

Respirator Performance As a Function of Facepiece Flushing

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ABSTRACT

An analytical respirator model was developed to explain the unexpected experimental behavior of a laboratory simulation of the pulmonary respirator system. The resulting model indicates the appropriate reference concentration to use when experimentally evaluating the bias associated with various in-facepiece sampling techniques. In addition, the model leads to the hypothesis that the protection provided by a respirator can be reduced by backflow through the inhalation valve of the respirator.

Introduction

Techniques for sampling from a respirator facepiece have recently been evaluated by Myers et al. (1986, 1988a, 1988b) and Myers and Hornung (1989). These studies demonstrated significant deficiencies in traditional facepiece sampling methods and identified improved sampling methods which will likely change the way respirator face fit testing and workplace performance testing are conducted in the future. During the course of those studies, certain unexpected behaviors were observed in the experimental pulmonary-respirator system. These unexpected behaviors are the subject of this discussion.

The laboratory studies of Myers were conducted with the respirator mounted on a headform connected to a mechanical breathing machine as shown in Figure 1. Leaks are introduced with an 18-gauge needle through the facepiece seal which is otherwise sealed to the headform. Acetone challenge vapor is drawn from the reservoir through the needle into the facepiece by the negative facepiece pressure during the inhalation cycle. A one-way valve prevents backflow through the needle during the positive facepiece pressure of the exhalation cycle. With this experimental system, four acetone concentrations can be determined:

- 1) The "in-facepiece" concentration is determined by sampling from the facepiece with the particular sampling method being evaluated.
- 2) The "pulmonary" concentration, C_p , is measured between the headform and the breathing machine. This concentration corresponds to that inspired by a respirator wearer.
- 3) The "exhalation valve" concentration, C_e , is that exhausted through the respirator exhalation valve.
- 4) The "calculated" concentration, C_c , is the inspired concentration calculated from the known leakage rate and the known concentration of the contaminant through the leak site as described below. The inspired concentration can be considered as a mixture of the concentration entering through the leak and the concentration entering through the inlet of the respirator. The calculated concentration is given by the conservation of mass to be:

$$C_c = C_L Q_L / (Q_L + Q_i) \quad (1)$$

Where C_L is the concentration entering the leak, Q_L is the volumetric flowrate through leak, and Q_i is the volumetric flowrate of clean air through the respirator inlet.

In the first series of studies (Myers et al. 1986, 1988a, 1988b) with half and full facepiece respirators, the measured pulmonary concentration, C_p , was in good agreement with the calculated inspired concentration, C_c . During these initial studies, the air exhaled from the breathing machine was vented to the atmosphere and not returned to the respirator. Because of the good agreement between these two values for the inspired concentration, there was confidence in the validity of using the measured pulmonary concentration as the reference concentration in judging the bias in the in-facepiece sampling methods.

However, in a later study (Myers and Hornung 1989)

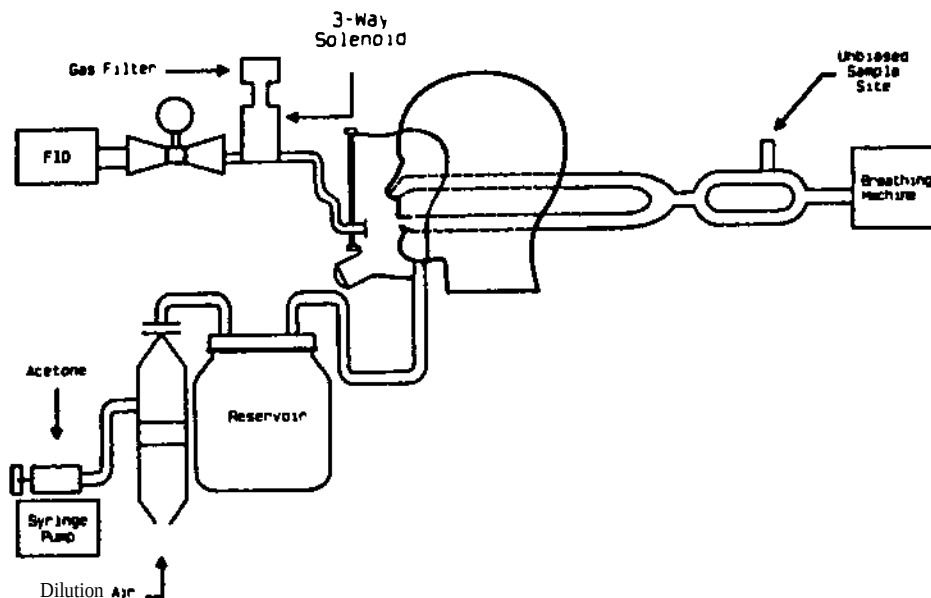


FIGURE 1

The test system used previously by Myers to experimentally simulate the **pulmonary-respirator** system

in which the breathing machine "exhaled" back through the respirator **without** removal of the **acetone**, the pulmonary, exhalation valve, and calculated concentrations were unexpectedly found to be unequal. Typical results are presented in Table 1 for two full facepieces not equipped with nose cups.

These **results** were quite surprising in two respects. First, a significant difference was noted between the pulmonary and the calculated concentrations. At the beginning of these **studies**, all **concentrations** (except for the in-facepiece concentrations) were expected to be equal. The in-facepiece concentration was expected to differ from other concentrations as a result of sampling bias introduced by poor mixing in the facepiece. Originally, either the calculated or the measured pulmonary concentration was to be used as the reference concentration in determining which in-facepiece sampling method gave the minimum bias or error. Since these concentrations were found to be **significantly** different, it became necessary to identify which of the two would serve as an **appropriate** reference concentration. Otherwise, the test system could not be used to determine the most appropriate **in-facepiece** sampling method.

The second **discrepancy** is the **difference** between the

TABLE 1
Experimentally Determined Acetone Concentration for Two Typical Full Facepiece **Respirators** Without Nosecups

Measured Concentration (ppm)	American Optical	Pulmosan
In-Facepiece, C_f	27.3	26.2
Pulmonary, C_p	28.3	29.5
Exhal. Valve, C_e	22.9	26.4
Calculated, C_c	17.8	14.3

*Experimental error $< \pm 10\%$

calculated **concentration** and the exhaust valve concentration. The system was designed so that the contaminant concentration enters through the leak and exits the exhalation valve. The system is otherwise sealed with no known sources or sinks of contaminant. The elevated concentration out the exhaust valve is an apparent contradiction to the principal of conservation of mass; **that is**, it appears that more acetone comes out of the system than goes in.

In an attempt to explain these two **apparent discrepancies**, the following analysis was undertaken.

Analytical Model

We begin by considering the **respirator-pulmonary** system at the beginning of the inhalation cycle, and by considering the four volumes that will ultimately be inspired into the respirator-pulmonary system. The four volumes are (1) the volume in the facepiece, V_f , (2) the volume of contaminant that will enter the system through the face seal leak, V_L , (3) the volume that will enter through the respirator inlet, V_i , and (4) the pulmonary volume after exhalation, $V_{p\text{ex}}$. These four volumes are shown symbolically on the left of Figure 2.

In this analysis we will track each of these volumes through one complete cycle of inhalation and exhalation. After inhalation these four volumes are combined into two volumes: (1) The volume of the facepiece, V_p and (2) the pulmonary volume after inhalation, $V_{p\text{in}}$. These two volumes are shown schematically in the center of Figure 2.

After exhalation the original four volumes are dispersed in three volumes: (1) The volume remaining in the facepiece, V_f , (2) the volume exhaled through the exhalation valve, and (3) the volume remaining in the pulmonary system, $V_{p\text{ex}}$. These three volumes are shown at the right side of Figure 2.

One-by-one we will track each of these initial volumes through the respiratory cycle. We begin with the

volume initially in the facepiece, V_f . As shown in Figure 2, a fraction, f_f , of that volume is inspired into the pulmonary system. The remaining fraction, $(1-f_f)$, remains in the facepiece. The fraction f_f is therefore a measure of the degree to which the facepiece is "flushed" during the inhalation cycle. If all of the volume in the facepiece is flushed from the facepiece into the respiratory system, the flushing fraction, f_f , would equal 1.0. At the other extreme, a flushing fraction of zero corresponds to none of the original volume being removed from the facepiece during inhalation. Realistic situation would, of course, be somewhere between these two extremes.

The flushing of the leak volume, V_L , can be similarly characterized. Of the volume that enters through the face seal leak, a fraction, f_L , enters the pulmonary system while a fraction, $(1-f_L)$ remains in the facepiece.

Of the volume of clean-air that enters through the respirator inlet, V_i , a fraction, f_i , enters the pulmonary system and the remaining fraction, $(1-f_i)$, remains in the facepiece.

The initial volume in the pulmonary system remains, of course, in the pulmonary system during inhalation.

It is evident that the three flushing fractions, f_f , f_L , and f_i are not independent. Selecting any two defines the third, since the volume of facepiece is considered unchanged during inhalation. This requires that the three

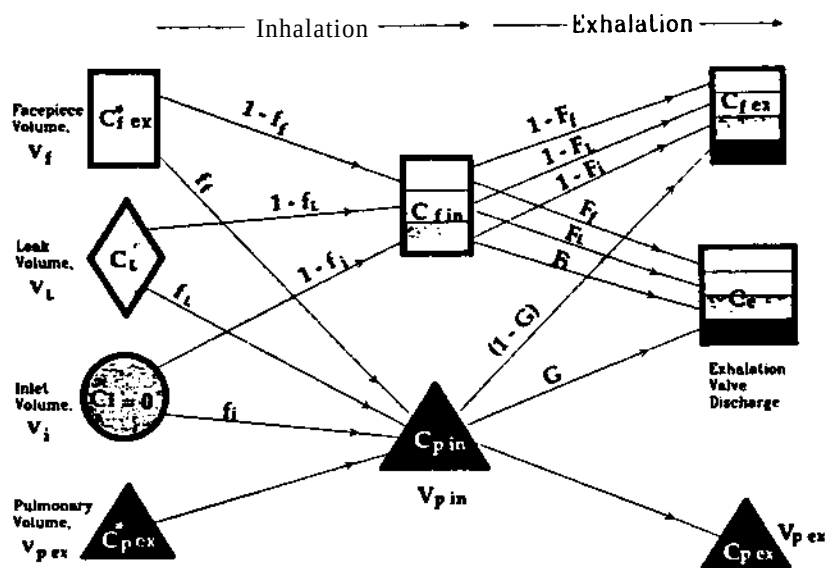


FIGURE 2

A **schematic** representation of the analytical model of the **pulmonary-respirator** system. The four volumes which comprise the system before inhalation are shown on left side of figure. these volumes are tracked through a complete cycle of inhalation and exhalation. The **facepiece** volume is represented by a **rectangle**. The volume that enters the face seal leak is represented by a **diamond**. The circle and the triangle represent the volume that enters the respirator inlet through the filter and the pulmonary volume, respectively. On the **right**, the square represents the volume discharged through the exhalation valve. The contaminated concentration for each of these volumes is shown within each symbol.

volumes in the facepiece **after** inhalation add up to the initial facepiece volume.

$$V_f = (1-f_p)V_f + (1-f_L)V_L = (1-f)V_i \quad (2)$$

Thus, the selection of any two flushing fractions defines the third.

After inhalation we then have three distinct volumes in the facepiece. Although we will individually track each of these volumes through the complete **cycle**, we will later **find** it convenient to have calculated the average of the three concentrations in the facepiece. The average concentration in the facepiece **after** inhalation, C_{fin} , can then be written as a **volume-weighted** average of the three concentrations.

$$C_{fin} = \frac{C_{fex}^* (1-f_p)V_f + C_L (1-f_L)V_L + C_i (1-f_i)V_i}{V_f} \quad (3)$$

In the above, $C_i = 0$, since it is assumed that clean air enters through the inhalation valve on each respiration.

The "*" is used in the above to indicate a value of a parameter at the beginning of the respiration cycle resulting from the previous respiration cycle.

We now track these volumes through the exhalation cycle. Refer to Figure 2 and consider the three volumes that reside in the facepiece after inhalation. Upon **exhalation**, a fraction, F , of each of these volumes is exhaled while a fraction, $(1-F)$, remains in the facepiece.

Specifically,

F_f = Fraction of facepiece volume $(1-f_p)V_f$ passing exhalation valve.

F_L = Fraction of leak volume $(1-f_L)V_L$ passing exhalation valve.

F_i = Fraction of inlet volume $(1-f_i)V_i$ passing exhalation valve.

Now consider the volumes that are in the pulmonary system after inhalation. The assumption is made that the four component volumes are well mixed in the pulmonary system. Since the contaminant concentration is known for each of these component volumes, computing the concentration in the pulmonary system after inhalation, C_{pin} , is straightforward and is given by:

$$C_{pin} = [f_f V_f C_{fex}^* + f_L V_L C_L + V_{pex} C_{pex}^* + f_i V_i C_i] / V_{pin} \quad (4)$$

In this expression, the concentration C_{pin} is divided into that remaining in the pulmonary system, that remaining in the facepiece, and that exhaled through the exhalation valve.

Of the exhaled volume, $(V_{pin} - V_{pex})$, a fraction, G , passes out the respirator while the remaining fraction, $(1-G)$, is left in the facepiece, as shown on the right side of Figure 2.

The parameter G is not independent but is defined by the selection of F_p , F_L , F_i , f_p , f_L , and the tidal volume $(V_{pin} - V_{pex})$ since we again require that the facepiece volume equal the sum of the component volumes.

$$V_f = (1-F_f)(1-f_p)V_f + (1-F_L)(1-f_L)V_L + (1-F_i)(1-f_i)V_i + (1-G)(V_{pin} - V_{pex}) \quad (5)$$

Which yields the following expression for G :

$$G = 1 + (1/V_T) [(1-F_f)(1-f_p)V_f + (1-F_L)(1-f_L)V_L + (1-F_i)(1-f_i)V_i - V_f] \quad (6)$$

$$\text{where } V_T = \text{tidal volume} = (V_{pex} - V_{pin}) \quad (7)$$

We are now in a position to express the concentrations in the facepiece, in the pulmonary system, and of the exhausted volume. Four volume components remain in the facepiece after exhalation. The volume and concentration of each is known in terms of the flushing fractions. The average facepiece concentration can then be computed as a simple volume-weighted average. The concentration in the facepiece after exhalation, C_{fex} , is then given by:

$$C_{fex} = \frac{(1-F_f)(1-f_p)V_f C_{fex}^* + (1-F_L)(1-f_L)V_L C_L + (1-G)(V_{pin} - V_{pex})C_{pin}}{V_f} \quad (8)$$

Similarly, the exhaust valve concentration, C_{ex} , is given as the following weighted average:

$$C_{ex} = \frac{F_f(1-f_p)V_f C_{fex}^* + F_L(1-f_L)V_L C_L + G(V_{pin} - V_{pex})C_{pin}}{(V_{pin} - V_{pex})} \quad (9)$$

Armed with these relationships we can determine the contaminant concentrations in the facepiece, in the pulmonary system, and exhausted through the exhalation valve at the end of a breathing cycle given these

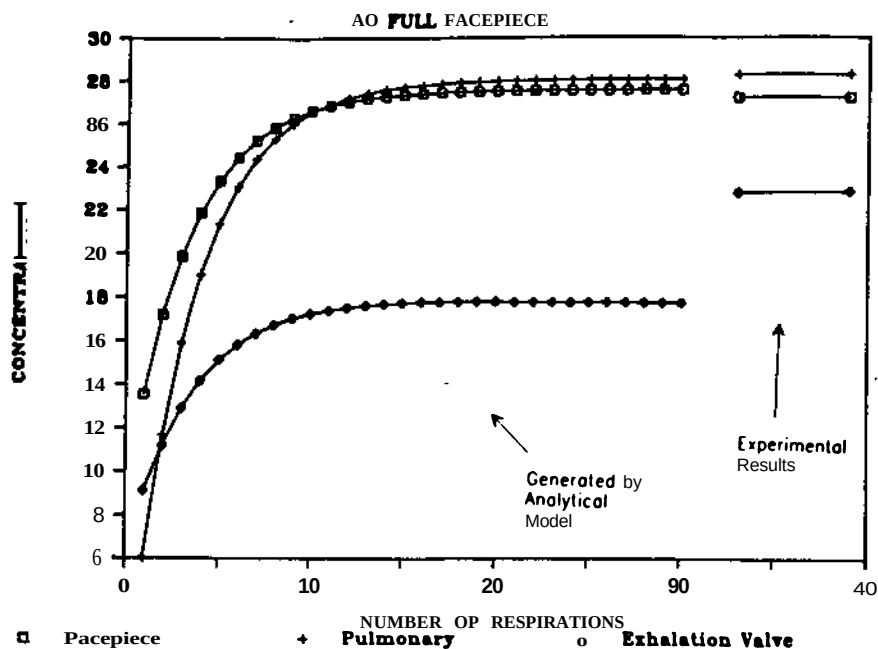


FIGURE 3

A comparison of the analytical results and the experimental results for the American Optical Respirator when inhalation valve backflow is not incorporated into the analytical model.

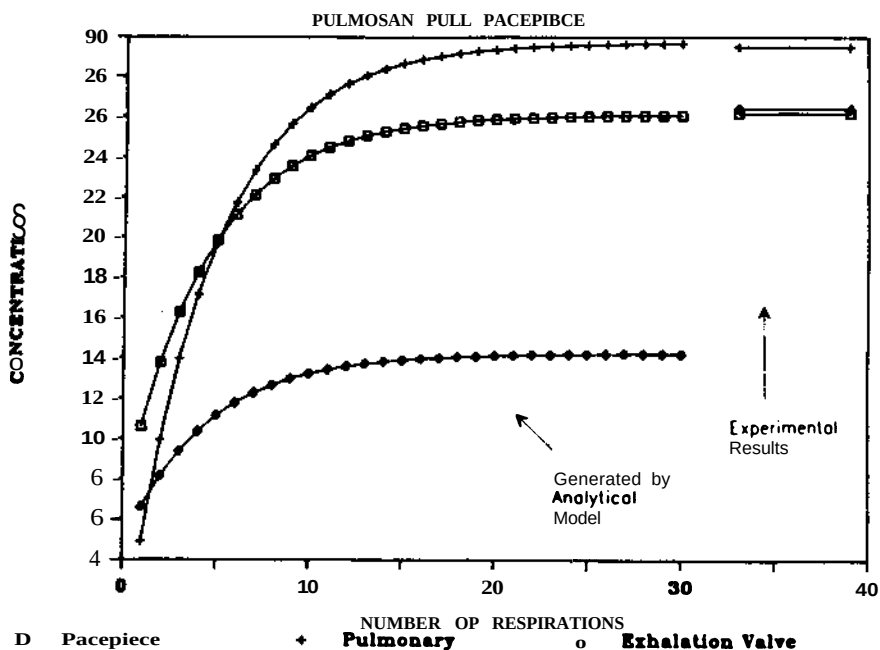


FIGURE 4

A comparison of the analytical results and the experimental results for the Pulmosan Respirator when inhalation valve backflow is incorporated into the analytical model.

concentrations at the beginning of the cycle and the flushing fractions. Multiple breathing cycles can be simulated by an iterative process in which the output of one cycle is used as the input for the next.

When we apply this analytical model to the two full facepiece respirators mentioned earlier in the Introduction and referenced in Table 1, we get the results shown in Figures 3 and 4. Figure 3 shows the results for the American Optical respirator. The extreme right shows the three experimentally measured concentrations: the average in-facepiece concentration, the pulmonary concentration, and the exhalation valve concentration. The calculated average in-facepiece concentration corresponds to that measured by continuous sampling from the facepiece. It was computed as the average of the in-facepiece concentration after inhalation, C_{fin} , and after exhalation, C_{fex} . The flushing fractions were adjusted until the model gave the best fit to the experimentally-determined concentrations. We see that the model can explain the increased pulmonary concentration and the increased facepiece concentration. It does not explain the increased exhalation valve concentration. Independent of the values selected for the flushing fractions, the exhalation valve concentration converges to the computed concentration rather than the elevated concentration determined experimentally.

Figure 4 shows the results for a Pulmosan full-facepiece respirator. The results are similar to the AL.

Again, we can use the model to explain the increased concentration in the facepiece and in the pulmonary system—increased above the calculated inspired concentration. Again, the model does not explain the increased exhalation valve concentration; the measured concentration is approximately twice the expected value.

We spent considerable effort trying to explain the increased exhalation valve concentration. The first such efforts were directed at finding error in the measured concentration. No errors could be discovered. The system passed all consistency checks we could devise. We considered several hypothetical explanations. All failed except one, in which we considered the possibility of backflow of contaminated air is then temporarily trapped in the respirator's inlet path, only to re-enter the facepiece during the next inhalation. We went back and modified the analytical model that was just discussed to allow for the backflow of a volume of contaminated air, V_{iv} , past the inhalation valve during exhalation. With this modification the concentration entering the inlet valve is no longer zero, but is given by $C_i = C^* (V_{iv} / V)$ where C^* is the contaminate concentration that ideally would all have exhausted through the exhalation valve on the previous respiration cycle. Instead, part of that contamination enters the respirator inlet circuit with each respiration. The previous model is therefore modified by inserting this expression for C_i into equations (3) and (4). Similarly, equa-

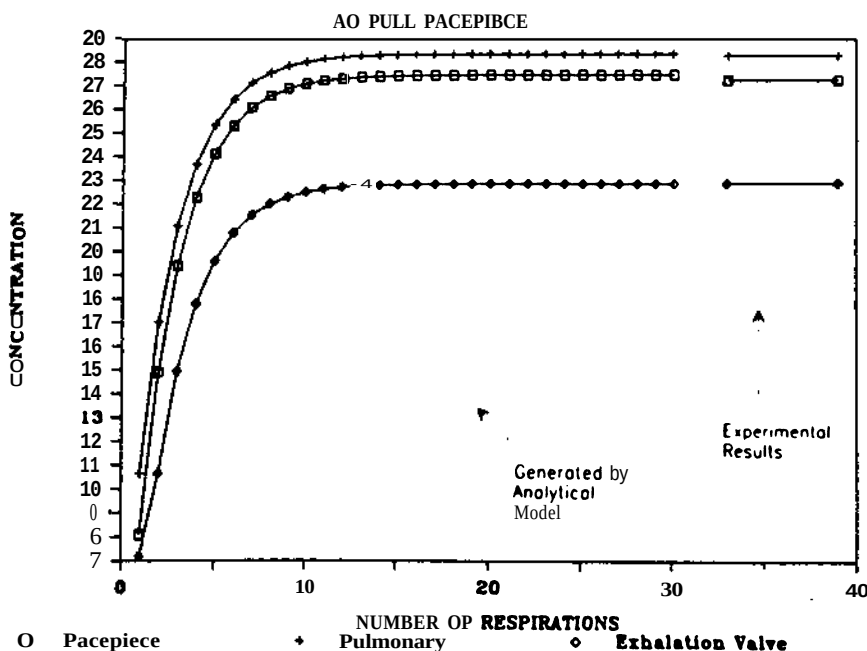


FIGURE 5

A comparison of the analytical and experimental results for the American Optical Respirator when inhalation valve backflow is incorporated into the analytical model.

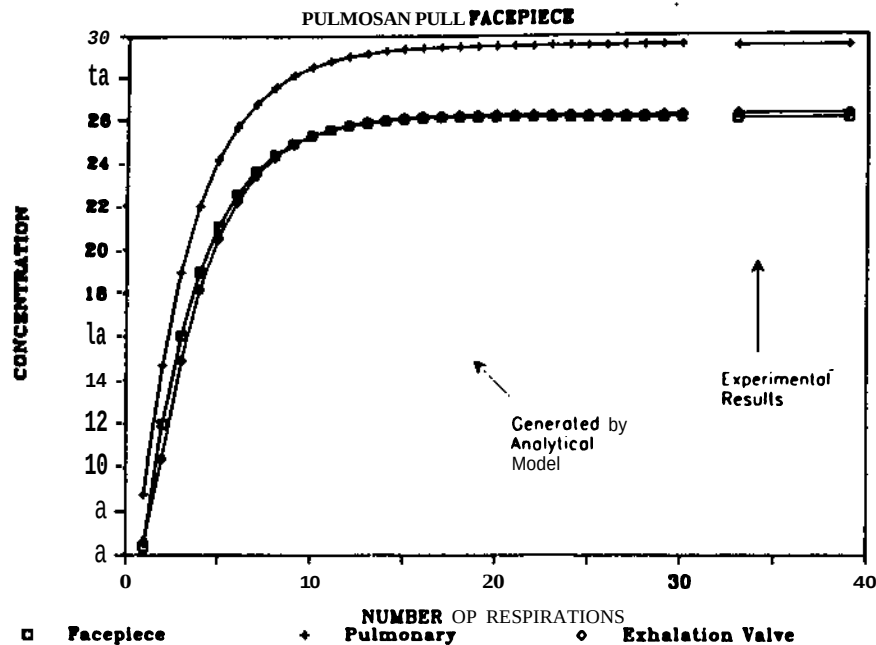


FIGURE 6

A comparison of the analytical and experimental results for the **Pulmosan** Respirator when inhalation valve backflow is incorporated into the analytical model.

tions (8) and (9) must be modified by inserting the term $(1-F_i)(1-f_i)V \cdot C_i$ into the numerator of equation (8) and inserting the term $F_i(1-f_i)V \cdot C_i$ into the numerator of equation (9). With this modification the model yields the results shown in Figure 5. There we see that all three concentrations computed by the analytical model converge to the experimentally-determined values.

We see that by considering backflow past the inhalation valve the model can provide a plausible explanation of the elevation of all three measured concentrations.

In Figure 6 we see similar agreement between the analytical model and the observed experimental results for the **Pulmosan** respirator.

Discussion

The analysis presented provides a plausible explanation of the observed experimental results. We have presented flushing mechanisms that can account for the elevated pulmonary concentrations observed experimentally. Alone these mechanisms could not account for the elevated exhalation valve concentration. To account for the elevated concentration we hypothesized a mechanism involving backflow through the inhalation valve. Thus, we have resolved what was at first considered to be experimental inconsistencies, and provided a justification for the use of the measured pulmonary concentration as the reference concentration to measure the bias associated with a particular in-face-

piece sampling method.

Beyond justifying particular experimental methods for measuring in-facepiece sampling bias, the analytical model hypothesized above has profound implications for respirator wearers. The model predicts that the protection provided by a respirator can be a function of the performance of the inhalation valve, a component not heretofore considered a critical respirator component.

References

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