Applied Occupational and Environmental Hygiene
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/uaoh20

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Published online: 24 Feb 2011.

To cite this article: William C. Hinds & Nani P. Kadrichu (1994) Effect of Dust Loading on the Performance of Half-Mask Respirators, Applied Occupational and Environmental Hygiene, 9:10, 700-706, DOI: 10.1080/1047322X.1994.10388397

To link to this article: http://dx.doi.org/10.1080/1047322X.1994.10388397

Effect of Dust Loading on the Performance of Half-Mask Respirators

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The effect of dust loading on the protection provided by an air purifying respirator is complicated because of the interplay of two factors: (1) the increase in filter resistance, with its attendant increase in facial seal leakage; and (2) the increase in filter efficiency that occurs with increased loading. The objective of this article is to characterize, based on experimental measurement, the effect of dust loading on the protection provided by three types of respirators: (1) dust and mist (DM, disposable); (2) dust, fume, and mist (DFM, dual cartridge); and (3) dust, fume, mist, and radionuclide (DFMR, dual cartridge). Respirator filters were loaded with AC Fine Test Dust (mass median aerodynamic diameter = 2.8 μm, geometric standard deviation = 2.9) to six successive loading conditions, approximately 0, 100, 200, 400, 800, and 1600 mg, using a breathing machine (work rate 68 W) and a dust chamber. At each loading condition penetration and resistance measurements were made at seven flow rates (2–150 L/min). Penetration was measured at 12 particle sizes (0.14–3.6 μm) with a PMS, Inc. LAS-X optical particle counter. The effect of changes in resistance and penetration on respirator performance was evaluated using a respirator performance predictive model. For DM and DFM respirators protection increased until a loading of 200 to 400 mg was reached and then decreased gradually. In situations where fit factors exceed 100, loading is beneficial in terms of protection factor for DM and DFM respirators, at least until more than 1 g of dust is collected on the filters. Loading decreases the protection provided by respirators using high efficiency (DFMR) filters. Under the usual conditions of use the change in protection factor due to loading is unlikely to exceed a factor of three. Hinds, W.C.; Kandrichu, N.P.: Effect of Dust Loading on the Performance of Half-Mask Respirators. Appl. Occup. Environ. Hyg. 9(10):700–706; 1994.

Introduction

The accumulation of collected dust in a respirator filter (loading) modifies respirator performance in two ways: (1) the collected dust causes an increase in filter resistance, which gives rise to an increase in facial seal leakage; and (2) the collected dust increases filter efficiency, thereby reducing direct penetration of particles through the filter.[1] Because these two effects influence respirator performance in opposite directions, their combined effect is unclear, and depends on precisely how filter efficiency and resistance change with dust loading.

There are two objectives of this study. The first objective is to characterize, based on experimental measurement, the effect of dust loading on the protection provided by three types of respirators: (1) dust and mist (DM, disposable); (2) dust, fume, and mist (DFM, dual cartridge); and (3) dust, fume, mist, and radionuclide (DFMR, dual cartridge). The second objective is to identify situations, using a predictive model, where loading leads to an increase or decrease in protection.

There are few studies on the effect of dust loading on respirator performance. A recent study by Chen *et al.*[2] describes the effect of loading with liquid aerosol on the filtration characteristics of filtering facepieces. There are several published studies addressing the effect of dust loading on high efficiency particulate air (HEPA) ventilation filters.[3-13] Some of these studies showed that filter resistance increased linearly with dust loading[3-6]; however, others showed a slight concave upward relationship between the two parameters.[7-13] Because of the involvement of facial seal leakage, the studies done on HEPA filters are not useful for predicting the effect of dust loading on respirator performance.

Experimental Material and Methods

Three types of air purifying respirator filters were tested: (1) a 3M (St. Paul, Minnesota) Model 8710 disposable filtering facepiece DM respirator; (2) an MSA (Pittsburgh, Pennsylvania) type S cartridge DFM; and (3) an MSA type H cartridge high efficiency DFMR filter. The latter two were used with a dual cartridge half-mask respirator. The respirator and filters characterized here are Mine Safety and Health Administration/National Institute for Occupational Safety and Health (MSHA/NIOSH) approved for the indicated exposure aerosol.

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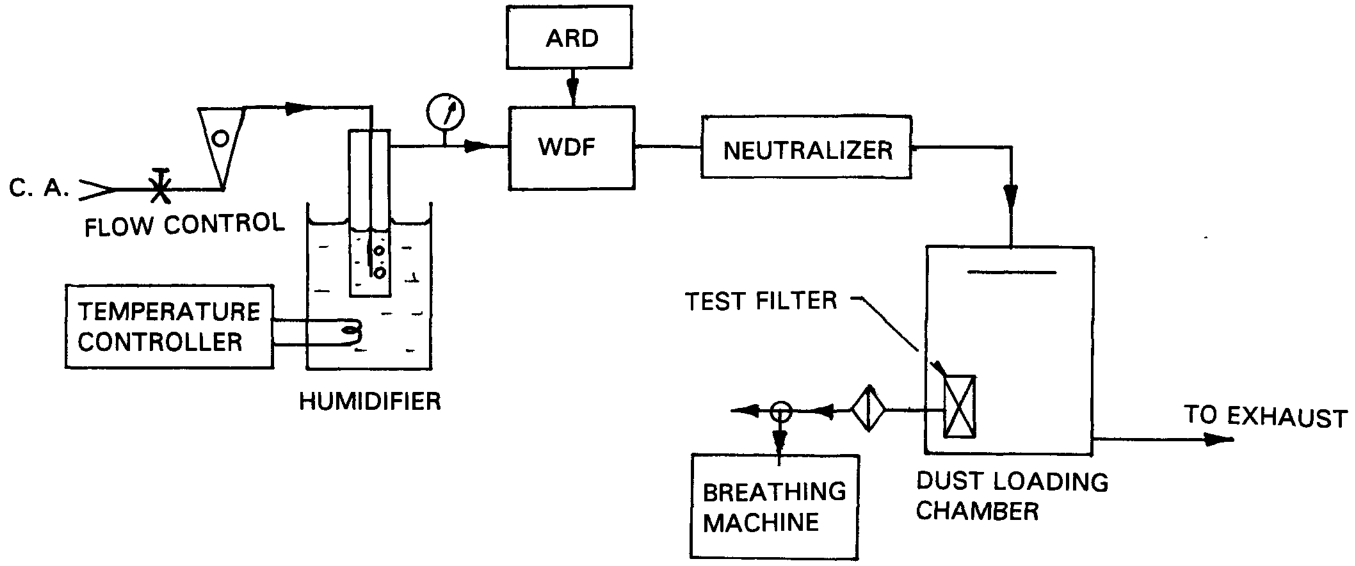

FIGURE 1. Schematic of filter loading setup.

A schematic for the experimental setup for dust loading is shown in Figure 1. A 30 × 25 × 15 cm chamber was fabricated from a steel electrical control box with a gasket-sealed door [National Electrical Manufacturers' Association (NEMA) type 3R rainproof electrical enclosure]. The chamber was modified so that the filter cartridges, or the disposable respirator, could be mounted inside and connected to the mechanical breathing machine located outside. The disposable respirator was sealed to a curved steel plate with hot-melt adhesive. The back of the plate was fitted with an adapter so that it could be mounted in the chamber in the same way as the cartridge filters. The test aerosol entered through a baffled inlet in the top of the chamber and exited to exhaust at the bottom. A one-way valve system on the breathing machine ensured that only inhalation air passed through the filters.

The test dust used was AC Fine Test Dust, also known as Arizona Road Dust (ARD) manufactured by the AC Spark Plug Division of General Motors Corporation (Flint, Michigan). This dust is representative of a wide variety of mechanically generated mineral dusts. It was dispersed by a Wright Dust Feeder (WDF) (BGI, Waltham, Massachusetts) operating at 16 psi. A Krypton-85 neutralizer (TSI, St. Paul, Minnesota) was placed between the WDF and the dust loading chamber to remove excess charge from the aerosol particles. Target dust loading conditions for the disposable mask or a pair of filter cartridges were 0, 100, 200, 400, 800, and 1600 mg.

Dust samples from the chamber were sized by a Sierra 210 cascade impactor (Anderson Samplers, Inc., Atlanta, Georgia). The particle size distribution of the dust had a mass median aerodynamic diameter (MMAD) of 2.8 μm and a geometric standard deviation (GSD) of 2.9. Chamber concentration was monitored during each run with a RAM-1 photometer (GCA, Inc., Bedford, Massachusetts). The coefficient of variation of five successive 30-second samples was about 5 percent.

A cam operated breathing machine simulated human breathing with a breathing cycle corresponding to moderate work-rate of 68 W (415 Kg-m/min) and a minute volume of 29.2 L as measured with a spirometer.

The relative humidity in the dust chamber was controlled by a humidification system to match the humidity in the laboratory, which ranged from 36 to 60 percent. The system humidified the compressed air for the dust feeder by passing it through a modified Greenberg-Smith impinger immersed in an adjustable temperature water bath. Humidity control was necessary to minimize errors due to any weight loss or gain of the filters between the dust loading process and weighing.

After each successive loading, the mask or filter cartridges were removed and tested for efficiency as a function of particle size and flow rate and resistance as a function of flow rate as described below. The cartridge filters were attached to a half mask elastomeric respirator sealed to a fiber glass mannequin (Model SM 701, Silvestri California, Los Angeles, California) in a respirator test chamber. The testing chamber and procedure have been described previously.[14] The respirators were sealed carefully to ensure that facial seal leaks were less than 0.01 percent of filter flow rate. At the conclusion of each efficiency test, filters were removed and returned to the loading chamber for additional loading.

Pneumatically generated oleic acid was used as the test aerosol for filter efficiency tests. The aerosol number concentration inside and outside the respirator was measured and recorded for 12 particle sizes (0.136 – 3.65 μm) by an optical particle counter (Model LAS-X, PMS, Inc., Boulder, Colorado). The LAS-X optical particle counter was calibrated in terms of aerodynamic diameter for oleic acid aerosol.[15] Five replications were performed for each set of inside and out-

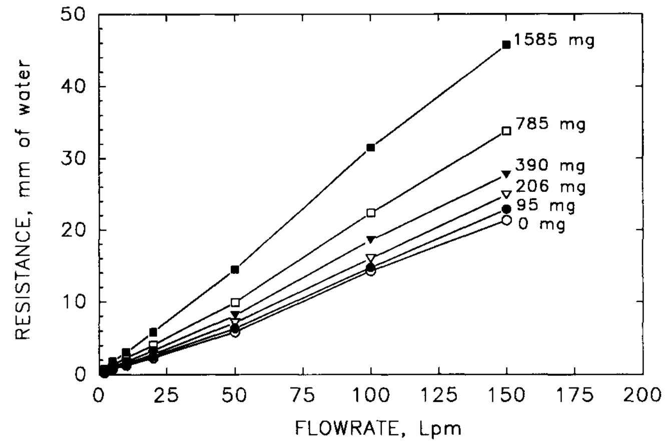

FIGURE 2. DFM filter resistance versus flow rate for six conditions of dust loading with AC Fine Test Dust.

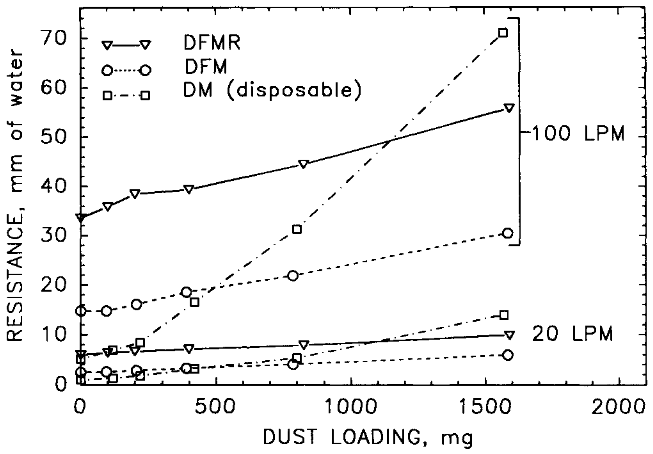

FIGURE 4. DFM filter resistance versus AC Fine Test Dust loading for three types of respirators at two flow rates.

side number concentration measurements at each of seven flow rates (2–150 L/min). This gave a total of 84 efficiency measurements (7 flow rates × 12 particle sizes). Aerosol efficiency data for each size and flow rate were reduced using a spreadsheet. The air flow resistance for the mask was measured by an inclined manometer, at each flow rate. This procedure was repeated for each loading condition.

Results

Figure 2 shows the relationship between resistance to air flow through the respirator (pressure drop) and air flow rate for six conditions of dust loading (AC Fine Test Dust) for a dual cartridge respirator with representative DFM filters. Figure 3 shows the same data plotted as filter resistance versus dust loading for seven flow rates. For any condition of loading, filter resistance is linear with air flow rate, as would be expected for laminar flow through the interior of the filter. Less obvious is the fact that for a given flow rate, resistance increases linearly with loading. This implies that the filter has not reached a clogging condition. It also suggests that each new particle collected interferes with air flow in much the same way at high or low loading. As shown in Figures 2 and 3 the overall effect of loading on resistance over this moderately heavy range is less than the effect of flow rate over the range of normal breathing.

Similar relationships were found for the disposable DM mask and the high efficiency DFMR filter cartridges, as shown in Figure 4 for two flow rates, 20 and 100 L/min. The two types of cartridge filters had approximately the same filter area and show similar slopes in Figure 4. The DFMR filters have about twice the initial resistance of the DFM filters. By contrast the disposable DM mask displays a much steeper slope for the resistance versus loading curve than the dual cartridge respirators at a given flow rate. This is believed to be the result of a much smaller filtering area compared to the cartridge filters: 149 versus 740 cm^2. Thus, the areal density (mass divided by filter area) of dust deposited in a disposable DM mask is greater than that for a dual cartridge respirator by a factor of almost five for the same total dust loading.

Figure 5 shows the effect of dust loading on filter effi-

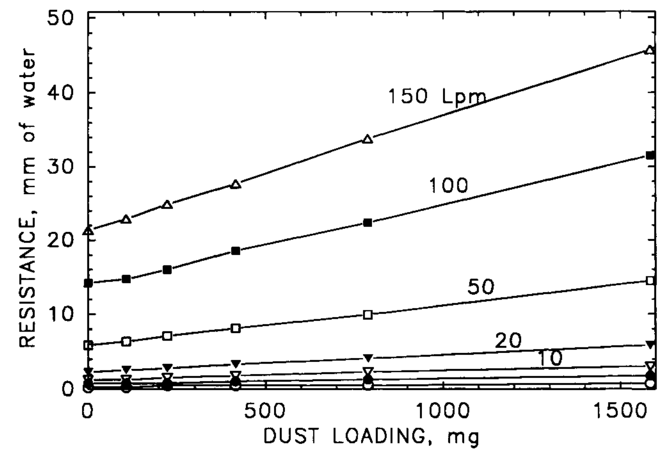

FIGURE 3. DFM filter resistance versus AC Fine Test Dust loading for seven flow rates.

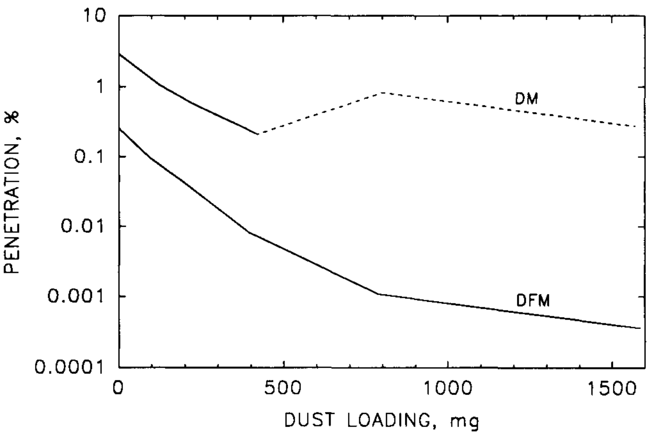

FIGURE 5. Filter penetration for AC Fine Test Dust versus loading with AC Fine Test Dust for two respirator types.

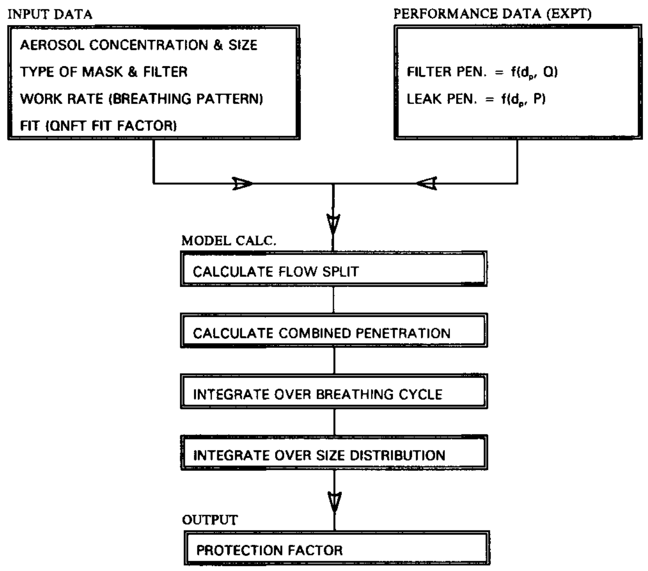

FIGURE 6. Flow chart of respirator performance model.

ciency. As described above, filters were loaded with aerosolized AC Fine Test Dust while connected to a breathing machine simulating human breathing corresponding to a work rate of 68 W (415 kg-m/min). For the DFM filters, efficiency increases (penetration decreases) with increased loading. Efficiency increases because the solid particles collected on the surface of the fibers represent additional collection sites. For the DFM filters the slope of the penetration curve becomes less steep with loading. This is a result of differential collection efficiency with particle size. As the filter becomes loaded and penetration decreases (by more than two orders of magnitude), the proportion of smaller, hard to collect, particles available for collection increases, so that unit loading produces a smaller decrease in penetration.[1]

The situation is different for the disposable DM mask. The penetration curve, although higher, has the same shape up to a loading of 400 mg, shown as a solid line in Figure 5. At a loading of 800 mg the resistance is sufficient to cause the mask to flex with each inhalation and exhalation. This flexing appears to result in a slight decrease in mask performance, increase in penetration, as shown in Figure 5.

Figure 5 suggests that filtration is most likely occurring by mechanical collection. If collection were due electrostatic effects, such as those associated with electret fibers, there would likely be a decrease in efficiency (increase in penetration) as the electret fibers became coated with dust.[2]

The detailed data on filter performance for each loading condition obtained in this article were used in a respirator performance model developed by Hinds and Bellin[16] to evaluate the effect of loading on the overall protection (combined filter penetration and facial seal leakage) provided by the three different half-mask respirators tested. The model also uses data on penetration through facial seal leaks as a function of particle size and pressure drop obtained in an earlier study by Hinds and Bellin.[16] Figure 6 shows a schematic diagram of the model. The model predicts the protection factor (PF) that will be obtained for a given type of respirator, aerosol exposure condition, work rate of the wearer, and fit of the respirator [as measured by quantitative fit test (QNFT)]. Input data include, type of filter used, workrate of the wearer, particle size distribution of the exposure aerosol (MMAD and GSD for a lognormal distribution), and QNFT results. It can only be used for filters for which detailed efficiency as a function of particle size and flow rate data are available.

For each of the seven flow rates used, the model calculates how the flow will split between that going through the filter and that going through the facial seal leaks. Based on the filter and leak penetration data, the model then calculates for each flow rate (7) and particle size (12) the total penetration, filter plus leak penetration. These data are integrated over the breathing cycle, inhalation flow rate versus time, using a 16-point Simpson integration, to give total penetration for each of the 12 particle sizes for a particular work rate. These data are then integrated by Simpson integration, over the exposure particle size distribution (lognormal) to get a predicted total mass penetration for a given use and exposure condition. From these results, various protection factors can be calculated, including the conventional concentration protection factor (outside concentration/average inside concentration during inhalation) used here.

The model was applied at each stage of loading to determine how protection factor changes with loading and to sort out the competing effects due to increased leakage and increased filter efficiency caused by dust loading. Figure 7 shows how the protection factor will change with loading for three types of respirators, each having a satisfactory fit corresponding to a QNFT fit factor of 100. For the DFM and DM respirators there is an initial increase in protection provided until loading exceeds 200 or 400 mg, respectively. For continued loading there is a gradual decrease in protection factor. These changes are the result of the competing ef-

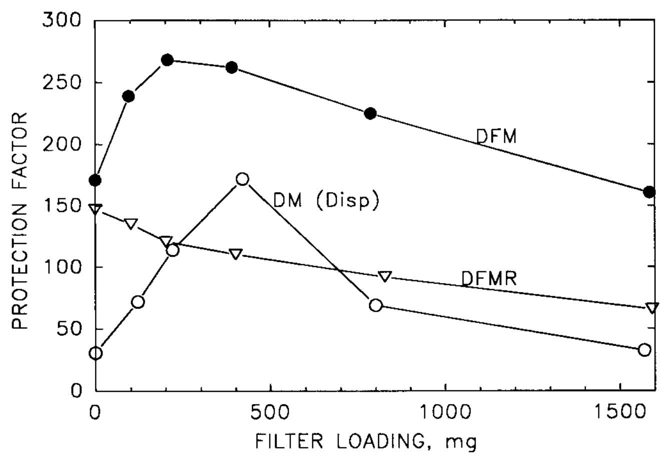

FIGURE 7. Predicted protection factor provided by three types of respirators used for protection against AC Fine Test Dust. QNFT fit factor is 100.

fects of increased filter resistance and efficiency discussed above. Initially the effect of increased filter efficiency is greater than the effect of increased resistance and its associated increase in leakage. The gradual decline results from continued increase in leakage, but with smaller and smaller decreases in penetration with increased loading, as shown in Figure 5. In this situation, when protection factor is decreasing with loading, the loss in protection from increased leakage exceeds the gain in protection from increased filter efficiency. The high efficiency DFMR filter respirator shows no initial increase in protection because the filter efficiency is already very high and the collected dust can only make a small change in efficiency. The collected dust, however, causes a significant increase in resistance, and its attendant leakage, resulting in a decline in protection factor.

It is interesting to note that for the conditions of Figure 7 the respirator equipped with DFM filters provides greater protection than the same respirator with DFMR filters. This is a result of greater facial seal leakage due to the greater resistance of the DFMR filters as compared to the DFM filters.

Because the effect of loading on protection provided by a respirator depends on fit, as well as other variables discussed above, a series of figures similar to Figure 7, each at a different fit factor, would be needed to fully characterize the effect of loading. An alternative approach is used here. Figure 8 summarizes the effect of loading on protection provided by DFM respirators for any value of QNFT fit factor (FF) from 2 to 160. The vertical axis is the initial fit factor from QNFT testing and the horizontal axis is the accumulated amount of dust loading in milligrams. For the purposes of illustration, the calculations for the graph assume that fit remains constant as the respirator becomes loaded with dust. The lines represent contour lines of change in protection factor from initial (clean filter) condition to the indicated loading condition. Thus the effect of loading on protection factor is found by following a horizontal line corresponding to a particular fit factor across (left to right) to the corresponding loading condition. Figure 9 presents similar information for the disposable DM respirator.

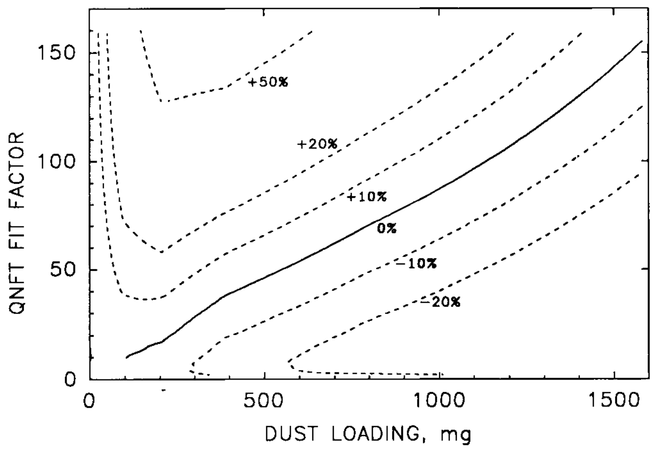

FIGURE 8. Contours showing the change in protection factor for a DFM respirator that occurs for a given loading (AC Fine Test Dust) and QNFT fit factor.

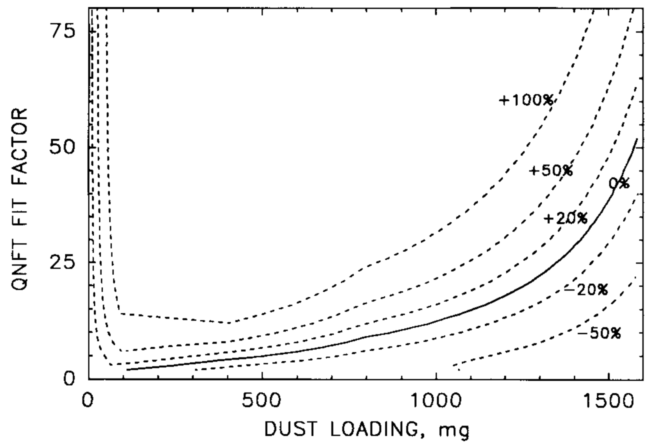

FIGURE 9. Contours showing the change in protection factor for a disposable DM respirator that occurs for a given loading (AC Fine Test Dust) and QNFT fit factor.

Discussion

The protection provided by a DFM dual cartridge respirator with a good fit increases initially, reaching a peak at a loading of about 200 mg (see Figures 7 and 8). This is followed with a gradual decrease in protection with loading. As loading proceeds the protection provided will eventually decrease to the point where it is less than that for the initial (clean filter) condition, defined here as the crossover point. This condition is represented by the 0 percent change line in Figures 8 and 9. For a fit factor of 100, protection reaches this crossover point at a loading of about 1200 mg (see Figure 8). For a DFM respirator with a poor fit, fit factor of 10 to 20, there is only a slight increase followed by a significant decrease in protection with loading. The crossover point thus occurs at much lower loading, about 200 mg.

The situation is more exaggerated for the disposable DM respirator as shown in Figure 9. Except for very poor fitting respirators there is a rapid and significant increase in protection factor with loading. This increase occurs more rapidly and to a greater extent than for the DFM respirator with the same loading. This is due to two factors. First, the initial efficiency is lower to begin with so there is more opportunity for a significant increase in filter efficiency, and second, the filter area of the disposable respirator is about 20 percent of that for the dual cartridge respirator. This means that for a given dust loading the areal density of the deposited dust is almost five times greater for the disposable respirator than for the dual cartridge respirators tested.

As a practical matter the resistance of a DM respirator will have increased significantly by the time it reaches the crossover point. Because of the discomfort resulting from the increased resistance, the respirator would normally be discarded before it reaches the crossover point. The loading required to reach the crossover point represents a use duration of one to two shifts at a dust concentration of 100 mg/m^3 [10 times the nuisance dust threshold limit value (TLV)], assuming an inhaled volume of 7 to 14 m^3/shift. Thus for a fit corresponding to a QNFT fit factor of 100 or greater, loading is unlikely to compromise the protection offered by the disposable DM mask tested except under prolonged exposure at unusually high dust concentrations. In fact, under most conditions of use, loading improves the protection provided.

For the DFMR respirator, the filter efficiency is already very high (greater than 99.9%), and although it increases with loading, this has little effect on overall protection except when used with exceptionally good fits, fit factors greater than a few thousand. Thus the protection provided by DFMR-equipped respirators is dominated by facial seal leakage rather than filter penetration. Loading causes a continuous increase in resistance and leakage with the result that protection factor continuously decreases with loading. Given that the DFMR filter resistance is initially high and the filter would normally be changed before reaching uncomfortable levels at high loading, the maximum decrement in protection factor is estimated to be about a factor of two over the useful life of the filters. It should be noted that, in general, the higher the initial filter efficiency the more likely dust loading is to cause reduced protection. This underscores the need for a good fit when using high efficiency filters.

The information developed here can be used in a different way to predict the lifetime of different respirator filters in a dusty environment. To estimate the practical lifetime of particulate filter respirators, it is necessary to identify the resistance at which most people will change their respirator filter. Unfortunately, there is no clear-cut way to identify this resistance level, because there is no research focused directly on the issue. There is a considerable body of research on the physiological changes that occur as a result of respirator wearing (see for example a summary by NIOSH[17]). There are a few studies that address subjective response to wearing respirators[18-24] but the objectives of each are different and discomfort means something different in each study. The most useful guideline comes from NIOSH respirator certification criteria[25] that identifies respirator resistance for which "the wearer should not experience undue discomfort because of airflow resistance. . . ." The maximum permissible resistance levels for DFM respirators range from 15 to 50 mm H_2O at an air flow rate of 85 L/min. For purposes of this analysis a value of 50 mm H_2O at 85 L/min was taken as a practical resistance limit for particulate filter respirators. Although somewhat arbitrary, 50 mm H_2O is assumed to be the resistance at which most people would notice it and seek to change the filter. This value is consistent with previously published values for the resistance at which discomfort occurs.[18-24] Using this value, an estimate can be made for the maximum useful life of each of the respirator filters tested here. Results are given in Table I as days of use (8-hour shift) at a moderate external work rate of 68 W (415 kg-m/min) to reach a resistance of 50 mm H_2O (at 85 L/min) at a dust concentration of 100 mg/m^3, 10 times the nuisance dust TLV. Higher or lower concentrations will have proportionately shorter or longer useful lifetimes.

TABLE I. Practical Lifetimes for Three Types of Respirator Filters*

Type of Respirator	Practical Lifetime (days)^A
Disposable dust and mist	0.9
Dual cartridge dust, fume mist	3.1
Dual cartridge dust, fume, mist, and radionuclide	1.3

*At a mineral dust concentration of 100 mg/m^3, work rate of 68 W (415 kg-m/min), and 8-h/day.
^{A}Practical lifetime is assumed to occur when filter resistance reaches 50 mm of water (see text).

Results for only one size distribution of dust are presented here, but these results should be typical of mechanically dispersed mineral dust. Although only one model of each respirator filter type was tested here, we expect similar results for other respirator filters meeting the same NIOSH certification tests.

Conclusion

The effect of dust loading on the protection provided by a respirator is complicated because of the interplay of two factors: (1) the increase in filter resistance, with its attendant increase in facial seal leakage; and (2) the increase in filter efficiency that occurs with increased loading. These effects can be evaluated by a combination of experimental and model analysis. The effects depend on the type and fit of the respirator and the size distribution of the exposure dust. Based on data presented here we can conclude that in situations where QNFT gives a fit factor of 100 or more, loading is beneficial in terms of protection factor for disposable DM and dual cartridge DFM respirators, at least until 1 g of dust is collected on the filters. Loading decreases the protection provided by respirators using high efficiency (DFMR) filters. Under the usual conditions of use the change in protection factor due to loading is unlikely to exceed a factor of two or three.

Acknowledgment

This research was funded in part by PHS (NIOSH) research grant number 1 RO1 OH 01595.

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