3M JobHealth HIGHLIGHTS

Technical Information for Occupational Health and Safety Professionals

Respiration, Respirators and Work Capacity

By Brian Sharkey, PhD. and Steven Gaskill, Ph.D.

Editor's note: *Because respirators may contribute to physical stress, it is important that both respirator designers and respirator program managers understand respiratory physiology and work capacity. Workers' limitations must be taken into account during respirator design as well as when scheduling work in areas where respirators are required. Secondly, the respiratory capabilities and limitations of the worker dictate performance characteristics respirators must have in order to provide acceptable protection. This article focuses largely on the physiological parameters relevant to these issues. The companion article* Principles of Physiology and Respirator Performance *concentrates on respirator performance.*

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Respiration

The human respiratory system is overbuilt for its duties, with a maximal capacity 1.5 times the volume used during maximal effort (e.g., 180 L/min vs. 120 L/min during a maximal treadmill test). For this reason respiration is seldom a limiting factor in work or sport. However, wearing a respirator can alter that situation by imposing an additional burden on the respiratory system. In addition, aging reduces maximal breathing capacity and increases residual volume, a measure of unused lung space, that combine to narrow the gap between demand and capacity. This article reviews the basics of respiration; illustrates the effects of respirators; identifies limits of the respiratory system; and shows ways to alter those limits. It draws heavily on the authors' extensive study of respiration in work and in sport.

Respiration has two major functions: getting oxygen into the body and eliminating carbon dioxide. Atmospheric air contains 20.93% oxygen and a small amount of carbon dioxide (0.03%). The balance is mostly nitrogen. Air enters the lungs when the diaphragm contracts, creating an area of lower pressure, and air rushes in. On exhalation, the diaphragm relaxes and the air is expelled from the lungs. During exercise, exhalation is assisted by abdominal and intercostal (between rib) muscles, so the energy cost of breathing increases. Oxygen enters the blood when it crosses thin alveolar and capillary membranes in the lungs. It is then transported to the cells via hemo-

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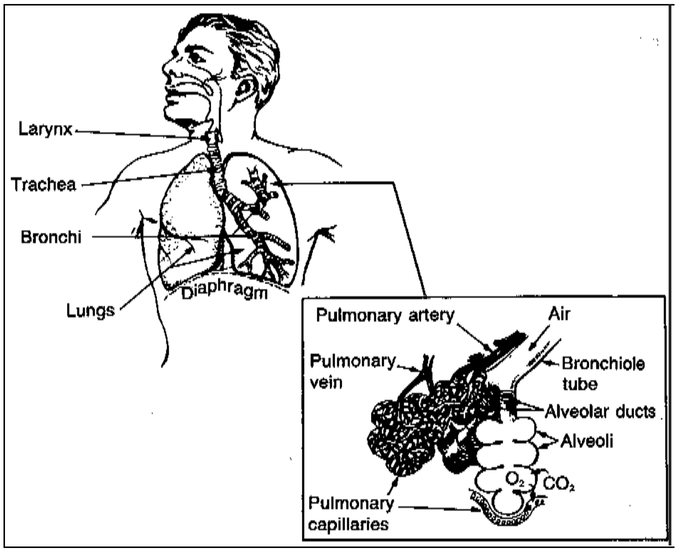

Figure 1 - Respiratory System (From Reference 1)

globin within the red blood cells. At the same time carbon dioxide exits the bloodstream and is carried to the lung for exhalation (see Figure 1).

Ventilation

Ventilation is the amount of air inhaled (V_i) or exhaled (V_e) per minute. It is the product of respiratory rate or frequency (f) and the volume of air per breath (tidal volume or TV): $V_e = f * TV$. A normal resting ventilation of 6 liters per minute (L/min) results from a rate of 12 breaths per minute and tidal volume of 0.5 liters. During moderate effort, ventilation increases to 30 to 50 L/min, and reaches 120 L/min at maximal exertion (e.g., 120 L/min = 40 breaths * 3 liters per breath).

While it is possible to consciously control the rate and depth of respiration during speech and singing, respiratory control is usually left to the autonomic nervous system, which seems quite able to fine-tune air intake to the demands of work and exercise. Sensory receptors in the joints first signal the need for increased ventilation. Then chemical receptors sense rising levels of carbon dioxide in the blood, and use that information to regulate the rate and depth of respiration.

Dead Space: A portion of the air inhaled never gets to the tiny air sacs (alveoli) where diffusion of oxygen from atmospheric air to the blood takes place. It remains in the passageways (nose, mouth, pharynx, larynx, trachea, bronchi and bronchioles) where it cannot transfer its oxygen into the blood. The volume of air in this so-called dead space amounts to about 0.15 liter, or almost one-third of the resting tidal volume. Because of the dead space, it is more efficient to take deeper breaths so a greater proportion of each breath reaches the lungs. Many respirators (e.g., half facepiece negative pressure) increase dead space, thereby requiring an increase in the rate or depth of breathing to deliver a given amount of air to the alveoli. The dead space may also contribute to the feelings of dyspnea while working with a respirator.*(see sidebar in next column)*

While rate and depth of respiration are normally self-adjusting, they can be influenced. Trained endurance athletes are able to take in more air per breath, thereby slowing the respiratory rate and lowering the oxygen cost of breathing. The improved efficiency is due to the training of the respiratory muscles, as well as the improved aerobic capacity and efficiency of trained skeletal muscles. Aerobic capacity (also referred to as VO_2 max) is defined as the maximum ability to take in, transport, and utilize oxygen.

Dyspnea: Have you ever seemed unable to get enough air? The sensation of difficult breathing (dyspnea) associated with vigorous exercise cannot be ignored, but that sensation doesn't mean that you lack oxygen or ran out of wind. Respiration has two major functions: getting oxygen into the body and getting rid of carbon dioxide. We tend to ignore the latter, but we shouldn't. Excess CO_2 contributes to the sensation of dyspnea, and anything that interferes with carbon dioxide removal may impose limits on our ability to sustain vigorous activity. Proof of the important role of carbon dioxide as a respiratory stimulus is easily demonstrated. Inhale and exhale deeply (hyperventilate) about 10 times or until dizzy, then take one more deep breath and hold it as long as you can. You'll find you can hold your breath much longer after "blowing-off" carbon dioxide, the primary respiratory stimulus.

V_e and Exercise: Ventilation is closely linked to the demands of exercise (see Figure 2). As exercise intensity increases, as measured by the increase in oxygen consumption or work, ventilation rises in a linear fashion. Further increases in intensity lead to the production of excess carbon dioxide and a steeper rise in ventilation. The threshold for this non-linear rise in ventilation relative to oxygen intake is called the ventilatory threshold (VT). The VT is important since it occurs at a work intensity that most individuals can sustain for several hours.

When working in physically demanding work environments for sustained periods, few workers will exceed VT for more than a few minutes before reducing their intensity of work.

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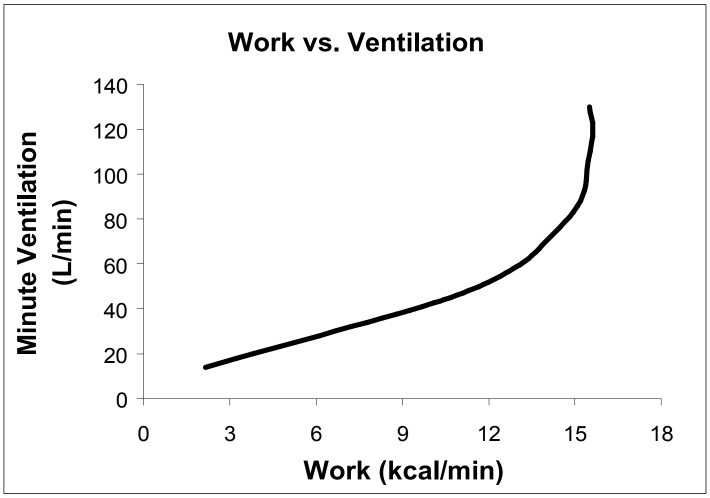

Figure 2. Work vs. ventilation for the average worker.

Sustainable Work and Ventilation

Sustainable work depends on many factors. These include the size of the individual, their muscle mass and the ability of their cardiorespiratory system to deliver oxygen to the working muscles. Also important is the fitness status of the individual, which will affect oxygen and carbon dioxide transport as well as determine the ability of the working muscles to use fats and/or sugars for energy. Fitness will also play a role in the type of muscle fiber that is recruited to meet work demands: aerobically fit workers recruit efficient slow twitch muscle fibers. Finally, the work environment, e.g., high temperature and humidity, will have an effect on sustainable work capacity. Since fitness is related to how much work an individual can sustain, which is further related to oxygen requirements, fitness will have an effect on ventilation rates during sustainable work. At moderate work intensities V_e is directly related to work and oxygen consumption. As work increases oxygen consumption increases linearly. However, once the work intensity increases above the VT, the cost of respiration (extracting oxygen and eliminating carbon dioxide) increases at a greater rate. This is much less efficient, so that respiration alone requires an increasing percent age of the work capacity.

During moderate work, oxygen transport to working muscles is not a limiting factor in healthy individuals. However, individuals differ in the amount of work that they can do at self-selected moderate intensities. The average sized person can maintain a workload requiring a V_e of about 35 to 40 L/min for several hours. This corresponds to an energy expenditure of about 7.5 kilocalories per minute (Kcal /min). However, with training that individual may be able to sustain a V_e of 55 L/min with an associated energy expenditure of about 12.5 Kcal/min. With detraining, or a sedentary lifestyle, the same individual's capacity may decline to a V_e of 30 L/min, expending only 6 Kcal/min.

Ventilatory Threshold: Have you ever wondered if there is a measure of how much work you can sustain for several hours? A good measure of sustainable aerobic work rate is the ventilatory threshold. This is a work intensity that can be determined from an exercise test in the lab requiring the collection and analysis of expired air during a graded treadmill test (speed or grade is gradually increased). The ventilatory threshold is determined by non-linear changes in oxygen consumption and carbon dioxide production in relation to ventilation. A field test to estimate VT from a submaximal step, bike or walking test has recently been developed at the University of Montana's Human Performance Laboratory. The simple test takes a heart rate monitor and a few minutes of moderate exercise.

A major consideration in determining V_e during sustainable work is the size of the individual. An average 160 pound (45kg) person has a V_e of about 40 L/min during maximal work sustainable for up to eight hours. The range of V_e for average fitness individuals doing maximal sustainable work is from about 27 L/min (100 pound [45kg]person) to about 60 L/min (220 pound [100 kg]person). If both body size and fitness are considered, V_e during maximal sustainable work ranges from 20 L/min in a small unfit individual to about 100 L/min in a large trained individual.

The pattern of work output must also be considered when estimating V_e rates during sustained work. That is, whether work requires steady output or fluctuations in intensity may have a dramatic effect on V_e rates. The average worker, depending on fitness, can sustain about 40-75% of their maximal short-term (3-5 min) work output for several hours at a time. As the intensity of work and V_e increase, the duration that work can be sustained decreases (See Table 1).

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Table 1. Time to exhaustion in averaged sized individuals (160 lbs) with similar maximal work capacities but different sub-maximal aerobic fitness levels as evaluated by their time to exhaustion in sustained work.

% VO_2 max	WORK Kcal/min	V_e (L/min)	Low Fitness Time to exhaustion	Average Fitness Time to exhaustion	Mod High Fitness Time to exhaustion
40%	6.3	35	1 hr	8 hrs	>8 hrs
50%	7.9	42	30 min	4 hrs	>8 hrs
55%	8.7	48	20 min	1 hr	8 hrs
60%	9.5	55	15 min	40 min	6 hrs
70%	11.0	67	10 min	35 min	2 hrs
80%	12.6	80	5 min	15 min	45 min

This table assumes that all individuals have the same maximal aerobic capacity of 42 ml/kg/min (average 20-30 year old male weighing 154 pounds [70 kg]). For each 22 pounds [10 kg] over or under 70 kg add or subtract 10% from the values for minute ventilation (V_e) and work (Kcal/min) shown. Fitness is evaluated by the percentage of VO_2 max that the individual can sustain for different intensities of work. Note: High and low fitness are evaluated as found in the normal workplace and do not include aerobic athletes.[2,3]

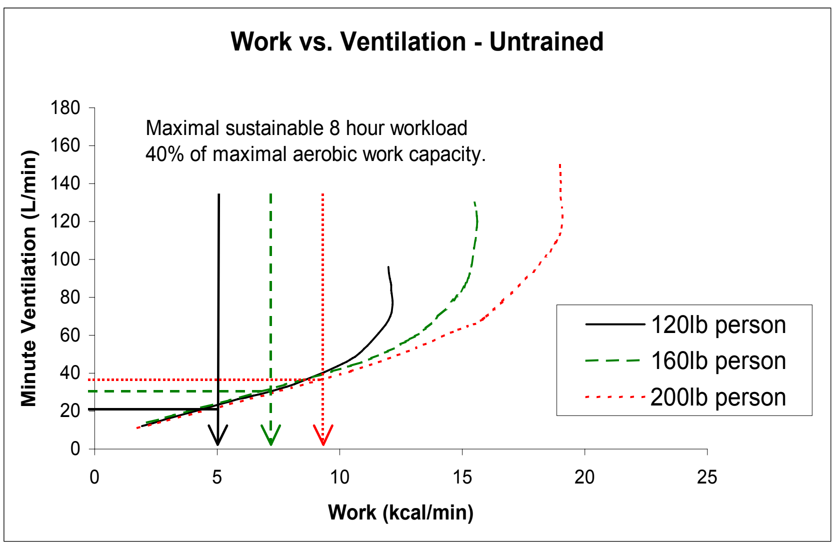

Figure 3A

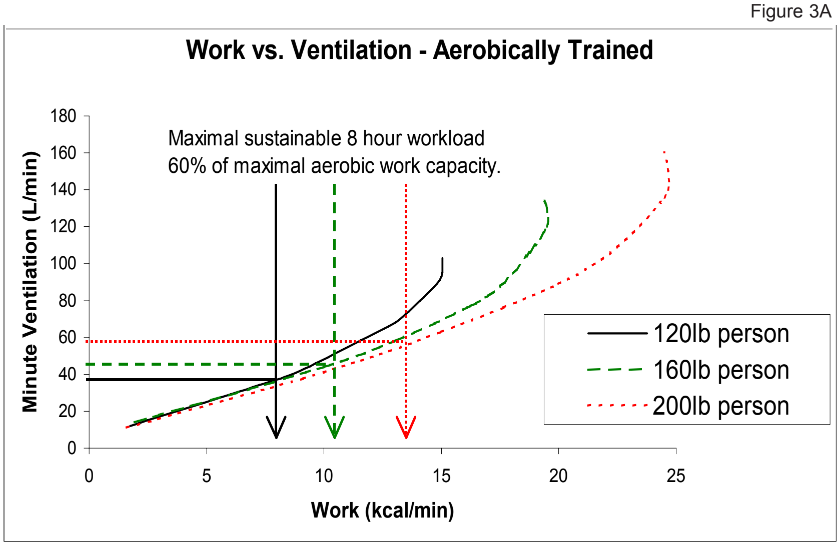

Figure 3B

Figure 3 shows average minute ventilation rates for small (120 pound [59kg]), average (160 pound [73kg]), and large (200 pound [91kg]) individuals over a range of work rates. The data in Figure 3A show the relationship of ventilation to work in individuals with low physical fitness levels. Also shown are the workloads (Kcal/min [vertical lines]) and V_e [horizontal lines] that can be sustained by these individuals over an 8-hour work shift with normal rest breaks. Figure 3B shows the same information for small, average and large individuals who maintain a moderate level of aerobic fitness. Note that maximal work capacity increases approximately 15-30%, and more importantly, sustainable work capacity increases as much as 30-50%.

Figure 3: Work vs. minute ventilation in small average and large individuals of low physical activity (Panel A) and moderate aerobic physical fitness (Panel B). After age 30 fitness declines 8-10% per decade for inactive individuals; 4-5% per decade for regularly active individuals; and 2% per decade for those who train to stay in shape.

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Obviously, minute ventilation and the ability to sustain absolute workloads have a relationship with body size as shown in Figure 3. However, aerobic fitness can have a dramatic effect on sustainable work capacity within an individual even though ventilation at these sustainable work rates increases only modestly.

Thus, average V_e at sustainable work rates can be expected to range from about 22 L/min at 5 kcal/min in smaller less aerobically fit individuals, up through 60 L/min at 14 Kcal/min in larger moderately fit individuals. The next section will discuss how these V_e values are related to peak inspiratory and expiratory flow rates.

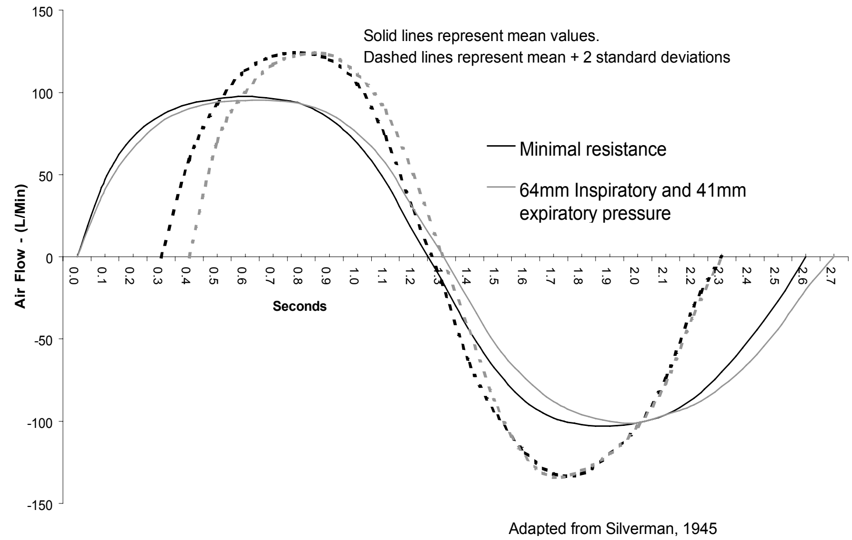

Figure 4: Typical flow rate pattern for one breath at an average sustainable work capacity of 7.5 Kcal/min and a ventilation rate of 37 L/min.

Ventilation and Flow Rates

Work done in 1945 by Silverman et al.,[4] evaluating flow dynamics of ventilation over a range of workloads, remains valid today. Figure 4, adapted from their work, shows average inspiratory and expiratory flow rates at an average workload of 7.5 Kcal/min. This corresponds to the maximal sustainable workload for an average weight untrained individual. The plot shows flow rates during respiration under conditions of both minimal and moderate (64 mm water inspiratory and 41 mm expiratory) resistance at a V_e of about 37 L/min. There is very little change in the flow dynamic between minimal resistance and moderate resistance during breathing. Also apparent from the graph is that average peak flows are about 3 times greater than V_e. However, if the mean flow plus two standard deviations is considered (dashed line), then peak flows are about 4 times greater than average V_e. Although Figure 4 shows little difference in flow characteristics between minimal resistance and moderate resistance breathing, with increased breathing resistance the cost of breathing to the individual goes up and the external work that they are able to do decreases.

Mean ventilation, peak flows, the range of flows (± two standard deviations) and the ratio of peak flow rates to ventilation are listed in Table 2. These data show that if one considers the full range of V_e at different work loads, a ratio of 4:1 should probably be considered when estimating peak flow rates from V_e . Normal sustainable workloads are generally in the moderate range but, as discussed earlier, this will depend on body size and aerobic fitness. The average day-long sustainable work rate is about 7.5 Kcal/min, although 10-13 Kcal/min or more may be sustained for short periods under demanding conditions.

Respirators and Performance

Some types of respirators, e.g., negative pressure air-purifying, affect work capacity via an increase in inspiratory and/or expiratory resistance. In these cases, the muscular work of breathing must be increased to overcome the resistance and maintain alveolar ventilation. The physiological cost of working with a respirator is directly proportional to the resistance.[5] Increased resistance leads to a decrease in oxygen consumption, minute ventilation, and work output. Respirators also increase dead space, which decreases the efficiency of respiration. Half and full-facepiece negative pressure devices may impose the added burden of heat stress and, possibly, psychological stress (claustrophobia). Figure 5 illustrates the decline in performance associated with the use of a respirator during a 50-minute work period. After 50 minutes of respirator wear, work performance declined over 20% vs. only 11% for controls. This illustrates the increased fatigue caused by the greater cost of breathing.

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Table 2: Minute ventilation and peak flow rates at different workloads for the average worker

Workload for average 160 lb person (kcal/min)	Minute Ventilation (L/min) [2 STD Range]	Peak Inspiratory Flow (L/min) [2 STD Range]	Peak Expiratory Flow (L/min) [2 STD Range]	Ratio of V_e to Peak Flows including 2 STD range
Resting (1.5)	10.3 [6.9-13.7]	40 [24-56]	32 [12-52]	5.4
Moderate (4.0)	20.8 [16.2-25.4]	63 [47-79]	58 [40-76]	3.8
Heavy (7.5)	37.3 [29.9-44.7]	100 [72-128]	107 [71-143]	3.8
Very Heavy (10.5)	54.7 [34.5-74.9]	149 [91-207]	154 [90-218]	4.0
Maximal (13.5)	75.3 [47.9-102.7]	194 [130-258]	211 [133-289]	3.8

STD=Standard Deviation

Adapted from Silverman

Subjects walked on the treadmill with or without a half facepiece air-purifying respirator with combination high-efficiency (HEPA) filters with organic vapor/acid gas (OV/AG) cartridges. Treadmill work was adjusted to maintain a heart rate of 150 bpm, corresponding to very heavy work for most individuals. Work output continued to decline throughout the 50-minute test. When identical facepieces with different levels of protection (HEPA filters only vs HEPA filters with OV/AG cartridges) were compared, the decline in performance was proportional to the breathing resistance (18 mm water for HEPA only vs. 36 mm water for HEPA with OV/AG).

The Occupational Safety and Health Administration (OSHA) requires medical evaluation of an individual's ability to work while wearing a respiratory protective device. OSHA permits this evaluation to be done with the questionnaire specified in Appendix C of 29 CFR 1910.134. However, many employers utilize a medical examination (which must gather the information required by Appendix C) and pulmonary function tests. Wilson and Raven evaluated pulmonary function tests as predictors of work performance during respirator wear.[6] They utilized a battery of tests including forced vital capacity, forced expiratory volume, residual volume, and the maximum ventilatory volume (MVV). The

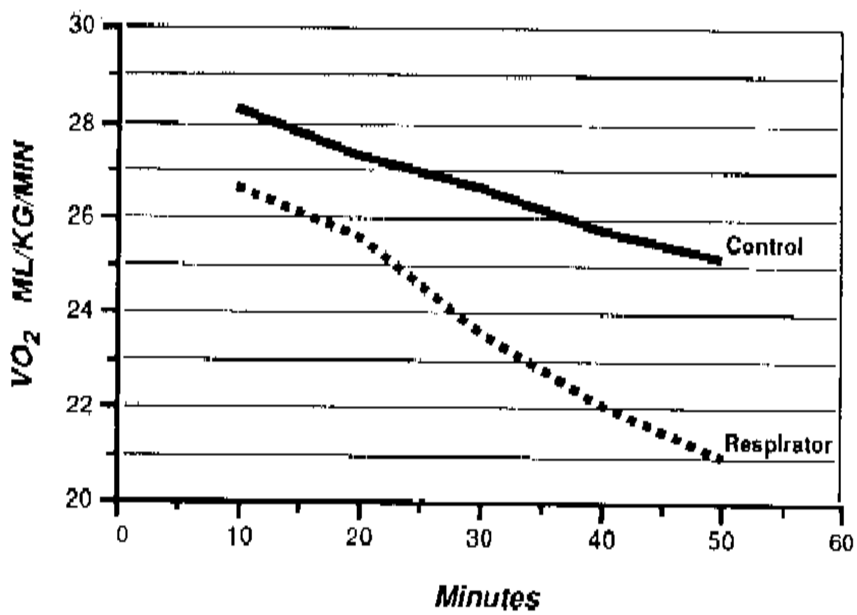

Figure 5: Energy Expenditure (VO_2) during prolonged work with and without a respirator. (From Reference 1)

MVV is a 15-second test that defines maximum breathing capacity. Subjects performed the test with and without the respirator to determine the maximum breathing capacity with the device. The resisted MVV (rMVV) was defined with the formula:

rMVV = MVV x 0.49 + 28.9L

To determine an individual's ability to work with the respirator, the adjusted (rMVV) score can then be multiplied by 0.7 for short-term work, or by 0.5 for prolonged work (to adjust for ventilatory drift - see sidebar on page 7). For example:

MVV = 120 L/min; rMVV = 87.7 L/min x 0.5 = 43.9 L/min

Work with wildland firefighters has shown the ventilatory demands of this job range from 40 to 60 L/min. As such, this individual has a marginal ventilatory capacity to perform day-long work using a respirator.

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Ventilatory Drift: During prolonged moderate work (under 50% VO_2 max) ventilation drifts upward with time. The drift is characterized by reductions in inspiratory and expiratory times, a 15-40% increase in breathing frequency (panting), and a drop in tidal volume. The net effect, a 10-30% increase in ventilation (V_e), must be considered when evaluating an individuals capacity to work while wearing a respirator.

A battery of pulmonary function measures and a work capacity test (a 3-mile hike with a 45 pound pack in 45 min) were compared as predictors of work performance with a respirator. It was found that workers with the fitness to pass the work test (45 ml O_2/kg-min) had the capacity to work with a respirator.[1] The pulmonary function measures did not add significantly to the prediction of performance with the respirator. This is not surprising, since fitness (VO_2 max, VT) and pulmonary function measures are highly correlated. The respiratory protection committee of the American National Standards Institute (ANSI) has recommended that a field test involving work with a respirator be included in the medical certification process.

Conclusion

Numerous factors affect respiration and the ability to work with a respiratory protection device. These include work rate, duration, respiratory resistance, environmental conditions (temperature, humidity, altitude), and more. Perhaps most important are the factors associated with performance: maximal aerobic fitness (VO_2 max) and sustainable aerobic capacity as measured by the ventilatory threshold. While it is important to select the most appropriate respirator for the job, it is equally important to identify physically qualified workers. An aerobically fit employee has several times the sustained working capacity as the unfit and is far better suited to work with a respirator. Employers would be wise to provide their workers the opportunity and incentive to improve or maintain the level of fitness associated with superior performance.

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Principles of Physiology and Respirator Performance

By Larry Janssen, CIH

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This article demonstrates application of physiological principles to two specific respirator performance issues.

Introduction

As noted in the previous article *Respiration, Respirators and Work Capacity,* worker physiological requirements and limitations are important considerations in respirator design. The article also describes how an individual's size, age and fitness influence the performance of their cardiorespiratory system and their ability to do muscular work. It is therefore apparent that there is a wide range of ventilation (V_e) requirements, aerobic capacity ($V0_2$ max), peak inspiratory flow rates (PF_I), and tolerance to the stresses of work among the population. Overall respirator performance must accommodate as many individuals as possible, given the constraints of technical feasibility, comfort and cost. This article will address the physiological and performance issues surrounding two respirator design criteria:

- Air flow rates used for testing air purifying respirator (APR) filters;
- Minute volume and peak air flow capabilities of powered air purifying respirators (PAPR), supplied air respirators (SAR), and self-contained breathing apparatus (SCBA).

Air flow rates for filter testing

Factors that affect filter performance: Particulate respirator filter tests conducted by approval agencies are intended to assure that all filters of a given type will have a stated minimum level of efficiency when tested under uniform laboratory conditions. To assure that approved particulate respirators will perform adequately in the workplace, filter test conditions are chosen to approximate a "worst case" situation. Table 1 describes several conditions that are known to affect filter performance and the test criteria the National Institute for Occupational Safety and Health (NIOSH) uses to approve N R and P series particulate respirators[1]. It is important to recognize that it is unlikely that one or more of these conditions will occur at any given time in a given workplace. As a result, filters can be expected to perform much more efficiently in the workplace than they do in the laboratory testing.

Table 1. Conditions that Affect Filter Efficiency and NIOSH Test Criteria

Condition and Effect	NIOSH "Worst Case" Test Criterion
Challenge aerosol: some materials may degrade filter efficiency	Sodium chloride or dioctyl phthalate are known to degrade some types of filters
Particle size: particles ~ 0.1-0.4 µm mass median aerodynamic diameter (MMAD) are most difficult to filter	Challenge aerosol particle size is approximately 0.3 µm MMAD
Air flow rate: high air flow decreases filtration efficiency for small particles	85 Lpm continuous flow
Electrical charges on small particles: charged particles may be attracted to opposite charges on the filter, increasing efficiency	Challenge aerosol is charge neutralized
Filter loading: high loading with degrading aerosols may decrease filter efficiency	Aerosol loading is at least 200 mg per respirator

Physiological considerations: As described in the previous physiology article, air flow rate during respiration is constantly changing. In particular, it has been argued that since PF_I exceeds V_e by four or more times, filters should be tested at PF_I rates[2]. In other words, although 85 Lpm continuous flow represents a very high work rate not sustainable by most individuals (Table 1 of previous article), it has been suggested that filters should be tested at more than 350 Lpm.

Filter performance modeling: A filter performance model based on single-fiber filtration mechanisms can be used to illustrate why there is no need to test filters at the suggested high flow rates. The mechanisms by which filters collect particles of various sizes are briefly summarized as follows:

Impaction: Effective in removing particles approximately 1µm or larger. The inertia of these large particles causes them to impact on the filter media. Because particle inertia is increased with velocity, impaction removal is favored by higher air velocity.

Interception: Aids in removing particles down to approximately 0.6 µm. Particles in an airstream passing around a piece of filter media make contact with the media and are removed from the airstream.

Diffusion: Most effective in removing particles less than 0.2 µm. These very small particles exhibit a random movement known as Brownian Motion. This random activity may cause the particles to "bounce" into the filter media. Since the probability that one of these particles will strike the filter media increases as the time the particle remains in the filter increases, diffusion removal improves with lower air velocity.

Some filters, commonly called "electrostatics", use electrical charges on the filter media to enhance removal of submicrometer particles. These charges attract airborne particles of opposite charge. "Electrostatic" filters also use the mechanical processes of impaction and interception to remove larger particles.

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The filter performance model incorporates characteristics of filter design, challenge aerosol and air flow which interact to affect filter efficiency. It allows these characteristics to be changed individually, and predicts both particle count and particle mass penetrations. Thus, it is easy to predict the effect of each individual change on the efficiency of the filter.

Table 2 summarizes the output of the model for a filter with typical design characteristics under various challenge conditions. Only the variables listed were changed in each case.

Table 2. Modeled filter Performance as a Function of Air Flow Rate and Aerosol Characteristics.

Air Flow (LPM)	Challenge Aerosol (μm MMAD)/GSD*	Count Penetration(%)	Mass Penetration(%)	Comments
85	0.3/1.8	4.55	4.34	Similar to NIOSH test conditions
30	5/3	0.9	0.03	Plausible workplace conditions
400	0.3/1.8	19.06	7.76	Performance against NIOSH aerosol at sug gested higher flow rate
400	5/3	12.19	0.09	Performance against plausible workplace aerosol at suggested higher flow rate

* GSD is geometric standard deviation. It is a measure of the variability of the particle sizes in the distribution.

Discussion: The following observations can be made from Table 2:
1) The filter is much more efficient under plausible workplace conditions than it is under NIOSH test conditions. This observation is consistent with the "worst case" assumptions about the NIOSH test conditions.
2) Increasing the flow rate to 400 Lpm significantly increases count penetration of the "NIOSH" aerosol, but has a much smaller effect on mass penetration. This is expected since particle mass increases with the cube of diameter. That is, one, 1µm particle has the same mass as 1000, 0.1 (µm particles. As such, a significantly higher number of particles penetrated the filter, but since they are small particles they have very little mass.
3) There is a very small difference in mass penetration of the workplace aerosol at 400 Lpm versus 30 Lpm. Again, this is expected since workplace aerosols are much larger than laboratory test aerosols. It is also evident in this case that the small particles with very little mass are those which penetrate more readily at the higher flow rates. This is explained by the fact that diffusion removal is less efficient at higher flow rates while impaction efficiency for larger particles (with much greater mass) is increased. This is a very significant point, since exposure limits for the great majority of particulate air contaminants are based on the mass of the inhaled contaminant , i.e., mass dose. An increase in the penetration of small particles has a minimal effect on the contaminant dose inhaled.

In addition to the fact that high flow rates have little effect on mass penetration, it is important to recognize that 400 Lpm is an unrealistically high flow rate to model filter performance in a workplace. As indicated in Tables 1 and 2 of the previous physiology article, 400 Lpm represents a PF_I value that is only achieved by a few individuals under extremely heavy, nonsustainable work activity. Further, the duration of the peak flow is no more than a few tenths of a second per breath.[4, 5] Since most exposure limits represent time-weighted average (TWA) exposures averaged over eight hours (or 15 minutes for short term exposure limits [STEL]), a brief increase in penetration of very small particles contributes little to overall dose.

Finally, it is important to consider what is known about respirator performance in the workplace. Workplace protection factor (WPF) studies measure the protection provided by a properly functioning respirator when correctly used by a properly fitted and trained worker. All sources of facepiece penetration, including filter penetration and faceseal leakage, are taken into account. WPF studies have been conducted with half-facepiece negative pressure respirators using dust/mist and dust/fume/mist filters. The approval tests for each of these respirator categories used an air flow rate of 32 Lpm and particle sizes outside the most penetrating range[6]. Nonetheless, 5th percentile WPF values above 10 (the value necessary for half-facepieces) were consistently found.[7] It is interesting that the 5th percentile WPFs for respirators using these filters were not significantly different from those found for half-facepieces with HEPA filters, which were tested with a most penetrating aerosol at 32 and 85 Lpm.

Therefore, it is clear that there is no need to conduct filter tests at flow rates above 85 Lpm.

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Minute volume and peak air flow capabilities for PAPR, SAR, and SCBA

Physiological considerations: PAPR, continuous flow and pressure demand SAR, and pressure demand SCBA are generally classified as positive pressure devices. That is, they are intended to maintain a slightly greater than ambient pressure in the facepiece, hood or helmet during both inhalation and exhalation. Because contaminants are unlikely to migrate from ambient pressure to a higher pressure, positive pressure respirators are assumed to provide a higher level of protection than negative pressure respirators. In order to maintain positive pressure at all times, a respirator's air flow capability must exceed both V_e and PF_I (neglecting the respirator's dead volume). It has been suggested that, since PF_I values in excess of 400 Lpm can occur, positive pressure respirators should be able to supply air at this rate to prevent negative pressure excursions in the breathing zone.[8]

Performance considerations for tight-fitting respirators: Numerous reports of tight-fitting positive pressure respirators allowing negative pressure excursions in the wearer's breathing zone (known as overbreathing) exist in the literature.[9,10,11] Most of these reports involved respirators designed and approved in the 1970's and early 1980's. Partly as a result of these reports, higher airflow performance criteria were adopted for SCBA used in firefighting.[12] These criteria require a minute volume of at least 103 ± 3 Lpm with a peak flow capability in excess of 300 Lpm. It was believed that the respiration requirements of 98% of firefighters would be satisfied at this level of performance. That is, it was thought positive pressure would be maintained essentially all the time for 98% of firefighters. At least two studies conducted with pressure demand SCBA that meet the higher airflow requirements have reported negative pressure excursions in the facepiece at high work rates.[13,14] Campbell et. al. collected data on pressure inside the facepiece of SCBA during actual fire fighting activities.[13] They used this information to develop a sophisticated mathematical model to estimate the effect of overbreathing on the protection provided by the SCBA. Their model takes into account the duration and frequency of overbreathing, protection provided when positive pressure is maintained as well as when overbreathing occurs, and additional factors. The authors concluded that the effect of overbreathing is not significant and recommended that the assigned protection factor (APF) remain at 10,000.

A much simpler approach using information from Burgess and Crutchfield supports this conclusion.[14] In this study, firefighters wearing SCBA exercised on a treadmill at 80% of their aerobic capacity. It must be emphasized that this is a work rate that most individuals could not sustain for more than 10-15 minutes at a time. Facepiece pressure was monitored and V_e was determined for each subject. The authors found that in the worst case a subject experienced negative pressure in the facepiece approximately 5.75% of the time. It is important to realize that the wearer still receives protection from the SCBA even during periods of negative pressure. It is reasonable to assume the APF of 100 listed for negative pressure (i.e.,demand) SCBA during negative pressure excursions.[15] This is a conservative approach, since the duration of negative pressure excursions in a pressure demand SCBA is considerably less than the duration of negative pressure in the facepiece of demand SCBA.[11] Using this information, it is possible to calculate a "protected" exposure level for the wearer. The APF for demand SCBA is applied during overbreathing and the APF for pressure demand SCBA is used when positive pressure is maintained.

Example:
A firefighter is wearing an SCBA in an atmosphere containing 100 ppm carbon monoxide (CO). Specific tasks require an effort of 80% VO_2 max. The firefighter is able to maintain this work rate for 15 minutes. During these tasks, negative pressure in the facepiece occurs 6% of the time (a total of 0.9 minute). The exposure limit for CO is 25 ppm as an eight-hour TWA.[16] The protected 15-minute exposure level is calculated as follows:

$$\frac{0.9\left(\frac{100}{100}\right) + 14.1\left(\frac{100}{10{,}000}\right)}{15} = 0.07 \text{ ppm}$$

The resulting protected exposure is not appreciably different than the protected exposure (0.01 ppm) if overbreathing had not occurred. The worker is well protected in either case. The difference in exposure narrows further if an eight-hour TWA is calculated, assuming a reasonable number of periods of high work rate that result in overbreathing.

Example:
The firefighter in the above situation performs four periods of work at 80% VO_2 max during an eight hour shift. If it is assumed the CO concentration remains constant and the firefighter is exposed the entire shift (both extreme assumptions), the protected eight-hour TWA exposure would be:

$$\frac{60(0.07) + 420\left(\frac{100}{10{,}000}\right)}{480} = 0.02 \text{ ppm}$$

Thus, it can be seen that a plausible number of negative pressure excursions have a negligible effect on the protection provided by a tight-fitting positive pressure respirator. This notion is supported by a WPF study on a full facepiece PAPR.[17] While facepiece pressure was not measured in this study, the authors estimated the

work rate was moderate to high.

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It is therefore likely that some over-breathing occurred. The 5th percentile WPF of 1335 found in this study is consistent with the APF of 1000 for tight-fitting PAPR.[15]

Performance considerations for loose-fitting respirators: There are fewer published studies that have reported negative pressure excursions in loose-fitting PAPR or SAR. The APF of 25 for loose-fitting facepiece PAPR was in part based on a simulated workplace protection factor (SWPF) study by daRoza, which reported overbreathing at 80% of the subjects' maximum work rate.[18]

A more recent SWPF study also found negative pressure excursions with hooded loose-fitting facepiece PAPR and SAR when subjects ran in place.[19] The authors reported no consistent relationship between the pressure measurements and the SWPF measurements. Mean air flow rates were above the required six CFM for all the devices, but flow rates as low as 4.66 and 5.27 CFM were found for one hooded and one loose-fitting facepiece PAPR, respectively. Interestingly, the 5th percentile SWPF measurements remained above 150,000 for these two devices. Fifth percentile SWPF values ranged from 86,000 to more than 250,000 for all but one of the remaining devices. The SAR with the highest mean and minimum air flows did not have the highest measured SWPFs, and the poorest performing device did not have the lowest mean or minimum air flow. The results of this study appear to indicate that:

1) The effect of occasional negative pressure spikes on the protection provided by loose-fitting respirators is not great.

2) Design characteristics other than air flow rate influence the performance of loose-fitting respirators.

Finally, it should be noted that recent WPF studies on a loose-fitting facepiece PAPR and SAR with hoods or helmets support the current APFs of 25 and 1000, respectively.[20,21]

Summary and Conclusions

Several respirator performance criteria are set to satisfy the physiological requirements of the worker. In particular, V_e and PF_I must be understood and used appropriately in the design process. Filtration principles and the nature of workplace aerosols must also be understood to determine appropriate test conditions for particulate respirator filters. Current filter test criteria assure that significant aerosol penetration will not occur in the workplace.

It is unlikely that existing positive pressure respirators can assure positive pressure in the breathing zone at all times for all wearers. High, unsustainable work rates and activities such as running in place have been shown to cause negative pressure excursions under laboratory and workplace conditions. Because these excursions are brief and infrequent for today's respirators, both logic and performance measurements indicate they have a negligible effect on exposure.

Filters could be designed to pass extreme test criteria. Similarly, it may be possible to design positive pressure respirators to maintain positive pressure 100% of the time for all users. However, it is likely that cost and size would increase and comfort could decrease. Further, available evidence demonstrates that today's respirators provide their expected level of protection when properly selected, used, and maintained. As such, there is no demonstrated need for radical design changes.

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2001 AIHCE Presentations on Respiratory Protection: A Review

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The 2001 American Industrial Hygiene Conference and Exposition was held June 2-7 in New Orleans, Louisiana. One roundtable discussion and one platform session addressed respiratory protection issues. The following article summarizes those sessions and provides brief commentary on their content.

Roundtable 211: Assigned Protection Factors – How Should They Be Established?

This roundtable was arranged and moderated by Larry Janssen of 3M OH&ESD. It was intended to present the types of data, information and methods used to recommend assigned protection factors (APFs). The roundtable objective was to provide industrial hygienists and other affected parties with an understanding of the assumptions behind the setting of APFs. This roundtable was particularly timely since OSHA is currently developing a table of APFs to include in its respiratory protection regulation 29 CFR 1910.134.

Alan Hack of Los Alamos National Laboratories was the first speaker. He described the evolution of the APF concept dating back to 1933 when a simulated workplace protection factor (SWPF) study was used to estimate protection offered by abrasive blasting hoods. The hoods were tested in a silica dust chamber at various air flow rates into the hood. The concentration of silica was monitored inside and outside the hood. The researchers noted that a flow rate of six cubic feet per minute (CFM) provided a SWPF of nearly 2000. For this reason, the air flow requirement of six CFM was incorporated into respirator approval regulations and remains in place today.

Alan went on to describe the large "protection factor" study at Los Alamos in the 1970s that lead to the first listing of what are now known as APFs. In fact, the data collected in the Los Alamos study were quantitative fit factors only. He described the small amount of data and, in some cases, only professional judgment, that went into the Los Alamos recommendations. Hack's presentation concluded with a discussion of how the original APFs have evolved and changed over the years in OSHA regulations and American National Standards.

Howard Cohen of the University of New Haven described the lack of a standardized method to determine protection offered by various types of respirators. Cohen advocated the use of SWPF studies to allow routine collection of performance data on individual respirator models. SWPF studies are conducted under laboratory conditions. Concentrations of a test atmosphere outside and inside the test respirators are measured while the subject performs a series of exercises intended to simulate real work. Cohen said the advantages of SWPF studies include the ability to measure high SWPFs; reproducibility; the potential to examine personal variability in respirator performance; and the capability to control environmental conditions such as temperature and humidity.

Howard stressed the need for a standardized SWPF protocol and for commitments from manufacturers and NIOSH to generate SWPF data. He emphasized the need for OSHA and

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NIOSH to accept SWPF data.
Based on the results of a recently completed SWPF study of loose-fitting supplied air respirators and powered air purifying respirators, he advocated assigning protection factors by respirator model rather than by class.

The third speaker was Craig Colton of 3M OH&ESD. He described the evolution of workplace protection factor (WPF) testing, which came about in part because laboratory fit factor testing may have overstated respirator performance.

WPF testing involves sampling the air both outside and inside a respirator while that respirator is correctly worn and used in a real workplace. Actual exposure conditions and test subject work activities are incorporated into WPF tests. Colton noted that WPF results indicate a clear difference in performance of loose-fitting facepieces as compared to true hoods and helmets. He pointed out this difference was not found in the SWPF study reviewed by Cohen. It therefore appears that something that occurs in real workplaces has not yet been replicated in SWPF testing. Colton also discussed the challenges of collecting and using WPF data, including extrapolation of the results of one study to other workplaces, test variability, problems in locating appropriate worksites, and problems with sample collection and potential contamination from handling. He concluded by listing issues to be resolved to increase the utility of WPF data. These include greater knowledge regarding which activities are critical to simulating work; improved sample collection methods; improved data analysis procedures; and wider acceptance of WPF data. Colton did not conclude however, that any current APFs overstate the protection afforded by a properly selected, fitted, and used respirator.

The final presentation was given by Thomas Nelson of NIHS, Inc. Nelson chaired the committee that developed the current ANSI standard for respiratory protection, Z88.2-1992. He described the issues that the committee dealt with in establishing the APFs in that standard. For example, the 1980 version of Z88.2 permitted APFs to be assigned to individuals based on quantitative fit testing results. Information available to the 1992 committee indicated that this needed to be reconsidered. Nelson went on to describe the process the committee used to set the APFs: WPF data was to be used where it existed for a specific respirator type. In the absence of WPF data, the committee decided to use design analogies or other types of existing data. When WPF data was available, it was critically reviewed by the committee to assure it met the criteria for a valid study. Some of the studies the committee reviewed were not published. The committee was able to gain access to the raw data in all cases, which helped in the review. The information that the committee used to set each APF was then discussed. Nelson emphasized that APFs will always need to be based on professional judgment and a variety of data. He also mentioned that the Z88.2-1992 APFs continue to be supported by subsequent WPF testing.

In the discussion that followed the panelists agreed there is a need for both WPF and SWPF data in setting APFs. Standardized methods for conducting both types of tests are needed, as well as agreement on how the data from each should be analyzed. Considerable professional judgment has been and will continue to be necessary to close the data gaps. There was consensus that OSHA should carefully consider all available data during the development of its APF table.

Platform session 123: Respiratory Protection

Platform session 123 on respiratory protection was held Wednesday afternoon, June 6. Twelve papers were presented during the session, with a range of topics that included cartridge and filter performance, comparison of fit testing methods, new product development, and comparison of assigned protection factors to workplace protection factor study results. Five of the 12 papers were presented by 3M OH&ESD personnel.

Behzad Samimi of San Diego State University began the session with a report on experiments meant to measure the performance of filtering facepieces and elastomeric respirators. Performance was measured using a high concentration of silica dust. The test method was similar to the NIOSH certification test for dust/mist respirators under 30 CFR Part 11. Three models of N95 filtering facepieces and two models of elastomeric respirators with P100 filters were tested. The respirator was mounted on a manikin head connected to a breathing machine. Real-time aerosol concentrations and air pressure were continuously monitored inside and outside the respirator under several modes of use. The results showed significant amounts of leakage into the respirators. For the filtering facepieces, the average laboratory protection factors ranged from 2.8 to 4.7; the two elastomeric facepieces averaged 80.3 and 14.6. The results presented are questionable. The performance found was very poor compared to other studies of similar respirators. Because approved N95 respirators are tested under “worst case” conditions, the filters used in this study would remove essentially 100% of the silica dust. Therefore, the method used to determine “respirator fit” on the manikin was likely the cause of the low results. These results are of no value in predicting respirator performance on people.

Roy McKay of the University of Cincinnati presented the results of a study that compared qualitative fit testing using sodium saccharin and the Controlled Negative Pressure (CNP) quantitative fit test. Seventeen subjects were fit tested on full-facepiece respirators using the CNP system to confirm acceptable respirator fit. Leakage was then introduced by modifying the valve to get a CNP fit factor of 60 to 90.

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The saccharin qualitative fit testing was conducted using the OSHA protocol with one modification: the subjects performed the face forward normal breathing maneuver for the entire 7-minute test. This was done to avoid potential leakage that could occur with head movements. Results showed that only 35% of the wearers could detect the saccharin during the test. These results differ from published studies of the saccharin test. Other work has shown that less than 5% of people are unable to detect saccharin with fit factors less than 100. The results of this study are readily explained by the behavior of airborne particles. Because the leaks introduced into the exhalation valve require air to make abrupt direction changes, they bear no resemblance to faceseal leaks on respirator wearers. It is well known that abrupt direction changes cause aerosol particles to be removed from the airstream by inertial impaction. For this reason, while saccharin has been shown to be an effective qualitative fit test, it is not intended to detect the size and shape of leak used in this study. It is also puzzling why the procedures for evaluating fit tests described in ANSI standard Z88.10-2001 were not used. These procedures have been available in draft form for several years.

Ernest Moyer of NIOSH investigated the use of the TSI Portacount® Plus as a field test method for evaluating the efficiency of N, R and P series particulate filters The study used a Portacount Plus to measure penetration of filters either chemically treated or subjected to an aerosol load. Chemical treatment included exposing the filters to dioctyl phthalate, single organic solvents, and mixed solvents. Diesel fuel was used for aerosol loading. Instantaneous filter efficiency testing was also conducted on filters using 42 CFR 84 certification test aerosols. A set of 40 high efficiency filters used at a battery plant were tested using the Portacount Plus and/or the 42 CFR 84 certification test. Two filters showing elevated penetration by the 42 CFR 84 protocol also had elevated penetration when measured with the Portacount Plus. These results suggest that the Portacount Plus might be useful to measure filter performance in the field, but much work remains before it is a valid method.

Philip Eitzman of 3M OH&ESD reported on a study conducted to determine the effect of solvent vapor on electrostatic respirator filter media. While particulate filters are not intended to remove solvent vapors, they may be used in work areas where solvent vapors are present (e.g., airborne solvent concentrations below the PEL, paint spray). Other research has shown that dipping filters into solvents may change the filters' efficiency against airborne particles. In this study, N95 and P95 filtering facepiece respirators were exposed to isopropyl alcohol, toluene, cyclohexane and methyl ethyl ketone vapors for four hours, at concentrations up to ten times the PEL. Each respirator class was tested with the appropriate aerosol, i.e., sodium chloride was used with the N95 respirators and dioctyl phthalate was used with the P95 respirators. Respirators not exposed to solvent vapors were used as controls to establish performance baselines. There was no significant difference in aerosol penetration between respirators exposed to solvent vapors compared with the control respirators. The results of this study demonstrate that normal exposure to solvent vapors will not significantly effect filter efficiency.

Erik Johnson of 3M OH&ESD presented a paper on the effect of high relative humidity on organic vapor cartridge performance. Cartridge change schedules required by OSHA are often based on service life estimates calculated with software available from respirator manufacturers. Certain parameters are required to calculate breakthrough times, including contaminant(s) present, airborne concentration, breathing rate, temperature and relative humidity. Early studies by Gary Nelson indicated that the breakthrough time for cartridges preconditioned and tested at 50% RH should be multiplied by 0.48 to account for the effect of relative humidity greater than 85%. However, these tests were conducted at a challenge concentration of 1000 ppm. Nelson's observation that humidity has a greater effect on cartridge performance at lower concentrations commonly seen in workplaces has generally been ignored. In this study, correction factors were determined for several NIOSH approved organic vapor cartridges for a wide range of organic solvents. Challenge concentrations of n-hexane, toluene, styrene, benzene, and perchloroethylene ranging from 5 ppm to 1000 ppm were used. Cartridges were tested without humidity preconditioning. Testing was done at a flow rate of 32 L/min per cartridge (equivalent to 64 L/min for a pair of cartridges) at several RH values up to 90%. Correction factors ranged from about 1.0 for styrene at 1000 ppm to about 0.04 for n-hexane at 5 ppm. These results point out the need to carefully consider the effect of relative humidity on cartridge service life for the specific vapor, concentration and relative humidity in the workplace. The "rule of thumb" that relative humidities greater than 85% reduce service life by 50% is applicable only at high vapor concentrations. 3M Service Life© software has a chart of correction factors that take into account the greater effect of humidity at low concentrations of contaminants.

Cathy Hall of the University of Cincinnati presented a study looking at the adequacy of user seal checks performed by respirator wearers. In-facepiece pressure was measured using a device called the User Seal Checker developed by the University of Cincinnati. Sixty-seven percent (67%) of test subjects who reported passing the negative pressure user seal check did not pass the User Seal Checker pressure-monitored criteria of 5 cm of water negative pressure for at least 3 seconds. Follow-up training on user seal check procedures increased the number of subjects passing with the User Seal Checker. These results are similar to previous studies, which

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demonstrate that user seal checks are not exact indicators of respirator fit. They are, however, easy to perform and provide some benefit. As such, OSHA requires that a user seal check be performed each time a respirator is put on.

Doo Yong Park of Hansung University described the potential use of a layered cartridge to extend service life. Two models of organic vapor cartridges were challenged with carbon tetrachloride vapor. Results indicated decreased carbon utilization with increased challenge concentrations. The study then used a three-layer cartridge to determine the effect on service life. Upon challenging the cartridge with the organic vapor, the front and middle sections were discarded and replaced with two clean layers placed behind the previous third layer. This modification resulted in the extension of cartridge service life by more than 20%. Although the development of a multi-layered cartridge offers the benefit of increased service life, the disadvantages in the workplace include the need for frequent cartridge changes and questionable cost savings.

Zane Frund of MSA examined the method OSHA recommends to determine service life for cartridges exposed to chemical mixtures. The method requires that the breakthrough times of each chemical in the mixture be estimated individually. If the predicted breakthrough times are within one order of magnitude, the material with the shortest breakthrough time is assumed to constitute the entire mixture. A breakthrough time for this concentration of the material with the shortest breakthrough time is then determined. To test this method, respirator cartridges were simultaneously challenged under controlled laboratory conditions to four or more organic vapors. Challenge concentrations were between the permissible exposure limit and the maximum use concentration. The results of the study indicate that the OSHA method is a conservative estimate of cartridge service life for mixtures. The presenter suggested that future studies look at the application of a second method that applies if the breakthrough times are more than an order of magnitude apart, and the effects of relative humidity and migration on service life.

Larry Janssen of 3M OH&ESD presented a study that compared three commercially available fit test methods. The ANSI Z88.10 standard "Respirator Fit Testing Methods" allows any of the current quantitative fit tests to be used as a reference method to determine the acceptability of a new test. This study determined the effect of the reference method on the apparent validity of a new test. Sequential fit tests were performed using the controlled negative pressure and particle counting quantitative fit tests and the bitter aerosol qualitative test. How well each test identified inadequate fits (defined as a fit factor less than 100 or a failure with the bitter aerosol test) was determined by using each test as the "reference method". A test under evaluation is required to identify at least 95% of inadequate fits identified by the reference method. None of the test methods met the sensitivity value of 95% when compared with either of the other two methods. This demonstrates that the apparent performance of a fit test depends on the reference method used. This is logical since each test measures "fit" in a different manner. The fit test methods are not defective; workplace studies show that each test leads to adequate performance. The results suggest that a single method should be chosen as the reference method to allow for more direct comparison among different fit test methods.

Ziqing Zhuang of NIOSH presented a study on the correlation of fit factor measurements using the TSI Portacount Plus and workplace protection factor (WPF) measurements. Test subjects in the study were burners, welders and chippers working at a steel foundry. Quantitative fit factors were obtained and the worker was sent out to work. Concentrations of iron were measured inside and outside the respirator to measure the WPF. At the end of the sampling period, a second fit factor was measured. The results showed that a correlation existed between the fit factors and the WPFs. Several other researchers have performed similar studies but have not found a significant correlation. More work is needed to understand the significance of this study.

Craig Colton of 3M OH&ESD presented an analysis of WPF studies to determine if respirator performance varies over the course of a day. Some work has suggested that performance can degrade over time, while other studies have not seen any change in performance. Four studies at lead battery plants, ship welding and ship breaking operations were reviewed. The data were divided into morning and afternoon samples. A comparison showed that the difference in performance between the two time periods was not significant. Wearing a respirator over the course of a day does not appear to cause a decrease in performance.

Colton presented a second paper describing the results of a WPF study done during aircraft sanding. Samples were collected on workers using a supplied air helmet. NIOSH recommends an assigned protection factor of 25 for this type of respirator, while ANSI recommends a value of 1000. The primary contaminants measured were zinc, chromium and strontium. Analysis of the data suggested contamination of the inside samples. A statistical analysis showed that the mean WPF is greater than 3500 and the 5th percentile is greater than 800. Further work needs to be done with this type of respirator, but it appears that the NIOSH recommended APF of 25 is overly conservative.

3M OH&ESD offers respiratory protection training courses

Since 1995, 3M has offered two professional development courses that provide valuable information to individuals involved in respiratory protection programs. The courses are based on the technical and regulatory aspects of a sound respirator program rather than specific products. A large equipment display from a number of respirator manufacturers is used to supplement the classroom and workshop presentations. These courses emphasize the important practical aspects of a successful program, including selection principles, cartridge change schedules, and testing breathing air quality. Both courses carry CEUs, American Board of Industrial Hygiene Certification Maintenance points, and other professional development credits.

Respiratory Protection is a comprehensive 4 ½ day course intended for anyone involved with managing all or part of a respiratory protection program. All respirator types and each element of a respirator program are thoroughly discussed. Workshop sessions are used extensively to reinforce the course material.

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