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PERFORMANCE MEASUREMENTS ON A POWERED AIR-PURIFYING RESPIRATOR MADE DURING ACTUAL FIELD USE IN A SILICA BAGGING OPERATION

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Abstract—The performance of Powered Air-Purifying Respirators (PAPR) has been measured in actual field use conditions that exist for silica dust baggers. The data indicate that the laboratory performance of this PAPR is better than its field performance measured during a silica bagging operation. A protection factor classification of 1000 is normally assigned to PAPRs; however, the workplace protection factors measured on this tight fitting facepiece PAPR ranged from 16 to 215. Reasons for the difference between the assigned protection factor and workplace protection factors measured with these devices are discussed.

INTRODUCTION

SILVERMAN and BURGESS (1964) described the development of an air-purifying respirator unique in its design and concept that would provide positive facepiece pressure—a Powered Air-Purifying Respirator (PAPR). The PAPR they designed consisted of a high efficiency filter system, a miniature air mover upstream of the filter system, a rechargeable battery, a breathing tube and a conventional, supplied air, respirator facepiece. The PAPR was tested on four subjects working at a rate of 622 kp-m min^{-1}. They found that respirator leakage could be maintained below 0.1% by providing an air supply in excess of 115 l min^{-1} (4 cfm) to the facepiece. Respirator leakage below 0.1% is equivalent to a protection factor of at least 1000.

Later studies by BURGESS and NETTLETON (1968), LUXON (1968) and BURGESS and REIST (1969) showed that PAPRs, in laboratory studies, could provide protection factors greater than 1000 if sufficient air supply was provided to the facepiece. Air supply rates to maintain positive facepiece pressure were found to vary depending on test subject work rate from 115 to 150 l min^{-1} for tight fitting facepieces and up to 170 l min^{-1} for loose fitting hoods and helmets.

These studies demonstrated that the positive facepeice pressure performance characteristic of the PAPR would minimize all facepiece fit leakage. Ideally then, the maximum protection afforded by these devices would depend on the efficiency of the air-purifying component of the PAPR system.

Respirator and occupational health specialists using results of quantitative facepiece fit testing and professional judgement have made recommendations concerning the level of protection (i.e. Protection Factor, hereafter referred to as PF) a PAPR should provide to its wearer. Some recommendations that appear in the literature are summarized in Table 1.

Powered air-purifying respirators were used on a limited basis in the U.S.A. until

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TABLE 1. MAXIMUM RECOMMENDED PROTECTION FACTOR LEVELS TO BE EXPECTED FOR POWERED AIR-PURIFYING RESPIRATORS (PAPR) UTILIZING DIFFERENT TYPES OF AIR-PURIFYING ELEMENTS

Source of recommendation	PAPR using a dust, fume or mist or any combination of dust, fume and mist air-purifying element	PAPR using a high efficiency* air-purifying element	PAPR using only a gas or gas and vapor air-purifying element
Hyatt (1975 American National Standards Institute Z88.2 Committee on Practices for Respiratory Protection (1980)	No recomendation 100	1000 3000	No recomendation Determined by maximum use limit of the gas and /or vapor air-purifying element
Joint NIOSH/OSHA Standards Completion Program—Respirator Decision Logic (1976)	No recommendation	1000†	1000†
OSHA—Occupational Exposure to Lead (1978)	No recommendation	1000	N/A
British Standard Specification BS4558 (1974)	20	1000	N/A
British Health and Safety Executive, Exposure to Lead Fume (1982 Revised)	20	333	N/A

* High efficiency means filter leakage of less than 0.03% (collection efficiency of 99.97%) against 0.3 μm particles.
† The joint NIOSH/OSHA Decision Logic cites 1000 as the minimal PF to be expected.

NIOSH/MSHA certified PAPRs became commercially available in the late 1970s. Since that time their acceptability and use in general industry has greatly increased.

This paper reports the results of a field study on a tight fitting facepiece PAPR used by workers for respiratory protection during the routine bagging of micro-crystalline silica in a typical silica processing plant.

MATERIALS AND METHODS

Three new PAPRs and a supply of high efficiency filters, identical to those routinely used by the workers involved with this study, were purchased from commercial sources. The PAPR assemblies were all identical and used either a tight-fitting half-mask or full facepiece. Both facepiece types are of a natural rubber compound and constructed with two exhalation valves. The half-mask sealing edge design is an internal roll and the full facepiece sealing edge design is flat with an inner flap. The complete PAPR assembly consisted of a facepiece, breathing tube, and a belt-mounted assembly consisting of blower, filters and battery pack. The filters on this respirator are mounted downstream of the blower.

I. Laboratory evaluation

Before conducting the field evaluation phase of the study, all three PAPRs were

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examined for structural defects (e.g., a cracked motor blower housing) and subjected to laboratory tests. The laboratory tests consisted of dioctyl phthalate (DOP) testing of the high efficiency filters and silica dust testing of the completely assembled PAPR.

(*a*) *DOP tests.* The efficiency of each filter was checked using a 0.3 μm thermally generated DOP aerosol at a test flow rate of 42.5 l min^{-1} for approx. 10 sec. Leakage measurements were made with an ATI Model Q127 DOP filter tester. This DOP test procedure is the same as that used for the high efficiency filter penetration test required for certification. Those filters subsequently used in the field evaluation phase of the study were retested with DOP after field testing to determine if holes had developed in the filter matrix.

(*b*) *Silica dust test.*

(1) *Aerosol generation*

The silica dust test atmosphere was generated by a lift tube dust feeder into a $5 \times 5 \times 7$ ft test chamber. The aerosol was passed through a cyclone separator to remove large particles and agglomerations before it was introduced into the chamber. The resulting aerosol had a MMAD between 2.2 and 2.5 μm with a $\bar{\sigma}_g$ of approx. 2. The concentration of silica dust was maintained between 50 and 60 mg m^{-3}.

The PAPR was prepared for each 4-h silica dust test with a fully charged battery pack and new filters. The air flow output of the PAPR (facepiece removed) was determined before and after each test with a dry gas meter having an operating pressure drop of approx. 12.7 mm water, which is similar to the pressure drop of either the half or full facepiece.

For testing, the respirator facepiece was mounted on an anthropomorphic head form. The concentration of silica dust in the facepiece was measured from a sampling port in the head form at the location of the mouth. This sampling port was connected to a filter sampling train and a breathing machine. The breathing machine simulated a 622 kp-m min^{-1} work rate breathing pattern at a breathing frequency of 24 cycles min^{-1} which produced a minute volume of 40 l min^{-1}. The in-facepiece and chamber concentration sampling filters were 76 mm glass fibre high efficiency filters. Pre- and post-weights were taken on each filter and reported to the nearest 0.1 mg with a lower limit of quantification on filter weight gain of 0.3 mg. The complete respirator test assembly, except for the breathing machine and sampling train, was placed in the test chamber for testing. This silica dust test procedure is the same as that used for the high efficiency filter resistance test required for certification.

II. Field evaluation

The field evaluation phase of this study was to determine the level of protection provided by the PAPR while it was being worn (personal) and when it was not worn (free standing) and to size characterize the ambient aerosol.

(*a*) *Personal.* Personal samples were taken simultaneously inside (IFP) and outside (OFP) the facepiece. These data were used to calculate a workplace protection factor (MYERS *et al.*, 1983) for the PAPR while used by silica dust baggers.

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(1) *Sampling technique*

For in-facepiece sampling, a modified Luer adaptor sampling probe was attached to the facepiece with rubber washers and nut to achieve an air-tight seal. The sampling probe site was on the midline of the facepiece in a position approximately opposite to the area between the upper lip and nasal openings of the wearer. The in-facepiece sampling cassette was attached directly to the facepiece probe. The OFP samples were taken on the lapel of the worker near to his breathing zone and yet not in a position to interfere with the respirator facepiece during head movements. A total dust sample instead of respirable dust sample was collected at both the ITP and OFP sites, since earlier dust sampling of the bagging operation and general area indicated that seventy per cent or more of the dust was in the respirable range (≤ 10 μm).

The IFP and OFP filter samples were taken with identical sampling trains. Each sampling train consisted of a two-piece filter cassette containing a 37 mm, 5 μm pore size, FWS-B, polyvinyl chloride, filter. The cassette was attached to an MSA model G sampling pump via $\frac{1}{4}$ in. Tygon tubing. Each sampling pump was calibrated to provide a flow rate of 1.5 l min^{-1}. The IFP and OFP air sample cassettes were changed during the lunch break, creating forenoon and afternoon intrashift sampling periods.

The amount of silica collected on each polyvinyl chloride sampling filter was determined gravimetrically and by X-ray powder diffraction according to NIOSH method P & CAM 259 for free silica (NIOSH, 1977). The total coefficient of variability for this method including sample pump variability is calculated to be 0.11. A t-value of 1.96 was used for calculation of the 95% confidence limits on the free silica concentration values. The gravimetric analysis was done with a Cahn model H700 automatic electrobalance housed in an environmental chamber controlled at 70 ± 0.5°F and 50 ± 5% relative humidity. Seven filter blanks were maintained with the sample filters. The mean blank filter weight change was +0.026 with a standard deviation about the mean of ± 0.013 mg. Filter weight gains for all IFP and OFP samples are corrected for the average blank gain and reported to the nearest tenth of a milligram.

An X-ray powder diffraction (XRD) analysis for silica was performed on each IFP and OFP sample filter because of the possibility that foreign material (e.g., phlegm, mucus, skin, hair, etc.), particularly on the IFP filter, could significantly contribute to the gravimetrically determined mass gain. Each filter sample was analysed quantitatively by step scanning the primary quartz and cristobalite peak. The normalized intensity counts were converted to micrograms of quartz using a silica dust calibration curve based on the silica particle size distribution obtained from several of the OFP samples collected at the study site. Use of the OFP sample particle size distribution as a calibration curve for XRD analysis could lead to errors in the mass estimates of silica on the IFP samples if the silica dust size distribution of the samples are not similar. Insufficient silica was collected on IFP samples to determine the particle size distribution of those samples.

(2) *Donning and doffing the PAPR*

During the field survey, the PAPRs were put on and taken off each worker participant by the survey officers whenever it was necessary (e.g., start or end of shift, lunch break or personal need). The belt-mounted assembly of the PAPR was laterally

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positioned on each worker to allow freedom of side-to-side head movement. Such movement was restricted by the breathing tube length when the assembly was positioned in the middle of the back. Donning and doffing were always done in a designated clean area. After the respirator was donned and adjusted for comfort the PAPR power supply was turned on first and then the IFP and OFP sampling pumps turned on and adjusted. When doffing the respirator the IFP and OFP sample pumps were turned off before turning off the PAPR power supply.

After the facepiece was removed from the worker during breaks, the facepiece cavity was examined for evidence of dust contamination before redonning. No evidence of gross dust contamination was observed by these examinations. The PAPRs were cleaned by the survey officers after each shift. Manufacturer's instructions were followed for changing batteries and filters. Volumetric air output of each PAPR (facepiece removed) was determined as in Paragraph I(b).

(3) *Worker instructions and observation*

Workers were instructed not to manipulate, lift or remove the facepiece of the PAPR. They were told that, if it was necessary to adjust or remove the facepiece, they should make that need known to a survey officer who would assist them. Any problems with the PAPR or IFP or OFP sampling trains were to be immediately brought to the attention of the survey officer. The survey officers observed the workers 100% of the time during periods when donning and doffing the PAPR occurred. At their work stations, workers were monitored by the survey officers approx. 80% of the time and workers were not always aware of when they were under observation.

(*b*) *Free standing*. Two PAPRs were run while in a stationary position to determine their performance when not worn. To accomplish this, the facepiece of each PAPR was removed and an 'air filtering head' substituted in its place. The air filtering head housed a pre-weighed 76 mm glass fibre filter. Each free standing PAPR was run for approx. 6–7 h with one battery change at 4 h. The filters in the air filtering head were weighed and the volumetric air output of the PAPRs determined as specified in Paragraph I(b). The ambient concentration of silica dust challenging the free standing PAPRs was estimated from the average of all ambient silica dust concentrations determined from personal and Andersen impactor samples collected on that respective day.

(*c*) *Aerosol particle size characterization*. The aerodynamic particle size of the ambient silica dust aerosol was determined using an Andersen impactor operated at 1 cfm. Anderson samples were collected in an area 4–8 ft from the workers on each day of the field evaluation. Sample length was varied but close to 3 h for each 4-h sampling period.

RESULTS

I. Laboratory evaluation

No structural defects of the PAPR units were identified from visual examination. Penetration results of the DOP test on new and used filters ranged from 0.01 to 0.001%.

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These values are well within the recognized penetration level for high efficiency filters of less than or equal to 0.03% (U.S. BUREAU OF MINES, 1972).

The minimum air output of the PAPRs after the 4-h silica dust test was above 4 cfm (*ibid*). The mass of silica dust collected on the in-facepiece sample during laboratory testing was below the 0.3 mg detection limit of the gravimetric analysis used.

II. Field evaluation

The aerodynamic mass median particle size was 5.8 μm with a σ_g of 7.1, and 5.5 μm with a σ_g of 7.7 for days one and three respectively. The impactor samples on day two were lost owing to a bagger malfunction.

(a) *X-ray powder diffraction analysis results.* The concentration of silica dust, calculated from the mass of free silica on each IFP and OFP sample, is shown in Table 2 for each worker during each sample period. The OFP concentrations ranged from 2 to 36.8 mg m^{-3} and the IFP concentrations ranged from 0.03 to 0.56 mg m^{-3}. The workplace protection factors calculated from the IFP and OFP XRD data ranged from 16 to 215 with a geometric mean of 54 and a geometric standard deviation of 2.24. The mean workplace protection factor measure on the PAPRs was significantly less ($P < 0.05$) than the PAPR assigned protection factor level of 1000.

(*b*) *Gravimetric analysis results.* The concentration of silica dust calculated from the gravimetrically determined mass gain ranged from 4.4 to 41.7 mg m^{-3} for the OFP samples and from 0.05 to 1.5 mg m^{-3} for the IFP samples. The workplace protection factors calculated from the OFP and IFP gravimetric data ranged from 8 to 181 with a geometric mean of 35 and a geometric standard deviation of 2.8.

(*c*) *Results of 'free standing' tests.* Only two of ten 76 mm filters had weight gains above the 0.3 mg lower limit of quantification (LLQ). These two filters had weight

TABLE 2. PROTECTION FACTORS, FREE SILICA CONCENTRATIONS AND OTHER SAMPLE DATA COLLECTED FROM SILICA BAGGERS WHILE WEARING A POWERED AIR-PURIFYING RESPIRATOR

Sample period	Worker number ID	Facepiece type worn	Sample time (min)	IFP sample (mg m^{-3})‡	OFP sample (mg m^{-3})‡	PF OFP/IFP
Forenoon	1	Half	320	0.08 (±0.02)	3.33 (±0.73)	42 (±9)
on day 1	2	Full	260	0.08 (±0.02)	1.98 (±0.43)	25 (±5)
Afternoon	1	Half	138	0.06 (±0.01)	5.24 (±1.15)	87 (±19)
on day 1	3	Full	136	0.08 (±0.02)	4.31 (±0.94)	54 (±12)
Forenoon	2	Full	282	0.03 (±0.01)	6.44 (±1.41)	215 (±47)
on day 2	3	Half	251	0.12 (±0.03)	23.12 (±5.07)	193 (±42)
Afternoon	3	Half	100	0.17 (±0.04)	2.79 (±0.61)	16 (±4)
on day 2	4	Full	84	*	2.78 (±0.61)	
Forenoon	4	Half	226	0.56 (±0.12)	36.76 (±8.05)†	67 (±15)
on day 3	3	Half	220	0.09 (±0.02)	4.38 (±0.96)	49 (±11)
Afternoon	3	Half	147	0.36 (±0.08)	6.85 (±1.50)	19 (±4)
on day 3	Worker stopped bagging after lunch break					

* Silica on sample was less than 0.005 mg limit of detection for pure quartz.
† Pneumatic bagger malfunction.
‡ Values in parentheses represent the 95% confidence limits on the sample concentration value.

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gains of 0.8 and 0.6 mg for sample volumes of 29.2 and 29.7 m^3 respectively, corresponding to a calculated leakage concentration of 0.027 and 0.020 mg m^{-3}. The calculated leakage concentrations for the 'free standing' units ranged from less than 0.004 (using LLQ of 0.3 mg) to 0.027 mg m^{-3} corresponding to protection factors ranging from 302 to greater than 2075.

DISCUSSION

Data collected and observations made during this study indicate that, in this use situation, the PAPR system under study did not provide the level of protection (i.e., PF) which is commonly expected for this type of respirator.

Three parameters can be identified that could directly impact on the field performance of the PAPR. They are wearer use behaviour, variability in methods used to obtain and analyse the IFP and OFP samples and respirator leakage.

Aberrant respirator use or wearer behaviour was controlled in this study through explicit instruction to workers about removing the PAPR facepiece, the high level of wearer monitoring done by the survey officers and the intimate participation of survey officers in donning, doffing and adjusting the PAPR each time these activities occurred. As a result, the impact of this parameter on the performance of the PAPR is felt to be minimal.

When collecting IFP samples it must be recognized that the sampling is occurring over the inhalation phases of the respiratory cycle. An IFP sample collected just during the inhalation phase would represent the true estimate of exposure level. An IFP sample collected just during the exhalation phase would be an underestimate of exposure level because of contaminate loss from lung deposition. An IFP sample collected over a complete respiratory cycle would estimate an exposure level between those found during just the inhalation phase and exhalation phase. SMITH *et al.*, (1980) estimated an IFP undersampling error of approx. 10%. However, with the PAPR this dilution effect is extremely small, since the PAPR is providing more than 115 l min^{-1} to the facepiece.

The effect of cyclic pressure fluctuation inside the respirator on sampling pump flow rate has been discussed previously in the literature (*ibid*). the positive facepiece pressure of the PAPR helps minimize the magnitude of the cyclic pressure excursions in the facepiece. The facepiece pressure on an operating PAPR mounted on an anthropomorphic head form was measured during the laboratory silica dust tests. The difference between the inhalation and exhalation pressures observed during the tests averaged 10 ± 2 mm of water. Based on the flowrate vs pressure drop data developed by WOOD (1977) on the MSA Model G personal sampling pump, this fluctuation in facepiece pressure should cause only minor deviation in sampling flow rate.

Sampling with low (1-2 l min^{-1}) flow rates to estimate IFP concentrations in PAPRs has been used extensively in performing quantitative fit testing and to a lesser extent in field studies on this type of respirator (SILVERMAN and BURGESS, 1964; BURGESS and REIST, 1969; LOWRY *et al.*, 1979; HACK *et al.*, 1980). A sample flow rate of 1.5 l min^{-1} is not considered a major source of error in estimating the in-facepiece concentrations of this PAPR.

The third parameter to effect PAPR performance is leakage. The very low leakage concentrations observed with the free standing PAPRs indicate that generally the non-

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worn PAPRs were performing well. This conclusion is supported by the laboratory silica dust test results obtained on the PAPRs prior to field testing.

Two factors which could affect the performance of the worn PAPRs that would not affect the 'free standing' PAPRs are body movement and facepiece fit. The silica bagging operation at the test site consists of bagging, carrying and stacking 50 lb bags of silica. The bags are filled by a pneumatic bagger which holds them approx. 3.5 ft off the ground. Each pneumatic bagger is located immediately in front of each worker. A worker will remove the filled bag from the bagger and pull it in close to his body, turn his body through an arc of approx. 90–120 degrees, walk one or two steps and stack the bag on a pallet. The stacking activity involves bending at the waist since the first row of bags on the pallet is approx. 6 in. off the ground and the last approx. 4.5 ft off the ground. Work rates of individual silica baggers performing these various tasks were not measured.

It was observed that the bagging operation resulted in routine bumping and rubbing of the workers arms against the belt-mounted motor blower housing and filter assembly of the PAPR. This movement on the PAPR could have caused lateral movement between the blower housing grommet and the neck of the filter. The result could be failure of the airtight seal between filter and blower housing allowing unfiltered air to by-pass the filter and enter the blower housing. Some visual evidence of silica dust inside the motor blower housing was found to support this mechanism of leakage. However, the significance of the contribution of this leakage component to measured IFP concentration is unknown.

Another possible source of leakage into the facepiece is from inadequate facepiece fit. One of the significant operational features of PAPR systems is positive facepiece presssure; thus, any leaks are outward and not inward. Laboratory quantitative facepiece fit testing (QNFT) results repeatedly indicate these devices will provide PFs of 5000 or higher (SILVERMAN and BURGESS, 1964; BURGESS and REIST, 1969; HYATT, 1975; LOWRY *et al.*, 1979). The ANSI Z88.2 recommendations on respirator selection state that no qualitative or quantitative tests are required with PAPR systems owing to the positive pressure operation of the respirator (ANSI, 1980). However, HACK *et al.* (1980) reported that test aerosol could migrate into the half facepiece of a continuous flow respirator at an airflow rate of 136 l min^{-1} (4.8 cfm) but not at a higher flow rate of 275 l min^{-1} (9.7 cfm). Therefore, the assumption that no inboard leakage can occur with a PAPR system delivering a minimum of 115 l min^{-1} (4 cfm) may not be valid under all use conditions, specially those involving moderate to heavy user work rates. Consideration of our data suggests that migration of contaminant into the facepiece of the PAPR system could be a significant source of leakage when the respirator is exposed to the wide ranging condition that exist in the work environment.

It is important to re-emphasize that the IFP and OFP samples taken in this study were collected while the respirator was worn and used under a very optimized set of procedural conditions. The protection factors observed in this study are well below the expected protection factor of a PAPR. However, they may represent a more accurate measure of the level of worker protection that can be expected from this type of PAPR system.

The consequences of over-estimating the protection factor provided by a PAPR or any other class of respirator can have an adverse impact on workers who are required to use them. Results of this study strongly suggest that near term research should be

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directed at re-evaluating the protection factor classifications currently assigned to PAPRs and other classes of respirators. Protection factor classifications should be changed, if research indicates it is warranted, to better reflect the work place level of protection that respirators provide.

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