CHAPTER THIRTY-TWO

Respiratory Protective Equipment

Warren R. Myers, Ph.D., CIH

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 1st century AD. Although respirators have been used for almost 2000 years, the genesis of their technical development is actually the mid-19th century. During that century, respiratory technology advanced rapidly as evidenced by the:

1. Appearance of the first early ancestors of modern atmosphere-supplying respirators.
2. 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.
3. Rapid advancement of particulate filter technology after the discovery of Brownian motion (first observed 1827).
4. Discovery of the adsorptive properties of activated charcoal for many types of organic vapors.

Despite these major advances in knowledge and technology, respirator development continued slowly. Chemical warfare agents, introduced in World War I, focused attention on the need for adequate respirators. In the United States, the Bureau of Mines successfully carried out this work for the army. The forerunners of present-day respirators began to

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appear after World War I. In those early years, misuse of surplus army gas masks by civilians and employers, who had sole discretion about deciding when and how respirators were used, highlighted the need for respiratory protection standards.

The Bureau of Mines in 1919 initiated the first respirator certification program in the United States and certified their first respirator, a self-contained breathing apparatus in 1920 (1). 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). Responsibility for the respirator certification program was housed within the Bureau of Mines.

Closely following 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 the National Institute for Occupational Safety and Health (NIOSH). The Occupational Safety and Health Administration is given the regulatory authority to require and monitor the use of respirators in general industry (Title 29 *Code of Federal Regulations* Part 1910.134 (29 *CRF* Part 1910.134)) and construction (29 *CFR* 1926.103) (3, 4). The OSHA promulgated a revision for 29 CFR Part 1910 and 1926 in January of 1998 (5, 6).

Responsibility for the respirator certification program was transferred from the Bureau of Mines to NIOSH in 1972 by a memorandum of understanding between the Departments of Labor and Health and Human Services. As a result, NIOSH shared a joint certification function with the Mine Safety and Health Administration (MSHA) and certification labels carried the designation of both agencies prior to 1995 (e.g., NIOSH/MSHA approved for . . .).

In 1995, NIOSH promulgated new certification regulations, Title 42 *Code of Federal Regulations* Part 84 (Part 84) to replace 30 *CFR* Part 11 (7, 8). At the present time, Part 84 addresses only revised performance tests for particulate filters used on or as a negative pressure facepiece (originally those devices tested under Subpart K, 30 *CFR* Part 11). Designation as "NIOSH-certified" indicates that a respirator has met the minimum performance standards, in 42 *CFR* Part 84, applicable to its particular class of RPE. Knowing the minimum performance standards and recognizing the limitations of the NIOSH certification tests are important when selecting and using a "NIOSH-certified" repirator. Achieving proper respiratory protection with NIOSH-certified RPE requires that (*1*) the RPE be properly selected for the environment in which it will be used; (*2*) its face fitting characteristics be adequately evaluated and considered in the selection process; and (*3*) workers receive periodic training that adequately prepares them to conscientiously and properly wear and use the RPE.

Three recognized standard-producing groups have produced guidance or standards on establishing and maintaining the elements of a good respiratory protection program. They are:

A. The American National Standards Institute (ANSI), "Practices for Respiratory Protection," 1992 (9).

B. The National Institute for Occupational Safety and Health (NIOSH) respirator approval regulations (42 *CFR* Part 84) and respirator use recommendations.

C. The Occupational Safety and Health Administration (OSHA) respirator use regulations for general industry (29 *CFR* 1910.134) and substance- or standard-specific respirator use regulations (e.g., lead 29 *CFR* 1910.1025, inorganic arsenic 29 *CFR* 1910.1018, benzene 29 *CFR* 1910.1028, etc.).

The primary objective of industrial hygiene is 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. But very often exposure control becomes an issue after the process(es) are operational and therefore control becomes a more difficult and costly proposition. However, 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 controls steps are (*1*) substitution of a less toxic substance, (*2*) encapsulation or isolation of the process, (*3*) use of local exhaust ventilation or general ventilation in conjunction with filters and scrubbers to control the effluents, (*4*) use of personal protective equipment (PPE).

Respiratory protective equipment 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 respiratory protective equipment (RPE) becomes the only technically and economically feasible adjunct to engineering controls to minimize and control respiratory exposures. According to recent estimates reported by the OSHA Office of Regulatory Analysis, roughly 5 million workers, 19–20% of the mining/manufacturing/construction workforce, in 1.3 million establishments use or have access to some type of respiratory protective equipment (5). Thus, RPE continues to be an important component in many respiratory exposure control plans. As a result, selection, use and evaluation of RPE have become more important as well.

2 LIST OF DEFINITIONS

Aerodynamic diameter. The diameter of a unit density sphere having the same settling velocity as a particle of arbitrary shape and density.

Airborne bacteria and virus. Airborne suspensions of living organisms usually found in the size range from 0.001 to 15 micrometers.

Air purifying respirator (APR). A respirator employing an air-purifying element to remove specific air contaminants by passing ambient air through the air-purifying element.

Air-purifying element. A component used in respirators to remove solid or liquid aerosols or gases or vapors from air.

Assigned Protection Factor (APF). The minimum expected workplace level of respiratory protection that would be provided by a properly functioning respirator or class of respirators, to a stated percentage of properly fitted and trained users.

Atmosphere-supplying respirator. A respirator that supplies the respirator user with breathing air from a source independent of the ambient atmosphere, and includes supplied-air respirators (SARs) and self-contained breathing apparatus (SCBA) units.

Canister or cartridge. A container with a filter, sorbent, or catalyst, or combination of these items, which removes specific contaminants from the air passed through the container.

Compressed-breathing gas. Oxygen or air stored in a compressed state and supplied to the wearer in gaseous form.

Demand respirator. An atmosphere-supplying respirator that admits breathing air to the facepiece only when a negative pressure is created inside the facepiece by inhalation.

Disposable respirator. A respirator that is discarded after the end of its recommended period of use, after excessive resistance or physical damage, or when odor breakthrough or other warning indicators render the respirator unsuitable for further use.

Dust. A solid mechanically produced particle usually found in the harmful size range of from 0.5 to 10 micrometers particle diameter.

Emergency situation. Any occurrence such as, but not limited to, equipment failure, rupture of containers, or failure of control equipment that may or does result in an uncontrolled significant release of an airborne contaminant.

End-of-service-life indicator (ESLI). A system that warns the respirator user of the approach of the end of adequate respiratory protection, for example, that the sorbent is approaching saturation or is no longer effective.

Escape-only respirator. A respirator intended to be used only for emergency exit.

Elastomeric facepiece or mouthpiece. A respirator component designed to provide a gas-tight or dust-tight fit with the face and may include headbands, valves, and connections for canisters, cartridges, filters, or respirable gas source.

Filter. An air-purifying element designed to remove solid or liquid aerosol from air.

Filtering facepiece. A particulate respirator with a filter as an integral part of the facepiece or with the entire facepiece composed of the filtering medium (see disposable respirator).

Fit test. The use of a protocol to qualitatively or quantitatively evaluate the fit of a respirator on an individual.

Fume. A solid condensation particle, generally of size range from 0.1 to 1-micrometer aerodynamic diameter.

Gas. An aeriform fluid that is in a gaseous state at 0° Centigrade and 760 millimeter of mercury.

Hazardous atmosphere. (*1*) Any atmosphere containing a toxic or disease producing gas, vapor, dust, fume, mist, or pesticide, either immediately or not immediately dangerous to life or health; or (*2*) any oxygen deficient atmosphere.

Helmet or hood. A respiratory inlet covering. A hood completely covers the wearer's head and neck, and may also cover portions of the shoulders and torso. Helmet refers to a rigid respiratory inlet covering that also provides head protection against impact and

penetration. Both are supplied with incoming respirable air for the wearer to breathe. They may include a headharness and connection for a breathing tube.

High efficiency particulate air (HEPA) filter. A filter that is at least 99.97% efficient in removing monodispersed particles of 0.3 micrometers in diameter. The equivalent NIOSH 42 *CFR* Part 84 particulate filters are the N100, R100, and P100 filters.

Immediately dangerous to life or health (IDLH). An acute respiratory exposure that poses an immediate threat to loss of life, immediate or delayed irreversible, adverse effects on health or acute eye exposure that would prevent escape from a hazardous atmosphere.

Loose-fitting facepiece. A respiratory inlet covering that is designed to form a partial seal with the face.

Mist. A liquid condensation particle with a size ranging from submicroscopic to macroscopic.

Negative pressure respirator (tight fitting). A respirator in which the air pressure inside the facepiece is negative during inhalation with respect to the ambient air pressure outside the respirator.

Not Immediately dangerous to life or health (non-IDLH). Any hazardous atmosphere which may produce physical discomfort immediately, chronic poisoning after repeated exposure, or acute adverse physiological symptoms after prolonged exposure.

Oxygen-deficient atmosphere. An atmosphere with oxygen content below 19.5% by volume at sea level or a partial pressure of less than 148 millimeters of mercury.

Positive pressure respirator. A respirator in which the pressure inside the respiratory inlet covering exceeds the ambient air pressure outside the respirator.

Powered air-purifying respirator (PAPR). An air-purifying respirator that uses a blower to force the ambient air through air-purifying elements to the respiratory inlet covering.

Pressure demand respirator. A positive pressure atmosphere-supplying respirator that admits breathing air to the facepiece when the positive pressure is reduced inside the facepiece by inhalation.

Qualitative Fit Factor (QLFF). A qualitative measure of the minimum assured fit of a specific respirator to a particular individual, when a validated qualitative fit test is used.

Qualitative fit test (QLFT). A pass/fail fit test to assess the adequacy of respirator fit that relies on the individual's response to the test agent.

Quantitative fit factor (QNFF). A quantitative estimate of the fit of a particular respirator facepiece to a particular individual defined under the conditions of a quantitative fit test.

Quantitative fit test (QNFT). An assessment of the adequacy of respirator fit by numerically measuring the amount of leakage into the respirator.

Respiratory inlet covering. A portion of a respirator that forms the protective barrier between the user's respiratory tract and an air-purifying device or breathing air source or both. It may be a facepiece, helmet, hood, suit, or a mouthpiece respirator with nose clamp.

Self-contained breathing apparatus (SCBA). An atmosphere-supplying respirator for which the breathing air source is designed to be carried by the user.

Service life. The period of time that a respirator, filter or sorbent, or other respiratory equipment provides adequate protection to the wearer.

Supplied-air respirator (SAR) or airline respirator. An atmosphere-supplying respirator for which the source of breathing air is not designed to be carried by the user.

Tight-fitting facepiece. A respiratory inlet covering that forms a complete seal with the face.

Respiratory tract. Includes the anatomical features of the nose and mouth, pharynx, larynx, trachea, bronchi and lungs.

Simulated workplace protection factor (SPF). Surrogate measure of the workplace protection provided by a respirator done in a laboratory simulation that has been shown to have a stated correlation to workplace protection factors.

Smoke. A chemically generated particulate matter of organic origin usually found in the size range from 0.01 to 0.3 micrometer.

Threshold limit values (TLVs). Occupational exposure guidelines published annually by the American Conference of Governmental Industrial Hygienists.

Vapor. The gaseous state of a substance that is solid or liquid at 0° Centigrade and 760 millimeters of mercury.

Workplace protection factor (WPF). A measure of protection provided in the workplace, under the conditions of that workplace, by a properly functioning respirator that is correctly selected, fit tested, worn and used.

3 REGULATORY UPDATE

In the last several years both NIOSH and OSHA have promulgated significant changes to their standards governing respiratory protection. In 1998 OSHA revised 29 *CFR* Part 1910.134 and 1926.103 and in 1995 NIOSH promulgated a new respirator standard 42 *CFR* Part 84 revising parts of 30 *CFR* Part 11 that became effective in 1998.

3.1 OSHA Revision to 1910.134

On January 8, 1998, OSHA promulgated a new standard for respiratory protection covering 29 *CFR* 1910.134 and 29 *CFR* Part 1926.103. The revisions apply to general industry as well as construction, shipyard, longshoring and marine terminal workplaces and biohazards, except *M. tuberculosis*. Respiratory protection against *M. tuberculosis* is covered under 29 *CFR* 1910.139. Some of the major changes and additions to the respiratory protection standard are briefly discussed.

The new standard replaces all references to MSHA/NIOSH certification or 30 CFR Part 11 with NIOSH certification under Part 84. It also includes a number of important definitions used in the standard, e.g., air-purifying respirator, canister or cartridge, end-of-service-life indicator, fit factor, immediately dangerous to life or health, etc.

The requirements for an acceptable respiratory protection program were modified and expanded. They were modified to reflect advances in respiratory protection technology,

such as the widespread use of modern methods of fit testing. OSHA also noted that several of the provisions of the previous standard were vague and had caused compliance difficulties for employers.

The 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 evaluate it.

The standard allows an employer to provide respirators on a voluntary basis on request by employees or permit employees to use their own respirators, if it is determined that respirator use itself will not create a hazard. The standard in these situations still requires the use of a NIOSH certified respirator for the contaminant of concern. It also stipulates, except for the use of filtering facepiece respirators that the employer must establish and implement those elements of a written respirator protection necessary to ensure that:

1. any employee using a respirator voluntarily is medically able to use that respirator, and
2. it is cleaned, stored, and maintained so that its use does not present a health hazard 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" (5).

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 employee with sufficient knowledge to demonstrate an understanding of:

a. Why the respirator is necessary and how improper fit, usage, or maintenance can compromise the protective effect to the respirator.
b. What the limitations and capabilities of the respirator are.
c. How to use the respirator effectively in emergency situations including situations in which the respirator malfunctions.
d. How to inspect, put on and remove, use, and check the seals of the respirator.
e. What the procedures are for maintenance and storage of the respirator.
f. How to recognize medical signs and symptoms that may limit or prevent the effective use of respirators.

The standard requires the employer to conduct evaluations of the workplace to ensure that the written respiratory protection program is being properly implemented, and to consult employees to ensure that they are using the RPE properly. Any problems that are

identified during this assessment must be corrected. Factors to be assessed in the evaluation are respirator fit, appropriate respirator selection of the hazard, proper respirator use and proper respirator maintenance.

The 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 medical status of the employee. Of interest to the industrial hygienist is the requirement of paragraph (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.

a. The type and weight of the RPE to be used by the employee.
b. The duration and frequency of RPE use, including use for rescue and escape.
c. The expected physical work effort.
d. Additional protective clothing and equipment to be worn.
e. 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 paragraph (e)(5)(iii).

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:

a. 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.
b. The need, if any, for follow-up medical evaluations.
c. 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 employee shall provide additional medical evaluations if:

a. An employee reports medical signs or symptoms that are related to ability to use RPE.
b. A PLHCP, supervisor or the respirator program administrator informs the employer that an employee needs to be reevaluated.
c. Information from the respiratory protection program including observations made during fit testing and program evaluation, indicates a need for employee reevaluation.
d. 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.

Other major changes in the standard include:

a. Establishment of a cartridge change schedule when gas or vapor respirators are used that do not have end of service life indicators.
b. Requirements for fit testing all tight-fitting respirators with a repeat frequency of at least once a year.
c. Specific protocols for conducting qualitative and quantitative fit testing.

3.2 NIOSH Adoption of 42 *CFR* Part 84

In July 1995, NIOSH replaced 30 *CFR* Part 11 with a new respirator certification regulation, 42 *CFR* Part 84. NIOSH recognized that some of the particulate certification tests incorporated into 30 *CFR* Part 11 in 1972, particularly in Subpart K, were Bureau of Mines particulate test procedures, some dating from the 1930s. NIOSH felt that particulate filter certification procedures in Subpart K of 30 *CFR* Part 11 should be revised based on laboratory and field research and testing conducted in the 1970s and 1980s as well as new and improved manufacturing technology. The new Part 84 reflects changes made to the performance requirements for particulate filters or particulate filtering facepieces used as certified, negative pressure, nonpowered, air purifying, particulate respirators. Certification test requirements for PAPRs using particulate filters were not addressed in the 1995 revision. NIOSH has indicated it plans future revisions to Part 84 to address PAPRs using particulate filters. The remaining certification test requirements were incorporated into Part 84 without change for exhalation valve leakage, gas and vapor cartridges and canister atmosphere supplying devices, etc. A new sequence of approval numbers (TC-84A-xxxx) is used for the particulate, air-purifying, nonpowered, negative pressure respirators certified under Part 84. Since the certification requirements for PAPRs and all other respirator types did not change they continue to use the sequence of approval numbers previously used with 30 *CFR* Part 11. Under Part 84, PAPR certification has been restricted to using only HEPA filters.

This rule also eliminates the combination categories of paint spray and pesticide respirator approvals; however, other combination respirators (e.g., particulate and acid gases or organic vapors) can be certified under Part 84. All particulate respirators have a certification label bearing the NIOSH and the Department of Health and Human Services (DHHS) emblems when certified under Part 84.

The new Part 84 certification regulations eliminate the silica dust, silica mist, lead fume, and thermally generated, dioctyl phthalate (DOP) filter efficiency tests. These tests challenged the filter with different aerosols having different particle sizes and had a pass/fail criterion based on mass efficiency, except for the hot DOP test. These tests have been replaced by an "oil aerosol", cold DOP or a "particulate aerosol", sodium chloride (NaCl) filter penetration test. NIOSH established the new test performance criteria to "simulate worst-case respirator use and very severe test conditions" (8). NIOSH states "that filters certified with the new criteria can be used without particle size analysis or filter penetration testing in the workplace" (8).

The Part 84 certification regulation eliminates the dust, mist, dust and mist and dust, fume and mist class respirators and replaces them with nine classes of filters. The nine

classes are based on three levels of filter efficiency, 95%, 99%, and 100% (actually 99.97%), and three categories of resistance to efficiency degradation, as evaluated with cold DOP oil aerosol.

3.3 Information Access Explosion on the WW

In the mid 1990s access to and management of information was forever changed with the development of the world wide web (www) and software tools to conveniently access and use it. The explosion of industrial hygiene and safety information from both free and subscription venues on the www is nothing short of phenomenal. Table 32.1 contains a listing of a small sampling of web sites that contain information on RPE. The information sources are divided into three groups: government (NIOSH and OSHA), manufacturers, and others. Web addresses given may change.

4 RESPIRATOR PERFORMANCE

The performance of RPE is typically evaluated in two ways. The first consists of NIOSH certification examinations that evaluate individual components (e.g., filter efficiency, exhalation valve leakage, etc.) or performance parameters (e.g., minimum flow rate for an air supply respirator) of the RPE.

The second consists of evaluations on completely assembled and worn RPE. These evaluations measure and compare total inward leakage (TIL) or the in-facepiece concentration, C_i, of the RPE with the contaminant concentration outside the RPE or the outside concentration, C_o. They consist of laboratory tests, (e.g., fit tests or simulated workplace studies) or workplace studies (e.g., workplace protection factor studies). Typically *TIL* or C_i is recognized to be the sum of all sources of leakage into the facepiece:

$$C_i = TIL = L_{fs} + L_{ape} + L_{ex} + L_n \tag{1}$$

where L_{fs} = leakage through the face seal
L_{ape} = leakage through the air-purifying element
L_{ex} = leakage through the exhalation valve
L_n = leakage through other pathways

One of the first reported evaluations using TIL to assess RPE performance was by the Bureau of Mines in its 1937 regulations governing the testing and approval of supplied air respirators (10). These regulations specified that the RPE was to be tested in a test atmosphere of flint (50 ± 10 mg/m^3; $D_p = 0.6$ μm and GSA ≤ 1.9) for thirty minutes while the test subject carried out each of the following activities for five minutes apiece:

1. Walking, turning head, and dipping chin.
2. Pumping air with a tire pump into a 1-cubic foot cylinder to pressure of 25 psi or equivalent work.

Table 32.1. Sampling of Websites for Information on RPE

Group	Item	Web Address (http://www.—)
NIOSH	Home page	cdc.gov/niosh
	Databases	cdc.gov/niosh/database.html
	Certified Equipment List	
	IDLH Values Documentation	
	Pocket Guide to Chemical	
	Hazards	
	NIOSH Documents	cdc.gov/niosh/topreg.html
	NIOSH Guide to Industrial	
	Respiratory Protection	
	NIOSH Respirator Decision Logic	
OSHA	Home page	osha.gov
	Standards and Interpretation—(search on respirators)	osha-slc.gov/oshdoc/oshdoc/toc_interps.html
	Directives (search on respirators)	osha-slc.gov/oshdoc/toc_directive.html
Manufacturers	Mine Safety Appliances	msanet.com
	Scott Aviation	corptech.com.
	Draeger Safety, Inc.	drager-usa.com
	E.D. Bullard, Co.	bullard.com
	3M	mmm.com
	UVEX Safety Inc.	uvex.com
	North Safety Products	SafetyOnline.net/north/
	Hornell Speedglas, Inc.	speedglas.com
	Glendale	glendale-laser.com
	Racal Health and Safety Inc.	recalhealth.com
	Neoterick Health Technologies, Inc.	nell.com/data/o1oo/htm/nroo546.htm
	Sellstrom Mfg. Co.	selstrom.com
Others	International Society for Respiratory Protection	llnl.gov/isrp

3. Resting.
4. Repeat of the 1st activity.
5. Repeat of the 2nd activity.
6. Repeat of the 3rd activity.

During the 30-minute period of testing, air was withdrawn continuously at the rate of 32 Lpm from the respiratory inlet covering at a point as near as convenient to the wearer's nostrils. The in-facepiece sample was analyzed gravimetrically to determine the total mass of flint collected. That amount was then compared to the total mass collected from sampling the supply of air that was feeding the respirator. Performance of the RPE was considered acceptable if the difference in mass estimates did not exceed 0.05 mg.

4.1 Protection Factors

Total inward leakage evaluations generally express performance as a ratio of the outside concentration and the in-facepiece concentration. The U.S. Bureau of Mines, in Approval Schedule 21B, issued in 1965, made reference to the term "Decontamination Factor" (11). It was defined as "the ratio of the concentration of dust, fume, or mist present in the ambient atmosphere to the concentration of dust, fume or mist within the facepiece while the RPE is being worn." This term is no longer used in the respirator literature, but an analogous term, "Protection Factor" (PF) has taken its place.

The protection factor, like the decontamination factor, represents an expression of the performance of RPE based upon the ratio of the two generalized concentration variables, C_o and C_i. These concentration variables, in addition to being used to define a protection factor, can be used to express the penetration (P) or efficiency (E) of the RPE. Equality exists between protection factor, penetration, and efficiency as follows (12):

$$P = C_i/C_o$$

$$E = (C_o - C_i)/C_o$$

$$PF = C_o/C_i = 1/P = 1/(1 - E)$$

As such, the protection factor is a generic term that lacks specificity of definition associated with the conditions around which C_o and C_i are collected. The respirator committee of the American Industrial Hygiene Association adopted a set of protection factor definitions to provide more specificity with the use of the term (13). They are used where applicable in this chapter and some are listed in the Definitions and Abbreviations section of the chapter.

4.1.1 Assigned Protection Factors

The first major step in the selection of RPE is to determine what type(s) of respiratory protection is suitable for control of the contaminant of concern. The second major step in the selection process is to determine how much of the contaminant is present and how much protection is required to reduce contaminant exposures to acceptable levels. Given that other considerations of the selection process are met, then the level of protection

needed is matched with the assigned protection factor (APF) given to different types of respirators.

Since the protection factor is an expression of the penetration or efficiency of the RPE, they serve to link the level of protection the RPE is thought capable of providing with the level of protection required by the worker. The ability to evaluate respirators and provide some assessment of their capacity to provide protection is thus a very key element for successful respirator selection.

Assigned protection factors also are used by regulatory agencies and occupational safety and health professionals to determine, for different classes of RPE, the limiting concentration of contaminants in the ambient environment against which the RPE would afford adequate protection to the user (12). For example, if a respirator has an assigned protection factor of 10, it would be considered suitable (given it was properly selected, fitted and used) to prevent workers from being overexposed at concentrations of up to 10 times the OSHA permissible exposure limit (PEL).

Assigned protection factor levels for different classes of RPE are recommend by NIOSH, the American National Standards Institute (ANSI) Z88.2 committee and OSHA health standards, e.g., cadmium (9, 14, 15). Historically the basis for these recommendations was Hyatt's 1976 APF recommendations for different classes of RPE. His recommendations were based on quantitative fit factors (QNFF) determined by a quantitative fit test (QNFT) and use of a safety factor (16). NIOSH and OSHA during the 1970s incorporated those APFs into their own recommendations and regulations (17). For example, in the NIOSH–OSHA standard completion project an APF of 1000 was adopted for PAPRs.

To use quantitative fit factors to establish levels of protection requires the fundamental assumption that they are related to or are indicative of the protection level provided by the RPE in the workplace. This assumption has been seriously questioned by a series of workplace studies that began in the early 1980s. Those studies will be discussed under the section on workplace testing. As a result, as more meaningful data become available NIOSH, OSHA, and ANSI have revised their APF recommendations, most notably, those for PAPRs and continuous flow SAR (9, 14, 15).

NIOSH states that "APFs based solely on laboratory fit testing should be viewed and applied with particular caution, even when the laboratory testing involves a simulated work regimen" (14). It also considered field performance data, when available, to make its APF recommendations. American National Standards Institute (ANSI) Z88.2-1992, *Practices for Respiratory Protection* states that when WPF data were available they were used to establish its APFs recommendations.

For the practicing occupational health and safety professional it is very important when considering selection of RPE to understand the potential limitations of the APF level given to a particular class of RPE. The most recent APF recommendations by NIOSH, ANSI, and OSHA are noted in Table 32.2. In its new respirator standard OSHA announced that it would be revising it's respirator APF requirements at a later date.

4.2 Fit Testing

The amount of protection provided by a respirator can be no better than its fit to the face. Face seal leakage, particularly for APRs, is often the largest component of the TIL. Given

Table 32.2. Assigned Protection Factor Levels Recommended by NIOSH and ANSI Z88.2-1992 or Required by OSHA in the Cadmium Standard for Different Classes of Respiratory Protective Equipment

Class of Respirator	NIOSH	ANSI-1992	OSHA[a]
Half facepiece			
Any dust filter	10	10	
HEPA or 100% filter	10	10	10
Chemical cartridge	10	10	
Full facepiece			
Any dust filter	10	100	
HEPA or 100% filter	50	100	50
Chemical cartridge	50	100	
Powered air-purifying respirator			
Half facepiece			
Any particulate filter	50	50	
HEPA or 100% filter			50
Chemical cartridge	50	50	
Full facepiece			
Any dust filter	50	100	
HEPA or 100% filter Chemical cartridge	50	1,000	250
Helmet/Hood			
Any particulate filter	25	100	
HEPA 100% or Filter	25	1,000	25
Chemical cartridge	25	1,000	
Loose-fitting facepiece			
Any particulate filter	25	25	
HEPA 100% or Filter	25	25	25
Chemical cartridge	25	25	
Supplied air respirator—continuous flow			
Half facepiece		50	50
Full facepiece		1,000	250
Hood or helmet	25	1,000	25
Loose fitting facepiece	25	25	
Supplied air respirator—demand flow			
Half facepiece	10	10	
Full facepiece	50	100	
Hood or helmet	25		
Loose fitting facepiece	25		
Supplied air respirator—pressure demand or positive pressure			
Half facepiece	1,000	50	1,000
Full facepiece	2,000	1,000	1,000
Supplied air respirator—pressure demand or positive pressure full facepiece with auxiliary SCBA operated in pressure demand or positive pressure	1,000		>1,000
SCBA—pressure demand or positive pressure with full facepiece	10,000	[b]	>1,000

[a]APF values taken from the cadmium standard 1910.1027 but they do vary from standard to standard.

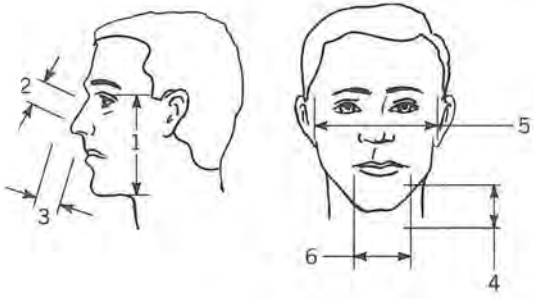
[b]Although positive-pressure respirators are currently regarded as providing the highest level of respiratory protection, a limited number of recent stimulated workplace studies concluded that all users may not achieve protection factors of 10,000. Based on this limited data, a definitive assigned protection factor could not be listed for positive-pressure SCBAs. For emergency planning purposes where hazardous concentrations can be estimated, an assigned protection factor of no higher than 10,000 should be used.

that a respirator is properly selected and used and conscientiously worn, fit is the crucial determinant of whether adequate respiratory protection is possible. If the facepiece does not fit, it does not protect regardless of how effectively other components of the respirator work. For example, any benefits to be achieved by using a HEPA filter that has penetration of only 0.03% would be quickly lost if the facepiece was not capable of providing a fit of comparable quality. Interest in respirator fit led to a study of facial measurements from which three measurements were chosen for use in facial sizing (18). The principal dimensions chosen in relation to respirator face fit are face length (Menton-nasal root depression), face width (bizygomatic breadth), and lip length (Fig. 32.1). The dimensions of face length and face width are used for full-face masks. The dimensions of face length and lip length are used for half and quarter masks.

Utilizing U.S. Air Force anthropometric studies, facial sizes for two 25-person panels were established to represent the working population (19). The panels in Figure 32.2(**a**) and (**b**) for full and half facepieces respectively 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. Today most manufacturers supply half and full facepiece respirators in multiple sizes that cover these facial groupings.

Over the years researchers have identified a number of factors that influence the degree and variability of the fit of RPE particularly, half and full facepiece APRs. They are (1) the design of the respirator's facepiece, (2) facial characteristics of the user, and (3) the conditions of use. As early as 1962, observations were made that the shape of the nose influenced the degree of fit achieved with a half facepiece (20). Hyatt also concluded that design of the facepiece influenced the degree of fit achieved with the respirator (21).

In his *Guide to Industrial Respiratory Protection*, Pritchard notes that facial characteristics including lack of teeth or dentures, scars, hollow temples, prominent cheek bones,



1. Nasion - Menton (face length)
2. Length of Nasal Bone
3. Pronasale - Subnasale (Nose protrusion)
4. Mandible Height (chin length)
5. Bizygomatic Diameter (face width)
6. Bichelion Diameter (mouth width)

Figure 32.1. Facial anthropometric dimensions for sizing half and full facepieces.

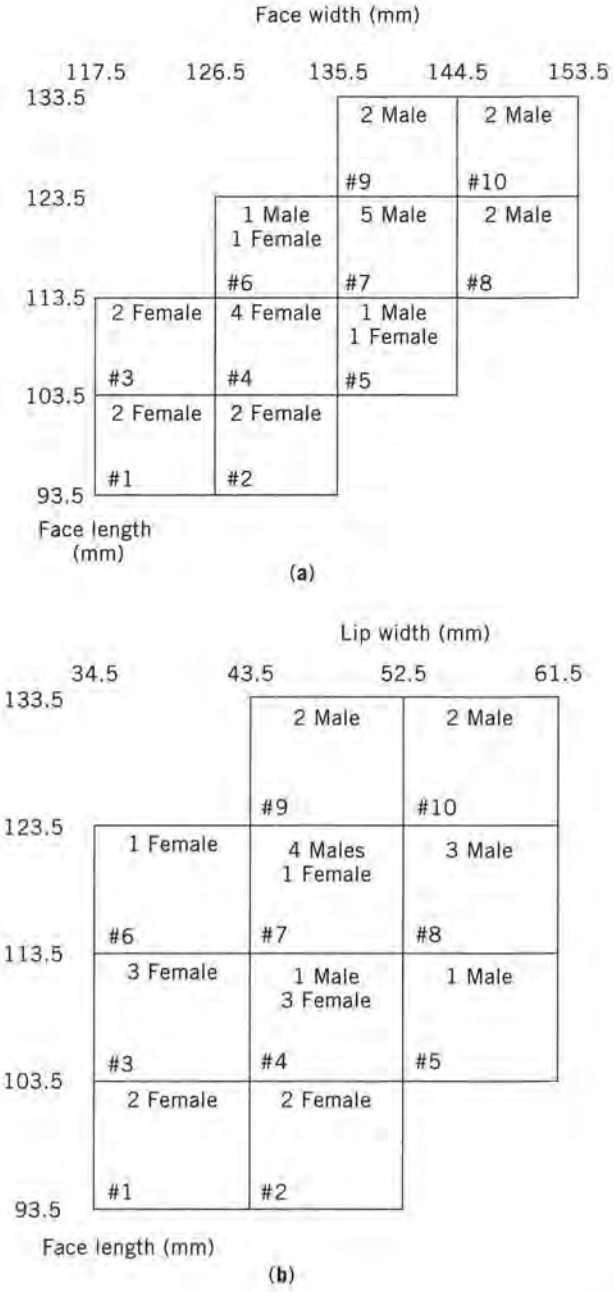


Figure 32.2. Twenty-five person respirator fit test panels developed by Los Alamos National Laboratory. (**a**) Full facepiece panel. (**b**) Half facepiece panel.

deep skin creases and changes caused by weight loss or gain can influence the level of fit achieved with RPE (22). Studies by Oestenstad et al. found that approximately 70% of the face seal leaks occurring with negative-pressure, half facepiece, respirators occurred at the nose (23–26). They found a significant correlation between face size, facial characteristics and the site of face seal leakage (nose, cheek, or chin) that varied by gender. These authors conclude that respirator fit test panels (e.g., the LANL 16 or 25 member half facepiece fit test panel) and respirator selection guidance should consider nasal dimensions.

Conditions of use also effect fit. These include presence of facial hair in the form of beard stubble, mustaches, goatees or sideburns that interfere with the face seal surface of the respirator during wearing. Other factors of use such as temperature, humidity, breathing pattern and rate, head and body movements, perspiration, etc., have been noted in the literature to influence face seal leakage.

Two generic procedures of assessing respirator fit have been developed that are widely used by general industry. They are the quantitative fit test (QNFT) and the qualitative fit test (QLFT). The quantitative fit test provides a numerical measure of fit, the QNFF that is assessed independently of interpretation by the wearer. The qualitative fit test on the other hand measures fit based on the wearer's interpretation as to whether the presence of a fit test agent is detected.

Both fit test procedures utilize a positive or negative (+/−) "fit check" that must be successfully conducted according to the respirator manufacturer's instructions before the actual fit test can be conducted. The fit check is not a fit test and should not be used in place of a recognized QNFT or QNLT. Myers et al. evaluated whether +/− fit checks were an effective aid in helping users of RPE achieve a good fit when donning the RPE (27). They evaluated three filtering facepiece respirators and one elastomeric facepiece respirator. Two randomly selected groups of 32 people each were used. One group was trained to don the RPE using the manufacturer's +/− check procedure as an aid, while the second group was trained to don the RPE without conducting a +/− check. The data obtained from the experiment suggested that, in general, RPE users obtained fewer unsuccessful donnings and more consistent donnings when fit checks were used as an aid in donning both types of RPE. Fit checks were found to be fairly useful, easy-to-learn tools for respirator wearers to discriminate between good and poor donnings.

4.2.1 Qualitative Fit Tests

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 QLFT methods expose the respirator user to an atmosphere with a contaminant, and the respirator is acceptable if the wearer can not detect the contaminant. These methods depend on the subjective opinion of the user to determine whether the respirator fits.

OSHA has accepted and published in Appendix A of the 1998 Respiratory Protection standard 1910.134, QLFT fit test protocols for isoamyl acetate, saccharin, Bitrex™ (denatonium benzoate), and irritant smoke (stannic chloride). When selecting a QNFT protocol, consideration must be given to properly matching the QNFT test agent to the

type of RPE to be fit tested. For example, a P95 particulate, filtering facepiece respirator could be tested with saccharin or Bitrex but not isoamyl acetate or irritant smoke. If the respirator program manager adopts QNFT, OSHA requires that the applicable protocol, as published in Appendix A, be followed.

4.2.2 *Quantitative Facepiece Fit Testing*

During the last 30 years, a substantial amount of respirator research has been focused on developing quantitative methods to evaluate how well a respirator fits. One of the first reported attempts to measure face seal leakage quantitatively was by Guyton and Lense (28). They developed a fit test involving *B. globigii* bacteria. The bacteria were aerosolized from suspension in saline into a test chamber. The amount of leakage into the mask was determined by collecting the bacteria on a cotton filter that was held in the mouth of the wearer of the RPE. Subjects were instructed to inhale through their mouth so that all the breath was filtered as it passed through the mouth-held filter. Exhalation was done through the nose. Thus, the collection of bacteria was accomplished only during the inhalation. By comparing estimates of the concentrations of bacteria in the chamber and inside the mask, a quantitative estimate of penetration (fit) could be made.

Burgess, Silverman, and Stein proposed another procedure to test the fit of RPE quantitatively that utilized uranine dye aerosol with a geometric mean particle size of 0.2 micrometers and a standard deviation of approximately 2 (29). Due to its fluorescent properties, the uranine was detectable in quantities as small as 0.1 nanogram per mL of water by photometric techniques. The uranine aerosol that leaked into the mask was sampled only during inhalation of each respiratory cycle. This was accomplished with a sampling detector, which used the output of a pressure sensor to initiate and terminate sampling in sequence with inhalation and exhalation. The open-face filter holder used to sample uranine leakage was placed inside the respirator so as to occupy a sampling position in the cavity between the facepiece and subject's face. This was one of the earliest reports of air sampling from inside a respirator using extractive sampling techniques.

Hounan et al. described a quantitative fit test method based on using an atmosphere containing submicrometer sodium chloride (NaCl) aerosol (30). The authors note that even though sodium chloride is hygroscopic (a potential limitation with inhalation studies), it is nontoxic and readily detectable with flame photometry. The quantitative assessment of the respirator's performance was based upon estimates of the concentration of NaCl aerosol in the exhaled air. The exhaled air was routed to a 2-L reservoir where it was mixed with dry air to prevent condensation and to dry the NaCl particles. An air sample was then collected from the reservoir volume and fed to a flame photometer. To deal with the problems of lung retention, the lung deposition of NaCl aerosol was measured on each test subject before testing began.

Flyger reported on a quantitative fit test method that utilized helium as the challenge agent (31). Helium was selected as the tracer gas because it has a low solubility in the lungs. Therefore, he reasoned, the helium concentration in the facepiece cavity would be independent of the breathing cycle so sampling could be done over the complete cycle without corrections for lung retention. In discussing the use of a gas challenge agent, the author made the following observation. "The penetration of particles through a leak is

limited by interception, impaction and diffusion of the particles during passage of the leak, while the penetration of helium varies only with the air flow through the leak. The penetration of helium must consequently be considered the upper limit to the penetration of particles."

White and Beal extended the NaCl quantitative fit method described by Hounan et al. to include various head and face movements and normal and deep breathing patterns into the test procedure (32). Burgess and Shapiro reported on a test method developed to evaluate the protection provided by a PAPR against daughter products of radon (33). The test subject was exercised at a 622 kp-m/min work rate. The radon gas was allowed to attach to cigarette smoke that was reported to have a mean particle size of 0.25 μm. This is possibly the first article in which fit test results are used to draw inference about what level of protection the respirator would provide during actual use conditions.

In 1962, Adley and Wisehart reported using dichlorodifluoromethane gas in a QNFT developed to evaluate SARs and APRs (34). In 1969, Adley and Uhle reported on a quantitative fit method utilizing Freon (35). Testing was done with the subject standing motionless, talking, breathing deeply to simulate hard work conditions, and lastly moving his/her head. This series of "exercises" was a forerunner to the "exercises" now commonly used in quantitative fit testing. Lowry et al. and Bentley et al. have used sulfur hexafluoride (SF_6) to compare gaseous and aerosol fit testing procedures (36, 37). Bentley et al. compared SF_6, argon, and sodium chloride as a fit test agent with SARs and SCBAs and found good correlation between them.

In 1972 Hyatt et al. at Los Alamos National Laboratory described quantitative fit methods using an oil aerosol of dioctyl phthalate (DOP) and an improved quantitative fit methods using polydispersed NaCl (38). 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. A forward light scattering photometer was used to measure the aerosol penetration in units of percent of the concentration of the DOP aerosol in the test chamber. While wearing the respirator in the test chamber, the test subject carried out the following exercises: (*1*) normal breathing; (*2*) deep breathing; (*3*) nodding head up and down; (*4*) turning head side to side; (*5*) bending forward and touching toes; (*6*) talking; (*7*) smiling if the respirator was equipped with a half-mask facepiece, or frowning if the respirator was equipped with a full facepiece; and (*8*) normal breathing.

The average of the peak DOP penetrations leaking into the interior of the respirator was determined for each exercise. The mean of the average penetration for all exercises was used in determining a respirator protection factor for each test. The authors felt that to assign a half-facepiece respirator to an individual test subject, the protection measured by the fit test had to equal or exceed 10. Similarly, to assign a full facepiece to an individual test subject, the protection factor measured by the fit test had to equal or exceed 100. These researchers used the data from in-facepiece sampling not only to assess the fit of individual respirators but also to compare the fit provided to a specific individual by different brands of respirators. As a result, they felt that the "best fitting" respirator could be provided to an individual. The methods described by Hyatt were rapidly accepted and viewed as models for quantitative fit testing in the U.S.

Hack et al. and Douglas et al. also assessed, within the constraints of this QNFT procedure, the protection provided by different classes of RPE (39–43). They found tight-fitting SARs and SCBAs operated in the demand mode provided the user with protection similar to that provided by the equivalent tight fitting, air-purifying respirator; continuous flow SAR provided protection lower than pressure demand SAR; and pressure demand SCBA provided the best protection to the wearer. Because of questions about the toxicity of DOP different oils, most notably corn oil and poly(ethylene glycol), are presently being used for the oil mist QNFT.

Condensation nucleus counter (CNC) technology was adapted for use in fit testing through a cooperative effort between the U.S. Army and private industry. The commercial model of the CNC is the Portacount Plus™. It is small, lightweight, portable and since it measures the condensation nuclei in room air it does not require a separate test chamber. Air drawn into the device by a small sampling pump passes through a heated chamber saturated with alcohol, and enters a cooled chamber that causes the alcohol vapor to condense on to particles in ambient air. The particles grow to about 10 μm in size during the alcohol condensation and enter a forward light scattering chamber for counting. The Portacount Plus™, Model 8020 is available from TSI, Inc. St. Paul, MN.

Until the 1990s all QNFT methods used in-facepiece sampling methods to detect the leakage of either an aerosol or gas/vapor challenge agent into the facepiece. Crutchfield et al. developed a QNFT method that does not depend on measuring aerosol or gas/vapor leakage (44). His method measures the amount of air leaking through the face seal while maintaining a predetermined level of pressure in the facepiece. The method is called controlled negative pressure (CNP). The CNP fit test instrument unit is small, lightweight, and easily portable and does not require a test chamber. It does require special airtight cartridge replacement manifolds. These are available for most brands of respirators. The method is based on exhausting air from a temporarily sealed respirator facepiece at a rate sufficient to generate and then sustain a constant negative pressure inside the facepiece while the wearer holds her/his breath. The magnitude of the negative pressure is preselected to replicate the mean inspiratory pressure inside the facepiece during normal wear. With the inhalation valve pathways temporarily blocked, measurement of the exhaust flow rate yields a synonymous measure of the leakage flow rate into the mask during inspiration under normal use conditions. The authors state that a major advantage of the method is that a worker can be fit tested with her/his assigned respirator because the method does not require a destructive sampling probe. The controlled negative pressure fit test instrumentation is available, as the Dynatech Nevada FitTester 3000 from Dynatech Nevada Inc. Carson City, NV.

OSHA has accepted and published in Appendix A of the 1998 Respiratory Protection standard 1910.134, QNFT fit test protocols for (5):

a. use of nonhazardous test aerosols (such as corn oil, polyethylene glycol 400 [PEG 400], di-2-ethylhexyl sebacate [DEHS], or sodium chloride) generated in a test chamber and employing instrumentation to quantify the fit of the respirator;
b. use of ambient aerosol as the fit test agent and appropriate instrumentation (condensation nuclei counter) to quantify the fit of the respirator; and
c. use of controlled negative pressure and appropriate instrumentation to measure the volumetric leak rate of a facepiece to quantify the fit of the respirator.

4.2.3 Problem and Limitations of QNFT

A major problem with QNFT techniques that rely on extracting a sample from inside the facepiece is that research has shown face seal leakage does not mix instantaneously and uniformly within the facepiece cavity. This leads to in-facepiece sampling biases of significant magnitude for both half and full facepiece respirators. Early researchers that developed QNFT methods commonly assumed that face seal leakage mixed uniformly and rapidly within the facepiece cavity (45). As a result, consideration given to issues such as where to locate the sampling probe, how deeply it should be extended into the facepiece cavity, etc. were based on professional judgement.

Studies by Myers et al. (45–47), Holton et al. (48, 49), Campbell and Myers (50), and Oestenstad et al. (24) have found that in-facepiece sampling will not provide representative samples of TIL. Myers et al. and Oestenstad et al. demonstrated that face seal leakage could streamline within the facepiece cavity clearly illustrating one reason for face seal leakage not mixing rapidly or uniformly (24, 45). These conditions lead to large, variable sampling biases in concentration or penetration measurements made by in-facepiece sampling. Variations in several parameters of the person–respirator system have been identified to cause significant changes in the sampling bias (45–48). They are

a. Location of the probe on the midline of the respirator.
b. Depth at which the probe is inserted into the facepiece cavity.
c. Breathing being done all through the mouth or all through the nose.
d. Area where the face seal leakage occurs.
e. An interaction between the area where face seal leakage occurs and whether breathing is all through the nose or mouth.
f. Size of the challenge aerosol.

A key observation from these works is that design features of the facepiece, for either half or full facepiece, negative pressure APR, can have a significant effect on the magnitude of the bias associated with using in-facepiece sampling with aerosol based QNFT. The important point to be made from this research is that it is difficult to determine if a higher QNFF obtained with one respirator brand and size over another brand and size is due to a "truly better fit" or sampling error. These observations may explain in part why a correlation between QNFF and WPF has not been demonstrated.

Myers and Hornung studied different in-facepiece sampling techniques for half and full facepieces (51). They compared a common in-facepiece sampling method using a probe mounted virtually flush on the wall of the facepiece in the general area between the nose and mouth situated on or near the midline. The flow rate typically used was from 1 to 2 Lpm. The method was compared to four other in-facepiece sampling methods. The mean bias was found to be -21.3% and -25.9% respectively for full and half facepieces. This average bias was the worst of all the methods evaluated. By simply having the wearer breathe through the mouth, increasing the flow rate and locating the sampling probe approximately 1/2 inch in front of the mouth the sampling bias decreased to -3.4% and -12.5% respectively for full and half facepieces. As a result of this study, they recommend

for those using an aerosol based QNFT system that the in-facepiece sampling probe be located, if possible, on the midline of the respirator, opposite the mouth and extended into the half facepiece cavity at least 1/4 inch. The wearer should be instructed to breathe through the mouth. If the sampling rate can be adjusted use something between 3 to 5 Lpm. When using full facepieces they recommend that the sampling probe be located in the nose cup if one is used and a sample rate of 3 to 5 Lpm. If the full facepiece has no nose cup the sampling probe should be on the midline opposite the mouth and extended to within approximately 1/2 inch to 1 inch of the mouth. Again a flow rate from 3 to 5 Lpm should be used.

Studies by Hinton (52), Myers et al. (53–56) and Lenhart and Campbell (57) have found no correlation between the QNFF obtained by a respirator–person combination and the WPF achieved in the workplace. Based on these studies, quantitative fit test data do not appear to be good predictors of workplace protection even when the respirator is used with a good respirator program. The relationship between quantitative fit testing and workplace protection is yet uncertain. Figure 32.3(**b**) is a plot of paired QNFF and WPF values measured on two brands of PAPRs. The QNFFs were determined immediately before the workers went into their workplace for the WPF measurements. The data plot clearly illustrates that no correlation exists between the data.

Two important questions were raised by these studies. (1) Will a respirator that gives the "best fit" in a quantitative fit test be the respirator that will provide the "best protection" in the workplace? and (2) Should QNFF data be the basis upon which assigned protection factors are established?

The answer to the first question is not clear. Considering all available data, it appears that there is little justification for making a respirator selection decision based solely on comparing QNFF values that a worker may achieve with different brands of respirators. The approach better supported by the data is to allow a worker to first select what is to her/him the most comfortable brand, size, etc. and then compare the QNFF to an accept/reject screening level. Historically, a commonly used screening level for QNFFs is 10 times the APF of the RPE. A recent laboratory study affirms the appropriateness of incorporating a safety factor of 10 in setting pass/fail criteria levels for QNFT (58). NIOSH advises that "When QNFT is used for fit screening, the fit factor screening level should be chosen with caution and with recognition of the uncertainty of its effectiveness. As appropriate, periodic evaluation of the effectiveness of each respirator during use in the workplace should be conducted to ensure that each wearer is being provided with adequate respiratory protection" (14). The OSHA respirator standard indicates that an acceptable pass/fail screening level for half and full facepiece is respectively 100 and 500 (5).

In regard to the second question both NIOSH and ANSI have used WPF data, when available, to develop their APF recommendations. NIOSH states in its respirator decision logic that "APFs based solely on laboratory fit testing should be viewed and applied with particular caution, even when the laboratory testing involves a simulated work regimen. To date no relation has been demonstrated between laboratory QNFF and measured workplace performance" (14). As NIOSH points out the problem is that QNFF results do not seem to correlate with the protection that is actually achieved with the RPE. However in late 1998, Coffey et al. reported observing a strong relationship between QNFF measures by some QNFT methods and dose in laboratory studies (58). They compared QNFF mea-

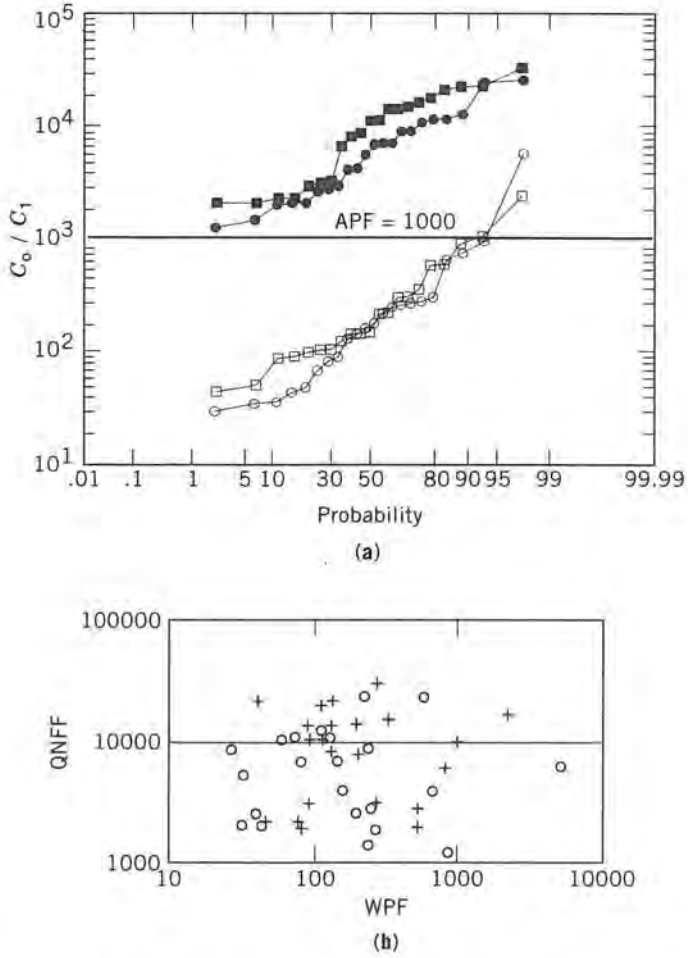


Figure 32.3. (**a**) Log probability plot of QNFF and WPF values for two brands of PAPR equipped with helmets and high efficiency filters; (**b**) Plot of paired QNFF and WPF values for the same two brands of PAPR + PAPR 1, ○ PAPR 2.

surements with a paired measurement of a respirator wearer's actual exposure assessed by end-exhaled air analysis for 1,1,2-trichloro-1,2,2,-trifluoroethane (Freon 113) under the same conditions. The QNFF measurements were then correlated with the paired Freon-113 exposures. They found that a corn oil–based QNFT had the strongest relationship (R Squared = 0.81) between QNFF measurements and total Freon 113 exposure dose. The corn oil QNFT utilized a chamber and light scattering photometry coupled with an in-facepiece sampling method that employed a deep probe position opposite the upper lip and a sample flow rate of 5 Lpm. The QNFT method representing that used with the Portacount Plus™, available from TSI, Inc. (St. Paul, MN) had the second strongest rela-

tionship (R Squared = 0.78) between the QNFF measurements and total Freon 113 exposure dose. This study represents the first research evidence that under controlled laboratory study some QNFT methods produced fit factors which strongly correlated with actual exposure.

It seems that some of the reasons postulated for observed differences between QNFFs and protection are becoming clear while others are yet undefined. The majority of the published work dealing with issues in this area are reviewed in the following.

Gaboury and Burd conducted a WPF study on negative-pressure, half-mask respirators (59). The QNFT was done with the TSI Portacount. They found that the QNFF values did not correlate with the WPFs they measured. Sampling bias associated with in-facepiece sampling on half and full facepiece respirators was evaluated in a series of studies (45–47). On one half facepiece the average sampling bias was found to be −16.6% and ranged from −99% to +98% which caused the measured QNFF values to vary from 44 to 4,728 while the actual QNFF was 87. On full facepieces average biases as large as −53% were found. These large biases on the full facepieces resulted from the sampling probe being in a position that clean inhalation air flowed over it. Circular or slit leak geometry was found to influence the TIL of half facepiece respirators.

Chen and Willeke, and Xu et al., using aerosol challenge found that a leak with a slit geometry or several circular leaks produced lower face seal leakage than a single circular leak of the same cross-sectional area (60, 61). They hypothesized that this was due to the complexity of the leak geometry. Of particular note was the observation a high-efficiency filtering facepiece respirator having the same number of face seal leaks as a dust and, may actually provide less protection at low breathing rates than the dust-mist filtering facepiece. This is due to the greater pressure drop (breathing resistance) of the high-efficiency respirator allowing the aerosol to take the path of least resistance through the face seal rather than through the filter. Campbell in a theoretical study of filter pressure drop and face seal leakage predicted that such could be the case (62). It has been suggested that the underlying assumptions of the quantitative fit tests may not be valid (63, 64). These assumptions are, (*1*) that aerosol fit test results are applicable to other types of contaminants, (*2*) aerosol samples collected with conventional in-facepiece sampling techniques are representative of the actual TIL, and (*3*) QNFT exercise protocols make the QNFT more predictive. Crutchfield et al. concluded that there may be aerosol loss, and thus, overestimation of protection factors using aerosol quantitative fit tests (65). They measured QNFFs by both an aerosol method and the CNP method. Consistently the QNFF values obtained by the aerosol method were a magnitude higher than those obtained by the CNP method. They concluded such factors as leak penetration losses, incomplete mixing due to streamlining, and lung retention may be causing the overestimation of fit factors by the aerosol QNFT methods.

A number of studies have evaluated facial anthropometric parameters and the type and location of face seal leaks on QNFT results. Oestenstad et al. using a florescent dye studied the shape and location of face seal leak sites on groups of respirator wearers with different types of half facepiece respirators (24, 25). They measured 12 different facial anthropometric dimensions on 73 subjects and then, by conducting QNFT, determined if QNFFs could be correlated with anthropometric dimensions. No significant correlation was found for the dimensions that were used to define the LANL half facepiece fit test panel [lip

width and Menton-Nasion length (face length)]. These authors noted that leaks at the nose, singularly or in combination with leaks at the chin or cheek accounted for approximately 79% of all occurrences of observed face seal leakage. About 71% of the significant differences in facial dimensions for leak site subsets were attributed to gender. The authors concluded that nasal dimensions should be considered when defining a respirator fit test panel and selecting a respirator for an individual.

Liau et al. also evaluated the relationship of facial anthropometric dimensions on QNFT results (66). They evaluated nasal root breadth and face-length, nose length, nose protrusion, chin length, mouth width, and face width. They studied 243 workers that wore four brands of RPE that came in multiple sizes. Regression analysis indicated that mouth width and face width were the two most important of respirator fit. However the correlation coefficient for these facial anthropometric determinants were only 0.22 and 0.30. These low correlation coefficients suggest that a particularly strong association does not exist. The authors do suggest though that these measurements should be made to aid in the proper selection of RPE.

A similar experiment was conducted with three filtering facepiece dust and mist respirators and three elastomeric facepiece equipped with dust and mist, dust, fume, and mist, and high-efficiency filters (67). The respirators, sealed to a mannequin, had face seal leaks introduced through the use of tubes and wires. The tubes and wire created seal leaks of different geometry. This study found that face seal leakage was dependent upon the aerodynamic diameter of the aerosol and the pressure drop characteristics of the respirator at different flow rates. Myers et al. (68) in a laboratory study confirmed that the measurement of face seal leakage was affected by the tidal volume of the respirator wearer as well as the aerosol size as originally reported by Tuomi (69), Hines (70), and Holton (48, 49). In addition to using different size polystyrene latex spheres they also used acetone vapor as a challenge agent and concluded that using a vapor as the challenge agent might be a more critical test of face seal leakage than a test using an aerosol. The effect of lung retention on WPF measurements has been evaluated mathematically and correction factors recommended for lung deposition and respirator dead space (70, 71).

Another source of error could be that the APF of a particulate respirator depends upon the particle size of the ambient aerosol. Leaks having a slit geometry, as compared to other types of leaks, allow fewer particles of all sizes into the facepiece and especially those particles having a size of 2 micrometer or larger (48, 49). It was noted that as the probe moved further away from the leak site a smaller number of particles were counted inside the mask. The maximum leakage through holes in nine of the respirator facepieces tested occurred with an aerosol having a size of 0.2 to 1.0 micrometers. Particles that were larger or smaller do not enter the leak site as easily. They suggest that aerosol QNFT procedures should take into account the size distribution of the test aerosol and of the aerosol in the workplace to which the respirator will be exposed. This helps to ensure that the measured leakage during the quantitative fit test reflects the actual leakage in the workplace.

Respirator field studies have demonstrated this to be true for PAPRs where the APF based on QNFF data was 20 to 40 times higher than the protection actually achieved (36, 53–57). Consequently NIOSH and ANSI have lowered their recommended APF levels for this type of RPE. On the other hand, numerous WPF studies involving negative pressure, half facepiece respirators (both filtering facepiece and elastomeric) appear to support the

recommended APF of 10 (57, 72–79). A review of half facepiece WPF studies by Nelson supports an APF of 10 for half facepiece APRs (80). He found from analyzing 390 WPF observations that the best estimate of the fifth percentile WPF was 13, with a 95% confidence interval of 10 to 18. Myers and Zhuang, using a probabilistic analysis of 205 half facepiece WPF data points, estimated the probability of a worker being over exposed (81). Their analysis found the probability of being overexposed, with a 95% confidence interval was less than 2.7%. If they considered an in-facepiece sampling error and lung loss error totaling 50% of the probability of being overexposed, with a 95% confidence interval was less than approximately 6%. They conclude, based on the studies reviewed, that an APF of 10 for half facepieces seemed to be appropriate. However, Nicas and Spears, using other assumptions and statistical models, analyzed a variety WPF data and concluded that an APF of 5 for half facepiece respirators would be more prudent (82, 83).

4.3 Workplace Testing

A limited number of workplace studies of respirator performance were carried out in the 1970s. Reist et al. evaluated the level of respiratory protection obtained by coal miners using half facepiece dust respirators (84). Revoir evaluated the protection provided by single-use (filtering facepiece) respirators against cotton dust (85). Samimi et al. measured the respiratory protection provided to sandblasters by continuous flow SAR equipped with hoods or abrasive blast helmets (86, 87). Moore and Smith evaluated three brands of half facepiece respirators for protection against SO_2 in a copper smelter (88). Toney and Barnhart evaluated the protection provide by SAR equipped with half and full facepieces in paint spraying operations (89). In the early 1980s, NIOSH began to conduct workplace studies. Their 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.

The first of these measured the workplace protection factors of tight-fitting, full facepiece, PAPRs used during silica bagging operations. The workplace protection factors obtained ranged from 16 to 215 (53). Follow up studies measured WPFs on two brands PAPRs equipped with a helmet and high efficiency filters at a secondary lead smelter and a battery manufacturing plant and a tight fitting, high efficiency PAPR and a half facepiece respirator at a primary lead smelter (54–57). In the secondary lead smelter study, workers were quantitatively fit tested in their PAPR before the shift in which the WPF was determined (55, 56). The WPF for one brand of PAPR ranged from 28 to 5500 with a geometric mean of 165 and a geometric standard deviation of 3.57 while, the quantitative fit factors ranged from 1,200 to 24,600 with a geometric mean of 5,100 and geometric standard deviation of 2.4 (Fig. 32.3(**a**)). The other brand of PAPR had WPFs ranging from 42 to 2,323 with a geometric mean of 205 and geometric standard deviation of 2.83 and quantitative fit factors ranging from to 2,000 to 31,500 (Fig. 32.3**a**). When the two mean WPFs were compared to each other, no significant difference was found. No significant difference was found when the two mean quantitative fit factors were compared to each other. However, when the mean WPF values were compared to the mean quantitative fit values, a significant difference was found. This study found no correlation between the QNFF mea-

sured on the workers at the start of the shift and subsequent WPFs measurements. At the time of these studies the recommended APF for PAPRs was 1000 or higher (17, 90).

The tight fitting, high-efficiency, PAPR and half facepiece study was conducted in the sinter plant and the blast furnace area of a large primary lead smelter (57). The study used 25 male workers who used respirators in their normal job activities. The workers were quantitatively tested before and after each shift. The workplace protection factors for both the negative-pressure and the powered air-purifying respirators were found to be log normally distributed. For the negative-pressure respirator, about 98% of the WPFs were above 10 while 75% were above 100. It should be noted that these numbers were for a population that had attained protection factors of at least 250 with the quantitative fit tests before the workplace testing. For the powered air-purifying respirators 98% of the WPFs were above 50, 90% above 110, 75% above 200, and only 25% above 1000. No correlation was found between QNFFs and WPFs. The APF for each class of respirator was calculated using a one-sided lower 90–95% tolerance limit. At a confidence level of 90%, approximately 95% of the negative pressure half-masks WPFs exceeded a value of 10 and 95% of the WPFs for the PAPR exceeded a value of 50. A study involving PAPRs used at a brass foundry measured average WPF values of approximately 100 (91). This series of studies strongly suggested that the APF level of 1000 used by NIOSH and OSHA for PAPRs was in gross error and served as the basis for NIOSH, OSHA and ANSI to lower their APF recommendations for PAPRs.

Dixon and Nelson conducted a field study involving half facepiece APRs used in a lead atmosphere. Each worker passed the isoamyl acetate QNLT fit test (72). The 37 workplace protection factor measurements made during this study had a geometric mean of 3,400 and a geometric standard deviation of 3.8. The WPF values ranged from 94 to 27,000, The authors concluded that the APF of 10 for a half-mask negative pressure respirator was appropriate since all the WPFs exceeded 10. Galvin et al. measured the performance of a chemical cartridge respirator used for styrene exposures in a fiberglass reinforced bathtub and shower stall manufacturing facility (75). Workers in two different jobs were studied. The workers were fit tested using the irritant smoke QNLT and trained in respirator use. The inside facepiece sampling data was corrected for pulmonary retention of the styrene. The study determined that the workplace protection factors did not vary between jobs. However, they did vary between workers and on single workers during different wearing periods. The geometric standard deviation between workers was 1.92, within worker 2.93, and the total deviation was 3.51. Gaboury et al. studied half facepiece negative pressure APRs equipped with combination organic vapor/acid gas/dust/fume/mist filters and PAPRs equipped with a helmet and combination organic vapor/HEPA filter cartridges at a primary aluminum smelting plant (59). Workers wearing half facepiece respirators were fit tested those wearing the PAPRs were not. Based on exposure to benzo-alpha-pyrene, the WPFs for the PAPRs were found to range from 371 to 8,658 with a geometric mean of 1,414 while for the half facepiece APR the WPFs ranged from 13 to 410 with a mean of 47. Ninety five percent of the WPFs for the PAPR exceeded 275 while 95% of the WPFs for the half facepiece respirators exceed 9. Wallis et al. evaluated the workplace performance of a filtering facepiece APR against manganese dust (76). Other studies of exposures to mineral sand and cadmium have been conducted on half-mask respirators (92, 93).

A number of workplace studies have also been conducted in Europe. Hery et al. measured the WPFs of six European respirators, two filtering facepiece and four elastomeric APRs (94, 95). All of the APRs provided geometric mean WPFs in the range of 8 to 13. Tannahill et al. conducted a WPF study on three brands of negative-pressure, full facepiece respirators used for asbestos stripping operations (96). The data indicated that the APF of 900 times set by the British Health and Safety Executive was too high. The three brands of respirators had geometric mean WPFs of 200, 577, and 120.

Popendorf et al. evaluated several classes of APR in a WPF study of workers engaged in indoor swine production, poultry production, and grain handling (97). The results showed that the filtering facepiece APR had a mean WPF of 13, the half facepieces 19, and the PAPRs 30. These values are similar to the values obtained in other studies. They also investigated the effect of relatively small random errors (imprecision) within multiple, independent variables and larger variability due to bias and in accuracy in the result. They found that small random errors put a practical limit on the precision of measuring high WPF values but did not present the same limit when measuring low WPF values. This is an area that still requires further investigation. Myers et al. measured the performance of three elastomeric and one filtering facepiece, dust/fume/mist class APRs in three brass foundries (77). To use one or more of the APRs the workers had to pass a QNFT using the TSI Inc., Portacount™ or the saccharin QNLT. The overall geometric mean WPF values for all four APRs were respectively 166, 80, and 75 for foundries 1, 2, and 3. No statistical difference was found between the WPF values for the elastomeric and filtering facepiece APRs. The 5th percentile estimate for the pooled WPF data was 9. Zhuang et al. reported on a WPF study conducted during aircraft paint-spraying operations (78). Three elastomeric APRs, equipped with combination organic vapor/HEPA cartridges, were evaluated during two different painting applications. They found a geometric mean of 3982 with a 5th percentile of 388. Elastomeric and filtering facepiece dust/mist class APRs have been evaluated in various operations of steel making (79). The geometric mean WPFs for all brands of RPE (three elastomeric and two filtering facepieces) were found to exceed 100 and all 5th percentile WPF values exceeded 24.

Based on a review of eight WPF studies of half facepiece APRs, Nelson found differences between mean WPF and the type of filter (dust, HEPA, etc.) used on the half facepiece APR (80). Elastomeric and filtering facepiece APR, of the same filter class, had WPF values that were not significantly different.

5 RESPIRATOR CLASSIFICATION AND CERTIFICATION

The term "certified respirator" has become a part of the language of industrial hygiene. In 1920 the Bureau of Mines (BOM) began to publish "Approval Schedules" for specific types of respirator, and approved their first respirator the same year (98). Manufacturers voluntarily submitted their devices for testing, which, if satisfactory, could be sold as BOM certified devices. In 1972 the testing and certification program was assumed by NIOSH, in its laboratories at Morgantown, West Virginia. The approval categories and some of the approval requirements are given below.

Respiratory protective devices are broadly classified as air purifying and air supplying devices. Each class of device can be equipped with a variety of respiratory inlet coverings. Respiratory inlet coverings can be configured as a half or full facepiece or a loose fitting hood or helmet. The loose fitting hood or helmet can be configured with a shroud that may include just the face, the entire upper body or in other cases an air supplied suit. 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. A device that does not fit easily into the foregoing categories is the mouthpiece respirator. 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. It has been used for mine rescue and is now used as an emergency escape device.

The facepiece is usually held in place by elastic or rubber straps. Half facepiece RPE are secured to the face with two straps attached at two points on each side of the facepiece, that is, four-point suspension. The four straps, instead of being attached to tabs on the edge of the facepiece, may be part of a yoke that is fastened to the facepiece by one or two points in the front of the facepiece. Full-face masks have a head harness attached to the facepiece at four, five, or six points. The large sealing surface of the full-face mask and the distribution of the headband attachment assists in maintaining a stable facepiece with less slippage than is experienced with quarter or half masks.

One of the best-known loose-fitting, hood respirators is the SAR equipped with a hood such as used in abrasive blasting. Air is provided through a hose leading into the hood. Because the hood is not tight fitting, it is important that sufficient air be provided to maintain an outward flow of air and prevent contaminants from entering the hood. The hood concept can be extended to cover the entire body and provide whole body protection. Disposable impervious clothing is available for this purpose. There are no NIOSH approval regulations for supplied-air suits. An example of a helmet device is a PAPR equipped with a helmet incorporating a face shield with or without a neck cuff. A fan draws or pushes air through an air-purifying device that is then supplied to the rear of the helmet where it travels inside the top and down inside the face shield.

5.1 Positive Pressure Classification

Respirator regulations and literature frequently contain reference to "positive pressure". The term is used to describe a mode 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 respiratory community that such operation affords the highest possible level of respiratory protection. The rational is that if a face seal opening(s) occurs the positive pressure would force air out of it rather than allow inward leakage of contaminant. Over the years pressure demand SCBA and SAR, continuous flow SAR and 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. It does, however, have approval criteria for pressure demand devices which requires that pressure

inside the respiratory inlet covering stay positive relative to atmospheric pressure during the certification test. That test is conducted with a breathing machine using a 622 kp.-m./min. work rate cam, operated at 24 respiration/min. The peak instantaneous flow rate under these test conditions is approximately 115 Lpm. So a device certified by NIOSH, as pressure demand is in fact a positive pressure device. As work rate increases both minute volume and peak instantaneous flow rate increase. 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 115 Lpm for tight fitting facepieces and 170 Lpm for loose fitting facepieces.

It is apparent from reported field studies (54–57, 91, 97) and laboratory studies (99, 100) that PAPRs equipped with helmets do not operate as positive pressure devices. These laboratory studies found that PAPRs equipped with a helmet may be susceptible to room air currents and point up the usefulness of a neck cuff of cape. Based in part on these field and laboratory studies, manufacturers of PAPRs equipped with helmets have modified their designs to incorporate a neck cuff with the shield of the helmet. Field studies on PAPRs equipped with tight-fitting facepiece are less numerous but the data do suggest that they are not operating as positive pressure devices (57). However, laboratory testing of PAPRs equipped with tight-fitting facepieces and HEPA filters under simulated strenuous work level continue to report QNFFs of at least 1000 (99, 100).

Under laboratory conditions, Hack et al. studied the performance of supplied air hoods (40). Using mild work exercises and an air supply of 170 Lpm, they found that of all 16 supplied-air hoods achieved a QNFF of 500, 15 achieved a QNFF of 1000, and 14 achieved a QNFF of 2000. All hoods achieved a QNFF of 2000 at 400 Lpm. The laboratory evidence does indicate negative pressure potential is created during the time of inhalation if the instantaneous inspiratory flow rate exceeds 170 Lpm, the minimum flow rate required for NIOSH certification. However Skaggs et al. testing supplied air hoods under simulated work conditions with an air supply of 170 Lpm measured a QNFF of 20,000 (100). They did note that reduced protection occurred when a fan blew contaminant under an unsecured cape. Raven et al. has measured negative pressure within the facepiece of pressure demand SARs at work rates of 35% maximum work rate (MWR), 65% MWR, 70% MWR, and 80% MWR (101). At higher work rates the time duration that the facepiece stays negative increases. 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. Stengel and Rodrigues bench-tested fourteen, pressure demand, SCBA on a breathing machine set at a high work rate (minute volume of 100 Lpm) (102). Ten of the 14 pressure demand SCBA maintained a positive pressure in the facepiece when the cylinder pressure was full. At the point when cylinder pressure dropped low enough to activate the low-pressure alarm, positive pressure was maintained in only one of the six. Myhre et al. tested subjects wearing pressure demand SCBA at 65 and 80% of MWR (103). They found the pressure in the facepiece to be negative 8% and 36% of the time, respectively. Dahlback and Balldin, testing pressure demand SCBA, found negative pressure in the facepiece at 80% of MWR (104). Wilson et al. recommend that SARs and SCBAs be designed to accommodate peak flows of 400 Lpm because there are respirator users in the work force with lung function capabilities sufficient to produce instantaneous

inspiratory flow rates of this magnitude (105). For pressure demand SCBA used in fire fighting, the National Fire Protection Association has recommended 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 103 Lpm (106). These conditions produce a peak instantaneous demand of approximately 330 Lpm. They feel these test parameters are sufficient to meet the respiratory demands of approximately 98% of the fire fighter population.

5.2 Respirator Facepiece Valves

5.2.1 Inhalation Valves

Inhalation valves prevent moisture-laden exhaled air from coming in contact with sorbents and filters. Exhaled air tends to increase breathing resistance of the filters and cause them to be changed more frequently. NIOSH requires that inhalation valves must be provided where necessary to prevent excessive exhaled air from adversely affecting filters unless the filters are specifically designed to resist moisture. With full facepieces, malfunctioning inhalation valves that allow significant amounts of leakage during exhalation result in maintaining higher than expected levels of contaminant in the facepiece cavity (107). Brosseau evaluated inhalation and exhalation valves from half facepiece, negative pressure RPE for leakage during an 8-hour cyclic breathing test using two work rates, 415 and 622 kg-m/min, and two particle sizes, 0.3 and 0.8 micrometer (108). Inhalation valves averaged 20% leakage for all experiments. The penetration of 0.3 micrometer particles was less than the penetration of 0.8 micrometer particles (13% vs. 27%). No inhalation valve failures occurred. Current NIOSH certification criteria include no performance tests for the inhalation valve(s).

5.2.2 Exhalation Valves

With the exception of some disposable respirators, NIOSH regulations require that tight fitting respiratory inlet coverings be designed to include an exhalation valve(s), which provide a one-way exit for exhaled air. This important component of the RPE, while out of sight and often neglected, needs frequent checking to ensure that it is working. A malfunctioning exhalation valve can render useless both positive and negative pressure respirators. If an obstruction such as a hair or a dirt particle comes between the valve and the valve seat, a serious leak can occur. NIOSH requires that exhalation valves be protected against damage and external influence. This is commonly done with a valve cover. In addition to protecting the valve the valve cover retains a small reservoir of exhaled air. A finite time elapses between the beginning of inhalation and the closure of the exhalation valve. During this period the clean, recently exhaled air prevents toxic material from entering the valve. Exhalation valves are evaluated by NIOSH as part of the certification evaluation. Test criteria are contained in several Subparts of Part 84, eg Subpart K paragraph 84.182. The valve(s) can not have a leakage rate of greater than 30 mL/min. when subjected to a suction of 25 mm of water column height. In a study of inhalation and exhalation valves, Brosseau reported that exhalation valve leakage ranged from 0.0 to 0.03% for all test conditions (108). No failure of exhalation valves occurred during the

eight-hour test. At a low work rate (415 kg-m/min), particle size had no effect on exhalation valve penetration but at a high work rate (622 kg-m/min), the 0.3 micrometer particles were found to be less penetrating than the 0.8 micrometer particles (0.035 vs. 0.06%).

5.3 Air-Purifying Respirators

Air-purifying devices 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. Air-purifying respirators incorporate an air-purifying element that is capable of removing aerosol, gas, or vapor contaminants from the air before the air can reach the respiratory tract. With the exception of filtering facepiece respirators, the air-purifying elements used with respirators are designed for replacing. The useful life of an air-purifying device is dependent upon 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 removal, and gas and vapor removal. For aerosol removal the aerodynamic size and 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 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. Air-purifying RPE can not be used for entry into IDLH atmospheres or atmospheres that are oxygen deficient.

Nonpowered APR 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 half, full face, or mouthpiece respirators as a negative pressure, APR. The mouthpiece respirator is a special APR that is held securely in the mouth of a user and used for escape purposes only. Powered air purifying respirators can be equipped with tight fitting as well as loose fitting hoods or helmets.

5.3.1 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 aerosol or fibers of the filter or both, 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 is predominating. The efficiency of aerosol removal is related to its aerodynamic size, with approximately 0.3-micrometer aerodynamic diameter aerosols being the most penetrating. This most penetrating particle size can shift slightly 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 improve, and breathing resistance increase, as the aerosol loads on the filter surface and begins to act like a sieve. Electrostatic charge can be added onto fibers by using resins or be engineered into synthetic fibers as permanent dipoles. 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 of electrostatic filters than particulate aerosols. It is hypothesized that the oil degrades the electrostatic charge of the resin or coats the fiber and in effect shields its internal dipole.

5.3.1.1 Filter Classification. NIOSH no longer classifies filters for use in nonpowered APRs as dust, dust and mist, dust, mist and fume, or high efficiency. In Part 84, Subpart K NIOSH now 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 particulate that includes oil-based liquid aerosols. The filters of each series are further classified by efficiency against a most penetrating particle size as: (*1*) 100 class filters which have a minimum efficiency $\geq$99.97%; (*2*) 99 class filters which have a minimum efficiency $\geq$99%; (*3*) 95 class filters which have a minimum efficiency $\geq$95%. These tests incorporate an approximately 0.3 micrometer aerodynamic diameter particle that filtration theory indicates should be a most penetrating particle size. Other significant changes in certification test performance parameter include using:

a. An air flow rate of 85 $\pm$ 4 liters that simulates a high work rate (42.5 $\pm$ 2 liters per minute through each filter for paired filters).
b. DOP and NaCl particles at Botzmann charge equilibration.
c. Measurement of instantaneous penetration rather than a time weighted average.
d. Using filter number efficiency rather than mass efficiency.
e. High total filter loading (up to 200 mg for N- and R-series filters, and continued loading until there is no further decrease in efficiency for P filters).

It should be noted that 42 *CFR* Part 84 still requires an evaluation of initial breathing resistance at 85 $\pm$ 2 Lpm however the requirement for an evaluation of final breathing resistance after filter loading was dropped. The test conditions and aerosols for the nonpowered respirator filters are summarized in Table 32.3. The degradation category (N, R, or P) is determined by using either DOP or NaCl as the test aerosol. Sodium chloride is only slightly degrading to filter efficiency, whereas DOP is very degrading. No particle size limits apply to respirators with Part 84 filters. Protection for the user is based on the efficiency of the filter and the PEL of the contaminant, usually determined by an industrial hygienist.

Table 32.3. Description of Filter Classes and Key Test Parameter for Filters Certified under Title 42 Code of Federal Registrations Part 84.

Class of Filter	Efficiency (%)	Test Agent	Test Maximum Loading (mg)	Type of contaminant	Service Time[a]
			N-series		
N 100	99.97	Sodium chloride	200	Solid or water-based particulate but *not* aerosol containing oil mist	Nonspecific[b,c]
N 99	99				
N 95	95				
			R-series		
R 100	99.97	Dioctyl phthalate (DOP) oil	200	Any	One work shift[b,d]
R 99	99				
R 95	95				
			P-series		
P 100[e]	99.97	Dioctyl phthalate (DOP) oil	Stabilized efficiency	Any	Nonspecific[b]
P 99	99				
P 95	95				

[a]If research indicates additional service time limitations may be recommended by NIOSH for specific workplace conditions.

[b]Limited by considerations of hygiene, filter damage, and breathing resistance.

[c]High (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., non-oil) aerosols in ther 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 8 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).

[d]No 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).

[e]The P-100 filter must be color-coded magenta. The Part 84 Subpart KK HFPA filter on a PAPR will also be magenta, but the label will be different from the P I00 filter, and the two filters cannot be interchanged.

Filters designated as N series are tested with NaCl and are not resistant to efficiency degradation by oils. Therefore, N-series filters may be used for any solid or non-oil containing particulate contaminant. In workplace conditions that result in high filter loading (i.e., 200 mg), service life for N-series filters should be limited to 8 hours. Extending service life beyond 8 hours of use (continuous or intermittent) should only be done after an evaluation of the specific workplace. This evaluation should demonstrate that:

a. service life exceeding 8 hours will not degrade the filter's efficiency below the level specified in Part 84, or
b. the total mass loading of the filter(s) is less than 200 mg.

Reevaluation is necessary when conditions change or modifications are made to processes that could change the type of particulate generated.

R-series filters may be used for any particulate contaminant. If used for an oil-containing particulate, a one-shift use limit applies. Service life for the R-series filters can be extended using the same two methods and qualification described for N-series filters.

P-series filters may be used for any particulate contaminant. Recent NIOSH laboratory studies indicate the efficiency of P-series filters may be significantly reduced with long term use in the presence of oil aerosols (109). Heavy oil loading reduces the efficiency of P100 filter levels much less than that required of P95 filters. The reduction in filter efficiency was not always accompanied by an increase in breathing resistance that would signal the user to replace the filter, or filter element. They found that the reduction in 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 has requested that each manufacturer of P-series filters establish service time recommendations as part of their user instructions and their customer support programs.

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.

5.3.2 Gas and Vapor Respirators

Gas and vapor respirators are commonly referred to a "chemical cartridge respirators" or "gas masks". The difference is that gas masks utilize only full facepieces and the air purifying element, called a canister, 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 chemical composition and physical properties of the gas or vapor. Sorbents are porous and have a large surface area per unit weight-up to 1500 m^2/g. As the gas or vapor passes through the sorbent bed, the molecules are sorbed on the surface. Adsorption, chemisorption, absorption, or catalysis captures gases and vapors when passing through a particulate (sorbent) bed of chemicals. Adsorption is the physical attraction of a vapor to an adsorbent surface. Chemisorption occurs when the sorbent surface and the vapor bond chemically. Absorption occurs when the vapor penetrates below the surface

of the absorbent and chemically reacts with it. 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. For such a substance, only nonoxidizable sorbents should be allowed.

NIOSH certified chemical cartridges and canisters are not for use against gases or vapors with poor warning properties, unless the respirator is approved with an effective ESLI or those that generate high heats of reaction with sorbent materials in the cartridge or canister. Specific MSHA or OSHA standards may permit use of chemical cartridges or canister for gases or vapors that do not have adequate warning properties. Generally, warning properties are defined according to odor, taste, eye irritation, or respiratory irritation. Adequate warning properties imply that the gas or vapor of interest has a persistent odor or irritant effect at concentrations at or below the OSHA PEL or other occupational exposure limit if a PEL does not exist. Gas and vapor APR cannot be used in IDLH atmospheres or in atmospheres containing less then 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. Although limited in number, there are special purpose gas and vapor APRs respirators, e.g., vinyl chloride or formaldehyde, that are approved by MSHA/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.

OSHA's respirator standard allows users to establish respirator change out schedules. At this time OSHA has not defined acceptable protocols for establishing change out schedules (5). However it is generally recognized that such schedules could be based on data obtained from breakthrough studies conducted in the workplace or in the laboratory under "worst" conditions. Definition and guidance for establishing change out schedules waits further development from OSHA, NIOSH, and ANSI.

5.3.2.1 Chemical Cartridge Respirators. NIOSH-certified chemical cartridges or canisters are permissible for use against gas or vapor contaminants up to a concentration that is the lesser of either the concentration from multiplying the respirator's APF classification by the contaminant's OEL, or the IDLH concentration of the contaminant, given an O_2 deficiency does not exist. Specific types of chemical cartridge respirators are approved under Part 84, Subpart L. Canisters can be equipped with particulate filters to form combination gas/vapor and particulate RPE.

Gas masks are similar to chemical cartridge respirators but the quantity of available sorbent material is greater. They are available with half or full facepieces and hoods or helmets. 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.

5.3.2.2 Gas Masks. Gas masks are defined as 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. Gas masks provide respiratory protection against certain specific gases and vapors in concentrations up to 2% by volume (20,000 ppm) or as specified on the canister label and against particulate matter. Specific gas masks are approved under Part 84, Subpart I. NIOSH certifies an escape gas mask that is designed for use during escape only from non-IDLH atmospheres.

5.3.2.3 Gas and Vapor Cartridges and Canisters. The effectiveness of any sorption cartridge or canister should be established for the particular gases or vapors to be captured. 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 Part 84. 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 32.4. The bench test requirements for escape canisters are similar, but not identical to those for chin-style canister listed in Table 32.4. The specific test criteria for escape gas masks can be found in Subpart I of Part 84. The NIOSH recommended maximum use concentrations for chemical cartridges and canisters are listed in Table 32.5.

Canisters and cartridges are evaluated by NIOSH against a relatively few gases and/or vapors so breakthrough information for many chemicals is not readily available and 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 (110). 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 min, which is the minimum time the cartridge must last under NIOSH test conditions. Eleven of the 19 failures occurred in the chlorinated hydrocarbon group.

The ability of a person to detect a given odor is strongly influenced by their innate olfactory powers, past experience with the odor and their level of attention (111). This is why NIOSH does not approve the use of cartridges for materials with poor warning properties NIOSH will and has approved sorption cartridges for materials with poor warning properties if they have an end of service life indicator on the cartridge. Such ends of service life devices are available for carbon monoxide, mercury vapor, and vinyl chloride. Without an end of service life indicator, information concerning the effectiveness of the sorbent with the contaminant should be obtained, and a conservative time of service set. The nose can then be used as a secondary alarm.

5.3.2.4 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 R 95 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 32.4. Combination cartridges must meet one-half the minimum

Table 32.4. 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 (lpm)	Maximum Allowable Penetration (ppm)	Minimum Service Life[a] (minutes)
			Cartridge(s)[b]			
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_3NH_2	1,000	64	10	25
	Equilibrated	CH_3NH_2	1,000	32	1	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
			Chin-style Gas Mask Canister			
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	As received	CCl_4	5,000	64	5	12
Vapor	Equilibrated	CCl_4	5,000	32	5	12
Ammonia	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 2 or 3 chin-style types[d]						
Combination of all chin-style types[e]						
		Front or Back Mounted Gas Mask Canisters				
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	As received	CCl_4	20,000	64	5	12
Vapor	Equilibrated	CCl_4	20,000	32	5	12
Ammonia	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 2 or 3 front or back mounted types[d]						
Combination of all front or back mounted types[e]						

[a]Minimum life will be determined at the indicated maximum allowable penetration.

[b]Where 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 shall 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 shall apply.

[c]Relative humidity of test atmosphere will be 95 ± 3%; temperature of test atmosphere will be 25 ± 2.5°C.

[d]Test conditions and requirements are as shown in the table.

[e]Test 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.

Table 32.5. NIOSH Recommended Maximum Use Concentrations[a] for Gas and Air Purifying Elements

	Classification of Gas and Vapor Air-Purifying Elements		
Type of Gas or Vapor	Cartridge(s)	Chin-Style Canister	Front- or Back-Mounted Canister
Organic vapors	1,000[b]	5,000†	20,000[c]
Acid gases			
Sulfur dioxide (SO_2)	50	100	100
Chlorine (Cl_2)	10	25	25
Hydrogen chloride (HCl)	50	100	100
Ammonia (NH_3)	300	500	500
Methyl amine (CH_3NH_2)	100	—	—
Carbon monoxide (CO)	NA[d]	NA[d]	1,500

[a]Expressed in ppm.
[b]Maximum use concentration will be 1,000 ppm or equal to or lower than the immediately dangerous to life or health (IDLH) value for the specific organic vapor, whichever is lower.
[c]Maximum use concentration for "entry into" will be limited to the value listed or to the IDLH value for the specific organic vapor, whichever is lower.
[d]NA = not available.

breakthrough times at the specific challenge concentrations and conditions noted in Table 32.4.

A chemical cartridge or canister combined with a particulate filter provides respiratory protection where exposure can be to 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 and meet a final breathing resistance limit, after filter loading, of 70 mm H_2O at a flow rate of 85 ± 2 Lpm.

*5.3.2.5 **Carbon Monoxide.*** Carbon monoxide is not sorbed, but by catalytic action is oxidized into carbon dioxide. The carbon monoxide canister is 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. Because carbon monoxide has no warning odor, an end of service life indicator shows when the drying agent is saturated and the life of the canister is ended.

5.3.3 Powered Air Purifying Respirators

The PAPR is designed with a battery-operated blower to push or pull air through the air-purifying element(s) and supply it to the user. As of July 10 1998, NIOSH only certifies PAPRs equipped with high efficiency (HEPA) particulate filters that have been tested against thermally generated monodispersed DOP aerosol under the test parameters described in Part 84, Subpart KK, paragraph 84.1151. Powered air-purifying respirators

equipped with a tight-fitting facepiece must provide a minimum of 115 Lpm of air to the facepiece. Those equipped with a hood or helmet must provide a minimum of 170 Lpm to the loose fitting facepiece. The PAPR is available in three configurations: tight-fitting facepieces, hoods, and helmets. Because the PAPR is an APR, they must not be used in an IDLH environment or in the presence of atmospheric contaminants for which the filters or sorbents are not designed. They should not be considered as positive pressure devices.

5.4 Atmosphere Supplying

5.4.1 Self-Contained Breathing Apparatus

Self-contained breathing apparatus provide complete 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 an air supply of compressed air, compressed or liquid oxygen, or oxygen-generating chemicals. No external connection to an air supply is necessary. Self-contained breathing apparatus are classified as open circuit 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 CO_2 and moisture, and reconditioned with fresh O_2. Self-contained breathing apparatus are certified under the test requirements of Part 84 Subpart H. The inhalation flow is engineered to operate in demand or pressure demand modes.

Pressure demand SCBA is 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 considerable higher than those required for poisoning through the respiratory tract must be present.

5.4.2 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 open-circuit SCBA must, at an inhalation resistance of 51 mm H_2O and an air pressure of 500 psi, deliver a minimum air flow of 200 Lpm. The duration of air supply can be certified at different intervals from a minimum of 3 min to a maximum of 240 min. Combination SAR and auxiliary SCBA units can be 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 aluminum, or a composite cylinder of an aluminum bladder inside a filament wound fiberglass cylinder. The fiberglass cylinder and the fiberglass wrapped aluminum 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 regular must be designed to have a manual bypass valve for emergency use by the wearer if the regulator were to malfunction.

The SCBA customary 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 min. 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. The SCBA can be obtained in demand or pressure demand mode. Only the pressure demand units should be used because they provide the highest degree of protection of any respirator. Only pressure demand SCBA respirators are recommended for use in environments that may be immediately dangerous to life or health (IDLH).

5.4.3 *Closed-Circuit Self-Contained Breathing Apparatus and Self-Contained Self-Rescuer*

Closed-circuit devices, available with up to a 4-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, the breathing air reservoir for the facepiece. Because oxygen is consumed during cellular respiration and the carbon dioxide is removed, 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. Canisters are available for up to 2-hr duration. Certain types of these units referred to as self-contained self-rescuers are used as emergency escape devices for miners. Most closed circuit SCBAs are demand mode devices. The units have been used successfully for many years in mine rescue operations. The rescue teams are given extensive training in the use of the equipment to ensure proper use.

5.4.4 *Supplied-Air Respirators*

Supplied-air respirators deliver breathing air from a remote storage site, through a supply hose to the respiratory inlet covering. Supplied-air respirators do not have air-purifying filters and cartridges; instead, they depend on delivering acceptable quality breathing air to the user from an external source. With the exception of hose masks equipped with blowers, these devices should be used only in atmospheres not immediately dangerous to life or health. Supplied-air respirators are certified under the test requirements of Part 84

Subpart J. They are divided into three classes A, B, and C. Class A and B SAR are hose masks and not widely used. Class C SAR can be equipped with half masks, full face masks, and hoods or helmets supplied by a hose with air under pressure not to exceed 125 psi. Class C may be approved in demand, pressure demand, or continuous flow modes. A minimum airflow delivery of 115 Lpm is required for use with a tight-fitting facepiece and 170 Lpm with a hood or helmet. The maximum allowable airflow for SARs is 425 Lpm. NIOSH certification of type "CE" refers to a device for abrasive blasting that has outer coverings. Hoses for class C devices can be obtained in 15-, 25-, or 50-ft lengths up to a maximum of 300 ft. The maximum inhalation and exhalation resistances are both 50 mm H_2O.

5.4.4.1 Hose Masks, Powered and Nonpowered. The oldest SAR unit is the type "B" hose mask. It consists of a large-diameter hose, anchored in an area with acceptable quality breathing air and connected to the wearer's facepiece. The diameter of the hose is large, which reduces inhalation resistance. Another version is the type "A" hose mask, which has a hand- or electric-powered air mover connected to the fresh air source to assist in supplying air. The Bureau of Mines started to approve hose masks in 1929. Considering the wide variety and use of airline SAR equipment today, hose masks are a rarity and there are really no use situations where they are the RPE of choice.

5.4.4.2 Type C SAR. The type "C" supplied-air respirator (often referred to as an airline respirator) differs from hose masks in that the air is delivered to the facepiece under pressure up to 125 psi. The NIOSH-approved 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 mode 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. This is in contrast with the open-circuit self-contained breathing apparatus, which has an airflow that varies automatically with the inhalation pressure of the user. Problems can be encountered in ensuring 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. Airflow can be engineered to occur in a demand mode, pressure demand mode, or continuous flow mode.

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. The negative pressure in the facepiece may reach 50 mm H_2O before the air starts to flow. Airflow ceases when inhalation ceases. The facepiece pressure is comparable to the negative pressure present when using an air-purifying respirator. The 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 air-purifying respirator with the same facepiece. Because demand mode SARs do not offer protection to the user that is superior to negative pressure, air-purifying respirator, their

selection as RPE of choice is very limited except for conditions where only an O_2 deficiency exists.

The problem of leakage into negative pressure facepieces led to the positive pressure facepiece, which greatly reduces contaminant leakage into the respirator facepiece. The pressure demand SAR is similar to the demand mode SAR except for the exhalation valve and the airflow regulator. The exhalation valve is spring loaded so that a pressure of up to 38 mm H_2O 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. It is possible under high work rates for the user to demand a higher instantaneous airflow than the SAR can deliver. Under this condition, negative pressure may occur in the facepiece for a short period of time. Regardless, the PDM provides the greatest degree of protection for the user of SAR. The only respirators carrying the positive pressure.

Continuous flow SARs can be equipped with tight fitting and loose fitting facepieces. The loose fitting SAR may consist of a supplied air hood, helmet, blouse, or full suit. It requires a minimum continuous airflow of 170 Lpm when in use. 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 Lpm when in use. The hood of the SAR introduces the air supply through a manifold above the head of the user. The air flows downward and exits under the edges of the hood. Better designs have neck cuffs. NIOSH certification regulations specify a minimum airflow of 170 Lpm for SARs equipped with hoods. The literature contains many references to the positive pressure nature of continuous flow devices. However, users are advised that numerous field and laboratory studies, reviewed earlier in this chapter, indicated that at minimum certification air flow rates (115 Lpm for tight fitting facepieces or 170 Lpm for loose fitting facepieces) these devices do not maintain positive pressure.

5.5 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 (109). Much is unknown about the design and use of airline suits. The traditional figure of 170 Lpm for supplied air hoods may not provide sufficient airflow to prevent inward leakage for these devices. Airline suits should be tested to determine their efficiency prior to use in atmospheres of high toxicity.

5.6 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: air-purifying respirators and self-contained breathing apparatus. Air-purifying respirators include the escape gas mask respirator, the gas mask (canister) respirator, and the filter self-rescuer. The escape gas mask 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. The escape gas mask, which utilizes a half-mask, removes contaminants from the air. These respirators may also be used 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. A self-contained breathing apparatus (SCBA) provides air to the user for escape from oxygen-deficient environments. Escape SCBA devices are commonly used with full facepieces or hoods and, depending on the supply of air, are usually rated as 3 to 60 minute units. All SCBA devices can be used in oxygen-deficient atmospheres. Self-contained self-rescuer (SCSR) devices are certified by MSHA/NIOSH for escape from mines, but these devices may also have application in other similar environments. SCSRs are mouthpiece respirators that 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. The majority of gas masks or escape gas masks 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 particulate. The information in Table 32.6 should be used to select the appropriate escape apparatus.

6 RESPIRATOR SELECTION AND USE

The primary objective of industrial hygiene it to prevent contaminants from escaping into the atmosphere. Obviously, hazard control should start at the process, equipment, and plant design levels where effluents can be effectively controlled at the outset. With operating processes, the problem becomes more difficult. However, in all cases, consideration should be given to the use of effective engineering controls to eliminate and/or reduce exposure to respiratory hazards. The preferred priority of controls steps is (*1*) substitution of a less toxic substance, (*2*) encapsulation or isolation of the process, (*3*) use of local exhaust ventilation or general ventilation in conjunction with filters and scrubbers to control the effluents, and (*4*) use of personal protective equipment (PPE). Respiratory protective equipment should be used only when all higher priority control steps are not technically or financially feasible. Since there are many types of RPE, it is important that they be selected with utmost care to ensure that workers receive proper protection. 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 particular 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.

Table 32.6. Selection Options for Escape Respirators

Escape Conditions	Type of Respirator
Short distance to exit, no obstacles (no oxygen deficiency)	Any escape gas mask[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 gas mask is a respirator designed for use during escape only from immediately dangerous to life or health (IDLH) or 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. Maximum use concentrations for canister air-purifying elements are listed in Table 34.5

[c]Escape self-contained breathing apparatus can have rated service lives of 3 to 60 minutes. All acceptable devices for entry into emergency situations can also be used.

Examples of the types and sources of information that need to be gathered are:

Material safety data sheets.

Specific regulations or guidelines for the use of this material.

Determination of contaminants physical, chemical, and toxicological properties of the contaminant(s).

Airborne concentration.

IDLH concentration.

PEL.

Does the material have adequate warning properties below it's exposure limit concentration?

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 the material have a carcinogen classification?

Does, or is there potential for, an oxygen deficient atmosphere to exist?

APF required (contaminant concentration/PEL)?

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 a self-contained breathing apparatus (SCBA).

Information obtained on the service life of the cartridge/canister under conditions of intended use should be evaluated regardless of the odor warning properties of the chemicals. These evaluations should be based on the gas and or vapor contaminants and the temperature and relative humidity extremes (high and low) existing in the workplace. NIOSH recommends when conducting a laboratory-based service life test that the challenge concentrations of the gases and vapors should be at least 10 times the maximum use concentration of the respirator. The service life obtained from these tests should be used to determine how long a cartridge/canister could provide protection under actual use conditions. This information can be used to set up cartridge replacement schedules and should be used in conjunction with sensory warning properties. 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 ANSI Z88.2 recommend 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 things 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 CFR1910.134, 29 CFR 1926 and respirator regulations specific to a particular contaminant;

American National Standard Practices for Respirator Protection, ANSI Z88.2-1992 Available from the American National Standards Institute, Inc., 1430 Broadway, New York, NY, 10018.

Respirator Decision Logic, National Institute for Occupational Safety and Health, DHHS (NIOSH) Publication No. 87-108

Respiratory Protection: A Manual and Guideline, 3rd ed. Available from the American Industrial Hygiene Association, 2700 Prosperity Avenue, Suite 250, Fairfax, VA 22031.

Breathing Apparatus for the Fire Service Available from National Fire Protection Association, 470 Atlantic Avenue, Boston, MA 02110.

Threshold Limit Values, Available from Secretary-Treasurer of the American Conference of Governmental Industrial Hygienists, 1330 Kemper Meadow Drive, Cincinnati, OH 45240-1634.

6.1 Restrictions and Requirements for All Respirator Use

To ensure that the RPE selected will provide adequate protection under the conditions of intended use the following requirements and restrictions should be considered:

1. An OSHA compliant respiratory protection program should be instituted. OSHA requires that a respiratory protection program must contain the following basic elements. Each of these program elements are reviewed and background information is given and discussed in later portions of the section. It is important to note that the new OSHA respirator standard specifies that the respirator program administrator be qualified by appropriate training or experience that is commensurate with the complexity of the program he/she has to administer or oversee and conduct the required evaluations of program effectiveness.
   a. Procedures for selecting respirators for use in the workplace.
   b. Medical evaluation of employees required to use respirators.
   c. Fit testing procedures for tight-fitting respirators.
   d. Procedures for proper use of respirators in routine and reasonably foreseeable emergency situations.
   e. Procedures and schedules for cleaning, disinfecting, storing, inspection, repairing,discarding and otherwise maintaining respirators.
   f. Procedures to ensure adequate air quality, quantity and flow of breathing air for atmosphere-supplying respirators.
   g. Training of employees in the respiratory hazards to which they are potentially exposed during routine and emergency situations.
   h. Training the employees in the proper use of respirators, including putting on and removing them, any limitation on their use and their maintenance.
   i. Procedures for regularly evaluating the effectiveness of the program.

2. NIOSH recommends that whenever possible, quantitative evaluation of the protection factor in the workplace should be performed to confirm the actual degree of protection provided by the respirator to each worker.
3. Qualitative or quantitative fit testing of tight fitting facepieces used with air-purifying and atmosphere supplying devices should be done as part of the selection process. When QNFT is used the pass/fail screening level should be chosen with

caution and with the recognition of the uncertainty of its effectiveness since no studies have demonstrated what QNFF values correlate with actual protection. OSHA requires as a minimum a QNFF of 100 for tight fitting half facepieces and 500 for tight fitting full facepieces.

4. Negative pressure RPE should not be used when facial scars or deformities interfere with the face seal.
5. Negative pressure RPE should not be used for entry into oxygen deficient atmospheres.
6. No RPE (including positive pressure) should be used when facial hair interferes with the face seal.
7. The RPE should be properly maintained, correctly used, and conscientiously worn.
8. The usage limitations of the air-purifying element particularly gas and vapor cartridges, should not be exceeded.
9. OSHA requires the use of RPE certified by NIOSH.
10. Workers should be instructed to leave the contaminated area immediately upon suspicion of respirator failure and then to determine the problem.
11. 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.
12. Respirator wearers should be aware of the variability in human responses to the warning properties of hazardous substances. When warning properties must be relied on as part of a respiratory protection program, each prospective wearer should be screened for the ability to detect the warning properties of the hazardous substances at exposure concentrations that are less than the exposure limit for each given substance.

6.2 Respiratory Hazards

In occupational settings, toxic materials generally enter the body in three ways: (*1*) through the gastrointestinal tract, (*2*) through the skin, and (*3*) through the respiratory tract. Of these 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.

6.2.1 Oxygen Deficiency

The normal concentration percent of oxygen in air at sea level is 20.9% by volume, which is equivalent to a partial pressure of approximately 160 mm Hg. The NIOSH and OSHA define an oxygen-deficient atmosphere as any atmosphere containing oxygen at a concentration below 19.5% at sea level or approximately 148 mm Hg. At oxygen concentrations below 16% at sea level, decreased mental effectiveness, visual acuity, and muscular coordination occur. At oxygen concentrations below 10%, loss of consciousness may occur,

and below 6% oxygen, death will result. Individuals exposed to low concentrations of oxygen note often only mild subjective changes and collapse can occur without warning (22). 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. 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 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, aerobic bacteria, etc., where oxygen is consumed.

6.2.2 Chemical Airborne Contaminants

Chemical airborne contaminants include particulate matter in the form of discrete particles of solids or liquids, gaseous material in the form of a gas or vapor, or a combination of both gaseous and particulate matter.

6.2.2.1 Particulate Hazards. Particulate contaminants may be classified according to their physical and chemical characteristics and their biological effect on the body. One of the key attributes of an aerosol's ability to enter the respiratory system is it size. More specifically its aerodynamic particle size. Particles below 10 micrometer aerodynamic diameter are generally considered to be respirable. That means that they are small enough to pass through the nose and the pharyngeal area of the respiratory tract and enter the trachea, bronchi and upper ciliated regions of the lung. In the healthy lung, particles from 5 to 10 micrometers aerodynamic diameter are generally removed from the respiratory system by the constant cleansing action of the ciliated epithelium in the upper respiratory tract. Particles below 5 micrometers aerodynamic diameter are more apt to reach the nonciliated regions of the deep lung and alveolar ducts and sacs. However, with excessive "dust" exposures, diseased systems, smoking etc. the efficiency of the cleansing action can be markedly reduced.

Occupationally related aerosols are generally classified as dust, mist, fume, smoke, airborne living organisms and allergens, or various combinations of these aerosols. The fate of particles that enter the respiratory tract depends on their solubility, aerodynamic particle size, chemical characteristics, and metabolism in the body. Hence, particulate contaminants are also classified according to their biological effects as:

1. Inert aerosol that produce minor irritation or discomfort but in sufficient quantity can overwhelm the protective mechanisms of the respiratory tract.
2. Allergy producers that cause severe reactions with some sensitized individuals.

3. Chemical irritants that can damage mucous membranes or lung tissue by chemical reaction.
4. Fibrosis producers that cause development or scar tissue in the lung such as silica or coal dust.
5. Carcinogens or suspect carcinogens such as asbestos, chrome VI or radioactive particulate matter.
6. Systemic poisons that have sites of action in additional organ systems of the body such as lead, cadmium, or arsenic.
7. Fever producers such as the fumes of zinc and copper.

6.2.2.2 Gaseous Contaminants. Gaseous contaminants occurring as true gases such as sulfur dioxide, carbon monoxide, etc., or vapors from organic liquids such as benzene or methyl ethyl ketone can likewise be classified according to their chemical characteristics and biological effect on the body. Chemically, gaseous contaminants may be classified as follows:

1. Inert gas which do not metabolize in the body but can produce an oxygen deficiency by displacement of air, e.g., helium, argon, neon, etc.
2. Acid gases which are acids or produce acids by reaction with water, e.g., sulfur dioxide, chlorine, hydrogen chloride etc.
3. Alkaline gases which are alkales or produce alkales by reaction with water, e.g., ammonia, phosphine etc.
4. Organic compounds which exist as true gases or vapors from organic liquids.
5. Organometallic compounds that are organic gases or vapors that have metals attached to organic groups within the molecule, e.g., tetraethyl lead and organic phosphates.

Gaseous contaminants may be classified according to biological effects as follows:

1. Asphyxiants that interfere with the uptake, transport or utilization of oxygen in the body. Asphyxiants can be simple asphyxiants that create an oxygen deficiency by air displacement, e.g., nitrogen, methane, hydrogen, etc. or chemical asphyxiants that interfere with the uptake and transport of oxygen in the blood system (e.g., carbon monoxide) or that interferes with "internal respiration" or oxidation of the tissue cells (e.g., hydrogen cyanide).
2. Chemical irritants that can irritate the respiratory system and cause the development of pulmonary edema or fluid in the lung, e.g., acid and alkaline gases.
3. Anesthetics that can cause loss of feeling, unconsciousness, and death, e.g., chloroform, ether, etc.
4. Systemic poisons that can damage critical organs and systems of the body, e.g., metallic mercury vapor, hydrogen sulfide, etc.

6.3 Selection

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. 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 32.4 contains an example of a decision logic adopted, with revisions and additions from NIOSH (14).

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 maximum use concentration up to the IDLH concentration. Some specific IDLH guidelines are provided in the literature such as the American Industrial Hygiene Association (AIHA) Hygienic Guides and the NIOSH Pocket Guide for Hazardous Chemical Substances (113).

Eye protection in the form of respirators with full facepieces, helmets, or hoods 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. 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 32.6 should be considered when selecting appropriate escape apparatus.

6.4 Training

The proper respirator is of no value without training for the user. The training experience should provide the user, in addition to the training elements listed subsequently, 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. Minimum training shall include the following components:

1. Instruction in the nature of the hazard, whether acute, chronic, or both, and an honest appraisal of what may happen if the proper device is not used.
2. Explanation of why respiratory protection instead of engineering controls is being used. If engineering controls are being used, explain why they are not adequate, and what efforts are being made to reduce or eliminate the need for respirators. Explanation of why more positive control is not immediately feasible.
3. Explanation of the respirator program and OSHA regulations.
4. A discussion of why this is the proper type of unit for the particular purpose.
5. A discussion of the device's capabilities and limitations.

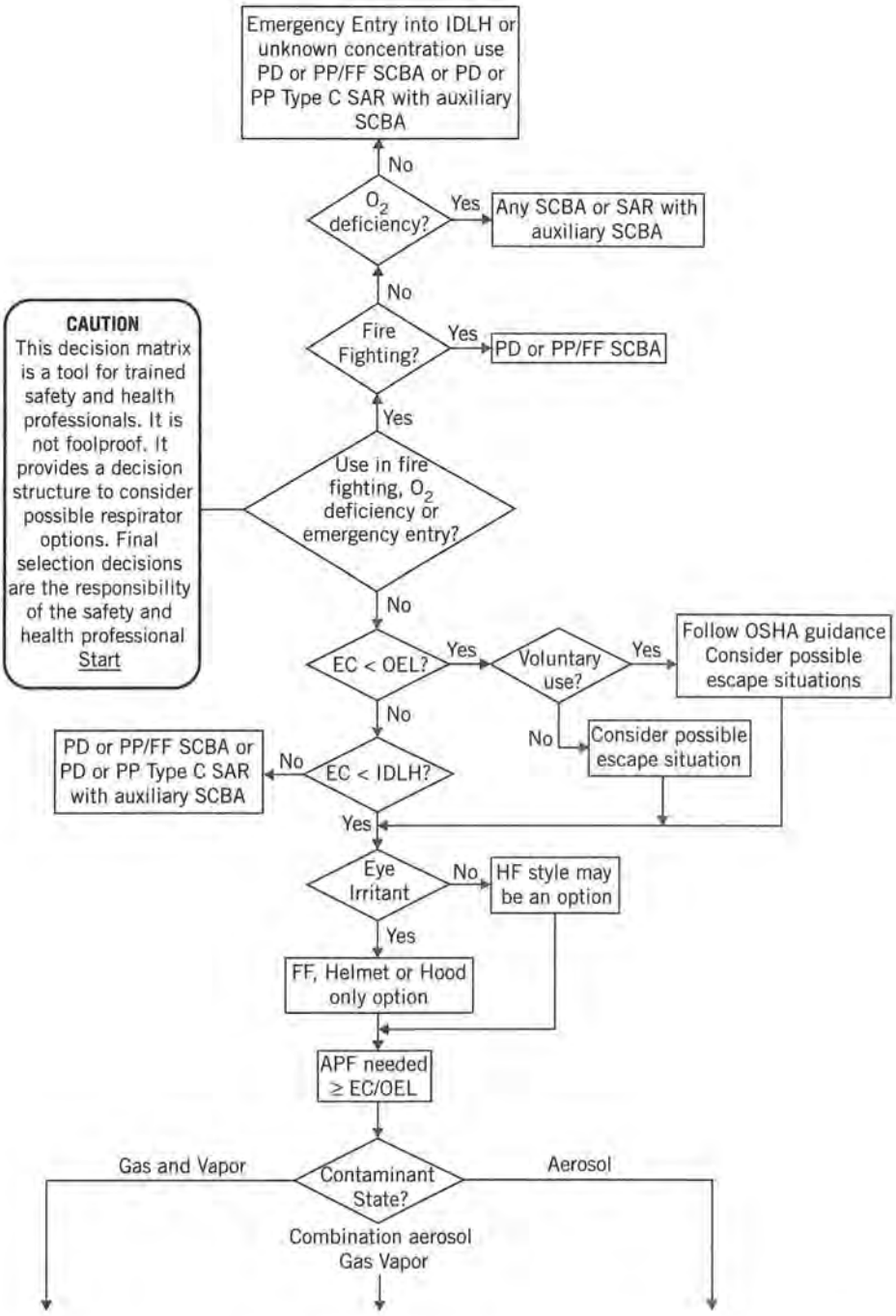


Figure 32.4. Respirator Decision Logic.

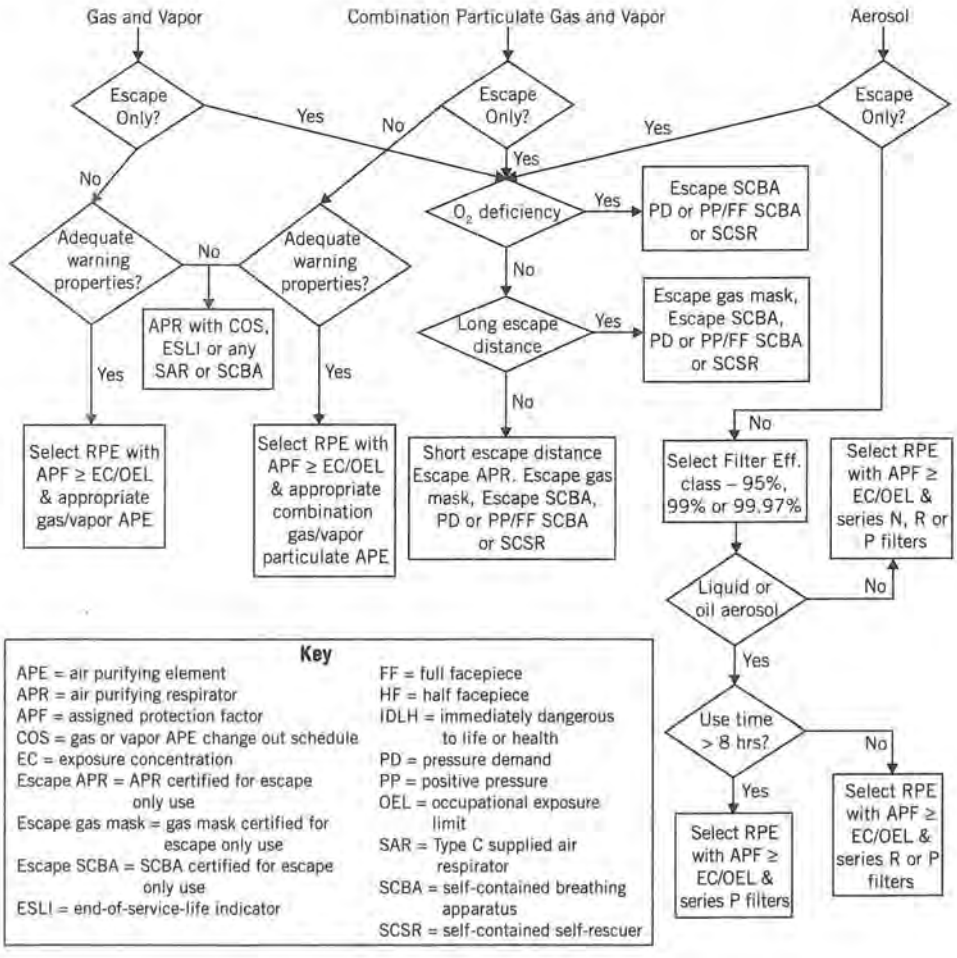


Figure 32.4. Continued.

6. Explanation of how to inspect, don, check the fit, and wear the respirator selected by the user.
7. Instruction and training in actual use (especially a RPE for emergency use) and close and frequent supervision to assure that it continues to be properly used.
8. Explanation and if needed field training of how to recognize and cope with emergency situations.

6.5 Medical Surveillance

Workers should never be assigned to any operations requiring respiratory protection until a physician has determined that they are capable physically and psychologically to perform

the work using the respiratory protective equipment. 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.

Some users experience breathing distress or claustrophobia while wearing a respirator (114). Recognition of such users should be made prior to entering life-threatening environments. Morgan and Raven, using an anxiety profile, are able to predict those who may experience problems wearing respirators in high work rate environments (115).

6.6 Evaluation of Respirator Program Effectiveness

OSHA 1910.134 states that respirator program effectiveness shall be inspected and evaluated regularly. Periodic 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 surveillance 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.

6.7 Maintenance and Care of RPE

Proper inspection, maintenance, and repair of RPE are necessary to ensure that it stays in good working order. The maintenance program differs on the basis on plant size, the complexity of the RPE used etc. 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 manufacturers recommended procedures if those procedures are of equivalent effectiveness as the cleaning and disinfecting procedures detailed in Appendix B-2 of 1910.134 (5). Respirators used by a single wearer should be cleaned and disinfected as often as necessary. Respirators used by different individuals should be cleaned and disinfected between each use. The RPE should be stored in accordance with any applicable manufacturer instructions. This should be 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 emergency situation should be inspected monthly according to the manufacturer 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 and recorded and maintained as a historical file. Never should RPE that fails inspection or is found defective 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.

6.8 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 (116). 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. 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 diesel 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. The most common air compressor used for breathing air is the oil-lubricated compressor, which add 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 CO_2. 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 personnel that the compressor has overheated. Although not required, continuous-reading CO monitors 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. The diaphragm pump, oil-less 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.

6.9 Special Problems with Selecting and Using Respirators

6.9.1 Respirators and Hair

Respiratory protective devices 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. Stobbe et al. in a review of facial hair and respirator fit studies, found that the face seal of negative pressure respirators was adversely affected by facial hair (117). 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 (118). A policy statement prohibiting facial hair that interferes with wearing a respirator should be concise and include only respirator users. It must be part of a respirator program, but not the only part enforced.

6.9.2 Cold Temperatures

In cold temperatures problems of facepiece flexibility, visibility, and frozen valves must be considered. Those who work in cold environments should ask the manufacturer about respirators for cold weather. The facepiece will fog in cold weather when exposed to warm exhaled breath. A nose cup, which must be used at temperatures below 32°F, is available for all full facepiece respirators to keep the warm air away from the visor (119). Valves and regulators should be carefully checked before the respirator is used to ensure that they are functioning satisfactorily.

6.9.3 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 masks interfere with proper seating of eyeglasses, the respirator fit is not satisfactory, and either another respirator or another style of eyeglass must be selected.

6.9.4 Communications

Communication through a facepiece is 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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E. W. Arp
T. E. Bernard
W. A. Burgess
D. C. Byrne
H. Cember
M. A. Coffman
M. J. Dainoff
R. L. Harris
P. A. Heinsohn
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