSHA promulgated a revision for 29 *CFR* Parts 1910.134 and 1926.103 in January 1998 (6). In addition to these respirator regulations, OSHA has substance-specific standards with respirator use requirements (e.g. lead 29 *CFR* 1910.1025, inorganic arsenic 29 *CFR* 1910.1018, and benzene 29 *CFR* 1910.1028). In 2006, OSHA revised 29 *CFR* Parts 1910.134 and 1926.103 to include assigned protection factors (APFs) and to revise the substance-specific standards, except for 1,3-butadiene, to have uniform APFs (7).

There are other consensus standards and publications that are extremely useful reference materials addressing the use of respiratory protective equipment (RPE). Specifically, ASTM International Standard F3387-19 addresses the various elements of respiratory protection such as respirator use and programs (8). Two American National Standard Institute (ANSI) standards address fit testing and medical evaluation (9, 10). In addition, the International Standards Organization (ISO) has developed standards on respirator performance, selection, and use, resulting in new respirator classifications (11).

The primary objectives of industrial hygiene are to protect workers and to prevent contaminants from escaping into the atmosphere. Hazard control should start at the outset of process, equipment, and plant design stages so those potential exposure sources can be engineered out. Unfortunately, exposure control often becomes an issue after a process is operational, and therefore control becomes a more difficult and costly proposition. Even then consideration should be given to the use of effective engineering controls to eliminate and/or reduce exposure to respiratory hazards. The preferred priority of control steps are (i) elimination of the substance or substitution of a less-toxic substance, (ii) encapsulation or isolation of the process, (iii) use of local exhaust ventilation or general ventilation, and (iv) use of RPE.

RPE should be used only when all higher priority control steps are not technically or financially feasible. Real-world circumstances, however, demonstrate that engineering controls often do not reduce exposures sufficiently to eliminate a respiratory hazard. As a result, RPE often becomes the only technically and economically feasible adjunct to engineering controls to minimize and control respiratory exposures. According to estimates reported by the US

Department of Labor, Bureau of Labor Statistics (2001), there are roughly 282 000 establishments with 3.3 million workers in the private sector industry using respiratory protection (12). Thus, RPE continues to be an important component in many respiratory exposure control plans.

2 RESPIRATOR PERFORMANCE

The performance of RPE is typically evaluated in two ways: in the laboratory and in the workplace. Laboratory tests include NIOSH certification tests that evaluate individual components (e.g. filter efficiency and exhalation valve leakage) or performance parameters (e.g. minimum flow rate for an air supply respirator) of the RPE. NIOSH also tests completely assembled and worn RPE. These evaluations have typically measured facepiece fit.

The second type of evaluation consists of workplace studies (e.g. workplace protection factor (WPF) studies). These types of studies evaluate performance of the complete respirator assembly under workplace conditions.

2.1 Laboratory Tests

Laboratory tests used by NIOSH to evaluate individual components include filter efficiency tests, chemical cartridge service life, exhalation valve leakage, end of service life alarms on SCBA, and performance requirements such as breathing resistance, and minimum flow rate requirements for supplied-air respirators (SARs) are described in detail in 42 *CFR* 84 (13). NIOSH also evaluates fit of the completely assembled respirator while worn by a panel of people. Knowing the minimum performance standards and recognizing the limitations of the NIOSH certification tests are important when selecting and using a "NIOSH-certified" respirator.

The panels in Figure 1a and b for full and half facepieces present the population distribution for facial sizes related to face length and face width and lip length and face width, respectively. These panels have been widely utilized to determine how respirators fit the general population (14). Today, most manufacturers supply half- and full-facepiece respirators in multiple sizes that cover these facial groupings. NIOSH performed a large anthropometric study (15) and, as shown in Figure 2, has an updated panel that may ultimately be widely used and is being implemented by NIOSH when performing certification fit testing. This panel, called the NIOSH Bivariate Panel, is used for certification of air-purifying respirators (APRs). The difference between these two panels is a shift to larger faces, reflecting the larger size of the general population. This test is to ensure that the respirator can fit a wide variety of people although it does not ensure it fits a specific individual. Individual fit testing

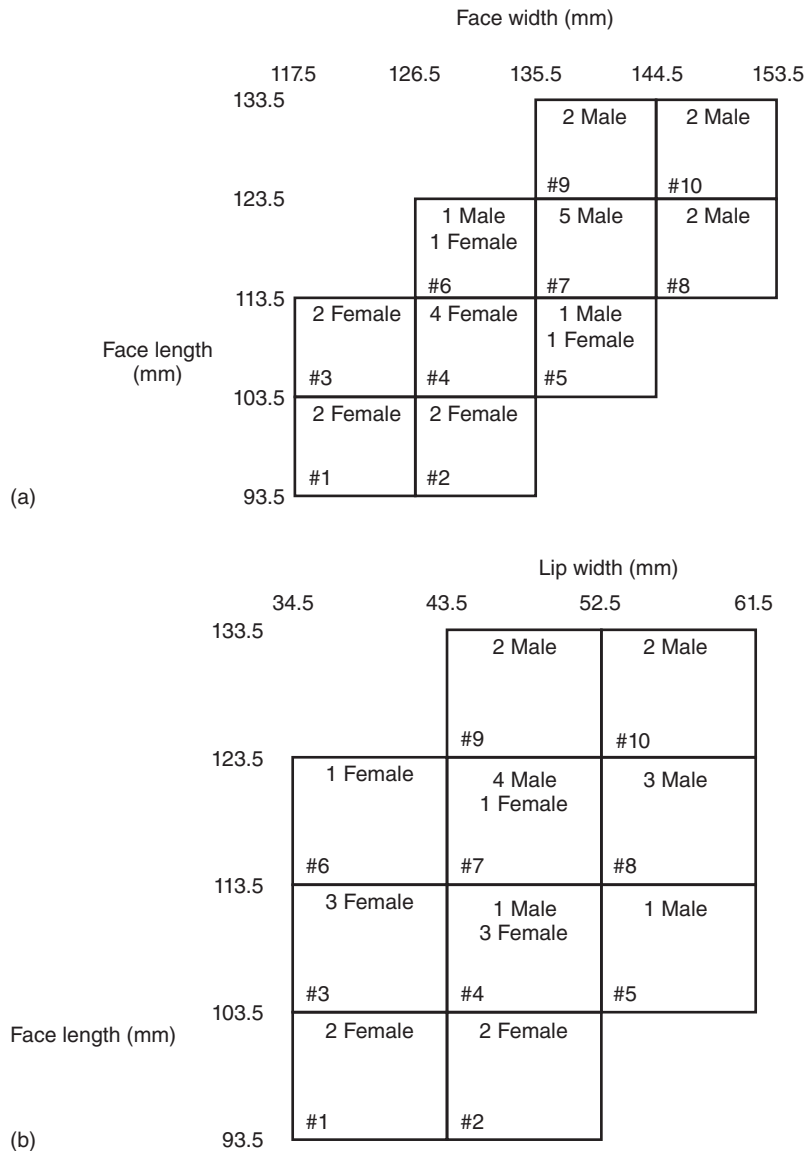


FIGURE 1 Twenty-five person respirator fit test panels developed by Los Alamos National Laboratory. (a) Full-facepiece panel. (b) Half-facepiece panel.

to ensure fit to the worker is discussed under the respirator program requirements.

Respirators passing the NIOSH tests are then certified by NIOSH as meeting specific requirements for various respirator classes. These requirements establish the respirator classification system used in the United States as discussed below. A unique approval number is then issued to the completely assembled respirator tested starting with the prefix indicated in Table 1.

SCBAs used for firefighting undergo additional laboratory tests described by the National Fire Protection Association (NFPA) standard, 1981 (16). The NFPA standard has specific tests that are more relevant to the firefighting environment.

These tests include flame and heat resistance, enhanced air flow rates compared to the NIOSH requirements, and vibration among others (16). For structural firefighting, an SCBA that is both NIOSH certified and compliant with NFPA 1981 is recommended.

Finally, completely assembled devices have been tested in laboratory environments when worn by people to look at overall performance. During the past 50 years, a substantial amount of respirator research has been focused on developing quantitative methods to evaluate how well a respirator fits.

In 1972, Hyatt and Richards (17), at Los Alamos National Laboratory, described quantitative fit methods using an oil

		Face width (mm)			
		120.5	134.5	146.5	158.5
		132.5	144.5		
Face length (mm)	138.5	#6 (2)	#9 (2)	#10 (2)	
	128.5		#7 (4)	#8 (2)	
	118.5	#3 (2)	#4 (5)	#5 (2)	
	108.5	#1 (2)	#2 (2)		
	98.5				

FIGURE 2 NIOSH respirator fit test panel. NIOSH panel based on face length and face width is shown. The cells are numbered 1–10, and the numbers in parentheses indicate the number of subjects to be sampled from each cell. When the subject's face length or face width falls on the boundaries, the subject is classified into the higher number cells with greater face dimensions. Source: Derived from NIOSH publication: Anthropometrics Research to Develop Respirator Fit Test Panels (https://www.cdc.gov/niosh/docket/archive/pdfs/niosh-036/0036-062607-zhuang_pres.pdf).

TABLE 1 NIOSH approval numbers for respirators.

Respirator class	NIOSH approval number
Self-contained breathing apparatus	TC-13F-XXX
Closed-circuit escape respirators	TC-13G-XXX
Gas mask	TC-14F-XXX
Supplied-air respirator	TC-19C-XXX
Particulate respirators	
• Nonpowered particulate respirators	TC-84A-XXX
• Powered air-purifying respirators	TC-21C-XXX
Chemical cartridge respirators	TC-23C-XXX

XXX, numerical indicator assigned in order of approval.

aerosol of dioctyl phthalate (DOP) and an improved quantitative fit method using polydispersed sodium chloride (NaCl). The unique aspect of both test methods was that they used in-facepiece sampling in conjunction with fast response detectors and recorders to provide a real-time measurement of leakage into a respirator. While wearing the respirator in the test chamber, the test subject carried out the following exercises: (i) normal breathing; (ii) deep breathing; (iii) nodding head up and down; (iv) turning head side to side; (v) bending forward and touching toes; (vi) talking; (vii) smiling if the respirator was equipped with a half-mask facepiece or frowning if the respirator was equipped with a full facepiece; and (viii) normal breathing.

These studies led to the first set of “protection factors” used to estimate the protection thought to be provided in

the workplace (18). The methods described by Hyatt were rapidly accepted and viewed as models for quantitative fit testing (QNFT) in the United States. As concerns developed about how close these conditions represented the workplace, more rigorous laboratory studies were designed and carried out as well as increasing the interest in workplace testing. These studies are commonly referred to as simulated workplace protection factor (SWPF) studies. This performance term and others have been described by the American Industrial Hygiene Association Respirator Committee (19). These studies were done to determine the overall performance of the various types of RPE.

2.2 Workplace Testing

A limited number of workplace studies of respirator performance were carried out in the 1970s. In the early 1980s, NIOSH began to conduct workplace studies. The studies measured the amount of protection provided by the respirator by measuring the concentrations of workplace contaminants inside and outside of the respirator when the respirator was properly fit, correctly used, and conscientiously worn. These studies ensured that these respirator program parameters were present to evaluate respirator performance while eliminating misuse conditions. Since then, several WPF studies have been conducted. Many of the techniques for conducting these studies have improved, and the products on the market place have changed. OSHA has reported on these studies during its rulemaking to establish APFs (7, 20). OSHA relied on carefully designed WPF and SWPF studies, since they focus on the performance characteristics of the respirator when used in an effective respirator program as required by OSHA.

In both studies, air sampling outside and inside the respirator is conducted simultaneously while the respirator is worn. The ratio of the outside concentration to the inside concentration is determined for each test subject (worker). This ratio is called, generally, a protection factor; if measured in a workplace, a WPF and if in a controlled laboratory environment, an SWPF. Several WPFs and SWPFs are measured on various people. These results are evaluated statistically. In addition to the geometric mean, the geometric standard deviation and the fifth percentile WPF or SWPF are often calculated. The fifth percentile WPF or SWPF has been the preferred statistic. The fifth percentile is the estimate for the given set of data for that respirator under those test conditions that one would expect 95% of the WPFs or SWPFs to exceed that value. The fifth percentiles from all the studies were used as the starting point for setting the APF. The number may have been rounded for ease of use. For example, one respirator type had fifth percentiles from various studies of 28, 31, and higher. OSHA set the APF at 25.

The conclusions reached by OSHA are listed in the APF Table I of 29 *CFR* 1910.134. This table is reproduced as

TABLE 2 Assigned protection factors.^a

Type of respirator ^{b,c}	Quarter mask	Half mask	Full facepiece	Helmet/Hood	Loose-fitting facepiece
Air-purifying respirator	5	10 ^d	50	—	—
Powered air-purifying respirator	—	50	1 000	25/1 000 ^e	25
Supplied-air respirator or airline respirator					
• Demand mode	—	10	50	—	—
• Continuous-flow mode	—	50	1 000	25/1 000 ^e	25
• Pressure-demand or other positive pressure mode	—	50	1 000	—	—
Self-contained breathing apparatus					
• Demand mode	—	10	50	50	—
• Pressure-demand or other positive pressure mode (e.g. open/closed circuit)	—	—	10 000	10 000	—

^aThese APFs do not apply to respirators used solely for escape. For escape respirators used in association with specific substances covered by 29 *CFR* 1910 Subpart Z, employers must refer to the appropriate substance-specific standards in that subpart. Escape respirators for other IDLH atmospheres are specified by 29 *CFR* 1910.134 (d)(2)(ii).

^bEmployers may select respirators assigned for use in higher workplace concentrations of a hazardous substance for use at lower concentrations of that substance, or when required respirator use is independent of concentration.

^cThe assigned protection factors in the table are only effective when the employer implements a continuing, effective respirator program as required by this section (29 *CFR* 1910.134), including training, fit testing, maintenance, and use requirements.

^dThis APF category includes filtering facepieces and half masks with elastomeric facepieces.

^eThe employer must have evidence provided by the respirator manufacturer that testing of these respirators demonstrates performance at a level of protection of 1000 or greater to receive an APF of 1000. This level of performance can best be demonstrated by performing a WPF or SWPF study or equivalent testing. In the absence of such testing, all other PAPRs and SARs with helmets/hoods are to be treated as loose-fitting facepiece respirators and receive an APF of 25.

Table 2. Understanding the APFs is vital for proper respirator selection. For a listing of the complete set of respirator performance studies evaluated by OSHA, discussion of the studies, and the process for setting each of these APFs, the reader is referred to the proposed rule and final rule publications (7, 20).

3 RESPIRATOR CLASSIFICATION

RPE is broadly classified as air-purifying and atmosphere-supplying devices. Each class of device can be equipped with a variety of respiratory inlet coverings. Respiratory inlet coverings are the part of the RPE covering the mouth and nose. These can be configured as a quarter, half, or full facepiece; a mouthpiece; or a loose-fitting facepiece, hood or helmet, or tight-fitting hood. The loose-fitting hood or helmet can be configured with a shroud that may include just the face, the upper body, or in other cases the entire body. The loose-fitting facepiece may be configured with a helmet to provide head protection or a hood, but in either case the back of the head and neck is not covered and it makes a partial seal with the face. The tight-fitting facepiece is intended to adhere snugly to the skin of the wearer. It is available in three varieties: quarter mask, half mask, and full-face mask. The quarter mask covers the nose and mouth; the half mask covers the nose, mouth, and chin; and the full-face mask covers the entire face from chin to hairline and from ear to

ear. The facepiece is usually held in place by elastic or rubber straps. A half-facepiece RPE is secured to the face with straps attached on each side of the facepiece, that is, a two- or four-point suspension. The straps may be attached to the facepiece in various ways such as tabs, yoke, or loop straps. Full-face masks have a head harness attached to the facepiece usually at four, five, or six points.

A mouthpiece is held in the wearer's mouth, and a clamp is placed over the nostrils. The lips are pursed tightly around the mouthpiece, and all air comes through the filtering device or air supply attached to the mouthpiece. Respirators utilizing this respiratory inlet covering are escape-only devices.

For loose-fitting respirators, air is provided through a hose leading into the respiratory inlet covering. Because they are not tight fitting, it is important that enough air be provided to maintain an outward flow of air and prevent contaminants from entering these respiratory inlet coverings.

3.1 Positive Pressure Classification

Respirator regulations and literature frequently contain reference to "positive pressure." The term is used to describe modes of operation in which the pressure within a respiratory inlet covering is higher (i.e. positive), relative to ambient pressure outside the respiratory inlet covering. It is the consensus of the RPE community that such operation affords the highest possible level of respiratory protection.

The rationale is that if a face seal leak occurs, the positive pressure would force air out rather than allow inward leakage of contaminant. Over the years, pressure-demand SCBA, SARs, continuous-flow SAR, and powered air-purifying respirators (PAPRs) have all been considered positive pressure RPE. However, it must be noted that NIOSH has no approval criteria for positive pressure devices *per se* in Part 84. In other words, "positive pressure" has never been defined. NIOSH does, however, have approval criteria for pressure-demand devices, which require that pressure inside the respiratory inlet covering stay positive relative to atmospheric pressure during the certification test. So, a device certified by NIOSH, as pressure demand is in fact a "positive pressure" device as defined by this requirement. The question of whether a device is positive pressure becomes one of defining a work rate and therefore an air delivery rate to which the RPE should be engineered. For continuous-flow SAR and PAPRs, the minimum flow rate required by NIOSH is 1151 min^{-1} for tight-fitting facepieces and 1701 min^{-1} for loose-fitting devices.

The laboratory evidence indicates that negative-pressure potential is created during the time of inhalation if the instantaneous inspiratory flow rate exceeds 1701 min^{-1} , the minimum flow rate required for NIOSH certification. However, Skaggs et al. (21) testing SAR with hoods under simulated work conditions with an air supply of 1701 min^{-1} measured quantitative fit factors (QNFFs) of 20000. Numerous field and laboratory studies have indicated that at minimum certification airflow rates (1151 min^{-1} for tight-fitting facepieces or 1701 min^{-1} for loose-fitting facepieces) these devices do not always maintain positive pressure as indicated by negative-pressure spikes.

However, the significance of these negative-pressure spikes is not known as these respirators still achieve high SWPFs even though the spikes occur (22). Although the pressure-demand SCBA is still considered to provide the best respiratory protection, it also has been found that negative facepiece pressure may occur at high work rates. Wilson et al. (23) recommended that SARs and SCBAs be designed to accommodate peak flows of 4001 min^{-1} because there are respirator users in the work force with lung function capabilities sufficient to produce instantaneous inspiratory flow rates of this magnitude. For pressure-demand SCBAs used in firefighting, the NFPA requires that positive pressure should be maintained in the facepiece when tested on a breathing machine operating at 30 respiration/min producing a minute volume of 1031 min^{-1} (16). These conditions produce a peak instantaneous demand of approximately 3301 min^{-1} . They feel these test parameters are sufficient to meet the respiratory demands of approximately 98% of the firefighter population. Meanwhile, air flow rates in PAPRs have increased due to requests of users. However, the pressure inside the respiratory inlet covering under work conditions has not been measured. Thus, referring to RPE as positive

pressure is not useful to describe respirator performance. Laboratory test conditions vary between standards, making it difficult to compare. The respirator APF is a better indication of the respirator performance rather than trying to classify the RPE as positive pressure.

3.2 Air-Purifying Respirators

APRs remove contaminants from the atmosphere and can be used only in atmospheres containing sufficient oxygen to sustain life (at least 19.5% by volume at sea level) and within specified concentration limitations of the specific device. They cannot be used in immediately dangerous to life or health (IDLH) atmospheres. APRs incorporate an air-purifying element that can remove aerosol, gas, or vapor contaminants from the air. Except for filtering facepiece respirators (FFRs), the air-purifying elements used with respirators are usually replaceable. The useful life of an APR is dependent on the concentration of the contaminant(s), the breathing volume of the wearer, and the capacity of the air-purifying medium. Air-purifying units can be divided into two functions: aerosol (particle) removal and gas and vapor removal.

For aerosol removal, the aerodynamic size, charge of the aerosol particles, and the face velocity of the air entering the filter influence the efficiency of filtration. Gas and vapor removal requires a suitable sorbent or catalyst material. The air-purifying element is composed of a filter, a gas or vapor sorbent, or a combination of both. NIOSH-certified air-purifying RPE is only designed for use during entry into or escape from atmospheres not IDLH.

Nonpowered APRs are negative-pressure devices and must have a tight-fitting facepiece. They rely on the negative pressure produced within the facepiece cavity during inhalation to draw ambient air through the air-purifying elements. NIOSH certifies quarter-, half-, full-face, or mouthpiece respirators as nonpowered APRs. Filtering facepieces are included in the tight-fitting half-facepiece category. PAPRs can be equipped with tight- as well as loose-fitting hoods or helmets. The usage limitations of the air-purifying elements, particularly gas and vapor cartridges, once determined, should not be exceeded.

3.2.1 Particulate Respirators

Air-purifying, particulate respirators utilize filters to remove aerosols from the air. Filters capture aerosols using a combination of filtration mechanisms. These mechanisms are impaction, interception, and diffusion. Filters relying solely on these mechanisms are commonly referred to as "mechanical filters." Electrostatic attraction, resulting from charge on the fibers of the filter, is often used to enhance these filtration mechanisms. Filters that use an engineered method to add

an electrostatic charge to fibers to enhance electrostatic attraction are commonly referred to as “electrostatic filters.”

Regardless of the chemical composition, it is the aerodynamic particle size of the aerosol that determines which of the mechanisms predominates. The efficiency of aerosol removal is related to its aerodynamic size, with approximately $0.3\ \mu\text{m}$ aerodynamic diameter aerosols considered to be the most penetrating. This most penetrating particle size can shift by changes in the face velocity challenging the filter. The efficiency of all mechanisms is improved as the filter fiber diameter is decreased and the fiber-packing density is increased. The resistance to airflow per unit of surface area of the filter usually increases as the filter fiber diameter decreases and fiber-packing density increases. A filter with high collection efficiency for small aerosols usually has a higher resistance to airflow than a filter having lower collection efficiency for small aerosols. The face area of the high-efficiency filter must be larger to keep the inhalation flow resistance equal to that of the lower efficiency filter. During use, the efficiency of filters improves, and breathing resistance increases, as the aerosol loads on the filter surface and begins to act like a sieve. Electrostatic charge can be engineered into synthetic fibers as permanent dipoles, called electrets. Electrostatic filters, when compared to mechanical filters of similar efficiency without an electrostatic charge, have lower resistance to airflow without decreasing filter efficiency. In general, oil aerosols are more penetrating for electrostatic filters than particulate aerosols. It is hypothesized that the oil coats the fiber of the electret and in effect shields its internal dipole. However, electrets can be made that are not affected by oil. The NIOSH filter classification is useful in determining if the filter is oil resistant or not, and the user does not need to be concerned with the filter’s construction.

3.2.1.1 FILTER CLASSIFICATION NIOSH classifies nonpowered air-purifying particulate filters into three series: N (not resistant to oil), R (resistant to oil), and P (oil proof). The N-series filters are restricted to use in those workplaces free of oil aerosols. The R- and P-series filters are intended for removal of any particles, including oil-based liquid aerosols. The filters of each series are further classified by efficiency against a most penetrating particle size as (i) 100 class filters that have a minimum efficiency $\geq 99.97\%$; (ii) 99 class filters that have a minimum efficiency $\geq 99\%$; and (iii) 95 class filters that have a minimum efficiency $\geq 95\%$. These tests incorporate an approximately $0.3\ \mu\text{m}$ mass median aerodynamic diameter particle that filtration theory indicates should be a most penetrating particle size. Other certification test performance parameters include using

- An airflow rate of $85 \pm 4\ \text{l min}^{-1}$ that simulates a high work rate ($42.5 \pm 2\ \text{l min}^{-1}$ through each filter for paired filters).

- DOP and NaCl particles at Boltzmann charge equilibration.
- Measurement of instantaneous penetration.
- Using filter efficiency expressed as percent penetration.
- High total filter loading (up to 200 mg for N- and R-series filters and continued loading beyond 200 mg until there is no further decrease in efficiency for P filters).

It should be noted that 42 *CFR* Part 84 requires an evaluation of initial breathing resistance at $85 \pm 2\ \text{l min}^{-1}$. The test conditions and aerosols for the nonpowered respirator filters and restrictions on use are summarized in Table 3. The filter efficiency degradation category (N, R, or P) is determined using either NaCl or DOP as the test aerosol. NaCl is slightly degrading to filter efficiency, whereas DOP is highly degrading. No particle size limits apply to respirators with Part 84 filters. This is because it is assumed that the filters have been tested against the most penetrating particle size under a “worst-case” test.

Therefore, N-series filters may only be used for any solid or nonoil liquid containing particulate contaminant.

R-series filters may be used for any particulate contaminant. If used for an oil-containing particulate, a one-shift (or eight hours of continuous or intermittent use) use limit applies.

P-series filters may be used for any particulate contaminant. Shortly after these filter requirements were published, NIOSH laboratory studies indicated the efficiency of P-series filters may be significantly reduced with long-term use (much greater than 200 mg) in the presence of oil aerosols (24). They found that the reduction in P-series filter efficiency varied significantly from model to model and therefore could not make a single filter change recommendation that was appropriate for all models. NIOSH requested that each manufacturer of P-series filters establish service time recommendations as part of their user instructions. As a result, the respirator user must consult the manufacturer’s instructions for the time use limitation for its P-series filters.

The service life of all filters is limited by considerations of hygiene, damage, and breathing resistance. All filters should be replaced whenever they are damaged, soiled, or causing noticeably increased breathing resistance, even if this occurs before the above time limitations are reached.

3.2.2 Gas and Vapor Respirators

There are two types of gas and vapor respirators, commonly referred to as “chemical cartridge respirators” or “gas masks.” The difference is that gas masks utilize an air-purifying element, called a canister, and is larger than the cartridge element used with chemical cartridge respirators.

Gas and vapor removal is accomplished with sorbents that have collection efficiencies that are dependent on the

TABLE 3 Description of filter classes and key test parameter for filters certified under Title 42 Code of Federal Regulations Part 84.

Class of filter	Efficiency (%)	Test agent	Test maximum loading (mg)	Type of contaminant	Service time ^a
<i>N-Series</i>					
N100	99.97	Sodium chloride	200	Solid or water-based particulate but <i>not</i> aerosol containing oil mist	Nonspecific ^{h,c}
PAPR100-N					
N99	99				
N95	95				
<i>R-Series</i>					
R100	99.97	Diocetyl phthalate oil	200	Any particulate	One work shift ^{h,d}
R99	99				
R95	95				
<i>P-Series</i>					
P100 ^e	99.97	Diocetyl phthalate oil	Stabilized efficiency	Any particulate	Nonspecific ^b
PAPR100-P					
P99	99				
P95	95				

^aIf research indicates, additional service time limitations may be recommended by NIOSH for specific workplace conditions.

^bLimited by considerations of hygiene, filter damage, and breathing resistance.

^cHigh (200 mg) filter loading in the certification test is intended to address the potential for filter efficiency degradation by solid or water-based (i.e. nonoil) aerosols in the workplace. Accordingly, there is no recommended service time limit in most workplace settings. In workplaces with high aerosol concentrations, service life should only be extended beyond eight hours of use (continuous or intermittent) by performing an evaluation in specific workplace settings that demonstrates that extended use will not degrade the filter efficiency below the certified efficiency level, or that the total mass loading of the filter is less than 200 mg (100 mg per filter for dual-filter respirators).

^dNo specific service time limit when oil aerosols are not present. In the presence of oil aerosols, service time may be extended beyond eight hours of use (continuous or intermittent) by demonstrating that extended use will not degrade the filter efficiency below the certified efficiency level, or that the total mass loading of the filter is less than 200 mg (100 mg per filter for dual-filter respirators).

^eThe P100, HE, and PAPR100 filters must be color-coded magenta. These filters are similar, but the label will be different from each other, and the filters cannot be interchanged.

chemical composition and physical properties of the gas or vapor or catalysts that chemically react with harmful agents to form less-toxic products. Sorbents are porous and have a large surface area per unit weight up to 1500 m² g⁻¹. As the gas or vapor passes through the sorbent bed, the molecules are adsorbed on the surface. Adsorption captures gases and vapors when passing through a particular (sorbent) bed. Adsorption is the adherence of gas or vapor molecules to the sorbent surface either by physisorption (physical adsorption) or chemisorption. In physisorption, the attractive force between the sorbent and the adsorbate molecule is small (on the molecular level) and is due to van der Waal's forces of adhesion. Since only weak physical forces are involved, the process can be reversed.

For gases and vapors that would otherwise be weakly adsorbed, sorbents (usually activated carbon) can be impregnated with chemical reagents to make them more selective. Chemisorption occurs when the sorbent surface and the vapor bond chemically (25). Chemisorption is usually irreversible. If the solid material causes the vapor to change chemically without affecting the solid, then it is a catalytic reaction.

The sorbent most widely used is activated carbon or charcoal. Alone, it is an excellent adsorbent of many organic vapors. Impregnating it with specific materials increases its retention efficiency for additional gases and vapors. Where there is reason to suspect that a sorbent has a high heat of reaction with a substance, use of that sorbent is not recommended.

Unlike aerosol filters, cartridges and canisters with sorbents have high removal efficiency initially and at some point become less efficient and lose the ability to trap the contaminant completely. The chemical cartridge or canister must be changed before significant breakthrough occurs. There are two ways to determine when the cartridge or canister needs to be replaced. These are to use a cartridge or canister with an end-of-service-life indicator (ESLI) or to develop and follow a change schedule. However, few models have ESLI.

OSHA has not defined acceptable protocols in the standard for establishing change schedules (6) but does provide guidance on their website (26). It is generally recognized that such schedules can be based on data obtained from breakthrough studies conducted in the workplace or in the

laboratory under “worst” conditions or estimated using various service life calculators that are available from NIOSH (27) and respirator manufacturers. These can be found by going to the websites of the specific manufacturer.

Gas and vapor APRs cannot be used in IDLH atmospheres or in atmospheres containing less than 19.5% oxygen by volume. Gas masks (canister respirators) may be used for escape if the atmosphere is not oxygen deficient. Gas and vapor APRs should not be allowed for either entry into or escape from hazardous environments when supporting evidence exists to demonstrate that unreasonably short service life would occur at the maximum use concentration (MUC). Although limited in number, there are special-purpose gas and vapor respirators, for example vinyl chloride or formaldehyde, that are approved by NIOSH for protection against gases and vapors when respirators approved for a given class of contaminants (e.g. organic vapors) cannot be used due to sorbent deficiencies.

3.2.2.1 CHEMICAL CARTRIDGE RESPIRATORS NIOSH-certified gas and vapor respirators are permissible for use against gas or vapor contaminants up to a concentration that is the lesser of either the respirator MUC – the concentration determined from multiplying the respirator’s APF classification by the contaminant’s occupational exposure limit (OEL) – or the IDLH concentration of the contaminant (whichever is lower), provided an oxygen deficiency does not exist. Cartridges can be equipped with particulate filters to form combination gas/vapor and particulate RPE.

3.2.2.2 GAS MASKS Gas masks are like chemical cartridge respirators, but the quantity of available sorbent material is greater. Although some of the approval test gases and vapors for chemical cartridge respirators are the same as those used to test gas masks, the test concentrations and the minimum sorbent life span differ. Gas masks are typically full facepieces attached by a breathing tube to a canister that can be carried on the front or back of the wearer or mounted on the chin of the facepiece. An exception is the escape gas mask, which may have a half mask or a mouthpiece and nose clip. NIOSH certifies gas masks for escape only from IDLH atmospheres.

3.2.2.3 GAS AND VAPOR CARTRIDGES AND CANISTERS The certification tests used by NIOSH do not test the sorption efficiency for all gases and vapors found in the workplace. The certification bench tests for gas and vapor canisters and cartridges are in Subpart I and L, respectively, of 42 CFR 84 (13). The challenge gas or vapor and its concentration, test flow rate, maximum allowable penetration, and minimum service life for these devices are summarized in Table 4. The bench test requirements for escape canisters are similar but not identical to those for chin-style canisters listed in Table 4. The specific test criteria

for escape gas masks can be found in Subpart I of Part 84. Unfortunately, these data are difficult to use to establish a change schedule for use in the field.

Canisters and cartridges are evaluated by NIOSH against a relatively few gases and/or vapors. Breakthrough information for most chemicals must be obtained from other sources such as the technical literature and respirator manufacturers. Nelson and Harder did extensive work in determining the service life for organic vapor cartridges exposed to various organic vapors (28). They exposed commercial organic vapor cartridges to high concentrations of organic vapors and recorded their breakthrough times. Using the NIOSH procedure for organic vapor cartridge testing, they tested the cartridges against 107 organic vapors. Nineteen of the 107 materials tested failed in less than 50 minutes, which is the minimum time the cartridge must last under NIOSH test conditions.

Without an ESLI, information concerning the effectiveness of the sorbent with the contaminant should be obtained, and a conservative time of service set. The sense of smell can then be used as a secondary alarm but must be used cautiously as individuals’ ability to detect a chemical varies greatly, and olfactory fatigue can occur for some chemicals. Other chemicals may be odorless, and others may not be detected (smelled) until the concentration exceeds the OEL. Examples of gases and vapors fitting these conditions include carbon monoxide, methyl alcohol, methyl chloride, methylene chloride, propane, and stibine. Odor should never be used as a primary indicator for changing cartridges.

Once the effectiveness of the sorbent for the contaminant has been determined, the MUC will need to be determined before selection can be completed. While this must be done for all respirators, there are more considerations than just the mathematical calculation to determining the MUC for gas and vapor respirators. These include the IDLH concentration and eye irritation. For example, if eye irritation for a specific chemical occurs at a lower concentration than the MUC for a half-facepiece respirator, the half-facepiece respirator MUC should be limited to the level causing eye irritation. For concentrations above the eye irritation level, a full facepiece needs to be considered.

3.2.2.4 COMBINATION CARTRIDGES AND CANISTERS Cartridges and canisters can be certified for more than one class of gas or vapor (e.g. organic vapor and acid gas), or they also may be used in combination with an aerosol filter (e.g. organic vapor and particulate P95 filter). A chemical cartridge or canister certified for more than one class of gas or vapor may contain more than one type of sorbent media. Combination canisters for gas masks must meet the minimum breakthrough times at the specific challenge concentrations and conditions noted in Table 4.

A chemical cartridge or canister combined with a particulate filter provides respiratory protection for exposure to

TABLE 4 Bench test requirements for NIOSH-certified gas and vapor cartridges and gas mask canisters.

Device type	Test condition	Gas or vapor	Concentration (ppm)	Flow rate (l min ⁻¹)	Maximum allowable penetration (ppm)	Minimum service life ^a (min)
<i>Cartridge(s)^b</i>						
Ammonia	As received	NH ₃	1 000	64	50	50
	Equilibrated	NH ₃	1 000	32	50	50
Chlorine	As received	Cl ₂	500	64	5	35
	Equilibrated	Cl ₂	500	32	5	35
Hydrogen chloride	As received	HCl	500	64	5	50
	Equilibrated	HCl	500	32	5	50
Methylamine	As received	CH ₃ NH ₂	1 000	64	10	25
	Equilibrated	CH ₃ NH ₂	1 000	32	10	25
Organic vapors	As received	CCl ₄	1 000	64	5	50
	Equilibrated	CCl ₄	1 000	32	5	50
Sulfur dioxide	As received	SO ₂	500	64	5	30
	Equilibrated	SO ₂	500	32	5	30
<i>Chin-style gas mask canister</i>						
Acid gas	As received	SO ₂	5 000	64	5	12
	Equilibrated	SO ₂	5 000	32	5	12
	As received	Cl ₂	5 000	64	5	12
	Equilibrated	Cl ₂	5 000	32	5	12
Organic vapor ammonia	As received	CCl ₄	5 000	64	5	12
	Equilibrated	CCl ₄	5 000	32	5	12
	As received	NH ₃	5 000	64	50	12
	Equilibrated	NH ₃	5 000	32	50	12
Carbon monoxide	As received	CO	20 000	64	60	
	Equilibrated ^c	CO	5 000	32	60	
	Equilibrated ^c	CO	3 000	32	60	
Combination of two or three chin-style types ^d						
Combination of all chin-style types ^e						
<i>Front- or back-mounted gas mask canisters</i>						
Acid gas	As received	SO ₂	20 000	64	5	12
	Equilibrated	SO ₂	20 000	32	5	12
	As received	Cl ₂	20 000	64	5	12
	Equilibrated	Cl ₂	20 000	32	5	12
Organic vapor ammonia	As received	CCl ₄	20 000	64	5	12
	Equilibrated	CCl ₄	20 000	32	5	12
	As received	NH ₃	20 000	64	50	12
	Equilibrated	NH ₃	20 000	32	50	12
Carbon monoxide	As received	CO	20 000	64		60
	Equilibrated ^c	CO	5 000	32		60
	Equilibrated ^c	CO	3 000	32		60
Combination of two or three front- or back-mounted types ^d						
Combination of all front- or back-mounted types ^e						

^aMinimum life will be determined at the indicated maximum allowable penetration.^bWhere a respirator is designed for respiratory protection against more than one class of gas or vapor, as for use in ammonia and in chlorine, the minimum service life should be one-half that shown for each type of gas or vapor. Where a respirator is designed for respiratory protection against more than one gas of a type, as for use in chlorine and sulfur dioxide, the stated minimal life will apply.^cRelative humidity of test atmosphere will be 95 ± 3%; temperature of test atmosphere will be 25 ± 2.5 °C.^dTest conditions and requirements are as shown in the table.^eTest conditions and requirements are as shown in the table except that the minimum service lives for acid gas, organic vapor, and ammonia will be six minutes.

mixed gas/vapor and particulate contaminants. In addition to meeting the requirements for gas and vapor certification, these combinations must also pass the applicable particulate filter tests.

3.2.2.5 CARBON MONOXIDE Carbon monoxide is not sorbed but by catalytic action is oxidized into carbon dioxide. The carbon monoxide canister is typically filled with a mixture of manganese and copper oxides, known as Hopcalite. This mixture catalytically converts carbon monoxide to carbon dioxide without the presence of moisture. Moisture stops the reaction. To prevent the entry of moisture, carbon monoxide canisters have layers of drying agents on both sides of the catalytic agent. An ESLI is required that shows when the drying agent is saturated and the life of the canister is ended.

3.2.3 *Powered Air-Purifying Respirators*

The PAPR is designed with a battery-operated (generally) blower to push or pull air through the air-purifying element(s) and supply it to the user. The PAPR is available in two configurations: (i) ones with tight-fitting respiratory inlet coverings and (ii) ones with loose-fitting respiratory inlet coverings. Tight-fitting respiratory inlet coverings include half facepieces, full facepieces, and hoods or helmets with neck dams that form tight seals around the neck. Loose-fitting respiratory inlet coverings include the loose-fitting facepiece, helmet, and hood. These helmets and hoods may have shrouds and collars but do not have tight seals around the neck. For particulate hazards, NIOSH certifies PAPRs equipped with one of three filter types: HE, PAPR100-N, and PAPR100-P filters. The HE filter, sometimes called a high-efficiency particulate air (HEPA) filter, is tested against DOP aerosol under the test parameters described in Part 84, Subpart K, paragraph 84.175 (3). The PAPR100 filters are tested as described in Part 84, Subpart K, paragraph 84.180 (29). The difference between the PAPR100 filters is that the PAPR100-N is tested with NaCl and PAPR100-P is tested with DOP. The PAPR100-N filter is restricted to use in atmospheres free of oil aerosols. The PAPR100-P filter is intended for all aerosol hazards, including oil-based aerosols. All three filter series; HE, PAPR100-N and PAPR100-P, are at least 99.97% efficient as determined in these tests. The differences are a result of different test aerosols, test duration, test concentrations, number of filters tested, and filter loading (29).

PAPRs are generally available with the same cartridges and canisters for the gas and vapor hazards as nonpowered APRs. PAPRs equipped with a tight-fitting respiratory inlet covering must provide a minimum of 115 l min^{-1} of air to the covering. Those equipped with a loose-fitting facepiece, hood, or helmet must provide a minimum of 170 l min^{-1} to the loose-fitting respiratory inlet covering.

Because the PAPR is an APR, it must not be used in an oxygen-deficient or an IDLH environment or in the presence of atmospheric contaminants for which the filters or sorbents are not effective.

3.3 *Atmosphere-Supplying Respirators*

3.3.1 *Self-Contained Breathing Apparatus*

SCBA provides breathing protection for various periods of time based on the amount of breathing air or oxygen supplied and the breathing demand of the wearer. The SCBA respirator carries a supply of compressed air, compressed or liquid oxygen (O_2), or oxygen-generating chemicals. No external connection to an air supply is necessary. SCBA are classified as open- and closed-circuit devices. In open-circuit devices the exhalation flow is dumped to the atmosphere. In closed-circuit devices, the exhalation flow is kept in the respirator, scrubbed of excess carbon dioxide (CO_2) and moisture, and reconditioned with fresh O_2 . SCBA are certified for (i) entry into and escape from or (ii) escape only from IDLH atmospheres including O_2 -deficient atmospheres. The inhalation flow is engineered to operate in demand or pressure-demand modes. However, demand devices are not the preferred choice for IDLH atmospheres and are disappearing from the marketplace. OSHA only allows pressure-demand SCBA with more than 30 minutes to be used for entry into IDLH atmospheres.

Pressure-demand SCBAs are often used in very high concentrations of contaminants. At such high concentrations, it must be recognized that certain materials, particularly some gases and vapors, are capable of harming the body by means other than through the respiratory tract. The possibility of dermal exposure must also be considered. To avoid that possibility, consideration must be given to selecting the appropriate protective clothing that should be worn in addition to just selecting the proper respiratory protection. For example, ammonia, in concentrations of approximately 3% or higher, can cause skin burns, particularly on moist skin. Hydrocyanic acid, a gas at slightly above room temperature, is capable of penetrating the skin and causing systemic poisoning, although to do so, concentrations considerably higher than those required for poisoning through the respiratory tract must be present.

3.3.1.1 OPEN-CIRCUIT SELF-CONTAINED BREATHING APPARATUS The most widely used SCBA is an open-circuit device consisting of a compressed air cylinder, airflow regulator, airline, and facepiece, all of which must weigh less than 35 lb. The duration of air supply can be certified at different intervals from a minimum of 3 minutes to a maximum of 75 minutes. Combination SAR and auxiliary SCBA units are approved as SCBA and thus approved for use in IDLH atmospheres. In the United States, SCBAs are

available in units with air cylinders pressurized to 2200 or 4500 psi. The air supply cylinders may be steel, aluminum, fiberglass-wrapped (hoop-wound) aluminum, a composite cylinder of an aluminum bladder inside a filament-wound fiberglass cylinder, or carbon cylinders that consist of an aluminum alloy inner shell and covered with a total overwrap of carbon fiber, fiberglass, and an epoxy resin. The fiberglass and carbon fiber-wrapped cylinders reduce the weight of the air cylinders significantly. The airflow regulator functions in the SCBA and the SAR in a similar manner. It opens to admit air into the facepiece when the pressure in the facepiece is decreased. The airflow can vary depending on the inhalation pressure. In contrast to the SAR regulator, it may be a two-stage pressure-reducing regulator because the air supply cylinder is under such high pressure. In addition, the SCBA regulator must be designed to have a manual bypass valve for emergency use by the wearer if the regulator were to malfunction.

The SCBA customarily used for entry into hazardous atmospheres is rated at 30 or 60 minutes; however, escape-only SCBA units can have rated service life of 3, 5, 10, or 15 minutes. Service life ratings given with this equipment are nominal and should not be regarded as absolute. High work rates combined with the stress of emergency conditions will markedly reduce the actual use time of the air cylinder.

3.3.1.2 CLOSED-CIRCUIT SELF-CONTAINED BREATHING APPARATUS AND CLOSED-CIRCUIT ESCAPE RESPIRATORS (CCERs) Closed-circuit devices, available with up to a four-hour service life, reuse and condition the exhaled air by circulating it through a chemical to remove the carbon dioxide. The exhaled air then flows to the breathing bag which is the breathing air reservoir for the facepiece. Because oxygen is consumed during cellular respiration and the carbon dioxide that is created is removed from the air by a scrubber, a small amount of oxygen is added back into the system. The oxygen can be added from a cylinder of liquid or compressed oxygen.

Oxygen may also be stored as a solid chemical compound for use with a closed-circuit SCBA. The chemical, usually a type of peroxide, reacts in the presence of moisture and carbon dioxide to produce pure oxygen. Because moisture and carbon dioxide are both components of exhaled breath, circulating exhaled breath through the oxygen-rich chemical forms a usable breathing mixture. The carbon dioxide is removed, as it becomes part of the reaction to release oxygen. The air then enters a breathing bag for mixing before being drawn into the facepiece. A disadvantage of this unit is that once the reaction has been started in the canister, it cannot be terminated until the chemical reaction is complete. Oxygen-generating canisters are available for up to two-hour duration. Certain types of these units referred to as closed-circuit escape respirators (CCERs), previously known as self-contained

self-rescuers (SCSRs), are used as emergency escape devices for miners. The name change came about to reflect differences in performance requirements in 42 CFR 84. Most closed-circuit SCBAs are demand-mode devices.

3.3.2 *Supplied-Air Respirators*

SARs deliver breathing air from a remote storage site, through a supply hose to the respiratory inlet covering. SARs do not have air-purifying filters and cartridges; instead, they depend on delivering acceptable quality breathing air to the user from an external source. These devices must not be used in IDLH atmospheres. They are divided into three types: A, B, and C. Type A and B SARs are not widely used. In fact, they are no longer manufactured and so will not be discussed. Type C SARs, also called airline respirators, can be equipped with half, full, and loose-fitting facepieces, hoods, or helmets supplied by a hose with air under pressure not to exceed 125 psi. Type C SARs operate in the demand, pressure-demand, or continuous-flow modes. NIOSH certification of type "CE" refers to a type C SAR that is designed for abrasive blasting that has outer coverings to protect the wearer from bounce back of abrasive materials.

3.3.2.1 TYPE C SARs The NIOSH-approved continuous-flow SAR includes the facepiece, breathing tube, belt-mounted air control valve, and air hose from 15 to 300 ft long. An airflow regulator is also required for demand and pressure-demand equipment. The user is responsible for providing the air supply, any necessary airline filters, manifold with airflow control valve for the air hose connection, and the airline pressure gauge. The airflow, set by a valve at the supply manifold, can be changed only by manually adjusting the airflow control valve. Problems can be encountered in ensuring that the minimum required flow is delivered. Changes such as an airline that is longer than design length, has a smaller diameter, or has been spliced can result in a drastic reduction in the air supply with the same setting of the pressure gauge.

The demand-mode SAR, as the name implies, supplies air to the user on demand. When the user inhales, the respirator airflow regulation valve opens and air under pressure enters the respirator. Airflow ceases when inhalation ceases. The demand SAR may have a half or full facepiece. In each case, because of the negative pressure in the facepiece during inhalation, the degree of facepiece leakage is comparable to that of an APR with the same facepiece. Because demand-mode SARs do not offer protection to the user that is superior to negative-pressure APR, their selection as RPE of choice is very limited except for conditions where only an O₂ deficiency exists.

The problem of leakage into negative-pressure SAR facepieces led to the pressure-demand facepiece, which

greatly reduces but does not eliminate contaminant leakage into the respirator facepiece. The pressure-demand SAR is like the demand-mode SAR except for the exhalation valve and the airflow regulator. The exhalation valve is spring loaded or uses some other type of resistance so that a positive pressure can be maintained inside the respirator facepiece. During inhalation, the pressure in the facepiece still drops, but at some point, while still above atmospheric pressure, the airflow regulator opens providing airflow. Normally when inhalation occurs, the positive pressure inside the facepiece is reduced but remains positive.

Continuous-flow SARs can be equipped with tight- and loose-fitting respiratory inlet coverings. The loose-fitting SARs may consist of a loose-fitting facepiece, hood, helmet, or full suit. The tight-fitting SAR is simply a facepiece with a continual flow of air through the mask. It requires a minimum continuous airflow of 115 l min^{-1} when in use. The hood or helmet of the SAR introduces the air supply above the head of the user. The air flows downward and exits under the edges of the covering. Some designs use double shrouds or have neck cuffs. NIOSH certification regulations specify a minimum airflow of 170 l min^{-1} for SARs equipped with loose-fitting respiratory inlet coverings.

3.4 Chemical, Biological, Radioactive, Nuclear (CBRN) Approval

Since the late 1990s the concern for exposures to chemical warfare agents has grown because of terrorist activity. This concern has resulted in numerous approval categories for respiratory protection for chemical, biological, radiological, and nuclear materials. Presently, CBRN respirators exist in the SCBA, APR, PAPR, and air-purifying escape respirator. These respirators have been tested for their permeation resistance to chemical warfare agents. The APRs have cartridges or canisters that have been tested against a wide range of chemicals that represent the chemical warfare agents and toxic industrial materials that may be used in acts of terrorism. This is a specialized field of respiratory protection. More information can be found on these devices at the NIOSH website (30).

3.5 Supplied-Air Suits

There are no official regulations governing the design, sale, and use of supplied-air suits, but the Department of Energy (DOE) has a supplied-air suit protocol for use in reviewing suits used by DOE contractors (31). Much is unknown about the design and use of airline suits. Airline suits should be tested to determine their efficiency prior to use in atmospheres of high toxicity.

3.6 Escape Respirators

Escape devices have a single function: to allow a person working in a normally safe environment sufficient time to escape from a suddenly developing respiratory hazard(s). Escape devices can be separated into two categories: APRs and SCBA. APRs include the escape chemical cartridge respirator, the gas mask (canister) respirator, and the filter self-rescuer. The escape chemical cartridge respirator consists of a half mask or a mouthpiece respirator. The mouthpiece respirator can be used for short periods of time to escape from low concentrations of organic vapor or acid gas. Escape gas mask respirators equipped with full facepieces can also be used for escape from IDLH conditions, but not from oxygen-deficient atmospheres. No air-purifying device is suitable for escape from a potentially oxygen-deficient atmosphere. An SCBA provides air to the user for escape from oxygen-deficient environments. Escape SCBA devices are commonly used with full facepieces, mouthpieces, or hoods and, depending on the supply of air, are usually rated as 3–60 minutes units. All SCBA devices can be used in oxygen-deficient atmospheres. CCERs are certified by NIOSH for escape from mines, but these devices may also have application in other similar environments. CCERs provide a source of oxygen-enriched air for up to 60 minutes.

When selecting escape apparatus, careful consideration must be given to potential eye irritation. This consideration is important for determining whether a gas mask or SCBA equipped with a full facepiece should be selected rather than a device equipped with a half mask or mouthpiece. Most of the gas masks or escape chemical cartridge respirators can be used in situations involving gas, vapor, or particulate. For escape from particulate-contaminated environments, an air-purifying element must be selected that will provide protection against the given type of particle. The information in Table 5 should be used to select the appropriate escape apparatus.

4 RESPIRATOR SELECTION AND USE

When it has been determined that employees at a specific worksite require the use of respiratory protection, ultimate responsibility falls on the employer to select the appropriate RPE. Additionally, the employer must ensure that their employees use the device properly. Proper selection requires not only evaluation of the hazard but also careful consideration of all the site-specific conditions that may impact the employee and their use of the device.

Often the help of a health and safety professional may be needed to make the appropriate evaluation of the workplace. Once the respirator has been selected, the employer must develop a comprehensive respiratory protection program in

TABLE 5 Selection options for escape respirators.

Escape conditions	Type of respirator
Short distance to exit, no obstacles (no oxygen deficiency)	Any escape chemical cartridge respirator ^a or gas mask ^b Any escape self-contained breathing apparatus having a suitable service life ^c Any acceptable device for entry into emergency situations
Long distance to exit or obstacles along the way (no oxygen deficiency)	Any gas mask ^b Any escape self-contained breathing apparatus having a suitable service life ^c Any self-contained self-rescuer having a suitable service life
Potential oxygen deficiency	Any escape self-contained breathing apparatus having a suitable service life ^c Any self-contained self-rescuer having a suitable service life

^a An escape chemical cartridge respirator designed for use during escape only from non-IDLH atmospheres. It may consist of a half-mask facepiece or mouthpiece, appropriate air-purifying element for the contaminant, and associated connections; maximum use concentrations for these types of respirators are designated by the manufacturer.

^b A gas mask consists of a full facepiece and either chin-style or front- or back-mounted canisters with associated connections. The maximum use concentrations for canister air-purifying elements are listed in Table 4.

^c Escape self-contained breathing apparatus can have rated service lives of 3–60 minutes. All acceptable devices for entry into emergency situations can also be used.

accordance with OSHA 29 *CFR* 1910.134, as a minimum. Usually, the complexity of the program will be dictated by the type of respirator(s) that will be used as well as the magnitude of the hazard of the work environment.

4.1 Respiratory Hazards

In occupational settings, toxic materials generally enter the body in three ways: (i) through the gastrointestinal tract, (ii) through the skin, and (iii) through the respiratory tract. Typically, the respiratory tract presents the quickest and most direct entry of contaminants into the body and the circulatory system. The two basic classes of respiratory hazard are oxygen deficiency and chemical airborne contaminants that can be in the physical form of a solid, liquid, gas, vapor, or a combination of these. The use of respiratory protection is growing for two respiratory hazards that are particulate in nature: biological agents (aerosols) and engineered nanoparticles.

4.1.1 Oxygen Deficiency

The normal concentration of oxygen in air at sea level is 20.9% by volume, which is equivalent to an oxygen partial pressure of approximately 160 mmHg. NIOSH and OSHA define an oxygen-deficient atmosphere as any atmosphere containing oxygen at a concentration below 19.5% at sea level or approximately an oxygen partial pressure of 148 mmHg. At oxygen concentrations below 16% at sea level, decreased mental effectiveness, visual acuity, and muscular coordination occur. The minimum requirement of 19.5% oxygen at sea level provides an adequate amount of oxygen for most work assignments and includes a safety factor. Nevertheless, when 19.5% oxygen levels are identified at sea level there should be a clear understanding as

to why these levels are below normal and efforts taken to ensure that they will not go below 19.5%. The safety factor is needed because oxygen-deficient atmospheres offer little warning of the danger, and the continuous measurement of an oxygen-deficient atmosphere is difficult. Since oxygen-deficient atmospheres are IDLH, only the most reliable respirators are recommended. The most reliable respirators are SCBA units or SAR units equipped with auxiliary SCBA units. Because a high protection factor is not necessary to ensure an adequate supply of oxygen even in an atmosphere containing no oxygen, any NIOSH-certified SCBA is adequate. Air-purifying RPE or SAR without auxiliary SCBA is not acceptable for use in oxygen-deficient atmospheres. In assessing exposure conditions, it is important to remember that oxygen deficiency can occur in confined spaces by displacement of air by other gases and vapors or by means of oxidation processes such as fire, rusting, and aerobic bacteria, where oxygen is consumed.

4.1.2 Biological Agents

One of the more recent areas seeing increased respirator usage is for biological aerosols, predominantly in health care settings. Respiratory protective devices have been used or are being purchased to reduce exposure to bioaerosols (such as droplet nuclei containing *Mycobacterium tuberculosis* (TB), virus-containing droplets causing severe acute respiratory syndrome (SARS), virus-containing droplets or aerosols causing COVID-19 (SARS CoV-2) or pandemic flu, and anthrax spores). Particle-removing respirators such as N95 filtering facepiece respirators and PAPRs have been recommended by the Centers for Disease Control and Prevention (CDC) for these agents. This area presents many challenges including unknown safe levels of exposure for these agents or respirator efficacy for bioaerosols. Acceptable airborne levels have not been established for potentially infectious

aerosols. NIOSH approved or certified respirators are not tested against bioaerosols.

Construction and general industry workers may also be at increased risk of disease from biological aerosols. Coccidioidomycosis, also known as Valley Fever, is a recognized occupational illness; however, no permissible exposure limits or methods for air sampling exist for the spores that can cause the illness. It is endemic in the southwestern United States. Workers engaged in soil-disrupting activities may be at increased risk for the disease. Das et al. (32) studied a Valley Fever outbreak in California. They concluded that multiple risk-based measures were needed to control occupational coccidioidomycosis including respirators in endemic areas. Use of PAPRs with an APF of 1000 was recommended in addition to other controls (32).

Sondermeyer Cooksey et al. (33) investigated a coccidioidomycosis outbreak among workers constructing two solar farms. They recommended utilization of personal and employer-driven safety practices, including respirator use in the context of a respiratory protection program (33).

This lack of information on exposure limits and levels for bioaerosols makes the respirator selection process difficult. Therefore, various approaches to respirator selection in health care and other settings may be required (34). Use of a properly selected respirator may reduce the risk due to exposure to these materials but cannot be expected to mitigate the risk completely. Respirators with high APFs should be expected to reduce risk to a lower level than respirators with lower APFs when used within a respirator program and worn properly and diligently by the worker. On the other hand, respirators with higher APFs are more complex, burdensome to the worker, and costly. The proper balance needs to be achieved. FFRs mentioned earlier have been used in health care settings because of their simplicity, cost, and efficiency and because of the ease of disposal if they become contaminated. Reuse of a respirator, or its disposal, must also be consistent with the operating procedures of the infection-control program of the health care facility. It is imperative that when respirators are used against biological agents, including health care settings, a respiratory protection program be implemented covering the same elements as those used in industrial settings and in accordance with 29 *CFR* 1910.134. In the past, there have been varied requirements for these types of uses, but OSHA does not distinguish between industrial and biological use settings.

4.1.3 Engineered Nanoparticles

While filtration theory predicts that as the particle gets smaller than the most penetrating particle size, the filter efficiency increases, a new concern has been raised with the introduction of engineered nanoparticles in the workplace. The filtration theory has been shown to hold true for particles in the 2–60 nm range (35). Rengasamy et al.

(36) investigated the filtration performance of five models of N95 FFRs and two models of P100 FFRs against six different monodisperse silver aerosol particles in the range of 4–30 nm diameter. They found that consistent with single-fiber filtration theory, N95 and P100 respirators challenged with these particles showed a decrease in percentage penetration with a decrease in particle diameter down to 4 nm. The authors concluded that the data from this study confirms that NIOSH-approved N95 and P100 FFRs provide filtration performance of greater than 95% and 99.97%, respectively. Another study conducted on NIOSH-approved and CE-marked (European) FFRs tested against particles below the most penetrating particle size showed a decrease in filter penetration levels with decreasing particle size, as expected by single-fiber filtration theory (37). This study evaluated two models each of NIOSH-approved N95 and P100 FFRs and two models each of CE-marked FFP2 and FFP3 FFRs tested against particles in the size range of 4–30 nm diameter. The authors stated that these respirators provide the expected levels of laboratory filtration performance against nanoparticles. All N95 and P100 respirators must meet the same minimum filtration efficiency regardless of the type of respirator for their respective category.

4.2 Respirator Program

When RPE is required by OSHA or the employer, a respirator program must be instituted. The respirator program ensures that the RPE selected will provide adequate protection under the conditions of intended use. OSHA requires that a respiratory protection program contain the following basic elements:

- Procedures for selecting respirators for use in the workplace.
- Medical evaluation of employees required to use respirators.
- Fit testing procedures for tight-fitting respirators.
- Procedures for proper use of respirators in routine and reasonably foreseeable emergency situations.
- Procedures and schedules for cleaning, disinfecting, storing, inspection, repairing, discarding, and otherwise maintaining respirators.
- Procedures to ensure adequate air quality, quantity, and flow of breathing air for atmosphere-supplying respirators.
- Training of employees in the respiratory hazards to which they are potentially exposed during routine and emergency situations.
- Training the employees in the proper use of respirators, including putting on and removing them, any limitation on their use, and their maintenance.

- Procedures for regularly evaluating the effectiveness of the program.

Each of these program elements are reviewed, and background information is given and discussed in this chapter. The reader is advised to refer to 29 *CFR* 1910.134 for specific requirements as well as other pertinent sections of this chapter.

4.2.1 Program Administration

The OSHA standard requires employers to designate a person as program administrator and to ensure that this person is qualified to perform the responsibilities of the position. Appropriate training or experience or both can qualify this individual. Qualifications need to be commensurate with the complexity of the program and the responsibility to oversee and conduct evaluations of the program's effectiveness.

The standard allows an employer to provide respirators on a voluntary basis on request by employees or permit employees to use their own respirators, when respirators are not actually required, provided that it has been determined that respirator use itself will not create a hazard. It stipulates, except for the use of FFRs, that the employer must establish and implement those elements of a written respirator protection program necessary to ensure that

- any employee using a respirator voluntarily is medically able to use that respirator,
- it is cleaned, stored, and maintained so that its use does not present a health hazard to the user, and
- supply information contained in 29 *CFR* 1910.134 Appendix D to the user.

OSHA states in the preamble of the standard that it allows this exception for filtering facepiece because it concludes "There are no medical limitations on the use of these respirators, so employers who allow their use need only ensure that masks are not dirty or contaminated, that their use does not interfere with employees' ability to work safely, and that they provide the employees with the information contained in Appendix D of the final rule" (6).

4.2.2 Respirator Selection

To select a respirator properly, the industrial hygienist must base her/his recommendation on an evaluation of all respiratory hazards in the workplace and an identification of all relevant workplace and user factors for a workplace. This requires thorough knowledge of the process, related equipment, raw materials, end products, and by-products that can possibly create an exposure hazard. When assessing the exposure potential for a respiratory hazard(s), consideration

should be given to potential emergency conditions that could produce unexpectedly high contaminant concentrations or even IDLH levels. This helps assure that proper emergency RPE and procedures are available and understood by affected personnel.

Examples of the types and sources of information that need to be gathered are

- Safety data sheets.
- Specific regulations or guidelines for the use of the material.
- Determination of physical, chemical, and toxicological properties of the contaminant(s).
- Airborne concentration.
- IDLH concentration.
- Occupational exposure limits (OELs).
- Does the material irritate the skin, nose, or eyes?
- Does the material readily pass through the skin?
- If the air contaminant is a gas or vapor, can the material be absorbed by a gas or vapor canister?
- Any service life information available (for cartridges and canisters)?
- Does or is there potential for an oxygen-deficient atmosphere to exist?
- APF required (contaminant concentration/OEL)?
- Other personal protective equipment that must be used by the employee.
- The work rate of the employee (i.e. light, medium, and high).
- What activities and movements the employee must do to perform his or her job.
- Ambient conditions such as temperature, humidity, and air movement.
- Physical hazards present.

Workers are not exposed to a single unvarying concentration of a hazardous substance; rather individual exposures may vary throughout a work shift and between days. The highest anticipated concentration should therefore be used to compute the required protection factor for each respirator wearer.

The information obtained on general use conditions for respirators should include a description of the actual job task, including the duration and frequency, location, physical demands, and industrial processes, as well as the comfort of the respirators. Some general use conditions may preclude the use of specific types of respirators in certain circumstances because the individual must be medically and psychologically suitable to wear a given respirator for a given task, particularly if the respirator is an SCBA.

The physical demands of the work can impact respirator selection in various ways. Some work activities may result

in worker motions and conditions where, depending on the respirator selected, the respirator “gets in the way.” This may include respirators increasing the heat load in hot environments and respirators with breathing tubes or trailing airlines. For negative-pressure, APRs, breathing resistance of the respirator may become an issue. As breathing (work) rate increases, so does the breathing resistance. A respirator that is acceptable at a low work rate may not be acceptable at a high work rate. If the respirator is dislodged or removed for any reason, (e.g. feeling of not getting enough air) in the contaminated area, the protection provided by the respirator is dramatically reduced, even for short periods of time. While the APF may be appropriate for the conditions, the resulting effective protection factor (EPF) may not be sufficient. EPF is determined by considering the worker exposure while wearing the respirator as well as when it is removed (19). Removing a half-facepiece APR (APF = 10) in the contaminated area for as little as 5% of the time results in an EPF of less than seven. Removal of the respirator for 20% of the time in the contaminated area results in an EPF of 3.6. Selecting a respirator with a higher APF will not correct the situation. For example, a full-facepiece air-purifying respirator (APF = 50) has a resultant EPF of 4.6 when removed 20% of the time. The solution is selecting a respirator with features that reduce the need to remove the respirator.

Information obtained on the service life of the cartridge/canister under conditions of intended use should be evaluated. These evaluations should be based on the gas and vapor contaminants and the temperature and relative humidity extremes (high and low) existing in the workplace. This information can be used to set up cartridge replacement schedules and should be used in conjunction with sensory warning properties as a secondary indicator of breakthrough. Workers should be trained to exit the contaminated area whenever they detect the odor of the contaminants. Obtaining complete information on all criteria needed to select RPE may be difficult. When conflicting or inadequate data are found, experts should be consulted before RPE selection decisions are made.

The adequacy of the respirator selected is very dependent on the validity of the exposure limit used. As a result, the assessment of the atmosphere for oxygen content and concentration levels of particulate and/or gaseous contaminants is critical. Furthermore, NIOSH, OSHA, and good industrial hygiene practice dictate that conditions in the work area and worker's exposure to respiratory hazards should be monitored to assure that they have not significantly changed. This necessitates periodic monitoring of the air contaminant concentration to which the respirator wearer is exposed. Many factors, such as changes in the operation or process, air movement, temperature, or humidity, affect the concentration of a substance in the work area atmosphere. Therefore, the air contaminant should be sampled. Preferably, sampling should be in the respirator wearer's breathing zone.

Both the time-weighted average and peak concentrations of the contaminant should be determined. However, the air-sampling campaign must be correctly planned and executed and the data properly analyzed for useful results to be obtained. The information in this section presents basic, but not all-inclusive, information useful for properly selecting RPE. More complete and detailed information is available from the following sources:

- OSHA General Respirator Regulations, 29 *CFR* 1910.134, 29 *CFR* 1926, and respirator regulations specific to a specific contaminant (4, 5).
- *NIOSH Respirator Selection Logic*. National Institute for Occupational Safety and Health, DHHS (NIOSH) Publication No. 2005-100 (38).
- *Standard Practices for Respiratory Protection (ASTM F3387-19)*, ASTM International, West Conshohocken, PA, 2019 (8).

With the advent of WPF studies, NIOSH encouraged evaluating the “actual protection being provided by the respirator” by sampling from inside the respirator (39). While this may be useful, the result is specific for that worker and respirator combination. Another worker/respirator combination may have a very different result due to a different fit and respirator use skills. Currently, it is OSHA's policy to sample as if the respirator is not being worn (i.e. outside the respirator). Sampling from inside the respirator can be done, but there are many variables making it difficult to obtain meaningful samples, which include the sampling location from within the respirator, analytical limit of quantification for the low concentrations of the contaminants typically found inside the respirator, worker-generated contaminants such as sweat and moisture confounding gravimetric determinations, off-gassing of contaminants from previous exposures or times when not wearing a respirator, and moisture affecting sampling capacity and analysis for gases and vapors. In addition, it may require extra respirators because the integrity of the respirator may be impacted in order to obtain the respirator sample. The challenges of sampling from inside of a respirator have been described in more detail and should be consulted before attempting this type of sampling (40–42).

Respiratory protective devices vary in design, application, and protective capability. The user must, therefore, assess the inhalation hazard and understand the specific use and limitations of available equipment to assure proper selection. The respirator selected must be certified by NIOSH. After collecting the information specified in earlier portions of this section it can be applied to a decision logic to help “walk-through” the respirator selection process. Figure 3 contains an example of a decision logic adopted, with revisions and additions from NIOSH (38).

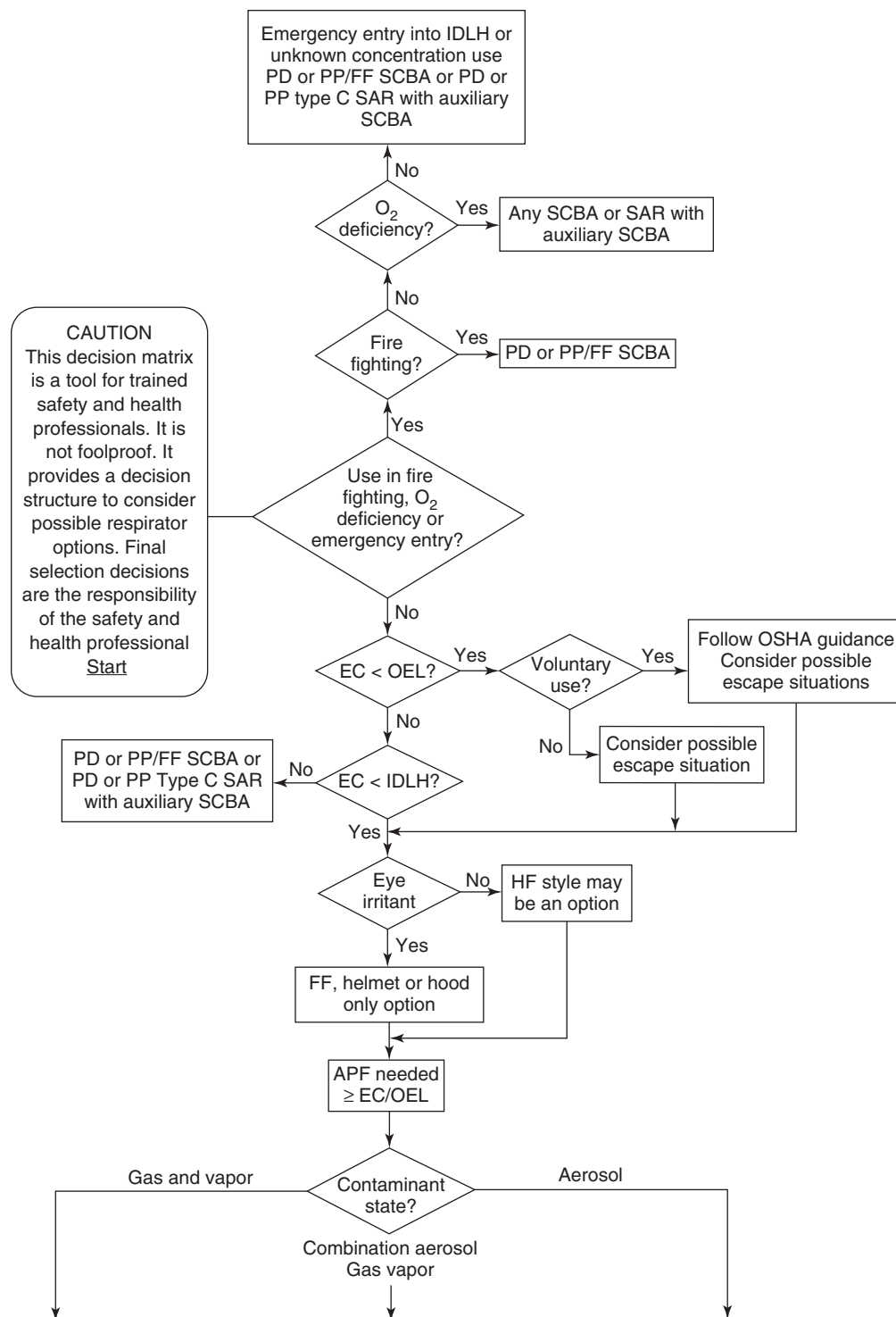


FIGURE 3 Respirator decision logic.

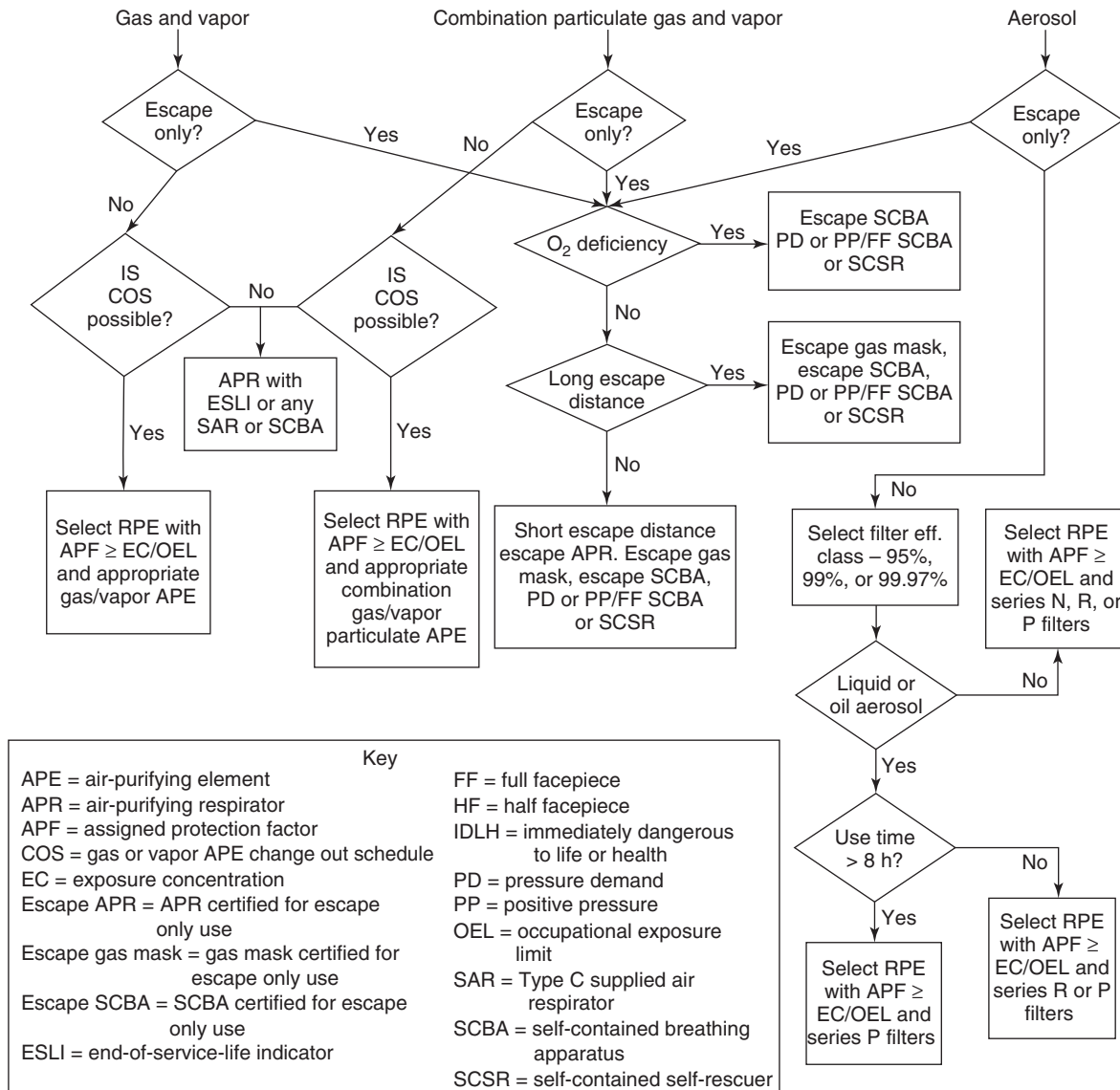


FIGURE 3 (Continued)

The purpose of establishing an IDLH exposure level in RPE selection is to ensure that the worker can escape from a given contaminated environment in the event of failure of the RPE. The IDLH is considered a maximum level above which only a highly reliable breathing apparatus providing maximum worker protection is permitted. Any appropriate approved respirator may be used to its MUC up to the IDLH concentration. If the concentration exceeds the IDLH level, then once again only the most reliable respirators must be selected: 30 minutes or greater pressure-demand SCBA units or pressure-demand SAR units equipped with auxiliary SCBA units. Some specific IDLH guidelines are provided in the literature such as the NIOSH Pocket Guide for Hazardous Chemical Substances (43).

When eye protection is required for routine exposures to airborne contaminants that cause any irritation to the mucous membranes of the conjunctivae or the cornea or cause any reflex tearing, selecting respirators that provide eye protection as well as respiratory protection such as full facepieces, helmets, or hoods can reduce the number of pieces of personal protective equipment required. Eye protection is required for contaminants that cause minor subjective effects as well as for those that cause any damage, including disintegration and sloughing of conjunctival or corneal epithelium, edema, or ulceration. For escape, some eye irritation is permissible if the severity of irritation does not inhibit the escape and if no irreversible scarring or ulceration of the eyes or conjunctivae is likely.

When selecting escape apparatus, careful consideration must be given to potential eye irritation. This consideration is important for determining whether a gas mask or SCBA equipped with a full facepiece should be selected rather than a device equipped with a half mask or mouthpiece. Escape gas masks can be used in situations involving gas, vapor, or particulate contaminants if the atmosphere is not oxygen deficient. The information in Table 5 should be considered when selecting appropriate escape apparatus.

4.2.3 Medical Evaluation

The OSHA standard recognizes that using RPE may place a physiological burden on employees. This burden is a function of the type of RPE worn, the job and workplace conditions in which the RPE is used, and the physical status of the employee. Of interest to the program administrator and industrial hygienist is the requirement of paragraph 29 *CFR* 1910.134(e)(5), supplemental information for the Physician or Other Licensed Health Care Professional (PLHCP). This subparagraph requires that the following information must be provided to the PLHCP before the PLHCP can make a recommendation concerning an employee's ability to use RPE.

- The type and weight of the RPE to be used by the employee.
- The duration and frequency of RPE use, including use for rescue and escape.
- The expected physical work effort.
- Additional protective clothing and equipment to be worn.
- Temperature and humidity extremes that may be encountered.

The PLHCP must also be provided with a copy of the written respiratory protection program and a copy of 29 *CFR* 1910.134.

The employer is required to obtain a written recommendation regarding the employee's ability to use the RPE from the PLHCP. The recommendation can provide only the following information:

- Any limitations on RPE use related to the medical condition of the employee, or relating to the workplace conditions in which the RPE will be used, including whether or not the employee is medically able to use the RPE.
- The need, if any, for follow-up medical evaluations.
- A statement that the PLHCP has provided the employee with a copy of the PLHCP's written recommendation.

Annual medical evaluations are not required, but at a minimum the employer should provide additional medical evaluations if

- an employee reports medical signs or symptoms that are related to their ability to use RPE;
- a PLHCP, supervisor, or the respirator program administrator informs the employer that an employee needs to be reevaluated;
- information from the respiratory protection program, including observations made during fit testing and program evaluation, indicates a need for employee reevaluation; or
- a change occurs in workplace conditions (e.g. physical work effort, protective clothing, and temperature) that may result in a substantial increase in the physiological burden placed on an employee.

Workers should never be assigned to any operations requiring respiratory protection until a PLHCP has determined that they are capable physically and psychologically to perform the work using the RPE. The OSHA respirator standard requires that no one should be assigned to tasks requiring use of RPE unless he/she has been found physically able to do the work while wearing the respirator. Readers are referred to the OSHA Standard 1910.134 (e) and the OSHA respirator medical evaluation questionnaire in Appendix C of the standard (4, 5).

Some users experience psychological stress such as claustrophobia resulting in breathing distress or other manifestations while wearing a respirator (44). Recognition of such users should be made prior to entering life-threatening environments. Morgan and Raven, using an anxiety profile, can predict those who may experience problems wearing respirators in high work rate environments (45). Additional guidance can be found in ANSI Z88.6 (10).

4.2.4 Fit Testing

Qualitative fit testing (QLFT) or quantitative fit testing (QNFT) of tight-fitting facepieces used with air-purifying and atmosphere-supplying devices must be done. Fit testing must be performed on all tight-fitting respirators initially before use of the respirator and repeated at least once a year. Additional fit tests may need to be conducted if the employee reports, or the employer, PLHCP, supervisor, or program administrator makes visual observations of or changes in the employee's physical condition that could affect respirator fit. Examples of these conditions include facial scarring, dental changes, cosmetic surgery, or an obvious change in body weight.

The importance of fit testing, especially for negative-pressure respirators, is often overlooked. The two major

sources of leakage for a maintained respirator are through the face seal and the air-purifying element (e.g. the filter or cartridge). A review of the APFs for negative-pressure, half-facepiece respirators in Table 2 shows that the APF is 10 in all cases, regardless of the filter efficiency level or if it is supplied air. The APF is based on the total of all penetration routes into the respirator: face seal, filter or chemical cartridge, and exhalation valve leakage when properly used. This is one indication that the major source of leakage is the face seal. The protection factor does not change whether the half facepiece is fitted with an airline or with a 95-level filter. The impact of filter selection for a negative pressure respirator has little, if any, impact on the overall protection. Fit testing is critical.

4.2.5 *Qualitative Fit Tests*

The QLFT methods expose the respirator user to an atmosphere with a contaminant, and the respirator is acceptable if the wearer cannot detect the contaminant. These methods depend on the subjective opinion and detection ability of the user to determine whether the respirator fits. Qualitative fit tests use simpler equipment than that required for QNFT and depend on the subjective opinion of the user as to whether the respirator leaks.

The OSHA Respiratory Protection Standard 1910.134 contains QLFT protocols using isoamyl acetate, saccharin, Bitrex™ (denatonium benzoate), and irritant smoke (stannic chloride) as test agents (4). When selecting a QLFT protocol, consideration must be given to properly matching the QLFT test agent to the type of RPE to be fit tested. For example, a P95 particulate, FFR could be tested with saccharin or Bitrex but not isoamyl acetate or irritant smoke. If the respirator program administrator adopts QLFT, OSHA requires that the applicable protocol, as published in Appendix A, be followed.

4.2.6 *Quantitative Fit Testing*

A QNFT measures the actual leakage of a test gas, vapor, or aerosol into the facepiece. Instrumentation is used to sample and measure the test atmosphere and the air inside the respirator facepiece. With this information, a QNFF, sometimes just referred to as a fit factor, is calculated. The QNFF factor is the ratio of the outside concentration to the concentration inside the respirator facepiece. The QNFT methods are based on the direct measurement of the contaminant inside the respirator to determine whether the respirator fits. Quantitative fit tests use more complex equipment than that required for QLFT. This instrumentation is costlier and needs highly trained personnel to conduct the test, operate the instrument, and probe the respirators to sample air from inside the respirator.

OSHA has published three accepted QNFT methods in Appendix A of its Respiratory Protection Standard 1910.134 (4):

- Generated aerosol QNFT protocol using nonhazardous test aerosols (such as corn oil, polyethylene glycol 400 (PEG 400), di-2-ethylhexyl sebacate (DEHS), or NaCl) generated in a test chamber and employing instrumentation to quantify the fit of the respirator.
- Ambient aerosol CNC QNFT protocol using ambient aerosol as the fit test agent and CNC instrumentation (condensation nuclei counter) to quantify the fit of the respirator.
- Controlled negative-pressure QNFT protocol using a controlled negative pressure and instrumentation to measure the volumetric leak rate of a facepiece to quantify the fit of the respirator.

4.2.7 *Minimum Fit Requirements*

OSHA requires, as a minimum, a qualitative fit factor (QLFF) or QNFF of 100 for half facepieces. This can be achieved by performing either QLFT or QNFT. QLFT is allowed because the methods in the OSHA standard have been shown to provide the wearer with a QNFF of 100. QLFT used for full-facepiece respirators only allows that the respirator be assigned an APF of 10 because these protocols were only validated for a QNFF of 100. Therefore, when using a negative-pressure full-facepiece respirator for protection in areas where an APF of greater than 10 and up to 50, QNFT must be performed, and the wearer must achieve a QNFF of 500.

It is important to note that negative-pressure RPE should not be used when facial scars, deformities, or any other conditions that interfere with the face seal exist. This restriction may become evident when fit testing is conducted. Additionally, no tight-fitting RPE (including positive pressure) should be used when facial hair interferes with the face or neck seal. Fit testing should not be performed unless the person conducting the fit test is comfortable that a subject's facial hair will not interfere with the seal, less than 1-day's growth.

4.2.8 *Training*

The standard requires the employer to provide effective training to employees who are required to use respirators. The training must be comprehensive, understandable, and recur annually or more often, if necessary. It should provide the wearer with sufficient knowledge to demonstrate an understanding of

- why the respirator is necessary and how improper fit, usage, or maintenance can compromise the protective effect to the respirator;

- what the limitations and capabilities of the respirator are;
- how to use the respirator effectively in emergency situations including situations in which the respirator malfunctions;
- how to inspect, put on and remove, use, and check the seal of the respirator;
- what the procedures are for maintenance and storage of the respirator; and
- how to recognize medical signs and symptoms that may limit or prevent the effective use of respirators.

The proper respirator is of no value without training for the wearer. The training experience should provide the wearer, in addition to the training elements listed above, an opportunity to handle the RPE, to receive donning instructions, and to undergo size selection and fit testing. Competent persons should instruct both supervisors and workers.

Workers should be instructed to leave the contaminated area immediately upon suspicion of respirator failure and then to determine the problem.

4.2.9 Evaluation of Respirator Program Effectiveness

OSHA Standard 29 *CFR* 1910.134 states that respirator program effectiveness must be inspected and evaluated regularly. Periodic program monitoring is necessary to ensure that workers are adequately protected. The program should be evaluated at least annually, and the written operating procedures should be modified to reflect the evaluation results, if necessary. Frequent inspection of respirator use determines whether the correct respirators are being used and worn properly. Examination of respirators in use and in storage indicates how well they are maintained. Wearers should be consulted periodically about their acceptance of respirators, including the discomfort, resistance to breathing, fatigue, interference with vision and communication, restriction of movement, and interference with job performance, and their confidence in the respirator's effectiveness. The results of periodic inspections of respirator use, consultations with wearers, measurements of hazard levels in work areas, and medical evaluation of wearers should be reviewed, studied, and analyzed to determine the effectiveness of the respirator program. Evidence of excessive exposure to hazards should be followed up to determine why inadequate protection was provided, and action should be taken to remedy the problem. The results of the program evaluation should be presented in a written report that should list plans to correct faults and the target dates for their implementation.

4.2.10 Maintenance and Care of RPE

The RPE should be properly maintained, correctly used, and conscientiously worn. Proper inspection, maintenance,

and repair of RPE are necessary to ensure that it stays in good working order. The maintenance program differs based on plant size and the complexity of the RPE used. However, the goal is to maintain the equipment in a condition that provides the same effectiveness it had when manufactured. To ensure that the respirator remains serviceable, a maintenance program must be in place the first day of respirator use. Respirators must be kept clean, sanitary, and in good working order. The RPE should be cleaned and disinfected following the manufacturer's recommended procedures if those procedures are of equivalent effectiveness as the cleaning and disinfecting procedures detailed in Appendix B-2 of 1910.134 (4, 5). Respirators used by a single wearer should be cleaned and disinfected as often as necessary. Respirators used by different individuals must be cleaned and disinfected between each use.

The RPE should be stored in accordance with any applicable manufacturer instructions. Generally, respirators should be stored in a clean, dry area and in a place where the respirator will not be adversely affected by the ambient environment. Specifically, they should be stored to protect them from damage, contamination, dust, sunlight, extreme temperatures, excessive moisture, and damaging chemicals. They should also be packaged or stored to prevent deformation of the facepiece and exhalation valve.

The RPE used in routine situations should be inspected before each use and during cleaning. RPE maintained for use in emergencies should be inspected monthly according to the manufacturer's instructions and checked for proper function before and after each use. Escape-only RPE should be inspected before being carried into the workplace for possible use. The inspection results should be dated, recorded, and maintained as a historical file. RPE that fails inspection or is found defective should not be used. Only personnel with adequate training to ensure the equipment is functionally sound after the work is accomplished should do repair or replacement of other than disposable parts. Only parts supplied by the manufacturer for the product being repaired should be used; otherwise, the NIOSH certification will be voided. Also, modifications to the respirator in any way not recommended by the manufacturer will void the NIOSH certification. The respirator must always be used in the NIOSH-approved configuration.

4.2.11 Breathing Air Quality

Air compressors or compressed air bottles can supply breathing air for SARs and SCBAs. OSHA and NIOSH require that compressed breathing air meet the Type 1 Grade D standards of the Compressed Gas Association (46). Grade D standards are met if the following contaminant levels are not exceeded: 10 ppm carbon monoxide, 1000 ppm carbon dioxide, and 5 mg m⁻³ condensed hydrocarbons and lack of noticeable odor.

Generally, there are two sources of contamination for compressed breathing air: the air intake and the air compression system. The air in the compressor system will contain the contaminants present at the air intake. Care should be taken to see that the air intake is not located near any point source emissions such as truck exhaust in shipping areas. In urban areas with serious air pollution problems it may be difficult to provide an air intake location free from contamination. An intake near a loading dock or other area with high vehicular traffic can lead to carbon monoxide introduced to the air. The most common air compressor used for breathing air is the oil-lubricated compressor, which adds the oil mist and hydrocarbon vapors to the compressed air. If for some reason the compressor overheats, it is possible for partial combustion of the oil to occur and generate carbon monoxide.

There are filters and sorbents available to remove the oil mist and hydrocarbon vapors from the compressed air, but carbon monoxide removal from the compressor air is more complex. Carbon monoxide catalytic removal units contain Hopcalite to convert CO to CO₂. Because moisture ruins Hopcalite, drying units protect the Hopcalite. Dual drying towers are installed on some Hopcalite units so that while one is removing CO from the air supply, the other is being dried. When dry, it will automatically cycle to replace the other unit. Carbon monoxide catalysis units are not mandatory on oil-lubricated systems, but periodic monitoring for CO is required. In addition, the compressor must be equipped with a high-temperature alarm to notify if the compressor has overheated. Although not required, continuous-reading CO monitors set to alarm at 10 ppm should be installed to monitor the CO concentration in the breathing air. A solution to the potential problem of carbon monoxide is to use a non-oil-lubricated compressor. Diaphragm pumps, oilless compressors with graphite or Teflon piston rings, and water-lubricated compressors are available.

Pressure-demand or demand SAR does not require a continuous flow of air and can use stored compressed air instead of an on-site air compressor. Breathing air certified to meet Type 1, Grade D standards can be purchased in cylinders holding more than 6000 liters. For users needing small quantities of breathing air, purchasing bottled air means no need for a breathing air compressor or to install breathing air monitors and filters.

4.3 Special Problems with Selecting and Using Respirators

4.3.1 Respirators and Hair

Tight-fitting RPE should never be worn when a satisfactory face seal cannot be obtained or maintained. Facial hair is a very common cause of an unsatisfactory seal. It is imperative that clean, smooth skin be in contact with the sealing edge

of the facepiece because even a mild growth of facial hair may interfere with this seal. Floyd et al. showed that QNFFs decreased with beard length especially beyond 0.125 in (47). Stobbe et al. in a review (48) of facial hair and respirator fit studies found that the face seal of negative and positive pressure respirators was adversely affected by facial hair. Restrictions on facial hair is an emotional subject to some, and company policies prohibiting facial hair, not carefully planned and carried out, have been successfully challenged (49). A policy statement prohibiting facial hair that interferes with wearing a respirator should be concise and include only respirator users. It must apply equally to all required to wear a tight-fitting respirator and be part of the respirator program.

4.3.2 Cold Temperatures

In cold temperatures, problems of facepiece flexibility, visibility, and frozen valves must be considered. The facepiece will fog in cold weather when exposed to warm exhaled breath. Those who work in cold environments should ask the manufacturer about respirators for cold weather. Some full-facepiece lenses are chemically treated during manufacturing to reduce fogging. A nose cup, which must be used at temperatures below 32 °F, is available for many facepiece respirators to keep the warm air away from the visor (50). Valves and regulators should be carefully checked before the respirator is used to ensure that they are functioning satisfactorily.

4.3.3 Corrective Lenses

Temple bars on eyeglasses interfere with the seal of full-facepiece respirators and are not acceptable. Eyeglass kits are available from all manufacturers for use with full facepieces. If half and quarter facepieces interfere with proper seating of eyeglasses, the respirator fit is not satisfactory, and either another respirator or another style of eyeglass must be selected. This is one reason why it is important to wear required eye protection when fit testing quarter- and half-facepiece respirators.

4.3.4 Communications

Communication through a facepiece can be difficult, and trying to speak loudly may affect the face seal. There are several devices available to assist the respirator wearer. Some respirators have built-in speaking diaphragms. Although they are protected, care must be taken that thin wire or hot sparks do not pierce the thin diaphragm. Wireless units are available that can be placed inside full-facepiece respirators for radio communication. Throat and ear microphones are also available. None of these units require penetration of the facepiece that can affect the respirator approval. Use of any electrical device must also consider potential explosive problems if flammable vapors are present.

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CHEMICAL PROTECTIVE CLOTHING

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1 INTRODUCTION

Chemical protective clothing (CPC) prevents hazardous chemicals from contacting the skin. These hazardous chemicals can cause skin irritation, burns or sensitization or affect internal organs. The skin is a significant “route of entry” for hazardous chemicals. The hazardous chemicals can move through the skin into the bloodstream leading to acute or systemic toxic effects.

A glove or garment material may protect very well against one chemical but perform poorly against another chemical. These chemicals can selectively degrade, penetrate, or permeate the material. This underlines the importance of determining the risks and the resistance of protective clothing materials for each chemical of interest.

Chemical resistance is not the only requirements in selection of the most appropriate CPC. For suits, heat stress, mobility, and coverage are important considerations while for gloves dexterity, cut resistance, and tactility are some important requirements.

1.1 How to Select the Most Appropriate Chemical Protective Clothing

This section contains several important factors to consider when selecting the most appropriate CPC for the work to be performed. This checklist (Table 1) is not only limited to the selection process but also includes use, care and maintenance, and disposal of CPC.

Much of the information in this chapter includes selected parts from *Quick Selection Guide to Chemical Protective Clothing*, Revised 7th ed., by Krister Forsberg, Ann Van den Borre, Norman Henry, III, and James P. Zeigler, John Wiley & Sons, Inc., 2020.

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1.1.1 Permeation, Penetration, and Degradation

Permeation, penetration, and degradation are the factors to consider when determining chemical resistance of materials used in CPC. Chemical can degrade (damage) a material reducing the ability to prevent chemical contact. Chemicals can penetrate through pores or holes in the material. Or chemical can permeate a material by diffusion on a molecular level. While degradation and penetration generally can be observed, permeation may not be readily noticeable since it occurs on a molecular or microscopic level. This process is represented by the illustration shown in Figure 1.

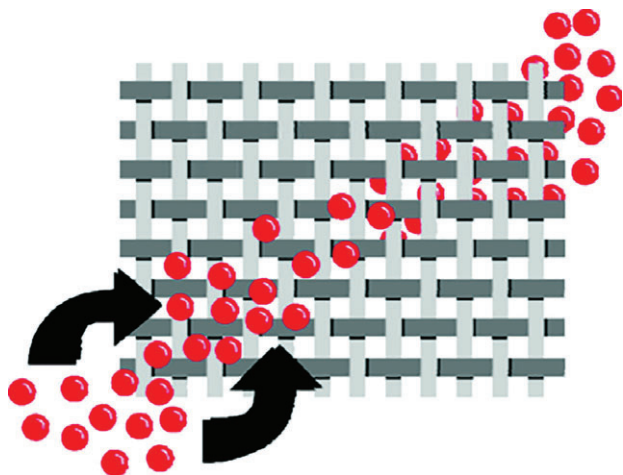
The time taken by the chemical to pass through the protective material until it is first detected is called the breakthrough time. The test for permeation and breakthrough time is represented by the illustration shown in Figure 2. The rate or speed of the movement of the chemical through the protective material, once it has broken through, is called the permeation rate.

Tears, rips, pinholes, and other damage or manufacturing defects can result in penetration of the chemical. Penetration is defined as the bulk flow of chemical through physical spaces of the barrier material. Penetration may not be always visible to the naked eye.

The three factors, permeation, penetration, and degradation determine the chemical resistance of CPC. For many chemicals, permeation is the most important factor in determining chemical resistance. Penetration is useful for determining the quality of the material and manufacturing process. However, if the material degrades in the presence of the hazardous chemical, there is not protection. Permeation testing can often but not always detect degradation since the

TABLE 1 Checklist for selection, use, care and maintenance, and disposal of chemical protective clothing.

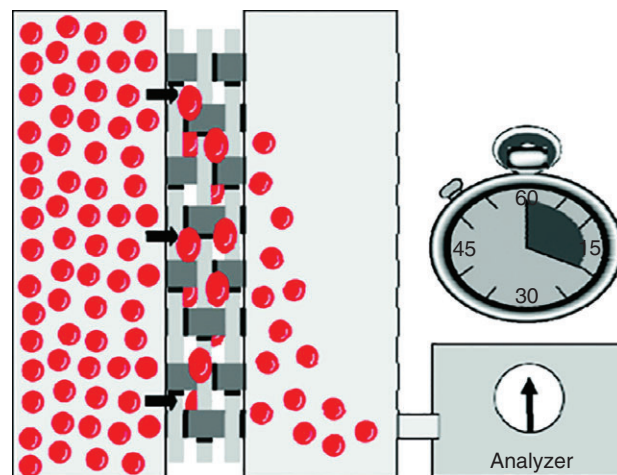
Checklist (applicable to all types of CPC)	To consider (example)	Checklist (applicable to all types of CPC)	To consider (example)
<i>Selection</i>		<i>Care and maintenance</i>	
1. Assessment of hazards and risks	 Check SDS	1. Skincare	 After cleaning add cream to skin
2. Assessment of need of protection by developing a product specification	 Tactility Maintenance 6 h	2. Decontamination and cleaning	 Air dry after cleaning in warm water
3. Determination of barrier material based on resistance data and usability	 Neoprene	3. Storage	 Avoid hot and cold temperature
4. Selection of the most appropriate CPC product based on steps 1–3	 Size 10 long sleeve	4. Inspection	 Check for damage
<i>Use</i>		<i>Disposal</i>	
1. Training of users	 Knowledge about risks	1. CPC contaminated with hazardous materials	 Dispose in accordance with regulations
2. Instruction for use	 Warnings	2. Disposal of CPC in designated container	

**FIGURE 1** Permeation.

material is not flexed after exposure of the chemical. Permeation testing will generally pick up penetration. Standard test methods are described in Section 5.

1.1.2 The Selection Process

CPC selection is a process that normally should be based on a number of factors. Some uses of protective clothing that involve unique situations or very serious hazards will

**FIGURE 2** Permeation test.

require a detailed analysis of the tasks to be completed and perhaps expert assistance in making the selection. However, the general process for selection can be simply stated as in Table 1. In all, there are seven key questions to consider in the selection process.

1. Can the work be done without CPC?
2. What type of exposure is most likely to occur?

3. What are the adverse effects of contact with the chemical?
4. What are the required physical properties?
5. What is the chemical resistance required?
6. What human factors are necessary?
7. What is the cost of use?

The first important question to be answered in the selection processes is whether or not CPC even needs to be used. This includes a consideration of other options, such as the replacement of the chemical with a less harmful one, the use of tools or other techniques to reduce or eliminate the need to be in proximity to the chemical(s), a redesign of the job, or the use of robotics. Even if CPC must be used for economic, feasibility, or other reasons, it may still be possible to reduce the level of hazard that the situation presents through a combination of administrative, engineering, or other control methods along with the use of CPC.

Determining the type of exposure most likely to occur is important in the selection of CPC. A job where the contact is likely to be immersion in a solvent may require a different approach from the one where contact is minimal and limited to an accidental splash. Following are the typical categories of contact or exposure potential:

- Immersion (continuous or intermittent)
- Spray (pressurized or nonpressurized; direction)
- Splash (continuous, intermittent, or not expected; direction)
- Surface contact (continuous or intermittent)
- Mist (continuous or intermittent)
- Vapors (gaseous contact).

In all cases, the CPC should protect the user from the effects of contact with the chemical. For example, job tasks with the potential for contact in the form of a pressurized spray (from a source that is under pressure) should include the requirement for sealing all exposed surfaces against penetration including any mist or vapor penetration.

An assessment of the adverse health effects from chemical contact is the most important factor in the determination of the right CPC to use once it is decided that CPC should be used. This should include the general toxicity and other hazards from the chemical (e.g. fire hazard) with an emphasis on the local effects on the skin (effects of skin contact such as chemical burns, corrosion, staining, irritation, etc.) and the systemic effects of chemicals that might permeate the skin and enter the bloodstream. Obviously, the more harmful the effects of chemical contact are, the more protection the user needs and the more important the proper selection becomes. The Environmental Protection Agency (EPA) and several

other agencies such as the National Institute for Occupational Safety and Health (NIOSH) have developed a selection scheme for personal protective equipment for hazardous waste operations and emergency response by level of protection required. Their scheme consists of four levels designated by the letters A, B, C, and D. The following list summarizes this scheme.

Level A. Self-contained breathing apparatus (SCBA) or positive pressure airline system (PPAS) with escape SCBA and totally encapsulating chemical protective garment capable of holding air and preventing inward vapor leakage, gas-tight ensemble with gloves (double layer), chemically resistant boots, plus other safety equipment.

Level B. SCBA or PPAS with escape SCBA and chemical resistant suit, gloves (double layer), chemically resistant boots, plus other safety equipment. The suit may or may not be encapsulating.

Level C. Full-face or half-mask air-purifying respirator and chemical resistant suit, gloves (double layer), chemically resistant boots, plus other safety equipment. Encapsulating suits cannot be worn with air-purifying respirators.

Level D. No respiratory protection and “coveralls” with an option for gloves, boots, boot coverings, and other related safety equipment.

These standard ensembles represent only two major options in terms of CPC: totally encapsulating suits and other chemically protective clothing. Encapsulating refers to the covering of the respiratory equipment as well as the body. Most industrial situations require a much more specific selection of protective clothing. This is usually much easier to accomplish since the chemicals and exposure situations are better known.

The physical resistance and properties required must be determined. The best chemically resistant material will be ineffective if torn, cut, punctured, or otherwise damaged. In addition, contamination within protective clothing can actually be worse than normal contact since the chemical can be held against the skin for long periods of time. Many of the materials, which offer excellent chemical resistance, may offer poor resistance to abrasions, cuts, and punctures. By using gloves, for example, possible solutions to this problem are double gloving (use of two different gloves on the same hand), the use of gloves, which are composed of more than one compound (e.g. dipped gloves), or the use of multilayered gloves. Some of the physical resistance factors to consider before evaluating chemical resistance needed are

- abrasion resistance
- cut resistance
- puncture resistance

- tear strength
- tensile strength
- flammability
- resistance to the effects of heat and cold.

Some other physical properties to consider for articles of protective clothing are closure strength (zippers, etc.), seam strength, bursting strength, flexibility, weight, and thermal insulation. The exact properties desired will depend on the hazards of the work and the requirements of the job to be performed.

Wearing CPC is not a trivial task. The wearers must be trained in properly putting on (donning) and removing (doffing) the garment. This may involve a second person to help dress and undress the wearer. Wearers should work in teams with backup ready to extract the first team if an emergency occurs. Wearers have to be physically fit. Heat stress must be monitored and managed. Exposed wears must be adequately decontaminated before doffing the garment and the contaminated garments must be properly handled.

The chemical resistance of the protective clothing against the hazardous material must be determined. Manufacturers and resources such as the *Quick Selection Guide to Chemical Protective Clothing* provided guidance on the efficacy of various materials against a range of chemicals. The standard test method measures the material's resistance to direct liquid or gaseous contact. For most situations, the laboratory test represents a "worst-case" scenario. Interrupted contact or splashes with the chemical may lengthen the breakthrough time. On the other hand, the laboratory-generated chemical permeation data may not always reflect conditions in the workplace. Elevated temperatures, flexing, pressure, and tears, may reduce the breakthrough time significantly.

Very little is known about the relationship between the breakthrough of protective clothing and human toxicity when permeation rates are extremely low. However, once the chemical has permeated the barrier material, the risk of toxicity is dependent on skin penetration and the inherent toxicity of the chemical. For protection against most potentially hazardous materials, usage of CPC that offers at least four or eight hours of breakthrough resistance provides a very conservative margin of protection. In some cases, finding a barrier that offers breakthrough resistance of at least four hours will not be possible. The user should use the CPC for a shorter time, that is, up to one hour or less. In these situations, it is best to review brand-specific permeation data to make the choice of the most chemically resistant CPC. Manufacturers' web sites are a good source of current information on the chemical and physical resistances of their products.

For those chemicals that have not been tested, some generalizations can be made about their ability to permeate various barriers based on their chemical class. However, caution must be exercised since the only way to be sure of the performance of CPC is to test it against the chemical of interest.

Mixtures of chemical substances are another complicating factor. They are commonly encountered, but little data exist on the performance of protective materials against mixtures. They do not always behave as might be expected in terms of permeation behavior. Again, the best approach to this problem is to have the mixture actually tested.

The usability of the CPC must be considered. Human factors (ergonomics) are those factors, which affect our ability to accomplish our jobs in an efficient and effective manner. Ideally, CPC should make us more productive and our work easier. Unfortunately, this is rarely the case. Can the job be accomplished wearing CPC? In most cases, the use of CPC at any level will increase errors and decrease productivity. The CPC can even present safety hazards (e.g. get caught in machinery) that would not exist without the use of it.

Probably the three major human factor problems in the use of CPC are proper sizing, heat stress, and the loss of the senses (tactile), such as touch and feel. Sizing is important to be able to function properly while heat stress is common to any article of protective clothing that offers good chemical resistance. Finally, with increases in thickness in gloves and hence chemical resistance, there is a corresponding decrease in dexterity, touch, and feel. The best prevention for human factor related problems is to try several different approaches, products, and materials to determine which combination works best for the user.

The last factor is the cost. This is not because it is least important (nor is it most important). The reason for listing cost in the factors to be considered is that it is always an important factor, but not the single most important factor. First, the "best" selection of CPC is a result of considering many factors such as those previously listed in this section. The best selection may not be the most chemically resistant material. Like generic drugs, there may be materials that offer more than adequate resistance at a much lower cost than some "name brand" product. Therefore, cost should be considered and given an equal weight with the other factors listed in this section.

Additional expertise and resource are available to adequately evaluate all of the factors listed in this section. Most vendors of CPC provide information on the performance of their products against national and international consensus tests and standards for protective clothing. Many of these vendors also offer technical assistance in the proper selection, use, and maintenance of their products without charge. The National Fire Protection Association (NFPA) has developed minimum standards for the performance of protective clothing used in hazardous material emergencies. These have application for some industrial uses as well. They are listed in Section 5.2.

Compliance with NFPA standards requires third-party certification and independent testing. Those products

meeting the battery of NFPA performance requirements are labeled as meeting the applicable standard. In Europe, a series of six levels of protection is available under European Committee for Standardization (Comité Européen de Normalisation) (CEN) standards.

In summary, there are several key factors to be considered when selecting CPC. They include a determination as to whether other options are available for control of exposures, determining the type of exposure and toxicity of the chemicals to be used, determining the physical and chemical resistances needed, determining what is required from the protective clothing to be able to perform the job, and finally a consideration of costs in the final selection.

1.1.3 Eleven Important Considerations for the Selection and Use of Chemical Protective Clothing

The following are the 11 important considerations for the selection and use of CPC.

1. All chemicals pass or permeate through protective barriers sooner or later. Remember, permeation can take place without any visible evidence or change in the protective materials. Color changes or changes in texture, as well as hardening or softening of protective barriers after use, usually indicate degradation.
2. Even the best protective clothing products will not perform properly if they are torn, cut, or damaged. You should always inspect protective clothing before and after each use. The integrity of gloves can be checked for leaks by air inflation or by filling with water (in the latter case they will then need to be dried). Garments should be inspected with a strong light to detect inspect for imperfections or breaks in the barrier or seams. Gas-tight totally encapsulated suits may require pressure testing. If the protective equipment becomes torn or damaged, it should be replaced. Contaminated garment should not be worn.
3. A barrier may protect against one chemical very well but perform poorly against another or a mixture of chemicals. Each chemical and material combination must be considered. No single protective material is an absolute barrier against all chemicals.
4. Recommendations are generally based on tests, which have been performed at room temperature. Higher temperatures usually decrease the breakthrough time of chemicals.
5. Generally, thicker is better. Increasing the thickness of the protective article, such as a glove, will normally increase the time to breakthrough, but the benefits may be offset by a decrease in tactility and dexterity. The use of multiple layers (e.g. double gloving) can increase thickness and provide desirable properties of different materials.
6. Chemical resistant gloves and other CPC may all look alike. Be sure that the material being used is the right one for the job being done. Do not depend only on the appearance or color of the material since most barriers are available in many different forms and colors.
7. Once the barrier material has absorbed a chemical, it will continue to permeate (pass through) the material. If the protective material has been contaminated to the point of breakthrough, it must be decontaminated before it may be used again or properly discarded. Chemical resistant gloves are normally intended for use from a period of 15 minutes up to eight hours. They cannot be reused when handling hazardous chemicals.
Once a material is exposed, the clock does not stop. A barrier of greater than eight hours does not mean one hour for each of eight days. It means eight hours after the initial exposure.
8. Many recommendations have been made on a generic basis; that is, the materials are shown by their common or generic name. Most of the polymer formulations vary by manufacturer and can vary from product lot to product lot. Research has shown this variation in chemical resistance can be significant for neoprene, nitrile, and polyvinyl chloride (PVC). Users should check with the manufacturers' web sites for the test results. Some of the manufactures may not report the results of all chemical tests, so contact the manufacturer directly if there are questions.
9. Some protective clothing has a shelf-life and/or requires special storage measures, such as the avoidance of sunlight, ozone, or moisture. Check with the manufacturers' instructions for the proper storage, maintenance, and care. Also, remember that alterations to suits or equipment may void the manufactures' warranty and change the performance of the equipment.
10. Very thin, ultra-lightweight synthetic rubber gloves are available for medical application where users have allergies to natural rubber medical gloves. These disposable gloves have much shorter breakthrough time and poorer physical properties than much thicker gloves made of the same materials.
11. Chemicals, which are highly corrosive, can change the barrier material properties through degradation before stated breakthrough times. The barrier material can become hard and brittle.

TABLE 2 Chemical protective clothing.^a

Barriers	Common uses
Butyl rubber	Gloves, boots, and suits
Chlorinated polyethylene (CPE)	Suits
Natural rubber	Gloves
Neoprene rubber	Gloves, boots, and suits
Nitrile rubber	Gloves and boots
Fluoroelastomer	Gloves
Fluoroelastomer/Neoprene	Gloves
Fluoroelastomer/Nitrile	Gloves
Kemblok [®]	Gloves
Polyethylene (PE)	Coveralls, gloves ^b
Polyvinyl alcohol (PVAL)	Gloves
Polyvinyl alcohol/Neoprene	Gloves
Polyvinyl chloride (PVC)	Gloves, boots, suits
Viton ^{®c}	Gloves and suits
Viton [®] /butyl rubber	Gloves and suits ^d
AlphaTec [®] 02-100 (PE/PA/PE) ^e	Gloves
Silver shield [®] (PE/EVAL/PE) ^e	Gloves, aprons, booties, sleeves
AlphaTec [®]	Suits
Chemprotex ^{®f,g}	Suits
ChemMAX [®]	Suits
Frontline [®]	Suits
Tychem [®]	Coveralls and suits
Zytron [®]	Suits

Responder[®], Tychem[®], and Tyvek[®] are registered trademarks of DuPont de Nemours, Inc. Silvershield[®] is registered trademarks of the Honeywell Company. AlphaTec[®] is a registered trademark of Ansell. Saranex[®] is a registered trademark of the Dow Chemical Company. Viton is a registered trademark of Chemours, Inc. ChemMAX[®] is a registered trademark of Lakeland Industries. Zytron[®] is a registered trademark of Kappler, Inc. Chemprotex[®] and Kemblok[®] are trademark of Respirex.

^aMost common applications in protective clothing. In some cases, this may represent a film or coating over another substrate such as coated polyester, polyamide, or spun bonded olefin fabrics.

^bLimited availability in gloves and aprons. Most of the PE recommendations are based on DuPont Tychem[®] 2000 test reports.

^cViton/Butyl recommendations are from tests of a Viton[®]/Butyl laminate coated on polyester or polyamide fabrics mainly. Respirex and Ansell manufacture Viton/Butyl suits. Respirex uses two layers of Viton[®] and one layer of Butyl in the Viton/Butyl laminate suits. Ansell uses two layers of Butyl and one layer of Viton[®] in the Viton[®]/Butyl laminate suits. Some of the recommendations are based on the Ansell, Du Pont, and Showa Viton[®]/Butyl gloves.

^dViton[®], a trademark of Chemours Company, is a copolymer or terpolymer belonging to the group of polymers called Fluoroelastomers or FKM.

^eAnsell AlphaTec[®] 02-100 and Honeywell Silver Shield[®] gloves are laminates of low-polar/high-polar/low-polar plastics films, where PA is polyamide, EVAL is ethylene vinyl alcohol, and PE is polyethylene.

^fSaranex[®] coated on Tyvek.

^gRespirex Chemprotex material is a spunbonded polypropylene laminated to a multi-layer barrier film.

2 BARRIERS USED IN CHEMICAL PROTECTIVE CLOTHING

No protective clothing material resists all chemicals. Each chemical and material used in CPC has its own interaction. Table 2 contains 10 generic barrier materials used in CPC. In Table 4, those barriers and a combination of barrier materials are listed vs. 21 test chemicals.

3 CHEMICALS USED FOR EVALUATING CHEMICAL PROTECTIVE CLOTHING

3.1 ASTM F1001 Standard Guide

ASTM F1001 Standard Guide for Selection of Chemicals to Evaluate Protective Clothing Materials provides a list of both liquid and gaseous chemicals for evaluating CPC.

TABLE 3 Chemicals for evaluating of chemical protective clothing according to ASTM F1001.

Chemical	Rational
Acetone	Ketone. Smallest of ketones
Acetonitrile	Nitrile compound; smallest organic nitrile molecules
Ammonia	Basic gas; high-volume chemical commodity. Refrigerant gas
1,3-Butadiene	Unsaturated hydrocarbon gas
Carbon disulfide	Sulfur-containing organic compound, smallest liquid organic sulfide
Chlorine	Acid gas; high-volume chemical commodity
Dichloromethane	Chlorinated paraffin smallest liquid chloralkane
Diethylamine	Amine, smallest liquid organic amine
Dimethylformamide	Amide
Ethyl acetate	Ester, one of the most common esters
Ethylene oxide	Heterocyclic ether gas
<i>n</i> -Hexane	Saturated hydrocarbon, representative of petroleum fuels
Hydrogen chloride	Inorganic acid gas
Methanol	Primary alcohol
Methyl chloride	Chlorinated hydrocarbon gas
Nitrobenzene	Nitro-compound
Sodium hydroxide	Inorganic base, representative of aqueous solutions, and strong alkalis
Sulfuric acid	Inorganic mineral acid; largest chemical production volume in the United States; concentration (93.1%, 66 Baumé) was chosen as common for transport and in several industrial applications
Tetrachloroethylene	Chlorinated olefin
Tetrahydrofuran	Both heterocyclic and ether compounds, smallest of ether molecules
Toluene	Aromatic hydrocarbon, one of the smallest aromatic solvent molecules

The chemicals in the list represent a wide range of possible chemical interactions with CPC materials. Other criteria included how common the chemical was in industrial operations and transportation, the ease of handling the chemical, the hazards of the chemical, and if the chemical was known to permeate some protective clothing materials easily. Not all chemical classes or categories are represented in this list. The 21 test chemicals listed in Table 3 represent 19 different chemical classes.

3.2 Selection Recommendations

In Table 4, representative trade names and barrier materials are listed by vs. the 21 test chemicals in Table 3 taken from the *Quick Selection Guide to Chemical Protective Clothing, Revised 7th ed.*, by Krister Forsberg, Ann Van den Borre, Norman Henry, III, and James P. Zeigler, John Wiley & Sons, Inc., 2020. In the Revised 7th edition, approximately 1000 chemicals are listed vs. 27 barrier materials. All chemicals are organized in accordance with ASTM F1186 Standard Classification Systems (see Table 5).

4 CLASSIFICATION FOR CHEMICALS

4.1 ASTM F1186 Standard Classification System for Chemicals According to Functional Groups

The chemicals in Table 5 have been grouped together into classes according to the ASTM F1186 Standard. Chemicals of the same functional group may have similar effects on barrier materials. This permits the user to estimate performance if no chemical resistance data are available.

5 STANDARDS FOR CHEMICAL PROTECTIVE CLOTHING

This section contains information on testing and performance standards for chemicals protective clothing including resistance to chemicals only. Standards for physical, human, and other factors are also important in selection of the most appropriate clothing material.

TABLE 4 Barrier materials and manufacturers. Selection recommendations for chemicals according to ASTM F1001 standard guide.^a

Barrier material	Manufacturer	Type of clothing ^b	Acetone	Acetonitrile	Ammonia gas	1,3-Butadiene	Carbon disulfide	Chlorine gas	Dichloromethane	Diethylamine	N,N-Dimethylformamide	Ethyl acetate	Ethylene oxide gas	n-Hexane	Hydrogen chloride gas	Methanol	Methyl chloride gas	Nitrobenzene	Sodium hydroxide, 50%	Sulfuric acid, 93%	Tetrachloroethylene	Tetrahydrofuran	Toluene
Butyl	Ansell	G	>8	>8			<1		<1	<1	>8	1-4		<1		>8		>8	>8	>8	<1	<1	<1
	Du Pont	G	>8	>4	>8	>4	<1	>8	<1	<1	>8	>4	1-4	<1	>8	>8	>8	>8	>8	>8	<1	<1	<1
	Guardian	G	>8	>8	>8	>4	<1		<1	<1	>8	>4	1-4	<1	>8	>8	1-4	>8	>8	>8	<1	<1	<1
	Honeywell	G	>8	>8			<1		<1	<1	>8	1-4	<1	<1		>8		>8	>8	>8	<1	<1	<1
	MAPA	G	>8	>8	>8		<1	>8	<1	<1	>8	1-4		<1	>8	>8			>8	>8		<1	<1
	Respirex	S	>4	>8	>8		<1	>8	<1	<1	>8	<1		<1		>8		>8	>8	>4	<1	<1	<1
	Showa	G	>8	>8	>8	>4	<1	>8	<1	<1	>8	1-4	1-4	<1	>8	>8	>8	>8	>8	>8	<1	<1	<1
Chlorinated polyethylene, CPE	Standard Safety	S	<1	>8	1-4		<1	>8	<1	<1	1-4	<1		>8	1-4	1-4		1-4	>8	>8	1-4	<1	<1
Neoprene	Ansell	G	<1	<1	>8		<1		<1	<1	<1	<1		<1		1-4		<1	>8		<1	<1	<1
	Du Pont	G	<1	<1	<1	<1	<1	>4	<1	<1	1-4	<1	<1	<1	>8	<1	<1	<1	>8	1-4	<1	<1	<1
	Guardian	G	<1	1-4	>8	1-4	<1	1-4	<1	<1	<1	<1	<1	<1	>8	>4		1-4	>8	>8	<1	<1	<1
	Honeywell	G	<1	<1			<1		<1	<1	<1	<1	<1	<1		<1		<1	>8	1-4	<1	<1	<1
	MAPA	G	<1	<1	>8		<1	>8	<1	<1	<1	<1		<1	>8	1-4		<1	>8	1-4	<1	<1	<1
	Respirex	S	<1	<1	>8	<1	<1	>8	<1	<1	<1	<1	<1	<1	1-4	>8		1-4	>8	>4	<1	<1	<1
Nitrile	Showa	G	<1	<1	<1	<1	<1	>8	<1	<1	1-4	<1	<1	1-4	>8	1-4	1-4	1-4	>8	>4	<1	<1	<1
	Ansell	G	<1	<1	>8		<1		<1	<1	<1	<1		>8		1-4		<1	>8	<1	>4	<1	<1
	Du Pont	G	<1	<1	>4	>8	<1	>4	<1	<1	<1	<1	<1	>8	>4	<1	<1	<1	>8	<1	1-4	<1	<1
	Honeywell	G	<1	<1			<1		<1	<1	<1	<1	<1	>8		<1		<1	>8	<1	>4	<1	<1
	MAPA	G	<1	<1			<1		<1	<1	<1	<1	<1	>8		<1		<1	>8	<1	1-4	<1	<1
Polyethylene, PE	Showa	G	<1	<1	>4	>8	<1	>8	<1	<1	<1	<1	<1	>8	>4	<1	>8	<1	>8	<1	>8	<1	<1
	Du Pont	S	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	>8	>8	<1	<1	<1

CHEMICAL PROTECTIVE CLOTHING

[illegible]

(continued overleaf)

TABLE 4 (continued)

Barrier material	Manufacturer	Type of clothing ^a	Acetone	Acetonitrile	Ammonia gas	1,3-Butadiene	Carbon disulfide	Chlorine gas	Dichloromethane	Diethylamine	N,N-Dimethylformamide	Ethyl acetate	Ethylene oxide gas	n-Hexane	Hydrogen chloride gas	Methanol	Methyl chloride gas	Nitrobenzene	Sodium hydroxide, 50%	Sulfuric acid, 93%	Tetrachloroethylene	Tetrahydrofuran	Toluene
<i>Frontline® 300</i>	Kappler	S	>8	>8	>8	>8	>8	>8	<1	>8	>8	>8	>8	>8		>8		>8	>8	>8	>8	>8	>8
<i>Frontline® 500</i>	Kappler	S	>8	>8	>8	>8	>8	>8	>4	>8	>8	>8	>8	>8	>8	>8	>8	>8	>8	>8	>8	>8	>8
<i>Hazmax® Boot</i>	Respirex	B	1-4	>4	>8	1-4	<1	1-4	1-4	1-4	>8	>4	1-4	>4	>8	>8	1-4	1-4	>8	>8	>8	1-4	>4
<i>Interceptor® Plus</i>	Lakeland	S	>8	>8	>8	>8	>8	>8	>8	>8	>8	>8	>8	>8	>8	>8	>8	>8	>8	>8	>8	>8	>8
<i>Kemblok® Glove</i>	Respirex	G	>8	>8	>8	>8	>8	>8	>8	>8	>8	>8	>8	>8	>8	>8	>8	>8	>8	>8	>8	>8	>8
<i>AlphaTec® 3000</i>	Ansell	S	<1	<1	<1		<1	<1	<1	<1	>8	<1		<1	<1	>8		>8	>8	>8		<1	<1
<i>AlphaTec® 4000</i>	Ansell	S	>8	>8	1-4	>8	<1	>8	<1	<1	>8	>8	>8	>8	>8	>8	>8	>8	>8	>8	>8	<1	>8
<i>AlphaTec® 5000</i>	Ansell	S	>8	>8	>8	>8	>8	>8	<1	>8	>8	>8	1-4	>8	>8	>8	>8	>8	>8	>8	>8	>8	>8
<i>AlphaTec® EVO</i>	Ansell	S	>8	>8	>8	>8	>8	>8	>8	>8	>8	>8	>8	>8	>8	>8	>8	>8	>8	>8	>8	>8	>8
<i>AlphaTec® VPS/VPS Flash</i>	Ansell	S	>8	>8	>8	>8	>8	>8	>8	>8	>8	>8	>8	>8	>8	>8	>8	>8	>8	>8	>8	>8	>8
<i>Tychem® 2000</i>	Du Pont	S	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	>8	>8	<1	<1	<1
<i>Tychem® 4000 Saranex®</i>	Du Pont	S	<1	<1	<1	>8	<1	>8	<1	<1	1-4	<1	<1	<1	>8	>8	>8	<1	>8	>8	<1	<1	<1
<i>Tychem® 5000</i>	Du Pont	S	>8	1-4	<1	>8	<1	>8	<1	>8	>8	>8	>8	>8	>8	<1	>8	>8	>8	>8	>8	>8	>8
<i>Tychem® 6000</i>	Du Pont	S	>8	1-4	1-4	>8	>8	>8	<1	>8	>8	>8	>8	>8	>8	1-4	>8	>8	>8	>8	>8		>8

<i>Tychem® 6000FR</i>																				
Du Pont	S	>8	1-4	>8	>8	>8	>8	<1	>8	>8	>8	>8	>8	>8	>8	>8	>8	>8	>8	>8
<i>Tychem® 9000</i>																				
Du Pont	S	>8	>8	<1	>8	>8	>8		>8	>8	>8	>8	>8	>8	1-4	>8	>8	>8	>8	>8
<i>Tychem® Responder CSM</i>																				
Du Pont	S	>8	>8	>8	>8	>8	>8	>8	>8	>8	>8	>8	>8	>8	>8	>8	>8	>8	>8	>8
<i>Tychem® 10 000</i>																				
Du Pont	S	>8	>8	>8	>8	>8	>8	>8	>8	>8	>8	>8	>8	>8	>8	>8	>8	>8	>8	>8
<i>Tychem® 10 000FR</i>																				
Du Pont	S	>8	>8	>8	>8	>8	>8	>8	>8	>8	>8	>8	>8	>8	>8	>8	>8	>8	>8	>8
<i>Zytron® 100</i>																				
Kappler	S																>8	>8		
<i>Zytron® 100XP</i>																				
Kappler	S																>8	>8		
<i>Zytron® 200, Saranex®</i>																				
Kappler	S	<1	<1		<1		<1	<1	1-4	<1		<1		>8		1-4	>8	>8	<1	<1
<i>Zytron® 300</i>																				
Kappler	S	>8	1-4	<1	>8	>8	>8	<1	>8	>8	>8	1-4	>8	>8	<1	>8	>8	>8	>8	>8
<i>Zytron® 400</i>																				
Kappler	S	>8	>8		>8		1-4	>8	>8	>8	>4	>8		>8		>8	>8	>8	>8	>8
<i>Zytron® 500</i>																				
Kappler	S	>8	>8	>8	>8	>8	>8	>8	>8	>8	>8	>8	>8	>8	>8	>8	>8	>8	>8	>8

^aNotation for the range listed:

>8 Recommended > 8 hours

>4 Recommended > 4 hours

1-4 Caution 1 to 4 hours

<1 Not recommended, <1 hour

Blank fields Not tested

^bG, Gloves; S, Suits; B, Boots.

TABLE 5 Chemical classes and subclasses.

100 Carboxylic acids
102 Aliphatic and alicyclic, unsubstituted
103 Aliphatic and alicyclic, substituted
104 Aliphatic and alicyclic, polybasic
110 Acid halides, carboxylic
111 Aliphatic and alicyclic
112 Aromatic
113 Chloroformates
120 Aldehydes
121 Aliphatic and alicyclic
122 Aromatic
130 Amides
132 Aliphatic and alicyclic
133 Aromatic, others
135 Acrylamides
137 Carbamates and guanidines
140 Amines
141 Aliphatic and alicyclic, primary
142 Aliphatic and alicyclic, secondary
143 Aliphatic and alicyclic, tertiary
145 Aromatic, primary
146 Aromatic, secondary and tertiary
148 Aliphatic and alicyclic polyamines
149 Aromatic polyamines
150 Hydroxy and ketoximes
160 Anhydrides
161 Aliphatic and alicyclic
162 Aromatic
170 Azo/azoxy compounds
210 Isocyanates
211 Aliphatic and alicyclic
212 Aromatic
220 Esters, carboxylic
221 Formates
222 Acetates
223 Acrylates and methacrylates
224 Aliphatic, others
225 Lactones
226 Benzoates and phthalates
227 Aromatic, others
230 Esters, noncarboxylic
231 Ortho esters
232 Carbonates
233 Carbamates and others
240 Ethers
241 Aliphatic and alicyclic
242 Aromatic
243 Alkyl-aryl
245 Glycol ethers
246 Vinylic
260 Halogen compounds
261 Aliphatic and alicyclic

(continued)

TABLE 5 (continued)

263 Vinylic
264 Aromatic
265 Alylic
266 Benzylic
270 Heterocyclic compounds
271 Nitrogen, pyridines
274 Nitrogen, others
275 Oxygen, epoxides
277 Oxygen, furans
278 Oxygen, others
280 Hydrazines
290 Hydrocarbons
291 Aliphatic and alicyclic, saturated
292 Aromatic
293 Aromatic polynuclear
294 Aliphatic and alicyclic, unsaturated
295 Acetylenes
296 Polyenes
300 Peroxides
310 Hydroxylic compounds
311 Aliphatic and alicyclic, primary
312 Aliphatic and alicyclic, secondary
313 Aliphatic and alicyclic, tertiary
314 Aliphatic and alicyclic, polyols
315 Aliphatic and alicyclic, substituted
316 Aromatic, phenols
318 Aromatic, others
330 Elements
340 Inorganic salts and solutions
345 Inorganic cyano compounds
350 Inorganic gases and vapors
360 Inorganic acid halides
365 Inorganic acid oxides
370 Inorganic acids
380 Inorganic bases
390 Ketones
391 Aliphatic and alicyclic
392 Aromatic
393 Alkyl-aryl
410 Quinones
430 Nitriles
431 Aliphatic and alicyclic
432 Aromatic
440 Nitro compounds
441 Unsubstituted
442 Substituted
450 Nitroso compounds
460 Organo-phosphorus compounds
461 Phosphines
462 Derivatives of phosphorus-based acids
470 Organo-metallic compounds
480 Organo-silicon compounds

(continued overleaf)

TABLE 5 (continued)

500 Sulfur compounds
501 Thiols
502 Sulfides and disulfides
503 Sulfones and sulfoxides
504 Sulfonic acids
505 Sulfonyl chlorides
506 Sulfonamides
507 Sulfonates, sulfates, and sulfites
508 Thiones
509 Halides
510 Nitrates and nitrites
521 Ureas
530 Zwitterions
550 Organic salts and solutions
595 Chemical warfare agents

Chemical class and subclass listings based on ASTM F1186.

Note: The class 595 is not included in ASTM F 1186.

5.1 ASTM Standards (www.astm.org)

Committee F23 on Protective Clothing of the American Society for Testing and Materials, ASTM International, has developed standards for biological, chemical, radiation, respiratory, thermal, and cut protective clothing. These standards are annually published in the *Annual Book of ASTM Standards*, Vol. 11.03. These standards have and continue to play a preeminent role in the selection and use of protective clothing. Chemical protection standards that are the responsibility of the F23.30, Sub-committee on Chemical Protective Clothing and Equipment are:

- F739 Standard Test Method for Resistance of Protective Clothing Materials to Permeation by Liquids or Gases Under Conditions of Continuous Contact
- F903 Standard Test Method for Resistance of Materials Used in Protective Clothing to Penetration by Liquids
- F1001 Standard Guide for Selection of Chemicals to Evaluate Protective Clothing Materials
- F1052 Standard Test Method for Pressure Testing Vapor Protective Suits
- F1154 Standard Practices for Evaluating the Comfort, Fit, Function, and Durability of Protective Ensembles, Ensemble Elements, and Other Components
- F1186 Standard Classification System for Chemicals According to Functional Groups
- F1194 Standard Guide for Documenting the Results of Chemical Permeation Testing of Materials Used in Protective Clothing
- F1296 Standard Guide for Evaluating Chemical Protective Clothing
- F1301 Standard Practice for Labeling Chemical Protective Clothing

- F1359 Standard Test Method for Liquid Penetration Resistance of Protective Clothing or Protective Ensembles Under a Shower Spray While on a Manikin
- F1383 Standard Test Method for Resistance of Protective Clothing Materials to Permeation by Liquids or Gases Under Conditions of Intermittent Contact
- F1407 Standard Test Method for Resistance of Chemical Protective Clothing Materials to Liquid Permeation-Permeation Cup Method
- F1461 Standard Practice for Chemical Protective Clothing Program
- F2130 Standard Test Method for Measuring Repellency, Retention, and Penetration of Liquid Pesticide Formulation Through Protective Clothing Materials
- F2588 Standard Test Method for Man-In-Simulant Test (MIST) for Protective Ensembles
- F2669 Standard Performance Specification for Protective Clothing Worn by Operators Applying Pesticides
- F2704 Standard Specification for Air-Fed Protective Ensembles
- F2815 Standard Practice for Chemical Permeation through Protective Clothing Materials: Testing Data Analysis by Use of a Computer Program
- F2962 Standard Practice for Conformity Assessment of Protective Clothing Worn by Operators Applying Pesticides.

5.2 NFPA Standards (www.nfpa.org)

NFPA has established performance standards for CPC for use in support areas, for splash protection, and for “Level A” – related spill cleanup work. These standards are as follows:

- NFPA 1991 – Standard on Vapor-Protective Ensembles for Hazardous Materials Emergencies and CBRN Terrorism Incidents
- NFPA 1992 – Standard on Liquid Splash-Protective Ensembles and Clothing for Hazardous Materials Emergencies
- NFPA 1994 – Standard on Protective Ensembles for First Responders to Hazardous Materials Emergencies and CBRN Terrorism Incidents
- NFPA 1999 – Standard on Protective Clothing and Ensembles for Emergency Medical Operations.

[NOTE: NFPA has announced plans to combined 1991, 1992 and 1994 into a new standard NFPA 1990, to be published in 2022.]

Protective clothing that have been certified compliant with these standards are listed by the Safety Equipment Institute (www.seinet.org) or Underwriter’s Laboratories (www.ul.com).

5.3 EN-ISO Standards (www.cen.eu and www.iso.org)

International Organization for Standardization (ISO) has published several standards for CPC:

- EN 16523-1 Determination of material resistance to permeation by chemicals
This standard will replace EN 374-3 and other EN standards on permeation including several parts (liquids, gases, splashes, etc.).
- EN 943-1 Protective clothing against liquid and gaseous chemicals, including liquid aerosols and solid particles – part 1: Performance requirements.
- EN 943-2 Protective clothing against liquid and gaseous chemicals, including liquid aerosols and solid particles – part 2: Performance requirements for “gas-tight” (Type 1) chemical protective suits for emergency teams (ETs).
- EN 14605:2009 Protective clothing against liquid chemicals. Performance requirements for clothing with liquid-tight (Type 3) or spray-tight (Type 4) connections, including items providing protection to parts of the body only (Types PB [3] and PB [4]).
- EN ISO 13982-1:2005 Protective clothing for use against solid particulates. Part 1: Performance requirements for CPC providing protection to the full body against airborne solid particulates (Type 5 clothing).
- EN 13034:2009 Protective clothing against liquid chemicals. Performance requirements for CPC offering limited protective performance against liquid chemicals (Type 6 and Type PB [6] equipment).
- EN ISO 374-1 Protective gloves against dangerous chemicals and micro-organism – Part 1: Terminology and performance requirements for chemical risks.
- EN ISO 374-2 Protective gloves against chemicals and micro-organism – Part 2: Determination of resistance to penetration by chemicals.
- EN ISO 374-3 See EN 16523-1.
- EN ISO 374-4 Determination of resistance to degradation by chemicals.
- EN 388 Protective gloves against mechanical risks.
- EN 420 Protective gloves – General requirements and test methods.
- EN ISO 6529 Protective clothing – Protection against chemicals – Determination of resistance of protective clothing materials to permeation by liquids and gases.

GLOSSARY

Absorbent	A material that picks up and retains a liquid distributed throughout its molecular structure causing the solid to swell (50% or more). The absorbent is at least 70% insoluble in excess fluid (ASTM F726)
Action level	The exposure level (air concentration) at which OSHA regulations take effect. Usually one-half of the PEL
Actual breakthrough time	See Breakthrough detection time
Actual use time	An estimated time from assessment of condition in the workplace. Elevated temperatures, flexing, pressure, and tears, along with product variation reduce the actual breakthrough time significantly. Interrupted contact or splashes with the chemical may lengthen the breakthrough time – if the chemical is removed from the surface of the barrier
Air-impermeable materials	A material through which gases cannot pass except by a diffusion process on a molecular level (CEN/TR 15419)
Breakthrough	The movement of a chemical through a protective barrier to the other side
Breakthrough detection time	The elapsed time measured from the start to the sampling time that immediately precedes the sampling time at which the challenge chemical is first detected
Butyl rubber	A type of synthetic rubber formed from isobutylene and isoprene as copolymers used in gloves and other protective clothing because of its chemical resistance
Chemical protective clothing (CPC)	Any material or combination of materials used in an item of clothing for the purpose of isolating parts of the body from direct contact with a potentially hazardous chemical (ASTM F23.70)

Chlorinated polyethylene	Polyethylene that contains chlorine atoms and is used for protective clothing. Also called CPE	Diffusion	The mixing of one substance into another when separated by barrier (i.e. movement of substance on a molecular level across the barrier to the other side)
Chlorobutyl rubber	A type of butyl rubber that contains chlorine atoms and is used in protective clothing	Dipped	Application of a liquid polymer coating to a substrate thereby forming a layer (e.g. elastomer-coated cotton gloves) or a method used to form a glove (e.g. latex-coated gloves)
Cloropel	A trademark for ILC Dover, Inc., chlorinated for polyethylene-coated fabrics used in protective clothing	Elastomer	A rubber or plastic with elastic characteristics
Contamination	The presence of any unwanted material or substance on or in PPE, equipment, structures, or the environment	Ensemble (chemical protective suit ensemble)	A combination of chemical protective clothing (e.g. suits, boots, gloves) and other protective equipment such as respirators, communication devices, cooling devices, and other equipment
Corrosive	A material that causes visible destruction or irreversible alterations in living tissue by chemical action at the site of contact (or that will severely corrode steel)	Ethylene vinyl alcohol	A plastic-like film with <i>excellent</i> resistance to chemicals used in protective clothing; also called EVAL or ethylene vinyl alcohol (EVOH)
CPC	Chemical protective clothing	EVAL	See ethylene vinyl alcohol
CPE	Chlorinated poly-ethylene	FEP	Copolymer of tetrafluoroethylene and hexafluoropropene, which is a plastic-like material used in protective clothing because of its excellent chemical resistance. Also called Teflon-FEP™
Cumulative permeation	The total amount of chemical that permeates during a specified time from when the material is first contacted (ASTM F23.30, F 1383, F 1407)	Fluoroelastomers	See VITON®. Also called FKM
Decontamination	The removal of a contaminant or contaminants from the surface or matrix, or both, of chemical protective clothing (CPC) to the extent necessary for its next intended action (e.g. reuse and disposal). (ASTM F23.70, F 1461)	Gas-tight	The ability to hold a gas under pressure within the suit
Degradation	A deleterious change in one or more physical properties of protective clothing or equipment as a result of contact with a chemical	GHS	Globally Harmonized System of Classification and Labelling of Chemicals administered by the United Nations
Dermal	Affecting the skin (or permeation through the skin)	HAZWOPER	Acronym for the U.S. Occupational Safety and Health Administration (OSHA) regulation entitled “Hazardous Waste Operations and Emergency Response.” Codified as 29 CFR 1910.120., it is designed to protect the health and safety of individuals handling hazardous wastes, performing environmental cleanups, or engaged in emergency response actions
Detection limit	A minimum limit of detection for the challenge chemical and the analytical technique used, when doing permeation testing. For the ASTM F739 permeation test, the detection limit is $0.1 \mu\text{g cm}^{-2} \text{ min}^{-1}$ and for EN 374 $1.0 \mu\text{g cm}^{-2} \text{ min}^{-1}$		

Latex	Originally extracted from the rubber tree. Currently also applied to water emulsions of synthetic rubbers or resins (<i>Fundamentals of Industrial Hygiene</i> , 3rd ed., National Safety Council, 1988, p. 873)	Neoprene	A rubber-like product used in protective clothing made from poly-chloroprene
Level A	The highest level of PPE defined in HAZWOPER. For protective clothing, this includes the use of a gas-tight totally encapsulating ensemble and a supplied air respirator, either self-contained (SCBA) or airline	Nitrile	A type of synthetic rubber used in protective clothing
Level B	The next to highest level of PPE defined in HAZWOPER. For protective clothing, this includes either an encapsulating or nonencapsulating chemically resistant splash suit and a supplied air respirator, either self-contained (SCBA) or airline	Normalized breakthrough time	The time at which permeation rate reaches $0.1 \mu\text{g cm}^{-2} \text{ min}^{-1}$ (ASTM F739 and ISO 6529) or $1.0 \mu\text{g cm}^{-2} \text{ min}^{-1}$ (EN374-1). Normalized breakthrough time is used in the manufacturer's reports enabling barrier material comparison. A normalized breakthrough time of >8 hours does not mean there was not permeation; it means that permeation did not exceed $0.1 \mu\text{g cm}^{-2} \text{ min}^{-1}$ or $1.0 \mu\text{g cm}^{-2} \text{ min}^{-1}$ during the eight hours test
Level C	The next to lowest level of PPE defined in HAZWOPER. For protective clothing, this includes the use of a chemically resistant splash suit and an air-purifying respirator	Penetration	The flow of a chemical through zippers, stitched seams, pinholes, or other imperfections in chemical protective clothing on a nonmolecular level
Level D	A HAZWOPER designation for the lowest level of protection. For protective clothing, a work uniform and safety glasses and gloves. Not worn with respiratory protection	Permeability	The ability of a chemical to pass or move into or through a substance or material
Limited use of CPC	Chemical protective clothing for limited duration of use, that is, to be worn until hygienic cleaning becomes necessary or chemical contamination has occurred is required. This includes protective clothing for single use and for limited reuse according to the information supplied by manufacturer. (CEN/TR 15419)	Permeation	The process by which a chemical moves through chemical protective clothing on a molecular (nonvisible) level
Natural rubber	Name for the rubber that is derived naturally from trees (gutta percha). A distilled version is called isoprene. Natural rubbers are used in protective clothing, but if untreated offer minimal chemical resistance	Permeation rate	The rate or mass flow of the chemical across the barrier, expressed as mass per unit area per time interval
		Personal protective equipment (PPE)	The equipment used to shield or protect an individual from chemical, physical, or thermal hazards that may be encountered during a response action or work activity
		Polyethylene	A common and relatively inexpensive plastic material (made of repeating units of ethylene) used in protective clothing or as a coating for protective clothing. Also referred to as PE

Polymer	A high-molecular-weight material formed by the joining together of many simple molecules (monomers). Natural rubber and cellulose are naturally occurring polymers. Most resins are chemically produced polymers (<i>Fundamentals of Industrial Hygiene</i> , 3rd edition, National Safety Council, 1988, p. 881)	Sensitizer	A material that can cause an allergic skin or respiratory reaction
Polyvinyl alcohol	A type of plastic (made of repeating units of vinyl alcohol) that has some solubility in water, but very good organic solvent resistance, and is used in protective clothing. Also called PVA, a trade name of the Ansell Company	Solubility	A term that normally expresses the amount of material (as a percentage by weight) that dissolves in a liquid, such as water at normal temperatures (producing a solution)
Polyvinyl chloride	A common type of plastic (made of repeating units of vinyl chloride), which is used in protective clothing. This is the product that is commonly thought of when someone refers to a "plastic"	Splash protective suit	A one-piece or multiple-piece garment constructed of protective clothing materials and designed to protect the wearer against chemical contact by splash
Protective clothing material	Any material or combination of materials used in an item of clothing for the purpose of isolating parts of the body from a potential hazard	Steady-state permeation	The constant rate of permeation that occurs after breakthrough when the chemical contact is continuous and all forces affecting permeation have reached equilibrium (ASTM F739)
Routes of entry	The ways that a toxic material can enter the body. The four major routes of entry are inhalation, absorption (skin contact), ingestion, and injection	Totally encapsulating chemical protective suit	A full-body garment that is constructed of protective clothing materials and covers all portions of the wearer's body as well as the respiratory protection equipment. <i>Gas tight</i> refers to the ability to be pressurized with minimal leakage
Saranex [®]	A trademark of the Dow Chemical Company for a film laminate of polyethylene, polyvinylidene chloride (PVDC), and ethane vinyl acetate (EVA). Used as a coating for protective clothing	Tyvek [®]	A trademark of the DuPont Company for nonwoven polyethylene used in protective clothing
SCBA	Self-contained breathing apparatus. A respiratory protection device usually consisting of a tank of compressed air, a pressure regulator, hosing, and a facepiece	Viton [®]	A trademark of the Chemours Company for a rubber-like copolymer of hexafluoropropylene and vinylidene fluoride (Viton [®] A) or terpolymer of hexafluoropropylene, vinylidene fluoride, and tetrafluoroethylene (Viton [®] B or F) or a terpolymer of ethylene, tetrafluoroethylene and poly(methyl vinyl ether) used in number of application includeng protective clothing. Viton [®] belongs to the group of polymers called Fluoroelastomers. Also called FKM. http://chemours-site.force.com/CRG_VitonOverview
Selection	Process of determining the type of protective clothing necessary to provide the required protection (CEN/TR 15419)		

CONTROL BANDING: BACKGROUND, EVOLUTION, AND APPLICATION

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1 INTRODUCTION

Control banding (CB) is a complementary approach to protecting worker health that arose in the mid to late 1990s and has become more mainstream in professional practice over the past decade. CB strategies offer simplified solutions for controlling worker exposures to constituents that are found in the workplace in the absence of firm toxicological and exposure data. Learning the history of CB and its evolution over time is essential for the understanding of its growing role in practice. The most significant force in the development of CB was the recognition that there were increasing limitations of the more traditional process for controlling worker exposures to chemicals (i.e. establishing occupational exposure limits (OELs) against which measurements of airborne concentrations of contaminants could be compared). This style of approach was losing ground due to the increasing number of chemicals being created, thus posing a threat to worker health. Associated with this change were the legal challenges to the process of developing standards. Also problematic was the lack of understanding of this approach on the part of workers and of operators of small and medium-sized enterprises (SMEs). SMEs are smaller businesses that typically employ fewer than 50 or 100 employees and, therefore, often lack the financial resources to conduct toxicological and epidemiological research to establish the OELs and to collect and analyze samples. The utility of the CB approach has been recognized by corporations, national and international organizations,

and is considered a practical approach for the prevention of work-related risks in developing countries. Although developing countries have fewer human and financial resources to invest in protecting worker health and have a working population far more susceptible to public health issues, when it comes to protecting workers from workplace exposures, they face many of the same challenges as developed countries (1).

1.1 Brief Description of CB

CB is a qualitative (2) or semiquantitative (3) approach to risk assessment and risk management that groups occupational risk *control* strategies into *bands* based on their level of rigor. For example, the United Kingdom Health and Safety Executive (UK HSE) Control of Substances Hazardous to Health (COSHH) Essentials CB strategy includes four levels for controlling exposures to chemicals: (i) good occupational hygiene practices, including personal protective equipment (PPE), (ii) engineering controls, including local exhaust ventilation (LEV), (iii) containment, and (iv) the need to seek specialist advice (4). CB is the stratification of work-related risks into “bands” that have each been assigned controls based on the potential hazard and, in some cases, the potential for exposure. Most CB strategies focus resources on the prevention of worker exposure to chemical substances purchased and used in bulk form, either liquids or powders used in larger quantities. However, CB approaches have grown well beyond these bulk chemical origins and now

are applied into the broader occupational safety, health, and hygiene (OSHH) realm. This new growth provides utility for even seasoned industrial hygiene (IH) professionals as the list now includes CB applications for nanomaterials, ergonomics, safety, environmental, construction, as well as a comprehensive framework for occupational risk management (ORM). A potential hazard may be captured by risk phrases (5) (previously known as “R-phrases” and now known as “Hazard Statements” (6, 7) or other indicators of toxicity or hazardous properties. Exposure potential, when used as a component of CB toolkits, may be based on quantity in use, volatility or dustiness, and frequency and duration of exposure. Other CB strategies focus on the dynamics of the task performed to directly assign PPE and control options without the interim step of assessing potential exposure (thus providing “direct advice”).

1.2 Terminology

As used in this chapter, *CB* is a strategy that is based on workplace hazards, the potential for exposure, and the simplified solutions for controlling exposures to the constituents typically encountered in the workplace. CB strategies are often found in singular applications known as *toolkits*, a narrowly defined solutions approach for the control of worker exposures within a limited range of hazards, as well as in a broader and often multidisciplinary *toolbox* as a more widely defined solutions approach for the control of worker exposures across multiple tasks. Many toolkits will fit within a toolbox. The word “scheme” is used frequently throughout the discussion of CB, especially in Europe, and is used without negative connotations in this chapter.

1.3 Scope and Objectives

The scope of this chapter includes CB strategies for addressing solutions to work-related chemical exposures, with limited reference to other toolkits in a proposed ORM toolbox. Chapter objectives are to

- establish the basis for CB approaches,
- describe the history and evolution of CB,
- review the validation and verification of CB strategies,
- evaluate CB and its growth internationally, and
- provide practical examples, lessons learned, and recommendations for CB implementation.

CB has now become an accepted approach to management of occupational exposures to chemicals and other hazards; therefore, this chapter balances a strong emphasis on peer-reviewed literature with a practical basis for applying these strategies for both new and experienced IHs. This approach presents a focus on the origins of CB and an

overview of validation and verification of CB models, as well as the expansion of CB strategies internationally while providing practical examples of CB as applied in practice. Readers who wish to learn how to conduct CB analyses should consult *AIHA Guideline 9-2007, Guidance for Conducting Control Banding Analyses*, prepared by the AIHA Control Banding Working Group (8).

2 PART I: ESTABLISHING THE BASIS FOR CONTROL BANDING APPROACHES

2.1 Challenges to the Traditional OEL Approach

The “traditional approach” to protecting worker health was pioneered in the late nineteenth century, when the first OELs were established in Germany in 1886 or 1887 (9). The first American Conference of Governmental Industrial Hygienists Threshold Limit Values® (ACGIH® TLV®) document was published in 1946 (10). In the following decades, this quantitative approach was adopted by many of the industrialized nations, and as a result, contributed to the improvement of working conditions, increased span and quality of life for countless workers, and decreased compensation costs. The problem of protecting worker health continues to grow with the increasing number of hazardous chemicals in production and a fairly static number of OELs. In 2018, nearly 90 000 chemical registration dossiers were submitted under the European Registration, Evaluation, Authorization, and Restriction of Chemicals substances (REACH) regulations (11). In the European Economic Community, only about 1000 OELs have been established for chemical substances (12), with the HSE having OELs for ~600 substances (13); yet over 100 000 substances are traded in the European Community (14). The problem is equally daunting in the United States, where the American Chemical Society (ACS) Chemical Abstracts Service (CAS) Registry contained 17 688 891 organic and inorganic substances (15). Furthermore, OELs are not consistent across the authoritative bodies that set them in Europe or the United States. Of the 1341 substances that had an OEL established by at least one of 18 authoritative bodies, more than one-third of the substances have an OEL set by only one authoritative body and less than 2% were mentioned by all 18 authoritative bodies (16).

Because the human and financial resources to establish and implement quantitative OELs were and still are limited, particularly in SMEs and the less-developed and economically developing countries (EDCs), it is becoming more apparent that the quantitative OEL approach alone will never solve the problem of protecting workers from chemical exposures on an international basis (16).

As a result of these challenges, individual companies, trade associations, and government agencies have developed innovative approaches to protecting both worker health and the environment. The chemical industries provided an early example of qualitative/semiquantitative methods to assess health and safety risks from catastrophic failures at major chemical facilities (17), sometimes using decision matrices to achieve these goals. The pharmaceutical industry is shifting from utilization of air and wipe sampling to document worker exposure, to the use of air and wipe sampling to verify the efficacy of operation controls. Environmental monitoring thus assumes the role of documenting the results of the risk assessment cycle (18).

2.2 The UK Experience: Response to COSHH Regulations

In the late 1980s, the UK HSE passed the COSHH regulations, requiring, *inter alia*, employers to perform risk assessments for all chemicals used in the workplace (19). Despite much optimism that these regulations would “bring greater emphasis on the assessment of risks to health in industry” (20), there were many challenges to their effective implementation (21). Despite some reports of programs developed by employers to meet COSHH requirements (22), an unpublished survey of 2000 companies showed “widespread ignorance of the new regulations and their implications among smaller concerns ...” (23). There were frequent reports on the deficiencies and needs of many workplaces in complying with COSHH, for example, particularly in health care settings (24–31). These authors stressed requirements to inform and train staff, evaluate risks, monitor exposures, and implement control measures. Similarly, despite the number of sensitizing agents present, relatively few hair-dressing establishments had attempted to comply with the 1988 COSHH regulations (32). Problems in this industry were reported with contact dermatitis in hydrotherapy pools due to inappropriate application of the COSHH risk assessment principles (33).

To better understand the problems with implementation of COSHH, UK HSE conducted market research to characterize industry’s perception of OELs and the degree to which decisions on control measures were affected by OELs (13, 34). A thousand randomly selected chemical users and 150 health and safety representatives of trade unions were interviewed by telephone about chemical use, sources of information, risk management, and understanding of COSHH and OELs. The majority (75%) of respondents were from small firms (<10 employees), mirroring the makeup of British industry; although most trade union representatives were from firms with >100 employees. It was found that even though larger chemical companies and OSH professionals understood the COSHH requirements, “many small firms wanted to be told

exactly what they need, and do not need, to do.” The UK HSE concluded that, given the widespread lack of understanding and sphere of influence of OELs, generation of additional lists of OELs would not be cost effective and that OELs should be limited to widely used substances of concern (13).

These findings are most likely applicable to the United States, as the employment composition of businesses in the United States is similar to that in the United Kingdom. In the United States, 98% (6.3 million establishments) of businesses have fewer than 100 workers with more than half (56%) of the American workforce being employed in these SMEs (35). In the United Kingdom, of the 3.8 million businesses, 99% have less than 200 workers; 69% are self-employed; and 20% have 1–4 employees. One-third (34%) use chemicals, and 47% are uncertain of how to get applicable compliance information (personal communication from Ref. (36)). In the European Union (EU) overall, SMEs account for over 99% of all businesses and employ more than 65% of the workforce (37).

The UK HSE was faced with the realization that there were many substances for which OELs would never be developed and that the majority of SMEs did not understand and did not have the resources to meet the COSHH requirements to conduct risk assessments for chemicals used in the workplace. In response, the HSE established a working group of key stakeholders to develop a simple system for generic risk assessment (34). This approach, which leads to selection of appropriate controls, was first published as *COSHH Essentials: easy steps to control chemicals* (38).

2.3 The Global Experience: What About the Others?

About 90%, or approximately 2.3 billion, of the world’s workers, do not have access to OSH professionals and traditional quantitative risk assessment methods to control and reduce exposures to chemical and physical agents and achieve prevention from acquiring work-related illnesses, diseases, and safety-related injuries (39, 40). Although risk factors for work-related illness and disease are well known, simple economics frequently prevent the allocation of adequate resources to OSH, in both developing and developed countries.

3 PART II: HISTORY AND EVOLUTION OF CONTROL BANDING

3.1 The Origins of CB

CB has its roots in several qualitative and semiquantitative risk assessment (SQRA) approaches, which began to appear

in the 1970s (17, 41, 42). An example would be a risk matrix describing the likelihood and probable severity of event (e.g. explosion or release of toxic material, developed for use by a chemical company). Historically, these approaches borrowed from each other and built upon previous efforts (17) and that it is not always possible to trace the steps by relying on chronological appearance in the peer-reviewed literature. The developers and authors undoubtedly knew one another and there was much exchange of information and ideas among occupational health practitioners and scientists in the pharmaceutical and chemical industries, governmental agencies, and professional and trade associations (43). Discussion of key components and contributions follows.

The developers of the early CB approaches recognized the need for consistent, accurate results among different nonexpert (those without IH technical expertise) users. Money (17) outlined six core principles that have been incorporated in most CB approaches:

1. Approaches must be understandable by users and by those affected, allowing the tools to both evaluate and communicate risk.
2. The required information must be readily available to the user, particularly SMEs, for example, by safety data sheets (SDSs).
3. The output must be practical advice.
4. The tool must be "user-friendly."
5. Users must have confidence in the tool.
6. Output must be provided in a transparent and consistent way.

3.2 Simple Measures of Toxicity

The earliest approaches were based on toxicity of substances encountered in the workplace, and according to the core principles outlined above, would thus require simple, readily available information on the toxicity of these substances. In 1991, Gardner and Oldershaw suggested the use of European risk phrases to provide a simple measure of the toxicity of substances (12, 44). In presenting their comparison of the United Kingdom, American (ACGIH TLVs), and German OELs to the designated risk phrases for volatile organic substances (45), they concluded that the risk phrases, while emphatically *not* OELs, could, when other information was lacking, be used as Pragmatic Exposure Control Concentrations (PECCs) for controlling inhalation exposure. This guidance would be useful to users who had neither adequate toxicological data on substances, nor ability to develop or understand such data.

3.3 Occupational Exposure Bandings

Another important component in the development of CB approaches was the concept of controlling airborne concentrations to a range or band of values, rather than a single point value. Spurred by COSHH regulations requiring employers to control exposures to "a level to which nearly all the population could be exposed, day after day, without adverse effects on health," the Association of the British Pharmaceutical Industry (ABPI) provided guidance on *occupational exposure bands* (OEBs) and OELs for its members (46, 47). The pharmaceutical industry has typically been faced with many situations in which there are insufficient data to develop OELs (48), such as during new-product development, for intermediate products, and for products with limited pharmacological and toxicological data. The level of exposure guidance recommended (i.e. occupational exposure banding [OEB] or OEL) would vary with the stage of product development and toxicity testing. As an example, the process of setting OELs might begin with consideration of an OEB at the end of the research and development phase when short-term toxicity and *in vitro* tests had been completed (see Table 1), and continue with refinement of the OEB or development of a health-based OEL at the transfer-to-production stage, when long-term toxicity, pharmacological, and clinical tests had been completed. Review and confirmation of the OEL would occur at the routine manufacture phase. As discussed below (Section 6.2.1), a comparable concept of OEBs would later come back into use through National Institute for Occupational Safety and Health NIOSH for chemical exposures.

3.4 Linking Toxicological Data with Appropriate Levels of Control

In an early, perhaps the first, published report in which toxicological data were linked to an appropriate level of control, Money (49) presented a structured approach to design and operation of a fine chemical plant, based on a carcinogenic ranking system for aromatic amines and nitro compounds. This was a broad approach for ensuring that

TABLE 1 Occupational exposure bands.

OEB	Vapors (ppm)	Dusts (mg m ⁻³)
A	10–500	1–5
B	1–10	0.1–1
C	0.1–1	0.01–0.1
D	<0.1	<0.01

Source: Modified from Brooke (55).

TABLE 2 Selected criteria for assignment of dust to OEBs.

OEB	Selected criteria for substances (Note 1)	
Category X	Special considerations	R45, R46, R49: should be handled according to COSHH carcinogens ACoP (Note 2) Respiratory and skin sensitizers (R42, R43) Substances showing adverse effects in humans at low doses: $<0.05 \text{ mg m}^{-3}$ by inhalation or $<0.01 \text{ mg}^{-1} \text{ kg}^{-1} \text{ day}^{-1}$
OEB A (Note 3)		Toxic to reproduction (R60, R61)
OEB B		Very toxic (R26, R27, R28) Toxic to reproduction (R62, R63) Toxic (R23, R24, R25, R48)
OEB C		Unknown toxicity not assigned to higher OEB Harmful (R20, R21, R22, R48) Dust not allocated to higher OEB

Note 1: Approved Code of Practice, current edition is (54). Note 2: As an example, the R-phras e R45 indicates "may cause cancer." See Ref. ((4) for further details). Note 3: This A–D rating system is opposite of that used in the COSHH Essentials ratings.

Source: Based on Guest (52).

appropriate measures would be in place to control risks from these chemicals from both routine and abnormal operations; however, it did not provide specific solutions and controls. Four categories of carcinogenic potential were linked with four levels of controls, which progressed in their complexity and stringency, each level building on the previous. After consideration of elimination and/or substitution of carcinogens, the following levels would be utilized for the various levels of carcinogenicity.

- Level 1. For all chemicals, good basic IH, with a facility built to sound industrial standards.
- Level 2. For suspected animal carcinogens of low to moderate potency, greater reliability and integrity than Level 1, plus isolation of the plant by physical or procedural measures, and possibly with health management systems.
- Level 3. For suspected human carcinogens with slight carcinogenicity to animals, or proven or suspect animal carcinogens, at moderate and low doses, respectively, a segregated plant with detoxification, high reliability and containment, and regular technical audits.
- Level 4. For proven human, suspect human/highly carcinogenic to animals, or proven or suspected animal carcinogens, at low to very low doses, respectively, an automated plant with bulk or semi-bulk transfers, process control, and plant audits.

The same concepts – linking hazard category (1–4), hazard classification (e.g. toxic, corrosive), associated risk phrase, guideline control level (8-h TWA), and

TABLE 3 Occupational exposure bands.

	Gases and vapors	Dusts
Category X	Special considerations	
OEB A	$<0.5 \text{ ppm}$	$<0.1 \text{ mg m}^{-3}$
OEB B	$0.5\text{--}5 \text{ ppm}$	$0.1\text{--}1 \text{ mg m}^{-3}$
OEB C	$5\text{--}50 \text{ ppm}$	$1\text{--}10 \text{ mg m}^{-3}$
OEB D	$50\text{--}500 \text{ ppm}$	Not applicable

Source: Guest (52) and Chemical Industries Association (CIA) (56).

recommendations for each hazard category – were further explored by the Chemical Industries Association (CIA) (50) in their guidelines for safe handling of colorants (second version), and their 1997 guidelines on OEBs (51). These guidelines provided a simple, broad-based, integrated approach for use by CIA members in classifying hazards, based on OEBs that defined the upper limit of acceptable exposure (see Tables 2 and 3).

Recognized needs included (i) reclassification of substances if/when more data became available, (ii) consideration of other routes of exposure, (iii) requirements for health surveillance and IH measurements for substances with limited toxicological data, and (iv) testing to provide a high degree of confidence in the predicted OEBs (52).

Throughout the 1990s, much work was being conducted on predicting exposures (53); however, at this juncture, no one had yet factored the *probability of exposure* into the risk assessment and risk management equation.

3.5 Hazard + Exposure → Risk → Control Strategy

The concepts and principles that had been developing since the 1970s were combined in the late 1990s to result in a simple but powerful concept:

Health Hazard + Exposure Potential
→ Generic Risk Assessment → Control Strategy

The UK HSE played a pivotal role in developing a regulatory approach based on these concepts (51, 54, 55). While the work of the HSE was based on that of the UK CIA (52, 56), which categorized substances into OEBs, it is apparent from the preceding discussion that many other groups have contributed to the development of COSHH Essentials. Based on the membership lists of the various task forces, for example, the CIA and the UK HSE, the authorship of many of the chapters included in this review, and recollections of two authors (DIN, DMZ), there was much communication within professional circles regarding qualitative and semiquantitative approaches to protecting worker health.

3.6 The COSHH Essentials Strategy

The earliest readily available, developed, and evaluated CB model comes from the UK HSE, and is known as COSHH Essentials. It was designed to help SMEs do the risk assessments for chemicals and mixtures of chemicals that employers were required to perform under the COSHH regulations. This led to the developmental work conducted by a working group established by the UK Health and Safety Commission's Advisory Committee on Toxic Substances (34). The basic idea is that while there are thousands of chemicals, there are only a few levels of risk management (control bands) available to control worker exposures to these chemicals. The user is guided through a simple risk assessment based on the type of task, the hazard of the chemical (which is assigned to hazard band A through E), the volatility (3 levels) or dustiness (3 levels) of the chemical or product, and the amount used in the task (3 levels). The system then steps the user through a simple matrix that immediately points to the level of risk management (or control band) based on this information. It provides specific guidance in the form of a Control Guidance Sheet (CGS) for the task being conducted and the recommended control band based on the 4-level strategy outlined above. COSHH Essentials remains available in an electronic database format as a simplified approach on the internet (4). A series of articles on the "UK Scheme to Help Small Firms Control Health Risks from Chemicals" in 1998 explored the basic concepts (51), the toxicological considerations (55), and IH considerations (54). The challenge facing the HSE was

Health hazard	+ Exposure potential	→ Generic risk assessment	→ Control approach
Substances allocated to a hazard band using R-phrases	Substances allocated to a dustiness or volatility band and a band for the scale of use	Combination of health hazard and exposure potential factors determine desired level of control	Type of approach needed to achieve adequate control

FIGURE 1 Factors used in HSE's core model. Source: Based on Money (58).

to develop guidance that was practical for SMEs, used available hazard information, was easy to use and understand, and which relied upon readily available information (see Figure 1). The HSE realized that these goals could be achieved by using R-phrases and simple predictors of exposure to conduct a generic risk assessment, which leads to straightforward recommendations on risk management, that is, control approaches (Table 4).

3.6.1 Basic Concepts

The COSHH Essentials approach, as it later came to be known as, builds on earlier approaches (12, 49, 56–60), but adds two other significant developments: it is specifically developed for SMEs and it includes control advice in the form of CGSs. This is a significant difference, as most earlier CB approaches were intended for expert use (1). The key components of the model include the hazard banding, exposure potential, and control approaches. Hazard banding is described more fully below (55). It is important to point out, however, that COSHH Essentials is limited to substances classified under the British chemical hazard information and packaging regulations (CHIP), thereby excluding, for example, pesticides and pharmaceuticals, which are outside the scope of those regulations, and also process-generated hazards such as wood dust, silica dust, and welding fumes (tending now to be covered by specific guidance, see below). Exposure banding is a function of physical properties leading to likeliness for the material to become airborne (volatility of liquids or dustiness of solids), and the quantity in use (54). These elements are combined to determine the appropriate control approach (see Figure 2).

A key point from Russell et al. (51) should be quoted directly as it is a common misperception that CB was developed to replace existing quantitative methods:

"However, the use of the scheme will not in itself constitute a suitable and sufficient workplace risk assessment as required by regulation 6 of COSHH.

TABLE 4 Allocation of R-phrases and H-statements to hazard bands.

Hazard band	Target airborne concentration range	R-phrases	H-statements
A	>1–10 mg m ⁻³ dust; >50–500 ppm vapor	R36, R38, all dusts and vapors not allocated to another band	H303, H304, H305, H313, H315, H316, H318, H319, H320, H333, H336, and all H-numbers not otherwise listed
B	>0.1–1 mg m ⁻³ dust; >5–50 ppm vapor	R20/21/22, R40/20/21/22	H302, H312, H332, H371
C	>0.01–0.1 mg m ⁻³ dust; >0.5–5 ppm vapor	R48/20/21/22, R23/24/25, R34, R35, R37, R39/23/24/25, R41, R43	H301, H311, H314, H317, H318, H331, H335, H370, H373
D	<0.01 mg m ⁻³ dust; <0.5 ppm vapor	R48/23/24/25, R26/27/28, R39/26/27/28, R40 Carc. Cat. 3, R60, R61, R62, R63	H300, H310, H330, H351, H360, H361, H362, H372
E	See specialist advice	R40 Muta. Cat. 3, R42, R45, R46, R49	H334, H340, H341, H350

Source: Brooke (55), Vaughan and Rajan-Sithamparamanadarajah (91).

Control approach 1 – General ventilation. Good standard of general ventilation and good working practices.
Control approach 2 – Engineering control. Ranging from LEV to ventilated partial enclosure.
Control approach 3 – Containment. Containment or enclosure, allowing for limited, small scale breaches of containments.
Control approach 4 – Special. Seek expert advice.

FIGURE 2 Control approaches used in COSHH essentials.
Source: Based on Money (58).

Employers should still consider other factors in their risk assessments, such as the need for health surveillance and the need to monitor exposure to ensure adequacy of control. Similarly, they will want to consider the suitability of the controls recommended by the scheme for their particular work situation. The scheme is therefore guidance to aid employers' risk assessment and selection of control measures, not a replacement for it ...

Russell et al. (51) recognized that an overprotective approach would lack credibility and would deter promotional efforts and implementation (51). On the other hand, an under-protective approach would not protect workers. Weighing these factors, it was generally agreed in the model development that a conservative approach would be the most responsible.

3.6.2 Toxicological Considerations

Brooke (55) outlined three criteria for the toxicological basis of the UK approach: (i) it had to be simple and transparent, so that it would be understandable and consistently used

by SMEs, (ii) it had to make best use of available hazard information, and (iii) recommended control strategies had to vary according to degree of health hazard of a substance.

The R-phrases (currently known as Hazard Statements, though part of this historical development) that were agreed to throughout the EU (5) facilitated these criteria, as they address all relevant toxicological endpoints. This idea had been proposed previously (12) and had formed the basis of similar strategies (48, 56, 57).

R-phrases and resulting target airborne concentrations for 111 substances were compared to the relevant health-based OELs on national lists (the United Kingdom and German MAK), utilizing the R-phrases leading to the most stringent controls, and representing the same endpoint used for the OEL. For 33 solids (100%), the OEL was within or higher than the target airborne concentration range of the hazard band. For 76 liquids (97%), the OEL was within or higher than the target airborne concentration range. While concluding that the R-phrases can be used effectively to allocate substances to hazard bands, Brooke stressed that the process is not intended to substitute for the health-based OEL setting process.

Brooke understood the critical role of R-phrases in the COSHH Essentials approach, stressing that *“the success of the scheme is crucially dependent on the accurate classification of substances by suppliers.”* The accuracy of this process has not been evaluated; however, concerns have been raised about the accuracy of the EU's classification of chemical substances (61). (Equally important to widespread implementation of CB strategies is the effort to standardize the categorization of hazards, a primary objective of the global harmonization initiative discussed below.)

3.6.3 IH Considerations

Money's criteria for a successful CB approach (17) appear to have been uppermost in the minds of the developers of the

COSHH Essentials approach, especially the requirement that the system be understandable by users, and that the required information be readily available.

In writing about the development of the model, Maidment (54) stressed the importance of limiting the number of factors in the model to control its complexity and applicability. The simplicity of the approach to exposure assessment in particular has been the source of much criticism of COSHH Essentials; however, it must be remembered that a key objective of the approach is that it be understandable by nontechnical users.

Five steps were undertaken to develop the control predictive model: (i) characterize control strategies, (ii) characterize exposure potential (physical factors of solids and liquids, operational factors), (iii) develop the exposure predictive model, (iv) establish the relationship between exposure potential and hazard band, and (v) substitute hazard band for exposure potential and invert the model to produce the control predictive model (54).

1. Control strategies were collapsed into four main categories: Level 1, general ventilation; Level 2, engineering containment such as LEV; Level 3, containment; and Level 4, special controls (reserved for experts).
2. Characteristics of exposure potential were summarized as those related to physical properties (dustiness of solids and the volatility of liquids) and those related to substance handling (quantity in use). The working group felt that three dustiness bands (low, medium, high) would adequately describe the properties of dusts and maintain the simplicity of the model. The volatility of a liquid would be captured by consulting a graph of boiling point (low, medium, high) versus operating temperature. Substance handling was characterized as small, medium, or large scale.
3. The exposure prediction model was developed by combining bands for quantity in use and physical exposure potential, resulting in four exposure predictor bands each for solids and liquids.
4. The working group then compared the exposure predictor bands against the predicted concentration bands resulting from control strategies 1–3. These allocations were later “validated either by comparison with measured data or by wider peer review within the British Occupational Hygiene Society (BOHS) and the British Institute of Occupational Hygienists (BIOH)” (54).
5. The final step was to invert the *exposure* predictive model to a *control* predictive model by replacing the exposure range in the exposure predictive model with the hazard band. This produces an empirical model that can be used to predict the appropriate control

strategy (CS) to achieve adequate control based on the hazard and the exposure bands. A series of matrices were then produced that allowed the user to select the recommended CS level (1–4) based simply on the R-phrased, the dustiness/volatility of the substance, and the volume in use. Knowing the recommended control level, the user could then obtain specific control advice by selecting a CGS appropriate for the task at hand and the recommended control level.

With these three chapters (51, 54, 55), the wider OSHH community was thus introduced to the basics of the COSHH Essentials approach. While this strategy leans heavily on the work of historical models and approaches, it has several unique features, including the online version that made a CB toolkit globally accessible for the first time. It meets all six of Money's (17) core principles (understandability, availability, practicality, user-friendliness, confidence on the part of users, and transparent, consistent output). Despite its attributes, however, it is subject to several limitations relative to the development of the model, development of databases, use of the model, and its validation and verification. Oldershaw (62) has cautioned that the COSHH Essentials approach could not be adopted uncritically by other countries; further, the approach must be seen in the context of personal protection, training, and health surveillance as appropriate. A key point is that the approach is not meant to replace exposure measurement, interpretation, substance, and chemical control, as emphasized by Russell above as well.

3.6.4 Providing Control Guidance to Users

CGSs for both common and specialized tasks form a key component of COSHH Essentials. Over 300 CGSs have been published (63, 64). In addition, there are over 200 additional Direct Advice Sheets (DAS) covering many industries, including microelectronic chip manufacturing, offshore oil, printing, welding, and construction work. Each CGS and DAS is structured according to a standard format, and contains sections on access, design and equipment, maintenance, examination and testing, cleaning and housekeeping, PPE, training, supervision, a short list of references, a sample schematic of an engineering control, and an employee checklist for proper utilization of controls. The Asbestos Essentials series is a good example of the applications of the CB strategy where direct advice can be given in the form of CGSs, based on good control practice reached by consensus of industry experts. These CGSs require no detailed data input. They can be downloaded by selecting task sheets on equipment and methods and activities, such as nonlicensed work with asbestos cement, textured coatings, insulating board, and other asbestos-containing materials (64).

The adoption of the Globally Harmonized System (GHS) of Classification and Labeling of Chemicals has been an important concept for expanding the reach of CB in a standardized format within national regulations. The GHS is a common and coherent approach to classifying the health, physical, and environmental hazards of chemicals, and to communicating the hazards through labels and SDSs. GHS includes a core set of label elements and has harmonized hazard statements (“H-statements,” formerly R-Phrases) for each category and class of chemicals covered. It also has a harmonized approach to classifying mixtures of these chemicals. Adopted by the United Nations in 2003, the GHS is now aligned within legislation in 50 countries (28 within the EU), partially implemented in 15 countries (including the United States, Canada, and Mexico), and not yet addressed in 128 countries (65). Global implementation of the GHS would thus provide an international system upon which to base CB. This standardization of hazard statements for expanding the reach of CB has already been implemented by regulation in the EU and the United States (6, 7) and US OSHA is now aligned with the Hazard Communication Standard with the latest edition of GHS. The International Labour Organization (ILO) has already included the GHS hazard categories in its International Chemical Control Toolkit (ICCT) (66). The International Chemical Safety Cards (>1700) prepared under the International Program for Chemical Safety (IPCS) have been modified to follow the GHS criteria for classification and the harmonized H-statements and are updated periodically to account for the latest scientific developments, providing a source of information on many of the most commonly used chemicals (67).

4 PART III: VALIDATION AND VERIFICATION OF CB STRATEGIES

Before CB strategies can be accepted, adapted, and implemented on a wide scale, a few issues must be addressed regarding validation and verification. (In this chapter, validation refers to the many components related to accuracy of the model itself, and verification refers to the correct installation, operation, and maintenance of controls.) As has been noted frequently, underprescription of control could lead to serious injury, even death, while overprescription could lead to significant unnecessary expense (51, 68). There are multiple decision points in the application of CB that may contribute to error; each step of the CB strategy should be validated independently of the others, including issues related to the creation of the model, application of the model, and failure analyses at each step of the CB process (e.g. assignment, reporting, and understanding of R-phrases/H-statements, etc.).

Verification would include evaluating the installation/operation/use of controls to reduce exposures in specific workroom situations through follow-up surveys. While it would be useful to validate all the CB strategies that have been proposed, the early validation efforts were quite comprehensive and primarily had only two models readily available for researching: COSHH Essentials and the ICCT (68). Formerly known as the ILO Toolkit, this second model was produced in collaboration with the UK HSE and the International Occupational Hygiene Association (IOHA). Based on COSHH Essentials, the ICCT incorporates the GHS and is thus adapted for use worldwide.

4.1 Exposure Monitoring

Although the need for exposure monitoring within the context of COSHH Essentials has been expressed by many authors (51, 52, 62, 68), including its developers, it is not necessary to conduct exposure monitoring to obtain control advice from the model. Kromhout (69) took strong exception to the lack of exposure monitoring in generic risk assessment tools as they “... are known to be inaccurate and they do not take into account the various components of variability in exposure levels ...” Kromhout built a strong case, estimating the variability in an 8-h shift to be between 3- and 4000-fold, and delineating the sources of variability as spatial, between workers, and between groups (69–71).

4.2 Validation Studies

COSHH Essentials has been the subject of validation studies in the United Kingdom, Germany, and the United States. According to Maidment (54), the core model was validated by comparison with measured data, and by extensive peer review of the logic and content by experts. He noted that it was extremely difficult to find quality data for comparisons (a problem reported by other researchers), and further, that the information describing control strategies often seemed to indicate that several control strategies were in use. (Jones and Nicas (72) similarly brought up the issue about information lacking in historical reports, limiting the usefulness for validation studies.)

The first and most complete external validation of the COSHH Essentials to date was conducted by Tischer et al. (73, 74) at the German Bundesanstalt für Arbeitsschutz und Arbeitsmedizin (BAuA – Federal Institute for Occupational Safety and Health). The primary empirical basis for their analysis was measurement data collected within the preceding decade during several BauA field studies. The outcome data were presented as histograms for the percentage of data points that were lower than, within, or higher than the predicted exposure (73). A rough calculation indicates that 98% of the measurements were within or below the OEL, although an evaluation by Naumann et al. (75)

has questioned these findings, indicating geometric standard deviations in the range of 2–3. Tischer et al. were quick to point out that a limited number of data points, representing a limited number of possible combinations of Exposure Predictor Bands and Control Strategies, were available for evaluation. In particular, their database had limited data on exposures related to handling of milliliter or tonne quantities of low or high volatility/dustiness substances (73, 74).

The only other comprehensive validation studies of COSHH Essentials have been conducted by Jones and Nicas (68, 72, 76) of the University of California, Berkeley. Their evaluation of COSHH Essentials for vapor degreasing and bag filling operations was based on the US NIOSH Health Hazard Evaluations and Control Technology Assessments. Under controlled errors were defined as situations in which the airborne concentration exceeded the upper limit of the exposure band in the presence of control technology; over controlled errors occurred when the airborne concentration was within or below the exposure band in the absence of control technology when COSHH Essentials recommended controls. They determined that under controlled errors occurred in 78% (139/179) of vapor degreasing operations where LEV was present, and 48% (76/159) of bag filling operations with control technologies. Over controlled errors were observed in 61% (102/167) and 8% (3/26) of operations, respectively.

These authors commented that they were unable to determine the capture or containment efficiency of controls, due to limited information in the NIOSH reports. In our opinion, this suggests a *verification* issue rather than a *validation* issue, with verification referring to the proper installation and operation of controls, and validation referring to the ability of the COSHH Essentials model to predict the appropriate level of control technology (77–79).

Many experts who have written on CB confirm its potential value as a risk assessment and management tool in the workplace but express caution about the need for systematic, critical evaluation of the approach before widespread adoption (1, 2, 17, 62, 73, 80). A thorough evaluation of the main components of the COSHH Essentials and the ICCT was performed by an ACGIH task force (80). This expert group was tasked with identifying the most important issues associated with these nearly identical toolkits and their use, then offering recommendations for improvement of these main components. The task force evaluated the use of R-phrases and GHS Hazard Classes for hazard group prediction, the grouping of these R-phrases into four classes of exposure limit prediction, the exposure prediction step, and predefined control strategies and verification of achieving control. They found that the use of R-phrases for hazard group prediction, although limited by an inherently rudimentary summary of toxicology and unchecked variability, tended toward an appropriate conservative control of exposure, apart from Hazard Group A as a default for chemicals

with limited data. They also found that the exposure limit prediction step, crucial to achieving a simplified approach in these toolkits, has predictably created a less accurate and therefore crude estimate of OELs.

Subsequently, the NIOSH developed a CB Literature Review and Critical Analysis that captured many of these issues; however, NIOSH focused on its potential usefulness in the United States by informing users of its strengths and weaknesses to stimulate dialogue (81). As an outcome, the document addressed the promise of CB concepts and its potential for considering GHS applications while pursuing further validation of these strategies and opportunities to expand CB models to address additional workplace hazards. Collectively, these studies and expert comments presented in this section were not seen as “project stoppers,” but rather emphasize the need for collection of data under controlled scenarios to validate the predictions of the soon-to-be evolving model. This validation still must be seen as a separate activity from the verification of proper installation and maintenance of controls prescribed by a CB approach.

5 PART IV: CB EVALUATION AND THE INTERNATIONAL EXPERIENCE

5.1 The International Paradox for Simplified Solutions to Reduce Risk

The growth of international acceptance of CB models has gone through a unique process as it has been viewed through the lens of the “haves” and “have nots” in countries around the world. In the developed countries, where OSHH resources are greatest, the acceptance of CB is predicated on accuracy in selecting appropriate controls, efficacy in protecting workers, and whether its models can compare to the gold standard of traditional IH. However, in the economically developing and transitional countries where OSHH professionals and resources are minimal to nonexistent, CB is seen to have the potential to reduce work-related risk for over two billion workers while providing the educational foundation to develop and grow the IH profession where it is most needed globally (82). Therefore, it is just as important to learn of the history and evolution of CB concepts for those areas in the world in need as it is to focus on the science and quantitative methods required by those more resource rich.

There has been a longstanding need for developing an international agenda for simplified approaches and with this is an equally robust historical progression of research-based programs promoting solutions worldwide. Early initiatives to compile solutions include the noise control solutions from the UK HSE (83), in mining from Australia (84), and chemical substitution strategies from Denmark, the United Kingdom, the United States, and The Netherlands (85).

This process has evolved into efforts such as the European Solbase, with many nations teaming to develop a database of effective controls (2).

The unfolding of global CB leadership can serve as a model for internationalizing OSHH efforts in both developed and developing nations. Efforts to promote international cooperation on development of practical solutions may be traced to a workshop on preventive measures held at the first IOHA Scientific Conference in Belgium. This 1992 workshop was the seed for the WHO Prevention and Control Exchange (PACE) for airborne dusts (86). WHO continued its leadership role in this arena, with the 5th meeting of the WHO Collaborating Centers in Occupational Health (WHOCC) (Thailand, 2001) resulting in a unified research agenda intended to validate and verify the effectiveness of the CB strategies. The International Programme on Chemical Safety (a joint program of ILO, WHO, and the United Nations Environment Programme) serves as secretariat of the International Task Group (ITG) on CB, which held its first meeting at the first *International Control Banding Workshop* (ICBW, London, 2002) (87). The ITG had a long-standing role as a global platform for a solidified scientific research and implementation agenda for both developed and EDCs (88).

The CB workshops have provided excellent forums for teaching and research presentations, open debate, and development of research and implementation agendas. At ICBW 2002, the ILO officially released the ICCT (known then as the ILO Toolkit) (89) and as described above, the ITG was launched. The second ICBW, held in Cincinnati, OH, in March 2004, introduced US-based OSHH professionals to CB. Outcomes of this meeting included the US *National Control Banding Workshop* (NCBW) Organizing Committee, an International Implementation Strategy for the ITG, and plans for follow-up workshops. The *Practical Applications Workshop* (June 2004 in The Netherlands) succeeded in creating and implementing CB pilot projects in South Africa, Brazil, and India through twinning strategies with more developed countries. The NCBW (March 2005, Washington, DC) developed a US strategy to conduct and critically evaluate CB research. The third ICBW was held later in 2005 in Pilanesberg, South Africa, in conjunction with the WHOCC Planning Meeting in Johannesburg. The inter-relationship of key concepts was highlighted at the AIHA symposium on *Hazard Communication and Risk Management for Global Business – GHS, REACH, and Control Banding*, (14–15 September 2006, San Jose, CA). The joint CB workshop and WHOCC meetings benefited both by providing an opportunity to develop the WHOCC 2006–2010 Work Plan while reviewing the effectiveness of the 2001–2005 Work Plan. This synergism between the ICBWs and the WHOCC can be seen in the incorporation of themes from the ICBW sessions in the WHOCC 2006–2010 Work Plans (global trends in CB collaborations, silica, and

expansion of range of CB models beyond chemicals). A fourth ICBW was held in 2008 in South Korea (92), and a fifth ICBW was held in 2009 in Cape Town, South Africa. The sixth ICBW was held in 2010 in Rome, Italy and the seventh ICBW went back to its roots in 2015 in being held again in London, England. The eighth ICBW was held in Washington, D.C. in 2018. Much has blossomed from the roots of the original practical solutions initiatives, early global collaborations, the initial efforts of the developers of COSHH Essentials, and the ICBWs have become a highlight event for showcasing the latest in CB research and innovation.

5.2 International Validation and Growth from the COSHH Essentials

COSHH Essentials has remained an important element in advancing the international growth of CB for both the “haves” and the “have nots” as it is readily available on the internet for everyone to access and apply. COSHH Essentials is an evergreen program, in that the UK HSE has continued to review existing models while developing new tools in keeping with the original intent of creating a product that is simple and useful for SMEs. Nearly 20 000 guidance sheets are downloaded monthly, either from the COSHH Essentials or other Web sites; however, less than one visit in six results in a completed assessment. Many users are part of the health and safety community, but fewer are small businesses (who make up more than 50% of the British workforce) who do not use the Internet to access information.

However, as COSHH Essentials was created, implemented, and distributed from a developed country it has been held to a higher level of professional scrutiny. Its original design of providing SMEs with a simplified tool to complement exposure assessment and personal monitoring requirements remains an important component of this process. A recent validation exercise sought to confirm this mindset by seeking to extend the original validation effort (55) by using 850 OELs used by more than one standard-setting organization to establish the appropriateness of the previously assigned COSHH Essentials Exposure Range Band (ERB) approach (91). Considering the variability of OELs internationally, the study found that approximately 90% of inhalation exposure assessments are equally or better controlled, thus this toolkit’s target airborne concentrations remain a valid strategy (91). It has been shown, in comparison with expert judgment, that improvements can be made on the limitations for gasses and vapors and potential overcontrol issues as part of professional decision making by using Bayesian decision analysis (92). COSHH Essentials outcomes were also compared with the Chemical Hazard Risk Management (CHARM) CB tool from South Korea for 59 highly hazardous substances. COSHH Essentials was

found to be an appropriate CB benchmark as its assessment outcomes were rated at risk level (RL) 3 or higher for all substances, whereas CHARM was found by its evaluators to have underestimated the risk in comparison for nearly all the hazardous chemicals (94).

5.3 The Reach of REACH

Running parallel to the early emergence of the COSHH Essentials was the introduction of the Chemical Agents Directive by the EU in 1998 (94). As chemical risk assessment regulation is wont to do, this process spurred interest in CB strategies on the part of the wider European IH community (17, 95) and the implementation of the EU regulations on REACH (96) have provided an ongoing catalyst to the growth of CB. REACH created a fundamentally new approach to chemical control by shifting the burden of risk assessment and management from the regulatory authorities to chemical manufacturers, formulators, or importers. Downstream users (employers) must follow "Risk Management Measures" developed to control exposures in foreseeable use scenarios.

Additional activities also were part of the historical progression of CB, serving as ongoing motivation for the development of national models in the EU. The European Chemical Industry Council (CEFIC) exposure management system was intended to provide a guidance tool for SMEs, to collect workplace exposure data. This data could then be coupled with hazard information to deliver advice on risks and risk management (incorporating a validated CB model) and recommend whether exposure monitoring should be conducted (17). Faced with registering and evaluating tens of thousands of chemicals into the next decade, the European Centre for Ecotoxicology and Toxicology of Chemicals (ECETOC) targeted risk assessment (TRA; ECETOC-TRA) was developed. ECETOC-TRA is a tiered process that utilizes banding approaches to identify chemicals that present a risk to workers and/or consumers (17, 97) that is also available online to registered users. Hazard and exposure are considered together to determine the level of detail and complexity required for risk evaluation. Tier 0 screens out chemicals not presenting an immediate risk to humans or the environment. Tier 1 identifies uses of a chemical that may present further risks, to be investigated in greater depth in Tier 2. In Tier 1, margins of exposure (MoE) are compared with generic OELs for the chemical's hazard category. Tier 2 assessments are conducted in accordance with EU risk assessment principles. Another important CB model in this process is the Advanced REACH Tool (ART), also developed as a higher tier exposure assessment tool. ART uses a Bayesian approach to combine available exposure data with mechanistically modeled inhalation exposure predictions (98–106).

CB models from EU countries have indeed been impacted by REACH regulations. In addition to serving as a Tier 1

risk assessment tool, aiding manufacturers and importers in estimating workplace exposures to their chemical products and suggesting appropriate control strategies, CB may also aid manufacturers in formulating safer products. For example, a product classified as harmful by inhalation with high emission potential would require CS 3 (containment) when used in ton quantities. Altering the physical form of the product from a high-emission powder to a low-emission granular form would reduce the CS to level 1 (general principles of IH) (105). COSHH has not been revoked or substantially amended by REACH, as the latter does not repeal the EU's Chemicals Agents Directive, Carcinogens, and Mutagens Directive, or Biological Agents Directives, all of which COSHH implements. REACH and COSHH duties relate to one another with respect to the duty to decide how to control exposure and the control of exposure by inhalation.

Heading into the twenty-first century significant efforts were being made in European countries to develop a CB model for SMEs, Germany being one (106). In addition to the SME issues common internationally, Germany has faced an ongoing loss of OSHH knowledge resulting from the splitting of formerly large chemical firms into small, independent units. The German Occupational Safety and Health (Bundesanstalt für Arbeitsschutz und Arbeitsmedizin, BauA) has adopted and advanced the COSHH Essentials approach that they have also made readily available as the "Easy-to-use workplace control scheme for hazardous substances" (EMKG) available on its website since 2005 (107). Using readily available information from SDSs (substance-related) and workplaces (task-related), the user of the scheme can derive control strategies to minimize exposure via inhalation or skin contact. An extensive number of generic CGSs are offered on BauA's webpage with the same numbering as those from HSE. The CGSs are accepted by the competent authorities in the federal states of Germany as a procedure to improve compliance with the Hazardous Substances Ordinance for substances without an OEL (108). In 2008 EMKG 2.0 was launched on the BauA homepage. The new version includes all 300 substances with a legal OEL in Germany and is now providing great value in complying with REACH demands for Tier 1 exposure scenarios in the registration procedure for chemical substances (109). From its beginning, BauA has also worked to validate its EMKG as well as its CGSs that are similarly derived from COSHH Essentials. These studies include the use of workplace exposure monitoring data to further validation of CB in support of the EMKG approach (73, 74, 110, 111) and using Monte Carlo simulations for mixed substances to reproduce determinations that the protection provided from the process is satisfactory (112). To further validate the EMKG-Expo-Tool and its CGSs over a decade later, exposure band predictions were determined in line with tasks for filling containers with organic solvents while simultaneously performing air monitoring evaluations at the LEV, in the work area, and on

workers. When using the appropriate LEV there was a good agreement found between the CGS-derived exposure bands and quantitative measurements of airborne solvent concentrations, providing assurance that workers are protected when using this CB toolkit (113). This provided sufficient confirmation that the EMKG-Expo-Tool was acceptable for REACH Tier 1 exposure assessments.

The Netherlands was also involved in this process, developing another important CB model that has benefited from the international growth of the COSHH Essentials. Stoffenmanager (Dutch for substance manager) has been available online since 2003 and was designed to have expanded exposure assessment capability to assist SMEs. The toolkit was originally based on a conceptual model of exposure (114) and a quantified calibration with measured data (115). For inhalation, Stoffenmanager combines a hazard banding scheme like that of COSHH Essentials with an exposure banding scheme modified (118) from a model developed by Cherrie et al. (117, 118). The dermal exposure model is based on the RISKOFDERM Toolkit (119, 120). Unlike COSHH Essentials, this model factors in exposure potential using an interactive chemical risk management approach (115). The employer completes an exposure assessment, responding to seven questions, including proximity of the worker to the exposure source, to determine the chemical's exposure class. As originally developed, Stoffenmanager used this exposure assessment, and R-phrases (now Hazard Statements) categorized according to COSHH Essentials, to automatically calculate a risk score to complete an initial assessment of the health risk. The English version of the generic model creates wider opportunities for international use and has provided further validation and verification of the model.

Stoffenmanager is an excellent example of a CB model that has benefited from the collaborative efforts of the international CB workshops (e.g. the inclusion of a more detailed exposure assessment process) (121, 122). As part of its original validation process, the Stoffenmanager model was evaluated utilizing targeted field surveys for many dust (e.g. animal feed, flour processing, textile, and construction) and liquid (e.g. solvents for metal, car body repair, and printing) exposures for comparison with existing exposure data (116). This comprehensive study found relatively good correlation of the nonexpert Stoffenmanager score with expert evaluation overall for inhalable dusts ($r_s = 0.83$) and liquids ($r_s = 0.81$). The initial validation study suggests the value of Stoffenmanager as an exposure assessment tool for SME managers and confirms its use in REACH Tier 1 scenarios. The employer can then calculate the efficacy of various control measures and choose the most effective ones (121). The model was refined based on a database of approximately 1000 measurements as an initial attempt to verify Stoffenmanager's applicability for REACH for Tier 1 exposure assessments and reached a conservative 90th percentile estimate that was considered to be sufficient for REACH

applications (123). To further the evaluation and validation efforts of the Stoffenmanager model, the exposure database MEGA from Germany, a compilation of workplace measurements for preventative applications, was used (124). Specific task group measurements were selected from MEGA and organized by task, product, and control measures within scenarios to evaluate two of the model's equations for estimating inhalable dust personal exposures. As with Schinkel et al. (123), this provided good correlation with a conservative approach to show that Stoffenmanager would be a useful Tier 1 model for REACH (124). Stoffenmanager has also been found useful in practice based on its simplicity in a laboratory risk assessment for xylene (125).

CB became interwoven within the European Chemical Agency (ECHA) REACH guidance with a number of these computer-based toolkits specifically mentioned as suitable for exposure assessment for workers as part of the substance registration process, standardizing the exposure distribution for risk characterization at the 75th or 90th percentile to ensure conservative results (126, 127). The ICBW 2015 became the perfect global stage to present the initial results of research into this as part of the Evaluation of Tier 1 Exposure Assessment Models under REACH (ETEAM) Project presentation of its initial results. The ETEAM's genesis was an outcome of the previous six ICBWs and was initially presented at the first EU Control Banding 2011 conference in Dortmund, Germany (128). The ETEAM Project's aims were to compare and contrast the different exposure assessment models in terms of their determinants, scope of application, functionality, and user-friendliness. The included outcomes on these models and their conceptual evaluation and uncertainty, between-user reliability, and external validation were also part of the goals of this comprehensive project. Over 2000 measurements as part of a dataset were built for the evaluation of the five CB toolkits (ECETOC TRA, RISKOFDERM, EMKG-Expo-Tool, Metals-EASE (129), and Stoffenmanager) that are accepted by ECHA for REACH Tier 1 assessments. Part of the ETEAM study outcomes showed that, for powders and volatile liquids evaluated, the ability to predict exposure assessment outcomes at conservative levels was found to be more balanced in the Stoffenmanager 4.5 model (130, 131). An evaluation of ECETOC TRA v3, ART 1.5, and Stoffenmanager 4.5 as part of a sensitivity analysis with the determining dominant factors of the models to assess overall robustness found that Stoffenmanager was a good tool for practitioners to use with difficult or uncertain entry data (132). Another evaluation of conservative outcomes that tested 90th percentile outcomes being above quantitatively measured exposure values also had positive outcomes for the Stoffenmanager 5.1 model (133). Stoffenmanager is now seen as a long-standing, validated higher tier tool for assessing and managing work-related hazardous substance risks by ECHA for REACH (134). With this growth in REACH applicable CB models and continuing

outcomes from the ETEAM Project, a steady stream of research continues into their evaluation and validation. With over 40 000 chemical substance dossiers submitted to ECHA as of 2014, consistent reminders of the necessity of quantitative exposure assessment are interspersed with research into exposure models as their necessity in the process has become quite evident (103, 135). The ECHA REACH guidance received a further ETEAM evaluation of several of these recommended CB toolkits, taking into account the relative simplicity of Tier 1 models as screening tools to evaluate the necessity of providing conservative exposure predictions (136).

Two years after ICBW 2015 nearly 4000 measurements of primarily powder handling and volatile liquid exposures from both Europe and the United States were used as part of the validation of ECETOC TRA, MEASE, EMKG-Expo-Tool, and Stoffenmanager (134). The comparison of toolkit estimates with measurement results indicated that these CB approaches were showing relatively appropriate levels of REACH guidance level of conservatism at the 90th percentile of outcome at or above quantitatively measured outcomes, although more so for powder handling than for work with volatile liquids. Toolkits also varied in their performance with a reduced conservatism for certain processes, although the higher tier Stoffenmanager was an exception for this during powder handling. This comprehensive validation effort reflected that these tools often, but not always, achieve the necessary conservatism and therefore may need ongoing adjustments (134). To address the user side of this process, the evaluation of between-user reliability was also performed for the varying input parameters within these CB toolkits as part of the ETEAM Project for these Tier 1 exposure assessment models (137). Comprehensive methods were utilized to ensure tool input factors and user demographics with 146 users generating over 4000 exposure estimates. Choice variations occurred for most input factors across the tools, with process category codes and dustiness level estimates leading to order of magnitude differences in some estimate ranges. Therefore, the continued availability of user support and quality control is essential to reduce consistency issues in the REACH processes (137). Scheffers et al. (138) sought to validate the hazard banding process outcomes of four CB toolkits, including the commonly available COSHH Essentials and EMKG, against data sets for 229 chemical substances with strong GHS classifications and OELs. These toolkits assigned 23–64% of the substances to the same band with the remainders differing by at least one band. This evaluation process reflected the need to consider the necessity for aligning hazard banding outcomes as an important validation component for standardizing concentration ranges across toolkits. These findings were first introduced at ICBW 2015, where an emphasis was made for aligning the underlying factors of these banding approaches and how the ICBWs are playing an important role in addressing this important

goal (138, 139). This is not the only call for a standardized approach to classification criteria and setting assignment rules for all CB toolkits to develop a unified hazard banding strategy for GHS-related compliance (140, 141).

Additional REACH-related evaluation of these toolkits has also led to mixed results. Spinazzè et al. (142) evaluated the accuracy and robustness of Stoffenmanager 6.0, ECETOC-TRA v 3.1, and ART 1.5 exposure modeling toolkits by comparing these toolkits using organic solvent and pesticide measured data. They found Stoffenmanager to be the most robust model, as well as the safest overall to use as its robustness can overcome minor exposure scenario interpretation errors, but ART results were more accurate if exposure scenarios are well documented (142). Stoffenmanager and ART were investigated for their validity via comparison of the lack of agreement between measured and estimated exposure as an outcome of these modeling tools (143). Multiple inhalable exposures to volatile liquids and powders were both estimated at the 50th percentile and measured for a geometric mean across seven different industries to evaluate both tools for their precision and mean differences of the task parameters presented. ART underestimated exposures in general and Stoffenmanager was shown to underestimate high exposures and overestimate low exposures overall. Stoffenmanager reflected its strength with powder exposures showing higher agreement than for the liquids. Conversely, ART showed higher agreement with liquids as tasks with powders were underestimated sufficiently that it may account for ART's exposure underestimation in general (143). Another evaluation of ART found it to overestimate lower exposures and underestimate higher exposures in comparison to 584 exposure measurements from a Swiss database, although these were considered to be sufficiently conservative at the 90th percentile across all measured exposures of both powders and liquids (144). Savic et al. (146), subsequently used a novel approach by adding ECETOC-TRA in a comparison with Stoffenmanager and ART of their exposure estimates in nearly 32 000 separate *in silico* exposure situations generated in the Translation of Exposure Models (TREMOMO) translation system. TREMOMO integrates six CB toolkits of ART, Stoffenmanager, ECETOC-TRA, MEASE, EMKG-Expo-Tool, and EASE to minimize input and data requirements by assuming the necessary parameters can be translated between models (145). The outcome of the comparison of ECETOC-TRA, Stoffenmanager, and ART via TREMOMO showed higher consistency in the models for volatiles than for powders, indoors rather than outdoor exposures, and in the near-field rather than far-field (146). There were some issues presented on the Stoffenmanager related model algorithms and those in TREMOMO leading to different outcomes (147). These were acknowledged when compared to Stoffenmanager 6.0 and less so with the version 5.1 included in TREMOMO (148). This interchange led to important outcomes on both the value of

TREXMO's goal to serve as a "translator" for multiple algorithms to reduce between-use variability versus the value-added consideration of selecting the right CB model for the task and managing the users through the process to improve overall worker safety (145, 147, 149).

5.4 CB as a Gold Standard; The Nanomaterial Challenge

As challenging and potentially divisive as generating and assessing exposure scenarios can be in REACH-related models, the simplicity afforded by CB can best be seen when dealing with something as complex as engineered nanomaterials (ENM). ENM presents several real challenges to IH practitioners. As products utilizing nanotechnologies are becoming more commonplace and given the general lack of understanding of their toxicological parameters and therefore no OELs developed to date, there has been an urging for caution as groups of ENM that appear promising in, say, nanomedical applications have themselves been found to be potentially toxic to the patient (149, 150). The potential for worker exposures during the handling of ENM is also very real, as evidenced by worker exposures to polyacrylate nanoparticles in a Chinese factory (151), silicon dioxide ENM playing a major role in the development of cardiovascular diseases (152), and nickel ENM powders causing sensitization (153). Recognizing the power of people to decide which technologies succeed and which do not, whether based on real or perceived risks (154), the role of the IH practitioner cannot be overemphasized in relation to society's ability to reap the full benefits of nanotechnologies.

Traditional IH has not provided a comprehensive and accurate quantitative risk assessment of ENM. This realization led to CB gaining legitimate recognition as a viable risk assessment strategy in the eyes of occupational health experts for challenging work-related hazards. The use of CB strategies has become a primary route for the assessment and management of potential health risk prioritization resulting from work-related nanoparticle exposures (82, 155–158). The number of CB strategies has grown in support of this pragmatic approach to preliminary risk management (159). These CB strategies for ENM include CB Nanotool, Stoffenmanager Nano 1.0, and the French Agency for Food, Environmental and Occupational Health and Safety (ANSES) as well as others that have not been formally published (160–164). Regardless of the CB strategy used, the uncertainty of the potential health risks of nanomaterials seems to result in a conservative hazard characterization that results in a high level of risk determination and consequently the need for a high level of exposure control (159, 165). Prior to the existence of the CB Nanotool, expert IH advice was used to select the most appropriate controls

for a given activity with ENM. Therefore, outcomes were directly compared with existing professional expertise as a strategy for validating the method in the absence of an OEL gold standard. A total of 32 risk assessments with the CB Nanotool were performed, producing control recommendations that were generally equal to or more conservative than the existing controls implemented by expert IHS (162, 163).

Balancing conservative outcomes with end-user flexibility for addressing the uncertainty of ENM scientific information appears to be the most useful path forward. The CB Nanotool's approach is considered by numerous researchers to have the potential to offer the greatest utility to ENM producers, as well as users, on both the local and the national scale (166–168). Flexibility for weighting unknowns is seen as especially useful for performing risk assessment and obtaining commensurate control outcomes associated with what may be a temporary or highly variable application as well as with specific changes in a given task's processes (166). It was found that the CB Nanotool provides a factor for understanding uncertainty without using a worst-case approach, even with temporary or highly variable applications (166, 170). Even within the paradigm of traditional IH methods based on quantitative exposure measurements to establish controls, the uncertainty in work-related health effects relating to ENM render the CB Nanotool an integral component of risk management programs (155, 166, 169, 170). The CB Nanotool also has a freely available (<https://controlbanding.inl.gov>) application that applies Monte Carlo simulation to account for risk and qualitative analysis in planning and decision-making to afford changing input parameters to identify the best and most economical methods to decrease RL outcomes in the design phase (171). Acknowledgment of this utility has also been seen by the International Standards Organization (ISO), which issued a new technical specification standard on the use of CB for managing inhalation risk from ENM (172). The standard provides a description of CB for both proactive and retroactive risk assessment, which is distinguished by whether or not existing controls are used as input variables in determining the control band. The CB Nanotool is described as an example of the proactive approach and Stoffenmanager Nano is described as an example of the retroactive approach. It is also suggested that the retroactive approach can be considered a means for periodic re-evaluation of the proactive approach.

Although validated against experts, acknowledged in research for its utility and end-user effectiveness, and identified in international standards, many experts maintained a questioning attitude about the CB Nanotool because it lacked the IH gold standard criteria of a quantitative validation (159, 166, 169, 173, 175). Even though ENM lacks established OELs to aid in this process, this rightfully holds as a constant for all CB-related successes attained

for qualitative risk management methods and quantitative methods should continue to be evaluated for their role in validating the qualitative outcomes (166, 169). Owing to the lack of guidance on a single exposure assessment methodology, various methods were used to collect information for the quantitative validation of the CB Nanotool (176). Zalk et al. (176) assessed 30 activities using the CB Nanotool 2.0 and quantitative data were collected or previously collected data were reviewed for each of those activities using a variety of sampling methods, including real-time detection, filter analysis, and microscopic analysis. All the quantitative data indicated that the control recommendations from the CB Nanotool qualitative assessment were sufficient to prevent workers from being exposed to ENM at levels beyond recommended exposure limits or background levels. This quantitative validation of the CB Nanotool gives even further credence to the use of the CB Nanotool to effectively control worker exposures in the absence of quantitative air monitoring results. The call for OELs for ENM began before the release of the CB Nanotool. Over 10 years later the IH profession still does not have OELs for ENM, but this quantitative validation of the CB Nanotool and a decade of successful implementation and verification serves to provide CB its first gold standard (176).

6 PART V: PRACTICAL EXAMPLES OF CB APPLICATION FOR THE NEW IH

Up to this point, we have focused on the history and evolution of CB, its scientific basis, and the continually growing body of research to evaluate, validate, and reveal its strengths and weaknesses. For many in professional IH practice, this is the most important aspect of the CB discussion and based on this information they can decide whether to apply CB within their realm of practice in the traditional IH model. A growing number of professionals are already encountering CB in use as part of their job scope. Questions often arise about its appropriateness in practice. However, for those entering their first IH job and those early in their career, CB may be a vital component for their practice. Understanding how, where, and when CB is best applied is essential.

An All Too Familiar Scenario

Imagine yourself, for a moment, as a newly-minted IH. Your first steps after walking off the graduation

stage are straight into the office of Big Consulting Firm LLC, and with a job offer in hand, you receive your first assignment: you are to report at 0600 to a 350-employee chemical manufacturer on the outskirts of town that has just received a multitude of serious violation notices from OSHA. Your boss is called away last minute to tend to Big Consulting LLC's highest-profile oil and gas client, so you report to your first assignment alone. You meet with the sole full-time health and safety person on-site and review the violations: employees exposed to fall hazards because stairways were not guarded by standard railings; failure to provide training to ensure employees understood the purpose of energy control programs; and a variety of citations for noncompliance with the Respiratory Protection standard.

After reviewing the violations, you proceed into the expansive high bay of the production building. As you tour various lines, you note some troubling observations: employees are consistently relying on machine interlocks to stop equipment to allow for quickly making adjustments down-stream, without a lock or tag in sight. When you are led into a side room, you notice an overwhelming amine-odor and employees that are working over open tanks with no local ventilation quickly grab nearby full-face air-purifying respirators from a heap of discarded supplies on the corner of a mezzanine and continue without seal checks, and one employee's mask looks much too big for his small face. At the next line, employees use lifting equipment to dump one-ton poly bulk bags full of powdered pigment into hoppers for use in other areas of the plant, and a fine haze of particulate never quite seems to settle across the room in between the dumping of each tote. In a small maintenance shop separate from the production building, employees strip paint off salvaged parts using a dichloromethane-based paint remover, with only a semi-adjacent spray paint booth with the door sometimes propped open acting as exhaust ventilation.

There is a single Environment, Health, and Safety (EHS) manager on-site that needs your help. He is familiar with the company's struggles with lockout-tagout (LOTO) and fall protection, but he finds most of his time is occupied with new employee general safety training – employee turnover here is high – and preparing for a weekly presentation of illness and injury statistics. You have a total of 40 billable hours, 4 of which have already been consumed, and a \$1000 sampling and analysis budget to collect any needed samples, review the company's written health and safety programs, and prepare to finalize a report to the

on-site EHS manager, plant manager, and the parent company's corporate health and safety manager.

With the limited time and budget available, you form a list of questions: what are the highest priority issues at this site? What needs to be fixed now, and what can be ignored or recommended to fix later? Some of the chemicals you observed on site have long-established OELs, but what about the nanoparticles used in the dry pigments that were being loaded? How do you prioritize sampling for complex mixtures of chemicals in the open-top tank room? What resources and will does the company have to implement your recommendations if they go beyond inexpensive purchases of new PPE, or re-writing certain training programs? And finally, how can you communicate your findings in clear and effective language?

6.1 Limited Time, Resources, and OEL Guidance

Even a long-tenured IH can identify with the struggle of the new IH to effectively prioritize OSHH resources. The world of IH is no longer governed by the reactionary, compliance-focused mindset of the asbestos- and lead-centered profession of the 1980s. EHS budgets are flat or shrinking, with management expecting increased return on investment (ROI) for every dollar invested in health and safety (177). Increasingly, firms are reducing their in-house EHS staff and seeking outside help from consultants on an as-needed basis (178). Any decision to hire EHS support, whether in house or on-site, is often based on external market forces such as the cost of worker's compensation insurance or the introduction of new or increasingly complex regulatory standards in a global market (178), rather than the presence or absence of uncontrolled health and safety hazards. In this challenging market, the new IH professional must be equipped with a versatile toolbox that can provide value added to their employer by improving workplace conditions within the framework of shrinking resources.

6.1.1 An IH World Without OELs

What is the new IH to do when confronted with a workplace that may expose employees to one or more of the 99.99% of chemical substances without an OEL? A newer graphical representation of the varying degree of existing exposure limit guidance is a "Hierarchy of Occupational Exposure Limits" – a pyramid-shaped visual of the larger body of occupational exposure benchmarks and guidance values (OEVs) (Figure 3). The base of the pyramid is hazard banding – the allocation of chemical substances to tiered,

graded-risk bands based on their hazard classifications (179). Hazard banding techniques produce a range of acceptable exposure levels, which are most useful when applied as screening techniques where little or no toxicological or epidemiological data exists. A middle-tier, moderately data-driven approach includes reviewing OEVs that are semi-quantitative and simple to derive but must be used with caution, such as the "Desired No Effect Levels" (DNELs) required in REACH legislation. The top tiers of the OEV hierarchy include quantitative, peer-reviewed, health-based OELs set by regulatory or authoritative bodies (i.e. PELs, TLVs, WELs, RELs, MAKs, etc.) A new IH is best suited to participate in the OEL selection or development process somewhere amongst the "bottom" and "middle" tiers of the pyramid. However, when working without OELs the newer IH should know that even hazard banding has its complications in practice that need to be understood.

6.1.2 A World of Generalists

As the IH and business community looks beyond OELs, a convergence is occurring among the allied disciplines that comprise environmental health and safety. As noted in the 2016–2018 AIHA Strategic Plan, IH competencies are "becoming specialized, fragmented, and integrated into generalist EHS roles." Simultaneously, the responsibilities of an IH have expanded to include broader environmental, safety, and health responsibilities (180). As early as 2000, internal surveys performed by AIHA showed that "traditional" IHs spent slightly more than half of their time on pure IH tasks, with an almost equal amount of time taken up with safety and environmental issues (181). Additionally, many IHs are looking to the environmental field to move upward on the career ladder. Considering that the EPA has a budget and staff 10 times that of OSHA, multimillion-dollar fines, and tough regulations, it is no wonder that up to 40% of IHs have said they may position themselves in environmental management in the future (181).

6.1.3 Developed and Still Developing Countries Approaching Parity?

Health and safety initiatives in developing countries often remain underfunded and neglected under the pressures of social, economic, and political challenges (182). Daniel Anna, AIHA president from 2015 to 2016, noted that as the globalization of manufacturing continues, "old" IH issues like controlling exposures to lead, silica, and asbestos, become a prevalent risk that are not controlled to the extent expected or achieved in the United States (180). Yet developed and developing countries share a surprising amount of occupational health and safety challenges.

SMEs employ approximately half of the employees in many developed countries (183). Yet even when an OEL

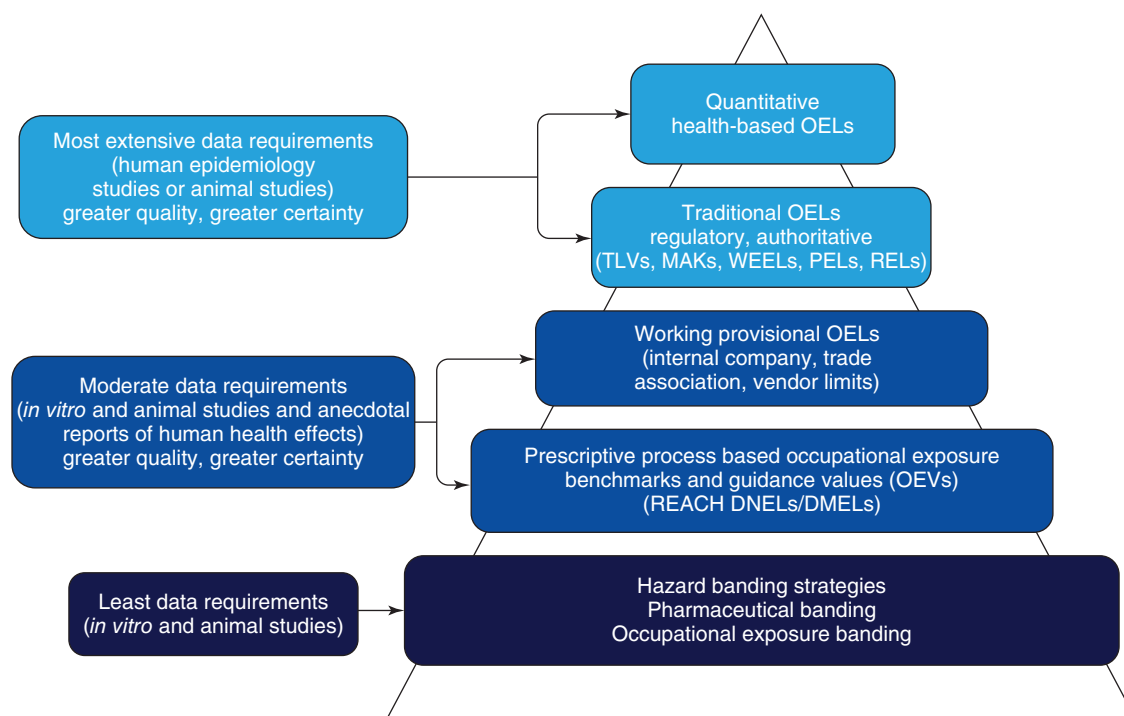


FIGURE 3 The hierarchy of OELs. Source: McKernan and Lentz (189).

exists, enforceable rules are in place, and knowledge is widely available, SMEs have less resources and expertise to implement exposure controls due to a lack of technical expertise and financial access to EHS resources and technology (184). A 2018 US Small Business Administration report found that small businesses with less than 20 employees, which account for 89% of all firms in the United States, pay approximately \$250 more per employee to comply with occupational safety, health, and homeland security regulations than those firms with 500 employees or more (183). Evidence exists that these small businesses in the developed world struggle with a lack of access to resources, information, and knowledge like their counterparts in developing countries. In a 1998 survey of UK employers that used chemicals, most of which employed fewer than 10 employees, less than 20% of the employers were aware of the existence of legally binding OELs (13). A survey of a randomly selected representative group of employers in Taiwan demonstrated that 65% of employers could not answer what a SDS was, and over 50% did not believe air monitoring was required if a worksite had an environment that could be considered hazardous (185). In Germany, only 1–2% of SMEs perform air sampling to test for compliance with existing OELs (112). Clearly, the gap between workplaces that can afford EHS expertise, and those that cannot, is not as simple as the developed vs developing country divide.

6.2 Control Banding and the Newer IH's Toolbox

There is unprecedented pressure on less experienced IHS to be more knowledgeable, useful, and versatile than ever before – with increasingly limited time and resources. Below we will explore CB's acceptance by national organizations, examples of CB tool kits, OEB, and applications in practice.

6.2.1 Occupational Exposure Banding

Hazard and CB provide a process for evaluating hazards and risks in situations where OELs may or may not exist. Ripple (186) stated that decoupling hazard banding from CB allows assessment of hazards to be used in hazard communication to promote greater understanding after a substance has been introduced into a workplace. Hazard banding, although not a substitute for OELs, yields insight into the relative toxicity of substances and can be used to aid in substitution and design of controls coupled with the knowledge of the physical state of the substance. There are limitations to hazard banding including unfamiliarity with R-phrases and H-statements, GHS, lack of standardization of hazard phrases on SDSs, degree of risk which may vary with the physical state, as well as lack of expertise in translating the hazard phrases by nontoxicologists. Even though the verification of these

methods needs more effort and they will not immediately replace OELs, they can offer greater protection of workers in situations where regulatory guidance is not available (or may never become available).

For an early-career IH seeking a comparable banding strategy in the United States to assist in GHS compliance for a substance without authoritative recommendations and/or an OEL, NIOSH's OEB approach may be a good place to start (187, 188). The OEB process took the CB approach to a different place. It tightens up the toxicity assessment component; however, it does not include the semi-quantitative exposure assessment component that can be found in COSHH Essentials or the EMKG-Expo-Tool and does not lead to a control outcome. In the NIOSH Occupational Exposure Band (OEB) Tier 1 process, substances are quickly and accurately assessed by first sorting the substance into "bands" C, D, and E based on toxicological potency and adverse health effects associated with exposure using GHS hazard codes (189, 242). Their Tier 2 approach sorts substances into bands A–E when sufficient data are available to assign bands with more confidence. It should be noted that the NIOSH OEB range of bands B–E represents the lowest range of exposure concentrations, while band A represents the highest range, which is the opposite of the rating system used in the COSHH Essentials ratings. The output of this process is an occupational exposure band, which corresponds to a range of exposure concentrations designed to be protective against adverse health outcomes. NIOSH has validated this Tier 1 approach by comparing Tier 1 results for 600 substances with both GHS codes and a full-shift OEL from an authoritative body and found that the Tier 1 banding protocol was "successful" in that it was at least as protective as the OEL > 80% of the time (188). By introducing the OEB approach to the health and safety community in the United States and openly requesting practical feedback, NIOSH identified two primary themes that needed to be addressed:

1. OEB should not be performed for chemicals with existing OELs.
2. The proposed NIOSH OEB document is complex.

The first item of feedback is relatively easy to address through increasing and strengthening communication. The second theme is a natural outcome of NIOSH experts developing a scientifically reliable and robust outcome; however, the professional effort to perform Tier 2 evaluations will always be more difficult and time consuming than the Tier 1 approach (189). To further aid end users, a user-friendly interface was created as an online draft of the NIOSH OEB e-Tool to be readily accessible for Tier 1 and Tier 2 assessments and to expand the opportunity for users to apply and trial this OEB process so that those utilizing this approach in practice can offer further feedback to NIOSH to improve the process and guide future related initiatives (190).

When faced with the dilemma of how to define acceptable workplace exposures, early career IHs will need to utilize and integrate a combination of traditional OELs; provisional, internally developed, or proprietary OELs; OEB approaches; and ancillary information like Skin Designations. Then, to build on this knowledge, the early career hygienist can use CB strategies beyond the OEB process – which is limited to assessing health hazard information to determine acceptable exposure ranges – and add a layer of risk exposure management to directly link a hazard to a specified control measure.

6.2.2 *Control Banding Tools – Bulk Chemicals and Beyond*

Similar to the CB tools available in the international sphere, including CB tools developed by national authoritative bodies and REACH-related qualitative chemical exposure models, large corporations have also been internally developing CB tools for their unique needs. Solvay, a Belgium-based multinational chemical company, developed a Microsoft Excel-based Critical Exposure Screening (CTES) tool to address the need for a "shop-floor" usable tool that incorporated the use of advanced higher tier exposure assessment models (191). The tool requires few inputs by the user and is focused mostly on concentration, task description, and duration – toxicological data including OELs and internally developed OEBs are read automatically from a database. The tool identifies an inhalation risk score for both particulates and vapors, identifies skin hazards, and gives users information on carcinogenic, mutagenic, or reproductive toxin effects. The final result of the CTES tool is one of three outcomes which are then banded into a category defined by the acceptable concentrations associated with the OELs or internal OEBs. The Green level is judged as acceptable residual risk, whereas Grey Priority 1 and 2 levels require a more detailed exposure assessment and/or control ranked by risk.

Smaller industries, categorized as SMEs, often lack resources to hire IH professionals or lack the budget to hire consulting expertise in this area. However, they still have the desire to protect their workers and meet regulatory requirements. A Chemical Hazard Assessment and Management Program (CHAMP) has been developed in Canada by Chemscape to focus specifically on SMEs by harnessing SDS information. As SDSs can be intimidating in complexity for SMEs, CHAMP serves to digest and combine SDS-related GHS hazard class, H-statements, boiling points, and more with CB tools enabling a transfer of IH knowledge to non-IHs (192). The CGS outcomes of CHAMP are designed to simplify control information with colors for RL outcomes paired with icons and images that have been proven to have a significantly positive effect on communication and long-term worker retention resulting from an increase in attention, comprehension, recall, and

adherence. Risk management programs like this for SMEs have been shown to beneficially affect changes as they are easy to implement with the CGSs designed to be helpful training aids for workers and are, therefore, more likely to follow the appropriate measures (192).

On the control guidance side of the CB tool applications, there has been the development of banding strategies for ventilation requirements in laboratories (193). Sweet and Stuart (194) developed a Laboratory Ventilation Management Program (LVMP) by using ANSI Z10 and ANSI Z9.5 and CB strategies to create a tool to establish institutional target ventilation rates. The control bands were based on laboratory spaces using air changes per hour (ACH) for occupied (eight ACH and, conditionally, six ACH) and unoccupied (four ACH and, conditionally, three ACH) lab spaces. The operating conditions to be met included use of volatile chemicals controlled by local ventilation, effectiveness of ventilation in avoiding significant chemical vapor accumulation, and effective housekeeping to avoid fugitive emissions. This process also identified chemical use in laboratories that required specialist review within the LVMP to determine the appropriate ACH for laboratories falling outside these control bands (194). A comparable methodology was also inspired by CB tools and strategies to provide OSHH professionals with limited resources the ability to conduct laboratory assessments using a hazard mapping methodology to assist OSHH management in risk ranking to make informed decision recommendations to upper-level management (195). Further examples include a UK-based respiratory selection tool (196) that has been evaluated with a broad user base. The evaluation results demonstrate that 87% of the outcomes were considered by the authors to be appropriate when users applied H-statements and 98% appropriate when using process-generated substance scenarios (197). In addition, the Institut de Recherche Robert-Sauvé en Santé et en Sécurité du Travail (IRSST) has also developed a web-based respiratory protection guide for bioaerosols that can also be used in the healthcare, agricultural, and business sectors (198, 199) and US OSHA has created an Advisor Genius eTool to assist users in the selection of an appropriate respirator based on the NIOSH Respirator Decision Logic and the OSHA Respirator Standard (200).

In expanding CB concepts beyond management of bulk chemicals, it is recognized that while hazards vary, two criteria remain constant: (i) hazard, exposure, and RLs must be derived using rigorous scientific principles and (ii) less acceptable risks must be linked to increasingly stringent controls, using increasingly conservative decision criteria where knowledge is limited. While many questions about the specifics of this process remain unanswered, the basic premise of banding hazards, exposures, and controls holds continued promise for applications beyond bulk chemicals and for further refinement as screening tools for use by OSHH experts and nonexperts. Promising applications

include industry-specific and hazard-specific tools. For example, the UK HSE Silica Essentials series has made a significant contribution toward the reduction of silica exposures and potentially the occurrence of silicosis, which has been on the international docket since 1935 (201). Another novel approach was developed as a CB tool for the control of infectious diseases on a university campus (202). This risk assessment tool combines the likelihood of exposure and severity of the disease to determine a graded-risk response level outcome with response actions determined by the mode of transmission (e.g. droplet, aerosol, surface, food/water, or insect/vector borne). Other promising expansion-of-range projects include ergonomics (202, 203), safety (205), immediately dangerous to life and health (IDLH) situations (206), beryllium (206), concentrated flavorings (207), damp building environments (208), and glutaraldehyde in health care settings (8).

A useful outcome of the CB paradigm is the development of direct control advice that does not rely on risk phrases, but which points the user to job-specific control advice in professions such as dry cleaning, hairdressing, pesticide application, and paint spraying (94, 138). Taking this a step further, Silica Essentials directs users to control advice sheets that are industry and task-based and do not require the additional step of inputting exposure prediction data (138). The WHOCC 2006–2010 Work Plan includes efforts to implement and validate Silica Essentials in China (quartz and concrete making), India (silica flour mills), and South Africa (quarries). NIOSH is leading a special focus on silica in Latin America where millions of workers face uncontrolled exposures; this program will simplify the advice sheets even further to build professional capacity and increase technical knowledge in the highest risk industries. Projects in Brazil (mining, mineral processing, ceramics, and glass manufacturing) and Chile (mining, quarries, dental labs, and stone crafts) should result in Spanish language control advice that can be utilized throughout most of Latin America, although Brazil would need them in Portuguese. Hints of applied CB principles can also be seen in newer occupational health and safety legislation. The adoption of 2016 Final Rule on Occupational Exposure to Crystalline Silica in the Construction Industry (209) is incredible for its sheer scope of influence in the United States – an estimated 2.3 million workers are exposed to silica in 676 000 workplaces, with the number of lives saved per year estimated by OSHA at 600. Building on the example of COSHH Essentials CGSs, the OSHA 1926.1153 standard includes the Table 1 Specified Exposure Control Methods, one of three compliance options under the new standard. Table 1 provides the many construction industry employers without the means to access an IH with a table of task, duration, and location-specific engineering, administrative, and PPE control guidance. By following Table 1, employers will not have to establish alternative exposure control methods, including written

exposure assessments and follow-up air sampling that must be performed each time there is a change in the production process, control equipment, or work practices. AIHA's submission of comments on the final rule in 2014 supports the use of Table 1 due to the avoidance of complicated and possibly costly air sampling strategies required to capture the inherent variability of exposures on a construction site, the establishment of administrative controls including regulated areas that will protect the co-located worker, and the dual table format that incorporates a time-based task exposure (> 4 hours or <4 hours) that may reduce unnecessary respirator use, among others.

6.2.3 Control Banding Tools – Moving Away from IH

CB ideas and toolkits have also been developed outside of the IH realm. The Psychosocial Risk Management European Framework (PRIMA-EF) incorporates CB concepts to integrate the hazards of chemical and physical stressors such as solvents, noise, or stress into the realm of the mental well-being of employees (210). This framework acknowledges that the hazards of these stressors, in a social and organization context, can contribute to different sorts of harm such as the systemic stress that is manifested from fear of exposure to harmful solvents. The need for ergonomic toolkits is global, given that 40% of the world's occupational and work-related health costs are attributed to musculoskeletal disorders (MSDs) (39). Toolkits for the prevention of MSDs have an advantage over those for chemicals in that new chemical products continue to be created, whereas ergonomics has a finite group of well-researched and defined risk factors and effective programs (211, 212). Rather than presenting prescriptive guidance such as specific joint positions, angles, postures and durations of tasks, the second edition of the ILO/International Ergonomics Association (IEA) *Ergonomics Checkpoints* (213) provided practical, pictorial advice for an even wider range of workplace scenarios and could thus be the basis of an ergonomics toolkit (203). A CB framework has also been incorporated into the ILO's Ergonomic Checkpoint materials – publications that aim to reduce work-related accidents and injuries by suggesting proven and inexpensive ergonomic solutions such as better designed tools, use of carts, materials-handling techniques, and workstation arrangements. The original CheckPoints manual presents 132 realistic and flexible interventions that are aimed at reducing injury in the workplace without the expense of hiring consultants. The efforts of the ILO checkpoints program have resulted in a series of three mobile applications, which address ergonomics (general and agriculture) and stress prevention at work. Users can access detailed checkpoints with illustrations, create custom checklists, and prioritize and export notes in the workplace right from the app. The Checkpoints program, presented as a multi-day

seminar with a hands-on component, has been tested in developing countries and resulted in effective training at the local level.

CB approaches for industrial safety professionals could also play a major role in reducing the annual toll of nearly 6000 workplace deaths from acute traumatic injury in the United States and 270 million nonfatal injuries internationally (82, 214). Under the WHOCC umbrella, IOHA, partners in The Netherlands, and the Canadian Industrial Accident Prevention Agency (IAPA) are incorporating simplified solutions in an Injury Prevention Management Toolkit using a CB-like safety strategy known as Barrier Banding (215). Like the banding of chemicals by toxicity, classifications already exist for various variables of accident causation. Banding safety risks for selection of appropriate barriers for injury prevention is similar to selecting appropriate engineering controls based on chemical hazard bands in CB. Barriers to injury, including management factors, are strongly related to the quality of safety management systems and are important parameters for risk prevention (204). The Barrier Banding model would apply safety phrases to accident scenarios or related situations and guide the user to the type of precautions needed to prevent traumatic injuries (215, 216). Kudryavtsev et al. (217) developed a comparable risk management system for industrial safety field practitioners to assist in performing risk assessment of accidents based on expert evaluation data to assist in the development of guidelines to develop preventative barriers and their maintenance. The implementation of this RL assessment protocol assists in providing the right information to management to prioritize decisions necessary to achieve emergency prevention, the ongoing assessment of safety barrier maintenance proactively, and accident prevention measure effectiveness overall. Another CB approach applied for industrial safety was produced for craft making shops in higher education to simplify the identification, evaluation, and controlling of hazards to improve safety, tailor controls, and prioritize specific needs based on the level of risk (218).

With health and safety now well represented among the CB toolkit strategies, it was only natural that the growth of banding would expand into the environmental arena to encompass the EHS professions. In the OSHH world, risk communication among environmental analysts is often limited in discussions of work-related environmental contaminants due in part to the depth and breadth of applicable regulatory requirements. Coleman and Zalk (219) developed a qualitative, risk-based CB strategy for the assessment and control of potential environmental contaminants using the same 4×4 risk matrix approach based on severity and probability that is also used in other OSHH-related CB models and risk management in general. Using this same graded approach not only provided a simplified risk assessment and control format that is easy for environmental analysts to use, but it also provides a standardized

and beneficial approach to risk communication to address EHS professionals, management, and workers alike. The CB model they created provides an effective means for determining standardized responses and controls for common environmental issues based on the level of risk. The model is designed for integration within occupational health and safety management systems like ISO 45001 to provide a multidisciplinary environmental and ORM approach. Qualitative environmental CB strategies are now available to identify controls for tasks in the United States and for addressing other local, regional, and national regulations for construction, research activities, facility maintenance, and spill remediation that affect air, water, soil, and waste disposal (219).

6.2.4 Control Banding Acceptance by National Organizations

Recently, CB approaches have been integrated into guidance developed by both industry groups and consensus standard organizations outside of the realm of IH-focused organizations such as NIOSH, ANSI, and the ACS (194, 220). In 2015, a subgroup of the ANSI A10 Construction and Demolition standards committee, with support from US labor groups, published ANSI/ASSE A10.49 Control of Chemical Health Hazards in Construction and Demolition Operations. Working on the knowledge that most construction companies do not employ a full-time certified IH (CIH) and have limited monetary resources and experienced personnel for collecting personal air samples, the A10.49 standard provides a CB framework that combines toxicity information and exposure potential much in the same way as the COSHH Essentials in the sense that operations involving low hazard/low toxicity operations can be handled with simple precautions prescribed by a health and safety generalist, while higher toxicity/high exposure scenarios require a Job Health Hazard Analysis plan (JHHAs). The A10.49 standard suggests that the JHHAs should be authored by risk assessors with increasing credentials based on a sliding scale of risk, from the contractor-level up to “qualified person,” such as a CIH.

In response to a 2014 OSHA request for information, the North American Building Trades Union (NABTU) submitted formal comments requesting that OSHA investigate modeling future regulation on a task-based CB approach like that in ANSI 10.49 standard to find a way forward in the current difficult climate for updating OELs (221). Likewise, on a recommendation from the US Chemical Safety Board, the Hazard Identification and Evaluation Task Force of the ACS's Committee on Chemical Safety released chemical hazard assessment toolkits including a CB approach that combines fire, reactivity, chronic toxicity, and acute toxicity hazard schemes to band substances in one of four Chemical Safety Levels. ACS has published corresponding generic

facility-level, training, oversight, response, and PPE control recommendations. Despite having a well-educated membership base with an above-average comprehension of the physical properties of dangerous substances, ACS chose to create a process that was simple and straightforward enough for all participants in laboratory work, including chemists, laboratory techs, and facility/maintenance personnel, to understand the basic requirements (220).

6.3 Control Banding – Multidisciplinary EHS Applications

The variety of hazards (chemical, ergonomic, safety, and environmental) faced by construction workers logically leads to the incorporation of individual toolkits into a Construction Toolbox. The ICBWs have facilitated toolkit approaches for ergonomics, silica, and safety in a manner that includes the provision of national-level guidance and coordination of pilot projects at a more local level. Other toolboxes are being developed in China, and at The Center for Construction Research and Training (CPWR) (222). Toward this end, CPWR has developed an Exposure Control Database as an interactive tool for the construction industry that helps to predict exposure to the workplace hazards of noise, lead, silica, and welding fumes (223). In addition, the WikiSafe Workplace under development for open access online for professional feedback and improvement is an innovative approach modeled on Wikipedia (224, 225). The ORM Toolbox approach is an outcome of this coordination, which has broadened the CB model to include a more comprehensive exposure control basis for universal industries such as construction. A toolbox addressing these composite exposures by trade and task is now in development within Stoffenmanager (226). An international working group that included the United States, the United Kingdom, and The Netherlands has collaborated on producing a Construction Toolbox model for task-specific approaches across the OSHH disciplines. The outcome of this process has led to a revolutionary approach to simplify multidisciplinary risk communication issues both within and between the OSHH professions as well as with the construction trade management and workers.

Zalk et al. (227) presented a framework and protocol design for a construction industry risk management toolbox as the construction industry needs a comprehensive, systematic approach to assess and control occupational risks. These risks span several professional OSHH disciplines, emphasized by multiple international occupational research agenda projects including falls, electrocution, noise, silica, welding fumes, and MSD. Yet, the International Social Security Association says, “whereas progress has been made in safety and health, the construction industry is still a high-risk sector” (228). As SMEs employ about 80% of the world's construction workers and CB has been effective

for this sector, it seems that this strategy would also provide an appropriate, simplified approach for reducing multidisciplinary work-related risks. The Construction Toolbox design includes international input on multidisciplinary approaches for performing a qualitative risk assessment on the severity and probability of a construction project within 4×4 risk matrix scoring framework. The outcome of this scoring determines a risk “band” for a given project that is used to identify the appropriate level of training to oversee construction work. Identifying a graded risk banding of projects is extremely important for planning and budgeting construction efforts. However, as this risk banding can be performed before the project begins, the input parameters for severity and probability can be adjusted in planning by modifying task parameters to ensure that the right level of oversight expertise is available in advance and fits the projected costs. Each of the construction project tasks is also given a graded risk Control Level (CL1–CL4) commensurate to risk that assists in identifying the appropriate control methods to perform the work safely. This format harnesses multiple solutions-based national programs and publications for controlling construction-related risks with simplified approaches across the OSHH professions (227).

A more comprehensive occupational risk model based on CB is the Risk Level Based Management System (RLBMS) that is designed to focus OSHH resources on the highest risk procedures at a given workplace (229, 230). The model utilizes CB with a stratification of four RLs for a variety of commonly performed maintenance and support activities to characterize risk consistently for research and development related tasks. RLBMS creates an auditable tracking of activities, the maximization of OSHH professional field time, and standardizes a graded approach to documentation as a control outcome commensurate to a given task’s RL. Validation of RLs and their exposure control effectiveness is collected in a traditional quantitative collection regime for regulatory auditing. However, qualitative risk assessment methods can also be used within this validation process. Participatory approaches are used throughout the RLBMS process. Decision making at the worker level assists in both empowering employees to actively participate in reducing their work-related risks as well as gathering and presenting control information for all OSHH-related hazards that have regulatory-based expectations and required documentation (88). Workers are involved in all phases of building, maintaining, and improving this model, which also serves to improve the implementation of established controls. Linking the RLBMS model to a comprehensive OSHH database assists in the calibration of risk-based decisions across OSHH disciplines and produces an auditable trail that affords the consistency necessary to perform work in a healthy and safe environment within a regulatory framework. The RLBMS has been recommended as a complement

to IH staff support as a multidisciplinary decision-making framework for both its utility in the absence of OELs as well as the strength of its participatory approaches for harnessing the knowledge base of workers to create workable and implemented control expectations (16). In addition, the environmental CB model described above (219) utilizes the same multidisciplinary CB strategies for delineating risk and complements the existing RLBMS. This approach offers an opportunity to expand into a singular occupational and environmental risk management process that also improves risk communications within and between EHS professionals, workers, and management.

RLBMS is also a proven method to reduce the amount of resources needed to produce auditable documentation of work activities in a highly regulated facility (230). Under the RLBMS, qualitative risk assessment strategies have succeeded in efficiently managing risk and producing satisfactory documentation for various regulatory authorities at a national research laboratory. Work activities are assigned a RL based upon the probability of exposure and severity of outcomes for each of the hazards presented. RL2 and RL3 assessment outcomes delineate the important decision of determining when to actively involve a member of the EHS team in work planning due to a reasonable chance of a regulatory derived reportable incident. Using a Bayesian statistical model, a quantitative validation was performed on one component of the RLBMS – “pre-analyzed tasks” (PATs) – which are standardized assessments for routine labor tasks with prescribed work methods and controls and associated risk levels. As part of the RLBMS’s initiative to shift resources away from low-risk activities and towards high-risk activities, EHS personnel developed a database that streamlined risk assessments called the Risk Assessment and Control (RAC) database. It serves as a semi-automated risk assessment platform that provides EHS professionals with tools, including CB tools, and information to conduct their assessments in accordance with established procedures and standards. To perform a risk assessment, one enters information regarding the task’s location, work operation, and hazards. The results of RLBMS’s qualitative risk assessments show that long-term efforts succeeded in redirecting resources away from low-risk activities. It was found that 89% of the resulting RLs are 2 or lower, the RLs at which EHS involvement is not directly needed, saving a considerable amount of effort from EHS personnel because, if PAT procedures are followed, new risk assessments will not be needed when these tasks are performed. The work environment at a national research laboratory shares important characteristics with the state of IH worldwide – it is tasked with developing rigorously validated risk management systems capable of reducing the amount of resources spent on routine tasks and efficiently prescribing control measures to a growing array of novel agents. Critiques of the RLBMS

and its CB-based components can inform developing CB strategies on how to operate more effectively and accurately (230).

6.4 Control Banding – See Workplaces Through a Professional's Eyes

Newer IHS and OSHH professionals around the world are often found in situations where staff and funding resources do not afford luxuries like precision, time, and experience. The overarching strategies of CB also help our new IH with the issues presented in the expansive high bay of the production building. The banding strategies are also seen as a “binning” of relative risk for each hazard presented, separating into bands the level of risk presented by each of the operations that are part of these manufacturing procedures. When an experienced IH walks into large high bay of activity, it is their experience and wisdom that initiates the process of binning of risk and priority for all that they see. CB is in its essence the translation of this professional experience through calibrated eyes as it is filtered into more simplified terms of figuring out which of the four containers of risk these hazards belong to. Therefore, the mechanics of systematically putting banding techniques into practice begins the rough transferring of professional wisdom into the mindset of a newer IH. Many more experienced IHS that learn of CB and its applications begin to appreciate this aspect of transferring knowledge and its growing value in practice. It is also fair to say others with comparable experience find it all too simplified, lacking the precision that comprise the scientific standards of the profession.

Control Banding, the New IH, and The All Too Familiar Scenario

Now our newly-minted IH has some very important information to assist their work in the office of Big Consulting Firm LLC. The assignment at the 350-employee chemical manufacturer on the outskirts of town with many serious violation notices from OSHA may just seem a bit more manageable. In the follow-up meeting with the sole full-time health and safety person on-site, a newer IH should begin by addressing the OSHA regulations behind the stairway fall hazards with a lack of railing, discuss the observed issues that are likely behind the company's noncompliance with the respiratory protection standard violations, and review the elements of the energy control programs that the chemical manufacturer needs to ensure are understood and implemented as part of developing

a new training program. A lot of this may seem straightforward, but now our new IH has a better understanding of how CB strategies can help prioritize these issues, assess the risks presented, identify controls commensurate to risk, and offer a standardized risk communication to involve the workers in addressing these OSHA violations.

Observations in our fictional high bay are simply extensions of these situations and CB can indeed be helpful putting the numerous issues in order of priority and investment. The employee reliance on machine interlocks can potentially expose them to high severity injuries, although the level of probability may depend on whether the manufacturer has a LOTO program that simply is not being implemented consistently. If they do have a program with spotty implementation, it is likely an RL3 that requires working with the employees to develop an implementation and oversight protocol as part of a new LOTO training requirement. If there is no program, then the increased probability of a severe injury elevates the risk matrix outcome to an RL4. The side room's overwhelming amine-odor, lack of local ventilation, and employees working over open tanks without respirators should quickly initiate an intervention. With the input of several employees, SDSs and online access, our newer IH can quickly derive the appropriate type of engineering control to recommend to management and identify the best respirator type and filters that are required in the interim by using their choice of available online CB tools described above for chemical hazards and respirator selection resources. Although it appears unlikely that they have an appropriate respiratory protection program from appearances, it will be good to confirm this and use the same RL outcomes and path forward as with the LOTO issues as a solid training protocol seems to be in order. The dumping of one-ton poly bulk bags of powdered pigment into hoppers for use around the plant requires a similar CB tool evaluation at this point source as well as open exposure sources downstream. Determining whether there are any additional controls being used in the dichloromethane-based paint process will be necessary, since the spray paint booth's exhaust ventilation will certainly be inadequate for this carcinogen and this OSHA chemical-specific regulation is most likely not being followed.

The lone EHS manager on-site does indeed need the new IH's help but is also fortunate that they are now armed with a CB toolbox in addition to our IH's newly-gained professional knowledge. After sorting the highest priority OSHH issues out and presenting them in the simplified risk communication that CB

provides, the manager will quickly understand that limited resources and primary focus on general safety training need to be re-assessed and new priorities need to be set. With only \$1000 for sampling and analysis, the IH knows to begin with the regulatory expectations of dichloromethane unless the employer can immediately substitute for less hazardous paint strippers if the process can be performed comparably without increasing exposures. The IH knows from overwhelming smells and limited visibility that the other chemical substance exposures may be far too high to be acceptable; however, the immediate implementation of engineering and administrative controls are more important than expending resources on sampling and analysis. The best investment of sampling resources will be after these controls, that the CB tools assisted in identifying, are put into place to verify that the controls are indeed appropriate to reduce employee exposures to acceptable levels. Some of the 40 billable hours should be spent first with the on-site EHS manager to discuss how all the manufacturer's processes and facilities fit well into an RLBMS and how participatory processes with the employees can help develop the controls and trainings necessary to protect themselves.

After a review of the company's written health and safety programs and the initial prioritization of these recommendations and requirements, the final report to the on-site EHS manager, plant manager, and the parent company's corporate health and safety manager will nearly write itself. Well, perhaps not write itself, but the inclusion of CB strategies and processes will certainly help in identifying required engineering and administrative control investments, OSHH priorities for the manufacturer, and the need for additional EHS staff to accomplish these objectives. In addition, the simplified risk communication that CB provides also flows from the same risk matrix used in corporate office board rooms. CB also speaks to economic and cost/benefit analysis outcomes and can, therefore, be a wonderful tool in assisting the new IH to frame the report's recommendations in a manner that can help secure additional resources from corporate to reduce the severity and probability of further regulatory violations, worker compensation costs, and of course the protection of employees from work-related injuries and illnesses. The utility of CB may also help our IH by impressing Big Consulting Firm LLC with how much has been accomplished in the 40 hours allotted.

7 PART VI: DISCUSSION

CB remains a subject of much enthusiastic praise as well as objective criticism. With all the growth and regulatory acceptance of the banding strategies, there remains a lack of understanding that CB strategies are intended for applications in specific situations, primarily in cases of inadequate data to assess toxicity and/or exposure, or in situations in which IH expertise is not available, affordable, or accessible. CB strategies are not intended to replace traditional industrial approaches, specifically OELs and monitoring of air contaminant levels, and in fact, many proponents of these approaches have made clear statements about the need to continue to monitor worker exposures.

Perhaps the greatest strength of CB is as a potentially powerful tool for knowledge management. Knowledge management is an emerging field focusing on assessing the creation, transfer, and utilization of knowledge to address specific challenges (231). The development of hazard control guidance materials and the application of CB strategies provide the means for effective OSHH knowledge management. The global explosion in electronic communications has shown itself to be well suited to facilitate management and transfer of this knowledge. Realistically, many of the several billion workers throughout the world, and even many millions in the United States, will never benefit from direct OSHH expertise; they may, however, benefit from the nonexpert advice transferred via CB strategies.

An important criticism of CB that the newer IH must keep in mind is the attitude that CB reduces IH to a one-size-fits-all set of controls that may entirely omit process knowledge and nuances obtained over years of practice. For example, in their written comments to OSHA regarding Table 1 in the 2016 OSHA Final Silica Rule, AIHA commented that several of the tasks in the less than 4 hours/day column that do not require any respiratory protection may be problematic in light of IHs knowledge that silica exposure can be widely influenced by numerous variables (e.g. weather conditions, topography of surface required to be flush with shrouds) and their unpredictable combinations. The confluence of these factors, coupled with no requirement for initial or periodic air monitoring under the Table 1 scheme, may lead to unknown overexposures and misplaced confidence in the effectiveness of engineering controls without verification.

In general, model validations of toolkits are well described in the literature. On the contrary, operational analyses are – to our knowledge – very rarely found in peer-reviewed literature. Tool developers mostly have an idea about implementation aspects, but this idea is based on ad-hoc information rather than on a thorough analysis. This means that a “plan, do, check, act, verify cycle” in the

development process and toolkit implementation is most often incomplete: the “check and act” in operational analyses is missing, as is “verify” to ensure recommended controls remain functionally in place. Consequently, it is often not known if toolkits in use lead to successful interventions at *individual* workplaces. Not unraveling this puzzle might lead to *virtually safe* workplaces without knowing if workers are *truly protected*. Ensuring these steps are complete may be the most important goal for the future of the IH profession.

7.1 CB and the State of the IH Profession

An apprehension often expressed by IH professionals is that by providing a less expensive alternative to IH expertise, CB will weaken and possibly eliminate the profession. Managers of industries of all sizes are under tremendous financial pressures, and the OSHH department is often the first to be hit (232). The US system is moving in the direction of encouraging the pure IH specialist to become an OSHH generalist (178). Offering managers an option like CB may be an economically wise decision that may lead further away from IH expertise, resulting in the short term in solutions without oversight and thus potentially harmful consequences. In the longer term, these economic decisions may result in less demand for IH professionals, and eventual closure of university IH programs (as charged in the United Kingdom, see Refs (69, 70)). The population of IH professionals in the United States is currently flat or declining and is mirrored by flat or declining membership in professional associations due perhaps in part to inability of the profession to publicize its value to the greater society at large (232). However, if widely promoted, CB strategies may present an opportunity to strengthen the IH profession. Several benefits may accrue when an SME manager utilizes CB. If awareness that employees are at risk is followed by the implementation of workplace controls, then employees will have received the benefits of IH services in absentia (17). In addition, CB toolkits like COSHH Essentials direct managers to seek specialist advice at a particular level of risk. If the manager does this, then both workers and the IH profession will have been served.

As part of an appropriate CB strategy, it is as necessary to acknowledge that basic IH controls can be identified through CGSs and checklists as there is a necessity for a threshold level of potential risk (based on toxicity and exposure) that would indicate that professional IH advice and consultation should be sought. In COSHH Essentials, this threshold level is at Control Band 4, the highest of the four levels. On a country-by-country basis, it may be appropriate to lower this threshold, depending on several factors including workplace conditions, availability of IH expertise and resources, the types of industries involved, the size of the enterprise, and the qualifications of the responsible person, for example (8)

- Level 1. Operator, manager.
- Level 2. Person competent in a specialty (by select education and training).
- Level 3. Professional IH (e.g. CIH or ROH).
- Level 4. Expert in area (e.g. ventilation, enclosed systems).

By raising or lowering the level of risk at which specialists' advice is recommended, the designers or implementers of a particular CB strategy could achieve an appropriate balance between reserving professional tasks for those persons qualified by education, training, and experience, and “off-loading” solutions to the proven and routine categories of CB. (Continued development of task-specific “Direct Advice” and CGSs will further facilitate the “off-loading” of determination of recommended controls to nonexpert managers.) In contrast, reserving higher levels of risk and expertise on controls to professional practitioners can take full advantage of their understanding of the science and the art of IH (e.g. dermal exposures, biological monitoring, mixtures, and by-products).

Many CB strategies are intended for use by those without technical IH or OSHH expertise, thus training in the use of the methodology is essential. CGSs provide an excellent tool for assisting with this as they provide a standardized checklist approach to help identify necessary controls and can help in implementing organizational health and safety programs. Training programs should be evaluated with respect to the following: target (e.g. was the training provided to those with authority to make decisions), reception (e.g. was the training offered sufficiently often, by a source considered trustworthy, in an environment conducive to processing), and outcome (e.g. was the training implemented, and was the system used in the correct manner).

7.2 Lessons Learned from CB in Practice

Labor inspectorates are the bellwether of CB in greater Europe. Some countries, like Belgium, have an older guard that do not yet accept new approaches like CB. However, wherever they are open to alternatives, CB is gaining strength if not already strong. Eastern Europe does not yet have the regulation, regulatory oversight, and/or labor inspectorate infrastructure to be like the current REACH regulations in rich EU countries. They are interested in REACH-related models, but at this point, it is too advanced. Therefore, they are much like other EDCs and perhaps developing countries where they are most happy with the basics of CB making a big difference. Generalist OHS mindset is now the future of the profession in most of the world and the global workforce. In EDCs, the IH profession works in the bottom two layers of the pyramid (Figure 3), moving up into OEL-based quantitative sampling where funding and resources afford

this luxury. This is not a limitation of CB that drives the use of the tools, but a byproduct of the economic business model that drives the necessity and funding levels for EHS oversight within companies. Companies also use the same risk matrix model with RL outcomes that has become so pervasive in CB, although their application is in upper management board rooms and their risk inputs for severity and probability are for economic risk and outcome costs of work-related injury and illness. In addition to CB applications, the OSHH professions should also become more proficient in using this risk matrix to develop economic arguments for increasing EHS oversight funding levels. With now over two decades of CB in practice, there are important lessons learned from the application of these strategies from the informal workplace to the executive board room that can truly benefit the IH profession:

- *Risk Assessment Required in Regulation.* Where regulations are strong for making risk assessments mandatory, the opportunity for CB flourishes. However, even where these regulations are strong, the level of enforcement is a key factor for the corporate sensitivity to OSHH-related economic risks. An equality of effort must be prioritized to make risk assessments a regulatory requirement where necessary while simultaneously ensuring that enforcement remains active and knowledgeable. Many risk assessments focus on preventing incidents and accidents to ensure workers go home safe and do not consider chronic health issues.
- *Labor Inspectorate Education.* The labor inspectorate is also a key factor, where it is necessary, even in developed countries, for them to be trained to understand the value of CB and its appropriate place in the OSHH toolbox. Where any of these factors are weak, the basics of CB are strongest. However, both OSHH professionals and the labor inspectorate must be trained to know how these CB tools work, where they fit best in the OHS Generalists toolbox, and how CB is most optimally applied.
- *Maximizing Resources.* CB is a great screening tool for prioritizing investment of limited EHS resources and budgets. CB is useful to recognize when an IH is needed and when it is not; a low toxicity chemical could be resolved with a CGS and the IH assigned to higher-value tasks more suitable to them. CB may be the optimum tool for addressing hazards for which there is little or no scientific information. The cumulative effort moving forward is to find the best place to integrate CB into the training of all affected parties. OSHH professionals need it integrated into their university courses. Labor inspectorates need to have it included as part of their professional workshops and conferences to update those who oversee regulatory enforcement. OSHH generalists need to learn of CB's strengths and weaknesses as well as how these tools work so they can

minimize input error. EHS managers need to learn how CB can help maximize limited budgets for prioritization of their staff's time and effort.

- *CB as Risk Communication.* Wherever in the world there are individuals seeking to learn about the OSHH professions, we must integrate CB into their learning material. CB has proven itself internationally as the best risk communication tool for what the IH profession does and how we make decisions for optimum controls. Corporate board rooms do not need to learn about CB; however, we as professionals need to learn how to discuss economic risks and costs at that level using the same terminology and risk communication that CB offers us as an outcome of its standardized risk matrix models. Corporations understand what RL3 or RL4 means; they just have to know that their EHS funding can reduce the level of risk to afford them a better bottom line overall.
- *Healthy Workplaces Globally.* Developing countries and EDCs should strive to make their national institutes of health (NIHs) more fluent in CB. NIHs must establish close links with local and regional universities to integrate OSHH-related training and professional development and OSHH knowledge sustainability. Organizations like Workplace Health Without Borders (WHWB) and the Occupational Hygiene Training Association (OHTA) can assist with CB- and OSHH-related trainings and building toward this sustainability. However, it is essential that this process is tied to the development of national regulations that include risk assessment requirements, OSHH-related professions that also include IH specifically, and then to the national support for a labor inspectorate that is active in the field enforcing regulations and that they also understand the scientifically proven and reliable CB methods.
- *Quality Requires Quantitative.* A necessary message to all IHs and OSHH professionals, young and old; CB strategies will not and should not rid the workplace of quantitative exposure assessments. Work-related exposures to hazards will always be rife with variability and the quantitative measurement and analysis will always be an essential component of the IH profession (1, 135, 233). With CB there is indeed a new tool in the professional toolbox and we must ensure that the outcomes of its application truly reduce work-related risks and fulfill our obligation to protect the workers of the world (82). However, consistently honing its utility on the whetstone of professional experience and science is a necessary exercise to ensure ongoing innovations like CB are consistently improved to become an essential tool in workplaces of the future (234).
- *Unknowns Require CB.* Risk perception is an important component in the consideration and identification

of multidisciplinary OSHH and EHS risks in the workplace, as findings show that risk perceptions associated with emerging technologies are easier to predict at the individual level than manufacturing-related risks (235). It has become widely acknowledged that CB can be useful for those managing risks and in simplifying otherwise complex risks, especially for occupational hazards with limited information; however, in scientific research arenas like epidemiology, it is considered a less useful tool (236). CB has proven it can be a gold standard for unknowns, as with nanomaterials, and can certainly do so for other future challenges.

- *Harnessing Databases and Modeling.* CB has also proven itself as valuable for both multidisciplinary applications and as a framework for environmental and occupational risk management programs. The more quantitative the exposure assessment measurements are that become integrated into databases, the more strength is given to programmers to develop models with increased confidence for risk assessment and control. There is a tremendous effort in Asia to develop and test these models and the future of the profession requires more data to feed this process. CB offers a framework to both standardize the input of these measurements and apply outcomes of these models across the global industries and to strengthen risk management programs. Perhaps it can be seen as a shared responsibility to professionals and workers alike that we strive to learn, teach, and apply CB internationally, while ensuring that we verify controls consistently.

8 PART VII: SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

The obvious goal of any CB strategy is to reduce the burden of occupational injury and illness. Wider application of CB should increase public understanding of the need to control occupational exposures to chemicals and other hazards, leading to an increased recognition of the need for IH expertise and useful solution-based databases. CB strategies are clearly not the solution to assessment and management of all occupational hazards. There are undoubtedly situations in which CB cannot provide the precision and accuracy necessary to protect worker health; alternatively, there are undoubtedly situations in which CB will provide a higher level of control than is necessary. Despite these limitations, CB strategies have the potential to be excellent screening tools in the hands of both nonexperts and of IHSs. They can be an integral part of a tiered approach to risk assessment, in which simpler tools are used at a screening level, to be followed by a more complex approach as the need arises or

is indicated by the situation (237). Some experts have taken this concept a step further, insisting that CB strategies *must* be integrated into a tiered, continuous improvement approach to exposure/risk assessment and management if they are to achieve their full potential (238).

CB has been found to be most useful where there is an absence of information (e.g. no OELs) or an absence of expertise (e.g. SMEs and in EDCs) (1, 8). Many CB toolkit approaches have benefited from the COSHH Essentials and their strategies have been validated by experts to ensure an appropriate usage for SMEs in developed countries, for example, Stoffenmanager (116, 239). With nanoparticulate exposure and its many toxicological and quantitative measurement uncertainties, however, it can be argued at this time that the CB approaches such as the CB Nanotool may in fact be superior to traditional IH methods (162, 163, 176).

The United States does have an implicit requirement to protect workers, but it does not have the explicit legal requirement of the United Kingdom that risk assessments be performed for all chemicals in the workplace. The United States, does, however, face a similar situation in that there are literally thousands of chemicals in use, the vast majority of which are not covered by an OEL. Similarly, there is a lack of professional expertise; at one time it was said that there was less than 1 AIHA member for every 12 000 workers in the United States. With an increasingly reduced membership for AIHA, that differential is continually expanding. The need for risk assessment tools that can be utilized both by OSHH professionals and by nonexperts will only continue to grow as the impact of E.U. REACH regulations is realized in the United States (112, 229, 240–242). CB strategies offer a method to expand worker protection in the face of limited knowledge and expertise. In considering these approaches, the following recommendations should be kept in mind:

1. The IH profession needs to be treated as a scarce resource. Until this noble profession grows sufficiently to be available to the global workforce, there will be a need for CB and its related qualitative risk assessment and risk management strategies.
2. Any CB model must be utilized in the context of a complete IH program, including training, health surveillance, and where appropriate, exposure monitoring, interpretation, and control.
3. Guidance should be developed on circumstances under which personal monitoring should be conducted (e.g. highly toxic substances, higher-level control strategies, required by regulations). Monitoring should be periodically repeated to determine if controls have deteriorated over time.

4. A national body could provide important guidance in implementation of CB in the United States by, for example, standardizing terminology, developing a uniform and standardized protocol to update new information in hazard statements, and ensuring that adequate margins of safety are in place. This body should also consider assigning some chemicals to higher hazard bands to provide greater margins of safety. Alignment of liquids and solids should be standardized to mg m^{-3} metrics.
5. Additional routes of exposure, specifically dermal absorption, must be considered along with inhalation exposures.
6. Adoption of the GHS has contributed to ensuring the standardization of information available on labels and safety data sheets internationally, but it requires additional efforts to ensure that it becomes a truly global standard in national regulations.
7. The control level reserved for “specialists” should be carefully evaluated, with thought given to assigning Levels 3 and perhaps 2 to professional IHs. Specific issues (e.g. multiple exposures, mixtures, hot processes, spray applications, concentration cut-off values) should also be reserved for professional evaluation.
8. Additional information should be provided on CGSs, for example, contact information for qualified consultants or professional associations.
9. Research should continue in the validation of CB approaches. Development of an open-access database would facilitate validation. Slight revision of documentation collected by OSHA and NIOSH during site visits could contribute greatly to validation efforts. Research funds should be reserved specifically for prospective studies.
10. Incorporation of CB strategies in OSHH management systems would ensure that when adopted at the company level, the assessments are subject to periodic review. The Plan-Do-Check-Act-VERIFY cycle was updated with CB in mind, ensuring the verification of controls and reduction of work-related risk is a required step in risk management strategies.

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OCCUPATIONAL SAFETY AND HEALTH LAW

JOHN HOWARD AND STEVEN SMITH

1 INTRODUCTION TO THE FEDERAL OCCUPATIONAL SAFETY AND HEALTH ACT

State laws addressing workplace safety and health can be traced back to the early nineteenth century, but federal laws addressing the prevention of job-related injuries and illnesses were only enacted in the mid-twentieth century. In 1936, the Congress passed the Walsh–Healey Public Contracts Act¹ as a part of President Roosevelt’s New Deal legislation. The Walsh–Healey Act not only established overtime as work in excess of eight hours per day (i.e. what we now know as the “40-hour workweek”) but also established the first federal government workplace safety and health standards. From 1952 to the late 1960s, a number of other federal laws were enacted to prevent worker injury and illness. Among these laws were the Federal Coal Mine Safety and Health Act of 1952,² the Longshore and Harbor Workers’ Compensation Act of 1958,³ the Contract Work Hours and Safety Standards Act of 1962,⁴ the McNamara–O’Hara Service Contract Act of 1965,⁵ and the Federal Coal Mine Safety and Health Act of 1969.⁶

It was not until latter third of the twentieth century that, for the first time in the American history, comprehensive federal legislation regulating workplace safety and health was considered by Congress. On 17 December 1970, the Congress passed the Occupational Safety and Health Act of 1970 (“OSH Act”),⁷ which became effective on 28 April 1971. The OSH Act represents the first occupational safety and health legislation of national scope. As Congress stated in 1970, the purpose of the OSH Act was “... to assure so far

as possible every working man and woman in the Nation safe and healthful working conditions and to preserve our human resources ...”⁸

The OSH Act has generated considerable administrative and federal judicial law since its enactment nearly 50 years ago. This chapter provides an overview of the major provisions of the OSH Act as they have been administratively enforced and interpreted judicially in the years since its enactment.

1.1 Entities Responsible for Implementing the OSH Act

The Secretary of the United States Department of Labor (Secretary) is responsible for implementing the OSH Act. When the OSH Act became effective, the Department of Labor (DOL) administratively created Occupational Safety and Health Administration (OSHA) to carry out the responsibilities of the Secretary under the OSH Act. OSHA is headed by the Assistant Secretary of Labor for Occupational Safety and Health. The Assistant Secretary is responsible for, among other things, adopting and enforcing occupational safety and health standards and regulations, assessing civil penalties, referring cases to the U.S. Department of Justice for possible criminal prosecution, and evaluating, approving, and monitoring state occupational safety and health enforcement plans and consultation grants.

Section 12(a) of the OSH Act establishes the Occupational Safety and Health Review Commission (Review Commission) as an independent agency to adjudicate OSHA enforcement actions brought by the Secretary.⁹ The Review

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Commission is composed of three members appointed by the President for a term of six years. The Review Commission's chair is authorized to appoint such administrative law judges as the chair finds necessary to assist in the work of the Commission.

Sections 20 and 21 of the OSH Act give the Secretary of Health, Education and Welfare (HEW) (now named the United States Department of Health and Human Services or HHS) broad authority to conduct experimental research relating to occupational safety and health, to develop criteria for new safety and health standards, and to conduct educational and training programs.¹⁰ Section 22 establishes the National Institute for Occupational Safety and Health (NIOSH) to perform the functions of the HHS Secretary under Sections 20 and 21.¹¹ The OSH Act specifically directs NIOSH to develop criteria documents that describe safe levels of exposure to toxic materials and harmful physical agents and to forward standards for such substances that NIOSH recommends to the Secretary.¹²

Section 7(a) of the OSH Act establishes a National Advisory Committee on Occupational Safety and Health (NACOSH), whose basic functions are to advise and make recommendations to the Secretary and the HHS Secretary on matters relating to the administration of the OSH Act.¹³ NACOSH consists of 12 members who represent the perspectives of management, labor, the occupational safety and health professions, and the public. Eight members are appointed by the Secretary and four members are appointed by the HHS Secretary.

Section 27(b) of the OSH Act also established a National Commission on State Workmen's Compensation Laws (National Commission). The National Commission was directed to study and evaluate such laws to determine whether they provide an adequate, prompt, and equitable system of compensation for injury or death arising out of, or in the course of, employment.¹⁴ The National Commission's tasks were completed in July 1972 and it was disbanded.¹⁵

1.2 Scope of OSH Act's Coverage

The OSH Act applies to every private employer engaged in a business affecting commerce, regardless of the number of employees the employer employs.¹⁶ Section 19 of the OSH Act,¹⁷ and Executive Order 12196,¹⁸ directs the head of each federal agency to establish and maintain an effective and comprehensive occupational safety and health program that is consistent with the standards required of private employers.

The OSH Act applies "with respect to employment performed in a workplace in any of the 50 states, the District of Columbia, Puerto Rico, the Virgin Islands, American Samoa, Guam, the Trust Territory of the Pacific Islands, Wake Island, the Outer Continental Shelf Lands, Johnston Island, and the Canal Zone."¹⁹ However, the OSH

Act's definition of "employer" does not include states, political subdivisions of the states, or agencies of the US government.²⁰ Furthermore, the OSH Act does not apply to workers who are independent contractors. Independent contractors lack an "employment relationship" with a firm but have a business or entrepreneurial relationship.²¹ The increasing number of workers who are considered independent contractors in the "on-demand" or "gig" economy narrows the coverage scope of the OSH Act (2).

2 OCCUPATIONAL SAFETY AND HEALTH STANDARDS DEVELOPMENT

The OSH Act established processes for promulgating three types of occupational safety and health standards: (i) consensus standards; (ii) emergency temporary standards; and (iii) permanent standards.

2.1 Types of Standards

2.1.1 Consensus Standards

Consensus standards are standards derived from established federal standards²² or from national consensus standards²³ that were in existence when the OSH Act became effective. Section 6(a) of the OSH Act directed the Secretary to publish such standards in the *Federal Register* immediately after the OSH Act became effective or for a period of up to two years. These standards became effective as OSHA standards upon publication without regard to the notice, public comment, and hearing requirements of the U.S. Administrative Procedure Act (APA) of 1946.²⁴ The intent of the interim standards provisions was to give the Secretary a mechanism to promulgate standards with which industry was already familiar and to provide a nationwide floor of minimum health and safety standards.²⁵ The Secretary's two-year authority to promulgate interim standards expired on 29 April 1973. Most OSHA standards are 6(a) standards, and are based on scientific findings from the 1960s or earlier, and are widely viewed as obsolete.

2.1.2 Emergency Temporary Standards

Section 6(c)(1) of OSH Act authorizes the Secretary to issue an emergency temporary standard (ETS) if the Secretary determines that: (i) employees are exposed to grave danger from exposure to substances or agents determined to be toxic or physically harmful or from new hazards; and (ii) such emergency standard is necessary to protect employees from such danger.²⁶ An ETS may be issued without regard to the notice, public comment, and hearing requirements of the

APA. An ETS takes effect immediately upon publication in the *Federal Register*. The key to the issuance of an ETS is the necessity to protect employees from a grave danger.²⁷ After issuing an ETS, the Secretary must commence the procedures for promulgation of a permanent standard, which must issue within six months of the emergency standard's publication.

2.1.3 Permanent Standards

Pursuant to Section 6 of the OSH Act, the Secretary is authorized to adopt *permanent* occupational safety and health standards to serve the objectives of the OSH Act.²⁸ When setting a standard for toxic materials or harmful physical agents, Section 6(b)(5) specifically directs the Secretary to set a standard "which most adequately assures, to the extent feasible, on the basis of the best available evidence, that no employee will suffer material impairment of health or functional capacity even if such employee has regular exposure to the hazard dealt with by such standard for the period of his working life."²⁹

2.2 Requirements for Standards Adoption

The promulgation of permanent occupational safety and health standards is accomplished by adherence to procedures similar to informal rulemaking under the APA.³⁰ Upon determination that a standard should be issued, the Secretary must first publish the proposed standard in the *Federal Register*. Publication is followed by a 30-day period during which interested persons may submit written data or comments or file written objections and requests for a public hearing on the proposed standard. If a hearing is requested, the Secretary must publish in the *Federal Register* a notice setting a time and place for the hearing. Within 60 days after the period for filing comments, or, if a hearing has been timely requested, within 60 days of the hearing, the Secretary must either issue a rule promulgating a standard or determine that no such rule should be issued. The APA creates a right of action by an aggrieved person to compel unlawfully withheld or unreasonably delayed agency action.³¹ Delay in meeting the statutory timelines in Section 6 has been a pervasive feature of OSHA rulemaking.

In the case of the field sanitation standard, where rulemaking was initiated in response to a petition filed in 1972, the D.C. Circuit first held in 1977 that the statutory deadlines in Sections 6(b)(1) through 6(b)(4) are discretionary rather than mandatory, as long as the Secretary's exercise of discretion was honest and fair.³² In 1986, the D.C. Circuit decided OSHA's delay in completing work on the field sanitation standard represented an unreasonable delay.³³ In 1993, petitioners Public Citizen Health Research Group and the Paper, Allied-Industrial, Chemical & Energy

Workers International Union petitioned OSHA to update OSHA's exposure limit for hexavalent chromium (Cr(VI)). In 1997, Public Citizen petitioned the U.S. Court of Appeals for the Third Circuit to compel OSHA to complete rulemaking lowering the exposure limit to Cr(VI), but the court concluded in 1998 that there was no unreasonable delay and dismissed the lawsuit.³⁴ In 2002, Public Citizen again petitioned the court and the court granted Public Citizen's petition and ordered OSHA to proceed expeditiously with a Cr(VI) standard.³⁵

2.2.1 Significant Risk

Before OSHA promulgates a permanent occupational safety and health standard, the agency must determine that an exposure to a particular hazard could lead to material impairment of health and that exposure to the hazard poses a *significant risk* of harm which the new standard will reduce or eliminate. Although not explicitly stated in the OSH Act, the significant risk requirement arose from the Supreme Court's 1980 review of OSHA's benzene standard.³⁶ The Court said that Congress intended for OSHA to eliminate only of significant risks of harm. In 1991, the Eleventh Circuit struck down OSHA's attempt to update nearly 400 exposure limits by adopting more recent values from the American Conference of Government Industrial Hygienists.³⁷ The court said OSHA had to demonstrate that each exposure limit addressed a significant risk and was feasible to implement.³⁸

2.2.2 Economic and Technological Feasibility

In enacting the OSH Act, Congress did not intend to make employers strictly liable for unavoidable occupational hazards. Accordingly, the technological and economic feasibility of compliance with a standard is a factor the Secretary must consider. As the U.S. Supreme Court explained in *American Textile Mfrs. Inst., Inc. v. Donovan*,³⁹ OSHA's legislative history makes clear that any standard that is not economically or technologically feasible would not be "reasonably necessary or appropriate" as directed by Section 3(8) of the Act.⁴⁰ Thus, "Congress does not appear to have intended to protect employees by putting their employers out of business."⁴¹

Economic Feasibility. In analyzing economic feasibility, the Secretary has tried to determine whether a proposed standard threatens the competitive stability of an affected industry.⁴² The Supreme Court has yet to decide whether a standard that actually does threaten the long-term profitability and competitiveness of an industry would be "feasible."⁴³ In *American Textile Manufacturers*, the Supreme Court has expressly decided, however, that in promulgating a toxic material and harmful physical agent standard under Section 6(b)(5), the Secretary is not required to determine that the costs of the standard bear a reasonable

relationship to its benefits. Rather, Section 6(b)(5) directs the Secretary to issue the standard that “most adequately assures that no employee will suffer material impairment of health,” limited only by the extent to which this is economically and technologically feasible, or, in other words, capable of being done.⁴⁴

The Supreme Court left open the possibility, however, that cost-benefit analysis might be required with respect to standards promulgated under provisions other than Section 6(b)(5) of the OSH Act.⁴⁵ The Court also left open the question of whether cost-benefit balancing by the Secretary might be appropriate for deciding between issuance of several standards regulating different varieties of health and safety hazards.⁴⁶ In 1993, OSHA provided the D.C. Circuit a Supplementary Statement of Reasons⁴⁷ as a part of the court's consideration of the role of cost-benefit analysis for safety standards in *UAW v. OSHA*.⁴⁸ In the Supplementary Statement, OSHA rejected cost-benefit analysis for safety standard development.

Technological Feasibility. An OSHA standard must be technologically feasible for an employer to implement. The U.S. Court of Appeals for the District of Columbia Circuit (D.C. Circuit) has made it clear that OSHA is permitted to impose a standard that only the most technologically advanced plants have been able to meet in only some of their operations only some of the time,⁴⁹ and to require industry to implement an emerging technology, i.e. one that is “looming on today's horizon.”⁵⁰ In *United Steelworkers v. Marshall*, the D.C. Circuit stated:

“OSHA must prove a reasonable possibility that the typical firm will be able to develop and install engineering and work practice controls that can meet the PEL in most of its operations. OSHA can do so by pointing to technology that is either already in use or has been conceived and is reasonably capable of experimental refinement and distribution within the standard's deadlines ... Insufficient proof of technological feasibility for a few isolated operations within an industry, or even OSHA's concession that respirators will be necessary in a few such operations will not undermine this general presumption in favor of feasibility.”⁵¹

2.2.3 Rulemaking Analysis Requirements

The provisions of the OSH Act related to rulemaking procedures represent only one of a large number of mandatory requirements put in place since 1970 by the courts, by Congress, and by the White House Office of Management and Budget (OMB). In addition to the requirements of the OSH Act, OSHA must follow these additional requirements in promulgating any new occupational safety and health standard.

2.2.3.1 NATIONAL ENVIRONMENTAL POLICY ACT The National Environmental Policy Act (NEPA) of 1969⁵² requires all federal agencies, including OSHA, to prepare a detailed environmental impact statement in connection with major federal actions significantly affecting the quality of the human environment. The Secretary has identified the promulgation, modification, or revocation of standards that will significantly affect air, water or soil quality, plant or animal life, and the use of land or other aspects of the human environment as always constituting such major action requiring the preparation of an environmental impact statement.⁵³ However, promulgation, modification, or revocation of any safety standard, such as machine guarding requirements, safety lines, or warning signals would normally qualify for categorical exclusion from NEPA requirements. The exclusion for such standards is because “[s]afety standards promote injury avoidance by means of mechanical applications of work practices, the effects of which do not impact on air, water or soil quality, plant or animal life, the use of land or other aspects of the human environment.”⁵⁴

2.2.3.2 REGULATORY FLEXIBILITY ACT AND THE SMALL BUSINESS REGULATORY ENFORCEMENT AND FAIRNESS ACT The Regulatory Flexibility Act of 1980 requires OSHA to conduct a regulatory flexibility analysis when it proposes a rule that would have significant economic impact on a large number of small businesses, organizations, or state or local governments.⁵⁵ In 1996, Congress amended the Regulatory Flexibility Act by means of the Small Business Regulatory Enforcement and Fairness Act (SBREFA).⁵⁶ SBREFA requires OSHA to appoint a special panel of small business representatives to review all proposed rules,⁵⁷ allows courts to order OSHA to comply with any rulemaking procedure with which they fail to comply,⁵⁸ and requires that the regulatory flexibility analysis be a part a rulemaking.⁵⁹

2.2.3.3 PAPERWORK REDUCTION ACT The Paperwork Reduction Act (PRA) of 1980⁶⁰ (substantially amended in 1995⁶¹) was designed to reduce the total amount of paperwork burden the Federal Government imposes on private businesses and citizens and to maximize the practical utility of the information collected. For OSHA, the PRA mandates that OSHA engage in notice and comment rulemaking before the agency can require any entity to report information to it, or when it requires information to be reported to employees, for example, labeling requirements under the Hazard Communication Standard.⁶² OSHA has to show that any request for information (RFI) is not duplicative of an existing requirement, takes account of the difficulties that entities will have in collecting or reporting the information, and makes provision for the use of current information technology to reduce the paperwork burden on the entity who has to report, for example, by providing for electronic

reporting. The Obama Administration initiated an effort to improve implementation of the PRA.⁶³

2.2.3.4 EXECUTIVE ORDERS Beginning in 1981, a number of presidential executive orders have placed additional rule-making responsibilities on federal agencies like OSHA. President Reagan required that all draft rules from federal agencies be reviewed by the Office of Information and Regulatory Affairs (OIRA).⁶⁴ In September 1993, President Clinton issued Executive Order 12866,⁶⁵ which states that federal agencies must assess the costs and benefits of various regulatory approaches and should choose the approach that maximizes the net benefits to society.⁶⁶ Specifically, Executive Order 12866 requires OSHA to assess the costs and benefits of all proposed and final rules that are “economically significant.” In January 1996, OMB issued guidelines expanding Executive Order 12866, instructing agencies to consider alternative strategies for regulation and advising them to determine whether regulations should require different results for different segments of the regulated population.

On 18 January 2007, President George W. Bush issued Executive Order 13422⁶⁷ to strengthen President Clinton’s Executive Order 12866. Executive Order 13422 requires OMB to review significant agency guidance documents, just as it already reviews significant agency regulations. Executive Order 13422 requires agencies: (i) to give OMB advance notice of their upcoming significant guidance documents; and (ii) to provide OMB with a draft of the guidance document, an explanation of the need for the guidance, and how it would meet that need. OMB can notify the agency when additional consultation is required.⁶⁸ Unlike Executive Order 12866, Executive Order 13422 specifies that Executive Branch Regulatory Policy Officers in each cabinet level department be political appointees.

On 21 January 2011, President Obama issued Executive Order 13563,⁶⁹ reaffirming the principles of Executive Order 12866, and encouraging agencies to engage the public before issuing a notice of proposed rulemaking. Executive Order 13563 also required agencies to review its existing significant regulations periodically to determine if any should be modified or repealed in order to make an agency’s regulatory program more effective or less burdensome.

On 30 January 2017, President Trump issued Executive Order 13771 in an effort to reduce regulatory burdens and to control regulatory costs.⁷⁰ Executive Order 13771 requires that any incremental costs associated with new regulations be offset by the elimination of existing costs associated with at least two existing regulations.

2.2.3.5 INFORMATION QUALITY ACT A two-sentence rider included in a 2001 appropriations bill gave birth to what has become known as the Information Quality Act (also called the Data Quality Act).⁷¹ The Information

Quality Act directs the OMB to issue government-wide guidelines that “provide policy and procedural guidance to federal agencies for ensuring and maximizing the quality, objectivity, utility, and integrity of information (including statistical information) disseminated by federal agencies.” Following enactment of the Information Quality Act, OMB issued “Guidelines for Ensuring and Maximizing the Quality, Objectivity, Utility, and Integrity of Information Disseminated by Federal Agencies.”⁷²

Even though the text of the Information Quality Act does not explicitly provide legal rights for any third parties, the Salt Institute and the U.S. Chamber of Commerce asserted that they had the right to seek judicial review. Objecting to guidance issued by the National Institutes of Health that reducing sodium consumption would result in lower blood pressure, the Salt Institute and the Chamber sued the Federal Government. After a federal district court rejected their claim, they appealed. The U.S. Court of Appeals for the Fourth Circuit found that the Information Quality Act “does not grant the rights that appellants claim were invaded.”⁷³ No further appeal was taken.

3 EMPLOYER DUTIES UNDER THE OSH ACT

A private employer’s primary duties under the OSH Act are found in Section 5(a). Each covered employer is required to: (i) furnish to each employee employment and a place of employment that are free from recognized hazards that are causing or are likely to cause death or serious physical harm to employees; and (ii) comply with occupational safety and health standards promulgated under the OSH Act.⁷⁴

3.1 The General Duty Clause

The general duty clause of the OSH Act – the requirement that an employer has a duty of care even when there is no specific standard addressing the hazard in question – has four elements. In *National Realty & Construction Co. v. OSHRC*,⁷⁵ the D.C. Circuit required that OSHA prove that the workplace condition must present a hazard to an employee; that the condition is recognized as a hazard; that the hazard causes, or is likely to cause, death or serious physical injury to the employee; and that a feasible means exists to eliminate or materially reduce the hazard.

3.1.1 Condition or Activity Must Be a “Recognized” Hazard

The general duty clause does not apply to all hazards, but only to the hazards that are “recognized” by the employer or in the employer’s industry.⁷⁶ In *American Smelting and*

Refining Company v. OSHRC,⁷⁷ the U.S. Court of Appeals for the Eighth Circuit held that the general duty clause not only is limited to recognized hazards of types detectable only by the human senses but also encompasses hazards that can be detected by instrumentation only.

3.1.2 *Hazard Must Be Causing or Likely to Cause Death or Serious Physical Injury*

It is not necessary that there be actual injury or death to trigger a violation of the general duty clause. The purpose of the OSH Act is to prevent accidents and injuries. Thus, violation of the general duty clause arises from the existence of a statutory hazard, not from an injury-in-fact.⁷⁸ Proof that a hazard is “causing or likely to cause death or serious physical harm” does not require a mathematical showing of probability. Rather, if evidence is presented that a practice *could* result in serious physical harm from other than a freakish or utterly implausible circumstances, the Review Commission’s determination of likelihood will be accorded considerable deference by the courts.⁷⁹ Even though the term “serious violation” is defined in the OSH Act,⁸⁰ the term “serious physical harm” is defined neither in the OSH Act nor in the Secretary’s regulations, but rather in OSHA Field Operations Manual (FOM).⁸¹ Very few health cases have been brought under the General Duty Clause because the OSHRC has ruled that OSHA must show that a significant risk exists as a result of the hazard. In *Kastalon, Inc.*,⁸² a case involving exposure to a carcinogen, the OSHRC vacated a general duty clause citation because OSHA had not quantified a threshold level of hazardous exposure as required by the Supreme Court’s “Benzene” decision.⁸³

3.1.3 *Feasible Abatement Method*

Congress did not intend to make employers strictly liable for the presence of unsafe or unhealthful conditions on the job; therefore, the employer’s general duty must be an achievable one. The term “free” has been interpreted by the courts, and the Review Commission, to mean something less than the complete absence of hazards. Instead, the courts and the Review Commission have held that the employer has a duty to render the workplace free only of hazards that are preventable.⁸⁴ When technology does not exist to prevent a hazard, OSHA does not require prevention by shutting down the employer’s operation. Rather, the Secretary must be able to show that “demonstrably feasible” measures would have materially reduced the hazard.

3.2 **Employer Duties Arising from Single-Substance Health Standards**

Section 5(a)(2) of the OSH Act⁸⁵ imposes on employers a duty to comply with the occupational safety and health

standards promulgated by the Secretary. Specific safety or health standards take precedence over the general duty clause but only with respect to hazards expressly covered by the standard in question.⁸⁶ Occupational health and safety standards⁸⁷ promulgated by the Secretary pursuant to the OSH Act are often lengthy, encompassing hundreds of pages in the Code of Federal Regulations (C.F.R.). A comprehensive analysis of these standards, many of which were adopted in 1971 as interim standards under Section 6(b),⁸⁸ is beyond the scope of this chapter.⁸⁹

Previously established federal standards were used to set workplace exposure limits for approximately 400 chemical and hazardous substances. These were referred to as threshold limit values (TLVs) and were expressed in terms of milligrams of substance per cubic meter of air and/or parts of vapor or gas per million parts of air. TLVs were defined as representing conditions under which it was believed nearly all workers could be repeatedly exposed day after day for their working life without experiencing any adverse health effects.⁹⁰

Amid ongoing criticism that the exposure limits set in OSHA’s original start-up standards were out-of-date scientifically, OSHA proposed on 7 June 1988 to amend and expand the permissible exposure limits (PELs) for air contaminants covered in the 29 CFR 1910.1000 Z-Tables.⁹¹ The rule revised PELs for many of the approximately 400 contaminants that were the subject of the original standard. In addition, the air contaminants standard established PELs for substances not previously regulated by OSHA.⁹²

Immediately following promulgation, the revised air contaminants standard was challenged in court by various labor and industry groups. In 1992, the U.S. Court of Appeals for the Eleventh Circuit vacated the standard.⁹³ The Eleventh Circuit ruled that OSHA had failed to establish that *each* proposed PEL reduced a significant risk to worker health and that *each* exposure limit was technologically and economically feasible for the affected industries. OSHA decided not to appeal the decision to the U.S. Supreme Court, and returned to its original 1971 limits.⁹⁴ The Eleventh Circuit’s decision was a major blow to OSHA’s multiple-substance rulemaking approach, the proponents of which contended that OSHA could not feasibly undertake rulemaking for each regulated contaminant to the depth that the court required.

OSHA has promulgated single-substance health standards pursuant to Section 6(b). Each permanent standard adopted under Section 6(b) can be viewed as a “complete” standard since each provides not only a specific value for the level of exposure to the toxic substance but also the specifications as to monitoring, engineering controls, personal protective equipment (PPE), recordkeeping, medical surveillance, and training. What follows is a short summary of the major occupational health standards and regulations promulgated by OSHA since 1970. The reader is cautioned to consult the exact language of any particular standard in the C.F.R.

to determine the precise compliance duties set forth in the particular standard of interest.

3.2.1 Acrylonitrile

Acrylonitrile is used principally as a monomer in the manufacture of synthetic polymers, especially polyacrylonitrile that comprises acrylic fibers. Acrylonitrile is highly flammable and toxic and undergoes explosive polymerization. In September 1978, OSHA issued a permanent standard governing workplace exposure to acrylonitrile.⁹⁵ The standard sets a PEL of 2 ppm of air over an eight-hour period. The standard also sets a ceiling limit of 10 ppm for any 15-minute period and an action level (AL) of 1 ppm. Exposure above the AL triggers periodic monitoring requirements, medical surveillance, protective clothing and equipment requirements, employee information and training, and housekeeping. Skin or eye contact with the substance is prohibited.

3.2.2 Asbestos

In 1971, OSHA's first asbestos standard – derived from a national consensus standard – established an eight hour time-weighted average (TWA) PEL of 12 fiber/cc (fibers per cubic centimeter). In 1972, OSHA issued an ETS and limited the eight-hour TWA of airborne concentration of asbestos to five fibers greater than 5 µm in length per milliliter of air (the “5-fiber standard”),⁹⁶ and then provided that the PEL would decrease to 2 fiber/cc effective from 1 July 1976.⁹⁷ The D.C. Circuit upheld OSHA's new asbestos standard although the court noted that some of the questions involved in OSHA standard setting lie “on the frontiers of scientific knowledge” and that some of OSHA's “policy choices” are not “susceptible to the same type of verification or refutation by reference to the record” as adjudicatory decision-making.⁹⁸

In 1975, OSHA initiated new rulemaking proceeding and issued a proposed revised asbestos standard, but this proposal was never promulgated. Then, in 1983, OSHA issued another ETS for asbestos, this time reducing the PEL to 0.5 fiber/cc.⁹⁹ However, OSHA failed to convince the Fifth Circuit that workers faced a grave danger during the six-month lifespan of an ETS.¹⁰⁰ In 1986, OSHA issued a revised asbestos rule.¹⁰¹ The revised rule consisted of two simultaneously issued asbestos standards, one for general industry and the other for construction.¹⁰² The new rules covered asbestos and nonasbestiform tremolite, actinolite, and anthophyllite¹⁰³ and reduced the eight-hour TWA from 2 fiber/cc of air to 0.2 fiber/cc of air.

The revised standards were challenged by the Asbestos Information Association of North America (AIA) and by the Building and Construction Trades Department (BCTD) of the AFL-CIO. The unions challenged OSHA's refusal to set a lower eight-hour TWA of 0.1 fiber/cc of air. OSHA claimed

it promulgated the higher limit because the lower limit was not feasible in the entire industry, and OSHA had discretion to decide what industries should be grouped together for regulatory purposes. The D.C. Circuit disagreed and held that if OSHA was concerned with the administrative problems involved in desegregating industrial sectors for purposes of the TWA, it must make specific findings on the issue. Therefore, the D.C. Circuit remanded to OSHA on this issue, as well as on whether a short-term exposure limit (STEL) should be established.¹⁰⁴ In 1988, OSHA established an asbestos STEL of 1 fiber/cc of air over a 30 minute sampling period.¹⁰⁵ OSHA decided that the eight-hour TWA issue would require additional rulemaking, and the D.C. Circuit approved the OSHA decision.

In August 1994, OSHA published a final rule lowering the PEL for all three forms of asbestos – tremolite, anthophyllite, and actinolite – fibers to 0.1 fiber/cc of air.¹⁰⁶ The standard also required building owners to disclose the presence of asbestos in their buildings and enacted a new protective scheme requiring stricter controls for operations deemed to be more hazardous including provisions requiring building owners to inform employers of workers who may be exposed to materials within their facility presumed to contain asbestos. In addition, negative-pressure enclosures were required for workers removing “high-risk” asbestos-containing materials. The new rule affected general industry, the construction industry, and the shipyard industry.¹⁰⁷

Eighteen different legal challenges to the 1994 standard, and to revisions to the standard that were published in 1995 and 1996, were filed by various industry and labor groups, and the cases were consolidated in the Fifth Circuit. OSHA then set about settling these challenges with the various parties. In January 1995, OSHA settled with the National Brake Care Coalition, allowing the use of chemical solvent sprays to clean asbestos-lined brake and clutch assemblies. In March 1995, several roofing contractors and the Safe Buildings Alliance settled their challenges when OSHA agreed to amend the rule to allow employers to rely on information submitted by the roofers' association concerning negative exposure assessment and to allow alternative methods of compliance for installation, removal, repair and maintenance of certain roofing materials.

In settling with the AFL-CIO, OSHA agreed (among other things) to make certain modifications to the training programs prescribed for construction and shipyard workers. OSHA also agreed to require construction and shipyard employers to notify employees who are required to wear respirators under the rule that they may require their employer to provide a powered, air-purifying respirator instead of a negative-pressure one and to require that warnings about exposure be communicated to workers in an effective manner.¹⁰⁸ OSHA settled with the American Iron and Steel Institute by allowing (among other items) a “competent person” simply being “available,” not

necessarily at the worksite itself, for consultation while Class II, III, or IV work is being performed under 29 C.F.R. § 1926.1101. OSHA also allowed negative exposure assessments may be made by a competent person based on “professional judgment.” All the other challenges to the final asbestos rule were withdrawn, except for one.

In July 1997, in response to a challenge by the AIA, the Fifth Circuit vacated the construction and shipyard standards on asbestos-containing asphalt roof coatings and sealants, stating that the standards were not supported by substantial evidence.¹⁰⁹ Specifically, the court held that OSHA had not made a critical distinction between built-up roofing, which the court said “poses real risks of exposure,” and roofing sealants, which the Secretary had not seriously argued posed a significant risk of asbestos exposure. OSHA published revisions to the rule to conform to the Fifth Circuit decision¹¹⁰ and the litigation over the asbestos standard was concluded.

3.2.3 Benzene

In 1971, OSHA adopted an eight-hour PEL for benzene of 10 ppm based on a consensus standard adopted by the American National Standards Institute (ANSI) for nonmalignant health effects. In 1978, OSHA issued a new standard based on accumulating epidemiologic evidence that benzene caused leukemia, and set the PEL to the lowest feasible level industry could achieve, that is, 1 ppm.¹¹¹ The 1 ppm standard was first invalidated by the Fifth Circuit. On appeal, the U.S. Supreme Court affirmed, finding that OSHA had failed to show that exposure above the 1 ppm limit presented a “significant risk of material health impairment” to workers.¹¹² The court said that a standard, to be “reasonably necessary and appropriate” within the meaning of Section 3(8) of the OSH Act, had to materially reduce a “significant” risk to workers and that required OSHA to make a determination that risk at the current levels would be eliminated at the level in the new standard.¹¹³

In 1985, OSHA again proposed to reduce the PEL from 10 to 1 ppm.¹¹⁴ In 1987, OSHA issued a revised benzene standard.¹¹⁵ The revised standard sets the eight-hour TWA for benzene at 1 ppm, and the STEL at 5 ppm for a 15 minute sampling period.¹¹⁶ Under the revised standards, the employer must provide a medical surveillance program to monitor the health of employees exposed to benzene in amounts over the AL of 0.5 ppm for more than 30 days per year. In addition, OSHA requires a medical removal plan for temporary and permanent removal of employees showing adverse health effects from benzene exposure. The employer is required to provide six months of medical removal protection benefits to a removed employee, unless the employee has been transferred to a comparable job with benzene exposure below the AL.¹¹⁷ Union and industry petitions for judicial review of the new standard were withdrawn from the Third and D.C. Circuit Courts of Appeal in November

1987, shortly before the effective date of the new benzene standard.

3.2.4 Beryllium

The Atomic Energy Commission (AEC) was the first federal agency to develop an exposure limit for beryllium. In 1949, the AEC adopted an exposure limit of $2 \mu\text{g m}^{-3}$ for all workplaces under its jurisdiction. In 1971, OSHA adopted 425 PELs for air contaminants, including a beryllium exposure limit of $2 \mu\text{g m}^{-3}$.¹¹⁸ In 1975, OSHA proposed a beryllium standard for all industries based on studies showing that beryllium caused cancer in animals,¹¹⁹ but the rulemaking was never completed.

In 1999 and 2001, the Paper Allied-Industrial, Chemical, and Energy Workers Union, Public Citizen Health Research Group and others petitioned OSHA to issue an ETS on beryllium. OSHA denied the petitions for an ETS. In 2002, OSHA published a request for information (RFI).¹²⁰ The RFI solicited information pertinent to occupational exposure to beryllium including (i) current exposures to beryllium; (ii) the relationship between exposure to beryllium and the development of adverse health effects; (iii) exposure assessment and monitoring methods; exposure control methods; and (iv) medical surveillance.

In 2015, OSHA published a notice of proposed rulemaking.¹²¹ In 2017, OSHA published its final rule, *Occupational Exposure to Beryllium and Beryllium Compounds*.¹²² OSHA concluded that the new PEL of $0.2 \mu\text{g m}^{-3}$ reduced the significant risk that beryllium posed to health to the maximum extent that is technologically and economically feasible.¹²³ On 21 March 2017, OSHA published a delay of the effective date for the final beryllium rule to 20 May 2017¹²⁴ to be in conformance to the 20 January 2017 Presidential directive for agencies to consider further delaying the effective date for regulations across all federal agencies beyond the initial 60-day period.¹²⁵

In the final rule, OSHA issued three separate standards – for general industry, for shipyards, and for construction. Concerns were raised by the construction and shipyard sectors about ancillary procedures such as housekeeping and PPE that were required in the final rule relating to abrasive blasting. OSHA proposed to revoke the ancillary provisions applicable to construction and shipyards, but retain the new lower PEL of $0.2 \mu\text{g m}^{-3}$ and the STEL of $2.0 \mu\text{g m}^{-3}$ for these sectors.¹²⁶

3.2.5 1,3-Butadiene

Butadiene is a flammable and carcinogenic chemical used in the production of synthetic rubber. In October 1985, the Environmental Protection Agency (EPA), under the Toxic Substances Control Act (TSCA),¹²⁷ referred 1,3-butadiene to OSHA for regulatory action. In 1986, OSHA issued an

advanced notice of proposed rulemaking¹²⁸ and a proposed standard in 1990.¹²⁹ In November 1996, after a negotiated rulemaking process¹³⁰ involving OSHA, the United Steelworkers of America, the International Chemical Workers Union, the Institute of Synthetic Rubber Products, and the Olefins Panel of the Chemical Manufacturers Association, a final rule for exposure to 1,3-butadiene was published.¹³¹ The standard called for reduction in the PEL from 1000 to 1 ppm over an eight-hour period and for a STEL of 5 ppm. If exposures reach 0.5 ppm, additional engineering controls are to be implemented. The rule also covers medical surveillance, exposure monitoring, and other issues.

3.2.6 Cadmium

Cadmium is a heavy metal that has been linked to lung cancer and kidney disease. However, when OSHA first adopted a $100 \mu\text{g m}^{-3}$ eight-hour PEL for cadmium fume, and $200 \mu\text{g m}^{-3}$ for cadmium, it based those levels on noncarcinogenic health effects such as gastritis and anemia.¹³² In 1986, the International Chemical Workers Union, after OSHA rebuffed their request for an ETS, sued to compel OSHA to issue an ETS, but lost again.¹³³ The plaintiffs returned to court in 1989 because in the intervening time OSHA had not issued a proposed standard for cadmium. In February 1990, OSHA did finally publish a proposed standard.¹³⁴ OSHA asked the court for an extension of six months on the 1992 date for a final standard. The court set an August 31 deadline saying that OSHA's procrastination "has been too lengthy for us to temporize any longer."¹³⁵

OSHA issued its final rule for cadmium exposure on 14 September 1992.¹³⁶ The rule set an eight-hour PEL of $5 \mu\text{g m}^{-3}$ of air – to be achieved primarily by engineering controls – and an AL of $2.5 \mu\text{g m}^{-3}$. For operations in certain industries, OSHA found that the PEL could be feasibly be achieved through engineering and work practice controls and established a "separate engineering control airborne limit" (SECAL) of 50 and $15 \mu\text{g m}^{-3}$ depending on the industry and operation at issue.¹³⁷

After promulgation, nine different lawsuits challenging the standard were filed by various manufacturers and industry groups. By June 1993, OSHA had settled all but one of these challenges by addressing what specific measures the individual manufacturers needed to take to comply with the standard. In the remaining challenge by the Color Pigments Manufacturers Association (CPMA), who represented dry color formulators, CPMA argued that cadmium compounds used as pigments and paints should not have been given the same PEL as other cadmium compounds because they were less soluble. The court rejected CPMA's argument and held that the rulemaking record justified including cadmium pigments into the standard.¹³⁸ The court then found that OSHA lacked evidence about current exposures in the dry color formulator industry and remanded to

OSHA to restudy the technological and economic feasibility of the final cadmium standard for dry color formulators.¹³⁹

3.2.7 Cotton Dust

Exposure to cotton dust can cause byssinosis, a pneumoconiosis also known as "brown lung." In 1971, OSHA adopted an eight-hour PEL of total cotton dust of $1000 \mu\text{g m}^{-3}$ that had been issued under the Walsh-Healey Public Contracts Act. In June 1978, OSHA promulgated a new cotton dust standard that sets different PELs for yarn manufacturing, ($200 \mu\text{g m}^{-3}$) slashing and weaving ($750 \mu\text{g m}^{-3}$) and for all other processes ($500 \mu\text{g m}^{-3}$).¹⁴⁰

The cotton dust standard was challenged by the textile manufacturers on the grounds (among others) that OSHA had not adequately assessed the risk of exposure on the health of workers,¹⁴¹ but the Supreme Court rejected that argument saying "[I]t is difficult to imagine what else the agency could do to comply with this Court's decision in [Benzene]."¹⁴² The standard was also challenged as violating Section 3(8) of the OSH Act, which required that a standard be "reasonably necessary or appropriate ...", but OSHA pointed to Section 6(b)(5) "to the extent feasible" requirement as controlling. The Court agreed with OSHA stating that feasible means "capable of being done."¹⁴³ The Court also rejected the manufacturers' contention that OSHA should have done a cost-benefit analysis, by stating "cost-benefit analysis is not required by the statute because feasibility analysis is."¹⁴⁴

In 1978, OSHA also issued a companion standard regulating cotton dust in the cotton ginning industry requiring medical surveillance, work practices and respirator use, warning signs and training.¹⁴⁵ The standard was vacated by the Fifth Circuit because OSHA had not proved a significant risk of harm from exposure.¹⁴⁶

3.2.8 1,2-Dibromo-3-Chloropropane

In March of 1978, OSHA promulgated a permanent standard regarding 1,2-dibromo-3-chloropropane (DBCP), a pesticide compound used extensively in the 1970s, but later found to cause male sterility.¹⁴⁷ The DBCP standard, which became effective from 17 April 1978, sets a PEL of 1 ppb (part per billion) of air over an eight-hour period. Where engineering controls and work practices are not sufficient to reduce exposure to permissible limits, respirators may be used as a supplement in order to achieve the required protection. Protective clothing is required where eye or skin contact may occur. The standard does not apply to the use of DBCP as a pesticide, or when it is stored, transported, or distributed in sealed containers.

3.2.9 Ethylene Oxide

Ethylene oxide (EtO) has been manufactured in the United States since 1925 and is an important industrial chemical

used as an intermediate in the production of ethylene glycol and other chemicals, and as a sterilant for foods and medical supplies. It is a colorless, flammable gas or refrigerated liquid with a faintly sweet odor.

In 1971, OSHA adopted a standard for ethylene oxide, and in 1981 was petitioned to issue an ETS, but denied the petition and was sued. OSHA issued a final rule for ethylene oxide on 22 June 1984 and established an eight-hour TWA of 1 ppm, but deferred setting a STEL.¹⁴⁸ Several months later, OSHA concluded that a STEL was not warranted based on available health data. This decision was challenged in court, and the D.C. Circuit, while upholding the validity of the eight-hour TWA of 1 ppm, ruled that OSHA's decision regarding the STEL should be remanded for further consideration.¹⁴⁹ OSHA hesitated and received a reprimand from the D.C. Circuit. The court stated, "enough is enough," and warned OSHA that it was "treading at the very lip of the abyss of unreasonable delay."¹⁵⁰ Finally, in 1988, OSHA set an ethylene oxide STEL of 5 ppm for a 15 minute period.¹⁵¹ The ethylene oxide standard requires the use of engineering and work practice controls, when feasible, as well as medical surveillance, protective clothing and equipment, and employee training and warnings.¹⁵²

3.2.10 Formaldehyde

Formaldehyde is a common building block for the synthesis for more complex compounds and materials. Most formaldehyde is used in the production of polymers and other chemicals. OSHA set its original standard for formaldehyde in 1971 at an eight-hour TWA of 3 ppm, a maximum peak for 30 minutes of 10 ppm and a ceiling limit of 5 ppm for any 10-minute period.

OSHA was asked to lower the PEL for formaldehyde in 1981 but declined to issue an ETS. The United Auto Workers sued OSHA and a federal district court found OSHA's failure to issue a standard to be arbitrary and capricious and ordered OSHA to reconsider its decision.¹⁵³ On appeal, the D.C. Circuit threatened to hold OSHA in contempt if it did not issue a standard.¹⁵⁴ OSHA did issue an updated formaldehyde standard in 1987, and lowered the PEL to an eight-hour TWA of 1 ppm, revoked the peak limit and set a STEL of 2 ppm.¹⁵⁵

In 1992, the formaldehyde standard was significantly revised, among other things, to lower the existing PEL from 1 to 0.75 ppm for the eight-hour TWA.¹⁵⁶ The revisions were prompted by a decision of the D.C. Circuit to remand the 1987 standard for OSHA's reconsideration of several issues.¹⁵⁷ The standard, as amended, added medical removal protection (MRP) provisions for workers suffering from specific conditions that supplement its medical surveillance requirements. The revised standard also requires specific hazard labeling and annual employee training.

The amendments became effective from various dates in 1992.

3.2.11 Hexavalent Chromium

Hexavalent chromium (Cr(VI)) is a carcinogenic chemical used in the plating and welding operations, dyes and pigments, leather tanning, and wood preserving. The most common oxidation states of chromium are +2, +3, and +6, with +3 being the most stable. Oxidation states +1, +4, and +5 are rare. Chromium compounds of oxidation state +6 are powerful oxidants. An investigation into hexavalent chromium release into groundwater supplies of drinking water formed the plot of the motion picture *Erin Brockovich*.

In 1993, the Oil, Chemical and Atomic Workers Union petitioned OSHA to adopt a more stringent standard for hexavalent chromium based on the risk of cancer for exposed workers.¹⁵⁸ Many years went by without action by OSHA. In 2002, the U.S. Court of Appeals for the Third Circuit, in response to a petition from Public Citizen Health Research Group, ordered OSHA to promulgate a standard.¹⁵⁹

In 2006, OSHA published a final rule for exposure to hexavalent chromium and established a PEL of $5 \mu\text{g m}^{-3}$.¹⁶⁰ The standard also covers medical surveillance, exposure monitoring, respirators, training, recordkeeping, and other issues. In 2009, after several challenges were filed, a three-judge panel of the Third Circuit (including retired U.S. Supreme Court Justice Sandra Day O'Connor) upheld the PEL of $5 \mu\text{g m}^{-3}$ and all other aspects of the standard, but required OSHA to provide a fuller explanation for its employer exposure notification requirements (which OSHA limited to just those exposures which exceeded the PEL).¹⁶¹ In 2010, OSHA decided to revise its notification requirements to require employers to notify employees of the results of all exposure determinations.¹⁶²

3.2.12 Inorganic Arsenic

In May 1978, OSHA issued a permanent standard for inorganic arsenic.¹⁶³ The standard established an eight-hour TWA PEL of $10 \mu\text{g m}^{-3}$, and also specified various other requirements such as engineering and work practice controls, respiratory protection, and employee monitoring and training. The standard was challenged by industry,¹⁶⁴ and it was remanded to OSHA by the U.S. Court of Appeals for the Ninth Circuit for reconsideration in light of the Supreme Court's decision invalidating the benzene standard in *Industrial Union Dept. v. American Petroleum Institute*.¹⁶⁵ In 1983, OSHA published a final risk assessment indicating that the $10 \mu\text{g}$ limit reduced the risk of lung cancer by about 98% from the previous TLV of $500 \mu\text{g}$ and that such a reduction satisfies the U.S. Supreme Court's "significant risk" test.¹⁶⁶ The Ninth Circuit later upheld the standard

as supported by substantial evidence of a significant health risk.¹⁶⁷ The standard applies to all occupational exposures to inorganic arsenic, except employee exposures in agriculture or industries involving pesticide application, the treatment of wood with preservatives, or the use of wood preserved with arsenic.

3.2.13 Lead

In 1971, OSHA adopted a national consensus standard of an eight-hour PEL of $200 \mu\text{g m}^{-3}$ of lead. In 1975, OSHA issued a proposed standard that contained an eight-hour PEL of $100 \mu\text{g m}^{-3}$ and provisions for monitoring, training, medical surveillance, and MRP.¹⁶⁸

In November 1978, OSHA issued a permanent standard regulating occupational exposure to lead.¹⁶⁹ The final standard set an eight-hour PEL of $50 \mu\text{g m}^{-3}$ of air – one-half of what OSHA had proposed. The standard required, among other things, the use of respirators and protective work clothing and equipment whenever lead exposure exceeds the PEL, compliance with vigorous rules on housekeeping and hygiene, biological monitoring, and medical surveillance. The standard also required a controversial MRP provision pursuant to which certain workers must be removed from the exposed workplace without loss of earnings, benefits, or seniority for at least 18 months. The standard further required employers to create safety and health training programs for their workers exposed to lead; to keep detailed records on environmental (workplace) monitoring, biological monitoring, and medical surveillance; and to make those records available to workers, certain of their representatives, and the government.

The lead standard was challenged by the industry and by labor and the D.C. Circuit stayed compliance with the PEL. The D.C. Circuit rejected most challenges and upheld the standard (including the PEL and MRP provisions) as to 10 industries, including primary and secondary lead smelting and battery manufacturing.¹⁷⁰ However, with respect to 39 other industries, the court held that OSHA failed to present substantial evidence or adequate reasons to support the feasibility of the standard for those industries and thus remanded to the Secretary for reconsideration of the technological and economic feasibility of the standard as to those industries.¹⁷¹

OSHA subsequently amended the standard to require employers that cannot reach the PEL to reduce exposure only to the lowest feasible level. OSHA also found that the standard of $50 \mu\text{g m}^{-3}$ of air was technologically and economically feasible for all but nine of the remand industries.¹⁷² OSHA continued to gather information as to these nine industry sectors, and on 11 July 1989, OSHA issued a statement of reasons as to why the $50 \mu\text{g}$ standard was feasible through engineering controls for eight of the remaining nine sectors.¹⁷³ For the ninth industry sector, nonferrous

foundries, OSHA found the $50 \mu\text{g}$ standard was technologically, but not economically, feasible for small foundries, and therefore promulgated a bifurcated standard for large and small nonferrous foundries.¹⁷⁴

In March 1990, the D.C. Circuit upheld the standard with respect to all but six industries,¹⁷⁵ and finally, on 19 July 1991, the court lifted its existing stay of the standard's engineering and work practice control requirements with respect to all of those six industries, except the brass and bronze ingot manufacturing industry.¹⁷⁶ In a notice published in October 1995, OSHA set the final lead standard for brass and bronze ingot manufacturers at an eight-hour TWA of $75 \mu\text{g m}^{-3}$ of air, reflecting an agreement reached between the agency and the two trade associations that finally settled all litigation arising out of the 1978 standard. These employers had six years to meet the $75 \mu\text{g}$ limit.¹⁷⁷

In May 1993, in response to the Housing and Community Development Act of 1992,¹⁷⁸ OSHA published an interim final rule intended to protect construction workers who are exposed to lead on the job. The interim rule reduced the PEL for lead in construction from an eight-hour TWA of $200 \mu\text{g m}^{-3}$ of air to $50 \mu\text{g}$, and it established a $30 \mu\text{g}$ threshold beyond which exposed workers are to be provided additional protections, including medical surveillance. The interim rule is to remain in effect until OSHA promulgates a final rule on the subject.¹⁷⁹

The U.S. Environmental Protection Agency has published a final rule setting national training, certification, and accreditation standards for people conducting lead-based paint inspections, risk assessments, and abatement in certain houses and child-occupied facilities. The rule, which EPA was required to develop under Sections 402 and 404 of the Toxic Substances Control Act of 1976, includes a model state program by which states can seek permission from EPA to administer their own training, certification, and abatement programs. The agency omitted, however, controversial provisions that had targeted lead-based paint activities in commercial and public buildings.¹⁸⁰

In 2016, OSHA announced in its Spring Regulatory Agenda that it would start pre-rule activities to consider the blood lead level (BLL) for medical removal.¹⁸¹ OSHA stated "the lead standards for general industry and construction are based on lead toxicity information that is over 35 years old. OSHA lead standards allow for the return of the employee to former job status at a $\text{BLL} < 40 \mu\text{g dL}^{-1}$. The U.S. Department of Health and Human Services, Council of State and Territorial Epidemiologists (CSTE), and California's Medical Management recommends that BLLs among all adults be reduced to $< 10 \mu\text{g dL}^{-1}$." OSHA planned to publish an Advanced Notice of Proposed Rulemaking later in 2016 to seek input from the public to identify possible areas of the lead standards for revision to improve protection of workers in industries and occupations where preventable exposure to lead continues to occur.

3.2.14 Methylene Chloride

Methylene chloride, or dichloromethane, is a colorless, volatile liquid with a moderately sweet aroma. It is widely used as a solvent, the general view being that it is one of the less harmful of the chlorocarbons, and it is miscible with most organic solvents.

In 1971, OSHA adopted the Walsh–Healey Act eight-hour TWA PEL of 500 ppm, a ceiling limit of 1000 ppm and a maximum peak above the ceiling or 2000 ppm for three minutes in a two-hour period. In 1985, evidence began to emerge that methylene chloride was linked to an increased risk of cancer, heart attack, and nerve damage. The United Auto Workers petitioned for an ETS, but OSHA denied the petition.¹⁸² In 1992, OSHA proposed to reduce the eight-hour TWA PEL to 25 ppm (with an AL of 12.5 ppm) and to establish a STEL of 125 ppm averaged over 15 minutes.¹⁸³

On 10 January 1997, a final OSHA standard for exposure to methylene chloride was published after considerable debate about the cancer risk posed by methylene chloride.¹⁸⁴ The final rule was to be phased in over 3 years. Other than the reduction of the PEL to 25 ppm, other provisions required employers to provide training, medical surveillance, and exposure monitoring. On 22 September 1998, OSHA amended its methylene chloride standard by adding a provision for temporary MRP benefits for employees who are removed or transferred to another job because of a medical determination that exposure to methylene chloride may contribute to the worker's existing skin, heart, liver, or neurological disease.¹⁸⁵

The final rule on methylene chloride was challenged by the United Auto Workers (UAW), Eastman Kodak, and the Halogenated Solvents Industry Alliance (HSIA) and several individual companies. All cases were consolidated in the D.C. Circuit.¹⁸⁶ The trade association's suit sought review of the standard under the Small Business Regulatory Enforcement Fairness Act of 1996.¹⁸⁷ The UAW and the HSIA came to agreement with OSHA on the issues in dispute¹⁸⁸ and OSHA sought public comment on their Motion for Reconsideration.¹⁸⁹ In response to these challenges, OSHA revised its final rule to extend dates for certain employers to come into compliance with engineering controls and respiratory protection and to provide MRP.¹⁹⁰

OSHA also faced opposition over the standard from the American College of Occupational and Environmental Medicine (ACOEM). The physicians' group sought a reopening of the methylene chloride rulemaking, arguing that allowing required medical surveillance to be conducted by health care professionals other than licensed doctors was a "radical departure" from other OSHA standards and put employees at risk of incorrect diagnosis and treatment, but OSHA denied ACOEM's petition.

In 2007, OSHA announced a review of the Methylene Chloride Standard¹⁹¹ in accordance with the requirements

of the Regulatory Flexibility Act and Section 5 of Executive Order 12866.¹⁹² The review considers the continued need for the rule; whether the rule overlaps, duplicates, or conflicts with other federal, state, or local regulations; and the degree to which technology, economic conditions, or other factors may have changed since the rule was evaluated.

3.2.15 Methylenedianiline

In 1985, EPA prompted OSHA to examine what regulatory action OSHA should take to protect employees from methylenedianiline.¹⁹³ OSHA impaneled a negotiated rulemaking advisory committee to develop a permanent standard¹⁹⁴ and the committee's recommendations, covering general industry and construction, were published in 1987.¹⁹⁵ In 1989, OSHA proposed a methylenedianiline rule¹⁹⁶ and adopted a final rule in 1992.¹⁹⁷ No legal challenges to the final rule were filed.

3.2.16 Noise

In science and engineering, noise is an undesirable component that obscures a desired signal. For occupational health, noise is unwanted, and potentially harmful, sound. Sound is generally known as the vibrational transmission of mechanical energy that propagates through matter as a wave that is audibly perceived by living organisms by the sense of hearing. For humans, hearing is limited to frequencies between about 20 Hz (Hertz) and 20 kHz, with the upper limit generally decreasing with age. Since the human ear does not have a flat spectral response, sound pressure levels are often "frequency weighted" so that the measured level will match perceived levels more closely. The International Electrotechnical Commission (IEC) has defined several weighting schemes. A-weighting attempts to match the response of the human ear to noise and A-weighted sound pressure levels are labeled dBA. C-weighting is used to measure peak levels.

OSHA's standard for occupational exposure to noise specifies a maximum eight-hour TWA PEL of 90 dB (decibels on the A-weighted scale).¹⁹⁸ Employers are required to use feasible engineering or administrative controls, or a combination of both, whenever employee exposure to noise in the workplace exceeds the PEL. PPE may be used to supplement the engineering and administrative controls where such controls are not able to reduce the employee exposure to within the permissible limit.

In 1983, OSHA issued a final hearing conservation amendment to the noise standard.¹⁹⁹ Under the amendment, the employer must establish a baseline audiometric measurement from which it must compare subsequent annual measurements to determine if a shift in hearing capability has occurred for any employees whose exposures equal or exceed an eight-hour TWA of 85 dBA.²⁰⁰

To determine if the exposure equals, or exceeds this AL, employers are required to use personal sampling of noise where factors, such as high worker mobility or significant variation in sound levels, make area monitoring generally inappropriate.²⁰¹ The employer must make hearing protectors available to all employees whose exposure equals or exceeds an eight-hour TWA of 85 dBA and must ensure that hearing protectors are worn by any employee who has experienced a shift in hearing capability.²⁰² The U.S. Court of Appeals for the Fourth Circuit upheld the amendment.²⁰³

In 1987, OSHA sought public comments as to what extent the information collection requirements of the noise standard could be reduced without lessening the standard's effectiveness in preventing hearing loss. OSHA later announced, however, that no such changes would be made.²⁰⁴ On 1 July 2002, OSHA issued a final rule revising the criteria for recording hearing loss cases in several ways. In the final rule, OSHA required the recording of Standard Threshold Shifts (10 dB shifts in hearing acuity) that have resulted in a total 25 dB level of hearing above audiometric zero, averaged over the frequencies at 2000, 3000, and 4000 Hz, beginning in the year 2003.²⁰⁵

3.2.17 Respirable Crystalline Silica

The historical OSHA PEL for general industry is based on a formula recommended by the American Conference of Governmental Industrial Hygienists ("ACGIH"), first in a "Notice of Intended Change" in 1968, and then finally adopted in 1972.²⁰⁶ The historical PEL for construction and maritime, which was derived from ACGIH's 1962 TLV, was based on particle counting technology, which is now considered obsolete. NIOSH reviewed silica hazards in 2002 and recommended an exposure limit of 0.05 mg m^{-3} to reduce the risk of developing silicosis, lung cancer, and other adverse health effects.²⁰⁷

In 2006, the ACGIH revised their TLV, adopting an exposure limit of 0.025 mg m^{-3} for respirable crystalline silica. Both industry and worker groups have recognized that a new comprehensive standard for crystalline silica was needed to provide for exposure monitoring, medical surveillance, and worker training. The legal basis for developing such a proposed rule is a preliminary determination that workers are exposed to a significant risk of silicosis and other serious disease and that rulemaking is needed to reduce the risk. A standard for occupational exposure to crystalline silica appeared at the top of OSHA's Regulatory Agenda for many years.

On 12 September 2013, OSHA published a proposed rule, *Occupational Exposure to Respirable Crystalline Silica*,²⁰⁸ and published a final rule on 25 March 2016.²⁰⁹ OSHA issued two separate standards – one for general industry and maritime, and one for construction. The final establishes a new eight-hour TWA PEL of $50 \mu\text{g m}^{-3}$, and an

AL of $25 \mu\text{g m}^{-3}$ in all industries covered by the rule. It includes other provisions to protect employees such as requirements for exposure assessment, detailed methods for controlling exposure, respiratory protection, medical surveillance, hazard communication, and recordkeeping. On 19 October 2017, OSHA issued guidance for enforcing 29 C.F.R. Section 1926.1153, *Respirable Crystalline Silica*.²¹⁰

OSHA's *Respirable Crystalline Silica* final rule was legally challenged by industry and labor. The court rejected all five of industry's challenges.²¹¹ The North American Building Trades Union petitioned for review of two parts of the final rule: (i) the requirement that medical surveillance for construction workers be provided only if the employee has to wear a respirator for 30 days for one employer in a one-year period; and (ii) the absence of MRPs from the final rule. The court ruled that OSHA has failed to explain adequately its decision to omit MRPs from the rule and remanded that issue for further consideration by OSHA.²¹²

3.2.18 Vinyl Chloride

Vinyl chloride is used to make polyvinyl chloride (PVC). PVC is used to make a variety of plastic products, including pipes, wire and cable coatings, and packaging materials. A link between vinyl chloride exposure and angiosarcoma of the liver in rubber industry workers was published in the early 1970s (3). On 5 April 1974, OSHA promulgated an emergency standard for vinyl chloride and a permanent standard on 1 October 1974 that was shown great deference by the Second Circuit when it was challenged.²¹³ The rule set an eight-hour TWA PEL for vinyl chloride at 1 ppm.²¹⁴

Generally, the standard requires feasible engineering and work practice controls to reduce exposure below the permissible level wherever possible. Specifically, the employer is required to provide respiratory protection and protective garments for employees.²¹⁵ The employer must provide, for each employee engaged in vinyl chloride operation, a training program "relating to the hazards of vinyl chloride and precautions for its safe use."²¹⁶ Entrances to regulated areas must be posted with signs warning of the cancer-suspect nature of vinyl chloride.²¹⁷ Moreover, the employer must institute a program of medical surveillance for each employee exposed to vinyl chloride in excess of the AL, without regard for use of respirators.²¹⁸ Finally, the employer must maintain accurate medical records to measure employee exposure to vinyl chloride.²¹⁹

3.3 Employer Duties Arising from Generic Health Standards

3.3.1 Bloodborne Pathogens

In 1991, OSHA promulgated a standard aimed at controlling occupational exposure to infectious agents that can be

transmitted through contact with blood or other potentially infectious materials, that is, “bloodborne pathogens,” such as the human immunodeficiency virus (HIV) and the hepatitis B virus (HBV).²²⁰ Application of the standard is triggered by an employee’s reasonably anticipated contact with blood or other potentially infectious materials (defined by a list of specific body tissues and fluids). Affected employers must develop written exposure control plans that identify exposed employees and tailor the standard’s work practices and engineering controls to the particular work environment. Central to the standard is the mandatory use of “universal precautions,” a practice by which all blood and other potentially infectious materials are handled *as if* they are contaminated with bloodborne pathogens.²²¹ The standard has stringent requirements regarding the disposal of wastes and used needles, the use of PPE, employee training, and labels and warnings. Employers must offer exposed employees the HBV vaccine free of charge, and must also provide free post-exposure medical evaluation and testing. In addition, extensive recordkeeping, including documented follow-up of exposure incidents, is mandated by the standard. The standard is aimed at protecting over 5 million workers, many of whom are outside the health care industry.

The bloodborne pathogens standard was challenged by several health care industry groups, but the U.S. Court of Appeals for the Seventh Circuit upheld the standard in January 1993.²²² However, the court did agree with Home Health Services and Staffing Association, Inc. that OSHA needed to explain better the compliance obligations of home health care employers who do not control their worksites, and the court remanded the rule to the agency for clarification of its application to those employers.²²³

The U.S. Supreme Court declined to review the Seventh Circuit’s ruling, thus ending the challenge by the American Dental Association (ADA). The ADA had argued that dentists and their employees generally were exposed less to blood than other health care providers and that the standard – by its use of the term “ensure” when referring to employer’s obligation to ensure worker compliance – was imposing a form of strict liability. The court disagreed with the ADA and said that the employer was required to only take “all reasonable steps to prevent his employees from violating the rule but if despite these measures the employee violates the rule, the employer is off the hook.”²²⁴

3.3.2 Carcinogens

OSHA excluded the ACGIH’ list of carcinogenic chemicals from its 1971 interim standards promulgation package. After approximately 1 year of consulting with NIOSH and receiving data and commentary from interested groups, the Secretary promulgated ETSs on 3 May 1973 for a list of 14 chemicals found to be carcinogenic. Permanent standards for the 14 carcinogens²²⁵ were issued on 29

January 1974.²²⁶ In *Synthetic Organic Chemical Manufacturers Ass’n v. Brennan*,²²⁷ the Third Circuit upheld all the carcinogens standards except one. The standard for 4,4’-methylene bis(2-chloraniline) (MOCA) was subsequently revoked by OSHA.²²⁸

In January 1980, OSHA promulgated a generic carcinogen policy for identifying, classifying, and regulating workplace carcinogens.²²⁹ The policy includes a process for screening chemicals and establishing priorities for rulemaking. It places substances in two categories: potential carcinogenicity and suggestive potential. Model permanent and ETSs are included. Lists of carcinogen candidates were to be published by OSHA periodically pursuant to the policy, but the listing requirements have been administratively stayed since 1983.²³⁰

3.3.3 Coke Oven Emissions

In October 1976, the Secretary issued a permanent standard regulating workers’ exposure to coke oven emissions. The standard defines coke oven emissions as the benzene-soluble fraction of total particulate matter present during the destructive distillation of coal for the production of coke. It limits exposure to 150 µg of benzene-soluble fraction of total particulate matter per cubic meter of air averaged over an eight-hour period.²³¹

The standard mandates specific engineering controls and work practices that were to be in use by 20 January 1980. For example, the employer is required to provide protective clothing and equipment,²³² hygienic changing rooms,²³³ and lunchrooms with a filtered air supply.²³⁴ The employer must ensure that in the regulated area food and beverages are not consumed, smoking is prohibited, and cosmetics are not applied.²³⁵ The employer must provide training to employees regarding the dangers of the regulated area.²³⁶ In addition, the employer must post precautionary signs and labels.²³⁷ The employer must institute a medical surveillance program for all those employed in the regulated area at least 30 days per year.²³⁸ The employer also must maintain accurate medical records to measure employee exposure to coke oven emissions.²³⁹ The steel industry challenged the validity of the coke oven standard, but it was upheld by the Third Circuit in *American Iron and Steel Institute v. OSHA*.²⁴⁰

3.3.4 Hazard Communication

In an attempt to address multiple chemical hazards at one time, OSHA issued a hazard communication standard in November 1983.²⁴¹ The standard required manufacturers to establish a method to communicate the hazards of chemicals to those who worked with them, mainly through the use of labels on containers, materials safety data sheets (later revised to safety data sheets or SDSs), and training programs.²⁴² The Third Circuit generally

upheld the standard but remanded it to OSHA on several issues, including whether the scope of the standard should be expanded beyond the manufacturing sector.²⁴³ OSHA reopened the record to consider the scope issue, but the agency was reprimanded by the court for doing so and got a 60-day deadline to answer the court's remand order.²⁴⁴ On 24 August 1987, OSHA expanded the scope of the standard to encompass nonmanufacturing employment.²⁴⁵ The Third Circuit denied subsequent petitions for review of the expanded standard.²⁴⁶ The Hazard Communication Standard now applies to all industries, but before the standard's scope was finalized, OMB took exception to the requirement that SDSs be exchanged at multiemployer worksites based on the authority granted to them by the PRA. OMB's authority to interfere in the OSHA standard was challenged in court and the Third Circuit upheld the challenge.²⁴⁷ The Supreme Court affirmed,²⁴⁸ but Congress nullified the Court's holding when it amended the PRA in 1995.²⁴⁹

In 1994, while litigation was occurring, OSHA published a final rule clarifying the 1987 hazard communication standard. The clarifications and amendments include (i) certain exemptions from labeling requirements and other provisions in the standard; (ii) parts of the provision for a written hazard communication program; (iii) the duties of distributors, manufacturers and importers of hazardous chemicals to provide SDSs; and (iv) provisions regarding the content of the SDSs.²⁵⁰

In 1990, OSHA promulgated a separate hazard communication standard for laboratories. This laboratory standard superseded the hazard communication standard along with several other health standards for research and analytical type labs if the laboratory implemented a chemical hygiene plan that includes training, medicals, monitoring, hazard identification, and recordkeeping.²⁵¹ In 1994, OSHA promulgated another final hazard communication rule requiring employers who receive shipments of hazardous materials to leave any existing placards or warning labels on the shipments until the materials are removed from their containers.²⁵²

In 2006, OSHA published an advanced notice of proposed rulemaking, indicating it would update the hazard communication standard to be consistent with the internationally recognized *Globally Harmonized System (GHS) for the Labeling of Chemicals*.²⁵³ At the same time, OSHA made available on its Web site a GHS information topic page.²⁵⁴ In 2009, OSHA published a notice of proposed rulemaking²⁵⁵ and a notice of correction to correct misprints in the proposal.²⁵⁶

In 2012, OSHA promulgated a final rule. The final rule included: (i) revised criteria for classification of chemical hazards; (ii) revised labeling provisions that include requirements for use of standardized signal words, pictograms, hazard statements, and precautionary statements; (iii) a specified format for SDSs, and related revisions to definitions of

terms used in the Hazard Communication Standard; and (iv) requirements for employee training on labels and SDSs.²⁵⁷

3.3.5 Hazardous Waste Operations

Pursuant to the Superfund Amendments and Reauthorization Act (SARA) of 1986, OSHA issued an interim standard in 1986 on hazardous waste operations.²⁵⁸ In 1989, OSHA issued a final standard on hazardous waste operations and emergency response ("HAZWOPER").²⁵⁹ The HAZWOPER standard for the construction industry (29 CFR 1926.65) is identical to 29 CFR 1910.120 for general industry. The final standard was challenged by the AFL-CIO on the sixtieth day following issuance, but the D.C. Circuit, relying on Section 6(5)(b), dismissed the petition for review based on lack of timeliness in filing.²⁶⁰

In 1987, Congress amended the Superfund law to require OSHA to add provisions to the HAZWOPER standard to establish certification of training given to emergency responders.²⁶¹ OSHA proposed certification rules in 1990.²⁶² After developing nonmandatory guidelines to address training criteria for hazardous waste workers, and observing the private sector accreditation procedures, OSHA withdrew the accreditation of training programs for hazardous waste operations from their Regulatory Agenda on 9 December 2002.²⁶³ OSHA's current position is summarized on its Web site as follows:

The Hazardous Waste Operations and Emergency Response standard (HAZWOPER), 29 C.F.R. § 1910.120, states in paragraph (e)(5) that "Trainers shall be qualified to instruct employees about the subject matter that is being presented in training". In addition, 29 C.F.R. 1910.120(e)(5) explains that the qualifications of the instructors may be shown by academic degrees, completed training courses and/or work experience. At this time, OSHA does not have any specific requirements to certify an instructor. The subjects that trainers should be able to convey to employees at hazardous waste operations who need training are summarized in paragraphs (e), (p) and (q) of the HAZWOPER standard.²⁶⁴

3.3.6 Respiratory Protection

In January 1998, OSHA published a revised respiratory protection rule.²⁶⁵ The revised respiratory protection standard applies to General Industry (Part 1910), Shipyards (Part 1915), Marine Terminals (Part 1917), Longshoring (Part 1918), and Construction (Part 1926). Paragraph (a)(1) establishes OSHA's hierarchy of controls by requiring the use of feasible engineering controls as the primary means to control air contaminants. Respirators are required when "effective engineering controls are not feasible, or while they are being instituted." Paragraph (a)(2) requires employers to provide employees with respirators that are "applicable and suitable"

for the purpose intended “when such equipment is necessary to protect the health of the employee.”

If respirators are necessary to protect the health of the employer or respirators are required by the employer, the standard requires employers to develop and implement a written respiratory protection program with worksite-specific procedures. Such programs are to list all circumstances in the employees' working environment for which respirators are necessary to protect their health and are to contain workplace-specific procedures for respiratory protection. OSHA estimated that about five million workers at more than a million workplaces would be protected by the final standard that is considered a “building block standard” because future standards that call for respirator use in working with specific toxic substances will refer back to the final respiratory protection rule. Importantly, the respiratory protection standard provides that fit testing is required prior to initial use, whenever a different respirator facepiece is used, and at least annually thereafter. An additional fit test is required whenever the employee reports, or the employer or health care provider makes visual observations of, changes in the employee's physical condition that could affect respirator fit (e.g. facial scarring, dental changes, cosmetic surgery, or an obvious change in body weight).

The 1998 revised respiratory protection standard was challenged by several industry groups and upheld in its entirety by the U.S. Court of Appeals for the Eleventh Circuit.²⁶⁶ In 1998, when the new respiratory protection standard was adopted for all other industries, OSHA redesignated the previous §1910.134 as §1910.139, Respiratory Protection for *Mycobacterium tuberculosis* (TB). OSHA anticipated that §1910.139 would be replaced shortly by a final rule for TB since they had published a notice of a proposed TB standard in late 1997,²⁶⁷ which would have required that respirators be used to protect health care workers from TB exposure. When the tuberculosis infection rates decreased significantly in the late 1990s, OSHA abandoned its plans for a TB rule. In 2003, OSHA published a final rule revoking §1910.139 and terminated its TB rulemaking.²⁶⁸

The effect on the healthcare industry was to place them under a duty to comply with §1910.134, which requires initial and annual fit testing for all respirator wearers. The health care industry objected to the additional burden of performing the more frequent fit tests for respirators worn to protect against TB. In 2004, an appropriations rider was added to OSHA's budget preventing it from using funds appropriated in fiscal year (FY) 2005 (beginning on 1 October 2004) to enforce the annual fit testing requirement, when the respirators were worn solely to protect against occupational exposure to TB. In FY 2006 and FY 2007, the same budget language was enacted and OSHA refrained from inspecting or citing employers for requirement to do annual fit testing of respirators for occupational exposure

to tuberculosis. In the Consolidated Appropriations Act of 2008, no appropriations rider appeared to limit OSHA's enforcement of the respiratory protection standard in health care institutions.

In 2006, OSHA revised its existing Respiratory Protection Standard to add definitions and requirements for Assigned Protection Factors (APFs) and Maximum Use Concentrations (MUCs).²⁶⁹ The revisions also supersede the respirator selection provisions of existing substance-specific standards with these new APFs (except for the respirator selection provisions of the 1,3-Butadiene Standard). The final rule became effective from 22 November 2006.

3.4 Employer Duties Arising from Selected Safety Standards

3.4.1 Confined Spaces

Beginning in 1975,²⁷⁰ and extending through 1979²⁷¹ and 1980,²⁷² OSHA worked on developing a standard on confined spaces for general industry and for the construction industry. In 1989, OSHA issued a proposed rule on confined spaces, but for general industry only.²⁷³ In January 1993, OSHA published a final rule on permit-required confined spaces for general industry, requiring employers to establish permit systems and training programs for workers.²⁷⁴ The standard was designed to protect workers who enter storage tanks and other confined spaces nearly five million times each year from toxic atmospheres, lack of oxygen and other hazards. The rule requires employers to identify all confined spaces at their worksites that could pose a hazard and to establish policies preventing unauthorized entry into them. It also requires employers to provide trained rescue teams, although off-site emergency response personnel can be used to satisfy this requirement.

Following the settlement of several legal challenges that had been consolidated in the Eleventh Circuit, OSHA issued an amendment to the final confined spaces rule in December 1998 that provided for greater participation by employees in the permitting system, allowed for employees to observe testing or monitoring of confined spaces, and clarified employers' duties in providing the rescue program.²⁷⁵ OSHA also promulgated a separate final confined spaces standard for the shipyard industry, which requires shipyard employers to designate “competent” individuals to make initial evaluations of confined spaces, to ensure that detailed records of atmospheric testing of confined spaces are kept, and to label unsafe confined spaces.²⁷⁶ In 2007, OSHA proposed a rule for confined spaces in the construction industry and addressed issues that are unique to construction such as higher employee turnover rates, changing worksites, and the multi-employer business model that is common to construction sites.²⁷⁷ In 2015, OSHA promulgated a final rule for confined spaces in construction.²⁷⁸

3.4.2 Personal Protective Equipment

In 1971, OSHA adopted a national consensus standard on PPE. In April 1994, OSHA published a final rule setting out employers' requirements to provide their workers with protective equipment, including gloves, goggles, helmets and safety shoes.²⁷⁹ The rule was intended to provide improved eye, face, hand, head, and foot protection for nearly 11.7 million employees. In October 1994, OSHA established a policy on the issue of payment for required PPE and stated that for all PPE standards the employer must both provide and pay for the required PPE, except in limited situations.²⁸⁰

In October 1997, the Review Commission declined to accept OSHA's interpretation in its memorandum as applied to 29 C.F.R. §1910.132(a) because the Review Commission believed the memorandum was inconsistent with OSHA's previous position on the issue and vacated OSHA's citation to the employer for failing to pay for metatarsal foot protection.²⁸¹ Rather than appealing this decision, OSHA decided to revise its final rule to make clear that it intended for employers to pay for the required equipment.

In 1999, the OSHA published a proposal to require employers to pay for all protective equipment, including PPE, with explicit exceptions for certain safety shoes, prescription safety eyewear, and logging boots.²⁸² After an initial notice and comment period, an informal rulemaking hearing, a second notice and comment period on specific issues, and a filing of a lawsuit by labor unions in 2007 to force OSHA to issue a final rule, OSHA did finally issue its final PPE rule *Employer Payment for Personal Protective Equipment*.²⁸³

3.5 Other Standards Not Promulgated by OSHA or Nullified by Congress

OSHA has proposed standards in the past that have not been promulgated or, in the case of Ergonomics, promulgated by OSHA but subsequently nullified by Congress. OSHA continues to develop safety and health standards. For an up-to-date list of OSHA regulatory and deregulatory actions, the reader is encouraged to go to the *Unified Agenda of Federal Regulatory and Deregulatory Actions* at www.reginfo.gov.

3.5.1 Combustible Dust

In 2006, the U.S. Chemical Safety and Hazard Investigation Board (CSB) completed a study of combustible dust hazards and identified 281 combustible dust incidents between 1980 and 2005 that killed 119 workers and injured 718. The CSB recommended that OSHA pursue rulemaking to protect further loss of life from incidents of combustible dust. On 7 February 2008, a sugar refinery owned by Imperial Sugar in Port Wentworth, GA sustained a dust explosion, killing 13

people and injuring 42 others. The CSB report and the Imperial Sugar Refinery explosion resulted in OSHA's decision to consider rulemaking to develop a combustible dust standard for general industry.

There are a number of existing OSHA standards that address prevention of combustible dust explosion risk such as (i) 1910.22 Housekeeping; (ii) 1910.38 Emergency Action Plans; (iii) 1910.94 Ventilation; (iv) 1910.107 Spray Finishing; (v) 1910.146 Permit Required Confined Spaces; (vi) 1910.269 Electric Power Generation; (vii) Transmission and Distribution (coal handling); (viii) 1910.272 Grain Handling Facilities; and (ix) 1910.307 Hazard Communication. Despite these standards, OSHA lacks a comprehensive standard that addresses combustible dust hazards. However, OSHA has published a Safety and Health Information Bulletin on the topic²⁸⁴ that has implemented a Combustible Dust National Emphasis Program (NEP)²⁸⁵ and has conducting stakeholder meetings.²⁸⁶

3.5.2 Diacetyl

Health hazard evaluations performed by the NIOSH of workplaces using "butter flavorings" used in the microwave popcorn industry have implicated diacetyl as a cause of a rare, but severe, lung disease, called *bronchiolitis obliterans* (4). Severe obstructive airway disease has been observed not only in the microwave popcorn industry but also in other food flavoring manufacturing plants. Diacetyl is a chemical that is found as a natural constituent of butter as well as a chemical added as a flavoring to impart a "buttery" taste to foods.

On 26 July 2007, the United Food and Commercial Workers International Union (UFCW) and the International Brotherhood of Teamsters (IBT) filed a petition requesting that OSHA issue an ETS for all employees exposed to diacetyl. OSHA denied the petition on 25 September 2007. However, in July 2007, OSHA announced a National Special Emphasis Program for Microwave Processing Plants.²⁸⁷ In 2007, OSHA also published a Safety and Health Information Bulletin on the topic²⁸⁸ and issued Hazard Communication guidance for food flavorings containing diacetyl.²⁸⁹ In October 2007, OSHA also held a stakeholder meeting to consider Section 6(b) rulemaking for diacetyl and planned to set up a panel to assess the impact of diacetyl on small business in the face of congressional legislation to force OSHA to issue an interim PEL within 90 days and a final PEL within two years after enactment.²⁹⁰ OSHA published an advanced notice of proposed rulemaking on 21 January 2009,²⁹¹ but withdrew an advance notice of proposed rulemaking on 17 March 2009.²⁹²

3.5.3 Ergonomics

In 1991, various labor organizations petitioned OSHA to issue an ETS to address musculoskeletal disorders

among workers performing repetitive job tasks.²⁹³ OSHA declined to issue an ETS but did publish an advance notice of proposed rulemaking seeking information from the public for a permanent standard.²⁹⁴ OSHA promulgated a proposed Ergonomics Program rule on 23 November 1999,²⁹⁵ and a final rule on 14 November 2000.²⁹⁶ OSHA's Ergonomics Program standard rulemaking proved to be its most controversial. A provision requiring workplace removal protection – similar to MRP found in toxic chemical standards – was “particularly controversial (5).”

In 2001, OSHA's ergonomics standard became the first standard to be “nullified” by Congress by means of a resolution of disapproval under the Congressional Review of Agency Rulemaking Act (CRA).²⁹⁷ The resolution of disapproval under the CRA was signed into law by President Bush on 20 March 2000, and OSHA's Ergonomics Program Standard ceased to have any legal effect.²⁹⁸ OSHA has issued guidance documents to address ergonomic issues industry by industry.²⁹⁹ OSHA has issued ergonomic guidelines for meatpacking, nursing homes, retail grocery stores, poultry processing, and shipyards.³⁰⁰

The question arises whether OSHA can promulgate a new ergonomics standard considering the nullification by Congress of its first ergonomics standard. The CRA states in Section 801(b)(2): “A rule that does not take effect ... may not be reissued in substantially the same form, and a new rule that is substantially the same as such a rule may not be issued, unless the reissued or new rule is specifically authorized by a law enacted after the date of the joint resolution disapproving the original rule.” Although this is uncharted legal territory, OSHA could develop a rule that is not “substantially the same form,” or OSHA could conceivably reissue its previous standard if “specifically authorized” by the Congress.

3.5.4 Indoor Air Quality

In 1987, public interest groups petitioned OSHA to issue an ETS to prohibit environmental tobacco smoke in indoor workplaces,³⁰¹ but OSHA denied the petitions in 1989.³⁰²

In April 1994, as part of a larger rulemaking on indoor air quality in the workplace, OSHA proposed a rule that would require virtually all employers to ban tobacco smoking or to provide separately ventilated areas for smokers.³⁰³ In the face of stiff opposition, OSHA withdrew the indoor air quality proposed rule in 2001 citing that most states now ban smoking thus eliminating most of the indoor air quality concerns and that the nontobacco parts of the rule elicited few comments.³⁰⁴

3.5.5 Tuberculosis and other Infectious Diseases

OSHA proposed a tuberculosis standard in October 1997 that would have covered an estimated 5.3 million health care workers.³⁰⁵ The rule, as proposed, would have required

covered employers to develop written exposure control and response plans, install engineering controls, offer employees free TB skin tests and provide respiratory protection for workers exposed to certain conditions. In 2003, after a rulemaking hearing, OSHA withdrew its proposal for a separate TB standard.³⁰⁶ OSHA noted that the need for a tuberculosis standard had decreased because hospitals were adhering to guidelines issued by the Centers for Disease Control and Prevention.³⁰⁷

Even though OSHA's standard pertaining to tuberculosis was withdrawn, the issue of how to protect health care workers from disease-causing bioaerosols in the workplace has only increased since 2003. After OSHA withdrew its tuberculosis standard, State Occupational Safety and Health Plan states began consideration of bioaerosol standards. On 5 August 2009, California's first-in-the-nation Aerosol Transmissible Diseases (ATD) Standard took legal effect.³⁰⁸ The California Standard establishes a comprehensive approach to control of diseases identified as either requiring “droplet precautions” or “airborne infection isolation.” Among the controls required by the standard are written infection control procedures including source control measures such as providing surgical masks or other materials to symptomatic persons who enter the facility. The procedures should include how those patients can be placed in separate areas, to the extent feasible, to reduce exposure to employees.

In 2010, OSHA published a RFI on occupational exposure to infectious diseases in healthcare settings.³⁰⁹ OSHA intended to publish a proposed rule to address the risk to workers exposed to infectious diseases in healthcare and other related high-risk environments such as emergency response, corrections, homeless shelters and laboratories.³¹⁰

3.5.6 Workplace Violence Prevention

OSHA has issued a number of guidelines for employers on the topic. OSHA's violence prevention guidelines cover health care and social services,³¹¹ and late-night retail establishments.³¹² In addition to issuing guidelines on workplace violence prevention, in 2016 OSHA issued a RFI on a potential standard to prevent workplace violence in healthcare and social assistance settings.³¹³ The RFI requested information on topics such as effective strategies for reducing incidents of violence in various healthcare and social assistance settings.

3.6 Employer Duties Arising from Specific Regulations

3.6.1 Recordkeeping

The OSH Act requires the Secretary to adopt regulations in two areas of recordkeeping. First, Section 8(c)(2) requires the Secretary to issue regulations requiring employers

“maintain accurate records of, and to make periodic reports on, work-related deaths, injuries and illnesses other than minor injuries requiring only first aid treatment and which do not involve medical treatment, loss of consciousness, restriction of work or motion, or transfer to another job.”³¹⁴ Section 8(c)(1) also authorizes the Secretary to promulgate regulations requiring employers to make, keep, and preserve such records regarding the causes and prevention of occupational accidents and illnesses.³¹⁵ Second, Section 24(a) requires the Secretary to develop and maintain an effective program of collection, compilation, and analysis of occupational safety and health statistics.³¹⁶ After passage of the OSH Act, OSHA issued the required occupational injury and illness recording and reporting regulations as 29 C.F.R. Part 1904.³¹⁷

In 1990, OSHA and the Bureau of Labor Statistics (BLS) executed a memorandum of understanding that makes the BLS responsible for conducting the nationwide statistical compilation of occupational illnesses and injuries (Annual Survey of Occupational Injuries and Illnesses), while OSHA administers the regulatory components of the recordkeeping system. The BLS program requires employers to participate in periodic surveys of occupational injuries and illnesses. The survey form is OSHA Form 300S, and an employer who receives such a form has a duty to complete and return it promptly.³¹⁸

In 2001, OSHA updated significantly its recordkeeping regulations implementing Sections 8(c)(1) and (2).³¹⁹ OSHA’s new standard requires employers to keep the following records (or the equivalents thereof): (1) OSHA Form 300 – a log and annual summary of all recordable occupational injuries and illnesses and (2) OSHA Form 10 – a supplementary record for each occupational injury or illness.³²⁰ The regulations further require that a copy of Form 300, summarizing the year’s occupational illnesses and injuries, be posted in each establishment in a conspicuous place or places where notices to employees are customarily posted. The required records must be retained in each establishment for five years following the end of the year to which they relate.³²¹

Small employers are exempt from many, but not all, of OSHA’s recordkeeping requirements. For example, employers who had no more than 10 employees at any time during the calendar year preceding the current one are exempt from the requirements of keeping OSHA Forms 300 and 101. Such employers, however, are not exempt from the requirement of reporting accidents resulting in fatalities or multiple hospitalizations. In addition, small employers may be selected to participate in the BLS periodic surveys and, if selected, must maintain a log and summary on Form 300 for the survey year, and must make the required reports on survey Form 300S.³²²

Several studies have raised the issue that the Survey of Occupational Injuries and Illness (SOII) conducted by the

BLS based on a sample of collected OSHA Form 300s may not be representative of the true magnitude of nonfatal occupational injuries and illnesses (6, 7). As pointed out by the U.S. General Accountability Office (GAO) in its October 2009 report,³²³ the BLS does not verify the accuracy of the data it collected for the SOII and has recognized that the limited scope of its survey may affect how representative the SOII’s findings are for prioritization of governmental action on safety and health risks.

The GAO report also stated that many factors affect the accuracy of employers’ injury and illness data including disincentives that may discourage workers from reporting work-related injuries and illnesses to their employers and disincentives that may discourage employers from recording them. Among these factors include a worker’s fear of job loss or disciplinary action or fear of jeopardizing rewards based on having low injury or illness. Employers may not record injuries or illnesses because they are afraid of increasing their workers’ compensation premiums or jeopardizing their chances of winning contract bids for new work. In response to the GAO Report, OSHA announced in 2009 a National Emphasis Program to ensure that injuries and illnesses are accurately reported.³²⁴

In 2016, OSHA revised its *Recordkeeping and Reporting Occupational Injuries and Illnesses* regulation³²⁵ to add requirements for the electronic submission of injury and illness information employers are already required to keep under existing OSHA regulations.³²⁶ The final rule also amends OSHA’s recordkeeping regulation to update requirements on how employers inform employees to report work-related injuries and illnesses to their employer. The final rule requires “employers to inform employees of their right to report work-related injuries and illnesses free from retaliation; clarifies the existing implicit requirement that an employer’s procedure for reporting work-related injuries and illnesses must be reasonable and not deter or discourage employees from reporting; and incorporates the existing statutory prohibition on retaliating against employees for reporting work-related injuries or illnesses.”³²⁷

OSHA developed an *Injury Tracking Application* to aid employer in the electronic submission of the required records to OSHA.³²⁸ The electronic submission requirement became effective on 1 January 2017. The new reporting requirements will be phased in over two years. In 2017, all covered establishments must submit information from their completed 2016 Form 300A by 15 December 2017. In 2018, covered establishments with 250 or more employees must submit information from all completed 2017 forms (300A, 300, and 301) by 1 July 2018, and covered establishments with 20–249 employees must submit information from their completed 2017 Form 300A by 1 July 2018. Beginning in 2019 and every year thereafter, covered establishments must submit the information by March 2.³²⁹

3.6.2 *Reporting Occupational Injuries and Illnesses to OSHA*

Previously, employers were required to report to OSHA the death of any employee from a work-related incident or the inpatient hospitalization of three or more employees from a work-related incident. Employers had 48 hours to report, but in 1994 OSHA reduced the reporting period to eight hours.³³⁰ In 1995, the fatality and multiple hospitalization reporting rule was extended to federal agencies.³³¹

In 2014, OSHA revised the requirements for reporting work-related fatality, injury, and illness information and updated the list of industries that are partially exempt from requirements to keep records of work-related injuries and illnesses due to relatively low occupational injury and illness rates.³³² Revised 29 C.F.R. Section 1904.39 now requires employers to report the following events to OSHA: (i) all work-related fatalities; (ii) all work-related hospitalizations of one or more employees; (iii) all work-related amputations; and (iv) all work-related losses of an eye.³³³ Employers can report in three ways: (i) by telephone or in person to the OSHA Area Office that is nearest to the site of the incident; (ii) by telephone to the OSHA toll-free central telephone, 1-800-321-OSHA (6742); or (iii) by electronic submission using the reporting application located on OSHA's public Web site at www.osha.gov.³³⁴

3.6.3 *Access to Employee Exposure and Medical Records*

Section 8(c)(3) of the OSH Act authorizes the Secretary, in cooperation with the Secretary of Health and Human Services, to issue regulations requiring employers to maintain accurate records of employee exposure to potentially toxic materials or harmful physical agents, which are required to be monitored or measured under Section 6. Employees or their representatives have an opportunity to observe such monitoring or measuring, and to have access to the records.³³⁵ The *Access to Employee Exposure and Medical Records* regulation requires employers to maintain exposure and medical records pertaining to their employees' exposure to toxic substances and harmful physical agents.³³⁶ The regulation requires that the medical record for each employee shall be preserved and maintained for at least the duration of employment plus 30 years³³⁷ with exceptions.³³⁸

In 1980, OSHA promulgated a rule providing access to employer-generated exposure and medical records to employees and employee representatives.³³⁹ The rule was challenged on a number of grounds such as exceeding OSHA's authority, in violation of an employer's Fourth Amendment rights, and in violation of an employee's right to privacy, but upheld by the U.S. Court of Appeals for the Fifth Circuit in 1984.³⁴⁰ In 1988, OSHA made minor amendments to the standard.³⁴¹

4 CHALLENGING A STANDARD AFTER PROMULGATION

4.1 Judicial Review

Any person who may be adversely affected by an OSHA standard may file a petition under Section 6(f) challenging its validity in the U.S. Court of Appeals in the circuit wherein such person resides or has the principal place of business.³⁴² However, the OSH Act does not grant such special court status to OSHA regulations; judicial review of OSHA regulations must first occur within the jurisdiction of a federal district court.³⁴³ A petition for judicial review of an OSHA standard may be filed at any time prior to the sixtieth day after the issuance of the standard. Unless otherwise ordered, the filing of a petition does not operate as a "stay" of the standard.

Section 6(f) of the OSH Act directs the courts to uphold the Secretary's determinations in promulgating standards if those determinations are "supported by substantial evidence in the record considered as a whole." In practice, federal courts have generally declined to apply a strict "substantial evidence" standard of review. Instead, the courts have chosen to apply two different standards depending on whether the agency determination to be reviewed is one of "fact" or "policy." Courts have essentially taken the position that only the Secretary's findings of fact should be reviewed pursuant to a substantial evidence standard, while the Secretary's policy determinations should be substantiated by a detailed statement of reasons, which are subject to a test of reasonableness.³⁴⁴ The courts have adopted this approach with respect to ETSs as well as permanent standards.

4.2 Variance from Compliance with Specific Standards

4.2.1 *Permanent Variance*

Section 6(d) of OSHA provides that any affected employer may apply to the Secretary for a variance from an OSHA standard.³⁴⁵ The employer must show by a preponderance of the evidence that the conditions, practices, means, methods, operations, or processes used or proposed to be used will provide "employees with employment and places of employment that are as safe and healthful as those that would prevail if the employer complied with the standard."³⁴⁶ Affected employees are to be given notice of each application for a variance and an opportunity to participate in a hearing.

4.2.2 *Temporary Variance*

The OSH Act provides mechanisms to enable employers to obtain variances of a more temporary nature than those

sought under Section 6(d). Section 6(b)(6)(A) provides for “temporary” variances upon application when an employer establishes one of two conditions. First, the employer is unable to comply with a standard by its effective date because of unavailability of professional or technical personnel, or of materials and equipment needed to come into compliance with the standard, or because necessary construction or alteration of facilities cannot be completed by the effective date. Second, the employer is taking all available steps to safeguard employees against the hazards covered by the standard and has an effective program for coming into compliance with it.³⁴⁷ Temporary variances are limited by the circumstances of need or for one year.³⁴⁸

4.2.3 Experimental Variance

Section 6(b)(6)(C) authorizes the Secretary to grant a variance from any standard, or part of a standard, if it is determined by the Secretary (or upon certification by the HHS Secretary) that such a variance is needed to allow an employer to engage in an approved experiment. The aim of an experimental variance is for OSHA to gain additional knowledge about effective health and safety method that can be adopted by OSHA for wider application.

4.2.4 National Defense Variance

Section 16 permits the Secretary, after notice and an opportunity for hearing, to provide such reasonable limitations and rules and regulations allowing “reasonable variations, tolerances, and exemptions to and from any or all provisions of this Act as he may find necessary and proper to avoid serious impairment of the national defense.”³⁴⁹

5 ENFORCEMENT OF THE OSH ACT

The enforcement scheme set forth in the OSH Act has been subject to various legal challenges on several fronts, including challenges to its constitutionality. For instance, in *Atlas Roofing Company, Inc. v. OSHRC*,³⁵⁰ a cited employer argued that the OSH Act was constitutionally defective because civil penalties under the act are criminal in nature, and call for the constitutional protections of the Sixth Amendment and Article III of the U.S. Constitution. Second, the employer contended that even if, the penalties are civil in nature, the OSH Act violates the Seventh Amendment because of the absence of a jury trial for fact-finding. Third, the employer argued that the OSH Act denies the employer his or her right to a Fifth Amendment “prejudgment” due process hearing since Review Commission orders are self-executing unless the employer affirmatively seeks review. Finally, the employer asserted that the overall penalty structure of the OSH Act violates due process because it “chills”

the employer’s right to seek review of the citation and penalty. In *Atlas Roofing*, the Fifth Circuit rejected all the employer’s constitutional contentions. The U.S. Supreme Court granted a petition for *certiorari* in that case, limited to the Seventh Amendment issue, and subsequently upheld the OSH Act’s provision for imposition of civil penalties without fact finding by a jury.³⁵¹

There have been other constitutional challenges to various OSHA enforcement policies. In March 1998, the U.S. Court of Appeals for the Seventh Circuit rejected an employer’s contention that being fined administrative penalties even after it was criminally prosecuted for the same offenses under the OSH Act, violated the double jeopardy clause of the Fifth Amendment.³⁵² Finally, in a due process challenge, the Review Commission has held that OSHA did not violate an employer’s due process rights when it issued separate sets of citations, instead of only one citation, for alleged violations at nine different trenching sites on the same construction project.³⁵³

5.1 Types of Inspections

OSHA conducts two general types of inspections: unprogrammed and programmed. Unprogrammed inspections are conducted in response to specific evidence of a hazardous condition at a specific worksite (9). These types of inspections can be in response to a complaint filed by an employee or an employee representative,³⁵⁴ referral from media reports, report of an imminent danger, report of a fatality or catastrophe, or for the purpose of follow-up or monitoring.³⁵⁵ Programmed inspections are inspections conducted as a part of a national or regional inspection scheduling plan. The scheduling plan uses neutral criteria in selecting specific establishments to inspect. Criteria such as injury or illness incidence rates in a specific industry sector or type of establishment, previous citation history, or employee exposure to specific toxic agents are frequently used as the basis for programmed inspections.

5.2 Right to Inspect and Warrants

Section 8(a) of the OSH Act authorizes the Secretary to enter, inspect, and investigate places of employment to discover possible violations of the employer’s general and specific duties under the OSH Act.³⁵⁶ Even though Section 8(a) grants OSHA broad authority to enter and inspect workplaces, the Fourth Amendment has been held to apply to OSHA’s inspections.

In 1978, the U.S. Supreme Court held Section 8(a) unconstitutional insofar as it authorized nonconsensual, warrantless inspections at an employer’s establishment. In *Marshall v. Barlow’s, Inc.*,³⁵⁷ the Court held that an employer may refuse entry to an OSHA compliance officer unless a warrant

is obtained, reasoning that employers have a reasonable expectation of privacy in their commercial property and are, therefore, guaranteed the right, under the Fourth Amendment, to be free from unreasonable official intrusions.³⁵⁸ The Court explained, however, the Secretary does not need to make a showing of probable cause in the criminal sense to obtain an inspection warrant. Probable cause for an administrative inspection may be based either on a specific evidence of a violation or on a showing that reasonable legislative or administrative standards for conducting an inspection are satisfied with respect to a particular establishment.³⁵⁹ By way of illustration of the latter, the Court stated that a warrant could properly be issued upon a showing that a particular business was chosen for inspection pursuant to a general enforcement plan derived from "neutral sources."³⁶⁰

An inspection may proceed without a warrant, of course, if the employer³⁶¹ or an authorized third party consents to the inspection,³⁶² or if the conditions observed by OSHA are in "plain, obvious view" on the employer's premises.³⁶³ Modern technology can even be employed to obtain a "view" of a worksite. For example, in *L.R. Wilson & Sons, Inc. v. OSHRC*,³⁶⁴ the Fourth Circuit held that an OSHA inspector could videotape employer activities from across the street from the worksite. However, the general rule is that absent employer consent, the existence of the plain view exception, or when OSHA cannot show there was an emergency,³⁶⁵ a warrant is required.

5.2.1 Probable Cause Necessary for Warrant

Following the *Barlow's* decision, federal courts have addressed the question of what constitutes a showing of probable cause necessary to obtain an OSHA inspection warrant. The Supreme Court stated in *Barlow's* that probable cause authorizing an OSHA inspection may be based on evidence that a specific violation exists at the establishment to be inspected. Thus, probable cause for warrant issuance may be established by OSHA's receipt of a written, signed employee complaint, although circuit courts have held that the nature of the violation complained of must be described in the warrant application so the magistrate issuing the warrant may make an independent determination that probable cause exists. In addition, the majority of federal courts addressing the issue have concluded that a warrant based on specific employee complaints is overly broad if it purports to authorize a "wall-to-wall" inspection of the entire plant. Instead, the scope of the warrant and resulting inspection must bear a reasonable relationship to the specific violations that formed the basis of the complaint.³⁶⁶

5.2.2 Ex Parte Warrants

Ex parte warrants (without notice from OSHA or knowledge by the employer of the warrant) are the preferred form of

compulsory process for OSHA. In 1980, OSHA amended its regulation concerning "compulsory process."³⁶⁷ OSHA stated it may obtain an inspection warrant without prior notice to the employer.³⁶⁸

5.2.3 Challenging the Validity of a Warrant

An employer who wishes to contest a warrant has several choices. First, the employer may refuse to obey the warrant and may then move to quash it in district court. Second, the employer may refuse to comply with the warrant and litigate its validity in a civil contempt proceeding. Third, the employer may allow the inspection to proceed and move to suppress evidence after the warrant's execution (10).

In *Babcock & Wilcox Company v. Marshall*, the Third Circuit indicated that an employer may obtain a district court hearing on a warrant's validity *prior to* inspection by refusing to obey the warrant (thereby risking contempt), moving to quash the warrant, and promptly appealing if the motion is denied.³⁶⁹ However, the Third Circuit held that if the employer obeys the warrant, he must "exhaust his administrative remedies" before the Review Commission prior to obtaining judicial review of his objections to the warrant.³⁷⁰ The overwhelming majority of federal appellate courts have agreed with the Third Circuit that the doctrine of exhaustion of remedies precludes an employer from challenging an executed warrant in federal court.³⁷¹ In contrast, the Seventh Circuit has held that in certain circumstances an employer may obtain district court review of a warrant even after an inspection has been completed.³⁷² The same court, however, modified its stance on post-execution challenges when it joined the other circuits in requiring employers who challenge completed OSHA inspections on Fourth Amendment grounds to go to the Review Commission first before turning to the federal courts.³⁷³

5.3 Inspection Procedures

OSHA inspections must be made at reasonable times, in a reasonable manner, and within reasonable limits.³⁷⁴ In *Hamilton Fixture v. Secretary of Labor*,³⁷⁵ the employer challenged the reasonableness of OSHA's conducting a wall-to-wall inspection of a manufacturing facility during a work slowdown prompted by labor unrest. The employer claimed that a work slowdown was not a reasonable time to do the inspection, because it was unable to follow its normal safety procedures under those circumstances. The court, however, rejected this argument and held the inspection to be reasonable.

5.4 Imminent Danger Inspections

Section 13(a) of the OSH Act defines an imminent danger as "any conditions or practices in any place of employment

which are such that a danger exists which could reasonably be expected to cause death or serious physical harm immediately or before the imminence of such danger can be eliminated through the enforcement procedures otherwise provided in this Act.”³⁷⁶ If a complaint of imminent danger is received, OSHA can conduct an immediate inspection or arrange to have employees removed from the danger. If an inspection cannot be conducted in a timely fashion, or employees cannot be removed, OSHA may ask for injunctive relief. The Act confers jurisdiction on the U.S. district courts, upon petition of the Secretary, to restrain hazardous employment conditions or practices if they create an imminent danger of death or serious physical harm that cannot be eliminated through the OSH Act’s other enforcement procedures.³⁷⁷

Section 13(d) also provides that an employee, who may be injured by OSHA’s failure to protect him or her from an imminent danger, can bring a mandamus action to compel the Secretary to seek injunctive relief.³⁷⁸ A more realistic employee response to imminent danger is self-help rather than finding an attorney and seeking a mandamus writ (i.e. lawsuit used to compel OSHA to act).

5.5 Types of Violations

The OSH Act authorizes the Secretary to issue citations and propose penalties for employers who are believed to have violated the Act or its implementing standards and regulations. Section 9(a) directs the Secretary to issue citations “with reasonable promptness” following an inspection or investigation.³⁷⁹ According to Section 9(c), no citation may be issued after the expiration of six months from the occurrence of any violation.³⁸⁰

Each citation is to be in writing and must “describe with particularity the nature of the violation,” including a reference to the provision of the statute, standard, rule, regulation, or order alleged to have been violated.³⁸¹ Interpretations of the “particularity” requirements have generally dealt with the precision of the reference to the standard allegedly violated, and the adequacy of the description of the alleged violation. Several federal courts have held that, to meet the particularity requirement, a citation must provide the employer with “fair notice” of the violation sufficient to enable it both to prepare its defense and to correct the cited hazard.³⁸² The Fifth Circuit has held that an employer may raise a citation’s lack of particularity in a later failure-to-abate violation issued by the Secretary. The court reasoned that a citation that is too vague to give notice of the action necessary to correct the cited hazard also makes it impossible for the Review Commission to determine whether the hazard has been abated.³⁸³

Section 9(a) states that each citation must also fix a reasonable time for the abatement of the violation.³⁸⁴

Section 9(b) requires employers to post each citation prominently at or near each place where a violation referred to in the citation occurred. The mechanics of how, when, where, and how long to post the citations are set forth in regulations issued by the Secretary.³⁸⁵

Within a reasonable time after a citation has been issued, the Secretary is directed by Section 10(a) to notify the employer by certified mail of the penalty, if any, which will be assessed for the violation. Civil violations fall into the following general categories: *de minimis*, other-than-serious, serious, willful, and repeated. A civil penalty is based, at least in part, on the nature of the violation.³⁸⁶

5.5.1 DeMinimis Violations

If noncompliance with an OSHA standard or regulation presents no direct or immediate relationship to the safety or health of employees, the violation is *de minimis*.³⁸⁷

There are three situations which can result in a finding a *de minimis* violation. First, an employer complies with the clear intent of the standard but deviates from its particular requirements in a manner that has no direct or immediate relationship to employee safety or health. Second, an employer complies with a proposed standard or amendment or a consensus standard rather than with the standard in effect at the time of the inspection, and the employer’s action clearly provides equal or greater employee protection or the employer complies with a written interpretation issued by the OSHA Regional or National Office. Third, an employer’s workplace is technically beyond the requirements of the applicable standard and provides equivalent or more effective employee safety or health protection.³⁸⁸

5.5.2 Other-than-Serious Violations

An other-than-serious type of violation is “one in which there is a direct and immediate relationship between the violative condition and occupational safety and health, but is not of such relationship that a resultant injury is death or serious physical harm.”³⁸⁹ The OSHA *Field Operations Manual* (FOM) states that an other-than-serious type of violation “shall be cited in situations where the most serious injury or illness that would be likely to result from a hazardous condition cannot reasonably be predicted to cause death or serious physical harm to exposed employees but does have a direct and immediate relationship to their safety and health.”³⁹⁰

The original Senate version of the OSH Act treated all violations as “serious.” As finally enacted, however, the OSH Act incorporated a House proposal for violations “determined not to be of a serious nature.”³⁹¹ The statute does not describe the elements of an other-than-serious violation and provides no guidelines for determining when a violation is not serious. The Fifth Circuit, however, has

described other-than-serious violations as violations that do not create a substantial probability of serious physical harm.³⁹² The Review Commission has explained that serious, and other-than-serious violations, can be distinguished based on the seriousness of injuries that experience has shown are reasonably likely to result when an accident does arise from a particular set of circumstances.³⁹³

5.5.3 Serious Violations

Section 17(k) of the OSH Act provides that a violation is serious if, in the event of an accident, there is a substantial probability that death or serious physical harm *could* result.³⁹⁴

The *probability* of an *accident* occurring need not be shown to establish that a violation is serious. Rather, as the Ninth Circuit Court ruled in *California Stevedore and Ballast v. OSHRC*,³⁹⁵ a serious violation exists if any accident that *could* result from the violation would have a substantial probability of resulting in death or serious physical harm.³⁹⁶ No actual death or physical injury is required to establish a serious violation.³⁹⁷ Employer knowledge is a key element of a serious violation. The knowledge requirement in Section 17(k) can be satisfied by a showing of actual or constructive employer knowledge of practices or conditions that constitute violations of the OSH Act. The burden is on the Secretary to prove knowledge as well as the other elements of a serious violation.

5.5.4 Willful Violations

The OSH Act contains no definition of “willful” violation. Thus, it is not surprising that there has been some disagreement on the elements of a willful violation. In *Frank Irey Jr., Inc. v. OSHRC*,³⁹⁸ the Third Circuit initially held that “[w]illfulness connotes defiance or such reckless disregard of consequences as to be equivalent to a knowing, conscious, and deliberate flaunting of the Act. Willful means more than merely voluntary action or omission – it involves an element of obstinate refusal to comply.”

The majority of the circuits, as well as the Review Commission, declined to follow the *Frank Irey* definition of “willfulness.” The First and Fourth Circuits interpreted a willful action as a “conscious, intentional, deliberate voluntary decision,” regardless of venial motive.³⁹⁹ The Review Commission agreed that no showing of malicious intent is necessary to establish “willfulness,”⁴⁰⁰ and defined a willful violation as one “committed with either an intentional disregard of, or plain indifference to, the Act’s requirements.”⁴⁰¹ Most courts of appeals have adopted the Review Commission’s standard of intentional disregard or plain indifference, or have embraced similar definitions that do not require a showing of a bad motive.⁴⁰²

Thus, a conflict developed between the Third Circuit’s view, as expressed in *Frank Irey*, and the majority approach. The D.C. Circuit characterized this conflict as more apparent than real. In *Cedar Construction Co. v. OSHRC and Marshall*,⁴⁰³ the court indicated that the two approaches were likely to yield the same results in particular cases since there is little practical difference between “obstinate refusal to comply” and “intentional disregard” of the OSH Act. The Third Circuit later agreed when it again addressed the “willfulness” question in *Babcock & Wilcox Co. v. OSHRC*.⁴⁰⁴ This clarification by the Third Circuit resulted in general agreement among the circuits that the Review Commission’s “intentional disregard” standard is the correct one, and that no malicious intent need be shown to establish a willful violation.

5.5.5 Repeated Violations

The OSH Act provides no definition of a “repeated” violation. It is OSHA policy that “an employer may be cited for a repeated violation if that employer has been cited previously for a substantially similar condition and the citation has become a final order of the Review Commission. Generally, similar conditions can be demonstrated by showing that in both situations the identical standard was violated. In some circumstances, similar conditions can be demonstrated when different standards are violated. Although there may be different standards involved, the hazardous conditions found could be substantially similar and therefore a repeated violation would be appropriate.”⁴⁰⁵

5.5.6 Failure-to-Abate Violations

The OSH Act does not specify fixed periods within which violations must be remedied, but Section 9(a) does require that each citation “fix a reasonable time for the abatement of the violation.”⁴⁰⁶ The abatement period does not begin to run until the date of the final order of the Review Commission affirming the citation, as long as the review proceeding, if any, initiated by the employer was in good faith and not solely for delay or avoidance of penalties.⁴⁰⁷ An employer who fails to correct a violation within the period specified in the citation may receive an additional citation pursuant to Section 10(b) for failure to abate.

In 1996, OSHA instituted a nationwide “Quick Fix” abatement incentive program. Under the program, employers could be given a 15% penalty reduction for correcting a cited workplace hazard within 24 hours of the inspection. The penalty reduction does not apply to violations linked to fatal injury or illness, to serious incidents resulting in serious injuries to employees, nor to high- or medium-gravity serious, willful, repeat or failure-to-abate violations.⁴⁰⁸ In 1997, OSHA published an Abatement Verification final rule requiring employers to certify to OSHA that they have

corrected cited violations and to inform their employees of the abatement actions taken.⁴⁰⁹ Prior to the final rule, employer compliance with requests to provide verification of abatement was voluntary, and follow-up inspections often were necessary in order to determine whether abatement had occurred.

5.6 Civil Penalties

On 2 November 2015, Congress passed the Federal Civil Penalties Inflation Adjustment Act Improvement Act (2015 Inflation Adjustment Act) as part of a Bipartisan Budget Act of 2015.⁴¹⁰ The Inflation Adjustment Act amends the Federal Civil Penalties Inflation Adjustment Act of 1990. The Inflation Adjustment Act requires the DOL to adjust its civil money penalty levels for inflation (with an initial catch-up adjustment) no later than January 15 of each year. The DOL issued an interim final rule to adjust its civil monetary penalties for inflation on 1 July 2016,⁴¹¹ and a final rule on 18 January 2017.⁴¹² Annual updates are expected.

Importantly, the 2015 Inflation Adjustment Act amends the 1990 Inflation Adjustment Act by rescinding an exemption that previously disallowed inflationary adjustments for violations of the OSH Act. As a result of the 2015 Inflation Adjustment Act, OSHA's maximum monetary civil penalties were increased significantly for the years 2016⁴¹³ and 2017. For 2017, the maximum statutory monetary civil penalty for serious, other-than-serious, and posting requirements increased from \$7 000 to \$12 675.⁴¹⁴ The maximum statutory monetary civil penalty for failure-to-abate violations increased from \$7 000 per day beyond the abatement date to \$12 675 per day beyond the abatement date.⁴¹⁵ The maximum statutory monetary civil penalty for a willful or repeated violation increased from \$70 000 to \$126 749 per violation.⁴¹⁶

5.7 Criminal Sanctions

To secure a criminal conviction under Section 17(e) of the OSH Act, there must be evidence to support two elements of the offense: (i) the employer willfully violated a specific standard, rule, order or regulation of the OSH Act; and (ii) the violation caused the death of the employee. Willful violations that cause death to an employee are punishable upon conviction by a fine of up to \$10 000 or imprisonment for up to six months or both.⁴¹⁷ For a repeated willful violation that causes the death of an employee, the punishment is increased to a fine of not more than \$20 000 and 1 year in jail (or both).⁴¹⁸

Proof of willfulness can be shown by the employer taking deliberate action in spite of having knowledge of an OSHA requirement or being plainly indifferent to the requirement.⁴¹⁹ The second element is more easily satisfied;

all that needs to be shown is that the violation was a cause or a contributing factor to the death of an employee.⁴²⁰ OSHA will issue a civil citation even if the citation involves allegations under consideration for criminal prosecution.⁴²¹

The criminal penalties provided for in the OSH Act can only be imposed by federal courts and not by the Review Commission. For a case to be considered for criminal sanctions provided by the OSH Act, OSHA must make a referral for criminal prosecution to the U.S. Department of Justice. How the criminal provisions of the OSH Act have been used – or not been used – has come under criticism.⁴²² For example, the OSH Act's criminal provision is limited to willful violations that result in a worker death. But, in some of the most egregious examples of employer actions that have proved dangerous to workers, the worker suffered irreversible coma or another type of severe injury but did not die. In those cases, application of the criminal provisions of the OSH Act is inapplicable. Even when a worker death does occur, the crime is only a Class B misdemeanor, carrying a maximum sentence of only six months in jail.⁴²³

In addition to criminal sanctions under the OSH Act, employers can also be subject to criminal felony penalties for knowingly and willfully concealing a material fact, making a materially false statement, or making or using any false writing or document subject to OSHA's jurisdiction.⁴²⁴ Penalties include a fine of up to \$250 000 for an individual and up to \$500 000 for an organization (or two times any resulting financial gain or loss related to the falsification).⁴²⁵ Employers under the jurisdiction of an occupational safety and health state plan can also be prosecuted under that state's general criminal laws – homicide or manslaughter – for work-related deaths or serious injuries.

In 2005, OSHA joined the Department of Justice (Environmental Crimes Unit) and the EPA in a criminal liability initiative based on the notion that firms that violate OSHA laws may also violate environmental laws. In 2007, the joint effort has had positive results in a case where a company and its management officials were convicted of violating the Clean Air and Clean Water Act and making false statements to OSHA and obstructing OSHA's investigation of a forklift accident.⁴²⁶ In most of the cases brought by the Environmental Crimes Section at the U.S. Department of Justice, the Department has charged violations of the endangerment provisions of environmental protection statutes, or the general criminal provisions of Title 18 of the United States Code, instead of the criminal provisions of the OSH Act. Title 18 – the general criminal statute of the United States – makes it a crime to make false statements,⁴²⁷ obstruct justice,⁴²⁸ and commit conspiracy to defraud the United States by impeding effective implementation of government regulatory programs.⁴²⁹ Under Title 18, the Department of Justice was able to charge crimes that were charged as felonies – not misdemeanors – and were punishable by up to 15 years in jail for knowing

endangerment and 20 years in jail for some forms of obstruction of justice.

5.8 Specific Enforcement Policies

5.8.1 Cases Subject to Violation-by-Violation Penalties

In 1986, OSHA adopted what is commonly referred to as its “egregious penalty policy.” Cases subject to OSHA’s violation-by-violation penalty policy are those cases where the employer’s actions were so far outside of acceptable standards that the willful violation was “egregious.” Besides a violation that meets the willful serious characterization, one of six factors must also be present to meet the “egregiousness” standard. The violation must have led to fatalities, a worksite catastrophe, or a large number of injuries or illnesses. The violation must have led to persistently high rates of injuries or illnesses. The employer had an extensive history of violations. The employer has intentionally disregarded its safety and health responsibilities. The employer’s conduct, taken as a whole, amounts to clear bad faith in the performance of his or her OSH Act duties. Finally, the number of violations employer committed undermined the effectiveness of any safety and health program the employer might have implemented.⁴³⁰ Since a penalty is calculated for each instance of, or each employee subject to, the violation, the total amount of the penalty can be substantial.

After the Review Commission’s decision in *Ho*,⁴³¹ which rejected OSHA’s use of the egregious penalty policy and disapproved the assessment of separate, per-employee penalties, OSHA promulgated a final rule amending a number of its standards “to add language clarifying that the PPE and training requirements impose a compliance duty to each and every employee covered by the standards and that noncompliance may expose the employer to liability on a per-employee basis.”⁴³² In *National Ass’n of Home Builders v. OSHA*,⁴³³ the D.C. Circuit affirmed OSHA’s violation-by-violation penalty policy. The Review Commission has also affirmed OSHA’s authority to cite an employer on a per-employee basis by overruling *Ho* in its case entitled *E. Smalis Painting Co.*, which involved an employer’s failure to provide each exposed employee with medical surveillance under OSHA’s lead standard.⁴³⁴

5.8.2 Multi-Employer Citation Policy

OSHA’s longstanding multi-employer citation policy permits the agency to cite more than one employer for a violative condition. Although the multi-employer citation policy originated in the construction industry, the OSHRC has ruled that with respect to the citation policy there is no distinction between construction and nonconstruction workplaces.⁴³⁵

In the construction industry, there are often many different employers on the same worksite. Four different types of employers can be characterized based on their relationship to a condition that violates an OSHA standard. When a violation is observed and a particular employer’s employees are exposed to the hazard (regardless of whether that employer created the violative condition), OSHA may issue a citation to that employer – the “*exposing*” employer. The employer who created the condition is “*creating*” employer. A creating employer may be cited by OSHA even though the creating employer had no employees exposed to the hazard. Even if an employer has no employees exposed to the violative condition, nor did the employer create the hazard, he or she may still be cited by OSHA if that employer was in a position to control or correct the hazard – *controlling* or *correcting* employers. A controlling or correcting employer is often the general contractor.

OSHA’s multiemployer citation policy had its origin in 1976 when the Revision Commission stated (in a footnote) “the general contractor is well situated to obtain abatement of hazards either through its own resources or through its supervisory capacity.”⁴³⁶ In a 1999 OSHA Instruction, OSHA stated that citations should be issued not only to exposing employers, but also to creating, controlling, and correcting employers “whether or not their own employees are exposed.”⁴³⁷

Most circuit courts have held that general contractors – as controlling or correcting employers – may be cited by OSHA under Section 5(a)(2) even if their own employees were not their own.⁴³⁸ However, the Fifth Circuit has held that “OSHA regulations protect only an employer’s own employees.”⁴³⁹ In 2017, OSHA appealed a case originating in Texas (within the jurisdiction of the Fifth Circuit) of a willful citation to a general contractor based solely on exposure to a subcontractor’s employees.⁴⁴⁰ The outcome is uncertain at this writing.

6 CONTESTATION PROCEEDINGS

6.1 Contesting Citations and Penalties

Section 10(a) of OSH Act,⁴⁴¹ and the regulations of the Review Commission pertaining to that section,⁴⁴² provide procedures for an employer to “contest” or challenge an OSHA citation and its proposed civil penalties. After the employer has been notified of the penalty proposed by the Secretary, the employer has 15 working days to notify the Secretary that it wishes to contest the citation or the proposed assessment of civil penalty. A failure to notify the Secretary within 15 days of intent to contest the citation or proposed penalty will render the citation or penalty “a final order of the Review Commission and not subject to review by any court or agency.”⁴⁴³

OSHA regulations⁴⁴⁴ instruct employers “very notice of intention to contest shall specify whether it is directed to the citation or to the proposed penalty, or both.” Similarly, the courts have construed the OSH Act’s enforcement scheme as mandating a distinction between contesting a citation and contesting a proposed penalty.⁴⁴⁵ The Fifth Circuit held⁴⁴⁶ that an employer’s letter that contested the proposed penalty but failed to contest the citation (in fact, the letter affirmatively admitted the violation), constituted waiver of the employer’s right to challenge the citation on appeal. However, the Review Commission has stated that it will construe notices of contest that are limited to the penalty to include a contest of the citation as well, if the cited employer indicates later that it was his or her intent to contest the citation.⁴⁴⁷ If an employer files a timely notice of contest (or if within 15 working days of the issuance of a citation, a representative of the employees files a notice challenging the period of abatement specified in the citation), the Secretary must immediately advise the Review Commission of the intent to contest. The Review Commission then must afford an opportunity for an administrative hearing.⁴⁴⁸

The Commission’s Rules of Procedures govern all of its proceedings.⁴⁴⁹ Where the Commission has not promulgated a rule, the Federal Rules of Civil Procedure apply.⁴⁵⁰ In addition to the extensive, formal rules of practice, the rules of the Review Commission permit any party to request simplified proceedings before an administrative law judge in cases that do not involve alleged general duty clause violations or alleged violations of certain enumerated standards.⁴⁵¹ Procedures are simplified in several ways – pleadings are limited, discovery is generally not permitted, the Federal Rules of Evidence do not apply, and interlocutory appeals are not permitted. The Review Commission makes available an online publication designed for nonlawyers called the *Guide to Commission Procedures*.⁴⁵²

A Review Commission hearing is conducted pursuant to the U.S. Administrative Procedure Act and is presided over by a single administrative law judge employed by the Review Commission. After taking testimony, the judge writes an opinion that is subject to review by the full three-member Commission at its discretion. An aggrieved party may petition for discretionary review before the full Review Commission and any Commission member may direct review of a case on his or her own motion.⁴⁵³ If no Commissioner member directs review, or if a timely petition for review is not filed, the administrative law judge’s decision becomes a final order of the Review Commission.⁴⁵⁴

Section 17(j) further empowers the Review Commission to assess appropriate civil penalties, giving due consideration to the size of the business of the employer being charged, the gravity of the violation, the good faith of the employer, and the history of previous violations.⁴⁵⁵ The Review Commission has taken the position that it may exercise its power to increase the Secretary’s proposed penalty after

considering the factors outlined above, and courts of appeals have expressed the view that the Commission may act in this manner.⁴⁵⁶ However, the Commission has only very rarely acted on that authority. The Review Commission has also held that it does not have to give “substantial weight” to the Secretary’s proposed penalties.⁴⁵⁷ Courts have also sanctioned the Review Commission’s right to increase the degree of a violation from other-than-serious to serious.⁴⁵⁸ The Review Commission has taken the view that it can reduce the degree of a violation as well.⁴⁵⁹

6.2 Employer’s Affirmative Defenses

A number of defenses are available to the employer when contesting an OSHA citation and/or propose penalties. Some defenses are “affirmative” defenses. An employer wishing to use an affirmative defense must assert the defense in the employer’s appeal of the citation to the Review Commission.⁴⁶⁰ Once raised, the employer has the burden of proving the defense.⁴⁶¹

Affirmative defenses are varied. First, an employer can assert that the standard cited is too vague to be legally valid. Second, an employer can assert that the standard cited was not properly promulgated by OSHA. Third, the employer can assert that OSHA should have cited a more specific standard than the one they did. Fourth, the employer can assert that another federal agency regulates the same condition. Fifth, the employer can charge that all means of compliance with the standard are infeasible. Sixth, compliance with the standard will create a greater hazard than the one cited by OSHA. Seventh, the employer can assert that the inspection was unreasonable or that the citation represented vindictive prosecution by OSHA. Eighth, the employer can assert that the citation lacked particularity as required by Section 9(a). Ninth, an employer can assert that there was an unreasonable delay in issuing the citation. Tenth, the employer can assert that the violation was unpreventable because of employee misconduct. In asserting any of these affirmative defenses, the employer must show that the employer’s ability to defend against the citation was adversely affected.

6.3 Courts of Appeals Review

The final stage of an OSHA enforcement proceeding is review in a court of appeals (and thereafter, discretionary review by the Supreme Court). Any person adversely affected or aggrieved by the Review Commission’s disposition of its case may obtain review in an appropriate court of appeals pursuant to Section 11(a) of the OSH Act.⁴⁶² Section 11(b) provides that the Secretary may also obtain review or enforcement of any final order of the Review

Commission by filing a petition for such relief in the appropriate court of appeals. The reviewing court is bound by Section 11(a) to apply the “substantial evidence test” to the Commission’s findings of fact. The same section empowers the court to direct the Review Commission to consider additional evidence if the evidence is material and reasonable grounds existed for a party’s failure to admit it in the hearing before the Commission. Regarding the penalty imposed by the Review Commission, the reviewing court may inquire only whether the Review Commission abused its discretion because the assessment of a penalty is not a finding of fact but rather the exercise of a discretionary grant of power.⁴⁶³ The Seventh Circuit has held that interest on penalties assessed against an employer by the Commission accrues from the date the Commission’s order is entered, even when an employer appeals to a federal court.⁴⁶⁴

7 RIGHTS OF EMPLOYEES AND THEIR REPRESENTATIVES UNDER THE OSH ACT

7.1 Information Rights

7.1.1 Poster

Section 8(c)(1) of the OSH Act states that the “Secretary shall also issue regulations requiring employers to keep their employees informed of their protections and obligations under this Act, including provisions of applicable standards.”⁴⁶⁵ OSHA meets these requirements by requiring employers to post in a conspicuous place a poster furnished by OSHA containing basic information on the OSH Act and employee rights under the Act.⁴⁶⁶ Employers are subject to a citation and penalty for failure to post the required poster.⁴⁶⁷

7.1.2 Injury and Illness Log

Section 8(c)(2) requires the Secretary to prescribe regulations requiring employers to maintain accurate records of work-related fatalities, injuries, and illnesses. Under this provision of the Act, OSHA requires most employers to maintain a log of work-related injuries and illnesses,⁴⁶⁸ and to post an annual summary of the log in a conspicuous place in each workplace and to certify that the summary is accurate.⁴⁶⁹

7.2 Right to Refuse Hazardous Work under Section 11(c) of the OSH Act

An employee has no explicit right under the OSH Act to refuse a work assignment because of what the employee feels

is a dangerous working condition. However, Section 11(c)(1) of the Act prohibits discrimination against an employee because of their exercise of rights provided by the Act.⁴⁷⁰ In 1973, the Secretary issued an administrative regulation that interprets the Act as implying such a right under four limited circumstances.⁴⁷¹ First, the employee’s refusal must be made in good faith. Second, the condition the employee believes is a hazard is one that a reasonable person would conclude is one that poses a real danger of death or serious physical injury. Third, there is insufficient time to eliminate the hazard by use of the OSH Act’s normal enforcement means. Fourth, the employee must have asked the employer to correct the hazard, but the employee was unable to obtain such a correction from the employer. In *Usery v. Whirlpool Corp.*, the Supreme Court was faced with the question whether an employee is protected from retaliation by his employer if he walks off the job in an imminent danger situation.⁴⁷² In *Whirlpool Corp.*, the Supreme Court upheld § 1977.12(b)(2) as a valid exercise of the Secretary’s authority under the OSH Act. Thus, employees are afforded a limited right to refuse to work in imminent danger situations.

7.3 Right to Request and Participate in a Compliance Inspection

Section 8(f)(1) gives employees and their representatives the right to file a complaint and request an inspection.⁴⁷³ OSHA must conduct an inspection when a valid complaint is filed with an OSHA Area Office. To be valid, the complainant must identify themselves to OSHA. Section 8(e) of the Act grants the right to employees and their representatives to participate in the inspection and its opening and closing conferences.⁴⁷⁴ The Act also provides that “a representative of the employer, and a representative authorized by his employees, shall be given an opportunity to accompany the Secretary or his authorized representative during the physical inspection of any workplace ...”⁴⁷⁵ The term “representative” means: (i) an authorized bargaining unit representative; (ii) employee’s attorney; or (iii) any other person acting in a bona fide representative capacity.⁴⁷⁶ Even though a walk-around right is specified in the OSH Act, there is no requirement that the employer must compensate the employee for his or her time.

7.4 Rights to Participate in Litigation before the Review Commission

Two rights are granted in Section 10(c) of the OSH Act. First, Section 10(c) grants employees the right to file a notice of contest “alleging that the period of time fixed in the citation for the abatement of the violation is unreasonable” and in response,” the Commission shall afford an opportunity for a

hearing ...”⁴⁷⁷ Second, Section 10(c) also provides a right to employees to participate as parties to hearings.⁴⁷⁸ A lengthy history of litigation has occurred over the rights granted by Section 10(c).

7.5 Right to be Notified of Possible Imminent Danger and Right to Seek Relief for Imminent Dangers

Section 13(c) and (d) of the OSH Act grants employees the right to be notified of possible imminent danger situations, and the right to file an action to compel the Secretary to seek relief in such situations if the Secretary has “arbitrarily and capriciously” failed to do so.⁴⁷⁹

7.6 Right to File a Complaint against State Program Administration

Individuals, including employees, who have a complaint against the manner in which an OSHA-approved occupational safety and health state plan is being administered by the state have the right to lodge a complaint with the Secretary’s representative in the federal region in which the state is located.⁴⁸⁰

7.7 Right to Access Exposure Records

Section 8(c)(3) of the OSH Act give employees the right to observe any exposure monitoring to potentially toxic materials or harmful physical agents which are required under a Section 6(b)(5) standard and a right of access to those exposure records.⁴⁸¹

7.8 Antidiscrimination Rights

Section 11(c) of the OSH Act makes it unlawful for any person to discharge or in any manner discriminate against an employee because the employee has exercised his or her rights under the OSH Act.⁴⁸² This provision is designed to encourage employee participation in the enforcement of OSHA standards.⁴⁸³ Employees who believe they have been discriminated against in violation of Section 11(c) must file a complaint with the Secretary within 30 days after such violation has occurred.⁴⁸⁴ The prohibitions in Section 11(c) are not confined to employers only as it states that “[N]o person shall ... discriminate against any employee ...”.⁴⁸⁵ In *Solis v. Brighton Medical Clinic*, a federal district court held that a clinic physician could be held personally liable for retaliatory discharge of an employee under Section 11(c).⁴⁸⁶

The Secretary is required to investigate the complaint. If the Secretary determines that Section 11(c) has been violated, the Secretary is authorized to bring an action in federal district court for an order restraining the violation and for recovery of all appropriate relief, including rehiring or reinstatement of the employee to his or her former position with back pay. Section 11(c)(1) authorizes only the Secretary to bring an action for violation of Section 11(c), not the employee.⁴⁸⁷

8 VOLUNTARY COMPLIANCE PROGRAMS

8.1 On-Site Consultation Program

Since the mid-1970s, OSHA has administered a program where employers could obtain assistance free of charge from trained occupational safety and health personnel funded by cooperative agreements with state agencies or universities. In 1998, Congress and President Clinton provided express statutory authority for OSHA’s on-site consultation program by passing the Occupational Safety and Health Administration Compliance Assistance Authorization Act.⁴⁸⁸ The Act added new Section 21(d) to the OSH Act. In 2000, OSHA revised its 1970s regulations pertaining to OSHA’s agreements with states.⁴⁸⁹ A consultation visit parallels what happens during an enforcement inspection, except no penalties are assessed for violations that are identified.⁴⁹⁰ However, if an employer refuses to correct an imminent danger or a serious hazard, the consultant is required to inform the appropriate federal or state enforcement authority.⁴⁹¹ The on-site consultation program is maintained by states separate from their enforcement activities to ensure the confidentiality of information obtained from the employer.

8.1.1 Safety and Health Achievement Recognition Program (SHARP)

OSHA regulations require every state that receives consultation program funding to establish a consultation program aimed at small, high-hazard, employers. Employers who undergo a full on-site consultation visit, and meet other requirements such as maintaining an injury and illness prevention program that at a minimum addressed OSHA’s Safety and Health Management Program Guidelines,⁴⁹² may be recognized under SHARP for their exemplary safety and health management systems. Worksites that receive SHARP recognition are exempt from programmed inspections during the period that the SHARP certification is valid.

8.2 OSHA's Cooperative Programs

8.2.1 Alliance Program

Through the Alliance Program, OSHA works with groups committed to worker safety and health to prevent workplace fatalities, injuries, and illnesses. OSHA and the groups work together to develop compliance assistance tools and resources, share information with workers and employers, and educate workers and employers about their rights and responsibilities.⁴⁹³ In the Alliance Program, OSHA works with varied partners including unions, consulates, trade or professional organizations, faith- and community-based organizations, businesses, and educational institutions, to leverage resources and expertise to help ensure safe and healthy workplaces and worker rights under the Occupational Safety and Health Act.

8.2.2 OSHA Strategic Partnership Program

Occupational Safety and Health Administration Strategic Partnerships (OSPP) are "unique agreements designed to encourage, assist, and recognize partner efforts to eliminate serious hazards and enhance workplace safety and health practices."⁴⁹⁴ OSPPs are operated out of local OSHA Area or Regional Offices. They focus on ways to improve safety and health in major corporations, government agencies, at large construction projects and private sector industries where OSHA has jurisdiction.

8.2.3 Voluntary Protection Program

OSHA's Voluntary Protection Programs (VPPs)⁴⁹⁵ are partnerships between management, labor, and OSHA at workplaces that have implemented and maintain an exemplary comprehensive safety and health management programs. VPP membership is OSHA's official recognition of the outstanding efforts of employers and employees who have achieved exemplary occupational safety and health.⁴⁹⁶ VPP procedures involve submission of a detailed application, including detailed site injury and illness rates, a written safety and health management program, commitment from management and worker representatives, and a rigorous on-site review by OSHA personnel and special government employees (SGEs).⁴⁹⁷ VPP members represent nearly all industrial classifications⁴⁹⁸ and have their own association – the Voluntary Protection Programs Participants' Association (VPPPA).⁴⁹⁹

8.2.4 OSHA Challenge Program

The OSHA Challenge Program assists employers to improve their safety and health management programs through mentoring, training and progress tracking. Challenge

participants do not receive exemptions from OSHA programmed inspections.⁵⁰⁰

9 REGULATION OF OCCUPATIONAL SAFETY AND HEALTH BY THE STATES

One of the primary factors that induced Congress to enact a comprehensive OSH Act was the failure of many of the states to regulate workplace safety and health adequately.⁵⁰¹ In passing the OSH Act, Congress hoped to ensure at least a minimum level of protection for workers throughout the country.

The OSH Act preempts a state's occupational safety or health standard with respect to a standard promulgated by OSHA.⁵⁰² However, OSHA does not totally ban the states from developing and enforcing occupational safety and health standards on their own. Pursuant to Section 18(b) of the Act, a state may regain jurisdiction over development and enforcement of occupational safety and health standards by submitting to the federal government an effective State Occupational Safety and Health Plan ("state plan"). Final approval of a state plan can lead ultimately to exclusive authority by a state over the matters included in its plan. The process of regaining jurisdiction over the regulation of occupational safety and health begins with the submission of a plan that sets forth specific procedures for ensuring workers' safety and health. States can submit one of the two types of plans – a complete plan or a developmental plan.

A "complete" plan⁵⁰³ is a plan that, upon submission, satisfies the criteria for plan approval set forth in Section 18(c) of the Act, as well as certain additional criteria outlined by the Secretary in administrative regulations.⁵⁰⁴ Section 18(c) specifies the requirements a state must fulfill to receive approval of its own occupational safety and health plan.⁵⁰⁵ Complete plans are given "initial" approval by the Secretary upon submission. For at least 3 years following the "initial" approval, the Secretary will monitor the state plan to determine whether the criteria set forth in Section 18(c) are being applied. If this determination – as so-called Section 18(e) determination – is favorable, the state plan will be granted "final approval" and the state will regain exclusive jurisdiction with respect to any occupational safety or health issue covered by the state plan. Federal standards continue to apply to hazards not covered by the state program.

A "developmental" plan⁵⁰⁶ is a plan that, upon submission, does not fully meet the criteria set forth in the statute or in OSHA's regulations. A developmental plan may receive initial approval upon submission, however, if the plan contains "satisfactory assurances" that the state will take the necessary steps to bring its program into conformity within three years following commencement of the plan's

operation. If the developmental plan satisfies all the statutory and administrative criteria within the three-year “developmental period,” the Secretary will certify and will initiate an evaluation of the actual operations of the state plan for purposes of making a Section 18(e) determination. The evaluation must proceed for at least one year before such a determination can be made. Developmental plans that have received final approval will continue to be monitored and evaluated by the Secretary pursuant to Section 18(f) of the Act, which authorizes the Secretary to withdraw approval if a state fails to comply substantially with any provision of the state’s plan.

Although a state does not regain exclusive jurisdiction over matters contained in its plan until the plan receives final approval, a state with initial plan approval may participate in the administration and enforcement of the Act prior to final approval by satisfying four criteria.⁵⁰⁷ First, the state must have enacted enabling legislation conforming to that specified in OSHA and the regulations. Second, the state plan must contain standards that are found to be “at least as effective as” the comparable federal standards. Third, the state plan must provide for a sufficient number of qualified personnel who will enforce the standards in accordance with the state’s enabling legislation. Fourth, the plan’s provisions for review of state citations and penalties (including the appointment of the reviewing authority and the promulgation of implementing regulations) must be in effect. If the criteria above are met, the state plan is considered “operational.” The federal government then enters into an operational agreement with the state whereby the state is authorized to enforce safety and health standards under the state plan.⁵⁰⁸

Most states that are presently operating approved and/or certified plans have adopted standards that are substantially similar, if not identical, to the federal standards. At least five state plans, however, have standards that contain certain provisions that vary from the federal standards, yet have been approved as being “at least as effective” as the federal standards. The states are California, Hawaii, Michigan, Oregon, and Washington. In some instances, these states have adopted standards that are more stringent than the analogous federal standards.

Early on, OSHA developed numerical staffing requirements for states, so-called staffing “benchmarks.” These benchmarks were challenged by the AFL-CIO who argued that the benchmarks were too low. In *AFL-CIO v. Marshall*,⁵⁰⁹ the court agreed with the AFL-CIO. The court that, in referring to personnel and funding levels in terms of adequacy and sufficiency, Congress intended that states would have the resources “necessary to do the job” and that “such interim federal benchmarks must be a part of an articulated, coherent program calculated to achieve a fully effective program at some point in the foreseeable future.”⁵¹⁰ On remand, the district court ordered OSHA in 1978 to develop a five-year schedule for each state to meet

the “fully effective” enforcement staffing levels and made meeting the OSHA “benchmark” staffing schedule a prerequisite for final state plan approval.⁵¹¹ Since Congress failed to appropriate additional resources to meet the benchmark staffing levels, the benchmarks have since lost much of their impact.

10 REGULATION OF OCCUPATIONAL SAFETY AND HEALTH BY OTHER FEDERAL STATUTES

10.1 Partial Exemption from Coverage by the OSH Act

Section 4(b)(1) of OSH Act states that “[N]othing in this chapter shall apply to working conditions of employees with respect to which other federal agencies, and State agencies acting under Section 201 of Title 42,⁵¹² exercise statutory authority to prescribe or enforce standards or regulations affecting occupational safety and health.”⁵¹³ Although Section 4(b)(1) seems to be self-defining, it has generated a significant amount of litigation. Three major interpretive questions have been raised. First, what constitutes a sufficient *exercise of regulatory authority* to preempt OSHA regulation? Second, does the exercise of authority by another federal agency in substantial areas of employee safety and health *exempt the entire industry* from OSHA standards? Third, must the other *federal agency’s motivation* in acting have been to protect workers?

Exercise of Authority. The mere existence of statutory authority to regulate safety or health is not sufficient to oust OSHA’s regulatory scheme; some exercise of that authority is necessary.⁵¹⁴ Speculative pronouncements of proposed regulations by a federal agency are not sufficient to warrant preemption of OSHA standards; Section 4(b)(1) requires a concrete exercise of statutory authority.⁵¹⁵

Industrywide Exemption. Courts have also rejected the notion that the exercise of statutory authority by another federal agency creates an industry-wide exemption from OSHA regulations. Rather, the courts have agreed that the term “working conditions” in Section 4(b)(1) refers to something more limited than every aspect of an entire industry.

Working Conditions. Ambiguity remains, however, with respect to the scope of the displacing effect of another agency’s regulation of a “working conditions.” OSHA understands the term “working conditions” to mean particular hazards, to which an employee may be exposed.⁵¹⁶ First, Second and Eleventh Circuits follow the OSHA “hazard” approach. The Fourth Circuit defined “working conditions” as “the environmental area in which an employee customarily goes about his daily tasks.” In *Southern Railway Company*, the Fourth circuit explained that OSHA would

be displaced when another federal agency had exercised its statutory authority to prescribe standards affecting occupational safety or health for such an area.⁵¹⁷ In *Southern Pacific Transportation Company*, the Fifth Circuit explained that the term “working conditions” has a technical meaning in the language of industrial relations; it encompasses both a worker’s surroundings and the hazards incident to the work. The court stated that the displacing effect of Section 4(b)(1) would depend primarily on the agency’s articulation of its regulations.⁵¹⁸

Adequacy of the Other Agency’s Enforcement. How stringent the other agency’s enforcement of their regulations is not a consideration under Section 4(b)(1).⁵¹⁹ Preemption may still apply when the other agency’s regulations are not as strong as OSHA’s regulations.⁵²⁰ Once the other agency’s rule has been shown to have the effect of law, no further inquiry into how well the agency enforces that rule will be made.⁵²¹

10.2 Selected Other Federal Agencies Affecting Occupational Safety and Health

10.2.1 Mine Safety and Health Administration

Occupational safety and health matters with respect to the nation’s mining industry are regulated pursuant to the Federal Mine Safety and Health Act of 1977 (Mine Act).⁵²² The DOL established the Mine Safety and Health Administration (MSHA) to enforce the Mine Act. There are a number of important differences between the Mine Act and the OSH Act.

First, unlike the OSH Act which does not mandate inspection frequency, the Mine Act requires that MSHA inspect all underground mines at least four times per year and all surface mines at least twice a year. Further, MSHA does not require a warrant to conduct nonconsensual mine inspections. The purposes of these visits include determining whether an imminent danger exists and whether there is compliance with MSHA’s health and safety standards. Second, the Mine Act permits MSHA to shut down coal or other mine operations without a restraining order from a court. Section 107(a) of the Mine Act provides that when a federal inspector finds that an imminent danger is present in a mine, the inspector shall order the withdrawal of all other persons from a part, or all of that, mine until the imminent danger no longer exists.⁵²³

Third, mine operators are required to abate a violation immediately even if the mine operator challenges the citation before the Mine Commission. Fourth, recordkeeping and reporting requirements under the Mine Act are set forth in subsections 103(c)–103(e) and 103(h). The Mine Act contains a broad antiretaliation provision and grants other rights to mine employees as well. For example, Section 111

of the Mine Act provides pay for miners who accompany an MSHA inspector on an inspection. Section 107 also provides pay when a MSHA issues a “withdrawal order,” requiring the closure of a mine and removal of miners from the mine. Fifth, the Mine Act, unlike the OSH Act, does not permit state plans. A state may, however, enforce its own mine safety and health laws if they consistent with or more stringent than the Mine Act of MSHA regulations and standards.⁵²⁴

Following a January 2006 explosion at the Sago Mine in Sago, West Virginia, in which 12 trapped miners lost their lives, the Mine Act was amended by the Mine Improvement and New Emergency Response (MINER) Act of 2006.⁵²⁵ The MINER Act amended Section 316 of the Mine Act to require mine operators to “carry out on a continuing basis a program to improve accident preparedness and response at each mine” and to “develop and adopt have a written accident response plan.” The MINER Act also amended Section 103(j) to require a mine operator to notify MSHA “within 15 min” of the death or entrapment of any miner. The MINER Act also increases the penalty for willfully violating a mandatory health or safety standard, or knowingly refusing to comply with any order issued under Sections 104 and 107, to \$250,000 or imprisonment for not more than 1 year or by both. The MINER Act also provided MSHA with the authority to request an injunction to close a mine when the mine operator refuses to pay a final civil penalty.

10.2.2 U.S. Chemical Safety and Hazard Investigation Board

In 1990, Congress created the Chemical Safety and Hazard Investigation Board (CSB) to investigate the causes of any accidental chemical release resulting in a death or substantial property damage.⁵²⁶ Despite overlap between the investigation authority of OSHA and the CSB, the CSB’s reports focus on the root causes and often recommend changes in existing standards, or a new standard, to OSHA, EPA, NIOSH, and other federal agencies. Findings contained in the CSB’s Reports may be admitted as evidence in a civil action arising from the investigated accident.⁵²⁷ The CSB maintains a file of its current and completed investigation reports on its Web site.⁵²⁸

10.2.3 Nuclear Regulatory Commission

OSHA has published occupational health and safety standards regulating exposure to ionizing radiation (i.e. alpha, beta, gamma, X-ray, and neutron) and nonionizing (i.e. radiofrequency and electromagnetic) radiation for the General Industry, Shipyard Employment, and Construction.⁵²⁹ However, the primary federal law regulating human exposure to radiation is not the OSH Act, but is the Atomic Energy Act of 1954.⁵³⁰ Under the Act, the Nuclear Regulatory Commission (NRC) can promulgate

regulations about the safety of employees exposed to, or working with, nuclear materials.”⁵³¹

Any person holding a license issued under the Atomic Energy Act of 1954 and using “licensed material” (i.e. radioactive or radiation-emitting material) may not permit the exposure of individuals within a “restricted area” (i.e. an area in which radioactive materials are being used) to greater doses of radiation than are set forth in the regulations.⁵³² Although the primary thrust of the NRC regulations is to control ionizing radiation within the “restricted area,” the NRC has also published regulations on permissible levels of radiation in unrestricted areas, in effluents discharged into unrestricted areas, and for the disposal of radioactive materials by release into sanitary sewerage systems.⁵³³ The EPA Administrator, exercising authority under the Atomic Energy Act of 1954, has also promulgated regulations limiting exposure of the general population to ionizing radiation produced during the operation of nuclear power plants licensed by the NRC.⁵³⁴

There are additional federal agencies empowered to set standards for ionizing radiation control within areas under their jurisdiction. The DOL, for example, has promulgated regulations regarding radiation exposure in underground mines.⁵³⁵ The DOL has also issued radiation standards for uranium mining conducted under the Walsh–Healey Public Contracts Act.⁵³⁶ Radiation generated by devices and products that are not governed by the Atomic Energy Act and licensed by the NRC is regulated by the federal Radiation Control for Health and Safety Act of 1968.⁵³⁷ OSHA and the NRC established a Memorandum of Understanding in 1989 to govern mutual activities.⁵³⁸

10.2.4 Consumer Product Safety Commission

The Consumer Product Safety Act of 1972 created a Consumer Product Safety Commission (CPSC) and empowered it to promulgate “consumer product safety standards” applicable to consumer products found to present an unreasonable risk of injury. Under authority granted to it by the Federal Hazardous Substances Act,⁵³⁹ the CPSC may find that a substance distributed in interstate commerce is “hazardous.” The CPSC may impose packaging and labeling requirements to protect public health and safety or – in the cases of hazardous substances intended for the use of children or likely to be subject to access by children, or substances intended for household use – prohibit distribution altogether (“banned hazardous substance”).⁵⁴⁰ Insofar as safety in the workplace, the effect of the Federal Hazardous Substances Act is that hazardous substances distributed in interstate commerce and utilized by the U.S. worker will arrive safely packaged and accompanied by appropriate warnings. The CPSC does not have authority to regulate consumer product risk if such risk could be addressed by OSHA.⁵⁴¹

10.2.5 Environmental Protection Agency

Under Section 4(b)(1) of the OSH Act, when the EPA issues regulations that cover the same working conditions and employee safety as OSHA standards and regulations cover, the EPA regulations may preempt OSHA regulations, but only as applied to EPA regulations under the *Federal Insecticide, Fungicide, and Rodenticide Act* (FIFRA). Under other EPA statutes concerning waste disposal, toxic substances, air, and water, the relevant statute specifically provides that actions taken by EPA have no preemptive effect under the OSH Act.⁵⁴²

Under the *FIFRA* (also known as the Environmental Pesticide Act),⁵⁴³ EPA has the authority to regulate the use of pesticides and makes misuse of pesticides civilly and criminally punishable. The D.C. Circuit has held that the *FIFRA* authorizes EPA to promulgate and enforce occupational health and safety standards with respect to farm workers’ exposure to pesticides,⁵⁴⁴ and EPA has exercised that authority.⁵⁴⁵ In EPA’s regulations concerning pesticide use, there are standards pertaining to pesticide exposure in the workplace.⁵⁴⁶ OSHA is thus preempted from regulating in that area.

The *Clean Air Act* authorizes EPA to promulgate emission control standards and to inspect workplaces to see that its standards are being met.⁵⁴⁷ EPA has promulgated regulations designed to protect workers, among others, from accidental chemical releases. Under a final rule published by EPA in 1996, nearly 70 000 facilities that manufacture or handle certain hazardous chemicals were required to develop risk management plans by June 1999 to reduce the likelihood and severity of accidental chemical releases.⁵⁴⁸ However, Section 7412(r)(7)(D) requires EPA to consult with the Secretary before promulgating regulations pertaining to prevention of accidental releases.

The *Emergency Planning and Community-Right-to-Know Act*,⁵⁴⁹ also known as Title III of the SARA of 1986, requires the Secretary of Labor to issue regulations to protect workers at hazardous waste sites and during emergency response operations. In 1990, OSHA issued a hazardous waste operations and emergency response (HAZWOPER) standard.⁵⁵⁰ In 1994, OSHA published a nonmandatory appendix to the HAZWOPER standard for the certification and accreditation of training programs for workers handling hazardous materials.⁵⁵¹ The requirements of the Emergency Planning and Community-Right-to-Know Act do not preempt OSHA standards.⁵⁵²

The *Toxic Substances Control Act of 1976 (TSCA)* established a broad, nationwide program for the federal regulation of the manufacture and distribution of toxic substances.⁵⁵³ TSCA authorizes EPA to regulate the manufacture, processing, distribution, use, and disposal of chemical substances and mixtures of chemical substances. If EPA determines that a substance poses an unreasonable

risk to health or the environment, EPA may prohibit the manufacture or sale of the chemical or may adopt rules regulating its use. Actions taken by EPA under TSCA do not preempt actions OSHA takes under the OSH Act.⁵⁵⁴

In 2016, the TSCA of 1976 was amended by the *Frank Lautenberg Chemical Safety for the 21st Century Act*.⁵⁵⁵ The new law received bipartisan support in both the U.S. House of Representatives and the Senate. Amended TSCA includes: (i) a mandatory requirement for EPA to evaluate existing chemicals with clear and enforceable deadlines; (ii) new risk-based safety standard; (iii) increased public transparency for chemical information; and (iv) consistent source of funding for EPA to carry out the responsibilities under the new law. In addition, the word “workers” is now included in the definition of “potentially exposed or susceptible subpopulation.”⁵⁵⁶

10.2.6 Department of Transportation

The Department of Transportation (DOT) protects employees under a number of federal laws pertaining to aviation,⁵⁵⁷ railways,⁵⁵⁸ motor carriers,⁵⁵⁹ and pipelines.⁵⁶⁰ The DOT has issued regulations concerning employee safety in each of these areas.

Aviation. The Federal Aviation Act of 1958 (as amended) authorizes the Federal Aviation Administration (FAA) to promote safety of flight of civil aircraft in air commerce,⁵⁶¹ as well as to establish minimum safety standards for the operation of airports that serve any scheduled or unscheduled passenger operation of air carrier aircraft designed for more than 30 passenger seats.⁵⁶² It is generally accepted that FAA jurisdiction extends only to flight-crew members (pilots and flight attendants), not to ground personnel.

Railways. The Federal Railroad Safety Act of 1970 authorizes the Federal Railroad Administration (FRA), an agency within the DOT, to promulgate regulations for all areas of railroad safety, including employee safety. To date, however, the DOT has not adopted railroad occupational safety standards for all railroad working conditions or workplaces. OSHA retains jurisdiction over safety and health of railroad employees with respect to those “working conditions” for which the DOT has not adopted standards.

Motor Carriers. Motor carriers are regulated by the DOT through the Motor Carrier Act of 1984.⁵⁶³ Even though the DOT has promulgated regulations for commercial motor vehicle worker protection with regard to step, handhold and deck requirements,⁵⁶⁴ motor vehicle common carriers are still subject to OSHA standards in areas where the DOT has not specifically regulated.⁵⁶⁵

Pipelines. The Natural Gas Pipeline Safety Act of 1968 (NGPSA) authorizes the DOT Secretary to establish minimum federal safety standards for pipeline facilities and the transportation of gas in commerce. DOT’s authority under NGPSA preempts OSHA rules. In *Texas Eastern*

Transmission Corp.,⁵⁶⁶ the Review Commission determined that the DOT’s minimal federal safety standards regarding working conditions preempted OSHA standards regarding working conditions that were the subject of the alleged violations. However, a contractor engaged in repairing a pipeline would be subject to OSHA standards because NGPSA standards apply only to persons engaged in gas transport or operation of pipeline facilities.⁵⁶⁷

11 FUTURE OF OCCUPATIONAL SAFETY AND HEALTH LAW

After nearly 50 years, the OSH Act still enjoys broad support among stakeholders despite continuing concerns about the pace of standards development. The slower pace of OSHA’s development of occupational safety and health standards, and the obsolescence of many existing OSHA PELs heighten the influence of international consensus standards. In the twenty-first century, international standards may play a bigger role in determining multinational employer actions than national governmental laws and regulations. What impact the realities of the twenty-first century’s global economy will have on the OSH Act remains to be seen. What is certain is that many of legal and policy issues arising from the Occupational Safety and Health Act of 1970 will undoubtedly continue to occupy the attention of stakeholders, Congress, OSHA, the Review Commission, and the federal courts for many years yet to come.

ENDNOTES

- ¹ 41 U.S.C. § 35.
- ² 30 U.S.C. § 471.
- ³ 33 U.S.C. § 901.
- ⁴ 40 U.S.C. § 327.
- ⁵ 41 U.S.C. § 351.
- ⁶ 30 U.S.C. § 801.
- ⁷ Occupational Safety and Health Act of 1970, 29 U.S.C. §§ 651–678 (2000).
- ⁸ 29 U.S.C. § 651. The provisions of the OSH Act can be enumerated in two ways: (1) by reference to sections of Title 29 of the United States Code (U.S.C.), e.g., Sections 651, 652, and 653 and (2) by reference to internally numbered sections of the OSH Act, e.g., Sections 1, 2, and 3. In the text of this chapter, internally numbered sections will be cited (e.g., Section 4), but in the references, United States Code citations will be used (e.g., 29 U.S.C. § 653).
- ⁹ 29 U.S.C. § 661.
- ¹⁰ 29 U.S.C. §§ 669 and 670.
- ¹¹ 29 U.S.C. § 671.

- ¹² For a discussion of the weight to be accorded by the Secretary to NIOSH recommendations, *see* Industrial Union Department, AFL-CIO v. Hodgson, 499 F.2d 467, 476–477, 1 OSH Cases 1631 (D.C. Cir. 1974). References to “F.2d” designate the volume (e.g., 499) and page (e.g., 467) of the *Federal Reporter*, Second Series, which contains the official reported decisions of the U.S. Courts of Appeals as published by the West Publishing Company. References to “OSH Cases” designate the same decision as reported in the “Occupational Safety and Health Cases” published by Bloomberg Government (formerly the Bureau of National Affairs or BNA).
- ¹³ 29 U.S.C. § 656.
- ¹⁴ 29 U.S.C. § 676(b).
- ¹⁵ For a description of the activities of the National Commission on State Workmen’s Compensation Laws and an evaluation of its work, *see* Ashford (1).
- ¹⁶ The Review Commission has held that the Secretary may even cite individuals or companies who have gone out of business and fine them for violating OSHA regulations; such authority is intended to encourage future compliance with job safety rules. *See* Secretary of Labor v. Yandell, OSHRC, No. 94-3080, March 12, 1999; Secretary of Labor v. Kenny Niles Construction Co., OSHRC, No. 95-1539, March 12, 1999.
- ¹⁷ 29 U.S.C. § 668.
- ¹⁸ Executive Order 12196. *See* <https://www.archives.gov/federal-register/codification/executive-order/12196.html>.
- ¹⁹ 29 U.S.C. §§ 652 and 653(a).
- ²⁰ 29 U.S.C. § 652(5). In 1998, President Clinton signed legislation extending OSHA coverage to U.S. Postal Service facilities.
- ²¹ American Law Institute. 2015. Restatement of the Law, Employment Law: Conditions for the existence of employment relationship, Section 1.01.
- ²² An “established federal standard” is defined in 29 U.S.C. § 652(10) as “any operative occupational safety and health standard established by any agency of the United States and presently in effect, or contained in any act of Congress in force on the date of enactment of this Act.” 29 U.S.C. 653(b)(2) of the OSH Act listed several federal statutes from which established federal standards were to be derived, including, but not limited to, the Walsh–Healey Act (41 U.S.C. §§ 35–45), the Service Contract Act of 1965 (41 U.S.C. §§ 351–357), and the National Foundation on Arts and Humanities Act (20 U.S.C. §§ 951–960).
- ²³ A “national consensus” standard is defined in 29 U.S.C. § 652(9) of the OSH Act as any occupational safety and health standard, which “(1) has been adopted and promulgated by a nationally recognized standards producing organization under procedures, whereby it can be determined by the Secretary that persons interested and affected by the scope or provisions of the standard have reached substantial agreement on its adoption, (2) was formulated in a manner which afforded an opportunity for diverse views to be considered, and (3) has been designated as such a standard by the Secretary, after consultation with other appropriate federal agencies.” The principal sources for national consensus standards were the American National Standards Institute (ANSI) and the National Fire Protection Association (NFPA). American Federation of Labor v. Brennan, 530 F.2d 109, 111 at n. 2, 3 OSH Cases 1820, 1821 at n. 2 (Third Cir. 1975).
- ²⁴ Pub. L. No. 404, 60 Stat. 237, Chapter 324, §§ 1–12 (1946) (codified by Pub. L. No. 89-554 (1966) in 5 U.S.C. § 551–559, 701–706, 1305, 3105, 3105, 3344, 5372, 7521).
- ²⁵ The courts have held that OSHA does not have the right to change advisory national consensus standards (“should”) to mandatory standards (“shall”) upon adoption as OSHA standards without following formal rulemaking procedures. Absent such rulemaking, citations issued to employers pursuant to these standards have been vacated. *Usery v. Kennecott Copper Corp.*, 577 F.2d 1113, 1117–1118, 6 OSH Cases 1197, 1199 (Tenth Cir. 1977); *Marshall v. Pittsburgh-Des Moines Steel Co.*, 584 F.2d 638, 644, 6 OSH Cases 1929, 1933 (Third Cir. 1978). *See also* *Marshall v. Anaconda Co.*, 596 F.2d 370, 376–377, 7 OSH Cases 1382, 1385–1386 (Ninth Cir. 1979).
- ²⁶ 29 U.S.C. § 655(c)(1).
- ²⁷ *Florida Peach Growers Association v. Department of Labor*, 489 F.2d 120, at 124, 1 OSH Cases 1472, at 1475 (Fifth Cir. 1974). *See also* *Industrial Union Dept. AFL-CIO v. American Petroleum Institute*, 448 U.S. 607, 651 n. 59, 8 OSH Cases 1586, 1602 (1980).
- ²⁸ 29 U.S.C. § 655(b)(1) to (4).
- ²⁹ 29 U.S.C. § 655(b)(5).
- ³⁰ 5 U.S.C. § 553.
- ³¹ 5 U.S.C. § 706(1).
- ³² *National Congress of Hispanic Am. Citizens (El Congreso) v. Usery*, 554 F.2d 1196, 5 OSH Cases 1255 (D.C. Cir. 1977).
- ³³ *Farmworker Justice Fund v. Brock*, 811 F.2d 613, 13 OSH Cases 1049 (D.C. Cir. 1986, *vacated as moot*, 817 F.2d 890, 13 OSH Cases 1288 (D.C. Cir. 1987) (using the authority under Section 706(1) of the Administrative Procedure Act).
- ³⁴ *Oil, Chemical & Atomic Workers Union v. OSHA (“Oil Workers”)*, 145 F.3d 120, 122 (Third Cir. 1998).
- ³⁵ *Public Citizen Health Research Group v. Chao*, 314 F.3d 143 (Third Cir. 2002).
- ³⁶ *Industrial Union Dep’t v. American Petroleum Inst.*, 448 U.S. 607, 8 OSH Cases 1586.

- ³⁷ AFL-CIO v. OSHA, 965 F.2d 962, 15 OSH Cases 1729 (11th Cir. 1992).
- ³⁸ *Id.* at 986, 15 OSH Cases 1729.
- ³⁹ 452 U.S. 490, 509 (1981), 9 OSH Cases 1913 (1981).
- ⁴⁰ 452 U.S. at 513, n. 31; 9 OSH Cases at 1922, n. 31. Section 3(8) [29 U.S.C. § 652(8)] states “The term ‘occupational safety and health standard’ means a standard which requires conditions, or the adoption or use of one or more practices, means, methods, operations, or processes, *reasonably necessary or appropriate* to provide safe or healthful employment and places of employment” (*emphasis added*). For standards dealing with toxic materials or harmful physical agents, Section 6(b)(5) [29 U.S.C. 655(b)(5)], imposes the following additional requirements: “The Secretary, in promulgating standards dealing with toxic materials or harmful physical agents under this subsection, shall set the standard which most adequately assures, *to the extent feasible*, on the basis of the best available evidence, that no employee will suffer material impairment of health or functional capacity, even if such employee has regular exposure to the hazard dealt with by such standard for the period of his working life” (*emphasis added*).
- ⁴¹ Industrial Union Department, AFL-CIO v. Hodgson, 499 F.2d at 478, 1 OSH Cases at 1639, cited approvingly by the Supreme Court in American Textile Mfrs. v. Donovan, 452 U.S. at 513, n. 31, 9 OSH Cases at 1922, n. 31.
- ⁴² American Textile Mfrs. v. Donovan, 452 U.S. at 530, n. 55, 9 OSH Cases at 1928–1929, n. 55; United Steelworkers of America, AFL-CIO v. Marshall and Bingham, 647 F.2d at 1265, 8 OSH Cases at 1864.
- ⁴³ American Textile Mfrs. v. Donovan, 452 U.S. at 530, n. 55, 9 OSH Cases at 1928–1929, n. 55.
- ⁴⁴ *Id.* at 509.
- ⁴⁵ *Id.* at 513, n. 32.
- ⁴⁶ *Id.* at 509, n. 29.
- ⁴⁷ 58 Fed. Reg. 16,612 (1993).
- ⁴⁸ 938 F.2d 1310, 15 OSH Cases 1145 (D.C. Cir. 1991).
- ⁴⁹ United Steelworkers v. Marshall, 647 F.2d 1189, 1266, 8 OSH Cases 1810 (D.C. Cir. 1980), cert. denied, 453 U.S. 913 (1981).
- ⁵⁰ American Iron & Steel Inst., 577 F.2d at 838, 6 OSH Cases 1451.
- ⁵¹ United Steelworkers v. Marshall, 647 F.2d at 1272, 8 OSH Cases 1810.
- ⁵² 42 U.S.C. § 4332(2)(c).
- ⁵³ 29 C.F.R. § 11.10(a)(3).
- ⁵⁴ 29 C.F.R. § 11.10(a)(1).
- ⁵⁵ 5 U.S.C. § 603(a).
- ⁵⁶ Small Business Regulatory Enforcement and Fairness Act, Pub. L. No. 104-121, 110 Stat. 847 (codified at 5 U.S.C. § 611).
- ⁵⁷ 29 U.S.C. § 609(b) and (d).
- ⁵⁸ 29 U.S.C. § 611(a)(4).
- ⁵⁹ 29 U.S.C. § 611(b).
- ⁶⁰ Pub. L. No. 96-511, 94 Stat. 2812 (codified at 44 U.S.C. §§ 3501–3521).
- ⁶¹ 44 U.S.C. ch. 35; 5 C.F.R. Part 1320.
- ⁶² *Id.* §§ 3502(3)(A), 3506(c)(1). The 1995 amendments to the Paperwork Reduction Act overruled *Dole v. United Steelworkers*, 494 U.S. 26, 14 OSH Cases 1425 (1990) (holding that the OSH Act did not apply to OSHA’s hazardous communication standard because information was disseminated to the public rather than collected by OSHA).
- ⁶³ See 74 Fed. Reg. 55,269–55,272 (October 27, 2009).
- ⁶⁴ 46 Fed. Reg. 13,193 (February 17, 1981).
- ⁶⁵ Executive Order 12866, *Regulatory Planning and Review*, 58 Fed. Reg. 51,735 (October 4, 1993).
- ⁶⁶ *Id.* at Section 6(a)(3)(C).
- ⁶⁷ 72 Fed. Reg. 2763 (January 23, 2007).
- ⁶⁸ OMB issued a memorandum (M-07-13) on the implementation of Executive Order 13422 on April 25, 2007. See <http://www.whitehouse.gov/omb/inforeg/regpol.html>.
- ⁶⁹ 76 Fed. Reg. 3821 (January 21, 2011).
- ⁷⁰ 82 Fed. Reg. 9339 (January 30, 2017).
- ⁷¹ Treasury and General Government Appropriations Act for Fiscal Year 2001, Pub. L. No. 106-554, Section 515.
- ⁷² See https://www.whitehouse.gov/omb/fedreg_final_information_quality_guidelines.
- ⁷³ Salt Institute v. Leavitt, 345 F. Supp. 2d 589, 598-601 (E.D. VA 2004) (Fourth Cir. March 6, 2006).
- ⁷⁴ An employer’s general duty to provide a safe workplace may not necessarily be discharged simply by the employer’s compliance with specific OSHA standards. In *UAW v. General Dynamics*, 815 F.2d 1570, 1577, 13 OSH Cases 1201, 1206-07 (D.C. Cir.), cert. denied, 484 U.S. 976 (1987), the court stated [I]f ... an employer knows a particular safety standard is inadequate to protect his workers against the specific hazard it is intended to address, or that the conditions in his place of employment are such that the safety standard will not adequately deal with the hazards to which his employees are exposed, he has a duty under section 5(a)(1) to take whatever measures may be required by the OSH Act, over and above those mandated by the safety standard, to safeguard his workers. In sum, if an employer knows that a specific standard will not protect his workers against a particular hazard, his duty under section 5(a)(1) will not be discharged no matter how faithfully he observes that standard.”
- ⁷⁵ 489 F.2d 1257, 1285, 1 OSH Cases 1422 (D.C. Cir. 1973).
- ⁷⁶ Titanium Metals Corp. v. Uery, 579 F.2d 536, 541, 6 OSH Cases 1940, 1945 (Rev. Comm’n 1981).

- ⁷⁷ 501 F.2d 504, 2 OSH Cases 1041 (Eighth Cir. 1974).
- ⁷⁸ *Brennan v. OSHRC* (Vy Lactos Laboratories), 494 F.2d 460, 462, 1 OSH Cases 1623, 1624 (Eighth Cir. 1974).
- ⁷⁹ *National Realty & Constr. Co., v. OSHRC*, 1 OSH Cases 1049 (Rev. Comm'n 1972), *rev'd*, 489 F.2d 1257, 1265, 1 OSH Cases 1422, 1426 (D.C. Cir. 1973); *Babcock & Wilcox Co. v. OSHRC*, 622 F.2d 1160, 1165, 8 OSH Cases 1317, 1319 (Third Cir. 1980); *Illinois Power Co. v. OSHRC*, 632 F.2d 25, 28, 8 OSH Cases 1512, 1514–1515 (Seventh Cir. 1980); *Titanium Metals Corp. of America v. Usery*, 579 F.2d 536, 541, 6 OSH Cases 1873, 1876–1878 (Ninth Cir. 1978).
- ⁸⁰ See 29 U.S.C. § 666.
- ⁸¹ OSHA, *Field Operations Manual*, ch. 4.II.c.3.
- ⁸² 12 OSH Cases 1928 (Rev. Comm'n 1986).
- ⁸³ *Industrial Union Dep't AFL-CIO v. American Petroleum Inst.*, 448 U.S. 607, 8 OSH Cases 1586 (1980).
- ⁸⁴ *National Realty & Constr. Co., v. OSHRC*, 1 OSH Cases 1049 (Rev. Comm'n 1972), *rev'd*, 489 F.2d 1257, 1 OSH Cases 1422 (D.C. Cir. 1973).
- ⁸⁵ 29 U.S.C. § 654.
- ⁸⁶ 58 Fed. Reg. 35,308 (June 30, 1993).
- ⁸⁷ Health and safety standards promulgated by the Secretary pursuant to OSH Act can be found at 29 C.F.R. Part 1910. Federal health and safety standards for the construction industry were initially promulgated under the Contract Work Hours and Safety Standards Act, 40 U.S.C. § 327 et seq. These standards were incorporated by reference under the OSH Act, are enforceable under both laws, and can be found at 29 C.F.R. Part 1926. Health and safety standards for ship repairing, shipbuilding, shipbreaking, and longshoring were initially promulgated pursuant to the Longshore and Harbor Worker's Compensation Act, 33 U.S.C. § 901. These standards were incorporated by reference under the OSH Act, are enforceable under both laws, and can be found in 29 C.F.R. Parts 1915 and 1918. Health and safety standards originally promulgated under the Walsh–Healey Public Contracts Act, the McNamara–O'Hara Service Contract Act of 1965, and the National Foundation on the Arts and Humanities Act of 1965 can be found in 41 C.F.R. Part 50-204, 29 C.F.R. Part 1516, and 20 C.F.R. Part 505. These were adopted and are enforceable by OSHA. Standards promulgated under the aforementioned statutes will be superseded if corresponding standards that are promulgated under the OSH Act are determined by the Secretary to be more effective. See 29 U.S.C. § 653.
- ⁸⁸ For a listing of the initial package of national consensus and established federal standards, see 36 Fed. Reg. 10,466 (1971).
- ⁸⁹ In 1995, OSHA pledged to eliminate over 1000 of the over 3000 pages dedicated to the agency in the Code of Federal Regulations. Most of the standards to be done away with were included in 29 C.F.R. § 1910, which sets job safety and health provisions for general industry, and OSHA pledged also to revise and simplify the 1971 consensus standards. On March 7, 1996, OSHA published a final rule characterized as a “down payment” on OSHA's pledge and eliminated 275 of OSHA pages in the Code of Federal Regulations. See 61 Fed. Reg. 9228 (March 7, 1996).
- ⁹⁰ TLVs had been developed principally in 1968 by the American Conference of Governmental Industrial Hygienists (ACGIH) and were subsequently incorporated into the Walsh–Healey Public Contracts Act. Ashford, *supra* note 15 at p. 154. The Secretary did not include the ACGIH's carcinogen standards in his Section 6(a) package, but instead preferred to develop his own standards regarding carcinogens.
- ⁹¹ 54 Fed. Reg. 2332 (January 19, 1989). OSHA defines hundreds of *air contaminants* in three tables (Tables Z-1, Z-2, and Z-3 of 29 C.F.R. 1910.1000; often called the “Z Lists”).
- ⁹² The PELs established by OSHA can be found at 29 C.F.R. § 1910.1000, Tables Z-1, Z-2, and Z-3. Pursuant to a January 1989 rulemaking, OSHA made 212 PELs more protective, established 162 new PELs for previously unregulated substances, and left other PELs unchanged. In doing so, OSHA stated that it relied heavily on the widely accepted 1987–1988 TLVs published by ACGIH and the recommended exposure limits (RELs) developed by the NIOSH. 54 Fed. Reg. 2332, 2333–35 (January 19, 1989).
- ⁹³ *AFL-CIO v. OSHA*, 965 F.2d 962, 15 OSH Cases 1729 (Eleventh Cir. 1992).
- ⁹⁴ OSHA formally revoked the 1989 PELs in June 1993 with publication of a notice at 58 Fed. Reg. 35,338 (June 30, 1993). In so doing, OSHA republished the less stringent limits that were in effect prior to 1989.
- ⁹⁵ 29 C.F.R. § 1910.1045.
- ⁹⁶ 36 Fed. Reg. 23,207 (1971).
- ⁹⁷ 37 Fed. Reg. 11,318 (1972).
- ⁹⁸ *Industrial Union Department, AFL-CIO v. Hodgson*, 449 F.2d 467, 477–478, 1 OSH Cases 1631 (D.C. Cir. 1974). The court upheld the standard with two exceptions: OSHA had to reconsider (1) the effective date of the two-fiber standard and (2) the standard's record-keeping provision. However, OSHA took no action and the standard with the lower PEL went into effect in 1976.
- ⁹⁹ 48 Fed. Reg. 51,086 (1983).
- ¹⁰⁰ *Asbestos Information Ass'n v. OSHA*, 727 F.2d 415, 11 OSH Cases 1817 (Fifth Cir. 1984).
- ¹⁰¹ 51 Fed. Reg. 22,612 (June 20, 1986).
- ¹⁰² The asbestos standard for construction included provisions for asbestos removal and demolition work.

- 103 In 1992, OSHA deleted these latter three substances from the standard. See 57 Fed. Reg. 24,310 (1992).
- 104 Building & Constr. Trades Dep't, *AFL-CIO v. Secretary of Labor*, 838 F.2d 1258, 13 OSH Cases 1561 (D.C. Cir. 1988).
- 105 29 C.F.R. § 1910.1001(c)(2).
- 106 59 Fed. Reg. 40,964 (August 10, 1994). The rule was codified at 29 C.F.R. §§ 1910.1001, 1915.1001 and 1926.1101 (formerly 1926.58), and the several revisions that followed were written into those sections.
- 107 *Id.*
- 108 61 Fed. Reg. 43,454 (August 23, 1996).
- 109 *AIA/NA v. OSHA*, 117 F.3d 891, 17 OSH Cases 2089, 117 F.3d 891 (Fifth Cir. 1997).
- 110 63 Fed. Reg. 35,137 (June 29, 1998). The changes were made to 29 C.F.R. Parts 1915 and 1926. The asbestos provisions in 29 C.F.R. Part 1910, the general industry asbestos standard, remained unchanged.
- 111 43 Fed. Reg. 5918 (1978). OSHA based its reasoning on its carcinogen policy that mandated that OSHA set a PEL for a carcinogen at the lowest feasible level in the absence of any evidence that a higher level was safe. See 45 Fed. Reg. 5282 (1980)(codified at 29 C.F.R. Part 90).
- 112 *Industrial Union Dept. v. American Petroleum Institute (Benzene)*, 448 U.S. 607, 8 OSH Cases 1586 (1980). OSHA was required to review other standards (e.g., the arsenic standard) in light of this U.S. Supreme Court decision on significant risk.
- 113 448 U.S. at 607, 8 OSH Cases at 1596.
- 114 50 Fed. Reg. 50,512 (1985).
- 115 52 Fed. Reg. 34,460 (September 11, 1987)(codified at 29 C.F.R. § 1910.1028).
- 116 The 1 ppm limit is identical to that set in the 1978 standard. The 1987 standard, however, is followed by a risk assessment analysis from which OSHA determined the benzene level that posed a significant risk. The 1978 standard was based on a feasibility determination after OSHA simply assumed that no level of benzene exposure would be safe for humans. 43 Fed. Reg. 5918, 5946–5947 (1978).
- 117 29 C.F.R. § 1910.1028(i).
- 118 29 C.F.R. § 1910.1000, TABLE Z-2.
- 119 40 Fed. Reg. 48,814 (October 17, 1975).
- 120 67 Fed. Reg. 70,707 (November 26, 2002).
- 121 80 Fed., Reg. 47,565 (August 7, 2015).
- 122 82 Fed. Reg. 2470 (January 9, 2017).
- 123 *Id.* at 29,187.
- 124 82 Fed. Reg. 14,439 (May 20, 2017).
- 125 82 Fed. Reg. 8346 (January 24, 2017).
- 126 82 Fed. Reg. 29,182 (June 27, 2017).
- 127 15 U.S.C. § 2601.
- 128 51 Fed. Reg. 35,003 (1986).
- 129 55 Fed. Reg. 32,736 (1990).
- 130 61 Fed. Reg. 56,746 (1996).
- 131 61 Fed. Reg. 56,746 (November 4, 1996) (codified at 29 C.F.R. § 1910.1051).
- 132 57 Fed. Reg. 42,104 (1992).
- 133 *In re International Chem. Workers Union*, 830 F.2d 369, 13 OSH Cases 1402 (D.C. Cir. 1987).
- 134 55 Fed. Reg. 4052 (1990).
- 135 *In re International Chem. Workers Union*, 958 F.2d 11444, 1150, 15 OSH Cases 1529 (D.C. Cir. 1992).
- 136 57 Fed. Reg. 42,101 (September 14, 1992). The standard for general industry is codified at 29 C.F.R. § 1910.1027 and the standard for construction is codified at 29 C.F.R. § 1926.63.
- 137 29 C.F.R. § 1910.1027(f)(1)(ii) and Table 1. For those operations subject to a separate engineering control airborne limit in addition to lowering exposures through engineering and work practice controls, employers must also require employees to use respiratory protection. See 29 C.F.R. § 1910.1027(f)(2)(i).
- 138 *Color Pigments Mfrs. Ass'n v. OSHA*, 16 F.3d 1157, 16 OSH Cases 1665 (Eleventh Cir. 1994).
- 139 *Id.* at 1164.
- 140 43 Fed. Reg. 27,350 (1978) (codified at 29 C.F.R. § 1910.1043). The original standard was generally upheld by the U.S. Supreme Court in *American Textile Mfrs. Inst. v. Donovan*, 452 U.S. 490, 9 OSH Cases 1913 (1981). Cotton that has been washed in accordance with outlined processes is exempt from the standard. See 29 C.F.R. § 1910.1043(n). Some forms of cotton dust exposure not covered by the separate cotton dust standard are regulated pursuant to the air contaminants standard, 29 C.F.R. § 1910.1000.
- 141 Challenge was based on the Supreme Court's *Benzene* requirement that OSHA must establish that a significant risk of harm exists before regulating, even though the cotton dust standard preceded in time the *Benzene* decision.
- 142 *American Textile Mfrs. Inst. v. Donovan*, 452 U.S. 490, 506 n. 25, 9 OSH Cases 1913 (1981).
- 143 *Id.* at 508-509.
- 144 *Id.* at 509.
- 145 43 Fed. Reg. 27,418 (1978).
- 146 *Texas Indep. Ginners Ass'n v. Marshall*, 630 F.2d 398, 401, 8 OSH Cases 2225 (Fifth Cir. 1980).
- 147 29 C.F.R. § 1910.1044.
- 148 49 Fed. Reg. 25,734 (June 22, 1984) (codified at 29 C.F.R. § 1910.1047).
- 149 *Public Citizen Health Research Group v. Tyson*, 796 F.2d 1479, 12 OSH Cases 1905 (D.C. Cir. 1986).
- 150 *Public Citizen Health Research Group v. Brock*, 823 F.2d 626, 13 OSH Cases 1362 (D.C. Cir. 1987).
- 151 53 Fed. Reg. 1724 (January 8, 1988) (STEL is codified at 29 C.F.R. § 1910.1047(c)(2)).

- ¹⁵² The standard prohibits rotating employees in and out of exposure areas as a means of exposure control because of the risk to other employees.
- ¹⁵³ *United Auto Workers v. Donovan*, 590 F. Supp. 747, 11 OSH Cases 2017 (D.D.C. 1984).
- ¹⁵⁴ *United Auto Workers v. Donovan*, 756 F.2d 162, 12 OSH Cases 1201 (D.C. Cir. 1985).
- ¹⁵⁵ 52 Fed. Reg. 46,168 (December 4, 1987) (codified at 29 C.F.R. § 1910.1048).
- ¹⁵⁶ 57 Fed. Reg. 22,290 (May 27, 1992).
- ¹⁵⁷ *UAW v. Pendergrass*, 878 F.2d 389, 14 OSH Cases 1025 (D.C. Cir. 1989).
- ¹⁵⁸ *OCAW v. OSHA*, 145 F.3d 120, 18 OSH Cases 1321 (Third Cir. 1998).
- ¹⁵⁹ *Public Citizen Health Research Group v. Chao*, 314 F.3d 143 (Third Cir. 2002).
- ¹⁶⁰ 71 Fed. Reg. 10,100 (February 28, 2006) (codified at 29 C.F.R. § 1910.1026).
- ¹⁶¹ *Public Citizen Health Research Group v. Dept. of Labor*, 557 F.3d 165 (Third Cir. 2009).
- ¹⁶² 75 Fed. Reg. 12,681 (March 17, 2010).
- ¹⁶³ 29 C.F.R. § 1910.1018.
- ¹⁶⁴ *Asarco, Inc. v. OSHA*, 647 F.2d 1, 9 OSH Cases 1508 (Ninth Cir. 1981).
- ¹⁶⁵ 448 U.S. 607, 8 OSH Cases 1586 (1980).
- ¹⁶⁶ 48 Fed. Reg. 1864 (January 14, 1983).
- ¹⁶⁷ *Asarco, Inc. et al. v. OSHA*, 746 F.2d 483, 11 OSH Cases 2217 (Ninth Cir. 1984).
- ¹⁶⁸ 40 Fed. Reg. 45,934 (1975).
- ¹⁶⁹ 43 Fed. Reg. 52,952 (1978) (29 C.F.R. § 1910.1025). *See also* 43 Fed. Reg. 54,354 (1978).
- ¹⁷⁰ *United Steelworkers of Am., AFL-CIO v. Marshall*, 647 F.2d 1189, 8 OSH Cases 1810 (D.C. Cir. 1980), *cert. denied*, 453 U.S. 913 (1981).
- ¹⁷¹ *Id.* at 1311, 8 OSH Cases 1810 for a listing of the industries as to which the standard was remanded as well as for a summary of the court's order.
- ¹⁷² 46 Fed. Reg. 60,758 (December 11, 1981).
- ¹⁷³ 54 Fed. Reg. 29,142 (July 11, 1989).
- ¹⁷⁴ 55 Fed. Reg. 3146 (January 30, 1990). OSHA set the standard for small foundries at 75 µg and at 50 µg for large foundries.
- ¹⁷⁵ *American Iron and Steel Inst. V. OSHA*, 939 F.2d 975, 15 OSH Cases 1177 (D.C. Cir. 1991). Those six industries were nonferrous foundries, secondary copper smelters, brass and bronze ingot manufacturers, independent collectors and processors of scrap lead (including independent battery breakers), leaded steel-making operations, and lead chemical manufacturers.
- ¹⁷⁶ The court remanded the standard as to the brass and bronze industry for an economic feasibility determination of the 50 µg standard.
- ¹⁷⁷ 60 Fed. Reg. 52,856 (October 11, 1995).
- ¹⁷⁸ 42 U.S.C. § 4853.
- ¹⁷⁹ 58 Fed. Reg. 26,590 (May 4, 1993).
- ¹⁸⁰ 61 Fed. Reg. 45,778 (August 29, 1996) (codified at 49 C.F.R. Part 745 Subparts L and Q).
- ¹⁸¹ *See* <https://www.reginfo.gov/public/do/eAgendaViewRule?pubId=201604&RIN=1218-AD10>.
- ¹⁸² 51 Fed. Reg. 42,257 (1986); 56 Fed. Reg. 57,036 (1991).
- ¹⁸³ 56 Fed. Reg. 57,036 (1991).
- ¹⁸⁴ 62 Fed. Reg. 1494 (January 10, 1997) (codified at 29 C.F.R. § 1910.1052).
- ¹⁸⁵ 63 Fed. Reg. 50,712 (September 22, 1998).
- ¹⁸⁶ 28 U.S.C. § 2112(a).
- ¹⁸⁷ Pub. L. No. 104-121, 110 Stat. 857-874.
- ¹⁸⁸ The issues in contention were medical removal protection provision, extension of the date by which employers in certain industry sectors were required to conform to engineering and work practice controls and relaxing of the respirator requirements.
- ¹⁸⁹ 63 Fed. Reg. 24,501 (May 4, 1998).
- ¹⁹⁰ 63 Fed. Reg. 50,712 (September 22, 1998).
- ¹⁹¹ 29 C.F.R. § 1910.1052.
- ¹⁹² 72 Fed. Reg. 37,501 (July 10, 2007).
- ¹⁹³ 50 Fed. Reg. 27,674 (1985).
- ¹⁹⁴ 50 Fed. Reg. 42,789 (1985).
- ¹⁹⁵ 52 Fed. Reg. 26,776 (1987).
- ¹⁹⁶ 54 Fed. Reg. 20,672 (1989).
- ¹⁹⁷ 57 Fed. Reg. 35,630 (1992).
- ¹⁹⁸ 29 C.F.R. § 1910.95.
- ¹⁹⁹ 29 C.F.R. § 1910.95(c)–(p). The amendment exempts employers engaged in oil and gas well drilling and services operations.
- ²⁰⁰ 29 C.F.R. § 1910.95(g). The Review Commission has ruled that the action level of 85 dB excludes “impulse noise,” defined as sharp noise peaks lasting less than 1 s and spaced more than 1 s apart. *Collier-Keyworth Co.*, 13 OSH Cases 1208, remanded 13 OSH Cases 1269 (Rev. Comm’n 1987), on remand 13 OSH Cases 1940 (Rev. Comm’n 1988). An employer’s failure to make audiometric tests available to its employees is classified as a “serious” OSHA violation. *Secretary of Labor v. Miniature Nut and Screw Corp.*, 17 OSH Cases 1557 (Rev. Comm’n 1996).
- ²⁰¹ 29 C.F.R. § 1910.959(d)(1)(ii).
- ²⁰² 29 C.F.R. § 1910.95(i) (1), (2) (ii) (B). Notwithstanding the fact that an employer provides hearing protectors, employers may receive citations for failing to ensure their use. *See, e.g., United States Container Corp.*, 13 OSH Cases 1415 (Rev. Comm’n 1987).
- ²⁰³ *Forging Indus. Ass’n v. Donovan*, 773 F.2d 1436 (Fourth Cir. 1985).
- ²⁰⁴ 53 Fed. Reg. 26,437 (July 13, 1988).
- ²⁰⁵ 67 Fed. Reg. 44,037 (July 1, 2002).
- ²⁰⁶ The historical OSHA PEL was derived by assessing percent quartz in a respirable dust sample and using

the following arithmetical formula: $PEL = 10$ divided by the sum $2 + \text{percent quartz in the sample}$. The measured concentration of respirable dust is then compared against the computed PEL to determine compliance. If the respirable quartz is pure quartz (100%), the formula will result in a PEL of approximately 0.1 mg m^{-3} .

²⁰⁷ In 1974, NIOSH originally recommended setting a 0.05 mg/m^3 exposure limit. See NIOSH, *Criteria for a Recommended Standard for Occupational Exposure to Crystalline Silica*, DHEW (NIOSH) Pub. No. 75-120. In recommending the limit, NIOSH stated that “[U]ntil improved sampling and analytical methods are developed for respirable crystalline silica, NIOSH will continue to recommend an exposure limit of 0.05 mg m^{-3} to reduce the risk of developing silicosis, lung cancer, and other adverse health effects. NIOSH also recommends minimizing the risk of illness that remains for workers exposed at the REL by substituting less hazardous materials for crystalline silica when feasible, by using appropriate respiratory protection when source controls cannot keep exposures below the NIOSH Recommended Exposure Limit, and by making medical examinations available to exposed workers.”

²⁰⁸ 78 Fed. Reg. 56,274 (September 12, 2013).

²⁰⁹ 81 Fed. Reg. 16,285 (March 25, 2016).

²¹⁰ See Interim Enforcement Guidance for the Respirable Crystalline Silica in Construction Standard, 29 CFR 1926.1153 at https://www.osha.gov/pls/oshaweb/owadisp.show_document?p_table=INTERPRETATIONS&p_id=31349.

²¹¹ *North America's Building Trade Unions v. OSHA & Chamber of Commerce*, No. 16-1105 (December 22, 2017).

²¹² *Id.*

²¹³ *Society of the Plastics Industry v. OSHA*, 509 F.2d 1301, 1306, 2 OSH Cases 1496, 1500 (Second Cir.) *cert. denied sub nom. Firestone Plastics v. Department of Labor*, 421 U.S. 992 (1975) (finding vinyl chloride regulation proper where it was based on scientific evidence from animal studies and the occurrence of cases of rare liver cancers in three employees).

²¹⁴ 29 C.F.R. § 1910.1017.

²¹⁵ 29 C.F.R. § 1910.1017(h)(1)(ii).

²¹⁶ 29 C.F.R. § 1910.1017(j).

²¹⁷ 29 C.F.R. § 1910.1017(l).

²¹⁸ 29 C.F.R. § 1910.1017(k).

²¹⁹ 29 C.F.R. § 1910.1017(m).

²²⁰ 56 Fed. Reg. 64,004 (December 6, 1991) (codified at 29 C.F.R. § 1910.1030).

²²¹ 29 C.F.R. § 1910.1030(d)(1).

²²² *American Dental Association v. Martin*, 984 F.2d 823, 15 OSH Cases 2097 (Seventh Cir. 1993), *cert. denied*, 510 U.S. 859 (1993).

²²³ *Id.* at 830.

²²⁴ *Id.* at 829.

²²⁵ The original 14 chemicals included in the carcinogen standards were 4-nitrobiphenyl, alpha-naphthylamine, 4,4'-methylene bis (2-chloroaniline)(deleted in 1976), methyl chloromethyl ether, 3,3'-dichlorobenzidine (and its salts), bis-chloromethyl ether, beta-naphthylamine, benzidine, 4-aminodiphenyl, ethyleneimine, beta-propiolactone, 2-acetylaminofluorene, 4-dimethylaminoazobenzene, and *N*-nitrosodimethylamine.

²²⁶ 29 C.F.R. §§ 1910.1003–1910.1016.

²²⁷ 503 F.2d 1155, 2 OSH Cases 1159 (Third Cir. 1974), *cert. denied*, 420 U.S. 973 (1975) (upholding OSHA's decision to rely on animal studies showing a substance to be carcinogenic as the best available evidence of the substance's probable effect in human beings).

²²⁸ 29 C.F.R. § 1910.1005 was deleted in 41 Fed. Reg. 35,184 (August 20, 1976).

²²⁹ OSHA's Cancer Policy is codified at 29 C.F.R. Part 1990.

²³⁰ 48 Fed. Reg. 242 (January 4, 1983).

²³¹ 29 C.F.R. § 1910.1029.

²³² 29 C.F.R. § 1910.1029(h). This includes, but is not limited to, flame-resistant pants, jackets, gloves, footwear, and face shields.

²³³ 29 C.F.R. § 1910.1029(i)(1).

²³⁴ 29 C.F.R. § 1910.1029(i)(3).

²³⁵ 29 C.F.R. § 1029(i)(5).

²³⁶ 29 C.F.R. § 1029(k).

²³⁷ 29 C.F.R. § 1029(l).

²³⁸ 29 C.F.R. § 1029(j).

²³⁹ 29 C.F.R. § 1029(m).

²⁴⁰ 577 F.2d 825, 6 OSH Cases 1451 (Third Cir. 1978), *cert. dismissed*, 448 U.S. 917 (1980).

²⁴¹ 48 Fed. Reg. 53,280 (1983) (codified at 29 C.F.R. § 1910.1200).

²⁴² A federal district court has ruled, in the context of a product liability suit brought by a worker against a chemical maker and distributor, that OSHA's Hazard Communication Standard does not preempt a failure-to-warn claim. *Wickham v. American Tokyo Kasei, Inc.*, 927 F. Supp. 293 (N.D. Ill. 1996).

²⁴³ *United Steel Workers of America v. Auchter*, 763 F.2d 728, 12 OSH Cases 1337 (Third Cir. 1985).

²⁴⁴ *Steelworkers v. Pendergass*, 819 F.2d 1263, 13 OSH Cases 1305 (Third Cir. 1987).

²⁴⁵ 52 Fed. Reg. 31,852 (August 24, 1987).

²⁴⁶ *Associated Builders and Contractors, Inc. v. OSHA*, 862 F.2d 63, 13 OSH Cases 1945 (Third Cir. 1988),

- cert. denied*, 490 U.S. 1003, 13 OSH Cases 2168 (1989).
- 247 *Steelworkers v. Pendergass*, 855 F.2d 108, 13 OSH Cases 1825 (Third Cir. 1988).
- 248 *Dole v. Steelworkers*, 494 U.S. 26, 14 OSH Cases 1425 (1990).
- 249 Pub. L. No. 104-13, 109 Stat 163 (1995).
- 250 59 Fed. Reg. 6126 (February 9, 1994).
- 251 29 C.F.R. § 1910.1450.
- 252 59 Fed. Reg. 36,695 (July 19, 1994).
- 253 71 Fed. Reg. 53,617 (September 12, 2006).
- 254 See <http://www.osha.gov/dsg/hazcom/ghs.html> (last visited on November 26, 2009).
- 255 74 Fed. Reg. 50,279 (September 30, 2009).
- 256 74 Fed. Reg. 57,278 (November 5, 2009).
- 257 77 Fed. Reg. 17,574 (March 26, 2012). OSHA also modified and modified provisions of other standards including standards for flammable and combustible liquids, process safety management and most substance-specific health standards, to ensure consistency with the final rule.
- 258 51 Fed. Reg. 45,654 (1986).
- 259 54 Fed. Reg. 9294 (1989) (codified at 29 C.F.R. § 1910.120).
- 260 *AFL-CIO v. OSHA*, 905 F.2d 1568, 1570-71, 14 OSH Cases 1636 (D.C. Cir. 1990).
- 261 Pub. L. No. 100-203, 101 Stat. 1330 (1987).
- 262 55 Fed. Reg. 2776 (January 26, 1990).
- 263 67 Fed. Reg. 74,749 (December 9, 2002).
- 264 See <https://www.osha.gov/html/faq-hazwoper.html#faq6>.
- 265 63 Fed. Reg. 1152 (January 8, 1998) (codified at 29 C.F.R. § 1910.134).
- 266 *AISI (Am. Iron and Steel Inst.) v. OSHA*, 182 F.3d 1261, 1273 (Eleventh Cir. 1999).
- 267 62 Fed. Reg. 54,160 (October 17, 1997).
- 268 68 Fed. Reg. 75,776 (December 31, 2003).
- 269 71 Fed. Reg. 50,121 (August 24, 2006).
- 270 40 Fed. Reg. 30,980 (1975).
- 271 44 Fed. Reg. 60,334 (1979).
- 272 45 Fed. Reg. 19,266 (1980).
- 273 54 Fed. Reg. 24,080 (1989).
- 274 58 Fed. Reg. 4462 (1993) (codified at 29 C.F.R. § 1910.146). The Review Commission has held that OSHA's definition of a "confined space" is not unenforceably vague. See *Secretary of Labor v. CBI Services, Inc.*, 15 OSH Cases 2046 (Rev. Comm'n 1992).
- 275 63 Fed. Reg. 66,018 (December 1, 1998).
- 276 58 Fed. Reg. 37,816 (July 25, 1994) (codified at 29 C.F.R. Part 1915, Subpart B).
- 277 72 Fed. Reg. 67,351 (November 28, 2007).
- 278 80 Fed. Reg. 25,366 (May 4, 2015).
- 279 59 Fed. Reg. 16,334 (April 6, 1994) (codified at 29 C.F.R. § 1910.132).
- 280 OSHA Memorandum by Deputy Assistant Secretary Jim Stanley to Field Staff, "Employer Obligation to Pay for Personal Protective Equipment," October 18, 1994. OSHA stated that for all PPE standards the employer must both provide and pay for the required PPE, except in limited situations. The memorandum stated that where PPE is very personal in nature and used by the employee off the job, such as is often the case with steel-toe safety shoes (but not metatarsal foot protection), the issue of payment may be left to labor-management negotiations.
- 281 *Secretary of Labor v. Union Tank Car Co.*, 18 OSH Cases 1067 (Rev. Comm'n 1997).
- 282 64 Fed. Reg. 15,402 (March 31, 1999).
- 283 72 Fed. Reg. 64,342 (November 15, 2007).
- 284 OSHA, *Combustible Dust in Industry: Preventing and Mitigating the Effects of Fire and Explosions*, SHIB 07-31-2005, Available at <http://www.osha.gov/dts/shib/shib073105.html>.
- 285 OSHA, *Combustible Dust National Emphasis Program*, Reissued, March 11, 2008, (CPL 03-00-008).
- 286 74 Fed. Reg. 57,974 (November 10, 2009).
- 287 *Special Emphasis Program for Microwave Popcorn Manufacturing Facilities*, Available at http://www.osha.gov/pls/oshaweb/owadisp.show_document?p_table=DIRECTIVES&p_id=3649.
- 288 OSHA, *Respiratory Disease Among Employees in Microwave Popcorn Processing Plants*, Available at <http://www.osha.gov/dts/shib/shib092107.html>.
- 289 See <http://www.osha.gov/dsg/guidance/diacetyl-guidance.html>.
- 290 H.R. 2693, *Popcorn Workers Lung Disease Prevention Act*, Available at <http://thomas.loc.gov/cgi-bin/query/C?c110:/temp/~c11043NFgD>.
- 291 74 Fed. Reg. 3938 (January 21, 2009).
- 292 74 Fed. Reg. 11,329 (March 17, 2009).
- 293 See 64 Fed. Reg. 65,768 (November 23, 1999).
- 294 57 Fed. Reg. 34,192 (August 3, 1992).
- 295 64 Fed. Reg. 65,768 (November 23, 1999).
- 296 65 Fed. Reg. 68,262 (November 14, 2000).
- 297 5 U.S.C. §§ 801-808 (Congressional Review of Agency Rulemaking).
- 298 A resolution of disapproval was signed by President Bush on March 20, 2000 and became law. See Pub. L. No. 107-5.
- 299 In addition to guidelines for ergonomics, OSHA has also published guidelines for the prevention of workplace violence. See *Guidelines for Preventing Workplace Violence for Health Care and Social Services and Recommendations for Workplace Violence Prevention Programs in Late-Night Retail Establishments* (<http://www.osha.gov/SLTC/>

workplaceviolence/solutions.html). In *ConocoPhillips Co. v. Henry*, Slip Copy, 2007 WL 2908879 (N.D. Okla.), the court expressed serious concern about criminal laws depriving employer property owners from their right to exclude those workers and other individuals from carrying and transporting firearms in their vehicles and decided that such state laws impermissibly conflicts with the Occupational Safety and Health Act “which requires employers to abate hazards in their workplaces that could lead to death or serious bodily harm and which encourages employers to prevent gun-related workplace injuries.” See page 42.

300 OSHA, *Ergonomics Guidelines*, Available at <http://www.osha.gov/SLTC/ergonomics/guidelines.html>.

301 See 59 Fed. Reg. 15,969 (April 5, 1994) (describing the history of the issue).

302 *Id.*

303 59 Fed. Reg. 15,968 (April 5, 1994). While the proposed smoking ban would have applied to nearly all of the six million employers under OSHA’s jurisdiction, the broader indoor air quality provisions would have applied to only nonindustrial employers and would require those employers to ensure that their heating, air-conditioning and ventilation systems are operated and maintained to ensure healthful indoor air.

304 66 Fed. Reg. 64,946 (December 17, 2001).

305 62 Fed. Reg. 54,160 (October 17, 1997).

306 68 Fed. Reg. 75,767 (December 31, 2003).

307 *Id.* at 75,769, and 75,771.

308 See Title 8, California Code of Regulations, Section 5199 (Adopted May 21, 2009) at <http://www.dir.ca.gov/Title8/5199.html>.

309 See <https://www.gpo.gov/fdsys/pkg/FR-2010-05-06/pdf/2010-10694.pdf#page=1>.

310 See <https://www.reginfo.gov/public/do/eAgendaViewRule?pubId=201610&RIN=1218-AC46>.

311 *Guidelines for Preventing Workplace Violence for Healthcare and Social Assistance Workers*. OSHA 3148-06R 2016 at <https://www.osha.gov/Publications/osh3148.pdf>.

312 *Recommendations for Workplace Violence Prevention Programs in Late-Night Retail Establishments*, OSHA 3153-12R 2009 at <https://www.osha.gov/Publications/osh3153.pdf>.

313 81 Fed. Reg. 88,147 (December 7, 2016).

314 29 U.S.C. § 657(c)(2).

315 29 U.S.C. § 657(c)(1).

316 29 U.S.C. § 673(a).

317 OSHA’s recordkeeping and reporting regulations were challenged as vague, but the Review Commission found them to have been validly promulgated and dismissed the vagueness challenge. General Dynamics

Corp. Elec. Boat Div., Quonset Point Facility, 16 OSH Cases 1717 (Rev. Comm’n J. 1994).

318 29 C.F.R. §§ 1904.20–1904.21. In addition, since 1996, OSHA has conducted an annual survey that requires about 80,000 employers to submit injury and illness records directly to OSHA. The regulation creating this annual survey (29 C.F.R. § 1904.17) was invalidated by a federal district court in *American Trucking Associations v. Secretary of Labor*, 17 OSH Cases 1881, 955 F. Supp. 4 (D.C.D.C. 1997), and OSHA responded by promulgating a final rule to preserve its authority to collect the survey (62 Fed. Reg. 6434 (February 11, 1997)).

319 66 Fed. Reg. 5916 (January 19, 2001) (codified as 29 C.F.R. Part 1904).

320 In 29 C.F.R. § 1904.12(c), the Secretary has defined “recordable occupational injuries or illnesses” as those that result in: (1) fatalities, regardless of the time between the injury and death, or the length of the illness; (2) lost workday cases, other than fatalities, that result in lost workdays; or (3) nonfatal cases without lost workdays, which result in transfer to another job or termination of employment, or require medical treatment (other than first aid) or involve: loss of consciousness or restriction of work or motion. This category also includes any diagnosed occupational illnesses that are reported to the employer but are not classified as fatalities or lost workday cases. Employers should resolve doubts about whether an injury is recordable – e.g., because it is unclear whether an injury required first aid or medical treatment or whether the injury is occupationally related – in favor of recording. See, e.g., *General Motors Corp., Inland Div.*, 8 OSH Cases 2036 (Rev. Comm’n 1980); *General Motors Corp. Warehousing and Distribution Division*, 10 OSH Cases 1844 (Rev. Comm’n 1982).

321 29 C.F.R. § 1904.6. Effective January 1, 1991, the responsibility for establishing recordkeeping requirements for occupational illnesses and injuries was transferred from the BLS in DOL to OSHA and its newly created Office of Recordkeeping and Data Analysis.

322 29 C.F.R. § 1904.15.

323 U.S. General Accountability Office, *Enhancing OSHA’s Records Audit Process Could Improve the Accuracy of Worker Injury and Illness Data*, October 2009, GAO-10-10.

324 See <https://www.osha.gov/news/newsreleases/national/10012009>.

325 29 C.F.R. Part 1904.

326 81 Fed. Reg. 29,624 (May 12, 2016).

327 *Id.*

328 See Injury Tracking Application for Electronic Submission of Injury and Illness Records to OSHA at <https://www.osha.gov/injuryreporting/index.html>.

- ³²⁹ *Id.*
³³⁰ 59 Fed. Reg. 15,594 (1994).
³³¹ 60 Fed. Reg. 18,993 (April 14, 1995).
³³² 79 Fed. Reg. 56,130 (September 18, 2014).
³³³ 29 C.F.R. § 1904.39(a)(2).
³³⁴ 29 C.F.R. § 1904.39(a)(3)(i)–(iii).
³³⁵ 29 U.S.C. § 657(c)(3).
³³⁶ 29 C.F.R. § 1910.1020(d).
³³⁷ 29 U.S.C. § 1910.1020(d)(1)(iii).
³³⁸ 29 U.S.C. § 1910.1020(d)(1)(i)(A) to (C).
³³⁹ 45 Fed. Reg. 35,212 (1980) (codified at 29 U.S.C. § 1910.1020).
³⁴⁰ *Louisiana Chem. Ass’n v. Bingham*, 731 F.2d 280, 11 OSH Cases 1922 (Fifth Cir. 1984)(per curiam), *aff’d* 550 F. Supp. 1136, 10 OSH Cases 2113 (W.D.La. 1982).
³⁴¹ 53 Fed. Reg. 38,140 (September 29, 1988).
³⁴² 29 U.S.C. § 655(f).
³⁴³ The test for determining what is a standard and what is a regulation was first announced in a case *Louisiana Chemical Ass’n v. Bingham*, 657 F.2d 777, 10 OSH Cases 1017 (Fifth Cir. 1981) (holding that OSHA’s Access to Employee Exposure and Medical Records rule was a regulation not a standard). The court stated that a “standard [is] a remedial measure addressed to a specific and already identified hazard, not a purely administrative effort designed to uncover violations of the Act and discover unknown dangers. In short, standards should aim toward correction rather than mere inquiry into possible hazards.” *Id.* at 782. The Third Circuit followed this reasoning when they ruled that OSHA’s Hazard Communication Standard was a standard not a regulation. *See United Steelworkers v. Auchter*, 763 F.2d 728, 12 OSH Cases 1337 (Third Cir. 1985).
³⁴⁴ *Fellner and Savelson* (8). This approach has been summarized as one requiring the reviewing court to determine whether the agency (1) acted within the scope of its authority; (2) followed the procedures required by statute and by its own regulations; (3) explicated the bases for its decision; and (4) adduced substantial evidence in the record to support its determination. *United Steelworkers of America, AFL-CIO, v. Marshall and Bingham*, 647 F.2d 1189, 1206, 8 OSH Cases 1810, 1816 (D.C. Cir. 1980), *cert. denied*, 453 U.S. 913 (1981).
³⁴⁵ 29 U.S.C. § 655(d).
³⁴⁶ *Id.*
³⁴⁷ 29 U.S.C. § 655(6)(b)(A).
³⁴⁸ *Id.*
³⁴⁹ 29 U.S.C. § 655.
³⁵⁰ 518 F.2d 990; 3 OSH Cases 1490 (Fifth Cir. 1975); *aff’d*, 430 U.S. 442; 5 OSH Cases 1105 (1977).
³⁵¹ 430 U.S. 442, 5 OSH Cases 1105 (1977).
³⁵² *S. A. Healy v. Occupational Safety and Health Review Commission*, 18 OSH Cases 1193 (Seventh Cir. 1998). The Seventh Circuit’s decision was a reversal of its previous holding on the matter, which was vacated by the Supreme Court. On remand from the Supreme Court, the Seventh Circuit held that the administrative penalty was “civil” rather than “criminal” and thus did not constitute a separate criminal proceeding for purposes of double jeopardy.
³⁵³ *Secretary of Labor v. Andrew Catapano Enterprises, Inc.*, 17 OSH Cases 1776 (Rev. Comm’n 1996). In this case, the employer argued that all the nine trench sites should have been treated as a single workplace and the violations thus treated as a single case, but the Commission ruled that it was within OSHA’s discretion to prosecute the violations at each trench site as a separate case.
³⁵⁴ 29 U.S.C. § 657(f)(1).
³⁵⁵ *See* OSHA Field Operations Manual, Chapter 2, V.
³⁵⁶ 29 U.S.C. § 657(a)(1) & (2).
³⁵⁷ 436 U.S. 307, 6 OSH Cases 1571 (1978).
³⁵⁸ In contrast, the U.S. Supreme Court has upheld the constitutionality of warrantless inspections of stone quarries under the Federal Mine Safety and Health Act of 1977 because mining has long been a pervasively regulated industry, in which a businessperson can have no reasonable expectation of privacy against official inspections. In *Donovan v. Dewey*, 452 U.S. 594 (1981), the Court reasoned further that the Federal Mine Safety and Health Act inspection provisions are more narrowly drawn and provide for less administrative discretion concerning inspections than does OSHA, thus making such inspections reasonable under the Fourth Amendment.
³⁵⁹ 436 U.S. at 320–321, 6 OSH Cases at 1575–1576.
³⁶⁰ 436 U.S. at 321, 6 OSH Cases at 1575–1576. Such “neutral sources,” according to the Court, could include statistics indicating “dispersion of employees in various types of industries across a given area, and the desired frequency of searches in any of the lesser divisions of the area ...” 6 OSH Cases at 1576.
³⁶¹ *L.R. Wilson & Sons, Inc.* 17 OSH Cases 2059 (Rev. Comm’n 1997), *aff’d in part and rev’d in part*, 134 F.3d 1235, 18 OSH Cases 1129 (Fourth Cir.), *cert. denied*, 525 U.S. 962, 18 OSH Cases 1576 (1998).
³⁶² A general contractor can consent to OSHA’s inspection of a construction work site at which many employers work. *J.L. Foti Constr. Co. v. Donovan*, 786 F.2d 714, 12 OSH Cases 1737 (Sixth Cir. 1986).
³⁶³ *Ackermann Enters.*, 10 OSH Cases 1709, 1711–1712 (Rev. Comm’n 1982).
³⁶⁴ 134 F.3d 1235 (Fourth Cir.), *cert. denied*, 525 U.S. 962 (1998) (holding that work site videotaping not only does not violate the OSH Act but also does

not violate the Fourth Amendment's right to privacy because the employer "left the construction site open to observation from vantages outside its control."). The Seventh Circuit has also held that it is not unreasonable for an inspection warrant to allow videotaping of the workplace. *In re Establishment Inspection of Kelly-Springfield Tire Co.*, Seventh Cir., No. 93-1082, January 18, 1994.

³⁶⁵ *Camara v. Municipal Court of City and County of San Francisco*, 387 U.S. 523 (1967). *Accord* *Michigan v. Tyler*, 436 U.S. 499, 509-510 (1978). *See also* Mark A. Rothstein, *OSHA Inspections After Marshall v. Barlow's, Inc.*, Vol. 1979 (No. 1) *Duke Law Journal* 63 (1979).

³⁶⁶ *Marshall v. North American Car Co.*, 626 F.2d 320, 8 OSH Cases 1722 (Third Cir. 1980) (rejecting the Secretary's argument that 29 C.F.R. § 1, which provides that an inspection based on an employee complaint is not limited to matters complained of, permits a wall-to-wall inspection).

³⁶⁷ 45 Fed. Reg. 65,916 (1980) (codified at 29 C.F.R. § 1903.4).

³⁶⁸ The new regulation, held valid by the court in *Donovan v. Blue Ridge Pressure Castings, Inc.*, 543 F. Supp. 53, 10 OSH Cases 1217 (M.D. Pa. 1981), states "(d) For purposes of this section, the term compulsory process shall mean the institution of any appropriate action, including *ex parte* application for an inspection warrant or its equivalent. *Ex parte* inspection warrants shall be the preferred form of compulsory process in all circumstances where compulsory process is relied upon to seek entry to a workplace under this section." *See* 29 C.F.R. § 1903.4(d).

³⁶⁹ 610 F.2d 1128, 1135-1136, 7 OSH Cases 1880, 1884 (Third Cir. 1979). An employer's right to a pre-inspection hearing in federal court on a warrant's validity was reaffirmed by the Third Circuit in *Cerro Metal Products v. Marshall* (holding an employer could bring an action in district court, prior to inspection, seeking to enjoin OSHA from obtaining an *ex parte* warrant). The Seventh Circuit has also held an employer may raise a pre-inspection warrant challenge in district court under limited circumstances. *See* *Blocksom & Co. v. Marshall*, 582 F.2d 1122, 6 OSH Cases 1865 (Seventh Cir. 1978) (employer may raise invalidity of warrant as a defense in action seeking to hold it in contempt for failure to obey warrant).

³⁷⁰ 610 F.2d at 1135-1137, 7 OSH Cases at 1883-1885. *Accord* *Marshall v. Whittaker Corp.*, *Berwick Forge & Fabricating Co.*, 610 F.2d 1141, 6 OSH Cases 1888 (Third Cir. 1979); *Establishment Inspection of the Metal Bank of America, Inc.*, 700 F.2d 910, 11 OSH Cases 1193 (Third Cir. 1983).

³⁷¹ *In re Worksite Inspection of Quality Products, Inc.*, 592 F.2d 611, 7 OSH Cases 1093 (First Cir. 1979); *Marshall v. Central Mine Equipment Co.*, 608 F.2d 719, 7 OSH Cases 1907 (Eighth Cir. 1979); *Baldwin Metals Co., Inc. v. Donovan*, 642 F.2d 768, 9 OSH Cases 1568 (Fifth Cir.), *cert. denied sub nom. Mosher Steel Co. v. Donovan*, 454 U.S. 893 (1981); *In re J. R. Simplot Co.*, 640 F.2d 1134 (Ninth Cir. 1981), *cert. denied*, 455 U.S. 939 (1982); *Robert K. Bell Enters. v. Donovan*, 710 F.2d 673 (Tenth Cir. 1983), *cert. denied*, 464 U.S. 1041 (1984); *Establishment Inspection of Gould Publishing Co.*, 934 F.2d 457, 15 OSH Cases 1073 (Second Cir. 1991).

³⁷² *Weyerhaeuser Co. v. Marshall*, 592 F.2d 373, 7 OSH Cases 1090 (Seventh Cir. 1979); *Federal Casting Div., Chromalloy American Corp. v. Donovan*, 684 F.2d 504, 10 OSH Cases 1801 (Seventh Cir. 1982) (following *Weyerhaeuser*).

³⁷³ *In re Establishment Inspection of Kohler Co.*, 935 F.2d 810 (Seventh Cir. 1991).

³⁷⁴ 29 C.F.R. 1903.7(d). ("The conduct of inspections shall be such as to preclude unreasonable disruption of the operations of the employer's establishment.").

³⁷⁵ 16 OSH Cases 1073, 1081 (Rev. Comm'n 1993), *aff'd*, 16 OSH Cases 1889 (Sixth Cir. 1994).

³⁷⁶ 29 U.S.C. § 662(a).

³⁷⁷ *Id.*

³⁷⁸ 29 U.S.C. § 662(d).

³⁷⁹ 29 U.S.C. § 658(a).

³⁸⁰ The Review Commission has held that this 6-month limitation period does not apply if the Secretary's inability to discover the violation was caused by the employer's failure to report a fatal accident as the Secretary's regulations require (29 C.F.R. § 1904.8). The Review Commission reasoned that allowing an employer to escape a citation because of its own failure to comply with OSHA's reporting requirements would reward it for its own wrongdoing. *Yelvington Welding Service*, 6 OSH Cases 2013 (Rev. Comm'n. 1978). The Review Commission has held that OSHA may issue a citation for an alleged violation even though it may have had the opportunity during an earlier inspection to discover the same alleged violation and cite it—the holding was based on the idea that the purpose of Section 9(c) is simply to ensure that violations are prosecuted while events are still relatively fresh and that this purpose is not compromised so long as the subsequent violative conduct is prosecuted within six months. *Secretary of Labor v. Safeway Store No. 914*, 16 OSH Cases 1504 (Rev. Comm'n. 1993); *Johnson Controls, Inc.*, 15 OSH Cases 2132, 2135-2136 (Rev. Comm'n 1993).

³⁸¹ *See* 29 U.S.C. § 658(a).

- ³⁸² *Whirlpool Corp. v. OSHRC and Marshall*, 645 F.2d 199, 7 OSH Cases 2059 (Ninth Cir. 1980), *cert. denied*, 457 U.S. 1132 (1982); *Noblecraft Industries, Inc. v. Secretary of Labor and OSHRC*, 614 F.2d 199, 7 OSH Cases 2059 (Ninth Cir. 1980); *Whirlpool Corp. v. OSHRC and Marshall*, 645 F.2d 1096, 9 OSH Cases 1362 (D.C. Cir. 1981). *See also* *Otis Elevator Co.*, 13 OSH Cases 1791 (Rev. Comm'n 1988 (holding that the citation was not too vague because (1) the basic elements of the charge describing the hazard were present and (2) there was extensive pretrial discovery), *aff'd*, 871 F.2d 155, 13 OSH Cases 2085 (D.C. Cir. 1989).
- ³⁸³ *Marshall v. B.W. Harrison Lumber Co. and OSHRC*, 569 F.2d 1303, 6 OSH Cases 1446 (Fifth Cir. 1978);
- ³⁸⁴ 29 U.S.C. § 658(a).
- ³⁸⁵ The employer must post notice of OSHA citations at or near the place of the violation immediately upon receipt of the notice (29 C.F.R. §§ 1903.14 & 1903.16). If it is not possible to post the notice of citation at the violation site, employers must post it in a "prominent place where it will be readily observable by all affected employees" (29 C.F.R. § 1903.16(a)). If the employer settles with OSHA (to reduce the fines), a notice of settlement must also be posted (29 C.F.R. § 2200.100(c)).
- ³⁸⁶ Penalties are prescribed by 29 U.S.C. § 666. Applicable regulations on proposed penalties are found at 29 C.F.R. § 1903.15. In addition to the gravity of the violation, the size of the business, the employer's good faith, and the employer's history of previous violations are also taken into account in determining the amount of the proposed penalty. *See* 29 C.F.R. § 1903.15(b).
- ³⁸⁷ 29 U.S.C. § 658(a).
- ³⁸⁸ OSHA, *Field Operations Manual*, Chapter 4, Section VIII.A.1 through 3. https://www.osha.gov/OshDoc/Directive_pdf/CPL_02-00-160.pdf.
- ³⁸⁹ *Crescent Wharf & Warehouse Co.*, 1 OSH Cases 1219, 1222 (Rev. Comm'n 1973).
- ³⁹⁰ OSHA, *Field Operations Manual*, Chapter 4, Section IV. https://www.osha.gov/OshDoc/Directive_pdf/CPL_02-00-160.pdf.
- ³⁹¹ Conference Report 91-1765, 1970, U.S. Code Congressional and Administrative News, p. 5237; OSHA § 17(c).
- ³⁹² *Ryder Truck Lines, Inc. v. Brennan*, 497 F.2d 230, 233, 2 OSH Cases 1075, 1077 (Fifth Cir. 1974).
- ³⁹³ In determining whether a violation is serious or other-than-serious, the Commission has held that a number of other-than-serious violations may be grouped together to form a serious violation if the cumulative effect of the violations could result in an accident causing death or serious injury. *See* H. A. S. & Associates, 4 OSH Cases 1894, 1897-1898 (Rev. Comm'n 1976). When the violation poses a risk of illness through cumulative exposure to a toxic substance, the relevant question is whether the Secretary can show a substantial probability of serious harm resulting from the degree and length of actual employee exposure. *Bethlehem Steel Corp.*, 11 OSH Cases 1247, 1252 (Rev. Comm'n 1983); *Texaco, Inc.*, 8 OSH Cases 1758, 1761 (Rev. Comm'n 1980).
- ³⁹⁴ 29 U.S.C. § 666(k).
- ³⁹⁵ 517 F.2d 986, 3 OSH Cases 1174 (Ninth Cir. 1975).
- ³⁹⁶ *Accord* *Usery v. Hermitage Concrete Pipe Co. and OSHRC*, 584 F.2d 127, 6 OSH Cases 1886 (Sixth Cir. 1979); *Kent Nowlin Construction Co., Inc. v. OSHRC*, 648 F.2d 1278, 9 OSH Cases 1709 (Tenth Cir. 1981); *Central Brass Mfg. Co.*, 13 OSH Cases 1609, 1611 (Rev. Comm'n 1987).
- ³⁹⁷ *Brennan v. OSHRC and Vy Lactos Laboratories, Inc.*, 494 F.2d 460, 1 OSH Cases 1623 (Eighth Cir. 1974).
- ³⁹⁸ 519 F.2d 1200, 1207, 2 OSH Cases 1283, 1289 (Third Cir. 1974), *aff'd sub nom.* *Atlas Roofing Co., Inc. v. OSHRC*, 430 U.S. 442, 5 OSH Cases 1105 (1977).
- ³⁹⁹ *Messina Construction Corp. v. OSHRC*, 505 F.2d 701, 2 OSH Cases 1325 (First Cir. 1974); *Inter-county Construction Co. v. OSHRC*, 522 F.2d 777, 780, 3 OSH Cases 1337, 1339 (Fourth Cir. 1975), *cert. denied* 423 U.S. 1072 (1976).
- ⁴⁰⁰ *Kent Nowlin Construction, Inc.*, 5 OSH Cases 1051, 1055 (Rev. Comm'n 1977), *aff'd in relevant part* 593 F.2d 368, 369, 7 OSH Cases 1105, 1108 (Tenth Cir. 1979).
- ⁴⁰¹ *Kus-Tum Builders, Inc.*, 10 OSH Cases 1128, 1131 (Rev. Comm'n 1981); *A. Schonbek & Co., Inc.*, 9 OSH Cases 1189, 1191 (Rev. Comm'n 1980), *aff'd*, 646 F.2d 799, 9 OSH Cases 1562 (Second Cir. 1981).
- ⁴⁰² *A. Schonbek & Co., Inc. v. Donovan and OSHRC*, 646 F.2d 799, 9 OSH Cases 1562 (Second Cir. 1981), *aff'g*, 9 OSH Cases 1189 (Rev. Comm'n 1980); *Mineral Industries & Heavy Construction Group (Brown & Root, Inc.) v. OSHRC and Marshall*, 639 F.2d 1289, 9 OSH Cases 1387 (Fifth Cir. 1981); *Georgia Electric Co. v. Marshall and OSHRC*, 595 F.2d 309, 7 OSH Cases 1343 (Fifth Cir. 1979); *Empire-Detroit Steel Div., Detroit Steel Corp. v. OSHRC and Marshall*, 579 F.2d 378, 6 OSH Cases 1693 (Sixth Cir. 1978); *Western Waterproofing Co., Inc. v. Marshall and OSHRC*, 576 F.2d 139, 6 OSH Cases 1550 (Eighth Cir.), *cert. denied*, 439 U.S. 965 (1978); *National Steel & Shipbuilding Co. v. OSHRC*; *Kent Nowlin Construction Co. v. OSHRC and Marshall*, 593 F.2d 368, 7 OSH Cases 1105 (Tenth Cir. 1979), *aff'g in relevant part* 5 OSH Cases 1051 (Rev. Comm'n 1977).
- ⁴⁰³ 587 F.2d 1303, 6 OSH Cases 2010, 2012 (D.C. Cir. 1978).
- ⁴⁰⁴ 622 F.2d 1160, 8 OSH Cases 1317 (Third Cir. 1980).

- 405 OSHA, *Field Operations Manual*, ch. 4, VII.
- 406 29 U.S.C. § 658(a). In determining a reasonable abatement period, OSHA's *Field Inspection Reference Manual* advises consideration of the following factors: (1) the gravity of the alleged violation; (2) the availability of needed equipment, material and/or personnel; (3) the time required for delivery, installation, modification, or construction; and (4) training of personnel.
- 407 29 U.S.C. § 659(b).
- 408 OSHA Instruction CPL 02-00-112 – CPL 2.112 (August 2, 1996). See http://www.osha.gov/pls/oshaweb/owadisp.show_document?p_table=DIRECTIVES&p_id=1588.
- 409 62 Fed. Reg. 15,324 (March 31, 1997).
- 410 5 U.S.C. § 553(b)(3)(B).
- 411 81 Fed. Reg. 43,430 (July 1, 2016).
- 412 82 Fed. Reg. 5373 (January 18, 2017).
- 413 The new monetary civil penalty maximums take effect after August 1, 2016. Any citation issued after August 1, 2016 will be subject to the new penalties if the related violations occurred after November 2, 2015. See <https://www.osha.gov/Publications/OSHA3879.pdf>.
- 414 82 Fed. Reg. 5373, 5385 and 5386.
- 415 *Id.* at 5386.
- 416 *Id.*
- 417 29 U.S.C. § 666(e). A general duty clause violation cannot serve as the basis of a criminal charge because criminal liability is limited to a violation of a standard, rule or order.
- 418 *Id.*
- 419 *United States v. Dye Constr. Co.*, 510 F.2d 78, 81, 2 OSH Cases 1510 (Tenth Cir. 1975).
- 420 *United States v. Pitt-Des Moines, Inc.*, 168 F.3d 976, 18 OSH Cases 1609 (Seventh Cir. 1999) (where employer's failure to install the proper number of bolts in a structure resulted in the death of two ironworkers).
- 421 OSHA, *Field Operations Manual*, Chapter 4, VI.
- 422 David M. Uhlmann, Prosecuting Worker Endangerment: The Need for Stronger Criminal Penalties for Violations of the Occupational Safety and Health Act, September 2008, Issue Brief of the American Constitution Society, Available at <http://www.acslaw.org/node/6986>.
- 423 29 U.S.C. § 666(e).
- 424 See 18 U.S.C. § 1001.
- 425 See 18 U.S.C. § 3571.
- 426 *United States v. Atlantic States Cast Iron Pipe Co.*, No. 3:03-cr-00852 (D.N.J. Apr. 26, 2007) (verdict, reported in 36 OSH Rep. 424 (May 4, 2006)); *aff'd* 2007 WL 2282514 (D.N.J. Aug. 2, 2007) (upholding jury's verdict), reported in 37 OSH Rep. 734 (Aug. 16, 2007), *aff'd*, 695 F.3d 227 (Third Cir. 2012), *petition for cert.* filed, No. 12-976, 81 USLW (Jan. 16, 2013).
- 427 18 U.S.C. § 1001.
- 428 18 U.S.C. §§ 1503, 1505, 1512, and 1519.
- 429 18 U.S.C. § 371.
- 430 OSHA, CPL 02-00-080 - CPL 2.80, (October 1, 1990), *Handling of Cases to Be Proposed for Violation-by-Violation Penalties*, H.2., Available at http://www.osha.gov/pls/oshaweb/owadisp.show_document?p_table=DIRECTIVES&p_id=1657.
- 431 20 OSH cases 1361 (Rev. Comm'n 2003), *rev'd*, 401 F.3d 355 (Fifth Cir. 2005).
- 432 73 Fed. Reg. 75,568 (December 12, 2008).
- 433 602 F.3d 464, 23 OSH Cases 1033 (D.C. Cir. 2010).
- 434 22 OSH Cases 1553 (Rev. Comm'n 2009).
- 435 *Harvey Workover Inc.*, 7 OSH Cases 1687, 1689 (Rev. Comm'n 1979).
- 436 *Grossman Steel & Alum. Corp.*, 4 OSH Cases 1185, 1188 (Rev. Comm'n 1976).
- 437 OSHA, Multi-Employer Citation Policy, CPL 02-00-124 (December 10, 1999), at https://www.osha.gov/pls/oshaweb/owadisp.show_document?p_table=DIRECTIVES&p_id=2024. See also, the multi-employer worksite provisions in 29 C.F.R. § 1915.12(f) and 29 C.F.R. § 1915.501.
- 438 *Secretary of Labor v. Trinity Indus.*, 504 F.3d 397 (3d Cir. 2007); *Universal Constr. Co. v. OSHRC*, 182 F.3d 726, 728-31, 18 OSH Cases 1789 (Tenth Cir. 1999); *United States v. Pitt-Des Moines Inc.*, 168 F.3d 976, 18 OSH Cases 1609 (Seventh Cir. 1999); *Carbone Constr. Co. v. OSHRC*, 166 F.3d 815, 18 OSH Cases 1551 (Sixth Cir. 1998); *New England Tel. & Tel. Co. v. Secretary of Labor*, 589 F.2d 81, 81-82 (First Cir. 1978); *Beatty Equip. Leasing Inc. v. Secretary of Labor*, 577 F.2d 534, 6 OSH Cases 1699 (Ninth Cir. 1978); *Marshall v. Knutson Constr. Co.*, 566 F.2d 596, 6 OSH Cases 1077 (Eighth Cir. 1977).
- 439 *Melerine v. Avondale Shipyards, Inc.*, 659 F.2d 706, 711, 10 OSH Cases 1075 (Fifth Cir. 1981).
- 440 *Acosta v. Hensel Phelps Constr. Co.*, No. 17-60543 (Fifth Cir. Filed Aug. 4, 2017).
- 441 29 U.S.C. § 659(a).
- 442 The Review Commission's Rules of Procedure can be found at 29 C.F.R. §§ 2200.1 through 2200.212. In an area of procedure where the Commission has not promulgated a rule, the Federal Rule of Civil Procedure applies. See 19 C.F.R. § 2200.2(b).
- 443 Despite the requirements of OSH Act Section 10(a), the Review Commission may (in limited circumstances) entertain a late notice of contest pursuant to Federal Rule of Civil Procedure 60(b). This rule permits a federal court to grant relief from a final order for a number of reasons, including a party's mistake, surprise or excusable neglect, the presence of newly discovered evidence, and the fraud or misconduct of an adverse party. Rule 60(b), which was held applicable

to the Review Commission by the Third Circuit in *J. I. Hass Co. v. OSHRC*, 648 F.2d 190, 9 OSH Cases 1712 (Third Cir. 1981), has been viewed by the Review Commission as affording a possible basis for considering an untimely notice of contest.

- 444 29 C.F.R. § 1903.17.
- 445 *Brennan v. OSHRC and Bill Echols Trucking Co.*, 487 F.2d 230, 1 OSH Cases 1398 (Fifth Cir. 1973); *Dan J. Sheehan Co. v. OSHRC and Dunlop*, 520 F.2d 1036, 3 OSH Cases 1573 (Fifth Cir. 1975), *cert. denied*, 424 U.S. 956 (1976).
- 446 *Dan J. Sheehan*, 520 F.2d at 1038–1039, 3 OSH Cases at 1575.
- 447 *Turnbull Millwork Co.*, 3 OSH Cases 1781 (Rev. Comm’n 1975); *State Home Improvement Co.*, 6 OSH Cases 1249 (Rev. Comm’n 1977).
- 448 29 U.S.C. § 659.
- 449 *See* 29 C.F.R. §§ 2200.1–2200.211; *See also*, 70 Fed. Reg. 22,785 (May 3, 2005).
- 450 29 U.S.C. § 661(g); 29 C.F.R. § 2200.2(b).
- 451 29 C.F.R. §§ 2200.200–2200.212.
- 452 *See* <https://www.oshrc.gov/guides/guide-to-review-commission-procedures/>.
- 453 29 C.F.R. §§ 2200.91 and 2200.92.
- 454 29 C.F.R. § 2200.90(d).
- 455 The Review Commission’s failure to adequately consider these statutory penalty assessment factors can result in a court of appeals remanding the case to the Commission for more particularized findings regarding the penalty. *Astra Pharmaceutical Products, Inc. v. OSHRC and Donovan*, 681 F.2d 69, 10 OSH Cases 1697 (First Cir. 1982).
- 456 *REA Express v. Brennan*, 495 F.2d 822, 1 OSH Cases 1651 (Second Cir. 1974); *Brennan v. OSHRC and Interstate Glass Co.*, 487 F.2d 438, 1 OSH Cases 1372 (Eighth Cir. 1973). Reduction of the Secretary’s proposed penalty is also a matter within the Commission’s discretion. *Western Waterproofing Co., Inc. v. Marshall and OSHRC*.
- 457 *Secretary of Labor v. Hern Iron Works, Inc.*, 16 OSH Cases 1619 (Rev. Comm’n 1994).
- 458 *California Stevedore & Ballast Co. v. OSHRC*, 517 F.2d 986, 3 OSH Cases 1174 (Ninth Cir. 1975).
- 459 *See, e.g., Dixie Roofing and Metal Co.*, 2 OSH Cases 1566 (Rev. Comm’n 1975). *See also* *Consolidated Rail Corp.*, 10 OSH Cases 1564, 1568 (Rev. Comm’n 1982), in which the Commission reduced the degree of a violation from serious to other-than-serious without specifically discussing its authority to do so. Federal appeals courts have upheld the Commission’s authority to downgrade nonserious violations to *de minimis* status. *See, e.g., Secretary of Labor v. OSHRC and Erie Coke Corp.*, 16 OSH Cases 1241, 998 F.2d 134 (Third Cir. 1993) (noting that the Commission had exercised

this authority for over 20 years and that ruling in favor of the Secretary would create an “undesirable inter-circuit conflict”). The distinction between a “nonserious” violation and a *de minimis* one is important because a “non-serious” designation requires the employer to cease the violative practice, while a *de minimis* designation does not.

- 460 Commission Rule 34(b)(3), 29 C.F.R. § 2200.34(b)(3).
- 461 29 C.F.R. § 2200.34(b)(4).
- 462 Petitions for review of a Commission Order must be filed within 60 days of issuance of the Order. Review is obtained in either the court of appeals where the violation is alleged to have occurred, where the employer has its principal office, or in the D.C. Circuit Court. 29 U.S.C. § 660(a).
- 463 *Secretary of Labor v. OSHRC and Interstate Glass*, 487 F.2d at 442, 1 OSH Cases at 1375.
- 464 *Secretary of Labor v. Sea Sprite Boat Co.*, 17 OSH Cases 1331, 64 F.3d 332 (Seventh Cir. 1995).
- 465 29 U.S.C. § 657(c)(1).
- 466 29 C.F.R. § 1903.2.
- 467 29 C.F.R. § 1915(d). In 2017, a violation of the posting requirement are subject to a maximum civil penalty of \$12,675.
- 468 29 C.F.R. § 1904.2.
- 469 29 C.F.R. § 1904.5.
- 470 29 U.S.C. § 660(c)(1).
- 471 29 C.F.R. § 1977.12(b)(1)–(2).
- 472 *See* *Usery v. Whirlpool Corp.*, 416 F. Supp. 30, 34, 4 OSH Cases 1391, 1392–1393 (N.D. Ohio 1976), *rev’d sub nom. Marshall v. Whirlpool Corp.*, 593 F.2d 715, 7 OSH Cases 1075 (Sixth Cir. 1979), *aff’d*, 445 U.S. 1, 8 OSH Cases 1001 (1980) *on remand*, 9 OSH Cases 1038 (N.D. Ohio 1980).
- 473 29 U.S.C. § 657(f)(1).
- 474 29 U.S.C. § 657(e).
- 475 *Id.*
- 476 *See* *OSHA Field Operations Manual*, ch. 9, p. 9-3. *See also*, 29 C.F.R. § 1903.8(c).
- 477 29 U.S.C. § 659(c).
- 478 *Id.*
- 479 29 U.S.C. § 662(c) & (d).
- 480 29 C.F.R. § 1954.20(a).
- 481 29 U.S.C. § 657(c)(3). *See also* 29 U.S.C. § 1910.20.
- 482 29 U.S.C. § 660(c)(1).
- 483 *Dunlop v. Trumbull Asphalt Company, Inc.*, 4 OSH Cases 1847 (E.D. Mo. 1976).
- 484 29 U.S.C. § 660(c)(2).
- 485 29 U.S.C. § 660(c)(1).
- 486 23 OSH Cases 2079 (D. Colo. 2012).
- 487 *See* *Powell v. Globe Industries, Inc.*, 431 F. Supp. 1096, 5 OSH Cases 1250 (N.D. Ohio 1977). The National Labor Relations Board (NLRB) has concurrent jurisdiction over Section 11(c) cases. In 1975, the general

counsel of the NLRB and the Secretary entered into an understanding for the procedural coordination of litigation arising under Section 11(c) of the OSH Act and Section 8 of the National Labor Relations Act, to avoid duplicate litigation.

488 Occupational Safety and Health Administration Compliance Assistance Authorization Act of 1998, Pub. L. No. 105-197 (codified at 29 U.S.C. § 670(d)). See also, 29 C.F.R. Part 1908.

489 65 Fed. Reg. 64,282 (Oct. 26, 2000).

490 29 C.F.R. § 1908.6.

491 29 U.S.C. § 670(d)(3); 29 C.F.R. § 1908.6(f)(4).

492 See OSHA Guidelines for Safety and Health Programs at <https://www.osha.gov/shpguidelines/>.

493 See The OSHA Alliance Program at <https://www.osha.gov/dcsp/alliances/whatis.html>.

494 See OSHA Strategic Partnership Program at <https://www.osha.gov/dcsp/partnerships/index.html>.

495 See <http://www.osha.gov/dcsp/vpp/index.html>.

496 "Revisions to the Voluntary Protection Programs to Provide Safe and Healthful Working Conditions," 65 Fed. Reg. 45,649 (July 24, 2000).

497 OSHA Instruction CSP 03-01-001-TED 8-0.3 – Policies and Procedures Manual for Special Government Employee (SGE) Activity Conducted Under the Auspices of the Occupational Safety and Health Administration's (OSHA) Voluntary Protection Program, January 4, 2002.

498 See <http://www.osha.gov/dcsp/vpp/sitebysic.html>.

499 See <http://www.vpppa.org/>.

500 See <https://www.osha.gov/dcsp/vpp/challenge.html>.

501 See Ashford, *supra* note 15 at 47–51.

502 See Gade v. National Solid Wastes Management Ass'n, 505 U.S. 88, 15 OSH Cases 1673 (1992).

503 29 C.F.R. § 1902.3.

504 29 C.F.R. §§ 1902.3 and 1902.4.

505 29 U.S.C. § 667.

506 29 C.F.R. § 1902.2(b).

507 29 C.F.R. § 1954.3, 1954.10.

508 29 C.F.R. § 1954.3, 1954.10.

509 570 F.2d 1030, 6 OSH Cases 1257 (D.C. Cir. 1978).

510 *Id.* at 1036, 6 OSH Cases 1257.

511 AFL-CIO v. Marshall, 6 OSH Cases 2128 (D.D.C. 1978). For a history of the benchmark staffing issues, see 50 Fed. Reg. 2491 (1985).

512 These agencies regulate certain nuclear materials under agreements with the Nuclear Regulatory Commission. 29 U.S.C. § 653(b)(1).

514 Association of Am. R.R. v. DOT, 38 F.3d 582, 586, 16 OSH Cases 2084 (D.C. Cir. 1994); *In re* Inspection of Norfolk Dredging Co., 783 F.2d 1526, 1530, 12 OSH Cases 1715 (Eleventh Cir.), *cert. denied*, 479 U.S. 883 (1986); Donovan v. RedStar Marine Servs., Inc. 739 F.2d 774, 778, 11 OSH Cases 2049m 2052 (2d Cir.

1984), *cert denied*, 470 U.S.1003 (1985); PBR, Inc. v. Secretary of Labor, 643 F.2d 890, 896, 9 OSH Cases 1357 (First Cir. 1981); Southern Ry.v. OSHRC, 539 F.2d 335, 336-37, 3 OSH Cases 1940 (Fourth Cir.), *cert. denied*, 429 U.S. 999 (1976).

515 Southern Pacific Transportation Co. v. Usery and OSHRC, 539 F.2d 386; 4 OSH Cases 1693 (Fifth Cir. 1976), *cert. denied*, 434 U.S. 874, 5 OSH Cases 1888 (1977); Southern Railway Company v. OSHRC and Brennan, 539 F.2d 335, 3 OSH Cases 1940 (Fourth Cir.), *cert. denied*, 429 U.S. 999, 4 OSH Cases 1936 (1976); Baltimore & Ohio Railroad Co. v. OSHRC, 548 F.2d 1052, 4 OSH Cases 1917 (D.C. Cir. 1976).

516 See, e.g., Southern Ry. v. OSHRC, 539 F.2d 335, 336-37, 3 OSH Cases 1940 (Fourth Cir.), *cert. denied*, 429 U.S. 999 (1976) (restating OSHA's interpretation).

517 The Third Circuit has also adopted this definition of "working conditions." See Columbia Gas of Pennsylvania, Inc. v. Marshall, 636 F.2d 913, 9 OSH Cases 1135 (Third Cir. 1980).

518 539 F.2d at 391, 4 OSH Cases at 1696 (Fourth Cir.).

519 Pennsuco Cement & Aggregates, 8 OSH Cases 1378 (Rev Comm'n 1980).

520 Mushroom Transportation Co., 1 OSH Cases 1390 (Rev Comm'n 1973).

521 Northwest Airlines, 8 OSH Cases 1982, 1990 (Rev. Comm'n 1980).

522 30 U.S.C. §§ 801 et seq.

523 Imminent danger is defined by Section 3(j) of the Federal Mine Safety and Health Act of 1977 as "the existence of any condition or practice in a coal or other mine that could reasonably be expected to cause death or serious physical harm before such condition or practice can be abated."

524 30 C.F.R. § 955.

525 Publ. Law 109-236.

526 42 U.S.C. § 7412(r)(6).

527 42 U.S.C. § 7412(r)(6)(G).

528 For information relating to the Chemical Safety and Hazard Investigation Board, see <http://www.csb.gov/>.

529 See 29 C.F.R. § 1910.120 and § 1910.1096 for general industry; § 1915.57 for shipyards; § 1926.53 and § 1926.65 for construction.

530 42 U.S.C. §2011.

531 The Atomic Energy Act is codified at 42 U.S.C. §§ 2011 et seq. The Nuclear Regulatory Commission, an independent executive commission, was created by the Energy Reorganization Act of 1974, 42 U.S.C. § 5841(a), and all licensing and related regulatory functions of the Atomic Energy Commission were then transferred to the NRC. See 42 U.S.C. § 5841(f) and (g). The NRC's "Standards for Protection Against Radiation" can be found at 10 C.F.R. Part 20.

- ⁵³² The permissible dosage per calendar quarter within such a “restricted area” is 1.25 rems to the whole body, head, and trunk, active blood-forming organs, lens of the eyes, or gonads; 18.75 rems to hands and forearms, feet and ankles; 7.5 rems to the skin of the whole body. Dosage standards are also set forth for the inhalation of radioactive substances. *See* 10 C.F.R. §§ 20.101–103. Detailed personnel monitoring and reporting requirements are also included in the regulations.
- ⁵³³ 10 C.F.R. §§ 20.105, 20.106, and 20.303.
- ⁵³⁴ 40 C.F.R. Part 190 et seq.
- ⁵³⁵ 30 C.F.R. Part 57 et seq. These regulations are revisions of regulations previously promulgated by the Secretary of Interior under the Metal and Non-Metallic Mine Safety Act that was repealed by the Federal Mine Safety and Health Amendments Act of 1977.
- ⁵³⁶ The Walsh–Healey Public Contracts Act is codified at 41 U.S.C. §§ 35 et seq. The relevant regulations can be found in 41 CFR § 50-204. These standards were later promulgated by the Secretary as established federal standards under Section 6(a) of the OSH Act.
- ⁵³⁷ The Radiation Control for Health and Safety Act amended the Public Health Service Act and is codified at 21 U.S.C. §§ 360gg-ss. The regulations promulgated by the U.S. Food and Drug Administration under this statute can be found at 21 C.F.R. Parts 1000–1050 (Radiological Health). *See also* 21 C.F.R. § 1020.30, the standard applicable to diagnostic X-ray systems.
- ⁵³⁸ *See* CPL 02-00-086 at https://www.osha.gov/pls/oshaweb/owadisp.show_document?p_table=DIRECTIVES&p_id=1658.
- ⁵³⁹ 15 U.S.C. § 1261 et seq.
- ⁵⁴⁰ Regulations published under this statute can be found at 16 CFR Subchapter C, Parts 1500 et seq.
- ⁵⁴¹ 15 U.S.C. § 2080(a).
- ⁵⁴² *See, e.g.*, 15 U.S.C. § 2608(c) pertaining to the *Frank Lautenberg Chemical Safety for the 21st Century Act*.
- ⁵⁴³ The FEPCA is codified at 7 U.S.C. §§ 136 et seq. It is a comprehensive revision of the Federal Insecticide, Fungicide and Rodenticide Act of 1970, 7 U.S.C. §§ 135 et seq. (1970).
- ⁵⁴⁴ *Organized Migrants in Community Action v. Brennan*, 520 F.2d 1161, 3 OSH Cases 1566 (D.C. Cir. 1975). *But see* *Public Citizen Health Research Group v. Aucther*, 702 F.2d 1150, 1157 n.23, 11 OSH Cases 1209 (D.C. Cir. 1983) (EPA’s labeling requirements for ethylene oxide do not preempt OSHA’s Ethylene Oxide regulation because EPA has exercised minimal, if any, regulatory authority.).
- ⁵⁴⁵ Regulations promulgated by EPA to protect farm workers from toxic exposure to pesticides are found in 40 C.F.R. §§ 170.1 et seq.
- ⁵⁴⁶ 20 C.F.R. Part 170.
- ⁵⁴⁷ The Clean Air Act is codified at 42 U.S.C. §§ 7401 et seq. National primary and secondary ambient air quality standards are published at 40 CFR Part 50.
- ⁵⁴⁸ 61 Fed. Reg. 31,668 (June 20, 1996)(codified at 40 C.F.R. Part 68).
- ⁵⁴⁹ 42 U.S.C. § 11001 et seq. (1986).
- ⁵⁵⁰ 29 C.F.R. § 1910.120.
- ⁵⁵¹ 29 C.F.R. § 1910.120, app. E.
- ⁵⁵² 42 U.S.C. § 11041.
- ⁵⁵³ The Toxic Substances Control Act of 1976 is codified at 15 U.S.C. §§ 2601 et seq.
- ⁵⁵⁴ 15 U.S.C. § 2608(c) states “In exercising any authority under this chapter, the Administrator shall not, for purposes of section 653(b)(1) of title 29, be deemed to be exercising statutory authority to prescribe or enforce standards or regulations affecting occupational safety and health.”
- ⁵⁵⁵ Pub. L. 114-182 (June 22, 2016) (codified at 15 U.S.C. ch. 53).
- ⁵⁵⁶ 15 U.S.C. § 2602(12). “The term “potentially exposed or susceptible subpopulation” means a group of individuals within the general population identified by the Administrator who, due to either greater susceptibility or greater exposure, may be at greater risk than the general population of adverse health effects from exposure to a chemical substance or mixture, such as infants, children, pregnant women, workers, or the elderly.”
- ⁵⁵⁷ 49 U.S.C. § 40101.
- ⁵⁵⁸ 49 U.S.C. § 20101.
- ⁵⁵⁹ 49 U.S.C. § 30101.
- ⁵⁶⁰ 49 U.S.C. § 60101.
- ⁵⁶¹ 49 U.S.C. § 1432(a).
- ⁵⁶² 49 U.S.C. § 1432(a).
- ⁵⁶³ 49 U.S.C. 31136.
- ⁵⁶⁴ 49 C.F.R. Part 399.
- ⁵⁶⁵ *See, e.g.*, *Lee Way Motor Freight*, 4 OSH Cases 1968 (Rev. Comm’n 1977).
- ⁵⁶⁶ 3 OSH Cases 1601 (Rev. Comm’n 1975).
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INDEX

- 2D concentration maps, 96
- 8-iso-prostaglandin F2a (8-isoprostane), 8

- abatement program, 312, 317, 329–334
- abrasion, protective clothing, 253
- absorbent clothing materials, 264
- absorption
 - chemical exposure, 4–6, 11–15, 38–51
 - protective clothing, 264
- Absorption, Distribution, Metabolism, and Excretion (ADME), 13–14, 48
- acceptance testing, ventilation, 217–218
- access rights, exposure records, 335
- accounting, 171–172
- acrylonitrile, 313
- action levels
 - protective clothing, 262, 264
- additivity, biological monitoring, 51
- Advanced REACH Tool (ART), 141, 280–282
- advection, 132–133, 137–139
- aerodynamics, 127–128
- aerosols, 65–92
 - air contaminants, 65–92
 - chemical exposure control, 228–245
 - exposure monitoring, 65–92
 - measurement instruments, 70
 - metrics, 149
 - particulate matter, 149
 - photometers, 65–92
 - real-time video monitoring, 65–92
 - respirators, 228–245
 - sensor metrics, 149
 - sensors, 149
 - video exposure monitoring, 65–92
- age/aging factors, 47

- agency's enforcement adequacy, 338
- agriculture
 - air contaminants, 167–168
- airborne agents
 - ancillary equipment, 190
 - automation, 192–193
 - biological monitoring, 4–8, 12–49, 51
 - chemical exposure, 4–52, 65–92, 121–144, 163–176, 177–197
 - classification, 177–178
 - contaminant sources, 177–196
 - dust control, 185–187
 - dyes, 186–187
 - elimination, 178–179, 182
 - emissions, 121–143, 163–176, 177–196
 - enclosure, 179
 - engineering control, 177–197
 - environmental controls, 182–185
 - equipment, 188–196
 - exposure control/limits, 177–197
 - facility layouts, 193–196
 - fugitive emissions, 177, 190
 - historical perspectives, 177–178, 182–191
 - isolation, 179, 196
 - material transport, 193–194
 - moisture content, 185–186
 - operation segregation, 195–196
 - particle size, 186
 - particulates, 77–80
 - pharmaceuticals, 186–187
 - philosophy, 177–196
 - pigments, 186–187
 - processes, 188–192
 - production chemical impurities, 187–188
 - real-time video exposure monitoring, 77–80
 - reduction strategies, 182–185
 - replacement strategies, 178–179, 182–185
 - risk assessments, 141–142, 179–180
 - robotics, 192–193
 - rubbers, 186–187
 - sampling, 4–51, 95–116, 164–165, 188–190
 - segregation of operation, 195–196
 - service and maintenance, 194–195
 - slurries, 187
 - solvents, 187–188
 - standards, 196
 - substitution, 178–179, 182–185
 - toxic materials, 181–188
 - ventilation, 177–179, 191–196
 - worker isolation, 196
 - workstations, 194
 - work task modification, 192–193
- air cleaners, 202
- air contaminants/pollution
 - accounting records, 171–172
 - advection, 132–133, 137–139
 - aerosol photometers, 65–92
 - agriculture industries, 167–168
 - analytical laboratory records, 170
 - backpressure, 126, 139
 - case studies, 77–92, 174–175
 - chemical dispersion, 123–143
 - chemical emission rates, 121–143
 - chemical exposure, 4–52, 65–92, 121–144, 163–176, 177–197
 - combustion, 166
 - company records and reports, 169–173
 - concentration, 121–144
 - constant rates, 121–122, 125–134, 139
 - control, 163–176, 177–197

- air contaminants/pollution (*Continued*)
 - data and record quality, 172–173
 - dispersion, 123–143
 - eddy diffusion, 124, 132–133, 137–139
 - emission rates, 121–143, 173–174
 - emissions, 121–143, 163–176, 177–196
 - engineering records, 170–171
 - environment, 65–92, 140–142, 179–196
 - ergonomics, 67, 74, 83–86, 89–90
 - European Exposure Factors Sourcebook, 141–142
 - evaporation losses, 166
 - Excel, 139–140
 - exhaust ventilation removal, 126–127, 130–136
 - exposure, 4–52, 65–92, 121–144, 163–176, 177–197
 - far field dispersion, 123–124, 129–138
 - food and agriculture industries, 167–168
 - fugitive sources, 166–169
 - government-mandated records and reports, 172
 - historical perspectives, 65–68, 177–178, 182–191
 - home video systems, 65–92
 - indoor concentrations, 121–144
 - information, 141–142
 - inorganic chemical industry, 167
 - inventory, 163–164, 173–175
 - laboratory records, 170
 - liquid storage tanks, 167
 - local exhaust ventilation, 126–127, 130, 199, 201–222
 - location aspects, 123–124
 - loss rates, 125–138
 - Markov chains, 135–139
 - mathematical modeling, 121–144
 - metallurgical industry, 168
 - mineral products, 168
 - mixing instruments, 69–75
 - monitoring, 65–92, 95–116
 - Monte Carlo simulations, 139–140
 - near field dispersion, 123–124, 129–138
 - NIOSH, 65–67, 72–77, 80–83
 - particle settling, 138–139
 - particle size, 127–128, 186
 - personnel records, 172
 - petroleum industry, 167
 - physical–chemical mathematical models, 121–144
 - picture mix, 65–67, 72–74
 - plant records and reports, 169–173
 - probability, 135–139
 - process and production records, 170
 - quantification, 164–169
 - real-time video exposure monitoring, 65–92
 - receptor location, 123–124
 - recirculation, 126–127, 130, 140
 - records and reports, 169–173
 - regulatory requirements, 173
 - research and development, 169–170
 - resources, 141–142
 - reversible sinks, 133–137
 - risk assessments, 141–142
 - safety data sheets, 170, 174
 - sampling, 4–51, 95–116, 164–165, 188–190
 - secondary data and records, 172–173
 - settling models, 138–139
 - short-term exposure limits, 75, 78–80
 - sinks, 133–137
 - sites, 123–124, 164
 - software, 66–92
 - solid waste disposal, 166
 - source sampling, 164–165
 - stationary internal combustion, 166
 - stochastic methods, 139–141
 - storage tanks, 167
 - tanks, 167
 - time aspects, 65–67, 80–82, 122, 164
 - time-weighted average, 65, 67, 80, 82
 - toxicology, 141–142
 - treated air recirculation, 126–127, 130, 140
 - turbulent eddy diffusion, 124, 132–133, 137–139
 - two-zone models, 124, 130, 133, 139–141
 - variability, 68, 122, 128–132
 - ventilation, 126–136, 140–141, 177–179, 191–196, 199–224
 - video exposure monitoring, 65–92
 - well-mixed rooms, 123, 125–139
 - wood products industry, 168
 - worker (receptor) location, 123–124
 - workplace exposure estimates, 174–175
- air exhausts, 217
- airflow
 - ventilation, 199–200, 204–207, 217–219
- air-impermeable materials, 264
- air inlets, 217
- air monitoring, 95–116
- air-purifying respirators (APR), 229–243
- air quality, 324
- air sampling
 - biological monitoring, 4–8, 12–51
 - chemical exposure, 4–8, 12–51, 95–116
 - computed tomography, 95–116
- alcohols, 52
- algebraic reconstruction techniques (ART), 103–105, 109, 112
- Alliance Program, 336
- AlphaTec, clothing, 256, 259–260
- American Conference of Governmental Industrial Hygienists (ACGIH)
 - biological monitoring, 17–37, 44–47
 - chemical exposure, 17–37, 44–47
 - ventilation, 209–211
- American National Standards Institute (ANSI)
 - ANSI Z9 standards, 215
 - respirators, 226, 244
- American Standards for Testing and Methods (ASTM)
 - ASTM F1001 Standard Guide, 256–261
 - ASTM F1186 Standard Classification, 257, 262–263
 - chemical protective clothing, 256–267
 - respirators, 226, 241
- ammonia, 111–114, 99
- amperometry, 151–152
- analytical techniques
 - chemical exposure monitoring, 44–46
 - laboratory records, 170
- ancillary equipment, contaminant control, 190
- antagonism, 51
- antidiscrimination rights, 335
- appeal court reviews, 333–334
- arsenic, 46, 316–317
- asbestos, 313–314
- assessment strategies
 - air contaminants, 65–92
 - biological monitoring, 5–11, 14, 37, 43–53
 - chemical exposure, 5–11, 14, 37, 43–53
 - real-time video exposure monitoring, 65–92
- assigned protection factors, 226, 228–230, 233, 239–245
- atmosphere-supplying respirators, 225, 235–239
- authorities
 - OSH Act regulations, 337
- automation, 192–193
- aviation, 340
- background level biomarkers, 44
- background optical remote sensing, 112–116
- backpressure, 126, 139
- banding hazards, 269–305
- barometric pressure
 - ventilation, 199–201, 206, 209
- barriers
 - protective clothing, 251–252, 255–260, 264–266
- Bayesian approaches, 102–103, 116
- beer brewing companies, 87–91
- benchmarks, OSH Act regulation, 337
- bench tests, respirators, 233–234
- benzene, 314
- beryllium, 314
- binding sites, 52
- bioagents
 - chemical exposure, 237–239
 - hazards, 237–239
 - respiratory protection, 237–239
- biochemical change markers, 9
- biogenic air contaminants, 168
- biohazards
 - exposure, 237–239
- biological exposure indices (BEI), 17–38, 43–48, 51
- Biological Exposure Indices Committee (BEIC), 17–38, 43–44, 47–48, 51
- biological limits, 4, 17–40, 43–48, 51
- biological monitoring
 - absorption, 4–6, 11–15, 38–51
 - ACGIH, 4, 17–37, 44–47
 - additivity, 51
 - aging factors, 47
 - airborne contaminants, 4–8, 12–49, 51

- alcohol consumption, 52
- analytical methods, 44–46
- antagonism, 51
- arsenic, 46
- assessment techniques, 5–11, 14, 37, 43–53
- binding sites, 52
- biological exposure indices, 17–38, 43–48, 51
- biological limits, 4, 17–40, 43–48, 51
- blood, 3–36, 40–52
- bodily fluids, 3–53
- carbon dioxide, 41–42, 48
- carcinogens, 4, 8–10, 38–40, 44–46, 49–51
- chemical exposure, 3–64
- chromium, 45
- competition, 52
- contaminants, 5–6, 17–52
- diet, 46–47
- disease, 3–4, 6–10, 42
- distribution, 11–15, 41, 46–49, 52
- electrophilic metabolite deactivation, 49
- elimination, 11–16, 40–52
- environmental monitoring, 4–8, 14–16, 37–39, 42–53
- ethical issues, 40
- exhaled air, 7, 12, 15–16, 22–23, 41–44, 47–49
- exhaled breath condensate, 42, 45
- exposure, 3–64
- gases, 41–42, 47–48
- genetic material, 3–4, 7–11, 14–15, 49–50
- genotoxicity, 4, 7–10, 50
- glutathione conjugates, 49
- hair, 42–43
- half-lives, 4, 11–17, 40, 43
- hemoglobin, 4, 7–9, 12, 19, 22, 29–31, 41–44, 47–50
- inorganic gases, 47
- inorganic pollutants, 7, 45–47
- interference factors, 46–47
- internal dose, 3–53
- kinetics, 11–14
- lifestyle factors, 47
- macromolecules, 49–50
- medication effects, 52
- mercury, 46
- metabolites, 3, 6–19, 38–53
- metals, 3–4, 7–9, 28, 38–48, 52
- methyl chloroform, 12, 15–16, 34, 42–43, 51
- micronuclei, 4, 9–10
- mixtures, 50–52
- NIOSH, 37
- occupational exposure, 3–53
- organic compounds, 48–50
- parent compounds, 48
- pharmacokinetics, 13–15, 47
- physiology, 9, 13–15, 42
- pollutants, 5, 17–52
- PPE, 4–6
- practical approaches, 40–45
- proteins, 8–9, 13–15, 46, 50–53
- quality control, 40
- reference values, 6, 17–40, 43, 47, 50, 53
- risk assessments, 6–10, 14, 37, 43–53
- RNA, 8
- saliva, 42
- sampling, 3–53
- selection criteria, 43–45
- skin exposure, 4–6, 9, 14–15, 37–51
- stability, 45
- strategies, 11–40
- surface sampling, 5–6
- synergism, 51
- threshold limit values, 17, 37, 44, 51
- tissue, 7–10, 41–43, 47–52
- toxicodynamics, 51
- toxicokinetics, 11–14
- trends, 52–53
- trichloroacetic acid, 15–16
- trichloroethanol, 15–16
- urine, 3–9, 12–36, 40–50
- variability, 14–17
- volatile organic compounds, 41–42, 48
- biological reference values (BAR), 18–36, 38
- biological tolerance values (BAT), 6, 18–38, 43–44, 47
- biological variability, 14–17
- Biologische Leit-Werte (BLW), 18–19, 21–24, 28–32, 36, 38
- biomarkers, 3–53
 - background levels, 44
 - of early biological effects, 6
 - of effect, 3, 7, 9–11
 - of exposure, 3–7, 9–11, 15, 44, 53
 - selection criteria, 43–45
 - sensitivity, 44
 - of susceptibility, 6–7, 10–11, 50
- Bivariate Panels, 226–227
- blood
 - cell changes, 3, 41, 49
 - chemical exposure monitoring, 3–36, 40–52
 - composition, 41
 - concentration, 41
 - pathogens, 319–320
- Bluetooth, 70–71
- bodily fluids, 3–53
- booth type hoods, 203
- breakthrough time, 251, 254–255, 264, 266–267
- breathing air quality, 246–247
- breathing apparatus, 226–230, 235–237, 266–267
- breathing zones, 95, 115–116, 207
- brewing companies, 87–91
- buccal micronucleus cytome assays, 10
- bulk chemicals, control banding, 287–289
- Bureau of Mines (BM), 225
- 1,3-butadiene, 314–315
- butyls, 256, 258–259, 264–265
- cadmium, 315
- calorimetric sensors, 153
- camcorders, 71
- canisters, respiratory protection, 231–241
- capture hoods, 203–204, 207
- capture velocities, 204
- carbon dioxide
 - biological monitoring, 41–42, 48
 - brewing companies, 87–91
 - heart rate monitoring, 87–91
 - video exposure monitoring, 87–91
 - volcanic activity, 112
- carbon monoxide
 - breathing air quality, 246–247
 - classification, 234–235
 - respirators, 234–235, 246–247
- carboxyhemoglobin, 4, 7–8, 12, 22, 41, 47
- carcinogens
 - chemical exposure monitoring, 4, 8–10, 38–40, 44–46, 49–51
 - OSH Act standards, 320
- care and maintenance
 - protective clothing, 252
 - respirators, 246
- cartridge respirators, 226–241, 245
 - classification, 231–233, 237
 - performance, 226–228
 - selection/use, 238, 245
- case studies
 - air contaminants, 77–92, 174–175
 - video exposure monitoring, 77–92
- cells
 - blood, 3, 41, 49
- challenge programs, OSH Act, 336
- challenging standards, promulgation, 326–327
- chamber studies, 108–110
- characterization
 - air contaminant emissions, 163–176
- Chemical Abstract Service (CAS), 142
- chemical, biological, radiological, and nuclear (CBRN) approval, 237
- chemical cartridge respirators, 226–241, 245
- chemical classification, protective clothing, 257, 262–263
- chemical dispersion, air contaminants, 123–143
- chemical emission rate functions, 121–143
- chemical exposure
 - absorption, 4–6, 11–15, 38–51
 - ACGIH, 17–37, 44–47
 - additivity, 51
 - ADME, 13–14, 48
 - aging factors, 47
 - air contaminants, 4–52, 65–92, 121–144, 163–176, 177–197
 - air monitoring, 95–116
 - air sampling, 4–8, 12–51, 95–116
 - alcohol consumption, 52
 - analytical methods, 44–46
 - antagonism, 51
 - arsenic, 46
 - assessments, 5–11, 14, 37, 43–53
 - background optical remote sensing, 112–116
 - binding sites, 52

INDEX

- chemical exposure (*Continued*)
 - biological exposure indices, 17–38, 43–48, 51
 - biological limit values, 4, 17, 37–40, 43–44, 51
 - biological monitoring, 3–64
 - biological tolerance values, 6, 18–38, 43–44, 47
 - blood, 3–36, 40–52
 - bodily fluids, 3–53
 - carcinogens, 4, 8–10, 38–40, 44–46, 49–51
 - chromium, 45
 - comet assays, 9–10
 - competition, 52
 - computed tomography, 95–116
 - concentration mapping, 95–116
 - contaminants, air, 5–6, 17–52, 65–92, 121–144, 163–176, 177–197
 - design, 99–102, 113, 208–215, 223
 - diet, 46–47
 - direct-reading sensors, 145–148, 156
 - disease, 3–4, 6–10, 42
 - distribution, 11–15, 41, 46–49, 52
 - effective dose biomarkers, 7–8
 - electrochemical sensors, 149–152
 - electrophilic metabolite deactivation, 49
 - elimination, 11–16, 40–52
 - environmental exposures, 4–8, 14–16, 37–53, 95–116
 - ethical issues, 40
 - evaluation, 121–144, 145–157
 - exhaled air, 7, 12, 15–16, 22–23, 41–49
 - field studies, 110–112
 - fluids, 3–53
 - FTIR spectrometers, 96, 99, 103, 106–116
 - future perspectives, 156–157
 - gases, 41–42, 47–48, 146, 149–153
 - genetic material, 3–4, 7–11, 14–15, 49–50
 - genotoxicity, 4, 7–10, 50
 - hair, 42–43
 - half-lives, 4, 11–17, 40, 43
 - hand washing, 5–6
 - hazards, 156, 225–248, 269–305
 - hemoglobin, 7–9, 12, 19, 22, 29–31, 41–44, 47–50
 - historical perspectives, 98–99
 - hygiene practice, 145–157
 - indirect sensors, 145–149
 - industrial chemicals, 3–64, 145–157, 199–224
 - inorganic pollutants, 45–47
 - interference factors, 46–47
 - internal dose, 3–53
 - ionizing radiation sensors, 153–154
 - kinetics, 11–14
 - lifestyle factors, 47
 - local exhaust ventilation, 199–222
 - low cost sensors, 145–157
 - macromolecules, 49–50
 - mapping, 95–116, 156
 - mathematical modeling, 121–144
 - medication effects, 52
 - mercury, 46
 - metabolites, 3, 6–19, 38–53
 - metal–oxide–semiconductor sensors, 149–150, 152
 - metals, 3–4, 7–9, 12, 28, 33, 38–48, 52
 - micronuclei, 4, 9–10
 - mixtures, 50–52
 - monitoring, 3–64, 65–92, 95–116, 155–156, 208–215, 223
 - network sensors, 156
 - NIOSH, 37
 - noise exposure sensors, 153
 - non-ionizing radiation sensors, 153–154
 - occupational exposure, 3–64
 - optical sensing, 96–100, 105–116, 153
 - organic compounds, 48–50
 - parent compounds, 48
 - particulate matter sensors, 146–149
 - patch tests, 4–6
 - pharmaceuticals, 13–15
 - physiology, 9, 13–15, 42
 - pollutants, 5, 17–52
 - PPE, 4–6
 - practical approaches, 40–45
 - protection, 4–6, 225–249, 251–267
 - protective clothing, 251–267
 - proteins, 8–9, 13–15, 46, 50–53
 - quality control, 40
 - radiation, 3–4, 9, 153–154
 - rate constant, 11–12
 - real-time video monitoring, 65–92
 - reference values, 6, 17–40, 43, 47, 50, 53
 - remote sensing, 96–100, 105–116
 - risk assessments, 6–10, 14, 37, 43–53
 - sampling, 3–53, 95–116
 - scanners, 97–116
 - sensors, 145–157
 - skin, 4–6, 14–15, 37–51
 - sound level sensors, 153
 - stability, 45
 - susceptibility biomarkers, 6–7, 10–11, 50
 - synergism, 51
 - tape stripping, 5–6
 - temperature sensors, 153
 - threshold limit values, 17, 37, 44, 51
 - tissue, 7–10, 41–43, 47–52
 - toxics/toxicology, 11–14
 - trends, 52–53
 - urine, 3–9, 12–36, 40–50
 - variability, 14–17
 - vibration sensors, 153
 - video monitoring, 65–92, 155–156
 - volcanic activity, 111–112
 - volume of distribution, 13
 - washing, 5–6
 - wipe tests, 5–6
- chemical exposure control
 - aerosols, 228–245
 - air contaminants, 163–176, 177–197
 - atmosphere-supplying respirators, 225, 235–239
 - bioagents, 237–239
 - chemical protective clothing, 251–267
 - control banding, 269–305
 - engineering control, 177–197
 - filters, 225–248
 - nuclear materials, 237
 - open-circuit apparatus, 235–236
 - protective equipment, 225–249, 251–267
 - radioactive agents, 237
 - respiratory protection, 225–249
 - selection criteria/techniques, 43–45, 237–247
 - type C supplied-air respirators, 236–237, 242–243
 - ventilation, 199–224
- Chemical Hazard Assessment and Management Program (CHAMP), 287–288
- chemical hazard information and packaging regulations (CHIP), 274
- chemical hazards
 - control banding, 269–305
 - mapping, 95–116, 156
 - respiratory protection, 225–249
- chemical industry, air contaminant source characterization, 167
- chemical processing, airborne contaminants, 188–192
- chemical protective clothing (CPC), 251–267
 - barrier, 251–252, 255–260, 264–266
 - breakthrough time, 251, 254–255, 264, 266–267
 - butyls, 256, 258–259, 264–265
 - chemical classification, 257, 262–263
 - chemical resistance, 251–257, 263–267
 - costs, 254–255
 - cut resistance, 251, 253–255, 263
 - degradation, 251–252, 255–256, 264–265
 - fire hazards, 254–255, 263
 - gas-tight materials, 255, 264–267
 - gloves, 251–256, 261–267
 - manufacturers, 254–256, 258–261, 266
 - materials, 251–266
 - performance, 251–267
 - permeation, 251–255, 263–267
 - resistance, 251–257, 263–267
 - selection techniques, 251–267
 - splashes, 253–254, 263–264, 266–267
 - standards, 254–264
 - substance evaluation, 253, 256–267
 - suits, 251–256, 261–267
 - tests, 251–252, 254–257, 263–266
 - toxicity, 253–255, 267
 - usability, 252–256
- chemical resistance, protective clothing, 251–257, 263–267
- Chemical Safety and Hazard Investigation Board (CSB), 338
- Chemicals Industry Council (CEPIC), 53
- chemical warfare agents, 225, 237
- ChemMAX, 256, 259
- Chemprote, 256, 259
- chloride, 318–319
- chlorinated polyethylene (CPE), 256, 258, 266
- chlorobutyl rubber, 265

- chromium, 45, 316
- chromosomal aberrations (CA), 3–4, 9–10
- citations, contestation, 332–333
- civil penalties, 331
- classification
 - airborne contaminants, 177–178
 - chemical control banding, 277–282, 286–287
 - chemical protective clothing, 257, 262–263
 - respirators, 229–237
- Clean Air Act, 339
- cleaning
 - protective clothing, 252, 254–255, 265
- clearance
 - chemical exposure monitoring, 13
- clinical X-ray scanners, 96–97
- Cloropel, 265
- closed-circuit escape respirators (CCER), 236–237
- closed-circuit self-contained breathing apparatus, 229, 235–236
- clothing
 - chemical protection, 251–267
- Code of Federal Regulations (CFR)
 - respirators, 225–233, 236–241, 244–246
- coke oven emissions, OSH Act, 320
- cold temperatures, respirators, 247
- combustible dust, 323
- combustion
 - air contaminants, 166
- comet assays, 9–10
- Comité Européen de Normalisation (CEN)
 - standards, 255, 264
- commercial customer particulate matter sensors, 148–149
- commodity sensors, 148–149
- communication
 - hazards, 320–321
 - OSH Act, 320–321
 - respirators, 247
 - video exposure monitoring, 70–71
- Community Right-to-Know Act, 339
- company records and reports, 169–173
- competition, biological monitoring, 52
- compliance, 326–327, 334–335
- composition
 - blood, 41
 - exhaled air, 42
 - urine, 40
- computational fluid mechanics (CFD), 209
- computed tomography (CT)
 - air monitoring/sampling, 95–116
 - algebraic reconstruction techniques, 103–105, 109, 112
 - ammonia, 99, 111, 113–114
 - background optical remote sensing, 112–116
 - Bayesian approaches, 102–103, 116
 - challenges, 115–116
 - chamber studies, 108–110
 - chemical exposure mapping, 95–116
 - concentration mapping, 95–116
 - derivative methods, 102–103, 105, 112
 - design, 99–102, 113
 - environmental air sampling, 95–116
 - equal-angle parallel-projection geometry, 99
 - exposure mapping, 95–116
 - field studies, 110–112
 - FTIR spectrometers, 96, 99, 103, 106–116
 - future directions, 115–116
 - geometry, 105–110
 - historical perspectives, 98–99
 - image quality, 101–102
 - interferometers, 114–115
 - iterative methods, 103–105, 116
 - mapping chemical exposure, 95–116
 - maximum likelihood expectation maximization, 104–105, 109
 - monitoring chemical exposure, 95–116
 - nearness, 101
 - optical remote sensing, 96–100, 105–116
 - peak exposure/height/location, 101–102
 - plume location/shape, 110–112
 - projection data distance, 102
 - reconstruction algorithms, 102–106, 109, 112, 116
 - remote sensing, 96–100, 105–116
 - sampling, 95–116
 - scanners, 97–116
 - simulations, 105–108
 - smooth basis function minimization, 102–103, 105, 109
 - sulfur hexafluoride, 98, 108–111
 - swine confinement, 111
 - volcanic activity, 111–112
- computer-aided designs (CAD), 209
- concentration
 - air contaminants, 121–144
 - blood, 41
 - mapping, 95–116
 - particulate matter, 147–149
- conditional probability, 135–136
- confined spaces, 322
- Congress, nullified standards, 323–324
- consensus standards
 - OSH Act, 308
- conservation of mass, 199–200
- Consolidated Human Activity Database (CHAD), 142
- constant rates, air contaminants, 121–122, 125–134, 139
- Construction Toolbox, 290–291
- consultations
 - OSH Act compliance, 335
- consumer aerosol monitors (CAM), 148–149
- Consumer Exposure model (Cons Expo), 141
- Consumer Product Information Database, 142
- Consumer Product Ingredients document, 142
- Consumer Product Safety Commission (CPSC), 339
- contact exposure potential, 251–267
- containment
 - control banding, 269, 273, 275–280
- contaminants
 - biological monitoring, 5–6, 17–52
 - chemical exposure, 4–52, 65–92, 121–144, 163–176, 177–197
 - dilution ventilation, 216–218
 - local exhaust ventilation, 199–222
 - sampling, 4–51, 95–116, 164–165, 188–190
- contamination
 - air concentrations, 121–144
 - chemical exposure control, 199–224
 - chemical protective clothing, 251–267
 - mathematical modeling, 121–144
 - ventilation, 199–224
- contestation proceedings, 332–334
- continuity equations, 199–200
- control
 - engineering controls, 177–196
 - hazards, 225–248, 269–305
 - velocities, 204
- control banding (CB), 269–305
 - acceptance of, 290
 - application examples, 284–293
 - basis establishment, 270–271
 - bulk chemicals, 287–289
 - chemical exposure control, 269–305
 - classification, 277–282, 286–287
 - containment, 269, 273, 275–280
 - COSHH, 269–282, 287–290, 294–296
 - current status, 294–296
 - databases, 274–282, 287, 291, 296
 - description of, 269–270
 - developing countries, 285–286
 - Direct Advice Sheets, 276–277
 - dust, 273–276, 279, 281–282
 - ecotoxicology, 280–282
 - Environment, Health, and Safety managers, 284–286, 289–296
 - evaluation, 278–284
 - evolution, 271–277
 - examples, 284–293
 - exhaust ventilation, 269, 275–281, 284, 292
 - fall protection, 284–286, 288, 290, 292–293
 - familiarity issues, 284–286, 292–293
 - gases, 273–275, 278–279, 284, 287–288
 - global experiences, 271, 277–287
 - gold standards, 283–284
 - guidance provision, 274–277, 280–281, 285–288, 294–297
 - hazard control, 269–305
 - health and safety, 269–297
 - history, 271–277
 - international experiences, 271, 278–284
 - labeling, 277–282, 286–287
 - local exhaust ventilation, 269, 275–281, 284, 292
 - lockout tagout, 284–286, 292–293
 - modeling, 270, 274–296
 - multidisciplinary, 270, 290–296
 - nanomaterials, 270, 283–285, 296
 - national organization acceptance, 290
 - objectives, 270
 - occupational exposure, 269–305

INDEX

- control banding (CB) (*Continued*)
 - origins, 271–272
 - OSHH, 270–271, 276–280, 285, 288–297
 - parity considerations, 285–286
 - PPE, 269–270, 276–277, 285, 288–290
 - practical issues, 284–296
 - professional's viewpoints, 292–293
 - protection, 269–270, 276–277, 284–293
 - quality, 270, 277, 282, 289, 295–296
 - quantitative methods, 269–271, 278, 281–287, 294–296
 - REACH, 270, 279–287, 294–296
 - regulations, 269–297
 - resources, 285–286, 295
 - risk assessment, 269–283, 289–292, 295–296
 - risk communication, 289–295
 - risk management, 269–297
 - safety, 269–297
 - scope, 270
 - standards, 269, 273–275, 283–285, 288–292, 296
 - Stoffenmanager, 281–283, 290, 296
 - substance managers, 281–283, 290, 296
 - terminology, 270
 - time limitations, 285–286
 - toolboxes, 270, 285–292, 295
 - toxicology, 269–280, 283–296
 - traditional approaches, 270–271
 - UK HSE, 269–282, 287–290, 294–296
 - unknowns, 283, 293, 295–296
 - user guidance provision, 274–277, 280–281, 285–288, 294–297
 - validation, 277–280
 - vapors, 273–275, 278–279, 284, 287–288
 - ventilation, 269, 275–281, 284, 288, 292
 - verification, 277–280
 - WHO, 279, 288–289
 - workshops, 279–281, 291
- Control Guidance Sheets (CGS), 274–277, 280–281, 287–288, 294–297
- Control of Substances Hazardous to Health (COSHH), 269–282, 287–290, 294–296
- coronaviruses, 238
- corporate toxic use reduction program, 184–185
- corrective lenses, 247
- corrosion, protective clothing, 253, 255, 265
- COSHH Essentials, 269–282, 287–290, 294–296
- costs
 - protective clothing, 254–255
 - sensors, 145–157
- cotton dust, 315
- coulometry, 151–152
- counters, ionizing radiation, 147–148, 153
- Courts of Appeals Review, 333–334
- COVID-19 pandemic, 238
- craft beer brewing companies, 87–91
- crime protection, 331–332
- crystalline silicas, 319
- cumulative permeation, 265
- cut resistance, 251, 253–255, 263
- cytogenetic alterations, 4, 9–10
- cytotoxicity markers, 9–10
- damage, protective clothing, 251–267
 - databases
 - control banding, 274–282, 287, 291, 296
 - data communications, 70–71
 - data interpretation, 75–76
 - data quality, 172–173, 311
 - dead band, 146
 - deaths
 - causation, 312
 - control banding, 289
 - decision logic, 241–243
 - decontamination, 252–255, 265
 - degradation, protective clothing, 251–252, 255–256, 264–265
 - de minimis* violations, 329
 - density correction for air at non-STP, 200
 - dentistry, 80–83
 - deoxyribonucleic acid (DNA), 4, 7–10, 49–50
 - Department of Transportation (DOT), 340
 - dermal exposure
 - control banding, 281, 294, 297
 - protective clothing, 265
 - detection
 - chemical protective clothing, 264–265
 - limit, 265
 - time, 264
 - Deutsche Forschung Gemeinschaft (DFG), 4, 18–36, 38, 44–47
 - developing countries
 - control banding, 285–286
 - diacetyl, 323
 - diagnostics
 - airborne contaminants, 188–190
 - air sampling, 188–190
 - 1,2-dibromo-3-chloropropane, 315
 - dichloromethane, 318
 - diet, 46–47
 - diffusion
 - protective clothing, 251, 264–265
 - digital camcorders, 71
 - dilution ventilation, 199–202, 215–218, 222–223
 - dimethylaminothioacetamide hydrochloride, 77–80
 - dipped materials, 265
 - Direct Advice Sheets (DAS), 276–277
 - direct particulate matter sensors, 146–147
 - direct-reading instruments (DRI), 69–70, 145–148, 156
 - direct sensors, 145–151, 156
 - discrimination rights, 335
 - diseases
 - chemical exposure monitoring, 3–4, 6–10, 42
 - illness logs, 334
 - illness reporting, 326
 - OSH Act, 326, 334
 - tuberculosis, 238, 324
 - workplaces, 326
 - dispersion, air contaminants, 123–143
 - disposal
 - chemical protective clothing, 252
 - waste management, 166
 - distribution
 - chemical exposure monitoring, 11–15, 41, 46–49, 52
 - dosimeters/dosimetry
 - radioactive materials, 83–86
 - video exposure monitoring, 83–86
 - duct velocities, 208
 - ductwork, 202, 208, 213–214
 - dust
 - airborne contaminants, 185–187
 - control banding, 273–276, 279, 281–282
 - engineering control, 185–187
 - OSH Act, 323
 - video exposure monitoring, 65–68, 74–75, 78–79
 - dyes, 186–187
 - dynamic range, sensors, 146, 151
 - dynamics
 - aerodynamics, 127–128
 - toxicodynamics, 51
 - easy-to-use workplace control scheme for hazardous substances (EMKG), 280–282, 287
 - economics
 - economic feasibility, 309–310
 - ecotoxicology, 141–142, 280–282
 - eddy diffusion, 124, 132–133, 137–139
 - effective dose biomarkers, 7–8
 - effective protection factors (EPF), 241
 - elastomers, 256, 259, 265, 267
 - electrochemical gas sensors, 149–152
 - electrophilic metabolite deactivation, 49
 - elimination
 - airborne contaminants, 178–179, 182
 - chemical exposure monitoring, 11–16, 40–52
 - toxics/toxicology, 182
 - Emergency Planning and Community Right-to-Know Act (EPCRA), 339
 - emergency temporary standards (ETS), 308–309
 - emission rates, 121–143, 173–174
 - emissions
 - air contaminants, 121–143, 163–176, 177–196
 - engineering control, 177–196
 - inventory, 163–164, 173–175
 - sites, 164
 - time factors, 164
 - ventilation, 199–223
 - employment
 - exposure records, 326
 - generic health standards, 319–322
 - medical records, 326
 - non-promulgated standards, 323–324
 - OSH Act, 311–326, 332–335
 - regulations, 326
 - representation, 334–335
 - rights, 334–335

- safety standards, 322–324
- single-substance health standards, 312–319
- specific regulations, 324–326
- standards, 312–324
- encapsulating chemical protective suits, 253, 255, 266–267
- enclosures
 - airborne contaminants, 179
 - enclosure hoods, 203, 206–207
- end-of-service-life indicators (ESLI), 232–233, 235, 243
- energy losses, ventilation, 201
- enforcement, OSH Act, 327–332, 338
- engineered nanomaterials (ENM), 239
 - nanoparticles, 239
 - protective equipment, 239
- engineering controls
 - airborne contaminants, 177–196
 - ancillary equipment, 190
 - automation, 192–193
 - chemical airborne contaminants, 177–197
 - chemical processing, 188–192
 - classification, 177–178
 - dust control, 185–187
 - elimination, 178–179, 182
 - enclosure, 179
 - environmental controls, 182–185
 - equipment, 188–196
 - exposure control, 177–197
 - facility layouts, 193–196
 - fugitive emissions, 177, 190
 - guidelines, 196
 - historical perspectives, 177–178, 182–191
 - industrial ventilation, 177–179, 191–196
 - isolation, 179, 196
 - material transport, 193–194
 - operation segregation, 195–196
 - philosophy, 177–196
 - processes, 188–192
 - reduction strategies, 182–185
 - replacement strategies, 178–179, 182–185
 - risk assessments, 179–180
 - robotics, 192–193
 - sampling, 188–190
 - segregation of operation, 195–196
 - service and maintenance, 194–195
 - standards, 196
 - substitution, 178–179, 182–185
 - toxic materials, 181–188
 - ventilation, 177–179, 191–196
 - worker isolation, 196
 - workstations, 194
 - work task modification, 192–193
- engineering records, 170–171
- enhanced video analysis of dust exposures (EVADE), 67, 74–75
- EN-ISO Standards, 264, 266
- ensemble, chemical protective clothing, 253, 263, 265–266
- entities responsible for, OSH Act, 307–308
- entry routes
 - protective clothing, 251, 267
- environment
 - air contaminants, 65–92, 140–142, 179–196
 - engineering control, 182–185
- environmental exposure
 - air sampling, 95–116
 - biological monitoring, 4–8, 14–16, 37–53
 - chemical exposure, 4–8, 14–16, 37–53, 95–116
 - real-time monitoring, 65–92
 - variability, 15
- environmental health and safety (EHS)
 - air contaminants, 65–92
 - control banding, 284–286, 289–296
 - real-time monitoring, 65–92
- Environmental Protection Agency (EPA)
 - air contaminants, 140–142, 179–184, 192, 196
 - chemical protective clothing, 253
 - health and safety program, 339–340
 - indoor air, 140–142
 - mathematical modeling, 140–142
- environmental scanners, 97–116
- enzymes, genetic polymorphism, 50
- epigenetic modifications, 8–9, 53
- equal-angle parallel-projection geometry, 99
- equipment
 - airborne contaminant control, 71, 188–196
 - engineering control, 188–196
 - placement, 193–196
 - video exposure monitoring, 71
- ergonomics
 - air contaminants, 67, 74, 83–86, 89–90
 - OSH Act, 323–324
 - video exposure monitoring, 67, 74, 83–86, 89–90
- escape respirators, 228–229, 236–238
- ethics
 - biological monitoring, 40
 - chemical exposure, 40
- ethylene oxide, 4, 8, 27, 50, 315–316
- ethylene vinyl alcohol, 256, 265
- European Centre for Ecotoxicology and Toxicology of Chemicals (ECETOC), 53, 141–142, 280–282
- European Chemicals Industry Council, 53
- European Committee for Standardization (Comité Européen de Normalisation)
 - standards, 255, 264
- European Exposure Factors Sourcebook, 141–142
- European picture mix (PIMEX), 65–67, 72–74
- European Union (EU)
 - air contaminants, 141–142
 - biological monitoring, 37–40
 - chemical exposure, 37–40
 - mathematical modeling, 141–142
- evaluation
 - chemical exposure, 121–144, 145–157
 - control banding, 278–284
- indoor air, 121–144
- mathematical modeling, 121–144
- sensors, 145–157
- evaporation, 166
- evolution
 - control banding, 271–277
- Excel, 139–140
- executive orders, 311
- exemptions, OSH Act, 337–338
- exercise of authority, 337
- exhaled air, 7, 12, 15–16, 22–23, 41–49
- exhaled breath condensate (EBC), 42, 45
- exhaust air recirculation, 220–223
- exhaust ventilation
 - chemical exposure control, 199–222
 - control banding, 269, 275–284, 292
 - indoor air contaminants, 126–136
- Ex parte warrants, 328
- exponentially decreasing rates, air
 - contaminants, 128–132
- Expositions-äquivalente für krebserzeugende Arbeitsstoffe (EKA), 18–36, 38
- Exposure Assessment Models under REACH (ETEAM), 281–282
- exposure assessments
 - air contaminants, 4–52, 65–92, 121–144, 163–176, 177–197
 - mathematical modeling, 121–143
- Exposure Factors Handbook*, 142
- Exposure and Fate Assessment Screening Tool (E-FAST), 141
- exposure mapping, 95–116
- exposure records, 326, 335
- exterior hoods, 203
- external combustion, 166
- eyeglasses, 247
- facilities
 - airborne contaminant controls, 193–196
- failure to abate violations, 330–331
- fall protection, 284–286, 288, 290, 292–293
- familiarity issues, 284–286, 292–293
- fans, ventilation, 202–203
- far-field dispersion, 123–124, 129–138
- fatalities
 - causation, 312
 - control banding, 289
- fate assessment screening, 141
- feasibility, OSH Act, 309–310, 312
- Federal Insecticide, Fungicide, and Rodenticide Act (FIFRA), 339
- Federal law, 307–356
- Federal regulations
 - respirators, 225–233, 236–241, 244–246
- Federal statutes, 337–340
- filtering facepiece respirators (FFR), 230, 239–240, 245
- filters
 - chemical exposure, 225–248
 - respiratory protection, 225–248
- Finland, 39

INDEX

- fires
 - clothing, 254–255, 263
 - protection, 214–215, 254–255, 263
 - ventilation, 214–215
- first-order loss rates, 125–128, 133–138
- fit-testing, 226–230, 244–247
- flanging, exhaust ventilation, 206
- flavorings, 323
- fluids
 - bodily, 3–53
 - chemical exposure monitoring, 3–53
- fluoroelastomers, 256, 259, 265, 267
- foods
 - agriculture contaminants, 167–168
 - air contaminants, 167–168
 - flavorings, 323
- formaldehydes, 316
- Fourier transform infrared (FTIR)
 - spectrometers, 96, 99, 103, 106–116
- Frank Lautenberg Chemical Safety for the 21st Century Act, 340
- Frontline, 256, 260
- fugitive emissions, 166–169, 177, 190
- fungicides, 339
- future perspectives
 - computed tomography, 115–116
 - OSH Act, 340
 - sensors, 156–157
 - video exposure monitoring, 76–77, 91–92
- gases
 - air contaminants, 168
 - amperometry, 151–152
 - biogenic air contaminants, 168
 - biological monitoring, 41–42, 47–48
 - calorimetric sensors, 153
 - chemical exposure, 41–42, 47–48, 146, 149–153
 - control banding, 273–275, 278–279, 284, 287–288
 - coulometry, 151–152
 - dental offices, 80–83
 - electrochemical sensors, 149–152
 - metal–oxide–semiconductor sensors, 149–150, 152
 - optical sensors, 153
 - photoionization detectors, 153
 - protective equipment, 228–247
 - real-time video exposure monitoring, 80–83
 - respiration, 228–247
 - sensors, 146, 149–153
 - sorbents, 230–235, 247
 - video exposure monitoring, 80–83
 - voltammetry, 151–152
- gas masks, 228–234, 237–240, 243–244
- gasoline additives, 4
- gas-tight materials, 255, 264–267
- Geiger–Muller (G–M) counters/tubes, 153
- general duty clause, 311–312
- generic health standards, 319–322
- genetic material, monitoring, 3–4, 7–11, 14–15, 49–50
- genetic polymorphism, 50
- genotoxicity, 4, 7–10, 50
- geometry, optical remote sensing, 105–110
- German Commission for the Investigation of Health Hazards of Chemical Compounds in the workplace (MAK commission), 4, 38, 44, 50
- German Research Association (DFG), 4, 18–36, 38, 44–47
- Germany
 - chemical exposure monitoring, 4–6, 18–38, 43–47, 50
- Globally Harmonized System (GHS), 277–282, 286–287
- gloves, 251–256, 261–267
- glutathione conjugates, 49
- G–M (Geiger–Muller) counters/tubes, 153
- gold standards, 283–284
- gravimetry, 148–149
- grid translation, 104–105
- grid translation-multigrid (GT-MG) method, 104–105
- guidelines
 - airborne contaminant control, 196
 - control banding, 274–277, 280–281, 285–288, 294–297
- hair, 42–43, 247
- half-lives, 4, 11–17, 40, 43
- hand grinding, 210
- hands
 - washing, 5–6
- handwear, 251–256, 261–267
- Hazard (H-)Statements, 270, 275–277, 281, 286–288, 297
- hazardous waste
 - disposal, 166
 - OSH Act, 321, 339
 - protective clothing/equipment, 265–266
- Hazardous Waste Operations and Emergency Response (HAZWOPER)
 - OSH Act, 321, 339
 - protective clothing, 265–266
- hazardous work refusal rights, 334
- Haz-Dust II, 78–79
- Hazmax®, 260
- health care
 - respiratory protection, 225–249
- health and safety
 - air contaminants, 65–92
 - control banding, 269–297
 - CSB, 338
 - EPA program, 339–340
 - MSHA, 338
 - NRC, 338–339
 - program, 307–356
 - real-time video exposure monitoring, 65–92
 - ventilation design, 214–215
- Health and Safety Executive (HSE), 269–282, 287–290, 294–296
- health standards, 307–340
- heart rate, 87–91
- heat stress
 - chemical protective clothing, 251, 254
- hemispherical turbulent eddy diffusion, 132–133
- hemoglobin, 7–9, 12, 19, 22, 29–31, 41–44, 47–50
- hexavalent chromium, 316
- historical perspectives
 - air contaminants, 65–68, 177–178, 182–191
 - chemical exposure, 98–99
 - computed tomography, 98–99
 - control banding, 271–277
 - engineering control, 177–178, 182–191
 - real-time video exposure monitoring, 65–68
 - reference values, 17–40
 - respirators, 225–226
 - video exposure monitoring, 65–68
- hobbyist sensors, 148–149
- hood-related equations, 206
- hoods, local exhaust ventilation, 202–207
- horizontal planes, 100
- N-(2-hydroxyethyl)valine (HEV)
 - hemoglobin adduct, 4
- ill health/illnesses *see* diseases
- image quality, 101–102
- immediately dangerous to life or health (IDLH) atmospheres, 229–230, 233–243
- imminent dangers, 328–329, 335
- impermeable protective materials, 264
- Indicateurs Biologiques d'Exposition (IBE), 38–39
- indices
 - biological exposure, 17–38, 43–48, 51
- indirect assessments
 - particulate matter sensors, 147–149
- individual susceptibility biomarkers, 6–7, 10–11, 50
- indoor air, 121–144
 - advection, 132–133, 137–139
 - backpressure, 126, 139
 - chemical emissions, 121–143
 - concentration, 121–144
 - contaminants, 121–144
 - dispersion, 123–143
 - eddy diffusion, 124, 132–133, 137–139
 - emission rates, 121–143
 - EPA, 140–142
 - Excel, 139–140
 - exhaust ventilation, 126–127, 130–136
 - exposure methods, 121–143
 - far field dispersion, 123–124, 129–138
 - information, 141–142
 - location aspects, 123–124
 - Markov chains, 135–139
 - mathematical modeling, 121–144
 - Monte Carlo simulations, 139–140
 - near field dispersion, 123–124, 129–138
 - ongoing emissions, 137
 - OSH Act, 324

- particle settling, 138–139
- particle size distribution, 127–128
- physical–chemical mathematical models, 121–144
- probability, 135–139
- receptor location, 123–124
- recirculation, 126–127, 130, 140
- resources, 141–142
- risk assessments, 141–142
- settling models, 138–139
- sinks, 133–137
- stochastic methods, 139–141
- toxicology, 141–142
- treated air recirculation, 126–127, 130, 140
- turbulent eddy diffusion, 124, 132–133, 137–139
- two-zone models, 124, 130, 133, 139–141
- ventilation, 126–136, 140–141
- well-mixed rooms, 123, 125–139
- worker (receptor) location, 123–124
- Indoor Environmental Concentrations in Buildings with Conditioned and Unconditioned Zones (IECCU), 141
- industrial chemicals, 3–64, 145–157, 199–224
 - absorption, 4–6, 11–15, 38–51
 - ACGIH, 4, 17–37, 44–47
 - additivity, 51
 - ADME, 13–14, 48
 - aging factors, 47
 - airborne contaminants, 4–8, 12–49, 51
 - alcohol consumption, 52
 - analytical methods, 44–46
 - antagonism, 51
 - arsenic, 46
 - assessment techniques, 5–11, 14, 37, 43–53
 - binding sites, 52
 - biological monitoring, 3–64
 - blood, 3–36, 40–52
 - bodily fluids, 3–53
 - carcinogens, 4, 8–10, 38–40, 44–46, 49–51
 - chemical exposure, 3–64, 145–157, 199–224
 - chromium, 45
 - clearance, 13
 - comet assays, 9–10
 - competition, 52
 - contaminants, 5–6, 17–52
 - diet, 46–47
 - disease, 3–4, 6–10, 42
 - distribution, 11–15, 41, 46–49, 52
 - effective dose biomarkers, 7–8
 - electrophilic metabolite deactivation, 49
 - elimination, 11–16, 40–52
 - environmental monitoring, 4–8, 14–16, 37–39, 42–53
 - ethical issues, 40
 - exhaled air, 7, 12, 15–16, 22–23, 41–44, 47–49
 - exhaled breath condensate, 42, 45
 - exposure, 3–64, 145–157, 199–224
 - fluids, 3–53
 - gases, 41–42, 47–48
 - genetic material, 3–4, 7–11, 14–15, 49–50
 - hair, 42–43
 - half-lives, 4, 11–17, 40, 43
 - hand washing, 5–6
 - hemoglobin, 4, 7–9, 12, 19, 22, 29–31, 41–44, 47–50
 - inorganic pollutants, 45–47
 - interference factors, 46–47
 - internal dose, 3–53
 - kinetics, 11–14
 - lifestyle factors, 47
 - macromolecules, 49–50
 - medication effects, 52
 - mercury, 46
 - metabolites, 3, 6–19, 38–53
 - metals, 3–4, 7–9, 28, 38–48, 52
 - micronuclei, 4, 9–10
 - mixtures, 50–52
 - NIOSH, 37
 - occupational exposure, 3–53
 - organic compounds, 48–50
 - parent compounds, 48
 - patch tests, 4–6
 - pharmacokinetics, 13–15, 47
 - physiology, 9, 13–15, 42
 - pollutants, 5, 17–52
 - PPE, 4–6
 - practical approaches, 40–45
 - proteins, 8–9, 13–15, 46, 50–53
 - quality control, 40
 - rate constant, 11–12
 - reference values, 6, 17–40, 43, 47, 50, 53
 - risk assessments, 6–10, 14, 37, 43–53
 - RNA, 8
 - saliva, 42
 - sampling, 3–53
 - saturable kinetics, 13
 - selection criteria, 43–45
 - skin exposure, 4–6, 9, 14–15, 37–51
 - stability, 45
 - surface sampling, 5–6
 - susceptibility biomarkers, 6–7, 10–11, 50
 - synergism, 51
 - tape stripping, 5–6
 - threshold limit values, 17, 37, 44, 51
 - tissue, 4–10, 14–15, 37–38, 41–52
 - toxicity, 4, 7–14, 50–51
 - trends, 52–53
 - urine, 3–9, 12–36, 40–50
 - variability, 14–17
 - ventilation, 199–224
 - volume of distribution, 13
 - washing, 5–6
 - wipe tests, 5–6
- industrial engineering records, 171
- industrial hygiene practice
 - chemical exposure evaluation, 145–157
 - industrial hygiene profession
 - control banding, 269–272, 278–279, 283–296
 - current status, 294–296
 - Industrial Ventilation Manual*, 209–211
 - infectious diseases
 - OSH Act, 324
 - Information Quality Act, 311
 - injuries
 - causation, 312
 - control banding, 289
 - illness reporting, 326
 - OSH Act regulations, 325–326, 334
 - rights, 334
 - tracking, 325–326
 - workplaces, 326
 - inorganic arsenic, 316–317
 - inorganic chemical industry, 167
 - inorganic gases, 47
 - inorganic pollutants, 45–47
 - insecticides, 339
 - inspections, 327–329, 334
 - instantaneous chemical mass emission rate
 - function, 121–143
 - instrumentation/instruments
 - video exposure monitoring, 68–85
 - Interceptor protective clothing, 260
 - interference
 - biological monitoring, 46–47
 - industrial chemical exposure, 46–47
 - interferometers, 114–115
 - internal dose, 3–53
 - international experiences, control banding, 271, 278–284
 - International Organization for Standardization (ISO)
 - chemical protective clothing, 264, 266
 - respiratory protection, 226
 - Internet, 70–71
 - inventory
 - air contaminants, 163–164, 173–175
 - investigations
 - Chemical Safety and Hazard Board, 338
 - German Commission for, 4, 38, 44, 50
 - ionizing radiation
 - biological monitoring, 3–4, 9
 - chemical exposure evaluation, 153–154
 - counters, 147–148, 153
 - Geiger–Muller counters, 153
 - particle counting, 153
 - sensors, 153–154
 - isolation
 - airborne contaminants, 179, 196
 - 8-iso-prostaglandin F2a, 8
 - isopropane, 8
 - iterative methods, 103–105, 116
- Japan, 39
- judicial reviews, 308
- Kemblok®, 256, 260
- kinetics
 - chemical exposure monitoring, 11–14

INDEX

- labeling
 - control banding, 277–282, 286–287
- laboratories
 - air contaminant records, 170
 - radioactive materials, 83–88
 - respiratory protection, 226–228
 - tests, 226–228
 - video exposure monitoring, 83–88
- laminates, 256, 258–259, 267
- lamps, 256–259, 267
- latex protective clothing, 266
- laws
 - OSHA program, 307–356
- layouts
 - engineering control facilities, 193–196
- lead
 - chemical exposure monitoring, 3–9, 12, 28, 33, 38–48, 52
 - OSH Act, 317
- levels A, B, C, & D protective clothing hazards, 253, 263, 266
- lifestyle, 47
- lighting
 - lamps, 256–259, 267
- light scattering, 148–149
- limit of detection (LOD), 147, 151
- limited use, chemical protective clothing, 251, 253, 264, 266
- limit of quantification (LOQ), 146
- litigation, OSH Act, 334–335
- local exhaust ventilation (LEV)
 - air contamination, 126–127, 130, 199, 201–222
 - booth type hoods, 203
 - breathing zones, 207
 - capture hoods, 203–204, 207
 - capture velocities, 204
 - chemical exposure, 199–222
 - components, 202–204
 - computational fluid mechanics, 209
 - computer-aided designs, 209
 - contaminants, 199–222
 - control banding, 269, 275–281, 284, 292
 - control velocities, 204
 - design, 208–215, 223
 - duct velocities, 208
 - ductwork, 202, 213–214
 - emission source enclosure, 207
 - enclosure hoods, 203, 206–207
 - exterior hoods, 203
 - fans, 202–203
 - flanging, 206
 - hand grinding, 210
 - hoods, 202–207
 - makeup air provision, 207
 - performance, 204–208, 219–220
 - predesign phases, 208–209
 - problem characterization, 208–209
 - receiving hoods, 203–204
 - removal, 126–127, 130
 - stacks, 203
 - velocities, 200, 204, 208
 - welding benches, 210
- lockout tagout (LOTO), 284–286, 292–293
- loss rates, air contaminants, 125–138
- low cost sensors, 145–157
- low third derivative (LTD) methods, 102–103, 105, 112
- low volume high velocity (LVHV) exhaust ventilation, 207–208
- macromolecules, 49–50
- maintenance
 - protective clothing, 252
 - respirators, 246
 - ventilation, 220
- make-up air provision, 207, 220–223
- manuals, 209–211
- manufacturing
 - protective clothing, 254–256, 258–261, 266
- mapping hazards, 95–116, 156
- margins of exposure (MoE), 280
- Markov chains, 135–139
- mask, gas *see* respirators
- Massachusetts Toxic Use Reduction Act of 1989, 183
- mass concentration measures, 147–149
- mass conservation, 199–200
- materials
 - contaminant transport, 193–194
 - protective clothing, 251–266
- materials balance, 165
- mathematical modeling, 121–144
 - air contaminants, 121–144
 - EPA, 140–142
 - Excel, 139–140
 - exposure methods, 121–143
 - IECCU, 141
 - information, 141–142
 - Markov chains, 135–139
 - particle settling, 138–139
 - probability, 135–139
 - resources, 141–142
 - selection techniques, 142–143
 - stochastic methods, 139–141
 - two-zone models, 124, 130, 133, 139–141
 - validation, 139–140
- Maximale Arbeitsplatzkonzentrationen (MAK), 38, 44
- maximum likelihood expectation maximization (MLEM), 104–105, 109
- measurements
 - aerosols, 70
 - mass concentration, 147–149
 - particulate matter, 146–149
 - ventilation, 200–201, 206, 214–215, 218–222
- mechanically controlled ventilation, 215
- medical devices
 - respirators, 225–249
- medical records, 326
- medical X-ray imaging, 96–97
- medication effects, 52
- mercury, 46
- metabolism
 - biological monitoring, 3, 6–19, 38–53
- metabolites, 3, 6–19, 38–53
- metal–oxide–semiconductors (MOX) sensors, 149–150, 152
- metals
 - biological monitoring, 3–4, 7–9, 28, 38–48, 52
- meters
 - interferometers, 114–115
 - photometers, 65–92
- methemoglobin, 4, 8, 29–31, 41, 44
- methyl chloroform, 12, 15–16, 34, 42–43, 51
- methylene chloride, 77–80, 318
- methylenedianiline, 318
- micronuclei (MN), 4, 9–10
- Microsoft Excel, 139–140
- Mine Enforcement and Safety Administration (MESA), 225
 - see also* Mine Safety and Health Administration (MSHA)
- mineral products industry, 168
- Mine Safety and Health Administration (MSHA), 225–226, 338
- minimum fit factors, 245
- mining industry
 - chemical exposure, 225–226, 236–237
 - respirators, 225–226, 236–237
- mixing
 - air contaminant monitoring, 69–75
- mixtures
 - biological monitoring, 50–52
- modeling
 - control banding, 270, 274–296
 - exposure methods, 121–143
 - mathematical models, 121–143
- moisture content, 185–186
- monitoring
 - aerosols, 65–92
 - air contaminants, 65–92, 95–116
 - carbon dioxide, 87–91
 - chemical exposure, 3–64, 65–92, 95–116, 155–156, 208–215, 223
 - computed tomography, 95–116
 - control banding, 277–278, 280, 296
 - dentistry, 80–83
 - ergonomics, 67, 74, 83–86, 89–90
 - heart rates, 87–91
 - particulates, 77–80
 - physiology, 9, 13–15, 42
 - qualitative performance, 219–220
 - quantitative performance, 220
 - radiation, 3–4, 9, 83–88
 - real-time video exposure, 65–92
 - sampling, 3–53, 69–70, 76
 - ventilation, 217–220
 - video exposure monitoring, 65–92, 155–156
- monomer residuals, 187
- Monte Carlo simulations, 139–140
- motor carriers, OSH Act, 340
- Multi-Chamber Chemical Exposure Model (MCCEM), 141
- multidisciplinary control banding, 270, 290–296
- multi-employer citation policies, 332
- multigrid methods, 104–105

- Multimedia Video Task Analysis (MVTA), 74, 79–81
- multiplicative algebraic reconstruction techniques (MART), 104–105, 109
- Mycobacterium tuberculosis* (TB), 238, 324
- nanomaterials
- control banding, 270, 283–285, 296
 - gold standards, 283–284
- nanoparticles, 238–239
- National Fire Protection Association (NFPA)
- chemical protective clothing, 254–255, 263
 - respirators, 227, 230
- National Institute for Occupational Safety and Health (NIOSH)
- air contaminants, 65–67, 72–77, 80–83
 - chemical exposure monitoring, 37
 - chemical protective clothing, 253
 - respirators/respiratory protection, 225–243, 246
 - video exposure monitoring, 65–67, 72–77, 80–83
- National Personal Protective Technology Laboratory (NPPTL), 225–226
- natural rubber, 255–256, 266–267
- natural ventilation, 215
- near-field dispersion, 123–124, 129–138
- nearness, image quality, 101
- neoprene, 255–256, 258–259, 266
- networks, sensors, 156
- nitrile materials, 255–260, 266
- nitrous oxides, 80–83
- noise
- chemical exposure sensors, 153
 - OSH Act health standards, 318–319
 - sensors, 153
- non-ionizing radiation
- chemical exposure sensors, 153–154
 - sensors, 153–154
- non-iterative low third derivative methods, 102–103, 105, 112
- non-promulgated standards, 323–324
- non-standard air, 200
- normal defense variance, 327
- normalized breakthrough time, 267
- notification rights, 335, 339
- nuclear material protection, 237
- nuclear pharmacies, 83–88
- Nuclear Regulatory Commission (NRC), 338–339
- nullified standards, 323–324
- objectivity aspects, 270
- occupational exposure
- air contaminants, 4–52, 65–92, 174–175
 - biological monitoring, 3–64
 - chemical agents, 3–64
 - computed tomography, 95–116
 - control banding, 269–305
 - chemical exposure, 3–4, 6–10, 42
 - engineering control, 177–197
 - mapping, 95–116
 - mathematical modeling, 121–143
 - real-time video monitoring, 65–92
 - reporting, 326
 - risk management, 270, 290
 - screening, 141–142
 - ventilation control, 199–224
 - video exposure monitoring, 65–92
- occupational exposure limits (OEL)
- biological basis, 5–6, 14, 37–40
 - chemical agents, 5–6, 14, 37–40
 - control banding, 269–297
 - OSH Act, 308–309, 312–327, 332, 335, 338–340
- occupational health and safety
- control banding, 270–271, 276–280, 285, 288–297
- occupational injuries and illnesses, 326
- occupational risk management (ORM), 270, 290
- Occupational Safety and Health Act (OSH Act), 307–340
- civil penalties, 331
 - compliance, 326–327, 334–335
 - contestation proceedings, 332–334
 - cooperation, 336
 - criminal sanctions, 331–332
 - employment, 311–326, 332–335
 - enforcement, 327–332, 338
 - entity responsibility, 307–308
 - exemptions, 337–338
 - exposure levels, 308–309, 312–327, 332, 335, 338–340
 - federal statutes, 337–340
 - future directions, 340
 - general duty clause, 311–312
 - generic health standards, 319–322
 - hazards, 311–323, 327–339
 - health standards, 307–340
 - inspections, 327–329, 334
 - judicial reviews, 308
 - penalties, 331–335
 - policies, 332
 - program, 307–355
 - promulgation, 323–324, 326–327
 - records, 326, 335
 - regulations, 307, 310–340
 - representation, 334–335
 - respirators, 226
 - rights, 334–335
 - rulemaking analysis, 310–311
 - sanctions, 331–332
 - scope of coverage, 308
 - single-substance standards, 312–319
 - standards, 307–340
 - states, 336–337
 - violations, 329–331
- Occupational Safety and Health Administration (OSHA)
- airborne contaminants, 177, 184, 190, 196
 - law, 307–356
 - program, 307–356
 - respirators, 226, 228–229, 232–233, 235, 238–246
 - ventilation, 214–215
- Occupational Safety and Health Administration Strategic Partnerships (OSPP), 336
- occupational safety, health, and hygiene (OSHH), 270–271, 276–280, 285, 288–297
- OMICS field ranges, 53
- online resources, 70–71
- on-site consultation programs, 335
- open-circuit self-contained breathing apparatus, 235–236
- open-path Fourier transform infrared (OP-FTIR) spectrometers, 96, 99, 103, 106–116
- optical particle counters, 147–148
- optical remote sensing (ORS), 96–100, 105–116
- optical sensors, 96–100, 105–116, 153
- organic chemical process industry, 167
- organic compounds, biological monitoring, 48–50
- organs
- heart rate, 87–91
- other-than-serious violations, 329–330
- overlay techniques, 72
- oxidative stress, 8
- oxygen-deficiency, 237–238
- packaging regulations, 274
- pandemics, 238
- Paperwork Reduction Act (PRA), 310–311
- parent compounds, 48
- parity considerations, 285–286
- partial exemptions, OSH Act, 337–338
- participation, workplaces, 334–335
- particle counters, 147–148, 153
- particle settling, 138–139
- particle size, 127–128, 186
- particulate matter (PM)
- aerosols, 149
 - chemical exposure evaluation, 146–149
 - commercial sensors, 148–149
 - commodity sensors, 148–149
 - concentration, 147–149
 - consumer aerosol monitors, 148–149
 - direct sensors, 146–147
 - gravimetry, 148–149
 - hobbyist sensors, 148–149
 - indirect sensors, 147–149
 - light scattering sensors, 148–149
 - mass concentration, 147–149
 - measurements, 146–149
 - optical particle counters, 147–148
 - research devices, 148–149
 - sensors, 146–149
 - standards, 149
- particulates
- industry, 77–80
 - respirators, 228–245
 - video exposure monitoring, 77–80
- patch testing, 4–6
- pathogens
- OSH Act, 319–320
- peak exposure, 102

INDEX

- peak height error, 102
- peak location errors, 101–102
- penalties, OSH Act, 331–335
- performance
 - chemical cartridge respirators, 226, 228
 - chemical exposure sensors, 145–157
 - chemical protective clothing, 251–267
 - local exhaust ventilation, 204–208, 219–220
 - respirators, 226–229
 - self-contained breathing apparatus, 226–227
 - sensors, 145–157
 - supplied-air respirators, 226, 229
- periodic maintenance testing, 220
- permanent standards, OSH Act, 309
- permanent variance, 326–327
- permeation
 - protective clothing, 251–255, 263–267
- permissible exposure limits (PEL)
 - OSH Act, 312–319, 323, 340
- permits
 - air recirculation, 222–223
- personal exposure assessments
 - chemical exposure evaluation, 156
- personal protective equipment (PPE), 251–267
 - chemical exposure monitoring, 4–6
 - chemical protection, 251–267
 - control banding, 269–270, 276–277, 285, 288–290
 - OSH Act, 323
- personnel
 - records, 172
- petroleum industry, 167
- pharmaceuticals
 - airborne contaminants, 186–187
 - control, 186–187
- pharmacokinetics
 - biological monitoring, 13–15, 47
 - chemical exposure, 13–15, 47
- philosophy
 - contaminant control, 177–196
- photographic dyes, 179
- photoionization detectors, 70, 153
- photometers, 65–92
- physical agents
 - chemical exposure evaluation, 146, 153–155
 - sensors, 146, 153–155
- physical–chemical mathematical models, 121–144
- physical injury causation, 312
- physical relationships, ventilation, 199–201
- Physician or Other Licensed Health Care Professional (PLHCP), 244
- physiology
 - chemical exposure monitoring, 9, 13–15, 42
- picture mix (PIMEX), 65–67, 72–74
- pigments, 186–187
- pipelines, 340
- plant records and reports, 169–173
- plume location and shape, 110–112
- policies
 - OSH Act, 332
- pollutants/pollution
 - chemical exposure monitoring, 5, 17–52
- polyethylene, 256, 258–259, 265–267
- polymers
 - protective clothing, 255–259, 264–267
 - residual monomers, 187
- polymorphism, 50
- polyvinyl alcohol, 256, 259, 267
- polyvinyl chloride (PVC), 319
- positive pressure respirators, 229–230, 237, 245–247
- posters, 334
- powders, video exposure monitoring, 65–66, 77
- powered air-purifying respirators (PAPR), 229–230, 232, 235, 237–238
- practical perspectives
 - biological monitoring, 40–45
 - control banding, 294–296
- preconstruction detail checks, 218
- predesign phases, 208–209
- probability
 - air contaminants, 135–139
 - of exposure, 273–274, 291
- process and production records, 170
- production
 - chemical impurities, 187–188
 - records, 170
- program management
 - health and safety, 307–356
 - OSHA, 307–356
- programs
 - administration, 239–249
 - effectiveness evaluation, 246
- projection data distance, 102
- promulgation, 323–324, 326–327
- protection
 - chemical exposure, 4–6, 225–249, 251–267
 - control banding, 269–270, 276–277, 284–293
 - fires, 214–215, 254–255, 263
 - respiration, 225–249, 321–322
 - workplaces, 226–230, 241
- protective clothing/wear
 - chemical protection, 251–267
- protective equipment
 - chemical exposure control, 225–249, 251–267
 - engineered nanomaterials, 239
 - gases, 228–247
 - OSH Act, 323
- proteins
 - biological monitoring, 8–9, 13–15, 46, 50–53
- psychosocial risks, 289
- punctures, protective clothing, 253
- qualitative fit tests (QLFT), 244–245
- qualitative performance monitoring, 219–220
- quality
 - control banding, 270, 277, 282, 289, 295–296
- quality control, 40
- quantification
 - air contaminant emissions, 164–169
 - FTIR spectrometers, 113–115
- quantitative control banding, 269–271, 278, 281–287, 294–296
- quantitative fit factors (QNFF), 230, 245–247
- quantitative fit testing (QNFT), 228, 230, 244–247
- quantitative performance monitoring, 220
- radiation
 - biological monitoring, 3–4, 9
 - chemical exposure, 3–4, 9, 153–154
 - monitoring, 3–4, 9, 83–88
 - nuclear pharmacies, 83–88
 - real-time video exposure monitoring, 83–88
 - sensors, 153–154
 - video exposure monitoring, 83–88
- radioactive materials, 83–88, 237
- radio telemetry, 70
- radium units, 3
- railways, 340
- Raspberry Pi, 71, 77, 87–92
- rates
 - air contaminant emissions, 121–143, 173–174
 - heart rate, 87–91
 - rate constant, 11–12
- ratio method, 75–76
- reactive oxygen species (ROS), 8, 10
- real-time video exposure monitoring, 65–92
- receiving hoods, 203–204
- receptor location, 123–124
- recirculation, air, 126–127, 130, 140, 220–223
- reconstruction algorithms, 102–106, 109, 112, 116
- records
 - air contaminants, 169–173
 - locations, 172
 - recordkeeping, 324–325
 - retention, 173
- reduction strategies
 - airborne contaminants, 182–185
- reference values
 - chemical exposure monitoring, 6, 17–40, 43, 47, 50, 53
 - historical perspectives, 17–40
- refusing hazardous work rights, 334
- Registration, Evaluation, Authorization, and Restriction of Chemicals (REACH)
 - control banding, 270, 279–287, 294–296
 - indoor air contaminants, 141–142
- regression, 76
- regulations
 - air contaminant emissions, 173
 - control banding, 269–297
 - OSH Act, 307, 310–340

- particulate matter sensors, 149
- states, 336–337
- ventilation design, 214–215
- Regulatory Flexibility Act of 1980, 310
- relief seeking rights, 335
- remote sensing, 96–100, 105–116
- renal clearance, 40–41
- repeated violations, 330
- replacement strategies
 - airborne contaminants, 178–179, 182–185
- reporting/reports
 - air contaminants, 169–173
 - OSH Act, 325–326
- representation, employees, 334–335
- research
 - and development records, 169–170
 - particulate matter sensors, 148–149
- Residential Exposure Assessment*, 142
- residual monomers, 187
- resistance
 - protective clothing, 251–257, 263–267
- resolution, sensors, 146, 151–157
- resources
 - control banding, 285–286, 295
 - indoor air contaminants, 141–142
 - mathematical modeling, 141–142
- respirable crystalline silica, 319
- respiration, 225–249
 - gases, 228–247
 - protection, 225–249, 321–322
 - vapors, 230–247
- respirators, 225–249
 - aerosols, 228–245
 - ANSI standards, 226, 244
 - assigned protection, 226, 228–230, 233, 239–245
 - ASTM, 226, 241
 - bench tests, 233–234
 - bioagents, 237–239
 - breathing air quality, 246–247
 - canisters, 231–241
 - carbon monoxide, 234–235, 246–247
 - care and maintenance, 246
 - cartridge devices, 226–241, 245
 - CBRN approval, 237
 - chemical exposure control, 225–249
 - chemical respirators, 226–241, 245
 - classification, 229–237
 - cold temperatures, 247
 - communications, 247
 - corrective lenses, 247
 - COVID-19, 238
 - decision logic, 241–243
 - effectiveness evaluation, 246
 - effective protection, 241
 - end-of-service-life indicators, 232–233, 235, 243
 - engineered nanoparticles, 239
 - eyeglasses, 247
 - Federal regulations, 225–233, 236–241, 244–246
 - filters, 225–248
 - fit testing, 226–230, 244–247
 - gases, 228–247
 - hair, 247
 - hazard control, 225–248
 - health care, 225–249
 - historical perspectives, 225–226
 - IDLH atmospheres, 229–230, 233–243
 - laboratories, 226–228
 - maintenance, 246
 - masks, gas 228–234, 237–240, 243–244
 - medical evaluations, 244
 - mines, 225–226, 236–237
 - MSHA, 225–226
 - nanoparticles, 238–239
 - NIOSH, 225–243, 246
 - NPPTL, 225–226
 - nuclear materials, 237
 - OSHA, 226–229, 232–233, 235, 238–246
 - oxygen-deficiency, 237–238
 - particulates, 228–245
 - performance, 226–229
 - positive pressure, 229–230, 237, 245–247
 - program administration, 239–249
 - programs, 239–247
 - radioactive agents, 237
 - selection, 237–247
 - severe acute respiratory syndrome, 238
 - sorbents, 230–235, 247
 - standards, 226–233, 240–241, 244–247
 - supplied-air suits, 237
 - testing, 226–230, 233–234, 244–247
 - training, 245–246
 - utilization, 237–247
 - vapors, 230–245, 247
 - warfare agents, 225, 237
 - workplace protection, 228–230
- respiratory protective equipment (RPE)
 - see* respirators
- response
 - delay, 70
 - direct-reading instruments, 70
 - sensors, 146–148, 151–155
 - time, 146, 151–153
 - video exposure monitoring, 70
- reversible sinks, 133–137
- reviews
 - commission, 334–335
 - employees, 334–335
- ribonucleic acid (RNA), 8
- rights
 - employees, 334–335
 - right-to-inspect, 327–328
 - right-to-know, 339
- risk
 - screening, 142
- risk assessments
 - airborne contaminants, 141–142, 179–180
 - chemical exposure monitoring, 6–10, 14, 37, 43–53
 - control banding, 269–283, 289–292, 295–296
 - engineering controls, 179–180
- risk communication
 - control banding, 289–295
- risk level based management system (RLBMS), 291–293
- risk management
 - control banding, 269–297
 - occupational exposure, 270, 290
- risk phrases (R-phrases), 270, 273–278, 281, 286
- robotics/robots
 - airborne contaminants, 192–193
 - engineering control, 192–193
- rodenticides, 339
- routes of exposure, 251, 267
- rubbers, 186–187, 255–256, 266–267
- rulemaking analysis requirements, 310–311
- Safety and Health Achievement Recognition Program (SHARP), 335
- saliva, 42
- sampling
 - air contaminants, 4–51, 95–116, 164–165, 188–190
 - biological monitoring, 3–53
 - chemical exposure, 3–53, 95–116
 - computed tomography, 95–116
 - engineering control, 188–190
 - timing aspects, 43
 - video exposure monitoring, 69–70, 76
- sanction enforcement, 331–332
- Saranex, 256, 259–261, 267
- saturable kinetics, 13
- scanners, chemical exposure CT, 95–116
- scattering
 - light, 148–149
- Scientific Committee on Occupational Exposure Limits (SCOEL), 4, 37–40
- scintillation, 153
- scooping tasks, 65–68, 74, 78–79
- screening
 - exposure, 141–142
- secondary data and records, 172–173
- seeking relief rights, 335
- segregation of operation, 195–196
- selection criteria/techniques
 - biological monitoring, 43–45
 - biomarkers, 43–45
 - chemical exposure control, 43–45, 237–247
 - chemical protective clothing, 251–267
 - gas masks, 238, 240, 243–244
 - mathematical modeling, 142–143
 - respirators, 237–247
- selectivity, sensors, 146–153
- self-contained breathing apparatus (SCBA)
 - chemical exposure control, 225
 - chemical protective clothing, 266–267
 - classification, 230, 235–237
 - performance, 226–227
- semiconductors
 - sensors, 153–154
- semiquantitative performance monitoring, 219–220

INDEX

- sensitivity
 - biomarkers, 44
 - sensors, 146–155
- sensitizers
 - chemical protective clothing, 251, 267
- sensors, 145–157
 - aerosol metrics, 149
 - amperometry, 151–152
 - chemical exposure evaluation, 145–157
 - commercial customer devices, 148–149
 - commodity devices, 148–149
 - concentration measures, 147–149
 - consumer aerosol monitors, 148–149
 - costs, 145–157
 - coulometry, 151–152
 - counters, 147–148, 153
 - dead band, 146
 - direct techniques, 145–151, 156
 - dynamic range, 146, 151
 - evaluation, 145–157
 - future perspectives, 156–157
 - gases, 146, 149–153
 - Geiger–Muller counters/tubes, 153
 - gravimetry, 148–149
 - hazard maps, 156
 - hobbyist devices, 148–149
 - indirect techniques, 145–149
 - industrial hygiene practice, 145–157
 - ionizing radiation, 153–154
 - light scattering, 148–149
 - limit of detection, 147, 151
 - limit of quantification, 146
 - mass concentration measures, 147–149
 - networks, 156
 - noise exposure, 153
 - non-ionizing radiation, 153–154
 - optical particle counters, 147–148
 - particulate matter, 146–149
 - performance characteristics, 145–157
 - personal exposure assessments, 156
 - physical agents, 146, 153–155
 - radiation, 153–154
 - reading instruments, 145–148, 156
 - regulatory standards, 149
 - researcher devices, 148–149
 - resolution, 146, 151–157
 - response, 146–148, 151–155
 - scintillation, 153
 - selectivity, 146–153
 - semiconductor devices, 153–154
 - sensitivity, 146–155
 - short duration sampling, 155–156
 - sound levels, 153
 - specificity, 146–155
 - standards, 149
 - temperature, 153
 - utilization, 155–156
 - vibration, 153
 - video exposure monitoring, 155–156
 - voltammetry, 151–152
- serious violations, OSH Act, 329–330
- service and maintenance, air contaminant control, 194–195
- settling
 - air contaminants, 138–139
- severe acute respiratory syndrome
 - coronavirus 2 (SARS-CoV-2), 238
- severe acute respiratory syndrome (SARS), 238
- short duration sampling, 155–156
- short-term exposure
 - air contaminants, 75, 78–80
 - video exposure monitoring, 75, 78–80
- silicas
 - control banding, 288
 - OSH Act health standards, 319
- simulated workplace protection factor (SWPF), 228–230
- simulations, 105–108, 139–140, 228–230
- simultaneous algebraic reconstruction techniques (SART), 104–105, 112
- simultaneous iterative reconstruction technique (SIRT), 104–105
- single-substance health standards, 312–319
- sinks, air contaminants, 133–137
- sister chromatid exchanges (SCE), 4, 9–10
- size
 - air contaminants, 127–128, 186
 - particle size, 127–128, 186
 - protective clothing, 254
- skin
 - chemical exposure, 4–6, 14–15, 37–51
 - control banding, 281, 294, 297
- slurries, 187
- Small Business Regulatory Enforcement and Fairness Act (SBREFA), 310
- smooth basis function minimization (SBFM), 102–103, 105, 109
- sodium bicarbonate, 77–80
- software
 - air contaminants, 66–92, 139–140
 - video exposure monitoring, 66–92
- soil
 - biological monitoring, 47
- solid waste disposal, 166
- solubility, protective clothing, 267
- solutes, 77–80
- solvents
 - airborne contaminants, 187–188
 - video exposure monitoring, 77–80
- sorbents, 230–235, 247
- sound
 - intensity, 153
 - levels, 153
 - sensors, 153
- sources
 - air contaminants, 164–165
- spatial resolution, 95–116
- specialist advice, 269, 275, 294
- specific compliance standards, 326–327
- specific enforcement policies, 332
- specificity, 43–44, 146–155
- specific regulations, 324–326
- splash protection, 253–254, 263–264, 266–267
- stacks, ventilation, 203
- standardized urine biomarkers, 41
- standards
 - adoption requirements, 309–311
 - airborne contaminants, 196
 - CEN standards, 255, 264
 - chemical protective clothing, 254–264
 - Congress, 323–324
 - control banding, 269, 273–275, 283–285, 288–292, 296
 - design, 214–215
 - emergencies, 308–309
 - employers, 312–324
 - engineering control, 196
 - gold standards, 283–284
 - health, 307–340
 - OSH Act, 307–340
 - particulate matter sensors, 149
 - promulgation, 323–324, 326–327
 - respirators, 226–233, 240–241, 244–247
 - safety, 322–324
 - sensors, 149
 - ventilation design, 214–215
- standard temperature and barometric pressure (STP), 199–201, 206, 209
- start-up testing, ventilation, 217–218
- state regulations, 336–337
- static pressure (SP), 200–201
- stationary internal combustion, 166
- statutory authority, 337
- steady-state permeation, 267
- Stochastic Human Exposure and Dose Simulation (SHEDS), 141
- stochastic methods, air contaminant control, 139–141
- Stoffenmanager, 281–283, 290, 296
- storage
 - air contaminants, 167
- strategic partnerships, 336
- substance evaluation, protective clothing, 253, 256–267
- substance health standards, 312–319
- substance managers, 281–283, 290, 296
- substitution
 - airborne contaminants, 178–179, 182–185
 - toxic material controls, 182–185
- suits, protective clothing, 251–256, 261–267
- sulfur dioxide, 111–112
- sulfur hexafluoride, 98, 108–111
- supplied-air respirators (SAR), 229–230, 235–238, 242–247
- supplied-air suits, 237
- supplying air principles, 221–222
- surface sampling, 5–6
- susceptibility
 - biomarkers, 6–7, 10–11, 50
- swine, 111
- synergism, 51
- tactile sensitivity, 252, 254–255
- tape stripping, 5–6
- targeted risk assessments (TRA), 141–142, 280–282
- tears, protective clothing, 251, 254, 264
- technology
 - OSH Act, 309–310
- Teflon, 265

- temperature
 - respirators, 247
 - sensors, 153
 - ventilation, 199–201, 206, 209
- temporal resolution, 95–116
- temporary variance, standards compliance, 326–327
- testing/tests
 - concentration maps, 101
 - permeation, 252
 - protective clothing, 251–252, 254–257, 263–266
 - respirators, 226–230, 233–234, 244–247
 - ventilation, 217–220
- tetraethyl lead, 4
- theoretical aspects
 - FTIR spectrometers, 113–115
- threshold limit values (TLV)
 - chemical exposure monitoring, 17, 37, 44, 51
- time aspects
 - air contaminants, 65–67, 80–82, 122, 164
 - control banding, 285–286
 - sampling, 43
- time-weighted averages (TWA)
 - air contaminants, 65, 67, 80, 82, 122
 - real-time video exposure monitoring, 65, 67, 80, 82
- tissue
 - chemical exposure monitoring, 4–10, 14–15, 37–38, 41–52
- tolerance factors
 - biological tolerance values, 6, 18–38, 43–44, 47
- tools
 - control banding, 270, 285–292, 295
- totally encapsulating chemical protective suits, 253, 255, 266–267
- total pressure, ventilation, 201
- toxicants/toxicology
 - airborne contaminants, 181–188
 - air contaminants, 141–142
 - chemical exposure, 11–14
 - control banding, 269–280, 283–296
 - elimination, 182
 - engineering control, 181–188
 - EPA program, 339–340
 - material controls, 181–188
 - substitution, 182–185
- toxicity
 - chemical protective clothing, 253–255, 267
 - control banding, 269–280, 283–296
 - industrial chemicals, 4, 7–14, 50–51
- toxicodynamics, 51
- toxicokinetics, 11–14
- Toxic Substances Control Act (TSCA)
 - EPA program, 339–340
- traditional control banding, 270–271
- training
 - respirators, 245–246
- transport
 - OSH Act, 340
- treated air recirculation, 126–127, 130, 140
- trichloroacetic acid (TCAA), 15–16
- trichloroethanol (TCOH), 15–16
- tuberculosis, 324, 238
- turbulent eddy diffusion, 124, 132–133, 137–139
- two-dimensional (2D) concentration maps, 96
- two-zone models, 124, 130, 133, 139–141
- Tychem®, 256, 260–261
- type C supplied-air respirators, 236–237, 242–243
- Tyvek, 256, 267
- unconditional probability, 135–136
- United States of America (USA)
 - air contaminants, 65–92
 - biological monitoring, 17–37
 - mining, 225–226, 338
 - reference values, 17–37
 - video exposure monitoring, 65–92
- unknowns, control banding, 283, 293, 295–296
- urine
 - chemical exposure monitoring, 3–9, 12–36, 40–50
 - composition, 40
- usability, protective clothing, 252–256
- usage checklists, protective clothing, 252–253
- user guidance, control banding, 274–277, 280–281, 285–288, 294–297
- utilization
 - air-purifying respirators, 238–243
 - cartridge respirators, 238, 245
 - chemical exposure, 237–247
 - chemical protective clothing, 252–256
 - filtering facepiece respirators, 239–240, 245
 - gas masks, 238, 240, 243–244
 - powered air-purifying respirators, 238
 - respirators, 237–247
 - sensors, 155–156
 - supplied-air respirators, 238, 242–243, 246–247
 - video exposure monitoring, 69
- validation
 - control banding, 277–280
 - mathematical modeling, 139–140
- validity, OSH Act enforcement, 328
- vapors
 - control banding, 273–275, 278–279, 284, 287–288
 - protective equipment, 230–235, 247
 - respiration, 230–247
 - sorbents, 230–235, 247
- variability
 - air contaminants, 68, 122, 128–132
 - chemical exposure monitoring, 14–17
- variance, specific standards compliance, 326–327
- velocity
 - ventilation, 200, 204, 208
- ventilation
 - acceptance testing, 217–218
 - air contamination, 126–136, 140–141, 177–179, 191–196, 199–224
 - airflow, 199–200, 204–206, 217–219
 - ANSI Z9 standards, 215
 - barometric pressure, 199–201, 206, 209
 - chemical exposure, 199–224
 - conservation of mass, 199–200
 - contamination, 199–224
 - continuity equations, 199–200
 - control, 199–224
 - control banding, 269, 275–281, 284, 288, 292
 - definitions, 199–201
 - density correction for air at non-STP, 200
 - design, 208–215, 223
 - emission controls, 199–223
 - energy losses, 201
 - engineering control, 177–179, 191–196
 - exhaust air recirculation, 220–223
 - fire protection, 214–215
 - health and safety, 214–215
 - industry, 177–179, 191–196, 199–224
 - maintenance testing, 220
 - makeup air provision, 207, 220–223
 - manuals, 209–211
 - measurements, 200–201, 206, 214–215, 218–222
 - monitoring, 217–220
 - OSHA design, 214–215
 - performance, 204–208, 219–220
 - periodic maintenance, 220
 - physical relationships, 199–201
 - preconstruction checks, 218
 - qualitative performance, 219–220
 - quantitative performance, 220
 - recirculation, 220–223
 - regulations, 214–215
 - safety, 214–215
 - standards, 214–215
 - standard temperature, 199–201, 206, 209
 - start-up testing, 217–218
 - static pressure, 200–201
 - testing, 217–220
 - total pressure, 201
 - velocity, 200, 204, 208
- verification, control banding, 277–280
- vertical planes, 100
- vibration
 - sensors, 153
- video exposure monitoring (VEM), 65–92
 - air contaminants, 65–92
 - assessment strategies, 69
 - Bluetooth, 70–71
 - brewing companies, 87–91
 - carbon dioxide, 87–91
 - case studies, 77–92
 - chemical exposure assessments, 65–92
 - communications, 70–71
 - data communications, 70–71
 - data interpretation, 75–76
 - dental offices, 80–83
 - dimethylaminothioacetamide hydrochloride, 77–80

INDEX

- video exposure monitoring (VEM)
 - (Continued)
 - direct-reading instruments, 69–70
 - dosimeters, 83–86
 - dust, 65–68, 74–75, 78–79
 - equipment, 71
 - ergonomics, 67, 74, 83–86, 89–90
 - future directions, 76–77, 91–92
 - gases, 80–83
 - heart rate, 87–91
 - instruments, 68–85
 - Internet, 70–71
 - laboratories, 83–88
 - methylene chloride exposure, 77–80
 - mixing instruments, 69–75
 - NIOSH, 65–67, 72–77, 80–83
 - nitrous oxides, 80–83
 - nuclear pharmacies, 83–88
 - overlay techniques, 72
 - particulates, 77–80
 - photoionization detectors, 70
 - picture mix, 65–67, 72–74
 - radioactive materials, 83–88
 - radio telemetry, 70
 - Raspberry Pi, 71, 77, 87–92
 - ratio method, 75–76
 - regression, 76
 - response delay, 70
 - sampling, 69–70, 76
 - sensors, 155–156
 - sodium bicarbonate, 77–80
 - software, 66–92
 - solutes, 77–80
 - solvents, 77–80
 - utilization, 69
 - wireless data communications, 70–71
 - worker activity classification, 75
- video home systems (VHS), 65–92
- vinyl chloride, 319
- violations
 - OSH Act enforcement, 329–332
 - violation-by-violation penalties, 332
- violence
 - prevention, 324
- visual image quality assessments, 102
- Viton®, 256, 259, 265, 267
- volatile organic compounds (VOC)
 - biological monitoring, 41–42, 48
- volcanos, 111–112
- voltammetry, 151–152
- volume of distribution, chemical exposure, 13
- volume flow rates, ventilation, 216
- voluntary compliance, OSH Act, 335
- voluntary protection, OSH Act, 336
- Wall Paint Exposure Model (WPEM), 141
- warfare agents, 225, 237
- warrant enforcement, 327–328
- washing, 5–6
- waste management
 - disposal, 166
 - OSH Act, 321
- Waste Reduction Innovative Technology Evaluation (WRITE), 182–183, 192
- welding, 210
- well-mixed rooms (WMR), 123, 125–139
- wilful violations, 330–331
- wipe tests, 5–6
- wireless communications, 70–71
- wood products industry, 168
- worker activity classification, 75
- worker isolation, 196
- worker (receptor) location, 123–124
- working conditions, 337–338
- workplaces
 - air contaminants, 65–92, 174–175
 - ill health/illnesses, 326
 - injuries, 326
 - participation, 334–335
 - protection, 226–230, 241
 - respirators, 226–230, 241
 - task modification, 192–193
 - testing respirators, 228–230
 - violence prevention, 324
- workshops, control banding, 279–281, 291
- workstations, 194
- World Health Organization (WHO)
 - control banding, 279, 288–289
- X-ray imaging, 96–97
- X-ray scanners, 96–97
- Zytron®, 256, 261

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