

Evaluation of Portacount for Determining Respirator Fit Factors, Part II: Laboratory Breathing Machine Tests of Stability and Comparison with an Aerosol Photometer

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Abstract

We compared the performance of a portable condensation nucleus counter (the model 8010 Portacount by TSI.*) to that of an aerosol photometer for quantitative fit testing of respirators. Breathing conditions of 40 lpm at 23.6 respirations/min were simulated in a full-face respirator on a mannequin head. Two types of challenge aerosols were used in our experiments: an oil mist aerosol and the ambient room aerosol. For experiments using the oil mist aerosol, we found that fit factors as measured by the two instruments agree well at fit factors below 1000. For higher fit factors, the Portacount measures significantly lower fit factors than the photometer, with differences increasing as leak rates decrease. In 1-hr stability tests of fit-factor measurements, the Portacount performs as well as the photometer. In experiments using the room aerosol as the challenge agent, fit factors as measured with the Portacount were 2 to 7 times higher than those measured with the oil mist aerosol at identical leak-rate conditions. In large part such variations can be explained by differences in the size distributions of the challenge aerosols. In most workplace environments, the Portacount can be expected to accurately measure fit factors of up to 1000.

Introduction

We conducted an experimental comparison of how a portable condensation nucleus counter (CNC) and an aerosol photometer measured the fit factor of a respirator under simulated breathing and leak conditions. The portable CNC (the Portacount) has only recently become commercially available. Its portability and sensitivity to small aerosol particles have advantages in monitoring respirator perfor-

mance. Aerosol photometers have long been the instrument of choice for assessing both the protection afforded by respirators and the performance of filters. In addition to these two aerosol detectors, we included measurements using a laboratory-type CNC. Experiments were performed using both an oil mist aerosol and the laboratory ambient aerosol as the challenge to the respirator.

* TSI is a registered trademark of TSI, St. Paul, MN.

Aerosol photometers have historically been used to measure the performance of both respirators¹⁻³ and high-efficiency particulate air (HEPA) filters.⁴ Because photometer-type instruments measure the amount of light scattered from a system of particles, their measurement of aerosol concentration depends upon the size distribution of the particulates, their shape, and their index of refraction. To measure the performance of devices offering high levels of protection, a challenge aerosol having high concentrations, perhaps 20 mg/m^3 , must be generated. Only then will a detectable amount of aerosol be present inside the protection device for an adequate concentration measurement to be made.

CNCs measure the aerosol concentration by counting individual particles. As with the photometer, the CNC also uses light scatter to detect the particle. However, to detect the light scatter from individual particles, condensation of some vapor is induced on the particles. This results in particle growth and increased light scatter, so that even very small particles ($<0.1 \mu\text{m}$ in diameter) can be detected. Therefore, CNC-type instruments are much more sensitive to small aerosol particles than photometers, and lower concentrations of the challenge aerosol can be used to measure aerosol penetration.

An added advantage is that their concentration measurement generally does not depend on the characteristics of the aerosol. CNC instru-

ments have also been used to assess the performance of protection devices.^{5,6} However, much of the work has been done in conjunction with other aerosol instrumentation so that the relationship between penetration and aerosol particle size could be investigated.

Because the CNC and photometer instruments use different methods to detect aerosols, it should not be surprising that their assessment of the level of protection offered by a respirator may differ. We have previously shown how such differences can be explained from a theoretical standpoint and also experimentally in tests using filters under constant flow conditions.⁷ We found that several functions, which are generally dependent on particle size, interact to contribute to the differences. These include the particle-size distribution of the challenge aerosol, the filter efficiency of the protective device, and the response function of the photometer to particle size.

For our experiments in this investigation, we used an MSA Ultravue full-face respirator fitted on a mannequin head. Breathing conditions were simulated using a breathing machine operated at 23.6 respirations/min, yielding a flow of 40 lpm. Leaks were simulated by introduction of the challenge aerosol into the respirator using either capillary tubes or a variable valve arrangement. In addition to comparing the response of the instruments for various fit-factor measurements, stability and reproducibility tests were also conducted.

Experimental Configuration

To conduct this evaluation, the relevant laboratory instrumentation was assembled and configured in the arrangement shown in Fig. 1. This experimental test system permitted the assessment of respirator performance under a simulated breathing condition and various leak conditions. A 1-m^3 chamber was used to contain the challenge aerosol, MSA Ultravue respirator, and mannequin head. MSA Type H filter cartridges were used, yielding no greater than a ± 1.4 in.w.g. pressure drop at the breathing rate simulation used here. The respirator mask was fitted tightly, so that a typical no-leak condition resulted in fit factors well over 30,000. A continuous air flow of 283 lpm, monitored with a venturi flowmeter, was maintained through the chamber. By controlling the

chamber inlet and outlet valves, a negative pressure of about 0.1–0.2 in.w.g. was maintained during the tests.

To simulate the cyclic breathing condition, the mannequin head and mask were connected to a breathing machine.⁸ A cyclic breathing rate of 23.6 respirations/min was used for all tests, resulting in a moderate work-rate breathing condition of 40 lpm.

Two aerosols were used in these experiments, an oil mist aerosol and the ambient laboratory aerosol. The oil aerosol, dioctylsebacate (DOS), was produced using a Phoenix Precision SG-20 cold-bubbler generator operated at 6 psi. This

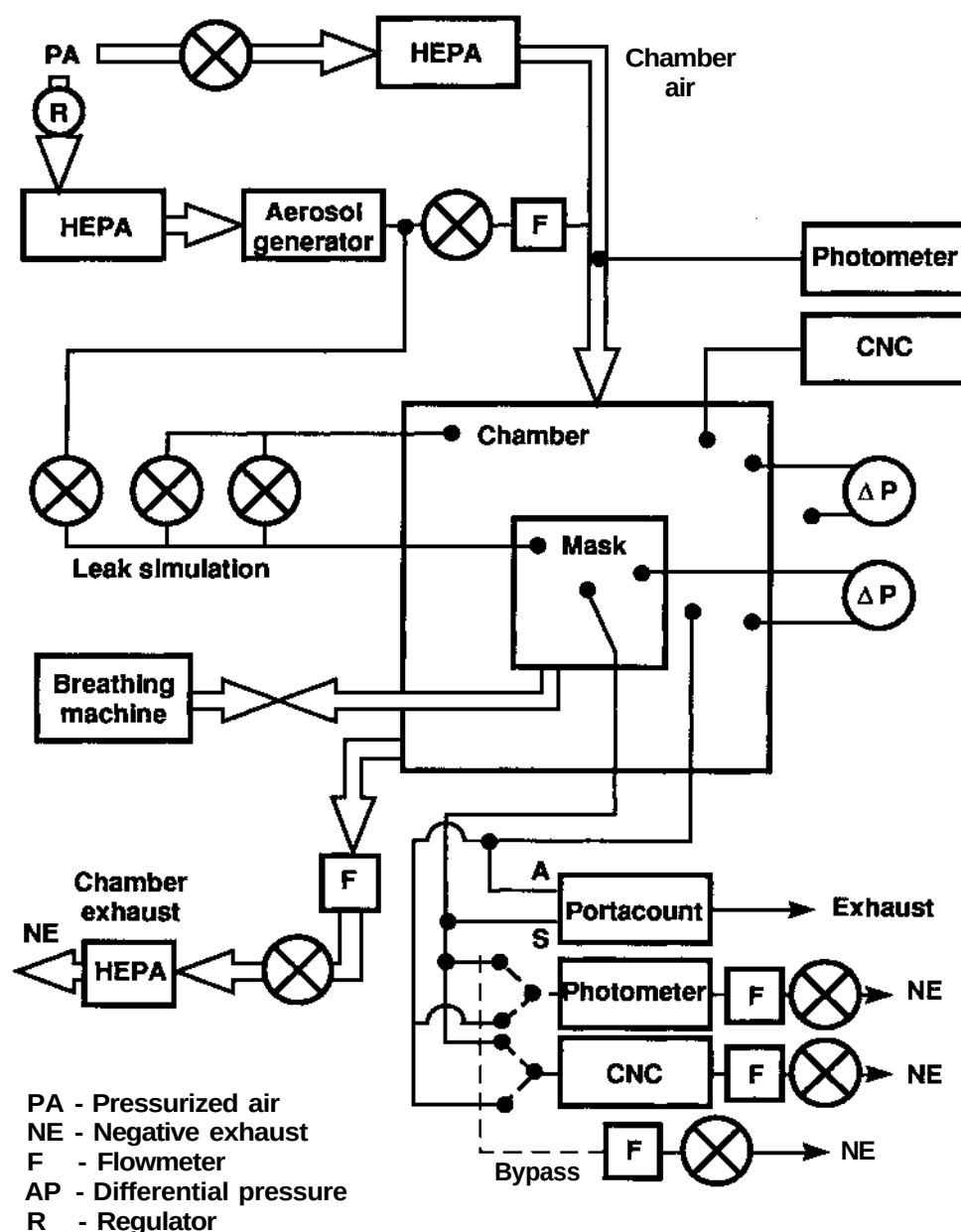


Figure 1. Configuration of Portacount experiment.

produces an aerosol similar to those used in quantitative fit testing of respirators. Flow control allowed a high aerosol concentration of 30 mg/m^3 or a low concentration of 5 mg/m^3 to be selected. A photometer (see Fig. 1) was used to initially set and then monitor the generator output to facilitate adjustments during a test to ensure concentration

stability. The aerosol from the generator was mixed with HEPA-filtered pressurized air before entering the chamber.

For experiments using the ambient aerosol of the laboratory, the inlet to the chamber was simply opened to the room. Aerosol size distributions of

the challenge aerosol were measured over a range of 0.01-3.0 μm in diameter using instrumentation described elsewhere.⁹

To simulate leaks, a parallel arrangement of different sized capillaries was inserted through the mask near the forehead of the mannequin. However, because this did not result in reproducible leaks from day to day, the approach was discarded. For better reproducibility, a system of two parallel valves was used to regulate the leak aerosol from the chamber into the mask through a 1/4-in. port. To achieve very high leak conditions corresponding to fit factors of 30 or less, another valve was required to allow additional aerosol directly from the generator to enter the leak (1/4-in. port).

Three aerosol instruments were used to measure the penetration of aerosol into the mask. These included a Sinclair-Phoenix model JM-7000 aerosol photometer, the Thermo Systems model 8010 Portacount, and the Thermo System model 3020 CNC. The output of all three instruments was directed to an LSI-11/23 computer for data storage and analysis. The photometer has a continuous analog output with a dynamic operating range of five decades over aerosol mass concentration typically ranging from 0.001 to 100 mg/m^3 . Under carefully controlled laboratory conditions using a breathing machine, aerosol fit factors of 100,000 can be measured. Because the precise aerosol concentration depends on the physical properties of the aerosol, the photometer was calibrated at a few higher concentrations of the DOS aerosol using gravimetric filter analysis.

The laboratory model CNC has a dynamic operating range of nine decades in particle number concentration ranging from 0.01 to 1×10^7 particles/ cm^3 . However, it accomplishes this by operating in either of two modes. The first mode is analogous to the Portacount in that individual particles are counted after they have grown to a detectable size by condensation of butanol. This mode is used for concentrations below 1000 particles/ cm^3 . For higher concentrations, the CNC operates in a photometric mode that is converted to an absolute number concentration by a factory calibration.

The Portacount has a dynamic operating range from 0 to 500,000 particles/ cm^3 . The entire range is covered by individual particle counting with correc-

tions for coincidence at the high concentration levels. For our experiments, we used it in either the fit-test or count mode of operation. In the count mode, the instrument collects samples at 1-s intervals and reports only particle counts. We used this mode to check the instrument zero and also for some periods while the photometer and CNC were sampling the chamber challenge aerosol.

In the fit-test mode, the Portacount samples alternatively from the chamber and mask in a preprogrammed manner. After an initial chamber sampling, the instrument has a 30-s cycle consisting of an 11-s purge, a 10-s mask sample, a 4-s purge, and a 5-s chamber sample. In this study, the fit factor is calculated as the ratio of an average chamber sample to mask sample where the average chamber is based on the samples immediately before and after that of the mask. A fit factor is reported about every 30 s. Sampling flow rates are 0.7 lpm, with only 0.1 lpm actually being counted. In the fit-test mode, zero counts in the mask are arbitrarily set to 1, or 0.05 particles/ cm^3 .

Sample flows for the photometer and the CNC were held at 0.9 and 0.3 lpm, respectively. Sample switching between the chamber and mask for the photometer and CNC was controlled manually. Preliminary tests indicated that switching the photometer and CNC from chamber to mask and the reverse resulted in detectable variances in the leak rate as measured by the Portacount. This in turn caused discrepancies in reported Portacount fit-factor measurements. As a consequence, a bypass flow system was designed and implemented. This allowed the same flow to be taken from the mask even when the photometer and CNC were sampling from the chamber. Thus, the simulated leak could be accurately maintained throughout the experiment.

Three types of experimental protocols were established. The first protocol was used to compare the fit factor as measured by the three instruments at different leak conditions. The range of leaks investigated corresponded to fit factors from 10 to the no-leak condition, a protection level of over 30,000. This protocol was also repeated on different days to assess the reproducibility of the Portacount relative to the photometer and CNC. The second protocol was used to assess the stability of the Portacount in making fit-factor measurements. Stability periods investigated ranged from

1 to 8 hr of continuous operation. The third protocol involved the use of the ambient aerosol for the challenge.

The photometer and CNC have larger internal air-sampling volumes. Hence, although the Portacount can switch from mask to chamber and back in 30 s, the other instruments required considerably more purge time. However, by using the bypass flow system previously mentioned, this purge time was reduced by manually increasing the flow through the instruments during the purge period.

Nevertheless, the chamber-to-mask cycle times for the photometer and CNC are much longer than that for the Portacount. Fit factors as measured by the photometer and CNC are based on averages of alternate mask and chamber samples: the chamber is sampled for a 2- to 5-min period, the mask is sampled for 2–8 min, and the chamber is repeated. The actual computer sample rate of signals from the photometer and CNC was usually one per second during each sample period. In the stability protocol, the mask sample lasted as long as 15 min.

To help determine the sensitivity of the Portacount, additional tests were conducted to

determine the background signal each instrument detects in the presence of no aerosol. This background concentration may be important in the cases of high fit factors, if the concentration of particles leaking into the respirator is not much greater than the background.

To establish this background level, filtered air was passed through all the instruments at the beginning of each experiment. This level serves as the photometer signal zero. The Portacount and CNC reported zero particle counts for the filtered air. However, it was later found that the volume within the mask contained a nonzero particle background level due to the breathing machine itself. Therefore, at the end of most experiments, a second background (breathing-machine background) sample was taken. This was done by bringing the chamber to a slightly positive pressure with particulate-free air and the breathing machine off. After establishing that the chamber was indeed free of particulates, the breathing machine was started and the breathing-machine background was obtained by sampling from the mask volume.

Results

We will discuss the results of this study, including size-distribution measurements, background concentrations, fit-factor comparisons and stability tests using the DOS aerosol, and fit factor and stability tests using the laboratory ambient aerosol.

Aerosol Size-Distribution Measurements

Reasons why we might expect discrepancies in fit-factor determinations from the photometer and Portacount and discrepancies when using different challenge aerosols have previously been investigated.⁷ It was not part of this study to delve into the theoretical nature of the problem. But, because the ambient laboratory aerosol is considerably different from the DOS aerosol, aerosol size distributions were taken to offer some explanation of experimental results. The ambient aerosol is compared with the low-concentration DOS aerosol in

Fig. 2. The geometric median diameter and standard deviations are 0.092 μm and 2.05, respectively, for the ambient aerosol and 0.32 μm and 1.8, respectively, for the DOS aerosol.

Background Determination and Implications

As we have already mentioned, two background counts were usually taken during each experiment for all instruments. These background levels are important in determining the minimum detectable leak that the instruments can sense. Table 1 summarizes the initial testing conducted for finding these background levels. The first was established using air filtered through a HEPA cartridge filter. In Table 1, this corresponds to a chamber with filtered air and the breathing machine off. The Portacount (and CNC) measured zero counts. The photometer zero would be adjusted according to this background, usually at 0.002 mg/m^3 .

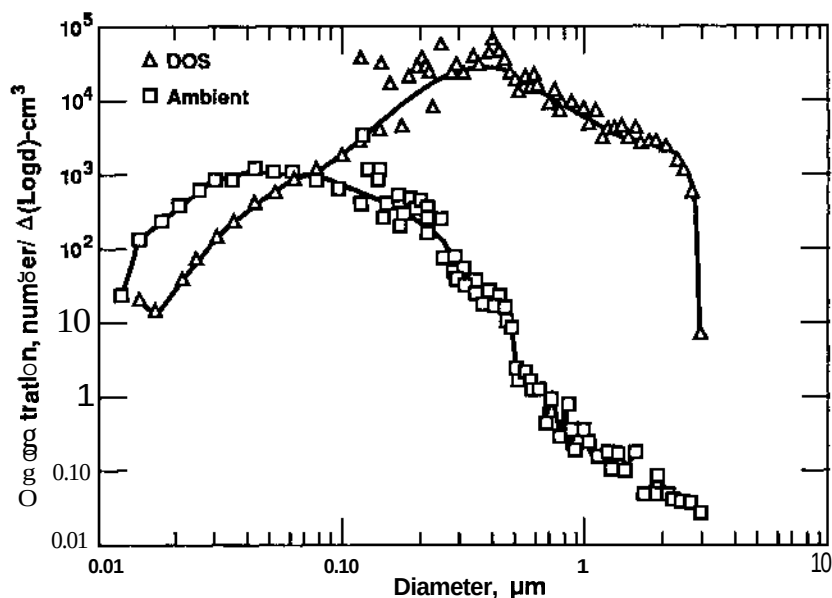


Figure 2. Size distributions for the DOS and laboratory room aerosols.

Table 1. Background concentration levels.

Sample location	Breathing machine	Portacount particle counts (per cm ³)	
		Directly to mask	Through filter to mask
Chamber	OFF	0.0	0.0
Mask	OFF	0.0	0.01
Mask	40 lpm	1.26	0.01
Mask	60 lpm	1.48	0.01

The second background is denoted as the breathing machine background, because it originates from the breathing machine. It is typically 1 to 2 particles/cm³ for the 40-lpm breathing rate used in our experiments. Further experiments confirmed that the leakage occurred from the internal mechanism of the breathing machine as well as leakage into the machine from the surrounding environment. Although the background level is very low (1 particle/cm³), it is significant when compared to the minimum detection limits for the Portacount and CNC, 0.05 and 0.01 particle/cm³. Thus, this background level could limit the maximum fit factor that these instruments could measure.

This breathing machine background could be reduced to near zero by placement of a filter between the machine and the mask. However, a portion of the leak would also be filtered. After some discussion, it was agreed to tolerate the nonzero breathing machine background. The primary reasoning is that an analogous background is present in humans when wearing respirators. Researchers have measured particulate concentrations of 0.1 to 3 particles/cm³ from human subjects.¹⁰ The Portacount manufacturer also warns in its operational manual to avoid fit testing of subjects who have smoked within the previous 30 min because of excess particles being expired.¹¹

With the inclusion of a background concentration measurement, fit factors can be calculated using the following equation:

$$F = C_c / (C_m - B) \quad (1)$$

where:

F = fit factor,

C_c = chamber concentration,

C_m = mask concentration, and

B = background concentration in the mask.

If we assume a background of 1 **particle/cm³** and arbitrarily require a measurable leak to be three times the background, then the maximum fit factor, F_{max} , that can be measured using the **Portacount** or CNC is shown below:

$$p_{\text{max}} = \frac{\text{Challenge aerosol concentration}}{(2 \text{ particles/cm}^3)} \quad (2)$$

To determine a fit factor of 1000, a challenge aerosol concentration of at least 2000 **particles/cm³** would be required. The expected maximum measurable fit factor using the **Portacount** and photometer at various challenge concentration levels is indicated in Fig. 3.

Two sets of calculations are included for the **Portacount**. The first is based on the fact that the **Portacount** sets a zero concentration in a mask sampling period to 1 **count**—or 0.05 **particle/cm³**. The second, incorporating a breathing-machine background concentration of 1 **particle/cm³**, predicts maximum measurable fit factors 20 times less. The dotted lines indicate concentrations that are normally restricted from use because the **Portacount** is internally set to not make fit-factor measurements with challenge aerosol concentrations less than 1500 **particles/cm³**. Aerosol concentrations in workplace environments have been reported to be 2000–30,000 **particles/cm³**.

Two data sets are also shown for the photometer, one with DOS challenge aerosol and the other using the room air. With the room aerosol, only very low fit factors are measurable because of the low photometer response to this aerosol. Because the **Portacount** is a more sensitive instrument to individual particles than the photometer, it can always measure higher fit factors at any specific challenge concentration.

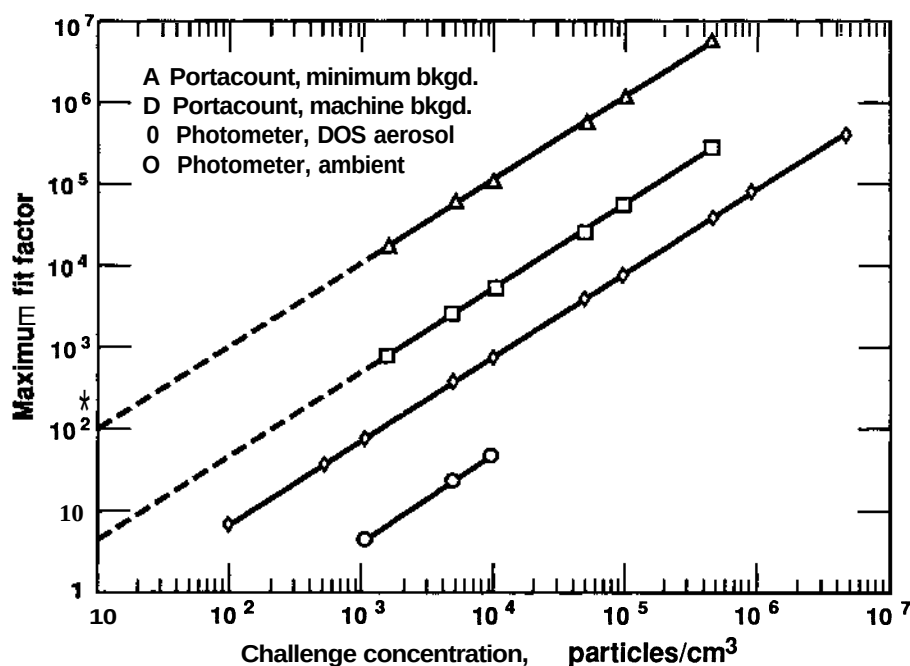


Figure 3. The maximum fit factors that can be measured at various challenge aerosol concentrations.

DOS Aerosol Challenge

One of the primary objectives of our investigation is the comparison of fit factors as measured by the Portacount and the photometer at different leak conditions. Using DOS as the challenge aero-

sol, leaks corresponding to fit factors from 10 to 15,000 were simulated with the valving arrangement. The comparison of fit factors as measured by the Portacount, photometer, and CNC are presented in Table 2.

Table 2. Comparison of fit factors as measured by the photometer, Portacount, and CNC at various leak conditions.

Leak condition	Portacount (serial no.)	DOS (mg/m ³)	Fit factor		
			Photometer	Portacount	CNC
1 (No leak)	337	30	>100,000	17,650.0	31,650.0
	337	30	>100,000	14,810.0	26,520.0
	337	30	>100,000	11,780.0	21,780.0
	250	30	97,600.0	9040.0	23,600.0
	337	5	>100,000	6840.0	12,400.0
2	337	30	12,270.0	5546.0	9439.0
	337	30	10,990.0	3804.0	6156.0
	337	30	11,400.0	4462.0	8027.0
	250	30	9060.0	3430.0	7390.0
3	337	30	3054.0	2002.0	4899.0
	337	30	2212.0	1268.0	2136.0
	337	30	2804.0	1884.0	5307.0
	250	30	1970.0	1370.0	2570.0
	337	5	1930.0	1470.0	2031.0
4	337	30	931.0	702.4	1277.0
	337	30	789.9	578.6	1016.0
	337	30	861.0	628.0	1248.0
	250	30	782.0	1120.0	1120.0
	337	5	1066.0	794.0	1230.0
5	337	30	261.8	213.9	246.9
	337	30	226.7	208.1	236.0
	337	5	317.0	304.0	489.0
6	337	30	99.55	88.66	107.3
	337	30	83.00	78.89	97.98
	337	30	90.88	73.33	98.70
	250	30	95.00	119.00	119.00
	337	5	98.00	132.00	132.00
7	337	30	28.52	21.03	23.40
	337	30	24.70	22.22	25.50
	250	30	22.00	21.00	21.00
	337	5	30.00	27.00	27.00
8	337	30	11.35	8.92	10.06
	337	30	8.43	7.23	7.23
	337	30	8.14	6.36	6.36
	250	30	10.00	7.00	8.00
	337	5	10.00	10.00	10.00

In this set of experiments, the mask sampling period ranged from 5 to 8 min, resulting in 10 to 18 Portacount measurements at each leak condition. Test results using a lower DOS challenge concentration of 5 mg/m^3 were reported, as well as those using a second Portacount. For fit factors above 1000, we see a considerable discrepancy in the values from the three instruments. The largest fit factor is usually predicted by the photometer data, with the CNC and the Portacount reporting lower values. The most extreme case is for the no-leak condition. Here, fit factors as measured by the photometer are 6 to 10 times those by the Portacount. Conversely, for larger leaks—and corresponding lower fit factors—the instruments show better agreement.

With the high-concentration DOS challenge, aerosol number concentrations as measured by the Portacount ranged from 1.71×10^5 particles/ cm^3 for the chamber to 9.1 particles/ cm^3 inside the mask for the no-leak condition. Mask concentrations at the no-leak condition are still nearly 10 times higher than the breathing machine background resulting in a credible fit-factor value. However, for the no-leak case as measured by the photometer, the mask concentration approaches the photometer

zero. Erroneously high or negative fit factors can result. Such values have been listed as $> 100,000$ in Table 2.

In one experiment, the Portacount filter zero could not be reduced to 0. We suspect this was due to an overfilling with alcohol, though we always exercised care during filling. This unit was returned to the manufacturer for servicing before reuse. Table 2 results are also shown graphically in Fig. 4, where the geometric average fit factors have been taken for each leak condition.

To depict the reproducibility of the Portacount and photometer data at different leak conditions, the Portacount-to-photometer ratio of fit factors is shown in Fig. 5. This type of absolute reproducibility comparison entails the careful measurement of both the breathing machine and leak flows. Unfortunately, we did not have this capability until later in the study's progress, so absolute reproducibility was not determined in these experiments.

We conducted one additional test using lower DOS concentrations. In this test, an initial simulated leak yielding a fit factor of approximately

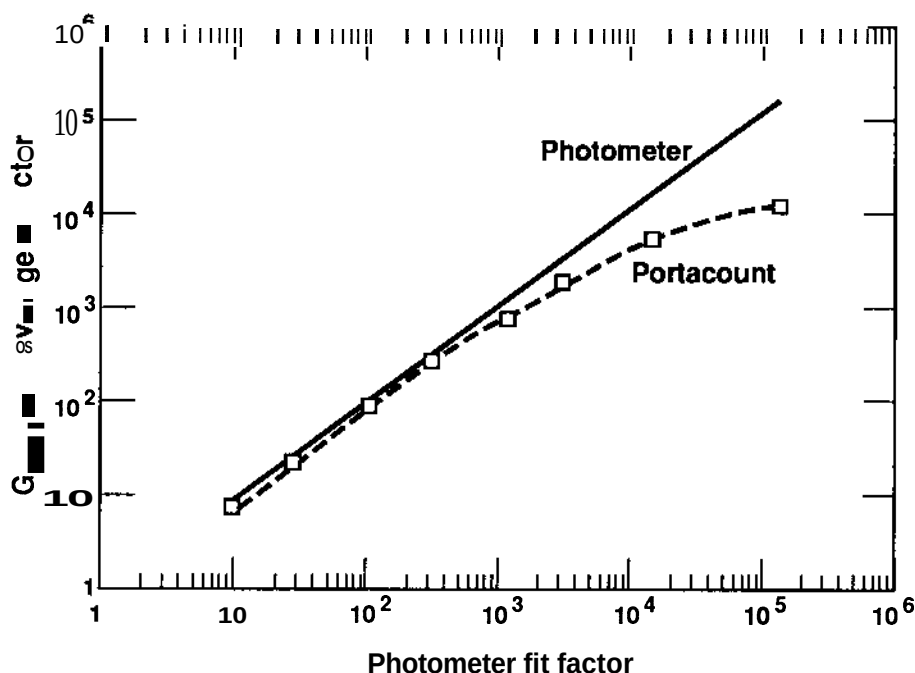


Figure 4. Comparison of fit factors as measured by the Portacount and photometer for various leak conditions.

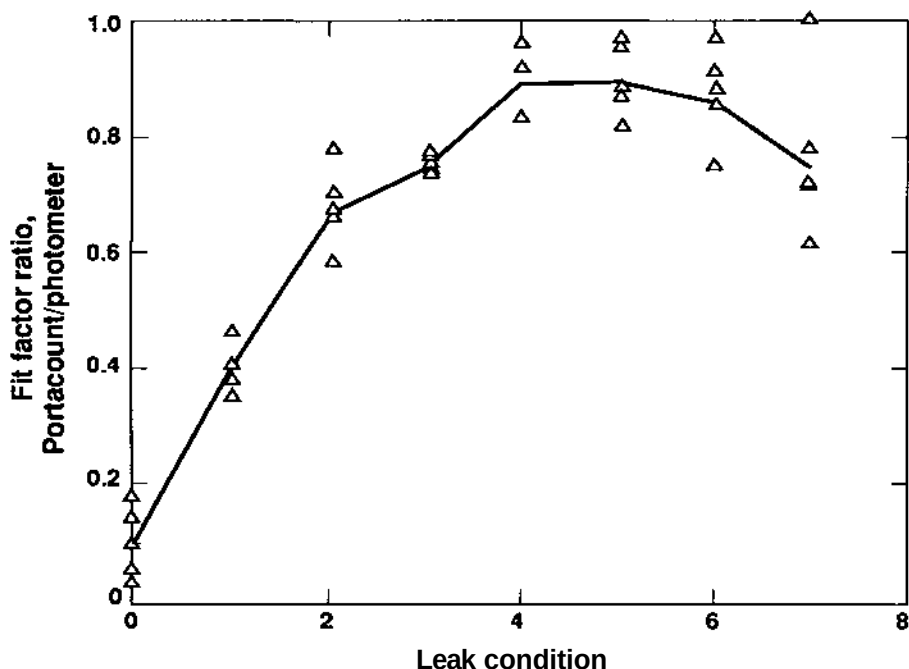


Figure 5. Ratio of fit factors as measured by the Portacount and photometer.

1000 was maintained while the chamber was incrementally purged with clean air. After each purge the fit factor was again measured. The results are shown in Fig. 6. We have illustrated two cases, one with the breathing-machine background subtracted and the other without, or showing how the Portacount would actually report. At the lowest concentration points, the mask concentrations were about three times the background.

Stability Tests Using the DOS Aerosol

Four 1-hr stability tests were conducted to assess variations in fit factors over the sample period. The tests were performed using the high-concentration DOS aerosol at fit factors of 350, 980, 9600, and 11,100, as measured by the photometer. The test having a fit factor of 11,100 was conducted at a constant flow rate of 40 lpm rather than the normal cyclic flow. We did this to ascertain if any of the variations in fit-factor measurements was due to the cyclic flow operation. The results of these stability tests are presented in Table 3.

The values listed in Table 3 are percent standard deviations relative to the average fit factor for the particular instrument. Each 1-hr test contains about 120 Portacount measurements and 3000 measurements each for the photometer and CNC. The standard deviation of the Portacount does increase at higher levels of protection. This is to be anticipated because there are fewer particle counts due to the lower aerosol concentration in the mask.

The higher standard deviations seen for the photometer and CNC are due to their faster sampling rates. For example, averaging photometer mask samples over the Portacount cycle before computing the average and standard deviations reduces the percent standard deviations to 2.8, 5.0, and 13.0 for the first three photometer tests in Table 3. At the constant flow condition, both the photometer and CNC had lower standard deviations in the fit factors, although the Portacount did not.

In addition to the above tests, one 8-hr stability experiment was conducted. The fit factors and their respective percent standard deviations are compiled in Table 4. The standard deviations are

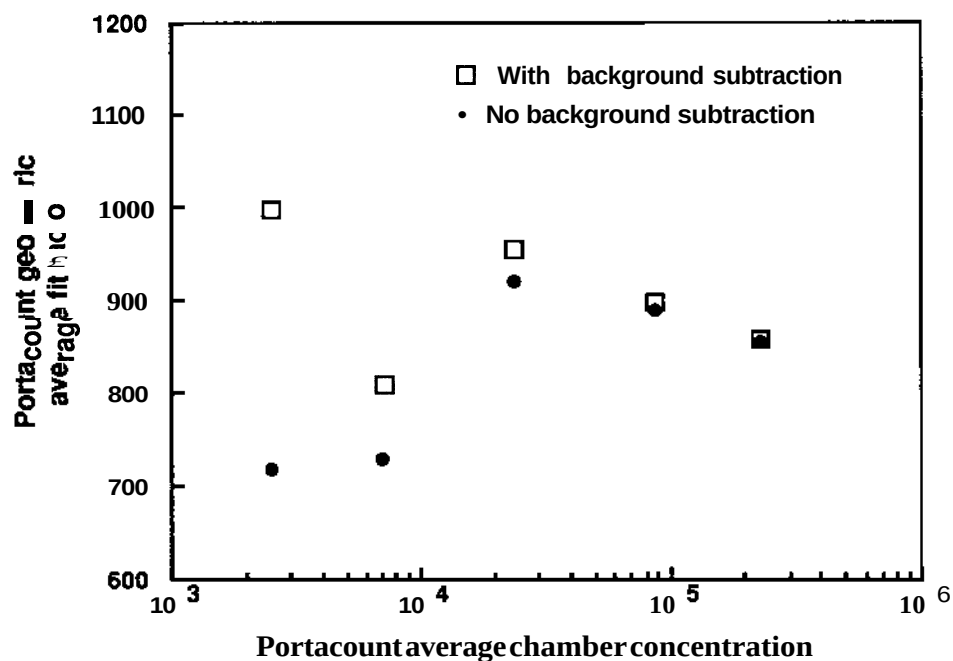


Figure 6. Portacount fit factors with decreasing concentrations of DOS aerosol challenge.

Table 3. Stability of fit-factor measurements during 1-hr testing

Aerosol	Photometer fit factor	Percent standard deviation		
		Photometer	Portacount	CNC
DOS	350.0	4.4	1.8	7.4
DOS	982.0	7.4	4.0	25.0
DOS	9600.0	18.0	5.0	36.0
DOS^a	11,100.0	12.6	5.5	7.1
Ambient	98.0	—	12.0	7.8
Ambient	200.0–300.0^b	—	18.0	14.0
Ambient	1060.0	—	23.0	9.5

^aThis experiment was done under a constant flow condition through the respirator (40 lpm).

^bEstimated value.

cumulative covering the period listed. During the 5- to 6-hr periods, the standard deviation in the Portacount fit factor increased dramatically. This occurred approximately 30 min before the low-battery indicator was displayed on the Portacount. At this time the Portacount fit factor decreased significantly. The fit factor during this period is

compared with that of the photometer in Fig. 7, which also includes the following period after replacing the battery. Here the instrument fit factors track normally. Although such behavior may be expected in battery-powered instruments, it should occur after the low-battery-level warning.

Table 4. Percent standard deviations of the fit factor 8-hr stability test.

Hours	Photometer fit factor	Percent standard deviation			
		Photometer cumulative	Portacount		CNC cumulative
			cumulative	interval	
0-1	993.0	8.4	4.7	4.7	6.2
0-2	949.0	9.6	5.0	4.4	7.3
0-3	925.0	9.9	5.3	3.5	7.8
0-4	908.0	10.2	5.4	4.5	7.9
0-5	892.0	10.5	5.6	4.4	7.9
0-6	878.0	10.7	8.8	10.1^a	8.0
0-7	874.0	10.5	9.0	5.7	7.9
0-8	875.0	10.4	8.6	4.7	7.8

^a Signal variation in the Portacount due to battery failure prior to low-level indicator.

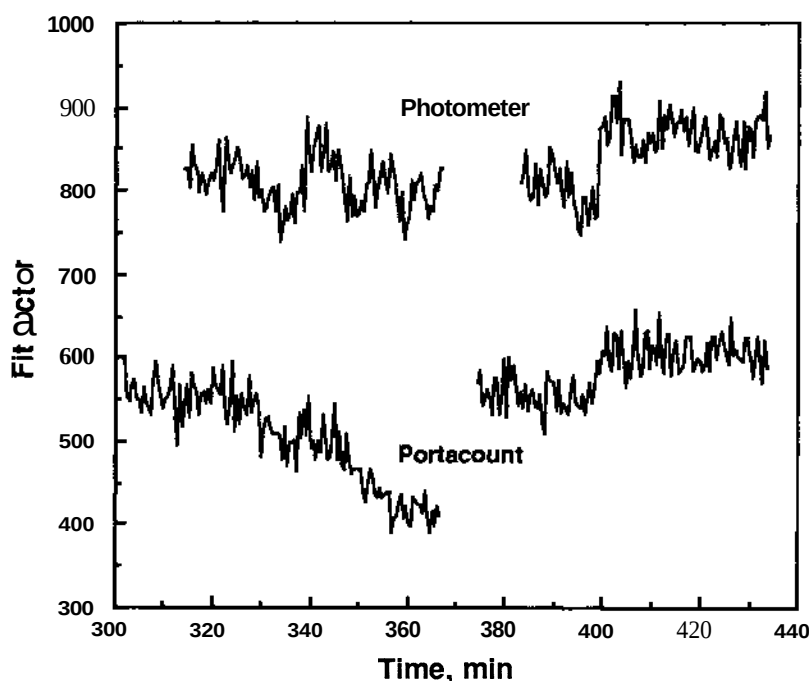


Figure 7. The fit factor as measured by the photometer and Portacount for the 5- to 6-hr and 6- to 7-hr periods of the 8-hr stability test.

Ambient Aerosol Challenge

When using the laboratory room aerosol as the challenge agent, the challenge aerosol concentration is severely reduced from that of the high DOS concentration. Challenge concentrations from our laboratory room aerosol varied from 3000 to 10,000 particles/cm³ as measured by the Portacount. This is two orders of magnitude less than that of the more concentrated DOS aerosol. For leak condi-

tions yielding fit factors over 1000, particle concentrations within the mask can approach the background level produced by the breathing machine.

In the case of the photometer, the situation is even worse because of its response to particle size. Because the room aerosol distribution is significantly smaller, the photometer measures this ambient aerosol to be 1000 times less than the DOS. Thus, using the room aerosol, the photom-

eter can only measure fit factors of 10 or less, and with all instruments we cannot expect as great a sensitivity in leak detection using the ambient aerosol.

Three 1-hr stability experiments using the Portacount were conducted with the laboratory air as the challenge aerosol. The protocol for these experiments was the same as that for the DOS challenge aerosol stability tests with the following exception: prior to the test, the leak condition is adjusted to the desired fit factor using the DOS aerosol as measured by the photometer. Subsequently, the chamber is purged with the ambient aerosol. The relative standard deviations for these experiments are presented in Table 3 for comparison to similar data for the DOS aerosol. The photometer fit factors listed in Table 3 are those using the DOS aerosol. No actual standard deviations are shown for the photometer because it is unable to make credible fit-factor measurements at these leak conditions using the ambient aerosol.

For the Portacount, standard deviations range from 12 to 23 percent—or 2 to 3 times higher than those encountered when using the DOS aerosol. The increased standard deviations are a direct result of the decrease in particle counts within the mask. The decrease in the standard deviation for the CNC is due to an increased integration time within the instrument for these lowered counts.

As with the ambient stability tests, the leak for experiments involving the Portacount's performance over a range of fit factors was set according to the DOS penetration. With the leak condition unchanged, the chamber is then purged with the room air for the challenge aerosol. This gives a direct comparison between fit factors as measured by the photometer/oil-mist method and the Portacount/ambient method. Of course, the comparisons are valid only for this particular aerosol size distribution. Table 5 presents the results of these experiments.

Table 5. Fit-factor comparisons between two challenge aerosols: DOS and the laboratory room aerosol.

Aerosol	Photometer	Portacount	CNC
First set of experiments:			
DOS	127.0	180.0	184.0
Ambient ^a	—	354.0	1480.0
Ambient ^b	—	1320.0	1490.0
DOS	836.0	1040.0	—
Ambient ^a	—	4400.0	—
Ambient ^b	—	6160.0	—
DOS	2150.0	1690.0	2000.0
Ambient ^a	—	4290.0	6578.0
Ambient ^b	—	-38,000.0	-71,000.0
Second set of experiments:			
DOS	4700.0	3177.0	4527.0
Ambient ^a	—	3021.0	4471.0
Ambient ^b	—	5717.0	7767.0
DOS	1054.0	1048.0	—
Ambient ^a	—	2278.0	—
Ambient ^b	—	2085.0	—
DOS	323.0	358.0	583.0
Ambient ^a	—	621.0	881.0
Ambient ^b	—	689.0	1004.0

^a Calculated assuming the minimum detection limit of the Portacount (0.05 particles/cm³).

^b CNC and Portacount values calculated using the breathing-machine background for the experiment.

With the room aerosol and the same leak, fit factors as measured by the Portacount are much higher than with the DOS challenge as measured by either the photometer or the Portacount. Portacount fit factors six times higher were encountered when the photometer/DOS fit factor equaled 836. Similar results are seen using the CNC. Such differences can be corroborated by theoretical calculations, given appropriate choices for the aerosol size distribution and penetration-size function.

Fit factors as measured by the Portacount without the subtraction of the breathing-machine

background are also listed. These values correspond to those taken directly from the Portacount itself and yield lower fit factors. The negative fit factor at the highest DOS fit-factor level occurs because the concentration within the respirator is less than the breathing-machine-produced background. Chamber concentrations range from 6620 to 7280 particles/cm³ in this experiment. Note that at this fit-factor level, the Portacount and CNC unable to make accurate measurements. This fit-factor point agrees well with the predicted value of 3000 for the maximum measurable fit factor from Fig. 3.

Discussion

Our study of the Portacount as an instrument for the determination of respirator performance involved experiments to assess its stability, reproducibility, and sensitivity, and to compare fit factors as measured by an aerosol photometer. In fit-factor comparison experiments using the DOS aerosol, we found that the Portacount usually measured lower fit factors than those of the photometer. The discrepancy in measurements between the two instruments was accentuated at the fit-factor levels above 1000, or the low-leak conditions.

Similar findings between a laboratory-model CNC and the photometer were also noted. For our no-leak condition, measured fit factors were 15,000 and 100,000 for the Portacount and photometer, respectively. The higher photometer-measured fit factors occur because the photometer's response function makes the challenge aerosol appear larger in size.

Stability tests of 1-hr duration indicated that percentage standard deviations relative to the average fit factors from the Portacount can be expected to be less than or equal to 6 percent. Lower standard deviations were found for lower fit factor levels where higher particle concentrations are found in the respirator. Standard deviations as high as 23 percent were encountered using the room aerosol as the challenge agent.

Correlation of fit factors measured by the Portacount with those measured by a photometer is a difficult task at best. Discrepancies in fit

factors between the two instruments are attributable to the aerosol characteristics, the instrument's response to the aerosol, and the fact that the aerosol penetration of the respirator is a function of particle size. The nuclei counter type, such as the Portacount, measures a fit factor based on the detection of individual particles. The photometer measures a fit factor based on the detection of scattered light. Both instruments integrate the dependence of particle size in their determination of fit factors. Photometer-measured fit factors are more closely associated with the surface or volume (mass) of the challenge aerosol.

For identical leak rates, the fit factors as measured by the Portacount and the laboratory CNC were 2 to 7 times higher when the laboratory room air, as opposed to DOS, was used as the challenge aerosol. This dramatic difference is due to variations in the size distributions of the challenge aerosols relative to the respirator penetration function as a function of particle size. The room aerosol distribution is a smaller aerosol having a number median diameter less than 0.1 μm and has a different penetration than the larger DOS aerosol. Thus, with an identical fit, a wearer may encounter a different protection level as he moves from one environment to another.

Aside from the discrepancy in absolute fit factor values, the Portacount performed as well as the photometer in measuring respirator fit factors using an artificially generated oil-mist aerosol. Its short-term stability (1 hr) was as good as—if not better—than our state-of-the-art photometer.

The **Portacount** presents a number of advantages for the measurement of fit factors, especially in the workplace environment. Its small size offers portability, allowing measurement of protection levels in the workplace. Because of its sensitivity ($0.05 \text{ particle/cm}^3$), artificial challenge aerosols need not be generated if the workplace aerosol concentrations are adequate. However, as we discussed, individuals generate aerosol particles from their own respiratory system. These particles, which are indistinguishable from those leaking into the respirator, result in a background contamination when measuring respirator performance.

This background limits the advantage of the **Portacount's** higher sensitivity over photometer-type test methods. Even though the instrument may be over 1000 times as sensitive as the photometer (depending upon the aerosol characteristics), a respiratory background of 1 particle/cm^3 can limit its use for fit-factor measurements using ambient aerosols to levels of 1000 to 3000. This is a factor of 10 less than is routinely achievable in quantitative fit testing using the photometer/oil-mist performance test.

Acknowledgments

Work performed under the Auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract W-7405-Eng.

References

1. R. N. Mitchell, D. A. Bevis, and E. C. Hyatt, "Comparison of Respirator Filter Penetration by Dioctyl Phthalate and Sodium Chloride," *Amer. Ind. Hyg. Assoc. J.* 32, 357 (1971).
2. E. C. Hyatt, J. A. Pritchard, and C. P. Richards, "Respirator Efficiency Measurement Using Quantitative DOP Man Tests," *Amer. Ind. Hyg. Assoc. J.* 33, 635 (1972).
3. R. A. da Roza, C. A. Cadena-Fix, G. J. Carlson, K. E. Hardis, and B. J. Held, "Reproducibility of Respirator Fit as Measured by Quantitative Fitting Tests," *Am. Ind. Hyg. Assoc. J.* 44, 788-794, 1983.
4. "Quality Assurance Testing of HEPA Filters and Respirator Canisters," *Nuclear Standard NE F 3-43*, Nuclear Standards Management Center, Oak Ridge National Laboratory, Oak Ridge, TN, June 1984.
5. A. W. Powell and B. A. Wilkinson, "The In-situ Testing of High Efficiency Particulate Filters in the CEGB South Eastern Region Nuclear Power Stations," in *Seminar on High Efficiency Aerosol Filtration*, pp. 183-196, Aix-en-Provence, France, November 22-25, 1976 (available from the Commission of European Communities, Luxembourg).
6. B. Y. H. Liu and K. E. Lee, "An Aerosol Generator of High Stability," *Amer. Ind. Hyg. Assoc. J.* 36, 861 (1975).
7. A. H. Biermann and W. Bergman, "Filter Penetration Measurements Using the Condensation Nucleus Counter and the Aerosol Photometer," *J. Aeros. Sci.* 19(4), 471-483 (1988); Lawrence Livermore National Laboratory, Livermore, CA, UCID-20654 (1986).
8. R. E. Johnsen, C. L. Lindeken, and R. D. Taylor, "Respirator Cartridge Efficiency Studies: III. Development of a Mechanical Breathing Machine to Simulate Human Respiration," Lawrence Livermore National Laboratory, Livermore, CA, UCRL-51072 (1971).

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9. W. Bergman, A. Biermann, W. Kuhl, B. Lum, A. Bogdanoff, H. Hebard, M. Hall, D. Banks, M. Mazumder, and J. Johnson, "Electric Air Filtration: Theory, Laboratory Studies, Hardware Development, and Field Evaluations," Lawrence Livermore National Laboratory, Livermore, CA, UCID-19952 (1983).
 10. C.I. Fairchild and J. F. Stampfer, "Particle Concentration in Exhaled Breath," *Am. Ind. Hyg. Assoc. J.* 48, 948–949 (1987).
 11. *Portacount Operation and Service Manual*, TSI, Inc., St. Paul, MN (November 1987).