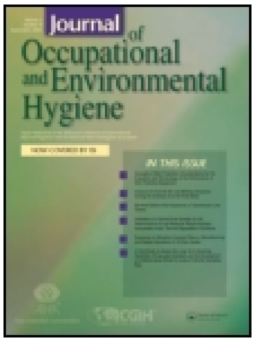

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Integrated Unit Performance Testing of Powered, Air-Purifying Particulate Respirators Using a DOP Challenge Aerosol

Stephen Martin,[1] Ernest Moyer,[1] and Paul Jensen[2]

[1]NIOSH, Division of Respiratory Disease Studies, Morgantown, West Virginia
[2]National Center for HIV, STD, and TB Prevention, Atlanta, Georgia

Although workplace protection factor (WPF) and simulated workplace protection factor (SWPF) studies provide useful information regarding the performance capabilities of powered air-purifying respirators (PAPRs) under certain workplace or simulated workplace conditions, some fail to address the issue of total PAPR unit performance over extended time. PAPR unit performance over time is of paramount importance in protecting worker health over the course of a work shift or at least for the recommended service lifetime of the PAPR battery pack, whichever is shorter. The need for PAPR unit performance testing has become even more important with the inception of 42 CFR 84 and the recent introduction of electrostatic respirator filter media into the PAPR market. This study was conducted to learn how current PAPRs certified by the National Institute for Occupational Safety and Health would perform under an 8-hour unit performance test similar to the dioctyl phthalate (DOP) loading test described in 42 CFR 84 for R- and P-series filters for nonpowered, air-purifying particulate respirators. In this study, entire PAPR units, four with mechanical filters and one with an electrostatic filter, were tested using a TSI Model 8122 Automated Respirator Tester, with and without the built-in breathing machine. The two, tight-fitting PAPRs, both with mechanical filters, showed little effect on performance resulting from the breathing machine. The two loose-fitting helmet PAPRs indicate that unit performance testing without the breathing machine is a more stringent test than testing with the breathing machine under the conditions used. The PAPR with a loose-fitting hood gave inconclusive results as to which testing condition is more stringent. The PAPR unit equipped with electrostatic filters gave the highest maximum penetration values during unit performance testing.

Keywords aerosol, dioctyl phthalate (DOP), electrostatic, powered air-purifying respirator (PAPR), respirator

Address correspondence to: Stephen Martin, NIOSH-Division of Respiratory Disease Studies, 1095 Willowdale Road, M/S H-2800.4, Morgantown, WV 26505; e-mail: smartin1@cdc.gov.

The findings and conclusions in this article are those of the authors and do not necessarily represent the views of the National Institute for Occupational Safety and Health (NIOSH). Mention of a commercial product or trade name does not constitute endorsement by NIOSH or the authors.

INTRODUCTION

Powered air-purifying respirators (PAPRs) have been a source of controversy within the respirator community for over two decades. The disagreement surrounding PAPRs centers around the establishment of assigned protection factors (APFs) to govern the use of PAPRs in the workplace. APFs currently established by the National Institute for Occupational Safety and Health (NIOSH), the Occupational Safety and Health Administration (OSHA), and the American National Standards Institute (ANSI) cover entire classes of respirators and are frequently challenged as being too low. NIOSH, in its 1987 Respirator Decision Logic,[(1)] established an APF of 50 for PAPRs with tight-fitting facepieces and high-efficiency filters and an APF of 25 for PAPRs with loose-fitting hoods or helmets. These values were maintained in the updated 2004 NIOSH Respirator Selection Logic.[(2)] The current ANSI Z88.2 Respiratory Protection Standard (1992)[(3)] establishes an APF of 1000 for PAPRs with tight-fitting, full facepieces and high-efficiency filters, as well as for PAPRs with a hood or helmet (that covers at least the entire head and neck) and high-efficiency filters. The ANSI standard establishes an APF of 50 for PAPRs with tight-fitting half masks and 25 for loose-fitting facepieces (i.e., hoods or helmets that do not cover the neck). OSHA currently refers to the NIOSH APF values for all respirator classes, except where APFs have been established in substance-specific standards.[(4)] OSHA has recently proposed new APFs for all classes of respirators, including PAPRs, but these have not yet been accepted for promulgation.[(5)]

The concept of quantitative respirator protection factors can be traced back to the mid-1970s and the work of Hyatt.[(6)] Hyatt evaluated self-contained breathing apparati (SCBA) and negative pressure respirators available in the United States using a panel of test subjects approximating the face sizes of the general population. A man-test method was used to determine the resulting quantitative protection factor (ratio of the contaminant concentration in the ambient environment to the contaminant concentration inside the respirator facepiece) for the respirator being tested. The respirators were fitted with flush-mounted probes to allow for in-facepiece sampling. Hyatt established APF values for each class of respirator studied so that every model within the class would provide protection factors greater than or equal to the APF for 95% of the test subjects. In addition, Hyatt made recommendations of protection factors for other classes of respirators based on his findings. PAPRs were assigned a protection factor of 1000 based on data gathered for SCBAs in the pressure-demand mode. This recommendation was based on the assumption that positive pressure always exists in the PAPR facepiece, hood, or helmet. In 1976, NIOSH incorporated Hyatt's APF values in *A Guide to Industrial Respiratory Protection*.(7) These values were lowered in the 1987 NIOSH Respirator Decision Logic(1) and the subsequent 2004 Respirator Selection Logic.(2)

One of the earliest published studies incorporating quantitative fit testing of PAPRs was the 1979 work of Lowry et al.(8) In this study, quantitative fit tests were performed on three different PAPR units in a total of eight different configurations. Only one of the PAPR units (three configurations) tested was NIOSH certified. Ten test subjects, one from each of the 10 categories from the Los Alamos Scientific Laboratory (LASL) test panel, tested each PAPR configuration against a dioctyl phthalate (DOP) challenge aerosol. The NIOSH-certified PAPR used a loose-fitting helmet and provided protection factors of 1000 to greater than 10,000, regardless of the configuration.

Because of the controversy surrounding existing APF values, the respirator standards community, respirator manufacturers, and certain industrial sectors have turned to workplace protection factor (WPF) and simulated workplace protection factor (SWPF) studies to help better understand the protection level offered by PAPRs (and other respirator classes) under "working" conditions. A WPF study is conducted at the job site under normal working conditions and operations, although extreme care is usually taken to assure proper respirator use. On the other hand, a SWPF study is conducted in a laboratory where conditions can be more closely controlled and repeated from one test subject to the next. SWPF test subjects are asked to perform exercises that closely mimic those motions encountered on the job while wearing the respirator.

Studies conducted by Myers and Peach(9) and Myers et al.(10) in the mid-1980s investigated the WPFs of PAPR units in a silica bagging operation and a secondary lead smelter. In the bagging operation, one tight-fitting PAPR model with high-efficiency filters was tested by four workers. The PAPR tested could be equipped with either a half-mask or a full-facepiece. Both facepieces were used during this study and the PAPRs were worn for an entire work shift. The WPFs measured for this bagging operation ranged between 16 and 215, with a geometric mean of 54 and no difference between facepieces.(10) These values were well below an APF of 1000 for this PAPR. The smelter study tested two PAPRs with helmets and high-efficiency filters. A total of 12 workers wore each PAPR model twice during the testing, with each test lasting a full work shift. The WPFs were compared with fit factors determined from quantitative fit testing prior to the study shifts. For one PAPR model, the WPFs ranged from 42 to over 2300, with a geometric mean of 205. The preshift quantitative fit factors for the same PAPR model ranged from 2000 to 31,500, with a geometric mean of 7900. The second model showed a range of WPFs from 28 to 5500, with a geometric mean of 165. The preshift quantitative fit factors ranged from 1200 to 24,600, with a geometric mean of 5100. Again, these results showed that WPFs were much lower than expected, with the mean WPF well below an APF of 1000. There was no correlation between the WPF results and the preshift quantitative fit factors. Thus, the preshift quantitative fit factors were not indicative of PAPR performance on the job.(10)

DaRoza et al.(11) conducted a SWPF study on three brands of PAPRs, all with high-efficiency filters. One PAPR studied used a tight-fitting, half-mask facepiece; the other two were helmet-type PAPRs. Aerosol penetration into the respirator facepiece was measured for six test subjects as they exercised on a treadmill at 80% of their cardiac reserve. This testing was done in a test chamber against a 400 molecular weight polyethylene glycol (PEG 400) challenge aerosol. The half-mask PAPR provided protection factors of about 5000. However, the helmet-type PAPRs provided protection factors as low as 10.

More recently, Cohen et al.(12) conducted a SWPF study on PAPRs and supplied air respirators (SARs). As part of this study, five NIOSH-certified, loose-fitting PAPR models with high-efficiency filters were tested. The SWPF testing was done in a test chamber against a PEG 400 challenge aerosol. Twelve test subjects tested each PAPR model and each performed 12 exercises for 2 min each. All five PAPRs gave median SWPF values of over 250,000 (upper limit of quantitation for the study) and lower fifth percentiles over 100,000. In establishing an APF value for each PAPR tested, Cohen et al. divided the lower fifth percentiles by a safety factor of 25 to account for possible differences between normal use and the exercises performed during the test. This safety factor of 25 was thought by the authors to be conservative and resulted in APF values for the five PAPRs of between 6000 and 10,000.

Although these WPF and SWPF studies serve to provide useful information regarding the performance capabilities of PAPRs under certain workplace or simulated workplace conditions, there is a level of disagreement between studies. Furthermore, some fail to completely address the issue of total PAPR unit performance over an entire use duration, whether a work shift or the recommended service lifetime of the PAPR battery pack, whichever is shorter. PAPR unit performance over time is of paramount importance in protecting worker health over the course of an entire use duration. Total PAPR unit performance over time should also be considered when deciding on APF values for the entire class of respirators or even for individual PAPR models and configurations. However, this need for total PAPR unit performance testing has been met with few results. Furthermore, the need for PAPR unit performance testing has become even more important since the inception of 42 CFR 84(13) and the introduction of electrostatic respirator filter media into the PAPR market.(14)

TABLE I. PAPR Units Tested

PAPR Model	Headpiece Type	Battery Life	Filter Name	Standard Configuration	Filtration Mechanism	Use Against Oil Aerosols?
3M W-3265	Tight-fitting full facepiece	Up to 8 hours	3M W-3267	1 Filter	Mechanical	Yes
MSA OptimAir 6A	Tight-fitting half-mask	Up to 8 hours	MSA OptiFilter XL	2 Filters	Mechanical	Yes
Racal Air-Mate HEPA 10[A]	Loose-fitting hood	Up to 8 hours	Racal Air-Mate HEPA	1 Filter	Mechanical	Yes
Racal Breathe-Easy 1[A]	Loose-fitting helmet	Up to 8 hours	Racal P3	3 Filters	Mechanical	Yes
3M AS-200LBC	Loose-fitting helmet	Up to 4 hours	3M AS-140	1 Filter	Electrostatic	No[B]

[A] 3M Company acquired Racal in 1998, but the products tested were purchased before the buyout and were, therefore, Racal products.
[B] User instructions supplied with filter clearly state that these filters are NOT for use against oil aerosols.

With the potential problems associated with electrostatic filter media,[15–21] it is important to gain an understanding of how PAPR units perform over time against various test aerosols. DOP is of particular interest, because an instantaneous DOP filter penetration test is currently used as part of the PAPR certification. Further, DOP aerosol is currently used by NIOSH for loading tests in the certification of R- and P-series nonpowered, air-purifying particulate respirator filters. PAPR loading tests with a DOP aerosol would allow comparisons to be made between PAPR filters and R- and P-series filters.

Martin et al.[14] conducted a recent DOP loading study on the performance of four mechanical PAPR filters and an electrostatic PAPR filter. Mechanical PAPR filters certified under 42 CFR 84 were tested using a CertiTest Model 8122 Automated Respirator Tester (TSI Inc., Shoreview, Minn.) over intermittent loading schedules. Mechanical PAPR filter performance against charged and neutralized DOP aerosols was then compared with the performance of an electrostatic PAPR filter certified under 42 CFR 84. Whereas the mechanical PAPR filters showed no difference in performance from the charged and uncharged DOP aerosol, the electrostatic PAPR filters showed significantly decreased performance against the neutralized DOP compared with the charged DOP aerosol. Because of the concern raised by the results obtained by Martin et al., interest arose in the performance of entire PAPR units.

In this study, total PAPR unit performance over time against a DOP challenge aerosol was evaluated. Five common PAPR models from three different manufacturers were tested for total PAPR unit performance. All five of the PAPRs tested meet all of the current NIOSH certification requirements outlined in 42 CFR 84. Four of the PAPR models tested used mechanical filters; the 3M AS-200LBC used an electrostatic filter for aerosol capture. The user instructions provided with the electrostatic PAPR filters clearly state the filter is not to be used in an oil mist environment. However, this filter (and the associated PAPR unit) was included in this study for several reasons previously discussed.[14]

EXPERIMENTAL METHODS

Table I gives the PAPR manufacturer and model for each PAPR tested. Also, Table I includes the type of headpiece used with each PAPR, the battery life, the filters used, the standard filter configuration, the filtration mechanism, and whether the filters are suitable for use against oil aerosols.

Testing was done with a CertiTest Model 8122 Automated Respirator Tester employing a DOP challenge aerosol. A detailed schematic of the 8122 tester is shown in Figure 1. The 8122 tester measures DOP penetration into the PAPR using a forward light-scattering photometer and is capable of measuring DOP penetrations of 0.001% (99.999% efficiency) to 100% (0% efficiency). The 8122's high output DOP aerosol generator produces an aerosol that meets the particle size (count median diameter [CMD] of 0.185 μm $\pm$ 0.020 μm) and size distribution (geometric standard deviation [σ_g] not exceeding 1.60) criteria used in the certification of R- and P-series nonpowered, air-purifying particulate respirators.[13] For reference, this equates to a mass median diameter (MMD) of 0.36 μm $\pm$ 0.04 μm with a σ_g less than 1.60.

Before PAPR testing was performed, the TSI 8122 was allowed to warm up for at least 1 hour, and tests were conducted to verify the instrument was functioning properly. During testing, the concentration of the DOP challenge aerosol was determined daily by taking two, 1-hour gravimetric samples at the beginning and end of each test and using the average value. The procedures for conducting verification and gravimetric tests have been previously described.[14]

A total of four unit performance tests were conducted with each PAPR model. For the 3M W-3265, MSA OptimAir 6A (MSA, Pittsburgh, Pa.), Racal Air-Mate HEPA 10 (Racal, Frederick, Maryland), and Racal Breathe-Easy 1 PAPRs, the unit performance tests lasted 8 hours (except one test with the Racal Breathe-Easy 1 that was cut short due to a problem with the TSI 8122 tester), because the batteries were approved for 8 continuous hours of use. Two tests for each of these PAPR models were conducted without using the breathing machine built into the TSI 8122 tester, which resulted in only air from

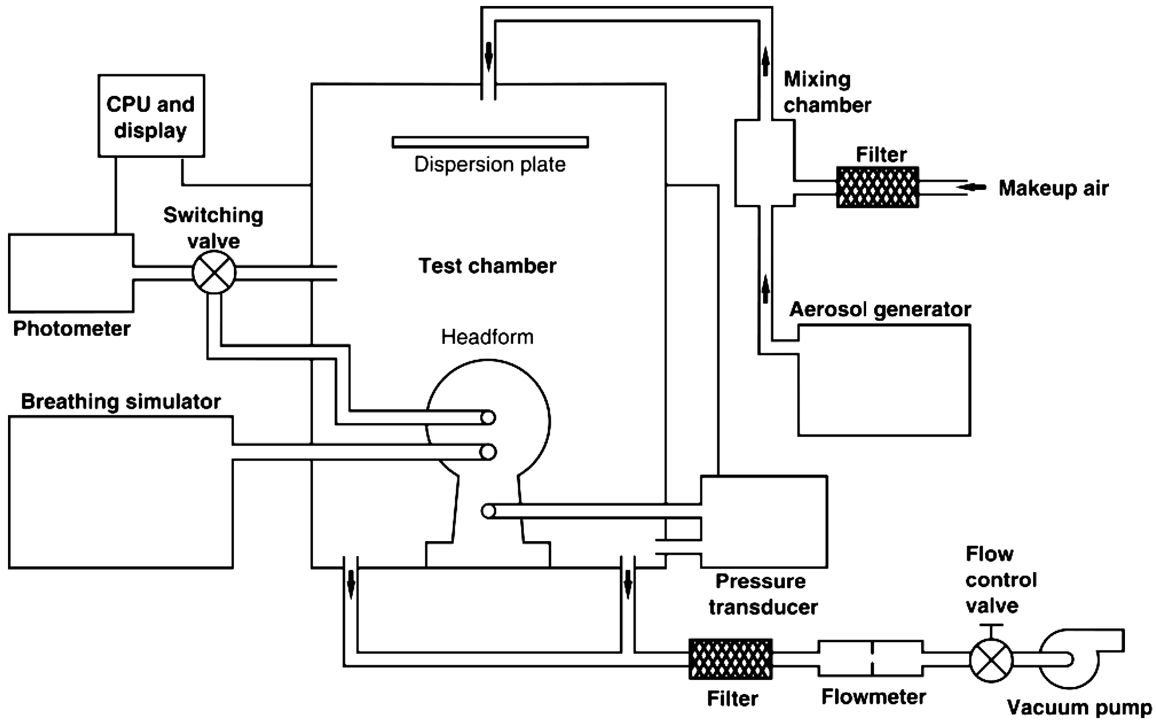

FIGURE 1. Flow schematic of CertiTest Model 8122 Automated Respirator Tester. Source reprinted with permission from TSI Incorporated.

the PAPR blower being introduced to the inside of the PAPR facepiece throughout the course of the test. Two additional tests were conducted with the breathing machine operated at a minute volume of 10.5 L/min and 14.5 respirations per minute. During these tests, the breathing machine was solely responsible for air removal (and subsequent reintroduction) from the PAPR. Each 8-hour test consisted of two, 4-hour loadings with a short break in the middle. This break was just long enough to replenish the DOP supply in the aerosol generator.

The standard battery pack provided with the 3M AS-200LBC was rated for only up to 4 hours. This required the 3M AS-200LBC to be tested in a different fashion than the other PAPRs in this study. Two unit performance tests were carried out on the 3M AS-200LBC for 4 hours—one without the breathing machine and one with it. Two additional unit performance tests were carried out for 8 hours—again, one without the breathing machine and one with it. For these 8-hour tests, the battery pack was replaced with a fresh one after the first 4 hours of testing (during the short break in testing to replenish the DOP in the aerosol generator).

Testing was performed on complete PAPR units. The headpiece of the PAPR being tested was placed on a standard headform in a manner consistent with normal donning of the respirator. The headform used for this study was not the headform included with the TSI 8122. The configuration of some of the PAPRs tested required the use of a different, taller headform to prevent pinching of the downstream aerosol concentration sampling line. A Sierra Engineering Company (Sierra Madre, Calif.) model 428 headform was modified to meet this requirement. This is the same headform currently used by NIOSH to conduct PAPR silica dust tests for respirator certification. The model 428 headform was probed to keep it as similar to the TSI 8122 test headform as possible. Once the PAPR headpiece was mounted on the headform, all sampling lines were properly connected. The rest of the PAPR system (breathing tube, blower, filter(s), and battery) was then connected to the headpiece as it would be under normal operating conditions. New high-efficiency filters certified under 42 CFR 84 were used on all PAPRs for each unit performance test. All PAPR units and filters were tested as received from a commercial distributor. The battery packs used for testing were all charged for at least 16 hours prior to testing. After the initial airflow rate of the PAPR unit was recorded (described below), the PAPR was mounted inside the testing chamber of the TSI 8122, and the battery pack was turned on. The primary and secondary flow rates were each adjusted to 200 L/min on the 8122 tester. The total air flow through the test chamber was kept at 400 ± 15 L/min. Keeping the total flow rate at 400 L/min helped to keep the DOP particle size and aerosol concentration in the test chamber as constant as possible. Also, preliminary testing on the TSI 8122 showed that a total flow rate of 400 L/min was the most efficient, effective, and stable operating condition. Once the airflow rates were set, the test was started and the entire PAPR unit was exposed to the DOP challenge aerosol. The aerosol neutralizer built into the TSI 8122 tester was powered on for all unit performance tests conducted during this study.

The airflow rate provided by each PAPR was measured immediately before and after the unit performance test using the NIOSH Standard Testing Procedure, "Determination of Air Flow for Powered Air Purifying Respirators."[22] This is the same test procedure used for PAPR certification to assure each certified PAPR meets the minimum flow rate requirements of 115 L/min (4 ft^3/min) for PAPRs with tight-fitting facepieces or 170 L/min (6 ft^3/min) for PAPRs with loose-fitting hoods or helmets.[13] Once the PAPR was mounted in the chamber used for the flow rate determination, the fully charged battery was turned on and the airflow rate was measured and recorded. The battery was then turned off while the PAPR was mounted inside the testing chamber of the TSI 8122. The power was turned on again immediately before the unit performance test began. About 5 min elapsed between the initial flow rate determination and the beginning of the unit performance test. The flow rate measurement taken after unit performance testing was done immediately following the DOP exposure, prior to turning off the battery power. This was done to minimize the chance of slight power surges resulting from turning the weakened battery pack off and on.

During unit performance testing, the aerosol particle size (count median diameter) and particle size distribution (geometric standard deviation) were periodically determined using a TSI Model 3934 Scanning Mobility Particle Sizer (SMPS). The particle size distribution was monitored to ensure the TSI 8122 produced an aerosol that met the 42 CFR 84 criteria.

RESULTS AND DISCUSSION

The unit performance testing results for the tight-fitting, full facepiece 3M W-3265 PAPRs are shown in Figure 2. This PAPR model showed no effects due to the breathing machine. Unit #1 without the breathing machine (Figure 2A) gave a maximum penetration of 0.024% with a total DOP load of 3900 mg. This maximum penetration value corresponds to a minimum protection factor (PF) of 4200. Whereas this is well above the NIOSH APF of 50 for tight-fitting PAPRs,

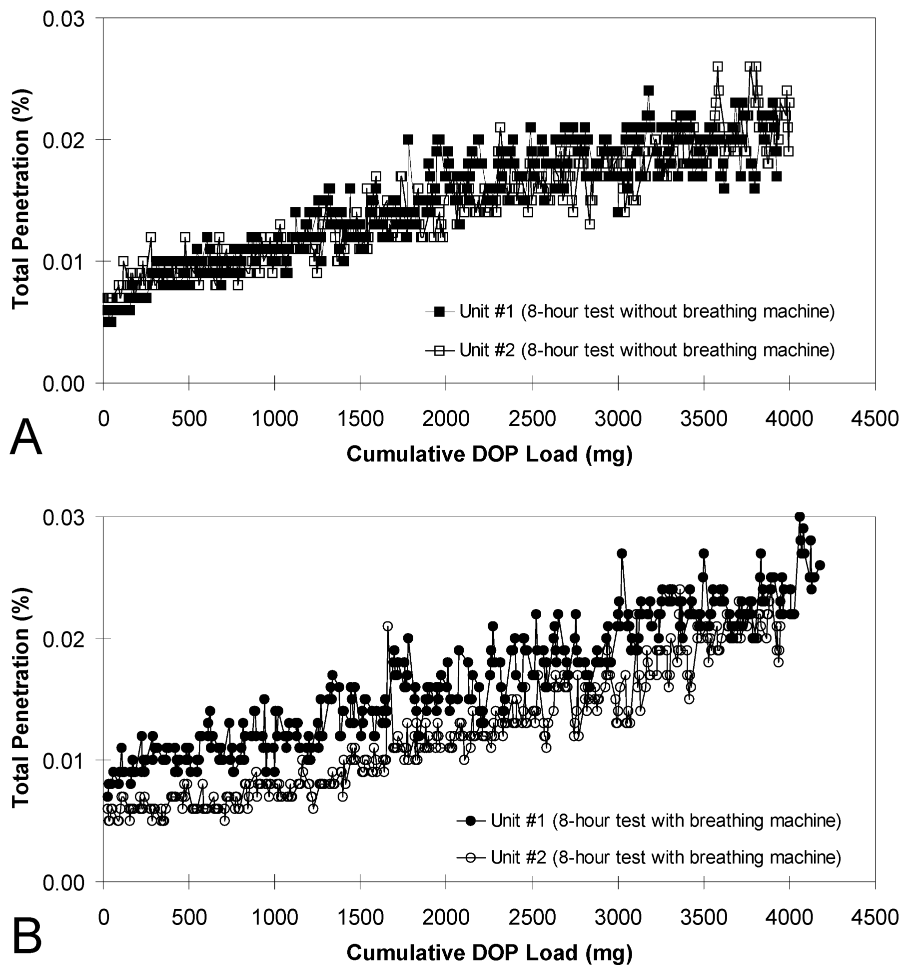

FIGURE 2. Total unit performance test results for tight-fitting full facepiece 3M W-3265 PAPR units: (A) two units tested for 8 hours with no breathing machine; (B) two units tested for 8 hours with breathing machine

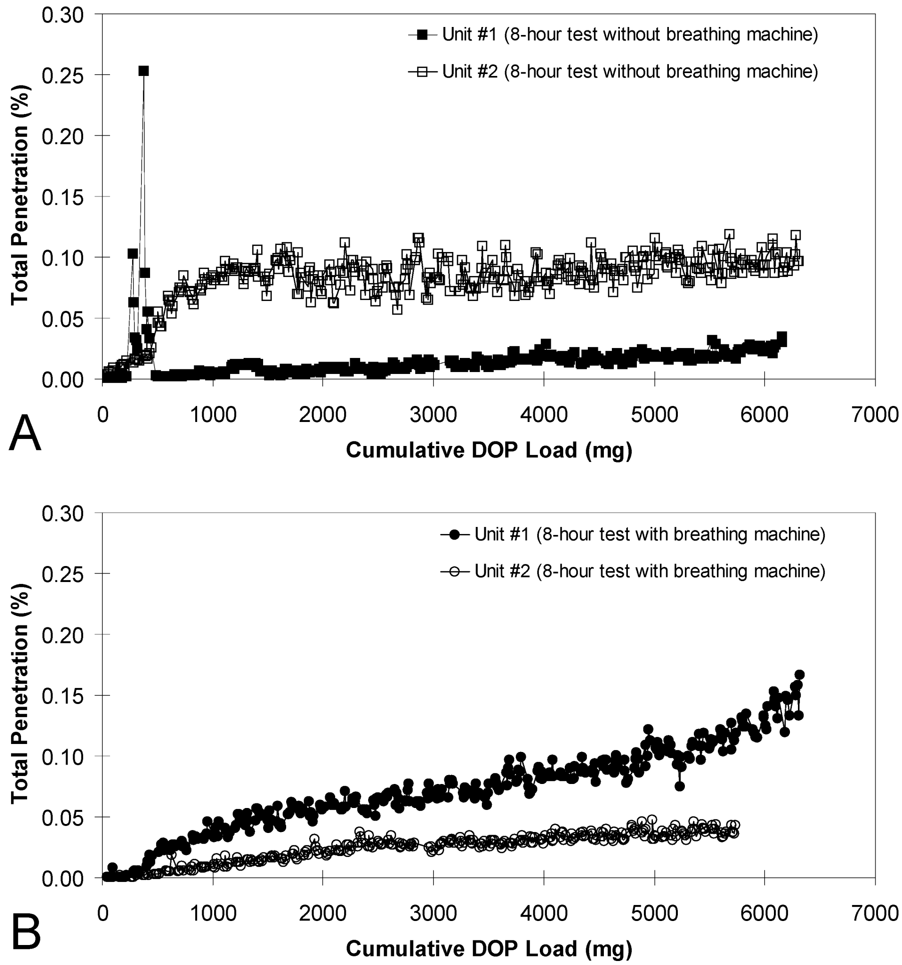

FIGURE 3. Total unit performance test results for tight-fitting half mask MSA OptimAir 6A PAPR units: (A) two units tested for 8 hours with no breathing machine; (B) two units tested for 8 hours with breathing machine

the NIOSH value is for the entire class of tight-fitting PAPRs and all models may not perform this well. The initial flow rate was 147 L/min, which dropped to 130 L/min at the end of the 8-hour test. Unit #2 without the breathing machine gave a maximum penetration of 0.026% (minimum PF of 3800) at a total DOP load of 4000 mg with the initial and final PAPR flow rates of 144 and 130 L/min, respectively. The tests conducted with the breathing machine (Figure 2B) gave maximum penetration values of 0.030% and 0.024% with 4200 mg and 3900 mg of total DOP load, respectively. These maximum penetration values correspond to minimum PFs of 3300 and 4200, respectively. The initial and final flow rates were 147 and 127 L/min for Unit #1 and 147 and 118 L/min for Unit #2. These relatively low flow rates exhibited by the 3M W-3265 model were not of concern, as it was a tight-fitting PAPR.

The 3M W-3265 (and the other four PAPR models) showed some variability in performance results between duplicate tests. The variability is due to a combination of factors, including differences between each PAPR unit (e.g., battery voltage, airflow rate, and tightness of seals), subtle differences between filters installed on each unit, and slight variances in test conditions from one day to the next (e.g., flow rate through the test chamber and mean aerosol concentration). Every effort was made to minimize the effect of these factors on testing results, but some day-to-day variability was unavoidable.

The results from the MSA OptimAir 6A unit performance tests are shown in Figure 3. The MSA OptimAir 6A used a tight-fitting half-mask as the headpiece and, like the 3M W-3265, a significant difference did not result from use of the breathing machine. The MSA OptimAir 6A unit performance tests with no breathing machine gave maximum penetration values of 0.253 (PF = 400) and 0.119% (PF = 840) with total DOP loads of 6200 and 6300 mg, respectively. The maximum penetration value of 0.253% for Unit #1 without the breathing machine occurred during a spike, but other penetration values were all around 0.10% and lower. Without the breathing machine, Unit #1 had an initial and final flow rate of 207 L/min and 170 L/min, respectively. Unit #2 gave an initial flow rate of 204 L/min and a final flow rate of

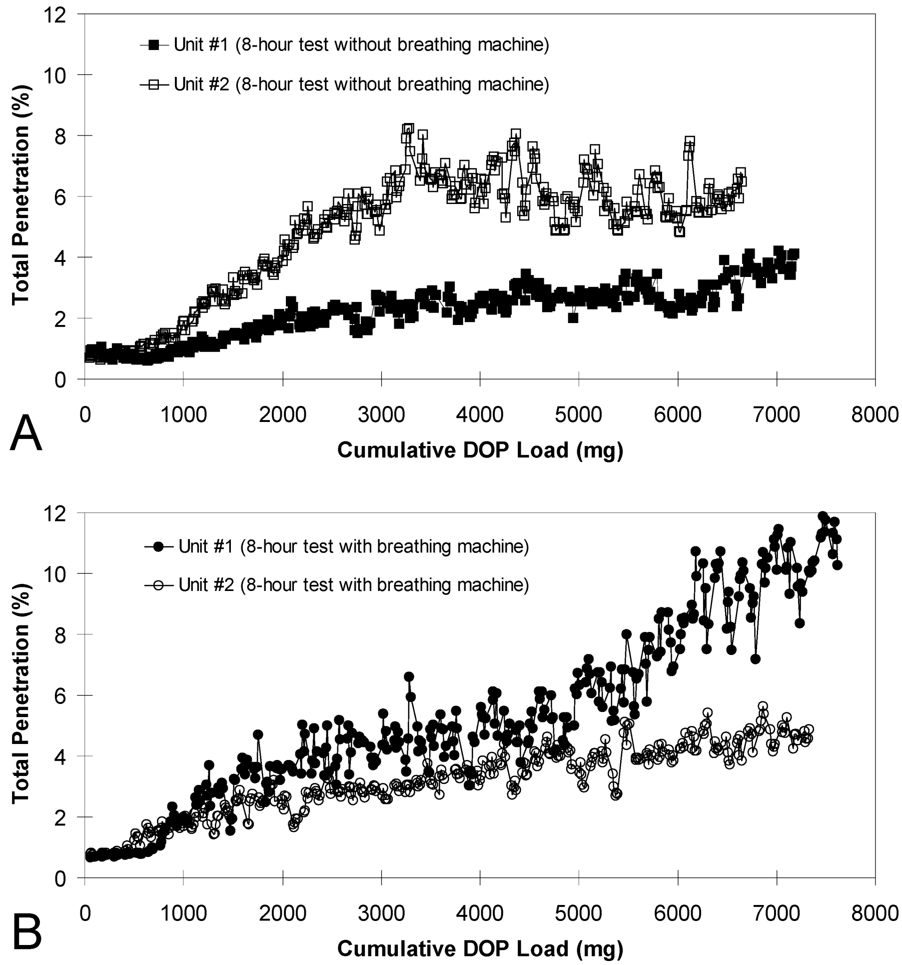

FIGURE 4. Total unit performance test results for loose-fitting hood Racal Air-Mate HEPA 10 PAPR units: (A) two units tested for 8 hours with no breathing machine; (B) two units tested for 8 hours with breathing machine

173 L/min. The MSA OptimAir 6A unit performance tests incorporating the breathing machine provided very similar results. The maximum penetration values were 0.167% and 0.048% at total DOP loads of 6300 and 5700 mg, respectively. Here, Unit #1 had an initial flow rate of 207 LPM and a final flow rate of 170 L/min, whereas Unit #2 had an initial and final flow rate of 207 and 173 L/min, respectively. These maximum penetration values correspond to PFs of 600 and 2100, respectively, which are well above the NIOSH-assigned APF of 50 for tight-fitting PAPRs.

The Racal Air-Mate HEPA 10 used a loose-fitting hood as the headpiece. The results from the Racal Air-Mate HEPA 10 unit performance tests are shown in Figure 4. Unit #1 with no breathing machine gave a maximum penetration of 4.21% (minimum PF of 24) at the end of the 8-hour test and a total DOP load of 7200 mg. The initial and final flow rates were 227 L/min and 173 L/min. Unit #2 without the breathing machine gave a maximum penetration value of 8.24%, which corresponds to a PF of 12. No penetration results from the second 4 hours of testing surpassed 8.24%, even with a total unit DOP load of 6600 mg. The PAPR flow rates recorded for this test were 218 L/min initially and 176 L/min at the end. Unit #1 with the breathing machine gave a maximum penetration value of 11.9% (PF = 8) after a total DOP load of 7600 mg. The initial flow rate was 229 L/min and the final flow rate was measured at 176 L/min. The reason the maximum penetration value for Unit #1 (with breathing machine) was so high cannot be explained, especially since the maximum penetration value obtained from Unit #2 with the breathing machine was only 5.63% (PF = 18) after a total DOP load of 7300 mg and initial and final flow rates of 229 and 181 L/min. The results obtained from the unit performance testing of the Racal Air-Mate HEPA 10 were somewhat confusing as there was not any pattern established from using or not using the breathing machine. Regardless, all four tests resulted in minimum PFs below 25, which is the APF value assigned to loose-fitting PAPRs by NIOSH.

The unit performance testing results for loose-fitting helmet-type Racal Breathe-Easy 1 are shown in Figure 5. The tests conducted without the breathing machine showed

TABLE II. Summary of PAPR Integrated Unit Performance Testing Results (with No Breathing Machine)

PAPR Model	PAPR Unit	Test Duration (hours)	Total DOP Load (mg)	Initial PAPR Flow Rate (L/min)	Final PAPR Flow Rate (L/min)	Maximum Unit Penetration (%)	Minimum Protection Factor[A]	NIOSH Assigned Protection Factor
3M W-3265	Unit #1	8.0	3900	147	130	0.024	4200	50
	Unit #2	8.0	4000	144	130	0.026	3800	
MSA OptimAir 6A	Unit #1	8.0	6200	207	170	0.253	400	50
	Unit #2	8.0	6300	204	173	0.119	840	
Racal Air-Mate HEPA 10	Unit #1	8.0	7200	227	173	4.21	24	25
	Unit #2	8.0	6600	218	176	8.24	12	
Racal Breathe-Easy 1	Unit #1	6.5	6000	228	203	2.12	47	25
	Unit #2	8.0	6400	242	183	2.94	34	
3M AS-200LBC	Unit #1	4.0	3100	238	182	2.80	36	25
	Unit #1	8.0	5600	204[B]	206[C]	19.9 (4.36)[D]	5	

[A]The minimum protection factor is the protection factor (PF) calculated from the maximum unit penetration measured during testing.
[B]Average flow rate for first battery pack (replaced after first 4 hours).
[C]Average flow rate for second battery pack.
[D]Value in parentheses is maximum penetration value after first 4 hours of testing (when battery pack was changed).

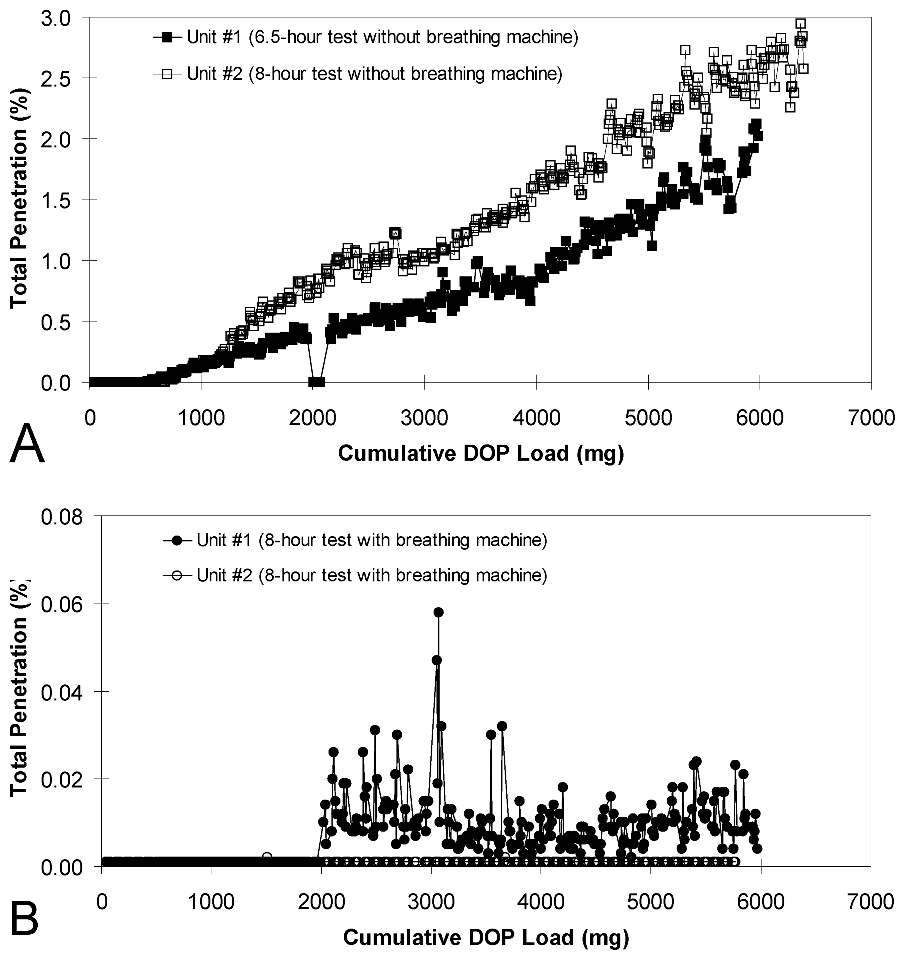

FIGURE 5. Total unit performance test results for loose-fitting helmet Racal Breathe-Easy 1 PAPR units: (A) two units tested for 8 hours with no breathing machine (Unit #1 lasted only 6.5 hours due to problem with 8122 tester); (B) two units tested for 8 hours with breathing machine. Note: Y-axes are not scaled the same.

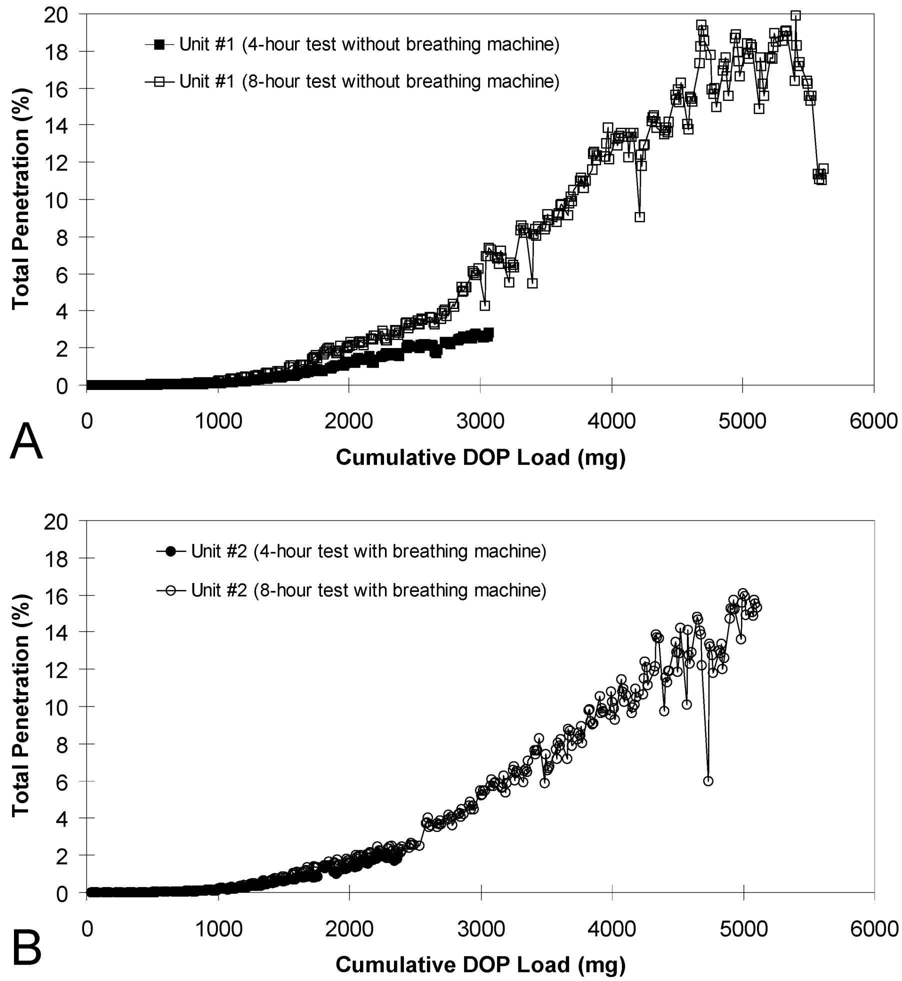

FIGURE 6. Total unit performance test results for loose-fitting helmet 3M AS-200LBC PAPR units: (A) one 4-hour test and one 8-hour test with no breathing machine; (B) one 4-hour test and one 8-hour test with breathing machine

significantly higher penetration values than those incorporating the breathing machine. Without the breathing machine, the Racal Breathe-Easy 1 gave maximum penetration values of 2.12% and 2.94% at total DOP loads of 6000 mg and 6400 mg, respectively. These penetration values correspond to minimum protection factors of 47 and 34, respectively. The initial and final PAPR flow rates were 228 L/min and 203 L/min for Unit #1 and 242 L/min and 183 L/min for Unit #2. Testing of Unit #1 without the breathing machine was terminated after only 6.5 hours because the 8122 tester stopped providing results. (The cause of this problem was never discovered, but it was not experienced again.) The Racal Breathe-Easy 1 unit performance tests incorporating the breathing machine provided better results, with maximum penetration values reaching only 0.058% (PF = 1700) and 0.002% (PF = 50,000) with total DOP loads of 6000 mg and 5800 mg, respectively. The initial and final flow rates for Unit #1 were 249 L/min and 211 L/min, whereas the initial and final flow rates for Unit #2 were 235 L/min and 209 L/min. Although all tests resulted in PF values exceeding the NIOSH APF of 25 for loose-fitting PAPRs, it is clear that testing this PAPR unit without the breathing machine is more stringent.

The unit performance test results for the 3M AS-200LBC are shown in Figure 6. For the 4-hour tests and 8-hour tests, the tests performed without the breathing machine (Figure 6A) provided slightly higher maximum penetration values. The 4-hour test without the breathing machine gave a maximum penetration value of 2.80% (PF = 36) with a total DOP load of 3100 mg and initial and final flow rates of 238 L/min and 182 L/min, respectively. The 4-hour test using the breathing machine gave a maximum penetration value of 2.17% (PF = 46) with 2400 mg total DOP load and initial and final flow rates of 215 L/min and 193 L/min, respectively. The same pattern was noticed with the 8-hour tests. For the 8-hour tests, without and with the breathing machine, the maximum penetration values were 19.9% and 16.1% (PFs of 5 and 6), respectively. The total DOP loads were 5600 mg and 5100 mg, respectively, with overall average PAPR flow rates of 205 L/min and

TABLE III. Summary of PAPR Integrated Unit Performance Testing (with Breathing Machine)

PAPR Model	PAPR Unit	Test Duration (hours)	Total DOP Load (mg)	Initial PAPR Flow Rate (L/min)	Final PAPR Flow Rate (L/min)	Maximum Unit Penetration (%)	Minimum Protection Factor^A	NIOSH Assigned Protection Factor
3M W-3265	Unit #1	8.0	4200	147	127	0.030	3300	50
	Unit #2	8.0	3900	147	118	0.024	4200	
MSA OptimAir 6A	Unit #1	8.0	6300	207	170	0.167	600	50
	Unit #2	8.0	5700	207	173	0.048	2100	
Racal Air-Mate HEPA 10	Unit #1	8.0	7600	229	176	11.9	8	25
	Unit #2	8.0	7300	229	181	5.63	18	
Racal Breathe-Easy 1	Unit #1	8.0	6000	249	211	0.058	1700	25
	Unit #2	8.0	5800	235	209	0.002	50,000	
3M AS-200LBC	Unit #2	4.0	2400	215	193	2.17	46	25
	Unit #2	8.0	5100	200^B	204^C	16.1 (2.46)^D	6	

^{A}The minimum protection factor is the protection factor (PF) calculated from the maximum unit penetration measured during testing.
^{B}Average flow rate for first battery pack (replaced after first 4 hours).
^{C}Average flow rate for second battery pack.
^{D}Value in parentheses is maximum penetration value after first 4 hours of testing (when battery pack was changed).

202 L/min, respectively (average of the averages for both battery packs).

The maximum penetration results after the first 4 hours of testing (when the battery packs were changed) were 4.36% without the breathing machine and 2.46% with it. The large increase in DOP penetration into the 3M AS-200LBC units during the second 4 hours of testing cannot be explained in definite terms. However, one logical explanation is that the electrostatic PAPR filters could have degraded under the large DOP load as previously described by Martin et al.[14] The user instructions did not specify a service lifetime for the electrostatic filters, but they did specify that the filters are not for use in oil mist environments. If filter degradation did occur, as was previously documented, the large increase in DOP penetration into the PAPR unit could be mainly the result of decreased filter efficiency over time.

CONCLUSIONS AND RECOMMENDATIONS

Tables II and III summarize the testing results for all of the PAPRs tested without the breathing machine and with it, respectively. The two tight-fitting PAPRs (3M W-3265 and MSA OptimAir 6A) showed little or no effect due to the use of the breathing machine. Further, both tight-fitting PAPRs provided APFs well in excess of the NIOSH-assigned APF of 50 for this class of respirators.

The unit performance testing results for the loose-fitting hooded Racal Air-Mate HEPA 10 were somewhat inconclusive. Additional testing needs to be conducted on the Racal Air-Mate HEPA 10 before a final determination about the most stringent test (breathing machine on or off) can be made. Regardless, the APFs for this hooded PAPR were all below the NIOSH assigned value of 25, irrespective of the testing protocol used.

Both the Racal Breathe-Easy 1 and the 3M AS-200LBC were equipped with loose-fitting helmets. The results from both of these PAPRs suggest that unit performance testing without the use of a breathing machine provides a more stringent test. Whereas both PAPRs showed a similar trend in the results, the maximum penetration values into the 3M AS-200LBC were much higher. The electrostatic 3M AS-140 filters may have experienced filter efficiency degradation from the DOP oil exposure as described recently by Martin et al.[14] Filter degradation could explain the significantly higher maximum penetration values at the end of the 8-hour tests compared with those after the first 4 hours of testing. The 3M AS-200LBC was the only PAPR tested in this study that used electrostatic filters. Even though the user instructions for the electrostatic filters clearly state that the filters should not be used in an oil mist environment, that limitation is not typical of other filters in this class. Additionally, all high-efficiency PAPR filters are a magenta color, which could create confusion among PAPR users.

The NIOSH certification program does not address all respirator characteristics but only those described in 42 CFR 84, which does not completely address total PAPR unit performance or the possibility of electrostatic PAPR filter degradation over time. Thus, the responsibility for addressing these issues rests with the respirator manufacturers. It is ultimately the job of the product manufacturer to ensure the level of safety offered to users of their products.

It is impossible to look at a PAPR and tell how well it will perform over the course of an entire work shift. Furthermore, a visual inspection cannot tell a respirator user if the respirator worn daily is equipped with electrostatic filters. From the results presented in this study, it is clear that total PAPR unit performance, particularly when electrostatic filters are used, could be an area of concern. In the case of the electrostatic 3M AS-140 filters, 3M was responsible in restricting the use of the AS-200LBC PAPR to environments free from oils. Until changes are made to the certification standards to better address the evolving PAPR units and filters available, PAPR manufacturers should follow the example set by 3M and restrict the use of electrostatic PAPR filters when necessary. To do this, manufacturers will need to conduct filter loading tests and total PAPR unit performance testing on their PAPR product lines. A test methodology similar to the one described here could be used as a starting point for this testing and could provide useful information as a supplement to the current NIOSH PAPR certification tests. However, the method used here does not address all aspects of total PAPR unit performance (e.g., the potential for overbreathing the PAPR unit under high work rates), and additional testing methods need to be investigated to fully understand PAPR unit performance.

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