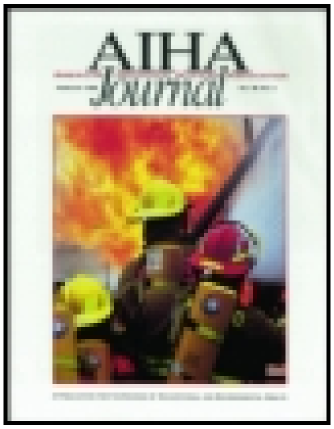

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Quantitative Respirator Fit Testing: Dynamic Pressure Versus Aerosol Measurement

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Quantitative Respirator Fit Testing: Dynamic Pressure Versus Aerosol Measurement

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A noninvasive, fast, inexpensive new fit testing method has been invented which relates the slope of the pressure decay inside a respirator during breath-holding to the fit of the respirator on the wearer's face. The dynamic pressure test has been compared with the conventional aerosol test at different leakage levels. The results of this comparison show that the sensitivity of the dynamic pressure test is similar to that of the aerosol test. The pressure test, however, is independent of leak site and probe location and can be performed on respirators before and after their use.

Introduction

Respirators are worn in the workplace to prevent the inhalation of contaminants. To determine how well a respirator performs this function, quantitative respirator fit testing conventionally is performed by comparing the concentration of aerosols surrounding the respirator wearer to the concentration of aerosols leaked to the inside of the respirator.[1-3] The traditional technique used most widely in the United States today consists of an aerosol generator, an exposure chamber and a photometric aerosol detector. The Willeke Particle Count Test eliminates the need for the aerosol generator and exposure chamber by measuring the aerosol concentration in the respirator cavity in comparison to that in the surrounding air environment through condensation nuclei counting.[4]

All quantitative aerosol fit testing techniques measure the percentage of aerosol leakage, which depends on the size of the test aerosol and the measurement method used.[5,6] This is analogous to quoting the collection efficiency of an industrial dust-cleaning device which depends on the particle-size distribution of the dust it collects from, and on the method of analyzing the dust concentration, *e.g.*, gravimetric versus particle count. When aerosols leak into the respirator cavity, a complex and incomplete mixing process results. During the short inhalation and exhalation cycles, the leaked aerosol cannot mix throughout the respirator volume. The concentration of aerosols sampled from the small respirator cavity, therefore, depends on the position of the sampling probe relative to the flow entries and exits: leak site(s), purified air intake(s), mouth, nose, and exhalation valve.[5,7]

The limitations of testing with aerosols have been overcome by the new dynamic pressure test which measures the leak-induced pressure decay inside the respirator while the wearer holds his/her breath for a few seconds.[8,9] Since pressure changes adjust very fast in the volume of the respirator cavity, the pressure measurement has been shown to be independent of leak site and probe location.[9] The impermeable pressure sensor, therefore, can be mounted into a capped air intake of a negative-pressure respirator or into the air-supply hose of an air-supplied respirator. This study compares the results obtained by the dynamic pressure test with those obtained by conventional photometric fit testing.

The new dynamic pressure test, as described, does not meet the current Occupational Safety and Health Administration (OSHA) and American National Standards Institute (ANSI) standards because this paper does not take issue with the various test exercises. This paper has been written to show the advantages of the new over the conventional techniques in meeting the standards' objective of determining the quality of respirator fit. Additional studies are warranted and will include the test exercises.

Experimental Design and Procedure

To perform this study, two test systems were required: a dynamic pressure measuring and data acquisition system and an aerosol test system (see Figure 1). The same respirators were used for both the pressure and the aerosol measurement tests. The respirators were modified so that specific leak locations and leak hole sizes could be tested.

The pressure measurement system consisted of a pressure transducer and data acquisition system.[9] The aerosol test system consisted of a corn oil aerosol generator, a test chamber and a near-forward light-scattering photometer. The first two had been used in the authors' previous studies.[5,6] The latter was a portable photometer used for conventional fit testing with corn oil aerosols (Model FE 250A, Frontier Enterprises, Albuquerque, N.Mex.).

To determine the effect of respirator cavity volume, three different brands of respirators were used. Each respirator had leaks in three locations: at the top near the bridge of the nose, at mid-height above the air intake on the right side of the face, and at the chin below the exhaust valve at the bottom of the respirator.[9] The leak hole diameters were 0.046, 0.053, 0.071 or 0.081 cm.[5,6,9]

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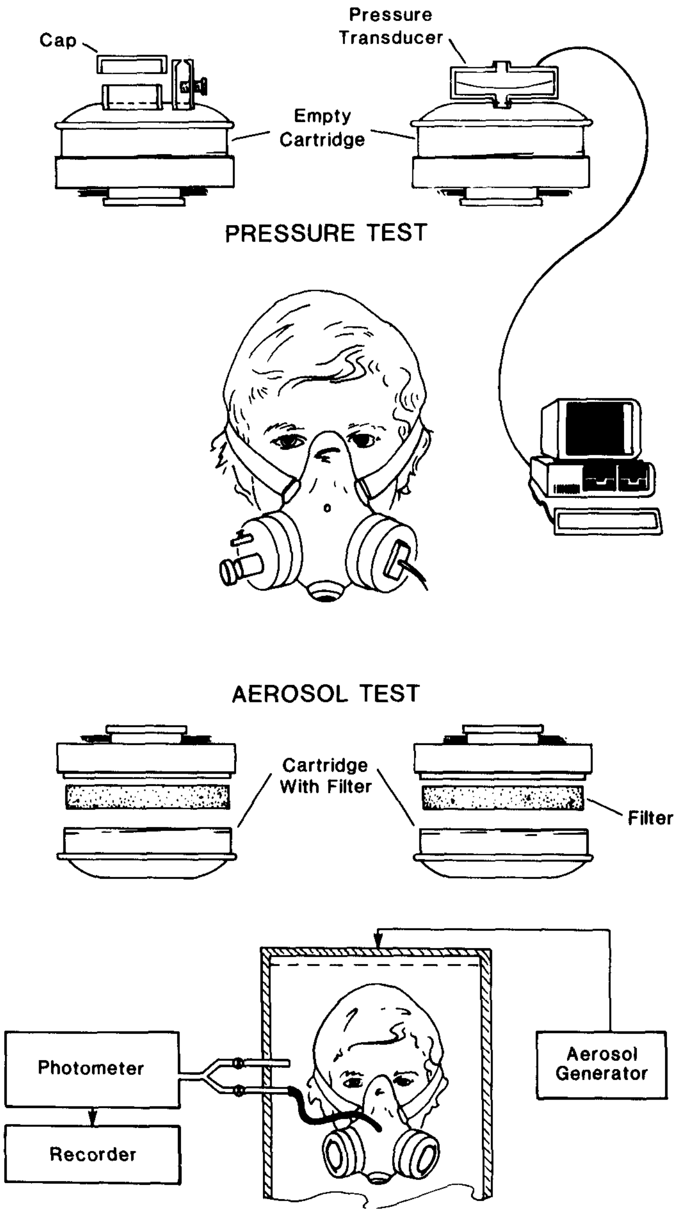

Figure 1—Schematic representation of comparison testing between the dynamic pressure method and the aerosol method.

In order to perform both tests for the same respirator leak, the regular filters were removed from the half-mask respirators, and a short coupling was attached connecting either the pressure sensor or the filter to the respirator body.[9] Thus, the same filter was used for all aerosol tests with all brands of respirators. Aerosols were sampled from the mouth/nose region of the wearer. During the pressure test, the sampling probe was capped.

For both the aerosol and the pressure test, the respirators were sealed to the subject's face to prevent any unwanted leakage. Leak location and leak hole size were tested in randomized order. The same test sequence was used for the pressure and the aerosol test on each respirator.

The aerosol test began with sealing the respirator to the subject's face. In the randomized order selected, each leak hole diameter and location combination was tested. No head movement or exercising was performed. Breathing was at a resting rate. The dynamic pressure test does not require any special test environment and, therefore, was performed in the open laboratory space. The seal was checked before, during and after testing by capping off all artificial holes.

Results and Discussion

Figure 2A shows a typical signal recorded during an aerosol test with the photometer. During an approximate 10-sec time interval, 2–4 peak values are recorded. Since the aerosol does not mix perfectly in the respirator cavity, the probe may sample different peak values in time, even when the leak rate is constant. If the trace is time integrated, the cumulative value reflects the amount of aerosol present at the probe during inhalation and exhalation. The aerosol concentration during exhalation, however, depends on the amount of aerosol deposited in the subject's respiratory tract, a highly variable parameter.[10,11]

The more aerosols are deposited in the subject's lungs, the lower are the minima in Figure 2A and, therefore, the lower is the integrated leakage value. Conversely, the reading of the peaks only is unsatisfactory as well since any aerosol dust entering the respiratory cavity through a leak site is integrated in space and time, depending on the length of the sampling line and the response time of the photometer and

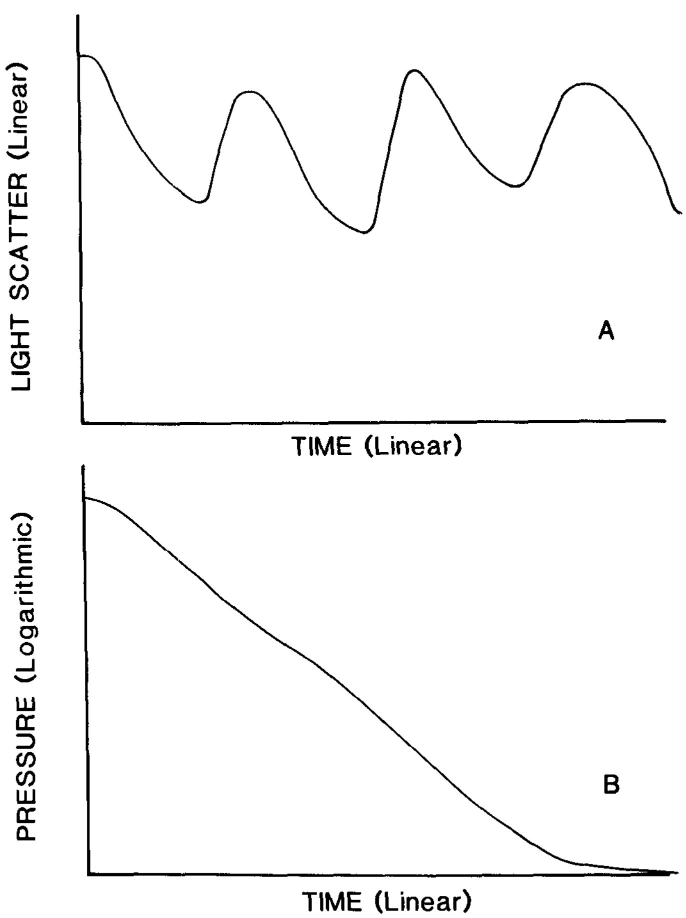

Figure 2—Typical time traces for (a) aerosol test with photometric recording and (b) dynamic pressure test.

its recording equipment. The peak height, thus, is system dependent and not an exact measure of fit.

The pressure decay signal, however (Figure 2B), is a straight line on a log-linear plot when the leak rate is constant during breath-holding for a few seconds. If the leak rate is variable during exercising (up-and-down or left-to-right movement of the head) or moving the mouth simulating speech while breath holding, the slope given by the initial and final pressure values represents the cumulative leakage into the respirator cavity. No accommodation for aerosol deposition in the lung nor for lack of aerosol mixing needs to be made.

The slope of the curve in Figure 2B has been defined[8,9] as the Willeke Leak Slope (WLS) given by the following equation:

$$WLS = \frac{\ln(P_1/P_2)}{t_2 - t_1} \qquad (1)$$

where P_1 is the initial negative pressure at time t_1, and P_2 is the pressure at time t_2. In order to give an overall impression of the relationship between aerosol leakage measured by the aerosol test and respirator fit represented by the WLS determined through the dynamic pressure test, Figure 3 shows the data for all 3 respirators tested with all hole and location combinations. A low aerosol leak rate results in a low WLS since the pressure decays slowly when air leaks through a small hole. Conversely, a high aerosol leak rate results in a high WLS. Each scale in Figure 3 covers a range of 3 decades, and the average of the data has a slope of approximately 1. Thus, the sensitivity of the 2 methods is approximately the same. The scatter of the data is highest at the low aerosol leak rates. To further study this observation, the data will be examined for the effects of leak location and respirator cavity volume with respect to leak hole diameter.

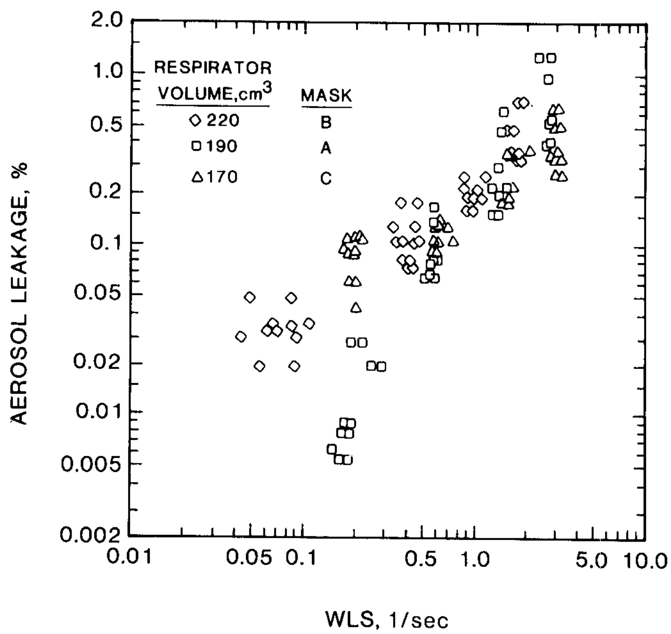

Figure 3—Data obtained by both tests for all respirator brands and location/hole size combinations. WLS = Willeke leak slope.

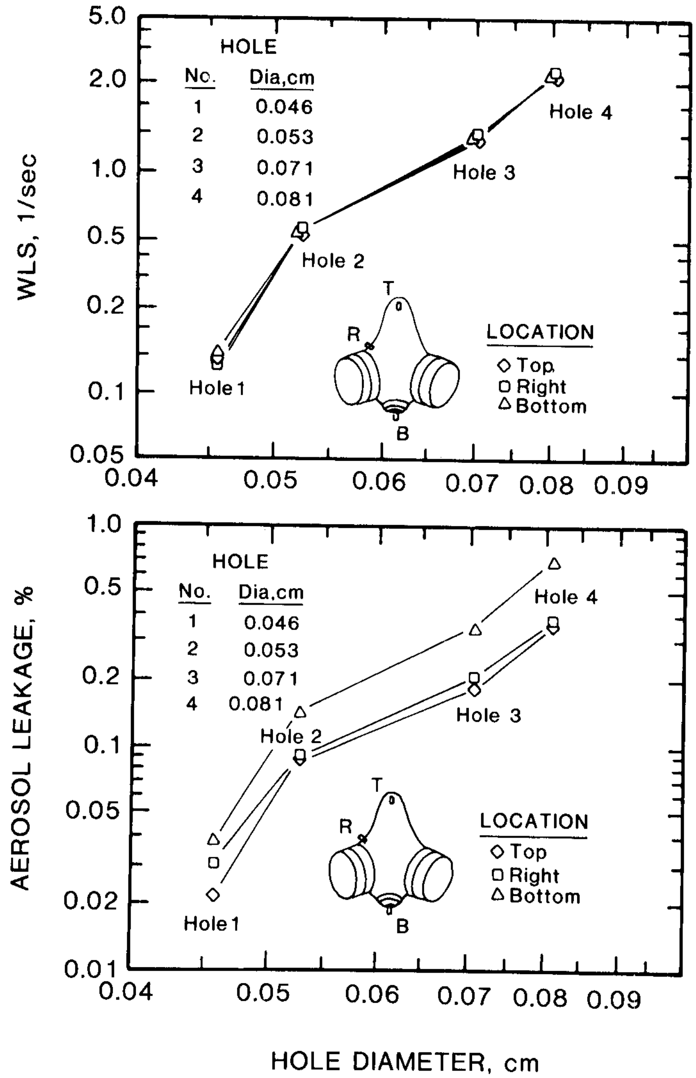

Figure 4—Effect of leak location on measured fit for all respirators used.

Figure 4 shows the measured leak slopes and aerosol leakages for different leak locations. As seen, the WLS is independent of leak location, while the recorded aerosol leakage is strongly dependent on location. The aerosol leakage is highest for holes near the bottom of the mask and lowest for holes near the top of the mask. The authors previously have interpreted that the aerosol leaked inward at the bottom is carried towards the sampling probe by the purified airflow coming through the filters, while the aerosols leaked inward at the top have more time to mix and appear in lower concentrations at the probe.[5] It also was found that more of the larger particles are lost for top-hole leakage than for bottom-hole leakage for the same reason.[5] It is possible that the diameter of Hole 2 was misrecorded. An upward adjustment of the recording of this hole size by 10% results in straight line curves in Figure 3.[9]

Three different respirators were used in this study, each resulting in a different cavity volume when worn by the same subject. Figure 5a shows that the WLS depends on the cavity volume in a consistent manner. For a given leak size, a small respirator cavity results in a higher WLS than a larger respi-

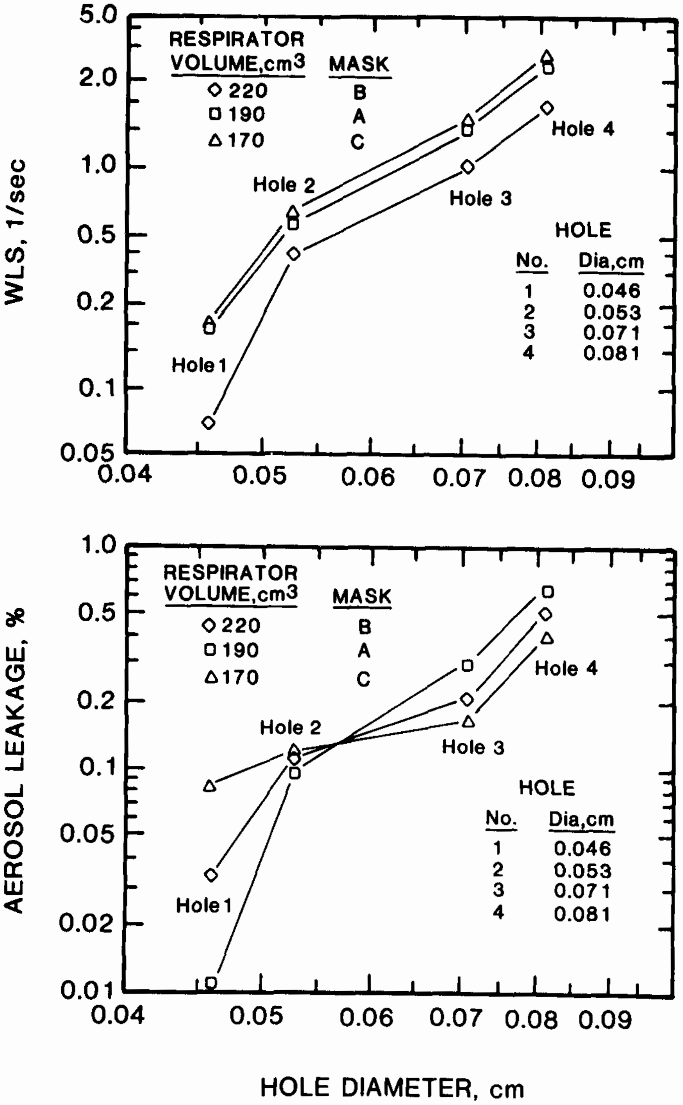

Figure 5—Effect of respirator cavity volume on measured fit for all leak locations.

rator cavity. The authors have related the leak rate to the respirator cavity and hole size and can predict one as a function of the two others.[9] Figure 5b shows that the aerosol leakage also is dependent on respirator cavity volume, but in an unpredictable manner. Because of the incomplete aerosol mixing, this relationship is likely to depend on the design of the respirator and, thus, is unique for each different respirator brand and possibly for each subject's facial contour.

In the aerosol test, the leak location affects the measured aerosol leakage. In a fit test performed with an unmodified respirator, the leak location is not known, and the results cannot be corrected for the leak location effect. Since no correction can be made to the measured leakage, the variability is greater in the aerosol leak test than in the pressure decay test. To illustrate this, the results of the authors' tests are plotted in Figures 6 and 7 without adjustment for respirator volume or leak location. The pressure decay test has less variability than the aerosol test.

Conclusion

The pressure decay method of quantitative respirator fit testing is independent of sensor and leak location. It is dependent on the respiratory cavity volume in a predictable manner. In contrast, the conventional aerosol method is dependent on sensor and leak locations and on respirator cavity volume in a quantitatively unpredictable manner. Thus, comparison of the two methods shows greater variability in fit factors when the aerosol method is used. The new pressure decay method, therefore, is judged to be a superior method of fit testing. Once commercialized, the cost for pressure sensor and electronic readout devices is expected to be considerably less than that of any other quantitative fit testing method available today. The dynamic pressure test can be used noninvasively, making it attractive as a screening device before and after exposure to hazardous contaminants and as a teaching tool used on the actual respirator worn by the worker. When entering or leaving a work environment, the wearer may exchange the air purifying elements with the pressure testing elements without taking off the respirator body itself.

It is hoped that future evaluations by researchers and user groups will focus further on various aspects of the new

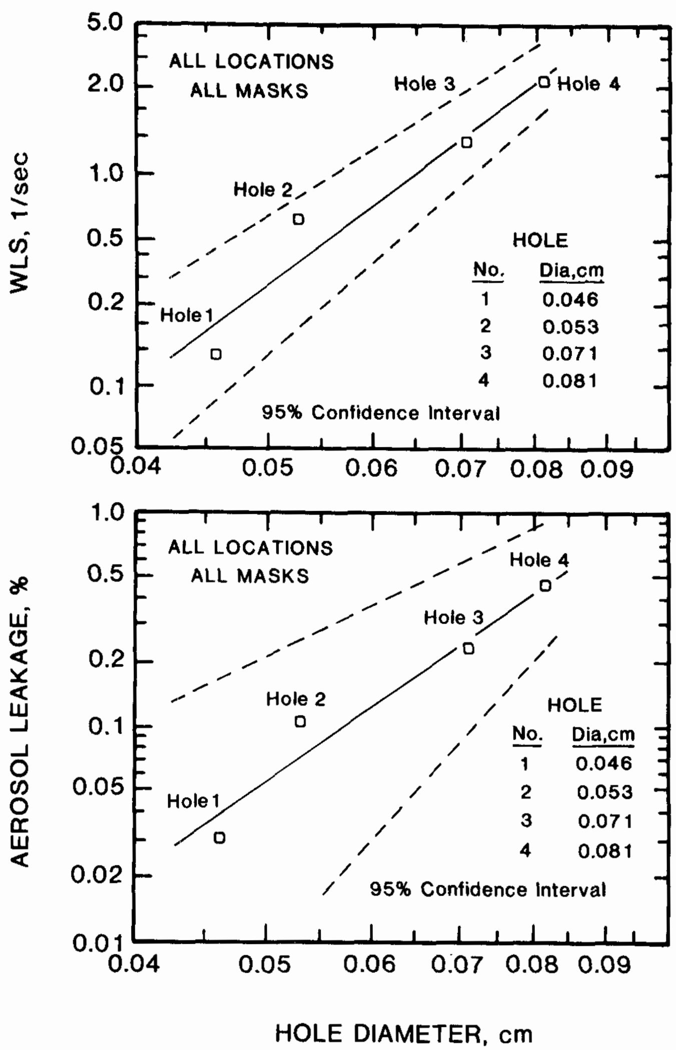

Figure 6—Averages and 95% confidence intervals for all leak locations and respirators.

method, such as the dependence of respirator fit on the wearer's physical stress and the comparison of this new quantitative method with presently accepted qualitative methods.

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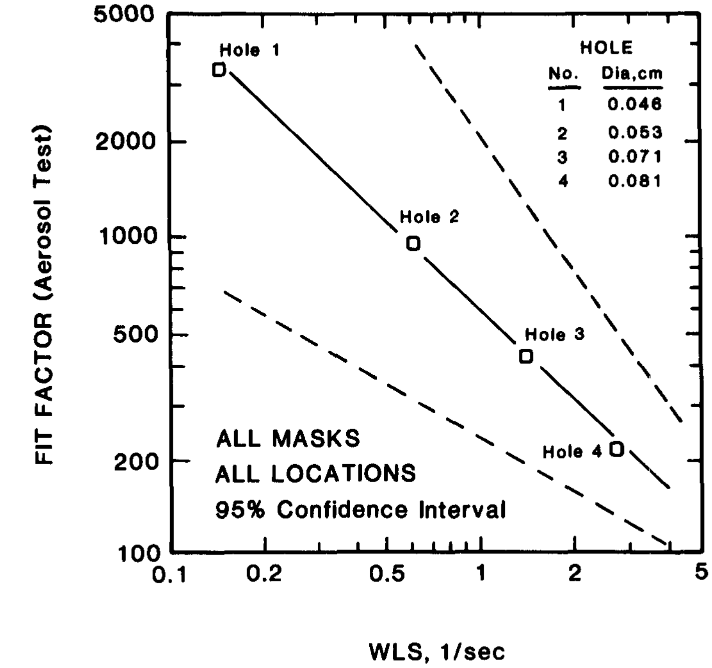

Figure 7—Relationship between fit factor, determined by aerosol test, and WLS, determined by dynamic pressure test.

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