

The Theoretical Effect of Filter Resistance and Filter Penetration on Respirator Protection Factors

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Abstract

We present a theoretical model that predicts how the performance of negative pressure aerosol respirators is affected by simultaneous changes in filter resistance and filter penetration. Specifically, the theory gives the protection factor of a respirator as a function of filter resistance and filter penetration. We consider future experiments to validate this model and discuss several potential applications.

Introduction

The level of protection provided to a worker by a respirator is commonly described by a parameter called the protection factor. The protection factor (PF) is defined as

$$PF = C_o/C_i = 1/P_r, \quad (1)$$

where C_i and C_o are the contaminant concentrations inhaled with and without the respirator in place, and where P_r is the respirator penetration, an alternate measure of respirator performance.

The protection factor is strongly dependent on properties of the facepiece which determine how well the facepiece seals with the wearer's face. The protection factor is also dependent on other characteristics of the respirator, such as filter penetration, filter resistance, exhalation valve leakage, etc. We wish to consider here how the protection factor of a given respirator is affected by changes in both filter penetration and filter resistance when all other factors affecting respirator performance are unchanged. This consideration relates directly to typical use situations. For example, as a particulate respirator is used, the filter resistance and filter penetration change

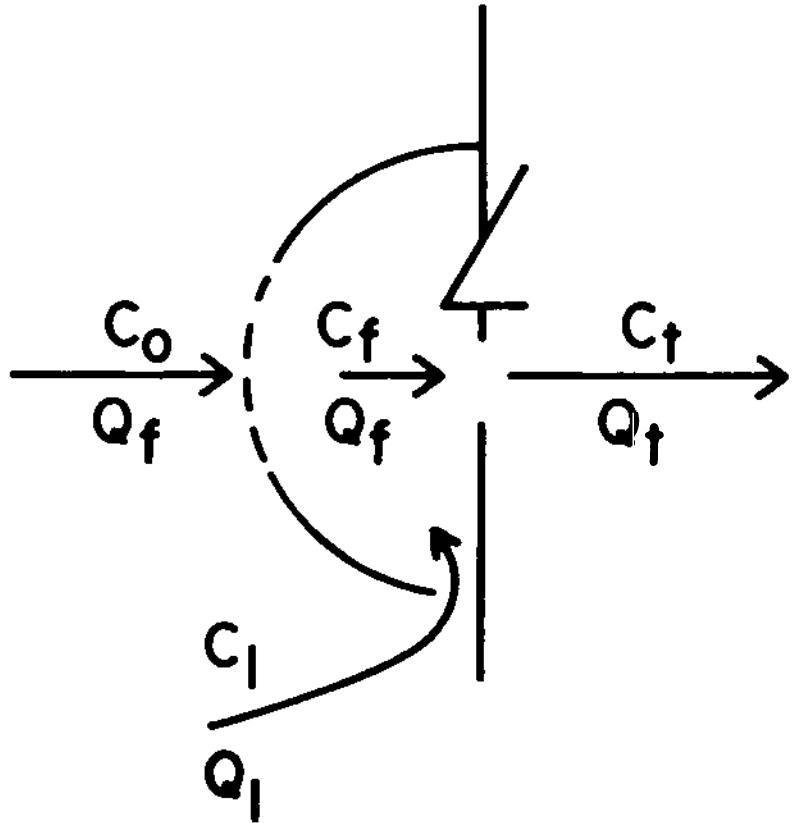
as a function of time due to filter loading. A similar situation occurs when the filters of one facepiece are replaced by filters having different efficiencies or different filter resistances. In both of these situations it is useful to know how the protection factor is affected by such changes.

Previously, Williams (1983) has considered how the protection factor is affected by filter penetration or filter resistance. This paper builds upon the concepts presented by Williams and develops a single model which accounts for simultaneous changes in filter resistance and filter penetration.

Derivation of Model

We start by considering a negative pressure aerosol respirator worn in a challenge concentration as shown symbolically in Figure 1. The inhaled volumetric flowrate (Q_i) is the total from two sources: the flowrate through the filter (Q_f) and the flowrate through the face seal leak (Q_ℓ). The inhaled aerosol concentration (C_i) is a mixture of the aerosol concentration passing through

Figure 1—Flow rates of a respirator during inhalation. Q_r , Q_f , Q_t are the volumetric flowrates through the filter, through the faceseal leak, and into the respiratory tract, respectively. C_o is the aerosol challenge concentration. C_f and C_ℓ are the concentrations passing through the filter and the leak, respectively. C_i is the aerosol concentration inhaled by the wearer.



the filter (C_f) and the concentration entering through the leak (C_ℓ).

The following initial assumptions are made:

1. The challenge concentration (C_o) is spatially uniform and time independent.
2. During each inhalation cycle, the inhaled concentration reaches equilibrium sufficiently quick that it can be considered a constant during the entire inhalation cycle.
3. The cyclic performance of the respirator can be characterized by a representative constant flowrate.
4. The pressure variations are sufficiently small that the fluid can be considered incompressible.
5. The aerosol concentration passing through the face seal (C_ℓ) is equal to the challenge concentration (C_o); that is, the penetration of the leak (P_ℓ) is given by $P_\ell = 1$.

Under these conditions, we have from mass balance

$$C_t Q_t = C_f Q_f + C_\ell Q_\ell \quad (2)$$

These concentrations are related to the challenge concentration (C_o) as follows:

$$C_t = P_r C_o \quad (3)$$

$$C_f = P_f C_o \quad \text{and} \quad (4)$$

$$C_\ell = P_\ell C_o = C_o \quad (5)$$

where P_r is the penetration of the respirator defined above, P_f is the penetration of the filter, and P_ℓ is penetration of the leak taken to be unity by assumption.

From Equations (2) through (5) we have

$$P_r = P_f (Q_f/Q_t) + (Q_\ell/Q_t) \quad (6)$$

We have from flow balance

$$Q_t = Q_f + Q_\ell \quad (7)$$

which can be substituted into Equation (6) to yield

$$P_r = P_f + (1 - P_f)(Q_\ell/Q_t) \quad (8)$$

This result is equivalent to that previously obtained by Williams (1983).

The leakage (Q_ℓ) is assumed to be related to the pressure drop (AP) across the facepiece by

$$Q_\ell = K (\Delta P)^X \quad , \quad (9)$$

where the parameters K and X are determined by the geometry of the leak path.

The dimensionless leakage exponent, X , is expected to fall between 1/2 and 1, since $X = 1$ is characteristic of flow through a capillary and, at the other extreme, $X = 1/2$ is characteristic of flow through a hole in a thin membrane. Substitution of Equation (9) into Equation (8) yields

$$P_r = P_f + (K/Q_t)(1 - P_f) \Delta P^X \quad . \quad (10)$$

This equation will serve as the basis for predicting how respirator performance will vary as a function of filter penetration and filter resistance.

We start by assuming that the parameter X has been determined by techniques to be discussed later. Consider a respirator determined to have a penetration P_r , when fitted with a filter having a penetration of P_f and a resistance of AP. The parameter (K/Q_t) can be determined from

$$K/Q_t = \frac{P_{r1} - P_{f1}}{(1 - P_{f1})(\Delta P_1)^X} \quad , \quad (11)$$

where the subscript 1 has been used to indicate the known values associated with the first filter.

If the respirator had instead been fitted with a different filter known to have a penetration P_{f2} and a resistance of ΔP_2 , the performance of this second filter can be predicted by substituting the known value K/Q_t from Equation (11) into Equation (10) giving

$$P_{r2} = P_{f2} + \frac{(1 - P_{f2})}{(1 - P_{f1})} \times (P_{r1} - P_{f1})(\Delta P_2/\Delta P_1)^X \quad , \quad (12)$$

where P_{r2} is the respirator penetration for the second filter.

Since the filter penetrations, P_{f2} and P_{f1} , are typically much less than 1, the term $(1 - P_{f2})/(1 - P_{f1})$ is to a good approximation equal to 1. Equation (12) can therefore be simplified with minimal error to

$$P_{r2} = P_{f2} + (P_{r1} - P_{f1})(\Delta P_2/\Delta P_1)^X \quad . \quad (13)$$

The use of Equations (12) and (13) is illustrated with the following example. Consider a particular half-mask aerosol respirator equipped with a filter known to have a penetration of 0.001 and resistance of 25 mm H₂O at some reference flowrate. Suppose a separate laboratory evaluation indicates that the facepiece is characterized by a leakage exponent (X) of 1.0. The protection factor for this respirator on a particular wearer is measured to be 50 ($P_r = 1/PF = 1/50 = 0.02$). What would the protection factor have been if the respirator had been equipped with a filter known to have a penetration of 0.003 and a resistance of 10 mm H₂O? Equation (12) yields

$$P_{r2} = 0.003 + \frac{(1 - 0.003)}{(1 - 0.001)} \times (0.02 - 0.001) (10/25)^{1.0} \quad ,$$

$$P_{r2} = 0.01058, \text{ and}$$

$$PF_2 = 1/P_{r2} = 94.48 \quad .$$

If the approximation of Equation (13) had been used, we would have had

$$P_{r2} = 0.003 + (0.02 - 0.001)(10/25)^{1.0} \quad ,$$

$$P_{r2} = 0.01060, \text{ and}$$

$$PF_2 = 1/P_{r2} = 94.34 \quad .$$

If X had been equal to 1/2 rather than 1, the change in predicted respirator performance would have been less dramatic. With $X = 1/2$ in the above example, we would have had a final protection factor (PF_2) given by

$$P_{r2} = 0.003 + 0.003 + (0.02 - 0.001)(10/25)^{0.5} \quad ,$$

$$P_{r2} = 0.01499, \text{ and}$$

$$PF_2 = 1/P_{r2} = 66.7 \quad .$$

The reference flowrate at which ΔP_1 and ΔP_2 are determined need not correspond to the pressure in the facepiece during respirator use. Only the ratio $\Delta P_2/\Delta P_1$ occurs in Equation (12) or (13), and, even though ΔP_2 and ΔP_1 are dependent on flowrate, the ratio $\Delta P_2/\Delta P_1$ is a very good approximation independent of flowrate. This point is discussed in detail in Appendix A.

Experimental Verification

Verification of the theoretical model presented here can be based on the observation that Equation (13) can be expressed as

$$\ln(P_{r2} - P_{f2}) = X \ln(\Delta P_2 / \Delta P_1) + \ln(P_{r1} - P_{f1}) \quad (14)$$

Therefore, if we conduct an experiment in which filter resistance (ΔP_2) and filter penetration (P_{f2}) are varied and the resulting change in respirator performance (P_{r2}) is observed, a plot of $\ln(P_{r2} - P_{f2})$ vs $\ln(\Delta P_2 / \Delta P_1)$ will produce a straight line if the model is accurate. This experiment could be conducted in a manner similar to that now used for quantitative fit testing. However, it will necessitate a controlled situation in which the respirator filter can be changed without significantly changing the fit of the respirator.

That same procedure could also be used to experimentally determine the leakage exponent X . The slope of the plot of $\ln(P_{r2} - P_{f2})$ vs $\ln(\Delta P_2 / \Delta P_1)$ would equal X .

Instead of testing the model directly as described above, the theoretical model can be tested indirectly by testing the individual assumptions upon which it is based. One of the fundamental assumptions to be tested is that the facepiece leakage follows a power function of the form $Q_L = K\Delta P^\lambda$. This would be expected to adequately describe flow through a leak of fixed geometry. However, this case is more complicated; an increase in AP can cause a decrease in the dimension of the leak geometry corresponding to an improvement in face seal resulting from the increased pressure of the facepiece on the face. It is anticipated that this effect will simply result in a decrease in the magnitude of X . If, however, it is determined that facesal leakage is not adequately characterized by the function $P = K\Delta P^\lambda$, a more appropriate function can be easily incorporated into the model.

Another fundamental assumption that could be investigated by independent experiment is the assumption that the concentration entering the facepiece through the leak (C_ℓ) equals the concentration outside the facepiece (C_o). Direct experimental determination of $P_\ell = C_\ell / C_o$ should be possible. The significance of this assumption can be seen by noting that if P_ℓ had not been set

equal to unity, Equation (12) would have taken the form

$$P_{r2} = P_{r2} + \frac{(P_{f2} - P_{f1})}{(P_{f2} - P_{f1})} \times (P_{r1} - P_{f1}) (\Delta P_2 / P_1)^\lambda \quad (15)$$

Inspection of this equation shows that it will reduce to Equation (13) if $P_{\ell 1}$ and $P_{\ell 2}$ are equal and large compared to P_{f1} and P_{f2} . In situations of practical interest, the filter penetrations (P_{f1} and P_{f2}) would be much less than the leakage penetrations ($P_{\ell 1}$ and $P_{\ell 2}$). However, $P_{\ell 1}$ may not be equal to $P_{\ell 2}$ because both are likely to be dependent upon the leakage flowrates ($Q_{\ell 1}$ and $Q_{\ell 2}$) which will not be equal. It is anticipated that these effects will be small and introduce little error into the predictions of Equations (12) and (13). Experimental investigation would, however, be appropriate.

Applications

Once verified, the theoretical relationships presented here can be useful in a variety of applications. These include the following:

1. Predicting how the protection factor of a particulate respirator would be affected by loading in the workplace in which both the filter resistance (AP) and the filter penetration (P_f) change as the respirator is used.
2. Predicting how the initial inhalation resistance affects the overall protection provided by the respirator. This is an important consideration in setting standards for initial inhalation resistance.
3. Predicting the performance of a whole product line of respirators when only one facepiece-filter combination is actually tested. (Here the term "product line" means a group of respirators with a common facepiece but different filters.)
4. Predicting how the distribution of protection factors measured on a group of individuals would be affected by changes in filter penetration and filter resistance.

For purposes of discussion, let us consider application 4 in detail. Consider a particular half-mask, air-purifying respirator with a filter having

a penetration of 0.001 and a filter resistance of 25 mm H₂O. Suppose that a laboratory evaluation indicates that the facepiece is characterized by a leakage parameter of 0.9, and that, in an evaluation of the respirator on a group of 25 workers in a particular workplace, the following 25 workplace protection factors are measured:

30	25	59	87	21
116	39	10	148	500
48	16	79	43	72
54	65	34	168	130
200	240	105	310	96

Analysis indicates that this data is lognormally distributed with a geometric mean of 70.3 and a geometric standard deviation of 2.62.

Now suppose that we wish to know what the distribution of protection factors would have been if a filter with a higher penetration of 0.003 and a lower filter resistance of 10 mm H₂O had

been fitted to the respirator, with all other factors being equal. The relationship of Equation (13) can be used to answer this question. Each workplace protection factor in the above set can be transformed to a new value that corresponds to the use of this new filter element. Consider the first value of $PF_1 = 30$ ($P_r = 1/30 = 0.0333$):

$$P_{r2} = P_{f2} + (P_{r1} - P_{f1})(\Delta P_2/\Delta P_1)^\lambda,$$

$$P_{r2} = 0.003 + (0.0333 - 0.001)(10/25)^{0.9}, \text{ and}$$

$$P_{r2} = 0.01717 \quad PF = 1/P_{r2} = 58.2.$$

When all values are similarly transformed, the result is a distribution which is only approximately lognormal with a geometric mean of 106 and a geometric standard deviation of 1.92. The performance of both the original and modified respirator are indicated in Figure 2 by showing the two distributions on a log probability graph.

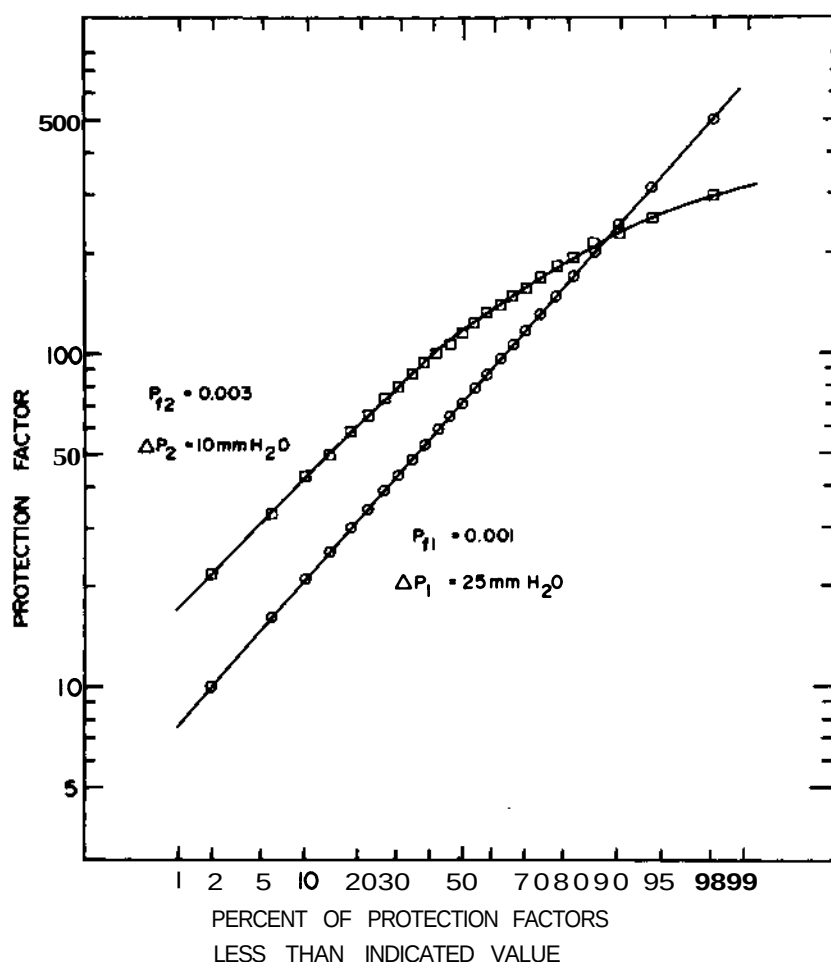


Figure 2—Predicted change in the distribution of protection factors resulting from a change in filter penetration and filter resistance.

There it is seen that the effect of the new filter element is to significantly improve the protection factors on the low side of the distribution and to significantly decrease the protection factors at the extreme high end of the distribution.

The higher protection factors of the distribution, corresponding to the better facial seals, are most sensitive to the filter penetration and, therefore, adversely affected by the higher penetration of the second filter. The lower protection factors, corresponding to the poorer fitting respirators, are most sensitive to the filter resistance and are, therefore, enhanced by the lower filter

resistance of the second filter element. It seems that the respirator equipped with the second filter, having higher penetration and lower filter resistance, provides the most desirable protection characteristics.

Notice that the improvement in respirator performance at the low side of the distribution would have been smaller if the facepiece had been characterized by a leak exponent smaller than the 0.9 used in this hypothetical example.

This is but one example of the possible uses of this analytical model once it has been verified experimentally.

Recommendations for Future Work

There is a specific need to test the theoretical model with the experiments outlined above. There is also the need to investigate the behavior of the leak exponent (X). The degree to which X remains constant will ultimately determine the usefulness of the model presented here. We need to understand how X varies from one respirator model to another, from one respirator type to another, from one individual to another, and from one individual fitting to the next.

Beyond these specific needs, a more general need exists for the respirator community to further consider the more fundamental question of how filter resistance affects the protection pro-

vided by a respirator. This is a question that has been largely neglected. There is a general appreciation of how filter penetration can affect respirator performance. The role of filter resistance in determining worker protection is not so well appreciated or understood. The role of filter resistance is usually investigated in terms of physiological considerations of comfort and acceptability. Similar careful consideration needs to be focused on the role of filter resistance in determining the protection provided by negative pressure respirators. It is hoped that the concepts presented here will serve to stimulate that consideration.

Bibliography

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Appendix A

Recall that the pressures ΔP_1 and ΔP_2 in Equations (12) and (13) can be determined at a single reference flowrate which does not necessarily correspond to the flowrates (Q_{f1} and Q_{f2}) through the filter during use, since to a good approximation the ratio $\Delta P_2/\Delta P_1$ is independent of flowrate. The purpose of this appendix is to propose a method to evaluate the accuracy of this approximation in any specific situation.

The pressure drop across a filter element can be expressed in the general form $\Delta P = kQ$, since respirator filters are typically linear devices; that is, the pressure drop across the filter is directly proportional to the flowrate. Therefore, we can write

$$\Delta P_2/\Delta P_1 = (k_2 Q_{f2})/(k_1 Q_{f1}) \quad , \quad (A1)$$

where k_1 and k_2 are constants characteristic of filters 1 and 2, respectively.

Similarly the ratio of pressures can be expressed as

$$\Delta P_{2ref}/\Delta P_{1ref} = (k_2 Q_{ref})/(k_1 Q_{ref}) \quad , \quad (A2)$$

where Q_{ref} is the reference flowrate, and where ΔP_{2ref} and ΔP_{1ref} are the pressure drops, or resistances, measured at this reference flowrate.

Equations (A1) and (A2) can be combined to yield

$$\Delta P_2/\Delta P_1 = (\Delta P_{2ref}/\Delta P_{1ref}) (Q_{f2}/Q_{f1}) \quad . \quad (A3)$$

Since respirators are typically used in a mode where the volumetric flowrate through the filter is much greater than the volumetric flowrate through the face seal, the ratio (Q_{f2}/Q_{f1}) is approximately 1. Thus, to the first approximation we have

$$\Delta P_2/\Delta P_1 = (\Delta P_{2ref}/\Delta P_{1ref}) \quad . \quad (A4)$$

To determine the error introduced into the calculation of protection factors as a result of this approximation, it is necessary to compare the results of computations based on the exact Equation (A3) with those based on the approximation of Equation (A4). Equation (A3) cannot, however, be used directly since Q_{f2} is an unknown which can only be determined from P_{r2} , the respirator penetration to be calculated. This difficulty can be circumvented by an iterative approach involving the following steps. First, compute P_{r2} from Equation (12) or (13) using the approximation of Equation (A4). Second, based on that value of P_{r2} , compute Q_{f2}/Q_{f1} from the following relation which is derived from the Williams equation, Equation (8).

$$Q_{f2}/Q_{f1} = \frac{(1 - P_{r2})/(1 - P_{f2})}{(1 - P_{r1})/(1 - P_{f1})} \quad . \quad (A5)$$

Third, using this value of Q_{f2}/Q_{f1} , determine $\Delta P_2/\Delta P_1$ from Equation (A3) and then recompute P_{r2} using Equation (12) or (13). Repeat steps 2 and 3 until the values of P_{r2} converge with the desired level of accuracy.