FINAL REPORT

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Respirator Performance Model for Particulates

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Public Health Service
Centers for Disease Control Assistance
National Institute for Occupational Health and Safety
Award Number 5 R01 O01595

November 1992

TABLE OF CONTENTS

Final Report in the Form of a Compendium of Manuscripts

1. Introduction

Half mask and disposable air-purifying respirators are used widely in American industry with the largest application of these respirators being for respiratory protection against airborne particles (aerosols such as dust, fume, smoke, and mist). Filter penetration, facial seal leakage, and, under some circumstances, exhalation valve leakage represent the primary routes of inhalation exposure for a respirator wearer.

The ability of airborne particles to penetrate the filters, exhalation valves, and facial seal leaks of air-purifying respirators depends strongly on particle size as does the respiratory hazard associated with these particles. Thus, the actual protection obtained for a given exposure to airborne particles will depend on the particle sizes present in the work place environment. No general data exist to describe the performance of respirators as a function of particle size distribution. This study characterizes the effect of particle size distribution on the performance of representative single-use, half-mask, and full-face respirators.

2. Objectives

Overall Objectives
The overall objective of this grant is to extend our understanding of the effect of particle size on the performance of air-purifying respirators for protection against particulate exposures. This is accomplished through experimental measurement of filter, exhalation valve, and facial seal leak performance as a function of particle size and flow rate and the use of these data in a computer model to predict overall performance for a respirator under a wide range of conditions based on measured leakage, airborne particle size distribution, and the work rate of the wearer. The model is a useful tool for respirator research and a useful screening tool for respiratory protection programs.

Specific Aims
Specific aims were to: 1) Develop an experimental set-up to measure respirator and leak penetration as a function of particle size and flow rate through the respirator. 2) Perform detail laboratory evaluations of respirator filter performance as a function of particle size and flow rate. 3) Perform detail laboratory measurements of penetration of particles through facial seal leaks as function of particle size and pressure drop. 4) Develop a predictive model using these data that gives performance (overall protection factor including filter penetration and facial seal leakage) of half-mask respirators for protection against aerosols. 5) Evaluate leakage of normal and impaired exhalation valves during inhalation as a function of particle size and flow rate. 6) Perform model validation measurements with human subjects wearing respirators. 7) Evaluate the performance of respirator filters as they become loaded with dust and determine the effect of dust loading on the protection provided. 8) Evaluate the penetration characteristics of facial seal leaks for full-face masks.

3. Significant Findings

1. Through this study we have demonstrated that the quantitative aspects of respirator performance for protection against aerosols can be modeled with sufficient precision to provide useful insight into the nature of the protection provided by half-mask respirators. The particular aspects that can be accounted for include 1) use of different filters for fit testing and use, 2) different breathing patterns associated with the work rate of the wearer, and 3) different particle size distribution of the exposure aerosol. Used in this way this predictive model represents a relatively simple and inexpensive alternative to workplace protection factor studies with comparable accuracy.

2. Because Dust and Mist (DM) and Dust, Fume, and Mist (DFM) filter penetration depend strongly on aerosol particle size, the particle size distribution inside a respirator will almost always be different from that outside the respirator. Filter penetration is low for DFM filters for particles greater than 1 μm and for DM filters for particles greater than 2 μm. Filter penetration and facial seal leakage for each particle size, and their relative contributions, are strongly influenced by the instantaneous flow rate through the respirator during the breathing cycle. The net effect for most dust exposures will be a significant enhancement in the relative mass contribution due to submicrometer particles inside the respirator. Thus a protection factor based on total mass may be misleading for a pneumoconiosis producing dust where the smaller respirable particles are of primary concern. Predicted protection factors for the same respirator and fit varied over a 100 fold range depending of the aerosol exposure size distribution.

3. As dust accumulates on respirator filters it modifies respirator performance in two ways. First, the accumulated dust increases the resistance of air flow through the filters. This increased resistance results in an increase in facial seal leakage. Second the accumulated dust increases the collection efficiency of the filters. These effect tend to counteract one another so that protection provided by DFM and DM filters increases initially with loading, but decreases as loading continues. For loading up to 1.5 g the protection factor at maximum loading is 50% or more of the initial protection factor.

4. Properly functioning exhalation valves allow minimal leakage of contaminants into the respirator, less than 0.01%. The exhalation valve is, however, a relatively sensitive component of a respirator. Significant leakage can occur if the exhalation valve becomes dirty or warped, or if fibers or foreign objects become trapped between the valve and the valve seat. Valve leakage of more than 1% was observed when a 250 μm wire was placed between the valve and the valve seat. Dirt or paint on the valve seat allowed a similar level of leakage. This amount of leakage is significant, especially for full-face masks and supports the recommendation that exhalation valves be inspected on a regular basis.

5. The model developed in this project was used to estimate the loss of particles from the airflow passing through a facial seal leak. Based on published size distributions, properly conducted quantitative fit test measurements using current equipment accurately reflect facial

seal leakage with particle size dependant loss in facial seal leaks introducing an error of less than 5%.

6. The proportion of inhaled air that goes through a facial seal leak varies with the instantaneous breathing rate and may change several fold over the normal range of inhalation flow rates. Consequently, the same respirator with the same fit (poor) may provide three times as much protection at a work rate 622 kg-m/min than at a work rate of 0 kg-m/min. By contrast a good fitting respirator can provide twice the protection at a work rate of 0 kg-m/min than at 622 kg-m/min due to lower filter penetration at lower flow rates.

7. Respirator filter performance was found to vary significantly between types and between brands within a type. A new filter was used for each test so results are equivalent to those for clean filters. The relative standard deviation of penetration measurements for three brands of Dust, Fume and Mist (DFM) filters was 65% and for three brands of disposable respirators it was 77%.

4. Publications

Relation to specific aims

Two publications, Hinds W, Kraske G: A bench-scale aerosol test chamber. Appl Ind Hyg 2:13-17, 1987 and Hinds WC, Kraske G: Performance of PMS Model LAS-X Optical Particle Counter. Journal of Aerosol Science 17:67-72, 1986, describes the development and calibration of the experimental set-up used for the filter and leak performance measurements, **specific aim 1)**. The set-up permits measuring penetration quickly for the full range of operating conditions necessary to assemble the filter data bases and predictive equations used by the model.

The publication, Hinds W, Kraske G: Performance of dust respirators with facial-seal leaks: I. Experimental. Am. Ind. Hyg. Assoc. J. 48:836-841, 1987, describes the measurements made for filter and leak tests, **specific aim 2) and 3)**. For a given leak condition the percentage of the total flow traversing the leak varied several fold over the usual range of air flow rates through a respirator. Aerosol penetration was found to depend strongly on particle size and flow rate for filters, and to depend strongly on particle size and less strongly on pressure drop for leaks.

The publication, Hinds WC, Bellin P: Performance of Dust Respirators with Facial-Seal Leaks: II. Predictive Model. Am Ind Hyg Assoc J 48:842-847, 1987, Describes the respirator performance model developed under this grant, **specific aim 4)**. The model predicts quantifiable aspects of respirator performance associated particle size distribution and work rate of the wearer. It utilizes the experimental databases on filter and leak performance to predict overall respirator performance for any work rate and exposure aerosol size distribution for a known respirator filter and facial seal leak condition. Simplified methods using regression equations are also given.

The publication, Hinds WC, Bellin P: Effect of Facial-Seal Leaks on Protection Provided by Half-Mask Respirators. Appl Ind Hyg 3:158-164, 1988, presents applications of the computer model for various use situations. This is directed to **specific aim 4)**. Through use of the model it can be shown that the error in quantitative fit measurement due to particle loss in facial seal leaks is less than 5% with current equipment. Predicted protection factors for the same respirator and fit varied over a 1000 fold range depending of the aerosol exposure size distribution.

As the title suggests the publication, Bellin P, Hinds WC: Aerosol Penetration Through Respirator Exhalation Valves. Am Ind Hyg Assoc J 51:555-560, 1990, addresses **specific aim 5)**. Under normal use conditions penetration of aerosol particles through exhalation valves is minimal. An object of 250 μm on the valve seat can cause valve leakage of about 1%, a significant degradation of valve performance.

The draft publication, Hinds WC, Bellin P: The Effect of Respirator Dead Space on Exposure Estimates, describes the development, testing, and application of equations that predict the effect of respirator dead space on average inhalation concentration and related quantities. This paper addresses an important requirement, necessary for correct data analysis, for the validation of the human subject tests, **specific aim 6)**. For example, workplace protection factor measurements with half-mask respirators under typical conditions have average inhalation concentrations that are 105 to 128% of measured full cycle average concentration. These results were presented at the Orlando, FL AIHC in 1990. Presentation was titled "Respirator Dead Space: Effect on Estimates of Dose."

In preparation is a paper describing the results of the human subject validation tests, **specific aim 6)**. Sixteen subjects were fit tested and wore respirators in a controlled test atmosphere with two aerosol size distributions and at two work rates. Overall penetration based on average inhalation concentration was measured and predicted with the model described above. Results are shown in Figure 1. The correlation coefficient between the measured and predicted penetration was 0.7, indicating that the model predicts about half of the variability of respirator performance.

Two papers are in preparation describing the effect of dust loading on overall respirator performance, including facial seal leakage, **specific aim 7)**. Loading with dry aerosol increases filter resistance and decreases filter penetration. Because the former increases facial seal leakage and the latter reduces filter penetration, the effects counteract each other and normal loading causes less than a factor of two change in overall respirator performance. Examples of the effect of loading on respirator performance for two fit conditions and three particle size distributions are shown in Figures 2 and 3. Figures 4 and 5 show the effect of loading on protection provided by three types of half mask respirators at two fit conditions.

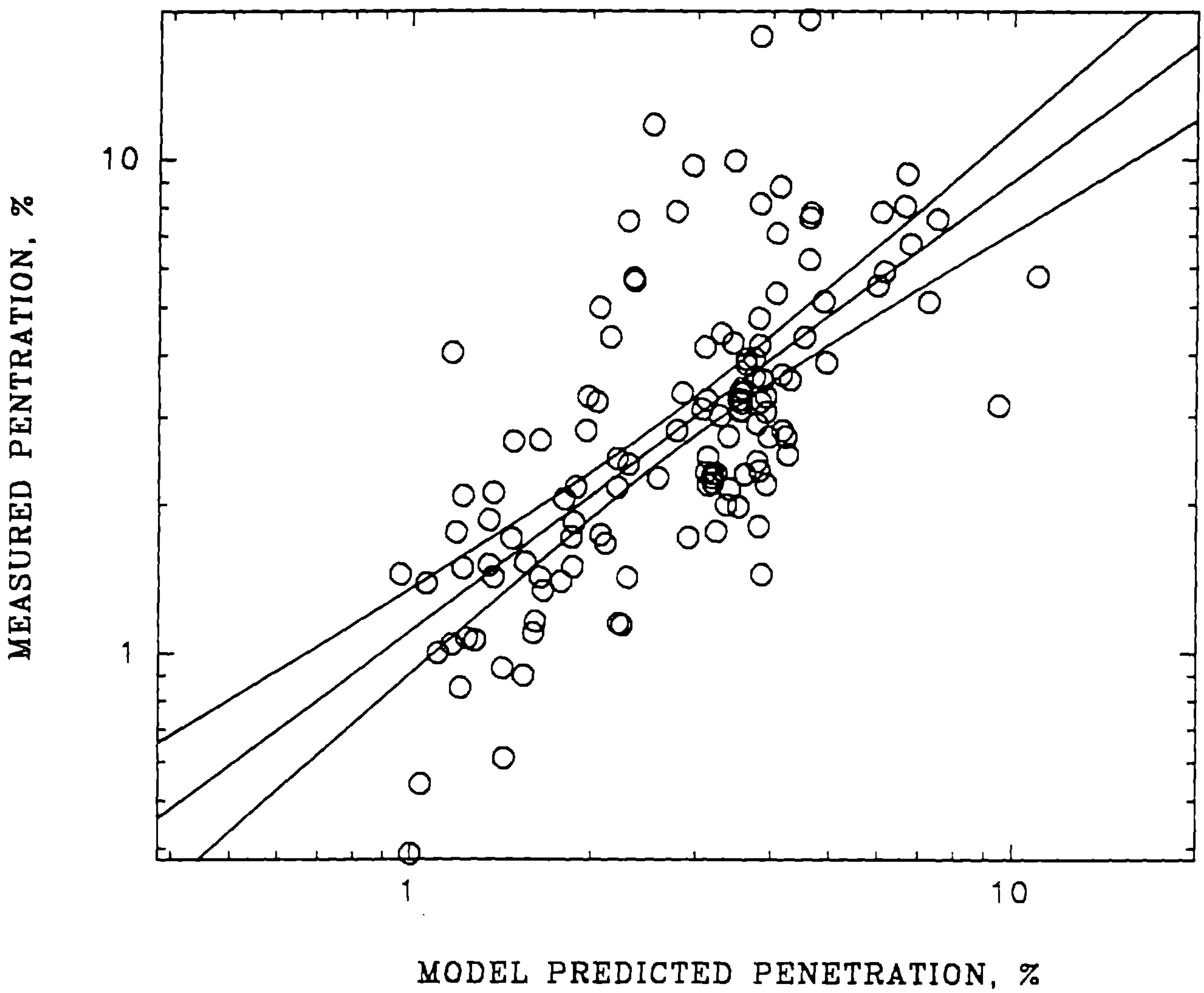

Figure 1. Results of Human Subject Validation Tests

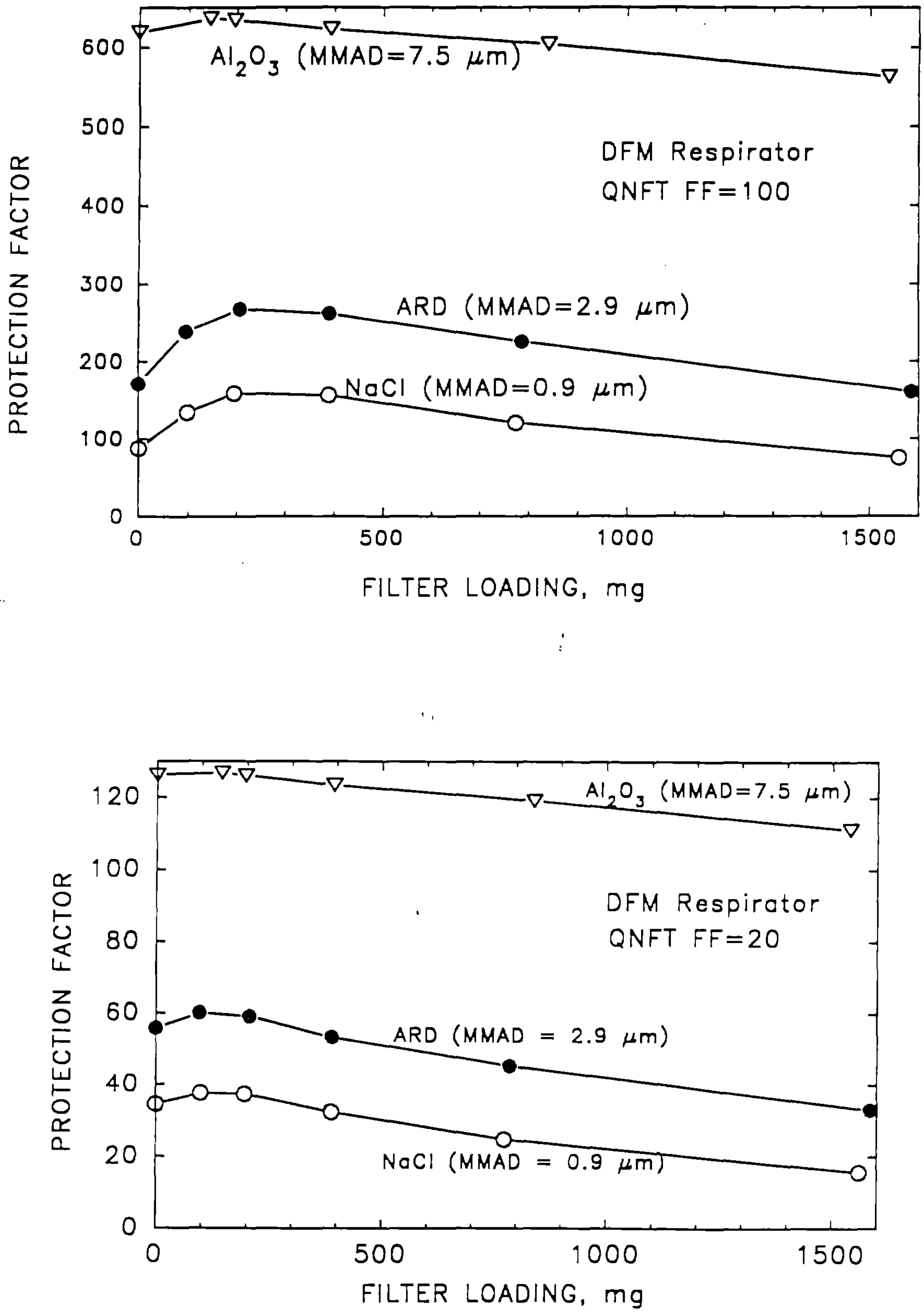

Figure 2 and 3. Effect of dust loading on predicted protection factor for three particle size distributions. Top: FF=100. Bottom: FF=20.

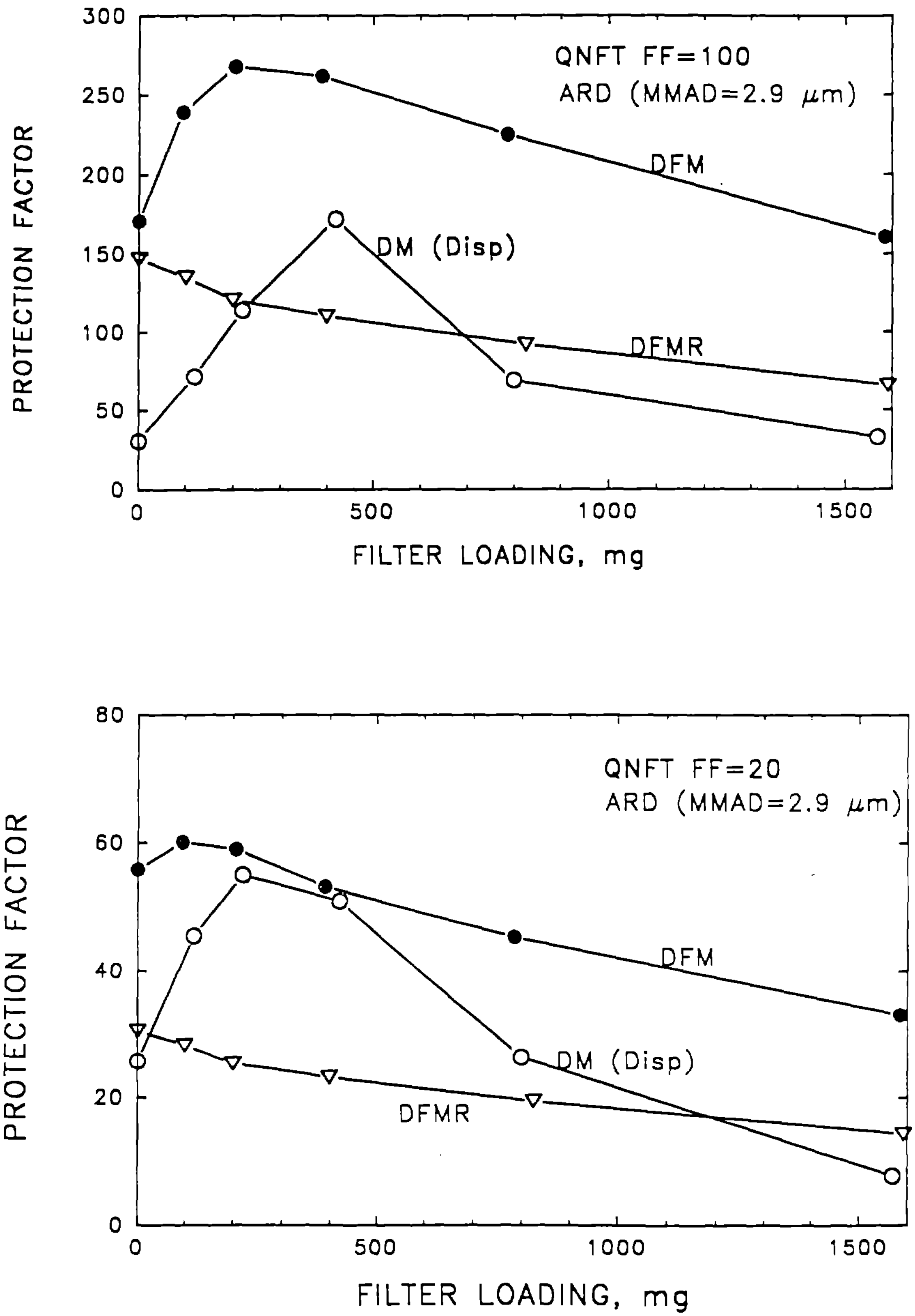

Figure 4 and 5. Effect of dust loading on predicted protection factor for three types of half-face respirators. Top: FF=100. Bottom: FF=20.

Measurements were conducted to determine facial seal leakage for full-face masks and to compare these results with those for half masks, **specific aim 8)**. Generally there was little difference in leak penetration as a function of particle size and pressure drop between the two types of masks. This allows the model to be used to predict the performance of full-face masks as well as half-masks.

List of publications

Hinds WC, Bellin P: The Effect of Respirator Dead Space on Exposure Estimates. Submitted.

Bellin P, Hinds WC: Aerosol Penetration Through Respirator Exhalation Valves. Am Ind Hyg Assoc J 51:555-560, 1990

Hinds WC, Bellin P: Effect of Facial-Seal Leaks on Protection Provided by Half-Mask Respirators. Appl Ind Hyg 3:158-164, 1988

Hinds WC, Kraske G: Performance of Dust Respirators with Facial-Seal Leaks: I. Experimental. Am Ind Hyg Assoc J 48:836-841, 1987

Hinds WC, Bellin P: Performance of Dust Respirators with Facial-Seal Leaks: II. Predictive Model. Am Ind Hyg Assoc J 48:842-847, 1987

Hinds WC, Kraske G: A Bench-Scale Aerosol Test Chamber. Appl Ind Hyg 2:13-17, 1987

Hinds WC, Kraske G: Performance of PMS Model LAS-X Optical Particle Counter. J of Aerosol Science 17:67-72, 1986

Hinds WC, Kraske G: Performance of PMS Model LAS-X Optical Particle Counter (extended abstract) in Aerosols: Science, Technology and Industrial Application of Airborne Particles. (eds. Liu, Pui, Fissan), p 31-34, Elsevier, New York. Presented at First International Aerosol Conference Minneapolis, MN. September 17-21, 1984

Unpublished Articles

Kadrichu NP, Hinds WC: The Effect of Dust Loading on Filter Characteristics. Poster presented at the Am Assoc Aerosol Res 11th Annual Meeting, San Francisco, CA, Oct 12-16, 1992.

Hinds WC, Kadrichu NP: The Effect of Dust Loading on the Performance of Half-mask Respirators. Presented at the 1992 American Industrial Hygiene Conference and Exposition, Boston, MA, June 1, 1992.

Kadrichu NP, Hinds WC: Practical Lifetime for Dust Respirators. Student Poster presentation at the 1992 American Industrial Hygiene Conference and Exposition, Boston, MA, June 1, 1992.

Hinds WC, Kadrichu NP: The Effect of Dust Loading on the Performance of Half-mask Respirators. Presented at the Am Assoc Aerosol Res 10th Annual Meeting, Traverse City, MI, October 7-11, 1991

Hinds WC, Bellin P: The Effect of Respirator Dead Space on Exposure Estimates. Am Ind Hyg Assoc J, submitted, 1991

Kuo TL, Risi D, Hinds WC: Experimental Design for Validation of a Respirator Performance Model. Student poster presented at American Industrial Hygiene Conference and Exposition, Salt Lake City, UT, May 1991 (Abstract)

Kadrichu NP, Chou CC, Hinds W: Prediction of the Effect of Dust Loading on Filter Performance. Student poster presented at American Industrial Hygiene Conference and Exposition, Salt Lake City, UT, May 1991 (Abstract)

Hinds WC, Bellin P: Respirator Dead Space: Effect on Estimates of Dose. Presented at the American Industrial Hygiene Conference, Orlando, FL, May 13-18, 1990 (Abstract)

Hinds WC: Modeling Respirator Performance for Aerosols. Presented at the Third International Meeting of the ISRP, November 6-9, 1989

Hinds WC: Effect of Respirator Dead Space on Inhaled Dose. Presented at the American for Aerosol Research Annual Meeting, Reno, NV, October 10-13, 1989

Bellin P, Hinds WC: Performance of Respirator Exhalation Valves. Presented at the American Industrial Hygiene Conference, St. Louis, MO, May 25, 1989

Bellin P: Respiratory Protection: An Evaluation of Exhalation Valve Performance, Effect of Dead Space on Inhalation Exposure, and Current Use, Ph.D. Thesis, U of California, Los Angeles, 1989

Hinds WC, Bellin P: Aerosol Leakage Through Respirator Exhalation Valves. Presented at American Association for Aerosol Research Annual Meeting, Chapel Hill, NC, October 10–14, 1988 (Abstract)

Hinds WC: Performance of Respirator Filters and Facial Seal Leaks. Presented at American Association for Aerosol Research Annual Meeting, Seattle, WA, September 14-17, 1987 (Abstract)

Hinds W, Bellin P: Modeling the Performance of Half-mask Respirators. Presented at the American Industrial Hygiene Conference, Montreal, PQ, Canada, May 31-June 5, 1987

Hinds WC, Kraske G: Performance of Half-Mask Respirators with Facial-Seal Leaks. Presented at the 1986 American Industrial Hygiene Conference, Dallas, TX, May 18-22, 1986 (Abstract)

Hinds WC, Kraske G: Evaluation of Nebulizers for Use With Optical Particle Counter. Presented at the 1985 meeting of the American Association for Aerosol Research in Albuquerque, NM, November 18-22, 1985 (Abstract)

Planned Publications

Hinds WC, Risi D, Kuo TL: Validation of a Predictive Computer Model for Respirator Performance.

Hinds WC, Kadrichu NP: The Effect of Dust Loading on Filter Characteristics.

Hinds WC, Kadrichu NP: The Effect of Dust Loading on the Performance of Half-mask Respirators.

50272-101

REPORT DOCUMENTATION PAGE	1. REPORT NO.	2.	PB93-214260

4. Title and Subtitle Respirator Performance Model for Particulates

5. Report Date 1992/11/30

6.

7. Author(s) Hinds, W. C.

8. Performing Organization Rept. No.

9. Performing Organization Name and Address Department of Environmental Health Sciences, Center for Occupational and Environmental Health, UCLA School of Public Health, Los Angeles, California

10. Project/Task/Work Unit No.

11. Contract (C) or Grant(G) No.
(C)
(G) R01-OH-01595

12. Sponsoring Organization Name and Address

13. Type of Report & Period Covered

14.

15. Supplementary Notes

16. Abstract (Limit: 200 words) The effect of particle size distribution on the performance of representative single use, half mask, and full face respirators was investigated. An experimental set up was developed to measure respirator and leak penetration as a function of particle size and flow rate through the respirator. Detailed studies were performed of respirator filter performance. Measurements were made of particles penetrating the facial seal leaks. A predictive model was developed using these data which can be used to determine the performance of half mask respirators for protection against aerosols. An evaluation was performed of the leakage of normal and impaired exhalation valves during inhalation. Model validation measurements were performed for respirator filters as they became filled with dust. The penetration characteristics of facial seal leaks for full face masks were evaluated. The authors conclude that it is possible to model the performance of respirators with enough precision to provide useful insight into the protection being offered by half mask respirators. Dust accumulating on the respirator increases the resistance of air flow through the filters and increases the collection efficiency of the filters. Respirator filter performance varied significantly between types and between brands within a type.

17. Document Analysis a. Descriptors

b. Identifiers/Open-Ended Terms NIOSH-Publication, NIOSH-Grant, Grant-Number-R01-OH-01595, End-Date-08-31-1992, Respirators, Personal-protective-equipment, Respiratory-protection, Equipment-reliability, Face-masks

c. COSATI Field/Group

18. Availability Statement	19. Security Class (This Report)	21. No. of Pages 12
	22. Security Class (This Page)	22. Price

(See ANSI-Z39.18) See Instructions on Reverse OPTIONAL FORM 272(4-77)
(Formerly NTIS-35)
Department of Commerce