

Evaluation of Portacount for Determining Respirator Fit Factors, Part III: Human Subject Tests and Comparison with an Aerosol Photometer

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Ed. Note: We are reprinting here the Executive Summary to summarize the background of this project and to recall the work presented in the first two portions published in the Spring and Summer issues of JISRP, respectively.

Executive Summary

We investigated the use of a portable condensation nucleus counter (the model 8010 Portacount by Thermo Systems, Inc.) as a detector for quantitative fit testing of respirators. Fit test results were compared with measurements using an aerosol photometer, which is the current instrument of choice for quantitative fit testing of respirators. In the first phase of this study, simultaneous measurements were made with the two instruments using both a mannequin head and breathing machine to test the instrumentation without the added variability of human test subjects. The second phase of the study involved characterizing the aerosols in the ambient environment, calculating the effect of fine particles generated by human breathing, and comparing the fit test results obtained by the Portacount and the photometer from human test subjects. We also compiled a supplementary manual of special instructions for using the Portacount, such as the application limit of the instrument, startup procedure, data collection, and maintenance. These supplementary instructions are included immediately following the Executive Summary.

In the first phase of our experiment, we fitted a mannequin head with an MSA Ultravue full-face respirator. The mannequin and respirator were enclosed in a 1-m³ exposure chamber. A cyclic breathing rate of 23.6 breaths/min, at 40 lpm, was simulated through the respirator using a breathing machine. The two aerosol detectors were compared

at several different simulated leak conditions. Two challenge aerosols were selected for these investigations: an oil mist aerosol and the ambient room aerosol. The oil mist aerosol is similar to that routinely used in fit tests using the photometer as the detector. The room aerosol was of interest because the Portacount can be used with less-concentrated aerosols due to its greater sensitivity. In addition to comparisons of measured fit factors, we were interested in the stability and sensitivity of the Portacount with regard to fit factor measurements.

Because the aerosol photometer measures the amount of light scatter from a concentration of particles within its sensitive volume, its output depends on aerosol properties such as size, shape, and index of refraction. Larger particles result in higher signal levels. The photometer's dynamic operating range is typically six orders of magnitude. In contrast to photometers, condensation nucleus counters such as the Portacount count individual particles after they have grown to a detectable size. In the fit test sample mode, the instrument automatically alternates between the chamber and mask volumes with 5-s chamber and 60-s mask sample periods, respectively. The dynamic range of the Portacount is 0.05 to 500,000 particles/cm³ in the fit test mode. Therefore, the Portacount is much more sensitive than the photometer. Unfortunately, the entire dynamic range is not applicable to fit testing. Other investigators have shown that aerosol concentrations of exhaled

air from respirator wearers can be on the order of several particles per cubic centimeter. This background aerosol negates a portion of the Portacount's greater sensitivity over the photometer.

Tests using the oil mist as the challenge aerosol were conducted with dioctylsebacate (DOS) concentrations of 5 and 30 mg/m³. The oil mist aerosol was produced by a cold, bubbler-type generator using DOS. This resulted in an aerosol having a size distribution with a geometric median diameter and standard deviation of 0.32 and 1.8, respectively. Corresponding particle concentrations of the higher challenge concentration were about 1.7 x 10⁵ particles/cm³ as measured by the Portacount. Leak rates were varied, resulting in photometer fit factors ranging from 10 to 100,000. For the higher leak conditions, corresponding to fit factors less than 1000, fit factors as measured by the two instruments agree to within 25%. However, with increasing protection levels, greater discrepancies are seen, with the Portacount indicating fit factors much lower than those of the photometer. Such differences are to be expected, since the means of aerosol detection differ between the two instruments.

Stability tests were conducted to assess the variability in fit factors for experiments that were 1 hr and 8 hr in duration. The 1-hr stability test indicated standard deviations in Portacount fit factors from 1.8 to 5.5% for fit factors ranging from 350 to 11,000 (as measured by the photometer). The higher standard deviations were the direct result of decreased particle counts at the lower leak conditions. These standard deviations are comparable to—if not somewhat better than—those of the photometer used in these studies. Portacount relative standard deviations in fit factors as great as 20% were noted when using the room aerosol for challenge because of the much lower particle concentrations.

In experiments using the room aerosol as the challenge, we were interested in determining the maximum fit factor that the Portacount could measure, as well as how these measurements compared with those using the DOS aerosol as the challenge. Using identical leak conditions, the Portacount fit factors were usually 2 to 7 times higher for the ambient aerosol challenge as for the DOS. Such discrepancies can be explained by the fact that the ambient aerosol was considerably smaller in size than the oil mist. Although measured in only a few tests, our laboratory room aerosol distributions had a median diameter of 0.092 µm and a corresponding

standard deviation of 2.1. The room aerosol posed a further constraint on fit factor measurements. Challenge particle concentrations are much lower—on the order of 10,000 particles/cm³. This value along with the exhalation background mentioned previously limits the measurement of protection levels to fit factors of 1000 or less. Naturally, in environments with higher particle concentrations, higher fit factors could be measured. Correspondingly, in cleaner areas, even a fit factor of 1000 would not be attainable. The ambient aerosol concentration in buildings was measured at 31 locations around the Lawrence Livermore National Laboratory. The concentrations ranged from 1.6 x 10³ to 2.8 x 10⁵ particles/cm³ with a median of 8.1 x 10³ particles/cm³.

The fit factor measured by the Portacount is based on the number concentrations of particles penetrating into the respirator. In contrast, the fit factor determined by the photometer is more closely related to the particle mass penetration. The Portacount compares favorably with the aerosol photometer in this study for fit factors below 1000 using the oil mist aerosol used as the challenge. The Portacount has the added advantages of portability and increased sensitivity. From these mannequin/breathing-machine experiments using an ambient aerosol, we found that the Portacount appears to be a satisfactory instrument to use when measuring fit test results on respirators for fit factors less than 1000. Care must be used to make sure an acceptable particle-size distribution and concentration are available in the area used to carry out the respirator fit test. To assure comparable fit test results for the Portacount and the photometer, tests should be performed on human subjects in both the laboratory and typical workplace environments.

The second phase of our study, which used human subjects, found results that were in agreement with the mannequin/breathing-machine results. The fit testing involved 10 human subjects using the eight exercises from the Occupational Safety and Health Administration (OSHA) asbestos standard. Masks that gave a broad range of fits to the subjects were used. Once the subject comfortably donned the mask, he or she did not readjust it until completing two series of the exercises. The first series used the ambient room aerosol as the challenge agent and the Portacount as the detector. The second series used on oil mist aerosol as the challenge. One sampling line was attached to the respirator, but the line was divided such that both the Portacount and the photometer received proper samples. We found good general agreement between the three sets of fit tests results. However, when we examined the results

critically, some differences were noted. There is a bias for the Portacount fit factors to be a factor of 1.7 less than the photometer fit factors. A nonparametric statistical analysis on the simultaneous measurements showed that at a fit factor of 100, the Portacount meets the ANSI Z88.10 criteria for validation of a new qualitative fit test method; however, it does not meet these criteria at a fit factor of 1000. The effect of fine particles in the exhaled breath was signifi-

cant—though conservative—at a fit factor of 1000 and low ambient aerosol concentrations. We concluded that the Portacount can be used with ambient aerosols to confidently measure fit factors of 100. When used to measure fit factors of 1000 with ambient aerosols, several complications can occur that cause the measured fit factor to be low. Although this is undesirable, it errs on the side of safety and can be tolerated.

Human Subject Tests and Comparison with an Aerosol Photometer

Abstract

This second phase of our study of the TSI Portacount involved characterizing aerosols in the ambient environment, calculating the effect of fine particles generated by human breathing on fit factor results, and comparing the fit test results obtained by the Portacount and the photometer from human test subjects. To characterize the aerosol levels in the ambient environment, ambient aerosol concentrations in buildings were measured at 31 locations around LLNL. The aerosol concentrations ranged from 1.6×10^3 to 2.8×10^5 particles/cm³, with a median of 8.1×10^3 particles/cm³. Ten human subjects were fitted with respirators and fit-tested using the eight exercises from the OSHA asbestos standard. Masks that gave a broad range of fits to the subjects were used. Once the subject comfortably donned the mask, he/she did not readjust it until completing two series of the exercises. The first exercise series used the ambient room aerosol as the challenge agent and the Portacount as the detector. The second series used an oil mist aerosol as the challenge with both the Portacount and a photometer as the detectors; one sampling line was attached to the respirator, but the line was divided such that both the Portacount and a photometer received proper samples. We found good general agreement between the three sets of fits tests results; however, when we examined the results critically, some differences were noted. There is a bias for the Portacount fit factors to be a factor of 1.7 less than the photometer fit factors. A nonparametric statistical analysis on the simultaneous measurements showed that at a fit factor of 100, the Portacount meets the criteria proposed in the American National Standards Institute's (ANSI) Standard Z88.10 for validation of a new qualitative fit test method, but it does not meet the criteria at a fit factor of 1000. The effect of fine particles in the exhaled breath was significant, resulting in a reduced fit factor when measuring a fit factor of 1000 in the presence of low ambient aerosol concentrations. We concluded that the Portacount can be used with ambient aerosols to confidently measure fit factors of 100. When used to measure fit factors of 1000 with ambient aerosols, several complications can occur that cause the measured fit factor to be low. Although this is undesirable, it errs on the side of safety. These conclusions agree with the first phase of our study using a mannequin head and breathing machine (see vol. 1 of this report) when one considers the added uncertainty in measurements made on human subjects.

Introduction

The **Portacount** is a new instrument for measuring respirator fit factors; it is a condensation nuclei counter made by Thermo Systems, Inc. The Portacount has several characteristics that are very desirable. It is portable, battery operated, and very sensitive to particles so that it can use the ambient aerosols for the measurement of respirator fit factors. Before the Portacount can be used in place of the standard aerosol photometer, however, there are several questions that need to be addressed. Most importantly, how do fit factors measured with the Portacount compare to those measured with the standard photometer? Is the Portacount's response affected by the particle-size distribution of the challenge aerosol? What is the effect of the ambient aerosol concentration? What is the effect of lung-generated aerosols?

All of these areas of concern were addressed in this study. We conducted testing on human subjects where we compared the fit factors obtained by both the Portacount and the photometer with a given **subject/mask** combination. The photometer results were measured in a test chamber containing an oil mist

aerosol as the challenge. The Portacount results were measured both in the test chamber and in the open laboratory using the ambient aerosol as the challenge. Thirty sets of data were obtained by testing each of our ten subjects three times; each data set consists of aerosol-penetration measurements from eight exercises, which makes a total of 240 penetration measurements for each of the following three measurement conditions: (1) the photometer with the subject in the chamber, (2) the Portacount with the subject in the chamber, and (3) the Portacount with the subject in the laboratory.

Particle-size distributions were measured at three work sites at LLNL where workers could conceivably be fit-tested with the Portacount. In addition, the ambient aerosol concentrations were measured at 33 sites around LLNL, including areas that appeared clean as well as those that appeared dirty. The data from these surveys were combined with published information from Los Alamos National Laboratory on the generation of fine particles by human breathing to calculate the overall effect of using the ambient aerosol as the challenge.¹

Equipment Used and Methodology

The instrument used in this study is the Portacount model 8010, serial number 250 by TSI, Inc. Information on its operation was obtained from "Portacount Operation and Service Manual."² Additional information was obtained from vol. 3 of this report ("Portacount Supplementary Manual").

The Portacount is programmed for measuring fit factors on an 80-s cycle. Sixty seconds are allotted for sampling from inside the respirator: 5 s for the ambient air and the remainder for purging the instrument. The Portacount was also used to measure the ambient particle concentration around the site.

The sizes of the ambient particle-size distribution smaller than 0.3 μm were fractionated by a TSI differential mobility analyzer and detected by a condensation nucleus counter. The sizes larger than 0.3 μm were measured by a Climet particle-size analyzer attached to a pulse height analyzer. The output of these instruments was recorded on

an audio/analog cassette recorder, which was later transferred to a DEC LSI-11 computer for analysis.

The LLNL test chamber has a volume of 10 m^3 . Air containing an oil mist aerosol was pumped through the chamber at a rate of about 3 m^3/min . The oil aerosol used was polyethylene glycol with an average molecular weight of 400 (PEG 400) and a concentration of about 15 mg/m^3 . The aerosol concentration was measured with a Phoenix 7000 forward-scattering light photometer. The data taken with the photometer were collected and analyzed by the LSI-11 computer. The Portacount data were analyzed directly in the Portacount and printed on its printer.

We found that the Portacount was convenient for pretesting various face pieces on the subjects so that they would obtain a fit factor between 100 and 2000 during the tests. Both half masks and full-face masks were used. If no mask

Table 2-1. Ambient particle concentrations around LLNL (in particles/cm³).

Building/Room	Reading	Building/Room	Reading
October 13, 1989		543/Lobby; People walking around; some air current from air conditioning	
3275/104; Fan on; can feel air current	9.2 x 10 ³		2.2 x 10 ³
3275/ Conference area; Not as much air current in this room	7.6 x 10 ³	543/Office (meeting room); Carpeting; several cloth-covered chairs and papers on the tables	
3275/108; Quiet room; 2 people in room	7.5 x 10 ³		2.3 x 10 ³
October 17, 1989		663 (medical)/Lobby; Receptionists only persons present; not a lot of traffic	
219/Lobby; Some activity; old barracks building	2.5 x 10 ⁴		1.6 x 10 ³
219/Office; Copier and microfiche in room; new carpet	2.4 x 10 ⁴	663/Our new lab	
314/Lobby; Old barracks building; can smell cigarette smoke; lots of activity	4.6 x 10 ⁴		1.1 x 10 ⁴
411/Receiving dock; Trucks, people moving boxes, some cigarette smoke; dusty	3.2 x 10 ⁴	663/1113; Contains medical supplies (gauze , bandages, etc.)	1.1 x 10 ⁴
411/Inside warehouse; Lots of boxes and movement thereof; people moving about	5.1 x 10 ⁴	571/Lobby; People walking in/out; some air current from front door that was propped open	
411/Plastic shop; People moving around; plastics machinery operating	3.1 x 10 ⁴		8.1 x 10 ³
412/Hallway; Nobody present; tile floorway , older building; slight air current	1.1 x 10 ⁴	571/Office; Lots of papers, manuals, etc.; person present and working	
412/Fiber optics room (1220); Nobody present; HEPA filter present on return vent	8.0 x 10 ³		7.8 x 10 ³
418/Paint shop; Slight air current in between paint booths; no painting occurred	2.2 x 10 ⁴	671/Lobby; Nobody present; front door is dosed	
October 20, 1989 (Cloudy and windy today)			5.3 x 10 ³
Outside water-cooling towers; Strong wind; droplets of water were large and tended to hit inside of the sample tubing	1.2 x 10 ⁴	671/Office; Person in office; lots of documents and computer paper present	
511/Woodshop; Some sanding going on; also sawing some wood	2.8 x 10 ⁵		5.2 x 10 ³
511/Welding; Some welding going on; slight breeze, otherwise quiet	3.4 x 10 ⁴	691/Lobby; HEPA filters present on air-conditioning system of building; two sets of doors to go through to get to lobby	
			1.6 x 10 ³
		691/Office; Large (designed for 2 people); relatively little in the room besides desks, chairs, etc.	
			1.6 x 10 ³
		Open land across from 691; Dusty and windy outside; no equipment around	
			9.9 x 10 ³
		490/Hallway; Tile throughout; quite sanitary; all doors are closed to hallway	
			2.8 x 10 ³
		391/Hallway; Carpeting; not a lot of activity; some air current	
			2.1 x 10 ³
		361/Lobby; Some people walking around; doors closed, but when opened, wind blows in	
			7.8 x 10 ³
		361/Office; No one present; lots of papers and manuals	
			7.4 x 10 ³

gave a fit factor in this range, a well-fitting mask was used that had a hypodermic needle inserted through the rubber. The tests were conducted in the following order: (1) a standard set of exercises was performed in the instrument control room using the Portacount to measure the ambient air challenge and leakage; (2) the same set of exercises were performed in the test chamber, only this time the sample from inside the mask was split and analyzed by both the Portacount and the photometer; (3) after leaving the chamber, the Portacount was used again with ambient aerosol to measure the leakage during the normal breathing exercises only; and (4) the subject then removed the mask even if he/she was going to be tested immediately thereafter. Thus, the mask was donned anew for each test series. The standard set of exercises are from the OSHA asbestos standard without the "grimace."³ The order of the exercises was also changed to the following: (1) normal breathing, (2) deep breathing, (3) touch toes, (4) head side to side, (5) head up and down, (6) jogging in place, (7) reading, and (8) normal breathing again.

The fractional penetration of the aerosol into the mask was taken as the ratio of the aerosol concentration inside the mask to that outside the mask. The photometer measured the concentration outside the mask (the challenge concentration) only just before starting a series of exercises and just **after** completing the series. If they were different, then a linear interpolation was made to obtain the challenge concentration at the time of the in-mask measurement and the penetration calculated from it. The chamber concentration is usually very stable. The Portacount measures the challenge concentration both before and after each exercise, then computes the fit factor from an average of the two challenge concentrations divided by the in-mask concentration. The Portacount prints the fit factor for each exercise and then prints the average fit factor for the series of exercises; however, it uses the reciprocals of the individual fit factors (i.e., the penetration) to calculate the average or integrated fit factor.

Results

Ambient Aerosol Concentration

Ambient particle concentrations were measured at 31 sites around LLNL over a period of 8 days. The Portacount was used to make the measurements. All types of environments were sampled to obtain the full range of likely concentrations. As is shown in Table 2-1, the concentrations ranged from 1.6×10^3 to 2.8×10^5 particles/cm³, with a median of 8.1×10^3 particles/cm³. Using these concentrations and the concentration of particles found in exhaled breath, we can calculate the error introduced into a fit factor measurement when using the Portacount at various ambient aerosol concentrations.¹

In Figs. 2-1a and 2-1b, we calculated and plotted the apparent fit factor that would be calculated by the Portacount when the real fit factor was 100 and 1000, respectively. The plots show the apparent fit factor for two different concentrations of particles in the exhaled breath (1 and 4 particles/cm³, respectively). For the worst situation (4 particles/cm³ in the breath and

only 1×10^3 particles/cm³ in the ambient air), we find an apparent fit factor of 70 when the real fit factor was 100 and an apparent fit factor of only 200 when the real fit factor was 1000. For a more usual ambient concentration of 1×10^4 particles/cm³ and the average concentration reported in the exhaled breath of 1 particle/cm³, we find a 10-percent reduction in a real fit factor of 1000. The effect on the apparent fit factor increases rapidly with the number of exhaled particles, as shown in Fig. 2-1c for an ambient concentration of 1500 particles/cm³. Until there are more studies published on particles in exhaled breath under various conditions, we must consider this effect when measuring fit factors of 1000 and over. To help alleviate the above problems, the Portacount gives an error message when the exterior environment is below 1500 particles/cm³ and the manual recommends that smokers wait 30 min after smoking in preparation for a fit test. The actual concentration inside the mask can be obtained from the Portacount to obtain an upper limit on exhaled particle concentrations.

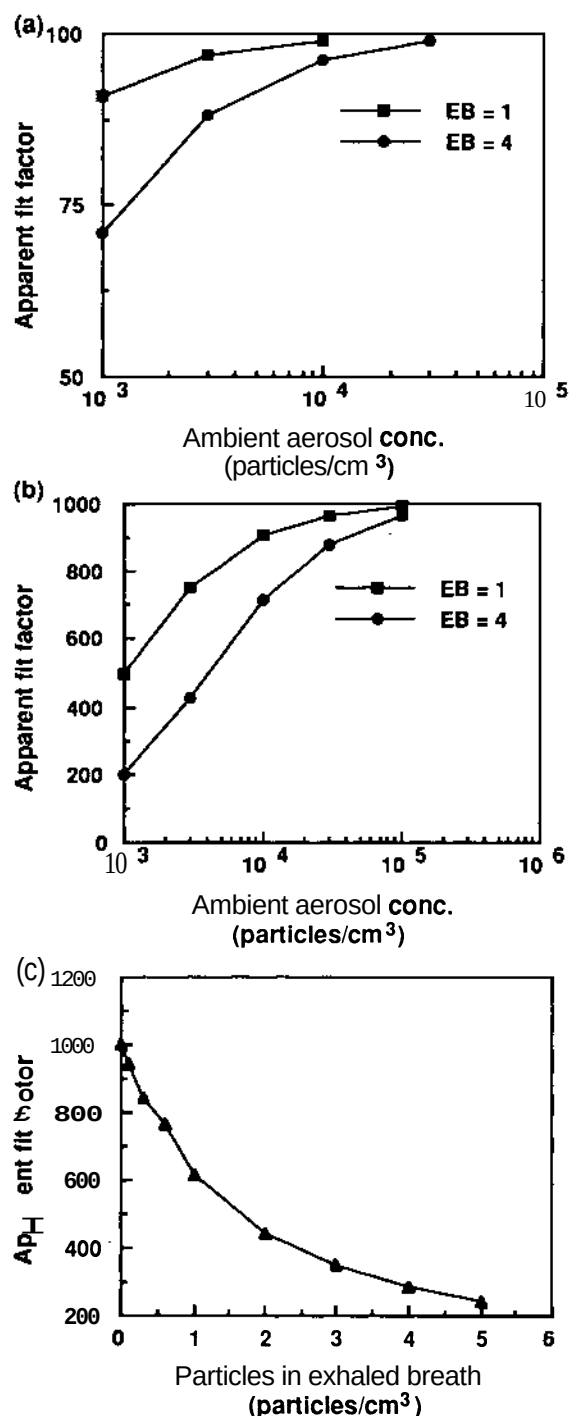


Figure 2-1. Effect of human-subject-generated particles on the apparent fit factor; (a) fit factor is 100, (b) fit factor is 1000, (c) effect increases rapidly with the number of exhaled particles.

Ambient Particle-Size Distributions

The effect of the ambient particle-size distributions must be considered when measuring fit factors above 1000 because the leakage through a high-efficiency particulate air (HEPA) filter that just meets the minimum requirement of removing 99.97 percent of 0.3- μm -diameter particles is equivalent to a fit factor of 3333. On one hand, an ambient aerosol that has a high concentration of particles ranging in size from 0.1 to 0.2 μm , where the filter media has poorer efficiency, would cause the apparent fit factor to be smaller than the real factor. On the other hand, an ambient aerosol that has a high concentration of particles greater than 2 μm in size would cause the apparent fit factor to be larger than the real factor because some of these large particles will not penetrate the leak, but will traverse the sampling tubing and be counted in the ambient aerosol.

To consider the magnitude of the above effects, we measured particle-size distributions at three shop locations we believed would represent the extremes of these effects: a welding shop, carpenter shop, and paint shop. The particle-size distributions are shown in Fig. 2-2.

The major activity in the welding shop was cutting of a thick aluminum plate with a plasma arc cutting torch, which is shown in Fig. 2-3. This produced a large number of particles ranging in

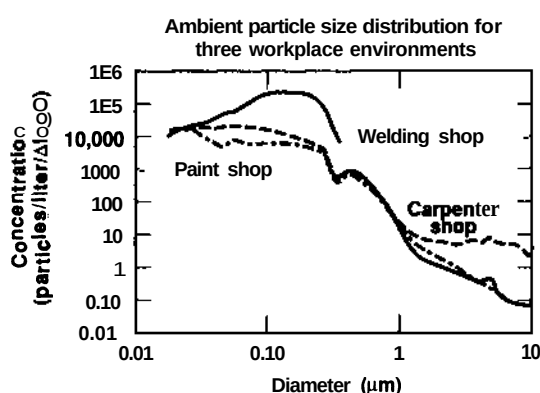


Figure 2-2. Ambient particle-size distribution for three workplace environments.

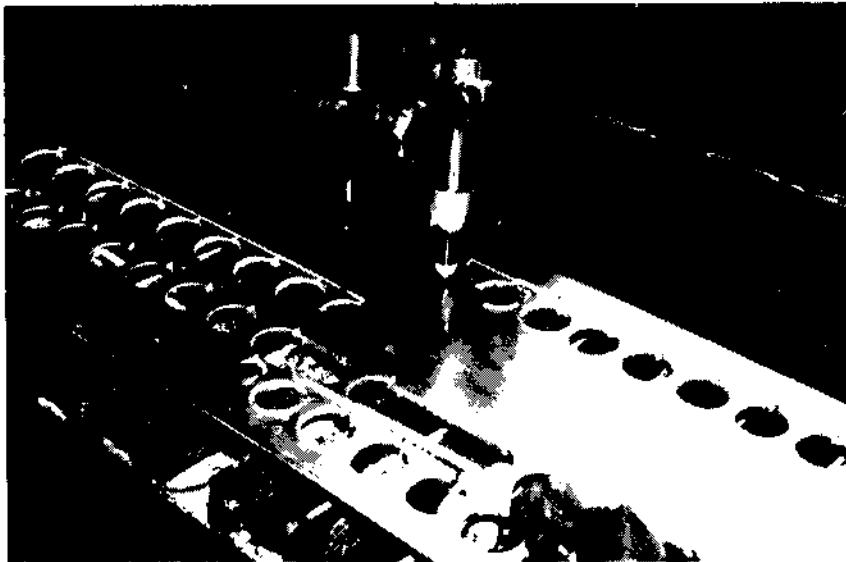


Figure 2-3. Plasma arc cutting of aluminum plate in welding shop.

size from 0.09 to 0.2 μm , which would have affected fit factors measured in this atmosphere.

Many different power tools were being used in the carpenter shop. The particle-size distribution in this shop shows a greater number of large particles compared to the distributions at the other locations. However, this would not have caused a measurable effect on the fit factor because the concentration of these large particles is several orders of magnitude less than that of particles smaller than 1 μm . Because the Portacount counts all sizes of particles with equal efficiency, the increase in the larger particles would not be detected.

The particle-size distribution in the paint shop is flat below 0.3 μm . The greater penetration of particles ranging in size from 0.1 to 0.2 μm would only cause a negligible decrease in the real fit factor.

Human Subject Testing

Scattergrams of the original penetration data are presented in Figs. 2-4a and 2-4b. We anticipated that the data pair would cluster around a line at $y = x$. This turned out to be generally true, but there were several groups of data points that were far from that line. The raw data for these data pair were reviewed, and it was determined that an experimental error had occurred when some of the data were taken. Notes found on the strip-chart recording for some data indicated that

(1) the hoses were connected incorrectly on the Portacount; (2) the flow through the photometer was too great, so that no sample from the mask reached the Portacount; and (3) with some of the very low penetrations, the photometer had not been flushed sufficiently after taking a chamber reading.

A data set is defined in this report as all of the data taken for a given subject during one fitting of a mask. The data sets for which there were known experimental errors were eliminated from the study (four of the thirty data sets). Originally, there were three data sets per subject, so now we had fewer than three sets to analyze for some of the subjects. All analyses were performed on this culled data consisting of 26 data sets. Each data set consists of the penetration measured while the subject performed the series of eight exercises. The penetration was measured simultaneously with the photometer and the Portacount while the subject was in the test chamber, and then again with the Portacount only while the subject was in the normal room air. This produced a total of 208 (26 x 8) data points for each of the three measuring techniques.

One method of testing the correlation of the Portacount results to the standard photometer method is to perform a regression analysis. Because the measurements in the chamber were made simultaneously, we expect to find the best correlation with these data pairs. The results are shown in Fig. 2-5. The regression was performed on the log of the penetration. Two lines are

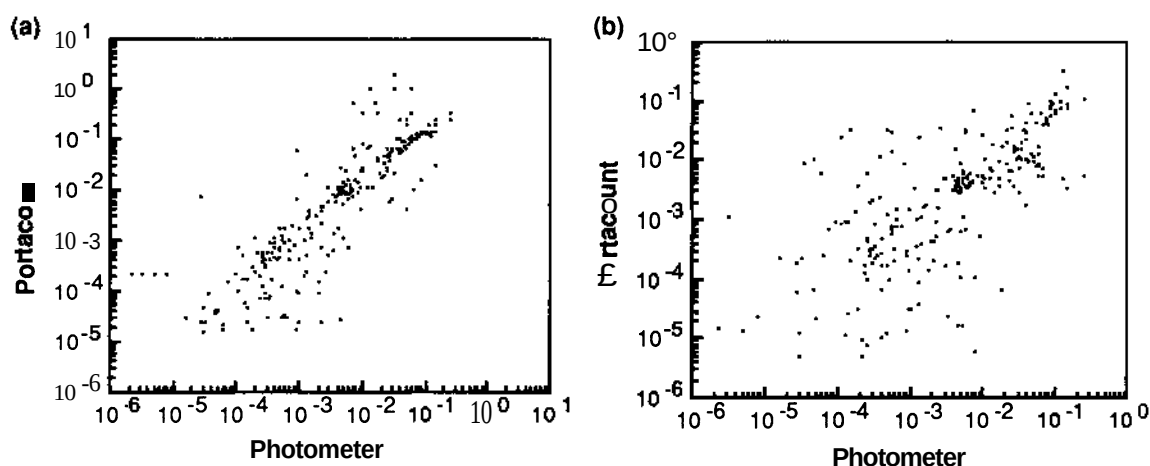


Figure 2-4. Correlation between original chamber photometer and (a) Portacount data and (b) room Portacount data.

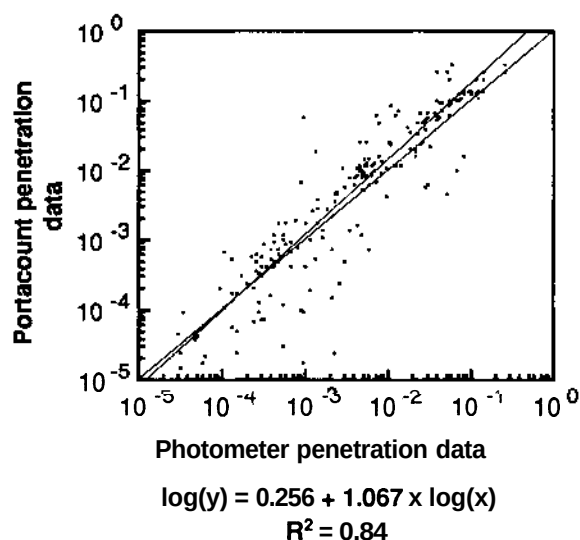


Figure 2-5. Correlation of "simultaneous" photometer and chamber Portacount penetration data.

shown Fig. 2-5: one is the best fit, or least squares line, and the other is $\log(y) = \log(x)$. The fraction of the scatter in the data that is explained by the regression line was calculated to be 0.84 (known as the R^2 value). The equation for the best fit shows that at penetrations greater than about 1×10^{-4} , the Portacount tends to over estimate the penetration. This is most pronounced at the higher penetrations. For example, at a penetra-

tion of 0.01 by the photometer, the Portacount estimates a penetration of 0.01324. In terms of fit factors, a fit factor of 100 would be estimated as 75 by the Portacount. Fortunately, the error is in a conservative direction.

The correlations for the nonsimultaneous measurements are shown in Figs. 2-6a and 2-6b. The fit for the photometer data taken in the chamber vs the Portacount data taken in the room (Fig. 2-6a) only accounts for 45 percent of the scatter. The plot of the Portacount data taken in the chamber vs the Portacount data taken in the room (Fig. 2-6b) showed so much scatter that we did not calculate a regression line.

The culled sets of data are presented in vol. 4 of this report (see Table 4-2) along with the arithmetic averages of the data taken by each instrument. The fit factor averages shown are not equal to the integrated fit factor, which is the reciprocal of the average of the penetrations. The latter method is the correct one for calculating the fit factor from a series of exercises and avoids the issue of the form of the distribution for the fit factors over a series of exercises (i.e., Is the distribution normal, log-normal, or something else?).

Integrated Fit Factors

The fit factor and penetration integrated over all exercises for each data set are summarized in Table 2-2. A comparison of the fit factors in this table and those from Table 4-2 shows the magnitude of error in the first method.

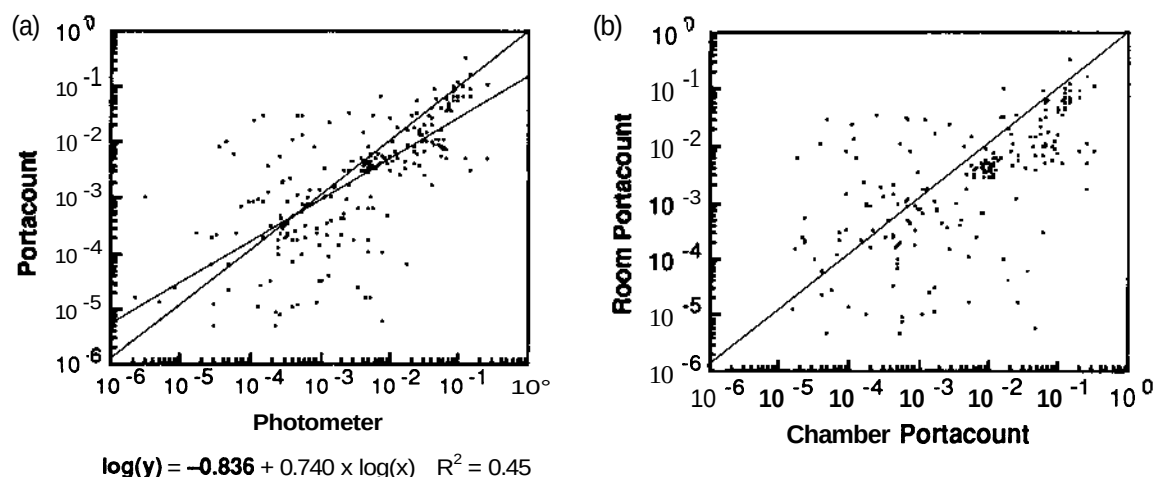


Figure 2-6. Correlation of “nonsimultaneous” (a) chamber photometer and room Portacount penetration values and (b) room and chamber Portacount penetration values.

Table 2-2. Fit **factor** and penetration integrated over all exercises.

Subject	Fit factor integrated			Penetration integrated		
	Chamber photometer	Chamber Portacount	Room Portacount	Chamber photometer	Chamber Portacount	Room Portacount
A1	37	29	298	0.0267	0.0343	0.00336
A2	37	12	48	0.0289	0.0862	0.0210
A8	14	6	19	0.0702	0.166	0.0534
B2	64	38	186	0.0155	0.0264	0.00538
B3	33	16	90	0.0300	0.0621	0.0111
C2	2290	311	5472	0.000437	0.00322	0.000183
D1	961	968	2546	0.00104	0.00103	0.000393
D2	3075	3037	736	0.000325	0.000329	0.00136
D3	346	393	1219	0.00289	0.00254	0.000820
E1	9	8	13	0.106	0.126	0.0745
E2	38	52	169	0.0260	0.0193	0.00593
E8	253	129	231	0.00395	0.00776	0.00432
F1	1451	3327	1939	0.000689	0.000301	0.000516
F2	11	7	13	0.0920	0.137	0.0780
F8	17	13	22	0.0592	0.0746	0.0445
G1	15	10	33	0.0872	0.0986	0.0304
G2	712	1410	173	0.00141	0.000709	0.00579
G3	898	469	1401	0.00111	0.00213	0.000714
H1	176	113	216	0.00569	0.00886	0.00463
H2	188	80	256	0.00532	0.0124	0.00390
H3	209	88	239	0.00478	0.0114	0.00419
AJ1	1366	2377	59	0.000732	0.000421	0.0168
AJ2	202	114	8736	0.00494	0.00874	0.000114
AJ3	653	221	167	0.00153	0.00452	0.00597
BJ1	796	73	22063	0.00126	0.0137	4.53E-05
BJ2	1243	286	21568	0.000805	0.00350	4.64E-05

* Instruments used: Photo = Photometer; Porta = Portacount

The correlation of the photometer and chamber Portacount integrated fit factors is shown in Fig. 2-7. We anticipated that a regression line through the integrated fit factors would account for a greater fraction of the scatter than it did for the fit factors from the individual exercises; however, it still only accounted for 85 percent of the scatter. The correlations for the nonsimultaneous data pairs are shown in Figs. 2-8a and 2-8b, and are somewhat better than those obtained for the individual exercises. The regression analyses show that there is a very strong correlation between the measurements with the two different instruments when they are both sampling at the same time.

Paired t-Tests

A powerful statistical test to compare the integrated fit factors obtained by the two instruments is the Paired t-test. Because it has been shown previously that fit factors follow a log-normal distribution, we performed the paired t-test on the logs of the fit factors. For the measurements made in the chamber, the log of the photometer fit factors averaged 0.220 greater than those made with the Portacount. Using a Student's t-distribution, we determined the 95-percent confidence interval to be 0.09 to 0.35—or in "normal" values, 1.23 to 2.24 times

the Portacount values—with the average being 1.66 times.

When we compared the fit factors from the photometer in the chamber to those made from the Portacount in the room, we found the 95-percent confidence interval for the room values to be 0.31 to 1.03 times the chamber values. Thus, the fit factors measured in the chamber correlate very well, but with an offset by a factor of 1.66. The fit factors measured with the photometer in the chamber, however, do not correlate well with those measured by the Portacount in the room, and we cannot say with much confidence that their averages are different.

Nonparametric Analysis

Nonparametric analytical methods can be used successfully to compare a new technique with a "standard" analytical technique. This method has been suggested in the proposed standard ANSI Z88.10 for respirators.⁴ It is particularly valuable when the new technique will be used to determine if the measurement is above or below some preset value. In this case, we performed the following four tests on the data:

- The sensitivity of the new technique to detect a failure to meet the preset value;
- The predictive value of a pass;

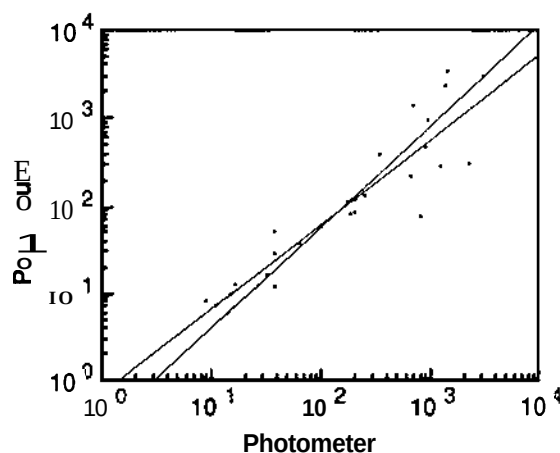
Figure 2-7. Correlation of photometer and chamber Portacount integrated fit factors.

The integrated fit factor is

$$\frac{1}{\text{Average penetration}} = \frac{1}{(P_1 + P_2 + P_3 + \dots + P_8) / 8}$$

NOT

$$(FF_1 + FF_2 + \dots + FF_8) / 8$$



Minimize residuals for Portacount = y
 $\log(y) = -0.170 + 0.978 \times \log(x)$

$R^2 = 0.85$

Minimize residuals for Photometer = y
 $\log(y) = -0.550 + 1.147 \times \log(x)$

$R^2 = 0.85$

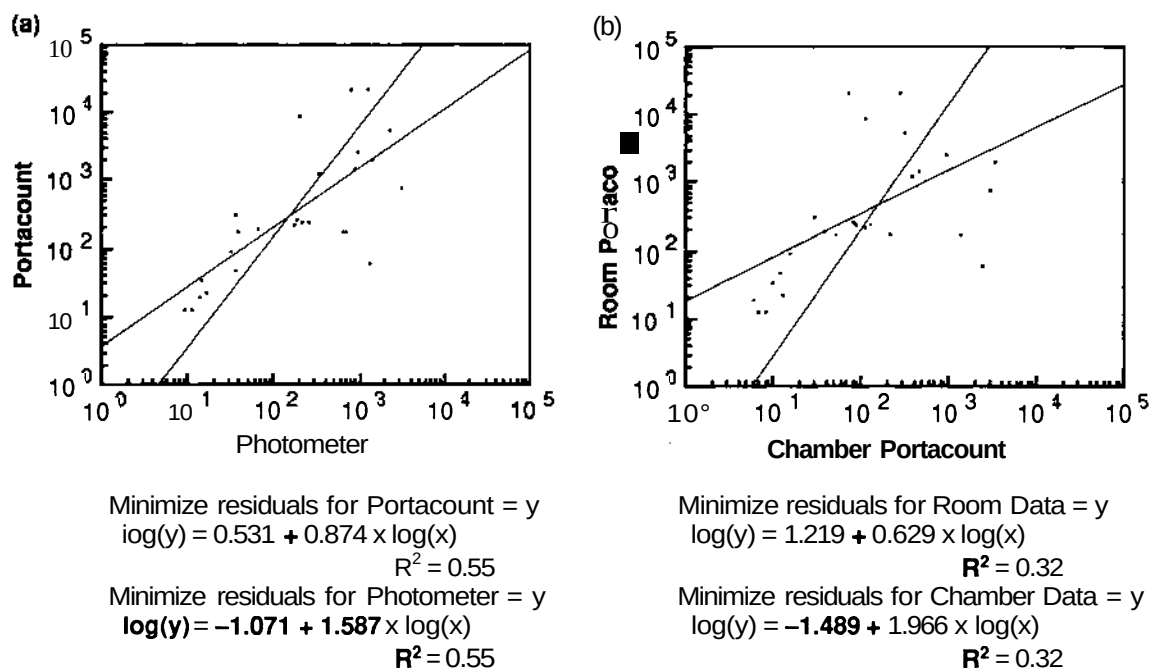


Figure 2-8. Correlation of (a) photometer and room Portacount integrated **fit** factors and (b) chamber and room Portacount integrated **fit** factors.

- The specificity of the test; and
- The predictive value of a fail.

These are further described in Tables 2-3 and 2-4.

The first step in this analysis is to sort the fit factors in ascending order by the chamber photometer value. This is shown in Table 2-5 for the integrated fit factors. The truth table for an integrated fit factor of 100 is shown in Table 2-6; this shows high reliability of the Portacount in screening face fits at a value of 100, which would be the right value for fitting half masks. In Table 2-4 we show the results of each calculation, the ANSI criteria, and how well the Portacount

performed. The preset value for fitting full **facepiece** respirators is 1000. The truth table for an integrated fit factor of 1000 is given in Table 2-7, with the calculated results in

Table 2-3. Truth table for **nonparametric** analysis of Portacount **fit** factors.

	Porta-pass	Porta-fail	Total
Photo-pass	A	B	AB
Photo-fail	C	D	CD
Total	AC	BD	ABCD

Table 2-4. Results of nonparametric analysis of Portacount for a **fit factor** of 100.

Test	Calculation	ANSI criteria	This study at 100
Sensitivity to detect a failure	D/CD	≥ 0.95	1.0
Predictive value of a pass	A/AC	≥ 0.95	1.0
Test specificity	A/AB	> 0.50	0.81
Predictive value of a fail	D/BD	> 0.50	0.77

Table 2-5. Integrated fit **factors** sorted in ascending order by the chamber photometer.

Subject	Chamber photometer	Chamber Portacount	Room Portacount
E1	9	8	13
F2	11	7	13
A3	14	6	19
G1	15	10	33
F3	17	13	22
B3	33	16	90
A1	37	29	298
A2	37	12	48
E2	38	52	169
B2	64	38	186
H1	176	113	216
H2	188	80	256
AJ2	202	114	8736
H3	209	88	239
E3	253	129	231
D3	346	393	1219
AJ3	653	221	167
G2	712	1410	173
BJ1	796	73	22,063
G3	898	469	1401
D1	961	968	2546
BJ2	1243	286	21,568
AJ1	1366	2377	59
F1	1451	3327	1939
C2	2290	311	5472
D2	3075	3037	736

Table 2-6. Truth table for **nonparametric** analysis of **Portacount** with an integrated fit factor of 100.

	Porta-pass	Porta-fail	Total
Photo-pass	13	3	16
Photo-fail	0	10	10
Total	13	13	26

Table 2-8. In this case, the Portacount does not meet the ANSI criteria for the predictive value of a pass; however, this is based on only four samples, so there is a large uncertainty in the ratio. It should be noted that ANSI requires at least 50 tests in each subtotal. Since there were only 26 integrated fit factors measure, neither Table 2-6 nor Table 2-8 meets this ANSI requirement.

We can use the same nonparametric method for the fit factors of each exercise. This gives us more than 50 tests in each subtotal. The results are given in Tables 2-9 through 2-11. Again, the Portacount does very well when the preset value is 100, but it still does not meet the ANSI criteria on the predictive value of a pass.

Discussion

Effect of Imperfect Coordination of Sampling Times

There were difficulties in starting the data collection with the computer (i.e., photometer value) and the Portacount at the same time. The Portacount has an internal timer that starts the in-mask sample; however, there is no definite external signal at the same time. If the computer sampling is started a little ahead or behind the Portacount, a significant difference can occur when a rapid change is occurring in the concentration of challenge in the mask. Two examples are shown in Figs. 2-9 and 2-10. In Fig. 2-9, the chart recorder trace is marked at the beginning

and end of the photometer samples for reading and normal breathing. It can be seen that a large peak occurred around the time that the reading exercise was ending and the normal breathing period was starting. An off-set in the sample starting times, would make a large difference in the measured penetration. Figure 2-10 illustrates a similar situation. Even though we recognized the existence of this off-set problem early in our tests, we were unable to eliminate it completely. It is believed to be a significant cause of the differences found in the individual exercise fit factors measure "simultaneously" with the photometer and the chamber Portacount.

Table 2-7. Truth table for nonparametric analysis of Portacount with an integrated fit factor of 1000.

	Porta-pass	Porta-fail	Total
Photo-pass	3	2	5
Photo-fail	1	20	21
Total	4	22	26

Table 2-8. Results of nonparametric analysis of Portacount for a fit factor of 1000.

Test	ANSI criteria	This study at 1000
Sensitivity to detect a failure	≥ 0.95	0.95
Predictive value of a pass	≥ 0.95	0.75
Test specificity	> 0.50	0.60
Predictive value of a fail	> 0.50	0.91

Table 2-9. Truth table for nonparametric analysis of Portacount with an individual exercise fit factor of 100.

	Porta-pass	Porta-fail	Total
Photo-pass	111	26	137
Photo-fail	3	67	70
Total	114	93	207

Table 2-10. Truth table for nonparametric analysis of Portacount with an individual exercise fit factor of 1000.

	Porta-pass	Porta-fail	Total
Photo-pass	55	9	64
Photo-fail	10	133	143
Total	65	142	207

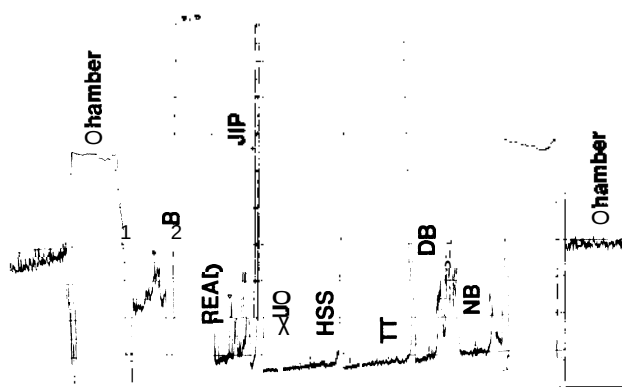
Table 2-11. Results of nonparametric analysis of Portacount from individual exercise fit factors.

Test	ANSI criteria	For fit factor of 100	For fit factor of 1000
Sensitivity to detect a failure	≥ 0.95	0.96	0.93
Predictive value of a pass	≥ 0.95	0.97	0.85
Test specificity	> 0.50	0.81	0.86
Predictive value of a fail	> 0.50	0.72	0.94

Comparison of Normal Breathing Fit Factors

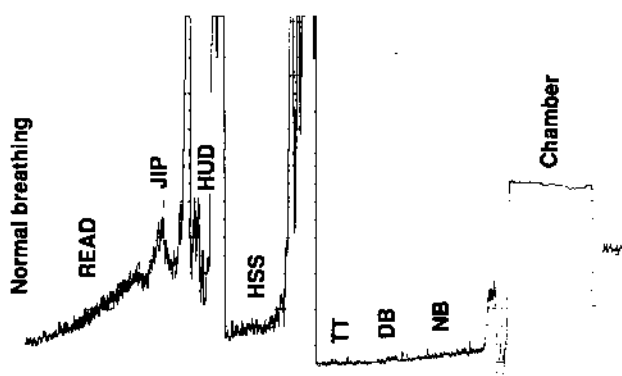
In most data sets, five measurements were made with the Portacount while the subject was doing normal breathing. These measurements are shown in Table 2-12. They have been arranged so that the fit factors for the first chamber sample are in ascending order. This arrangement provides the reader with a view of how much variation there is in the leakage between repli-

cates of the same exercise after a few other exercises, or in the cases of comparing the second room measurement with that of the first chamber and comparing the second chamber measurement with that of the third room, just moving between the chamber and the control room that is 20 ft away and reconnecting the sampling line. This comparison was not made for the photometer data, as only two measurements were made per data set.



Exercises	Fit factor	
	Chamber photometer	Chamber Portacount
NB	4472	1740
DB	3791	1650
TT	20276	24800
HSS	4444	1800
HUD	32622	65600
JIP	2103	579
READ	1096	17
NB	127	21

Figure 2-9. Strip-chart recorder trace of subject **BJ1** showing how **differences** in sampling time can cause major differences in fit factor measurements.



Exercises	Fit factor	
	Chamber photometer	Chamber Portacount
NB	10618	46800
DB	21085	42200
TT	1147	151
HSS	4129	14600
HUD	760	53
JIP	1881	32000
READ	3452	14200
NB	6780	41300

Figure 2-10. **Strip-chart** recorder trace of subject **C2** showing how **differences** in sampling time can cause major differences in fit factor measurements.

Summary and Conclusions

The effect of fine particles in the exhaled breath on fit factor measurements was calculated. It is significant at a fit factor of 1000 with a low ambient aerosol concentration, but the error is in the more conservative direction. Particle-size distributions measured in three workplaces at LLNL show that high concentrations of particles can exist, which would show some leakage through a HEPA filter at fit factors above 1000. Again, this error is conservative. Tests with human subjects showed a good correlation between simultaneous measurements made with a photometer and a Portacount; however, there is a bias for the Portacount fit factors to be a factor of 1.7 less than the photometer fit factors. A nonparametric statistical analysis on the simultaneous measurements shows that at a fit factor of 100, the Portacount meets the ANSI Z88.10

criteria for validation of a new qualitative fit-test method; however, it does not meet the predictive value of a pass criteria at a fit factor of 1000 (see Tables 2-8 and 2-11).

The Portacount can be used with ambient aerosols to confidently measure fit factors of 100. When used to measure fit factors of 1000 with ambient aerosols, several complications can occur that cause the measured fit factor to be low. Requiring an ambient aerosol concentration of at least 10,000—which was found at about half of the tested sites at LLNL—and requiring smokers to abstain from smoking at least 30 min before the fit test should reduce the error to about 10 to 30 percent. Although this is **undesirable**, it errs on the side of safety. The error could be reduced by purposely increasing the ambient aerosol concentration.

Table 2-12. Portacount fit factors for normal breathing.

Subject	1st room	2nd room	1st chamber	2nd chamber	3rd room
E1	192	18	4	7	—
A3	568	16	4	9	—
F2	8	11	7	5	15
F3	59	10	10	8	30
G1	136	101	10	16	26
A2	197	54	16	14	—
B3	105	93	24	15	27
AJ3	906	91	40	1820	330
H3	166	226	78	88	220
B2	138	184	86	39	129
E3	196	235	87	101	202
H2	214	265	93	80	181
E2	195	253	98	97	142
H1	191	209	110	114	272
AJ2	2560	9720	261	64	2480
G3	1430	1580	560	129	1330
D1	40,770	1190	709	1170	—
G2	1570	171	869	8020	49
AJ1	121	64	1300	606	156
A1	34	31	1390	61	—
BJ1	109,000	169,000	1740	21	20,000
D3	3120	1060	4340	278	—
D2	676	1110	10,900	5600	865
BJ2	36,700	95,600	18,100	864	36,100
F1	1960	2100	43,400	2770	83
C2	4090	5030	46,800	41,300	2390

References

1. C. I. Fairchild and J. F. Stampfer, "Particle Concentration in Exhaled Breath," *Am. Ind. Hyg. Assoc. J.* 48, pp. 948-949 (1987).
2. Portacount Operation and Service Manual, TSI, Inc., rev. B, St. Paul, MN, November 1987.
3. Code of Federal Regulations, Title 20, *Occupational Safety and Health Standards*, Part 1910.1001.
4. "Respirator Fit Methods," American National Standards Institute, New York, NY, Standard ANSI Z88.10 (in progress).