

Workplace Protection Factors for Negative Pressure Half-Mask Facepiece Respirators

Stephen W. Dixon
E. I. Du Pont de Nemours & Company
Central Research & Development Department
Haskell Laboratory
P.O. Box 50, Elkton Road
Newark, Delaware 19711

and

Thomas J. Nelson
E. I. Du Pont de Nemours & Company
Finishes & Fabricated Products Department
1007 Market Street
Wilmington, Delaware 19898

Abstract

The primary objective of our study was to determine the protection provided by respirators as used in the workplace by persons who have been adequately trained and have passed the isoamyl acetate qualitative fit test. A secondary objective was to determine whether spot quantitative fit tests could be used as a simpler and less expensive method of doing workplace protection factor studies. Analysis of the data collected shows that:

- Negative pressure half-face respirators with elastomeric facepieces, when properly selected, fit tested using the isoamyl acetate method, and used by trained wearers, provide *workplace protection factors* that exceeded the current assigned protection factor of 10.
- Negative pressure half-face respirators also provided *program protection factors* that exceeded the current assigned protection factor of 10, as shown by an analysis of biological monitoring and air monitoring data for lead.
- Quantitative fit testing cannot be used to quantitatively predict workplace performance of respirators for an individual.

Introduction

The respirator protection factor or assigned protection factor is defined by the ANSI Z88.2 (1980) standard as a measure of the degree of protection provided by a respirator to the wearer. It is generally assumed that a person using a particular class of respirator will achieve a degree of protection at a level above this assigned factor.

For half-mask facepiece respirators, the ANSI standard, the American Industrial Hygiene Association (Birkner, 1980), the NIOSH Guide to Respiratory Protection (Pritchard, 1976), and OSHA standards, e.g., lead (29 CFR 1910.1025), and acrylonitrile (29 CFR 1910.1045), contain a recommended assigned protection factor of 10. Using

this assigned factor, the capabilities and limitations of the respirator and the results of fit tests must be taken into account (ANSI Z88.2, 1980).

Assigned protection factors were developed as a result of the consensus of opinion on respirator performance, based on studies of respirator fit using quantitative fit-test methods (Hyatt, 1975). Insufficient data exist on whether assigned protection factors are actually achieved in the workplace.

The primary objective of this study was to determine the protection provided by half-mask facepiece respirators used in the workplace by persons who had been adequately trained and who had passed the isoamyl acetate qualitative fit test (National Paint and Coatings Association, 1982). A secondary objective was to determine whether quantitative fit tests could be used to check randomly the fit provided by respirators as they are worn in the workplace. This would be a simpler and less expensive method for conducting workplace protection factor studies.

We will be using new terms in this paper and they are defined below.

Quantitative Fit Factor (QNFF): A quantitative measure of the fit of specific respirator to a particular individual determined by a quantitative fit test. QNFF is the ratio of the concentration of the test atmosphere outside the respirator to the concentration inside.

Assigned Protection Factor (APF): The minimum expected degree of protection that is provided by a properly functioning respirator, or class of respirators, to a large percentage of properly fitted and trained users. It is the expected ratio of the contaminant concentration outside the respirator to that inside.

Workplace Protection Factor (WPF): A measure of the protection provided when a properly functioning respirator is correctly worn in the workplace. It is the ratio of the contaminant concentration outside the respirator to that inside. WPF is determined by sampling outside and within the respirator only during the time the respirator is worn.

Program Protection Factor (PPF): A measure of the actual protection provided by an established respirator program. It is determined by sampling outside and within the respirator during the workshift period, in the actual context of the existing respirator program, regardless of whether the respirator is properly functioning or worn.

Study Population

Subjects for this study consisted of 11 males (7 blacks and 4 whites). Ages ranged from 31 to 60.

The work rate of the study subjects was judged to be moderate to heavy, based on the amount of lifting and movement they were required to do (American Conference of Governmental Industrial Hygienists). Movements included walking, lifting, bending, squatting, and turning torso and head frequently.

Protective equipment worn in addition to the respirators included safety glasses and hard hats.

Training and Fit Testing

A protocol developed by DuPont and published by the National Paint and Coatings Association, "A Guide to Respirator Fit Testing" (National Paint and Coatings Association, 1982), which uses isoamyl acetate, was followed for training and fitting. Each employee viewed the slide/sound training program and then selected a respirator from an array of three mask sizes of Survivair 2000 half-mask facepiece respirators equipped with organic vapor/high efficiency particulate filters. Everyone in the study passed the fit test and was assigned a respirator. A quantitative fit test was run to compare with subsequent workplace protection factors. A log probability distribution plot of the initial quantitative fit factors is shown in Fig. 1.

All quantitative fit tests were run on the Dynatec/Frontier FE250A portable quantitative fit-test unit. For the fit test, the six exercises recommended in the ANSI Z88.2 (1980) standard were performed. Each fit factor was calculated by dividing the average chamber concentration by the average peak leakage. The average peak leakage was calculated by averaging the peak heights for each breathing cycle within an exercise and then averaging each exercise.

In addition to the initial quantitative fit tests, paired quantitative fit tests were conducted immediately before and after approximately half the workplace protection factor determinations. These paired fit tests were used to indicate whether quantitative fit tests can predict workplace protection factors. A log probability distribution plot of the average of paired before and after quantitative fit factors is given in Fig. 2.

Distribution of Quantitative Fit Factors - Initial Test

Geometric Mean = 1,000

Range = 350 to 1,750

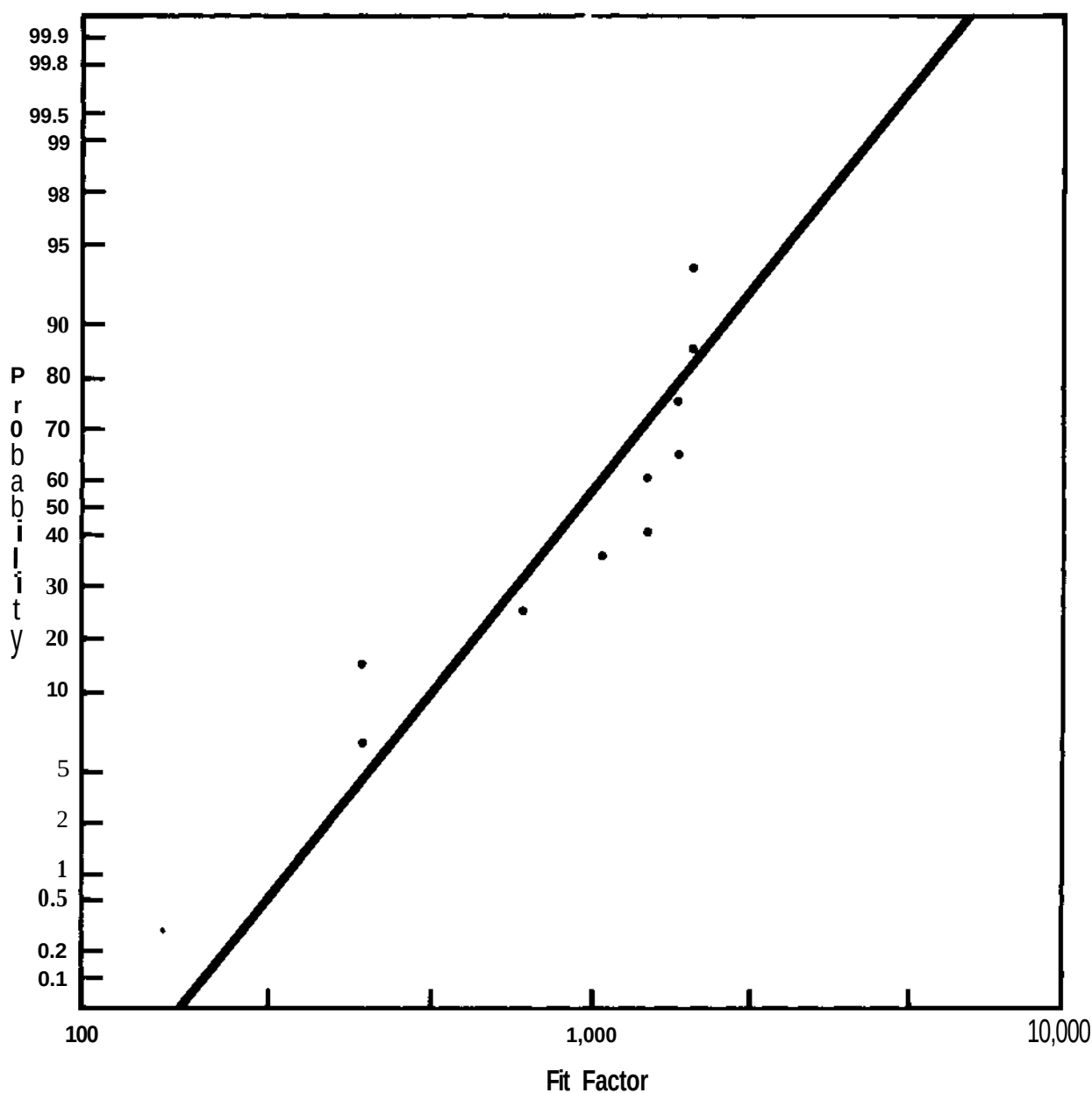


FIGURE 1

Sample Collection and Analysis

Air samples were collected for a sample period of 30 minutes to 2 hours, which represented a complete job cycle. During the period, the em-

ployee was observed to ensure that the sampling train and sampling pump performed properly and to document actions, such as readjusting the

Distribution of Averages of Before and After Quantitative Fit Factors Geometric Mean = 750 Range = 35 to 4,460

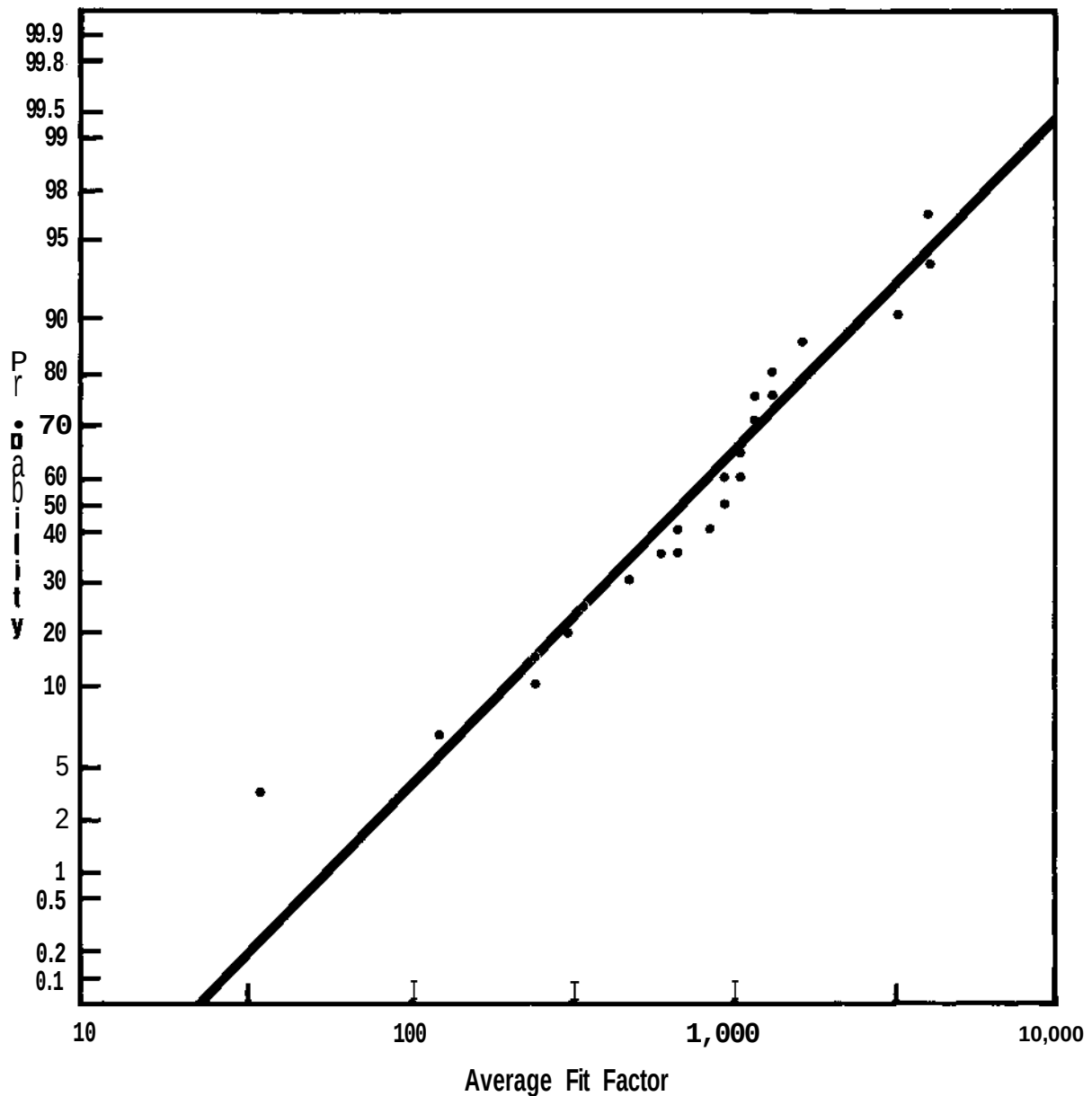


FIGURE 2

facepiece or talking, which might affect the workplace protection factor.

Prior to the start of our study, we told the employees that researchers would be following them around during sampling. To minimize the effect of our presence, we said the purpose of our

careful observation was to watch the sampling equipment. The employees soon ignored us since they were busy with their work activities.

A field procedure was devised and used to minimize potential sample contamination. This procedure is contained in Appendix A.

The respirators used in the field test portion of the study were equipped with high-efficiency filters. At the end of the each day, each respirator was disassembled, cleaned, and washed in a quaternary ammonium salt solution, dried, reassembled, and inspected.

Samples were collected using DuPont P2500 air pumps. The sampling equipment was calibrated before and after each day's sampling with a Kurz Model 541 mass flow meter. The mass flow meter was calibrated before and after each day's use with a bubble flow meter. All samples were collected at a flow of 2 liters per minute.

The workplace chosen for this study contained airborne lead. Based on past air monitoring data and the availability of a sensitive and precise analytical method, proton induced x-ray emission analysis (PIXEA), we anticipated that workplace protection factors in excess of 1000 could reliably be measured.

PIXEA is done by analysis of characteristic x rays which are emitted when outer shell electrons cascade to fill the inner shells of an atom. Inner shell electrons are ejected by bombardment of the sample with high energy protons. The energy of the characteristic x rays is equivalent to the energy difference between the inner and outer shells (Johansson and Johansson, 1976).

All samples were collected on 0.8 μm polycarbonate (Nucleopore®) filters because of their low background metal content (Table 1). Filter diameters of 25 mm were chosen to increase the sensitivity of PIXEA analysis and to minimize the

effect the sampling equipment might have on the workers' vision.

The advantages of this method over other analytical methods are:

- It is nondestructive.
- All elements with an atomic number greater than 10 are detected.
- There is minimal sample penetration.
- There is excellent sensitivity and precision.

The analysis was accomplished by mounting the filters on a Mylar® sheet. The mounting anchored the particulates and enabled the sample to be suspended in a Van de Graaff accelerator path where it was bombarded with high energy protons for analysis. The analyses were performed by Purdue University's Department of Physics.

Analytical precision (95 percent confidence limits) for lead was less than ± 6 percent at 0.07 $\mu\text{g}/\text{m}^3$ (geometric mean of airborne concentrations inside the respirators) and less than ± 5 percent at 225 $\mu\text{g}/\text{m}^3$ (geometric mean of airborne concentrations outside the respirators). The limit of detection was 2 nanograms (ng) per sample.

Table 1. Background leak on Nucleopore®, 0.8 μm filters (25 mm).

Number of filters	10
Mean	3.7 ng
Standard deviation	1.6 ng

Results and Discussion

The workplace protection factors were calculated using the following equation:

$$\text{WPF} = \frac{(M_O - M_B)/V_O}{(M_I - M_B)/V_I}$$

where

M_O = ng of analyte on outside filter

M_B = mean ng of analyte on blank filters

M_I = ng of analyte on inside filter

V_O = volume of air sampled through outside filter

V_I = volume of air sampled through inside filter.

No attempt was made to correct workplace protection factors for lung retention of lead particulates. The amount of particulates collected

during exhalation is generally expected to be lower than during inhalation because of deposition in the respiratory tract. Inhalation constitutes 40 percent of the breathing cycle (Gayton, 1976). Total respiratory deposition for the 1.8 μm aerodynamic diameter lead particulate we studied is approximately 20 percent (Chan and Lippman, 1980).

For our study, we sampled inside the facepiece during both inhalation and exhalation. We expected resultant concentrations inside the respirator would be approximately 12 percent lower than they would have been had we sampled only during inhalation. The calculated workplace protection factors were not adjusted for this small bias.

Simultaneous sampling also showed that the sample probes used to connect the filters to the respirator facepiece resulted in an approximately 25 percent sample loss. The probes used were the standard probes provided for quantitative fit testing by Frontier Enterprises. All results for samples inside the facepiece have been corrected for this loss.

Particle size analyses were done with light microscopy and scanning electron microscopy. Samples for light microscopy were collected on 25 mm, 0.8 μm cellulose ester filters. Samples for scanning electron microscopy were collected on 25 mm, 0.8 μm polycarbonate filters. The lead particulates had a mass mean diameter of 0.7 μm and a geometric standard deviation of 2.7. Adjusting for particle density (6.4 g/cm³) using Stokes law (Mercer, 1973) gives an approximate aerodynamic diameter of 1.8 μm .

The means and ranges of workplace protection factors found in this study are shown in

Fig. 3. A one-way analysis of variance showed the data are comparable for ten of the subjects and borderline for one at the 5 percent probability level. Therefore, workplace protection factors for all test subjects were statistically analyzed together for this paper.

The geometric mean of the 37 workplace protection factors is 3400. The geometric standard deviation is 3.8. The values ranged from 94 to greater than 27,000. The distribution of workplace protection factors is approximately lognormal as shown in the log probability plot in Fig. 4.

In some cases, we observed that an employee would break the facepiece-to-face seal to talk. When those values for workplace performance are combined with the undisturbed facepiece data, we find a geometric mean of 2400, a geometric standard deviation of 5.1, and a range from 40 to greater than 27,000. A log probability distribution similar to the one in Fig. 4 was found; it is shown in Fig. 5.

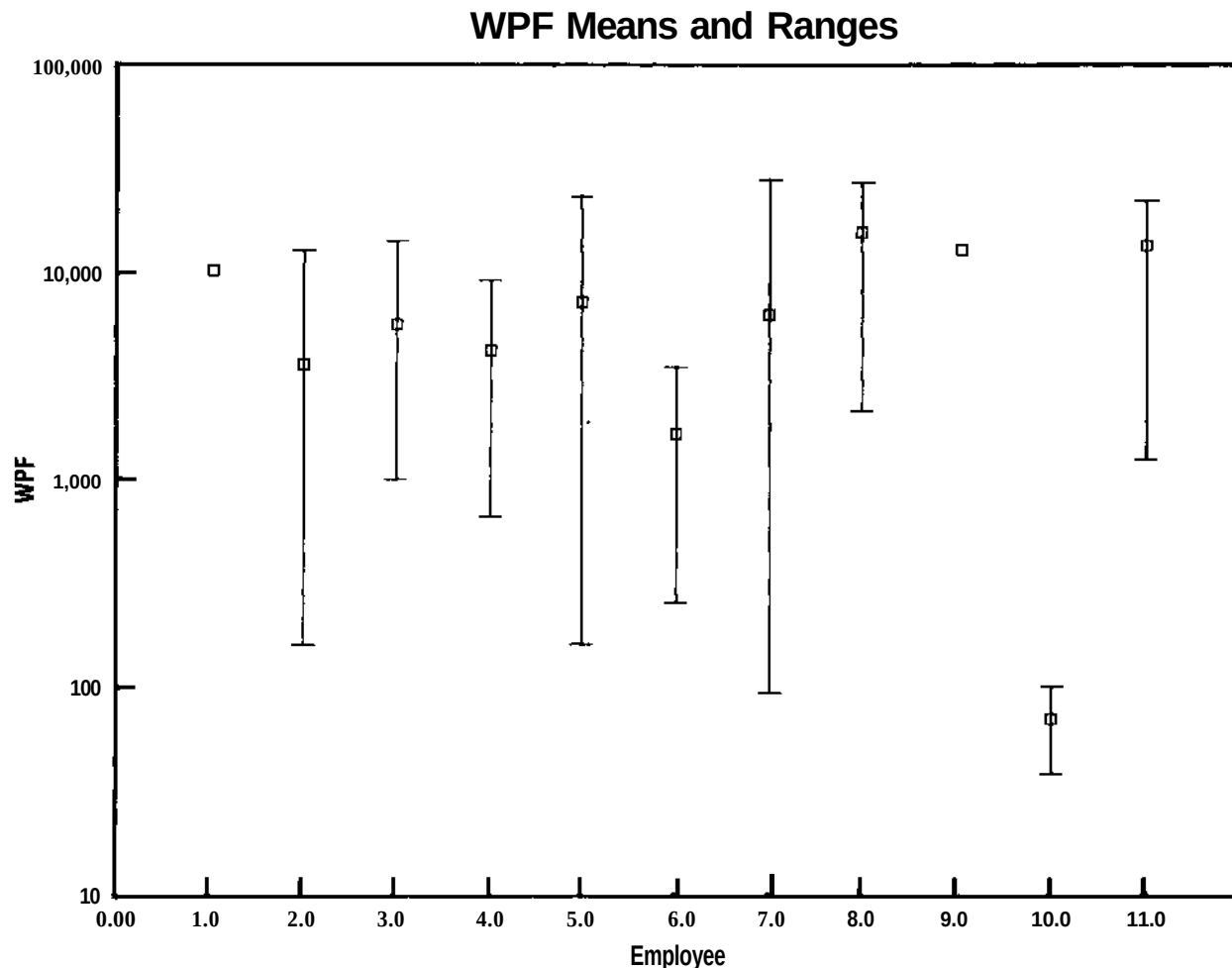


FIGURE 3

Distribution of Workplace Protection Factors

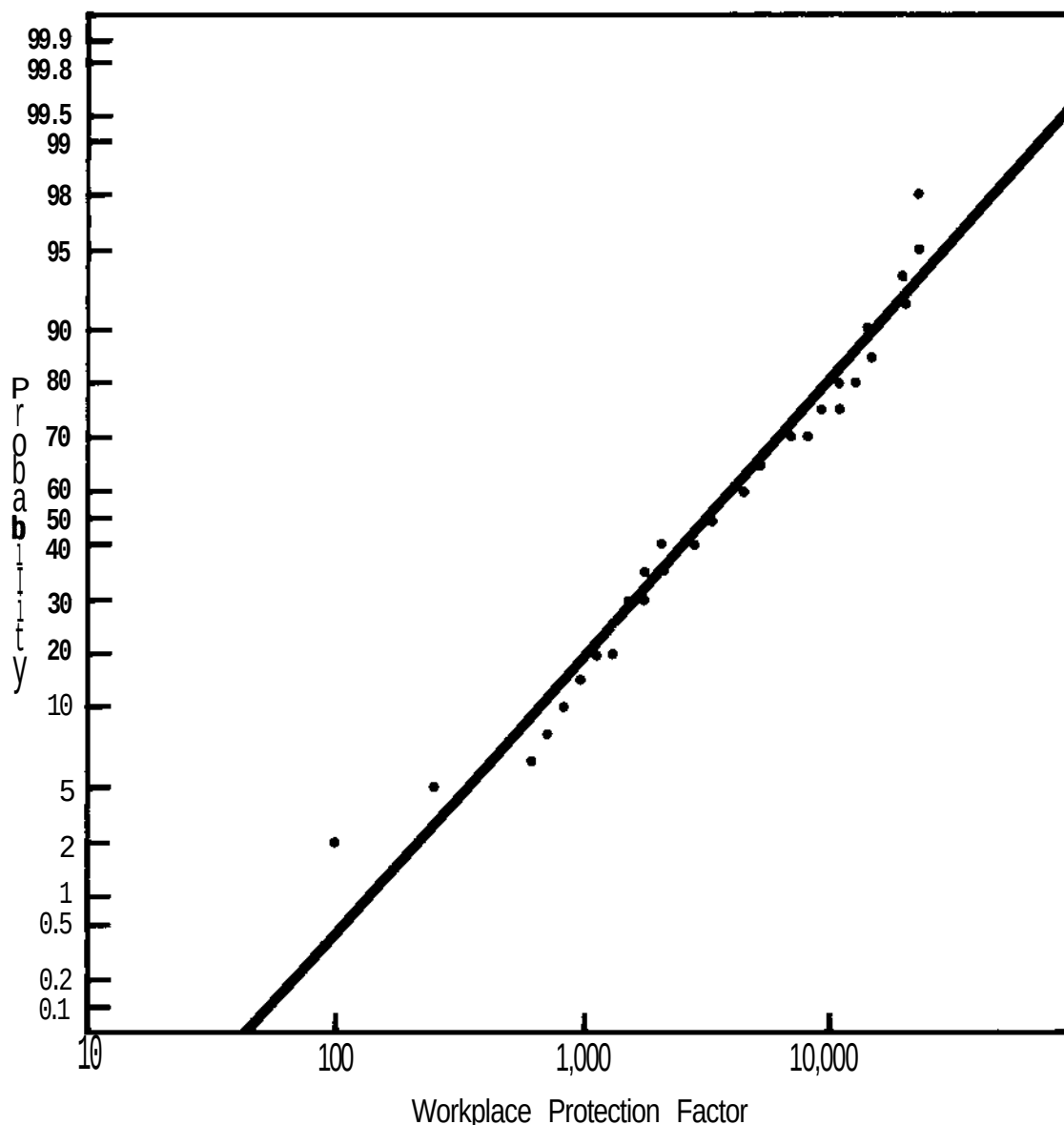


FIGURE 4

Overall distributions, geometric means, and ranges of workplace protection factors show that good protection is afforded by half-mask facepiece respirators when they are selected, fit-tested, and used properly. The protection exceeds the assigned protection factor of 10 for this class of equipment. Inside the respirator, concentrations of lead were well below a $50 \mu\text{g}/\text{m}^3$ exposure limit. Breaking the respirator-to-faceseal for even short periods of time reduced the protection provided; however, the workplace protection factors

still exceeded 10. The best estimates of fifth percentiles for the workplace protection factors found in this study are given in Table 2. These parameters represent workplace protection factors which will likely be exceeded.

To determine whether the workplace protection provided by respirators varied with the airborne concentration of lead, a regression analysis of outside lead concentration and workplace protection factors was done. The analysis of our data appears in Fig. 6. The correlation coefficient is

Distribution of Workplace Protection Factors - Facepiece Disturbed to Talk

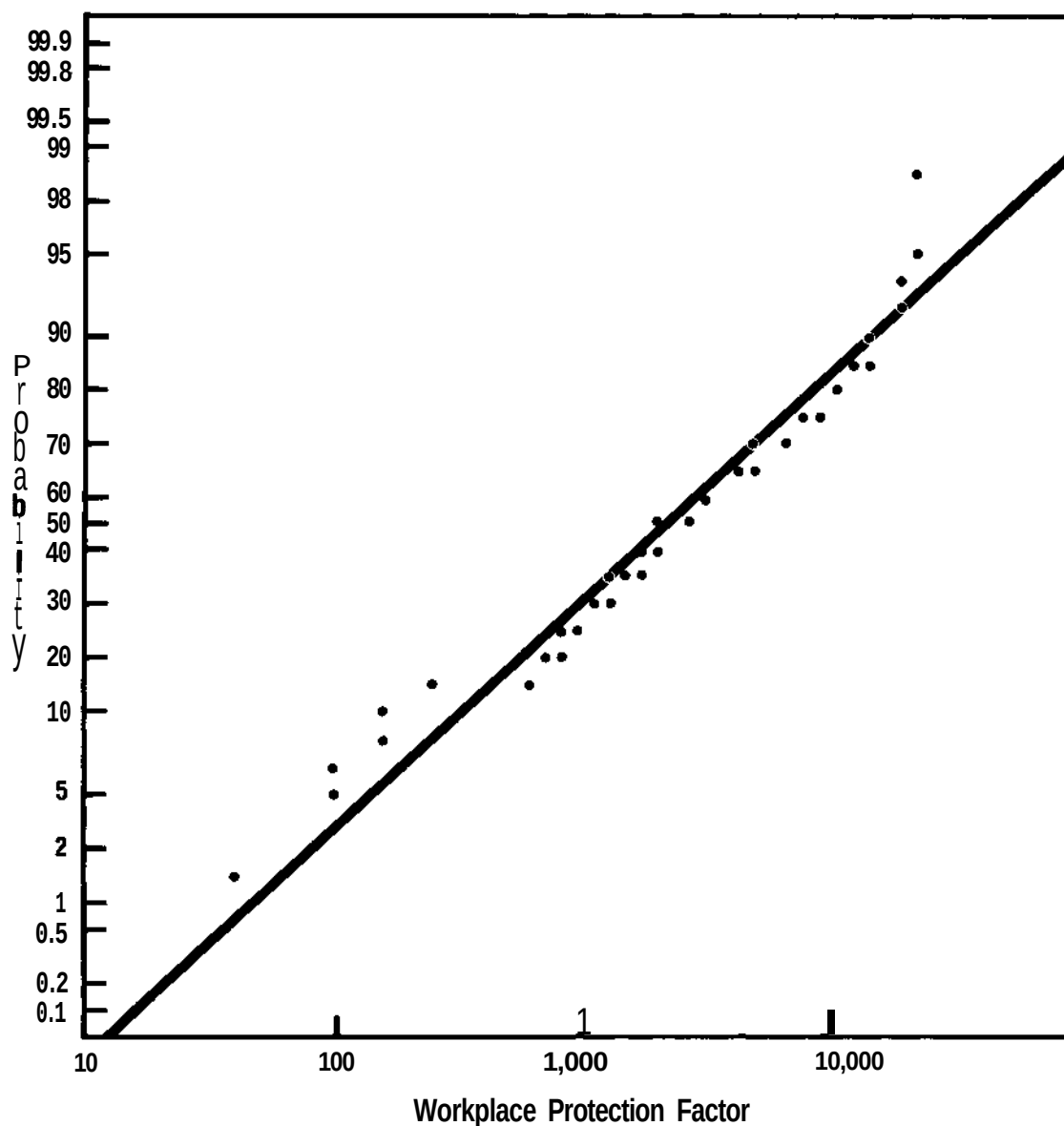


FIGURE 5

0.014; there is no significant correlation at a 5 percent probability level.

Table 2. Workplace protection factor parameters.

	GM ^a	Best estimate 5th percentile
Facepiece not disturbed	3400	390
Facepiece disturbed	2400	160

^a Geometric mean.

Estimation of Program Protection Factor Using Biological Monitoring

An evaluation of overall respirator performance includes more than measuring workplace protection factors. Other factors such as employee motivation, maintenance, storage, supervision, and work habits affect performance. An ideal measurement of how these factors affect protection would be a month-long or year-long measurement of protection, which would also be a program protection factor.

Outside Lead Conc. vs. WPF

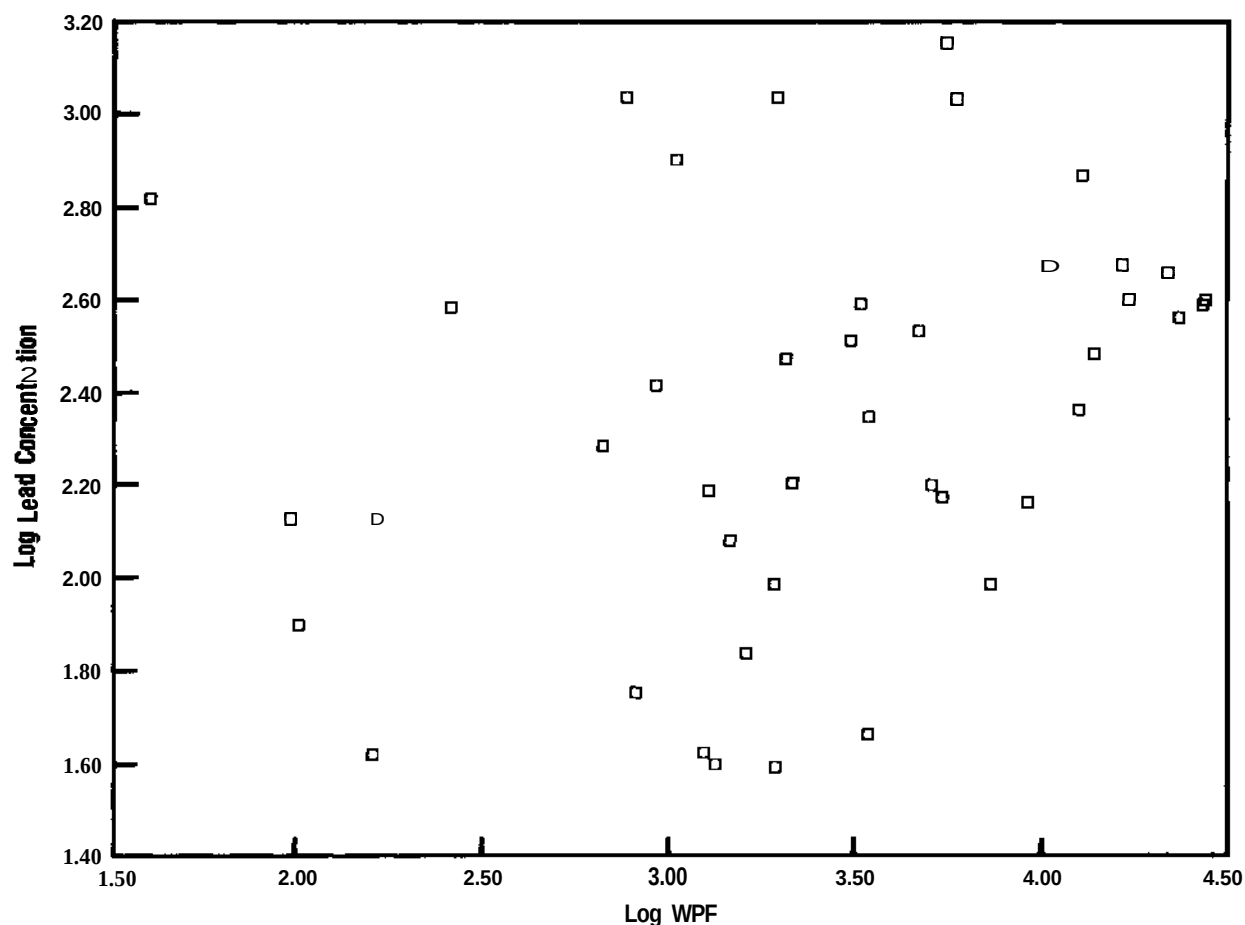


FIGURE 6

The lead operation studied has a large population of respirator users who form an ideal study group for long-term assessment of respirator performance. This group has distinct job classifications with well-documented air lead concentrations and biological monitoring results; it also has a good respirator program that closely follows the ANSI Z88.2 (1980) standard.

Table 3 lists the 1981 air lead exposures and blood lead levels for various job groups. During the year, MSA Comfo II half-mask facepiece respirators with high efficiency filters were worn in respirator-required areas. The air lead measurements were all 8-hour time-weighted averages. The data within each job group have a lognormal distribution; therefore, the geometric mean and the geometric standard deviation are proper descriptive terms. The blood lead data within each job group are normally distributed so comparisons are made using the mean and the standard deviation.

Analysis of the data shows that:

- Based on a linear regression analysis (Fig. 7), there is no significant correlation between mean blood and air lead levels. The correlation coefficient between the mean blood lead levels and geometric mean air lead concentrations is 0.134, which is not statistically significant at the 5 percent probability level.
- Based on an analysis of variance, mean blood lead levels for the control group and job assignments A through F are not significantly different from each other.
- Based on the analysis of variance, the mean blood lead level for job assignment G is significantly higher than that of the other groups.

The control group of operators who have low airborne lead exposures do not wear respirators. Operators in jobs A through G wear respirators at all times while they are working in areas with a potential exposure to lead. The overall program protection factor can be estimated by comparing

Table 3. Summary of air and blood lead data.

Job assignment	8-hr TWA airborne concentrations $\mu\text{g}/\text{m}^3$			Blood lead levels $\text{g}/100 \text{ g}$		
	GM ^a	GSD ^b	N ^c	Mean	SD ^d	N
A	18.5	2.67	34	19.0	8.2	46
B	22.4	2.94	24	18.4	11.1	17
C	67.5	3.56	12	18.9	12.1	7
D	78.4	4.61	25	14.1	7.6	27
E	130.9	3.44	45	12.6	7.7	17
F	236.0	1.99	26	20.4	10.8	8
G	297.0	3.20	24	29.6	5.9	7
Control group (respirators not normally worn)	6.6	2.17	16	19.5	6.07	14

^a GM is geometric mean.^b GSD is geometric standard deviation.^c N is number of samples.^d SD is standard deviation.

Blood Lead vs. Air Lead Correlation Coefficient = 0.134

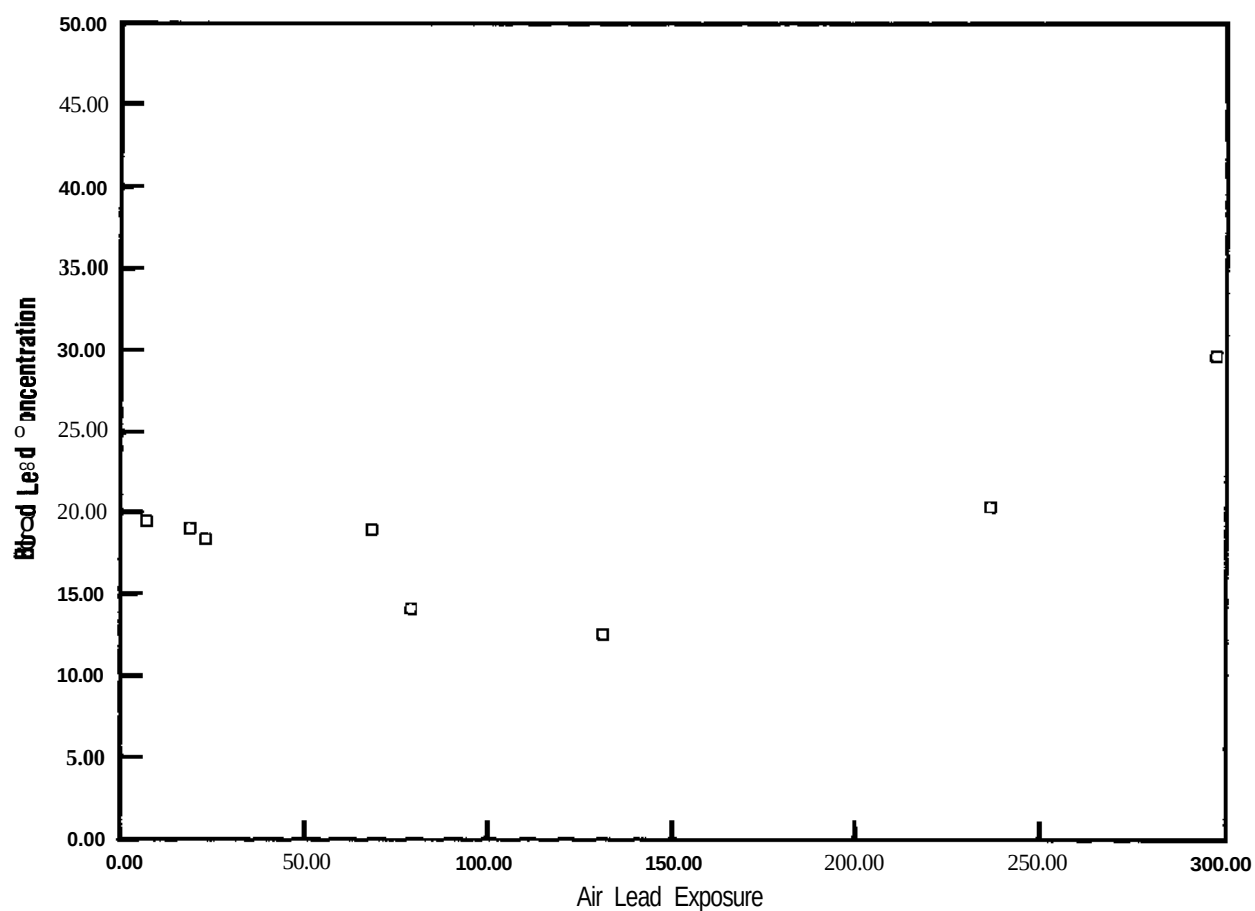


FIGURE 7

the airborne exposures for the control group to job assignment F. The control group has a blood level equivalent to job F: 19.5 μ g/100 g versus 20.4 μ g/100 g. Thus, the operators in job assignment F are exposed to airborne lead in an amount approximately equal to 6.6 μ g/m³. The program protection factor is estimated by dividing 236 by 6.6, giving us a factor of approximately 36.

Relationship Between Workplace Protection Factors and Quantitative Fit Factors

The second objective of this study was to determine whether random quantitative fit tests could be used to predict workplace protection factors, i.e., randomly performing quantitative fit tests on individuals during the workday. If random quantitative fit testing could be used, it would provide a simpler, less costly method of performing workplace protection factor studies.

To determine whether quantitative fit testing is a suitable method for estimating workplace performance, quantitative fit tests were taken on a paired basis immediately before and after half the workplace protection factor determinations. The paired quantitative fit factors and fit factors from the initial quantitative fit test were compared to the workplace protection factors.

It was possible that quantitative fit tests taken before and after workplace protection factor determinations could affect the WPF result. However, a paired T test, as shown in Table 4, demonstrates there was no difference between workplace protection factors with and those without quantitative fit tests. Therefore, we concluded that doing quantitative fit tests did not affect the results.

It was also possible that the respirator fit could change during the sample period, which would result in a difference in the before versus the after paired quantitative fit factors. In Table 4, a paired T test on before and after quantitative fit factors showed the two did not differ. Workplace protection factors were found to be significantly higher than before, after, and initial fit factors, based on paired T tests (Table 4). Although overall workplace protection factors are higher than the overall fit factors, there could still be a relationship between the two. Regression analyses were done to determine whether such a relationship exists. They showed that at the 5 percent probability level, there is no significant correlation between workplace protection factors and the initial fit factors (Fig. 8) or between the workplace protection factors and before and after fit factors (Fig. 9).

Some plausible reasons why fit factors are lower than workplace protection factors and which explain the lack of correlation include:

1. Standard exercises in the quantitative fit test cannot mimic exact movements of field tasks.
2. The breathing rate at a moderate to heavy work rate would be greater than the rate at rest. Typical rates may be 60 LPM at work versus 6 LPM at rest. Higher breathing rates may affect a respirator's efficiency.
3. Penetration through a leak site by the smaller diethylhexyl phthalate aerosol, which has an aerodynamic mass mean diameter of approximately 0.6 μ m, may be greater than penetration by larger lead particulates, which had an aerodynamic mass mean diameter of approximately 1.8 μ m.
4. We have observed in this and other studies that sputum aerosol or moisture in the breath sometimes appear to produce false low quantitative fit-test readings (Nelson, Skretvedt, Loschiavo, and Dixon, 1984).

Table 4. Paired T tests for significant differences.^a

	T Stat	Comp T	Conclusion
WPF with QNFF vs WPF without QNFF	0.19	2.06	No significant difference
Before QNFF vs after QNFF	0.26	2.06	No significant difference
WPF vs before QNFF	5.5	2.06	Significant difference
WPF vs after QNFF	6.0	2.06	Significant difference
WPF vs average before/after QNFF	5.9	2.06	Significant difference
WPF vs initial QNFF	2.5	2.06	Significant difference

^aAt a 5% probability level.

Regression Analysis: Log WPF vs. Log Initial QNFT Correlation Coefficient = 0.18

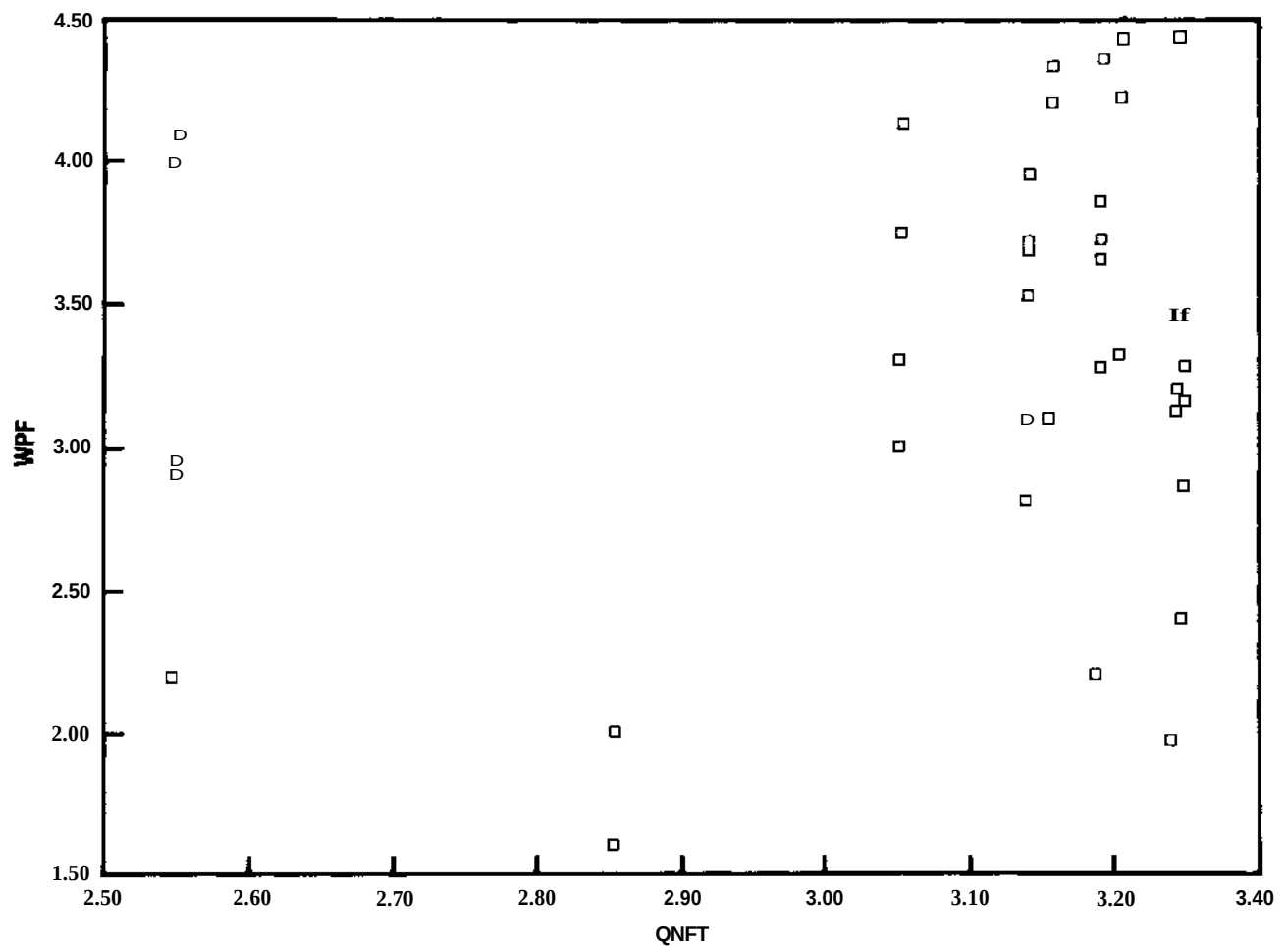


FIGURE 8

Conclusions

The conclusions of our study are:

1. Negative pressure half-mask facepiece respirators with elastomeric facepieces, when properly selected and fit-tested using the isoamyl acetate method and used by trained wearers, provided *workplace protection factors* which exceeded the current assigned protection factor of 10 and will likely exceed a factor of 100.
2. Negative pressure half-mask face respirators also provided *program protection factors*

which exceeded the current assigned protection factor of 10.

3. Distributions of workplace protection factors were approximately lognormal.

4. Fit factors from quantitative fit tests were not dependable as quantitative predictors of the protection actually afforded to individuals wearing respirators in the workplace.

Regression Analysis: Log WPF vs. Log Average QNFT

Correlation Coefficient = 0.05

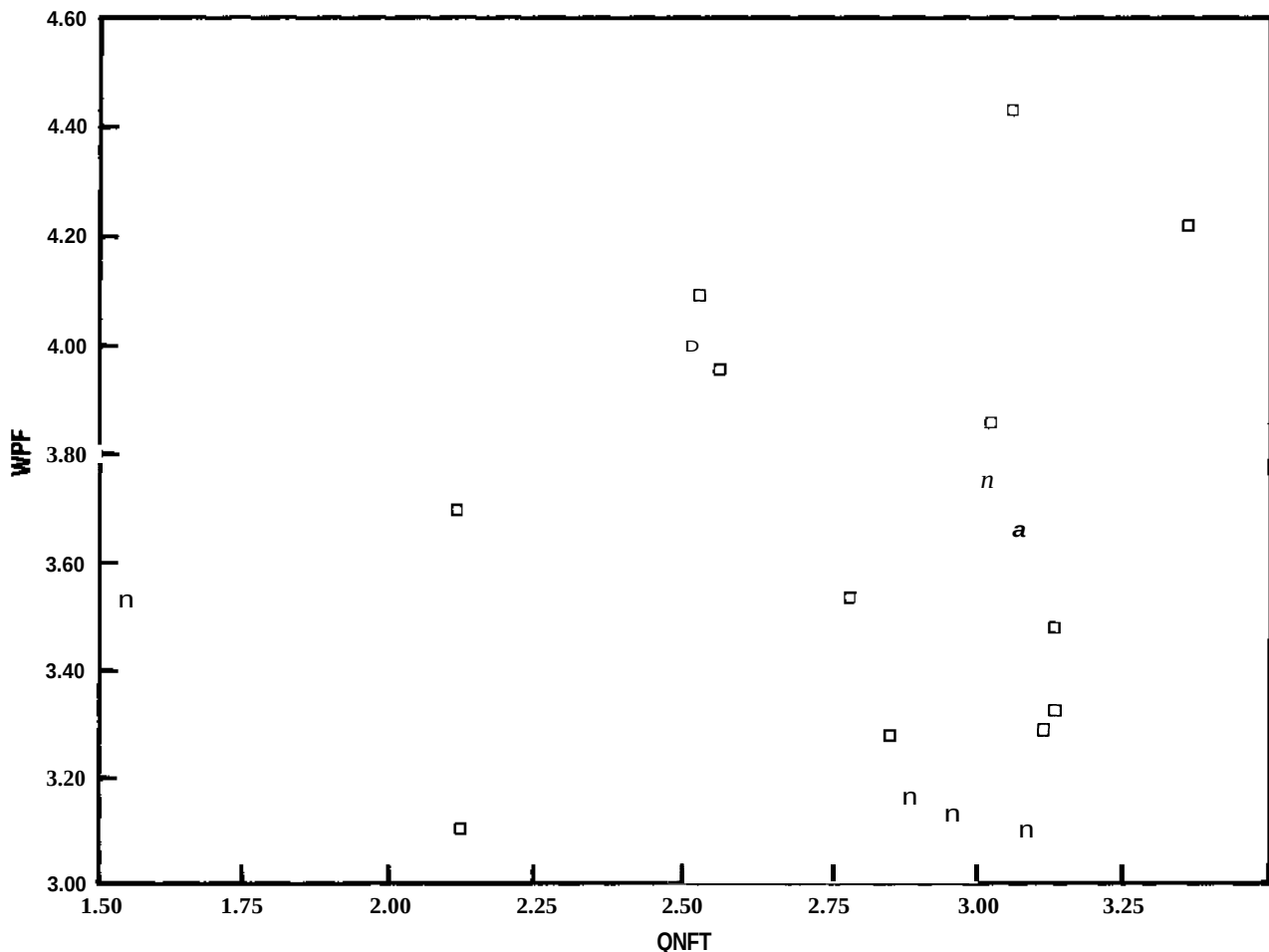


FIGURE 9

Acknowledgments

The assistance and cooperation of site study personnel, particularly that of R. F. White, are gratefully acknowledged. The assistance of W. C. Haaf, J. E. Henry, J. f. Viskocil, and C. Wiernicki in collecting field data, and of G. J. Graepel in doing statistical analyses is gratefully acknowledged. The assistance of P. L. Simms and F. A. Rickey, Department of Physics, Purdue University, in doing the PIXEA analysis and the assistance of Susan Herrmann in preparing the manuscript are also gratefully acknowledged.

References

- American National Standard Practices for Respiratory Protection* (1980), ANSI Z88.2 (American National Standards Institute, Inc., New York, NY).
- Birkner, L. R. (1980), *Respiratory Protection: A Manual and Guideline* (American Industrial Hygiene Association, Akron, OH).

- Chan, T. L. and M. Lippmann (1980), "Experimental Measurements and Empirical Modeling of the Regional Deposition of Inhaled Particulates in Humans," *American Industrial Hygiene Association Journal* 41(6):399-408.
- Gayton, A. C. (1981), *Textbook of Medical Physiology* (W. B. Saunders, Philadelphia, PA), 516.
- "Guide to Respirator Fit Testing" (1981), National Paint and Coatings Association, Washington, D.C.
- Hyatt, E. C. (1975 January), *Respirator Protection Factors*, Los Alamos Scientific Laboratory Report: LA-6084-MS.
- Johansson, S. E. and T. B. Johansson (1976), "Analytical Application of Particle Induced X-Ray Emission," *Nuclear Instruments and Methods* 137:473.
- Mercer, Thomas T. (1973), *Aerosol Technology in Hazard Evaluation* (Academic Press, New York, NY), 5.
- Nelson, T. J., O. T. Skretredt, J. G. Loschiavo, and S. W. Dixon (1984), "Development of an Improved Qualitative Fit Test Using Isoamyl Acetate," *Journal of the International Society for Respiratory Protection* 2(2):225-248.
- Occupational Safety and Health Standards (1982), *Code of Federal Regulations*, Title 29, Part 1910, Subpart 1025, as amended Nov. 12, 1982. (U.S. Government Printing Office, Washington, D.C.).
- Occupational Safety and Health Standards (1982), *Code of Federal Regulations*, Title 29, Part 1910, Subpart 1045, (U.S. Government Printing Office, Washington, D.C.).
- Pritchard, J. A. (1976), *Guide to Industrial Respiratory Protection*, National Institute for Occupational Safety and Health, Cincinnati, OH, Pub. No. 76-189.
- Threshold Limit Values for Chemical Substances and Physical Agents in the Work Environment with Intended Changes for 1983-84* (American Conference of Governmental Industrial Hygienists, Cincinnati, OH), 64.

Appendix A

Removing Filters

1. Escort wearer to relatively dust-free area.
2. Note time and turn off both pumps.
3. Don clean gloves.
4. Remove "inside" cassette from respirator probe and cap immediately with new cap.
5. Remove "inside" cassette from pump hose and cap immediately.
6. Cap wearer's respiratory probe.
7. Cap "outside" cassette and remove from shirt.
8. Remove other end of "outside" cassette from pump and cap.
9. Immediately transport cassettes to central facility.

Attaching Filters

1. Clean inside of respirator with towelette and inspect.
2. Have wearer don respirator.
3. Remove outlet cap and attach "outside" cassette to pump hose; attach pump to wearer.
4. Remove other outlet cap and immediately attach cassette to test subject's lapel.
5. Remove one outlet cap and attach "inside" cassette to pump hose; attach pump to wearer.
6. Remove other end cap and immediately attach cassette to respirator probe.
7. Start both pumps and note time.
8. Instruct wearer not to break the respirator seal during the test.