

This article was downloaded by: [CDC Public Health Library & Information Center]

On: 15 May 2014, At: 11:49

Publisher: Taylor & Francis

Informa Ltd Registered in England and Wales Registered Number: 1072954 Registered office: Mortimer House, 37-41 Mortimer Street, London W1T 3JH, UK



## American Industrial Hygiene Association Journal

Publication details, including instructions for authors and subscription information:

<http://www.tandfonline.com/loi/aiha20>

### Estimated Workplace Protection Factors for Positive-pressure Self-Contained Breathing Apparatus

Donald L. Campbell<sup>a</sup>, Gary P. Noonan<sup>a</sup>, Timothy R. Merinar<sup>a</sup> & Judith A. Stobbe<sup>a</sup>

<sup>a</sup> National Institute for Occupational Safety and Health, 944 Chestnut Ridge Road, Morgantown, West Virginia 26505-2888

Published online: 04 Jun 2010.

To cite this article: Donald L. Campbell, Gary P. Noonan, Timothy R. Merinar & Judith A. Stobbe (1994) Estimated Workplace Protection Factors for Positive-pressure Self-Contained Breathing Apparatus, American Industrial Hygiene Association Journal, 55:4, 322-329, DOI: [10.1080/15428119491018961](https://doi.org/10.1080/15428119491018961)

To link to this article: <http://dx.doi.org/10.1080/15428119491018961>

PLEASE SCROLL DOWN FOR ARTICLE

Taylor & Francis makes every effort to ensure the accuracy of all the information (the "Content") contained in the publications on our platform. However, Taylor & Francis, our agents, and our licensors make no representations or warranties whatsoever as to the accuracy, completeness, or suitability for any purpose of the Content. Any opinions and views expressed in this publication are the opinions and views of the authors, and are not the views of or endorsed by Taylor & Francis. The accuracy of the Content should not be relied upon and should be independently verified with primary sources of information. Taylor and Francis shall not be liable for any losses, actions, claims, proceedings, demands, costs, expenses, damages, and other liabilities whatsoever or howsoever caused arising directly or indirectly in connection with, in relation to or arising out of the use of the Content.

This article may be used for research, teaching, and private study purposes. Any substantial or systematic reproduction, redistribution, reselling, loan, sub-licensing, systematic supply, or distribution in any form to anyone is expressly forbidden. Terms & Conditions of access and use can be found at <http://www.tandfonline.com/page/terms-and-conditions>

# ESTIMATED WORKPLACE PROTECTION FACTORS FOR POSITIVE-PRESSURE SELF-CONTAINED BREATHING APPARATUS

**Donald L. Campbell**

**Gary P. Noonan**

**Timothy R. Merinar**

**Judith A. Stobbe**

National Institute for Occupational Safety and Health, 944 Chestnut  
Ridge Road, Morgantown, West Virginia 26505-2888

*An analytical model is presented that estimates the distribution of workplace protection factor (WPF) values for positive-pressure respirators. Input for the model is (1) the instantaneous facepiece pressure measured as a function of time and (2) the distribution of WPF values for a negative-pressure version of the respirator. As an example application, the model was applied to 57 measurements of facepiece pressure made in a previous National Institute for Occupational Safety and Health study called "Firesmoke." That study involved professional firefighters wearing positive-pressure self-contained breathing apparatus (SCBA). During Firesmoke, there were four donnings in which facepiece pressure momentarily went negative one or more times during use. The purpose of the effort described here was to assess the significance of these momentary, negative excursions in facepiece pressure. To that end, an analytical model was developed that estimates the ratio of the mass of contaminant that enters the facepiece during these negative excursions to that which would be expected to enter a negative-pressure respirator utilizing the same facepiece. Thus, the performance of a positive-pressure SCBA can be determined relative to the performance of a negative-pressure respirator with the same facepiece—either a negative-pressure SCBA or a negative pressure air-purifying respirator. The NIOSH-assigned protection factor (APF) for a negative-pressure full facepiece is 50; the APF for a positive-pressure SCBA is 10 000. The results of the application of this analytical model are consistent with the current NIOSH APF for a positive-pressure SCBA.*

**I**n order to assess the level of protection provided to firefighters by positive pressure self-contained breathing apparatus (SCBA), the National Institute for Occupational Safety and Health (NIOSH) conducted a respirator field study called "Firesmoke."<sup>(1)</sup> That project, jointly funded by NIOSH and the U.S. Fire Administration, Federal Emergency Management Agency, was conducted in

cooperation with 5 large city fire departments, at 26 active fire scenes, and involved 57 measurements of facepiece pressure on individual firefighters. Participating firefighters were provided new SCBA of the same model routinely used by their fire departments. Two SCBA models, both without facepiece nose-cups, were included. One of the many purposes of Firesmoke was to determine if positive-pressure SCBA complying with the 1987 edition of the National Fire Protection Association (NFPA) Standard 1981 (on Open-Circuit Self-Contained Breathing Apparatus for Firefighters)<sup>(2)</sup> maintained a positive facepiece pressure during actual firefighting activity. To that end, instantaneous facepiece pressure was measured with a miniature pressure transducer (Micro Switch model PK 87723, Micro Switch Division, Honeywell, Inc., Fort Washington, Penn.) and stored on a miniature, custom made, data-acquisition system worn by each firefighter while engaged in active firefighting. The data-acquisition system was started immediately before the firefighter entered the fire scene, and sampling continued at a rate of 20 measurements per second until the SCBA was removed. During that previous study, 4 of the 57 firefighters experienced one or more instances in which the facepiece pressure became negative during firefighting.

The purpose of this paper is to present an analytical model that can be used to determine the effect of these momentary negative excursions in facepiece pressure on workplace protection factors and on the currently assigned protection factor of 10 000.<sup>(3,4)</sup>

Positive-pressure SCBA rely on both a good face seal and a positive facepiece pressure to prevent the inward leakage of contaminant into the facepiece. A high level of protection is therefore expected in spite of the always-imperfect face seal. For this reason, OSHA requires in its regulation 29 CFR 1910.156 that only positive-pressure SCBA be used by fire brigades performing interior structural firefighting.<sup>(5)</sup>

Inward leakage can, however, occur if the SCBA is "over-breathed." Over-breathing is said to occur when, during rapid inhalation, the SCBA is momentarily unable to

provide the air flow necessary to prevent the facepiece pressure from going negative. This rapid inhalation is, of course, most likely to occur at high work rates.

Currently two standards apply to the performance of positive-pressure SCBA. The first is the NIOSH certification standard.<sup>(6)</sup> The second is NFPA standard number 1981,<sup>(2)</sup> which was revised and promulgated in 1987. The NFPA standard contains requirements additional to those needed for NIOSH certification.

In the test most indicative of the ability of positive-pressure SCBA to maintain positive facepiece pressure, the requirements of the NFPA standard are far more stringent than those of the NIOSH certification standard. Both standards require facepiece pressure to remain positive when tested on a mechanical breathing machine. The NFPA test is conducted with the breathing machine operated at a rate corresponding to a minute-volume of  $103 \pm 3$  liters, simulating a high work rate. The NIOSH test is conducted at a minute-volume of 40 liters, simulating only a moderate work rate.

Laboratory studies of the performance of positive-pressure SCBA conducted in the late 1970s and early 1980s, suggested that positive-pressure SCBA could be overbreathed by the high work rate experienced in firefighting.<sup>(7-12)</sup> There was concern that this overbreathing could reduce the protection provided to firefighters. The NFPA standard published in 1987, with its high flow requirements was, in part, a response to that concern.

A measure of the protection provided to an individual by a respirator is the workplace protection factor (WPF). The WPF is defined as the ratio of the contaminant concentration that would be inspired by a worker without a respirator to that inspired by the worker when wearing a respirator.<sup>(13,14)</sup> The WPF is, by definition, measured in a workplace setting on actual workers doing their normal work activities. WPFs are typically measured for a period of one workshift or less. For a given respirator type, the variation in WPF values is considerable due to the high variability of the fit, or seal, of the respirator on a wearer's face. Because of this high variation in protection, from individual-to-individual and from donning-to-donning, a useful measure of the protection provided by a class of respirator models (e.g., positive-pressure SCBA) to a population of workers is the "assigned protection factor" (APF). NIOSH and others defined the APF as the WPF value exceeded by 95% of the wearer population.<sup>(4,13,14)</sup> As determined by NIOSH, all classes of negative-pressure respirators utilizing a full facepiece have an APF of 50.<sup>(3,4)</sup> Thus, 95% of the wearers using that respirator would be expected to achieve a WPF of 50 or greater. The APF for positive-pressure SCBA is 10 000, which is reflective of the very high level of protection expected of these devices.<sup>(3,4)</sup> This APF is based primarily on the pioneering work of Hyatt in the early 1970s.<sup>(15)</sup>

A direct assessment of the APF was not possible during the Firesmoke study, because unmeasurably low concentrations of contaminants in the facepiece made it impossible to measure the WPF. As a result, assessments of the effective protection factor (EPF), were made instead. The EPF is a measure of the protection provided by the respirator

including the time the facepiece is removed, or the face seal is broken for communication, or some other purpose.<sup>(13,14)</sup> The EPF differs from the WPF in that the EPF is highly dependent on when the firefighter chooses to don and doff the SCBA, while the WPF is not. During the planning of Firesmoke it was thought that the high WPF values expected of a positive-pressure SCBA could be inferred by verifying that the facepiece pressure did indeed remain positive during all times of use. When unexpected negative-pressure excursions were observed, it became necessary to assess their significance; that assessment is described herein.

## PRESSURE MEASUREMENT DATA

During the Firesmoke study, the facepiece pressure data were temporarily stored on the miniature, custom-made, data-storage device worn by the firefighters. On the return of each firefighter to the fire vehicle, the pressure data were downloaded to a portable computer for permanent storage and for immediate display on the computer screen. Examples of the resulting pressure tracings are shown in Figure 1. Figures 1a and 1b are typical of the 53 firefighters having no negative excursions. Figures 1c and 1d are two examples of the four instances of negative excursions. Figure 1d shows the most extreme example of negative excursions.

The respiration rate can be readily determined from the tracings. In addition, based on laboratory experience, certain irregular pressure patterns can be identified with particular activities such as talking, shouting, or lifting the facepiece from the face to communicate. The instances of negative-pressure excursions do not seem to be associated with any such activity of the firefighters.

Many fine details can be observed from the pressure tracing, as can be seen by inspecting Figure 1. The resolution of fine structure in the present data were limited only by the sampling rate of 20 pressure measurements per second; the frequency response of the pressure transducer itself was sufficiently fast (response time less than one millisecond) so as to resolve any pressure signal of possible significance.

In order to investigate any limitation imposed by the sampling rate of 20 pressure measurements per second, an informal laboratory study was conducted with the SCBA previously used in Firesmoke. The in-facepiece pressure was measured with both the Firesmoke pressure logger and with a laboratory system capable of resolving higher frequency pressure variation. When this comparison was performed with the SCBA connected to a mechanical, cam-driven breathing machine, short duration pressure spikes were observed with the fast-responding laboratory system that were not accurately resolved on the Firesmoke pressure logger. However, when this comparison was performed with human subjects, rather than with a breathing machine, no such spikes were observed on either system. The machine appeared to be the source of the observed short duration pressure spikes. If pressure spikes also were produced by the SCBA regulator, the compliance of the human respiratory system seemed to dampen any rapid pressure

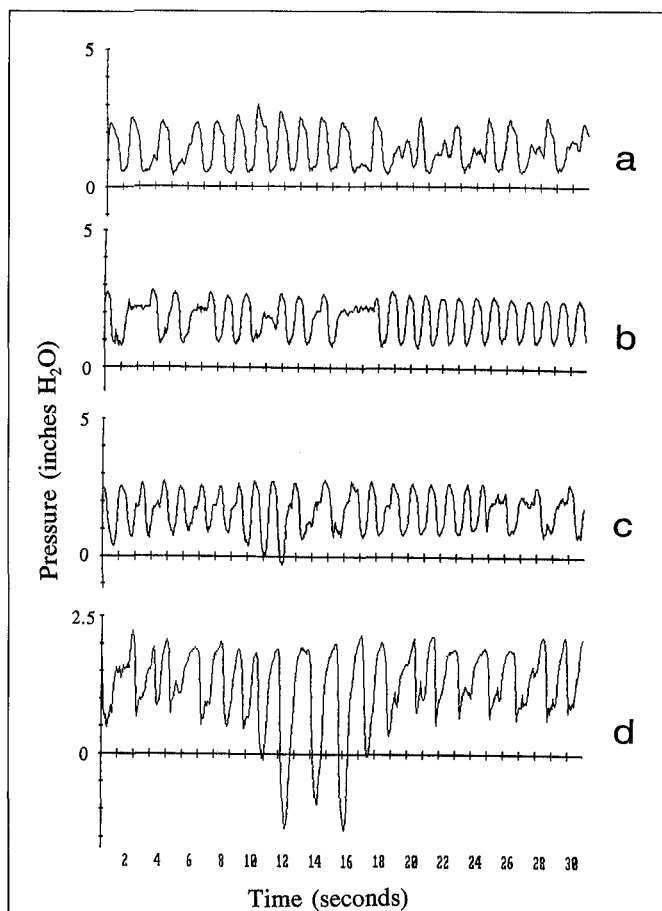


FIGURE 1. Examples of SCBA in-facepiece pressure measurements made during firefighting. The pressure is shown in inches of water-column height. Figures 1a and 1b are typical of SCBA maintaining a positive facepiece pressure. The specific shape of each is determined by activities such as shouting, talking, breath holding, coughing, etc. Figures 1c and 1d are examples of SCBA that allowed negative-pressure excursions.

excursion. Thus, it seems unlikely that any high frequency pressure variations were missed with the sampling rate of 20 per second.

The pressure sampling rate in the Firesmoke study was limited to 20 per second because of memory limitations in the data logger. As improved hardware becomes available, the authors recommend that future studies employ higher sampling rates to further assure that any negative-pressure excursions are not missed.

Facepiece pressure was monitored for the total time of SCBA use at the fire scene. Figure 1 shows 30-second segments of the total sampling time. The negative-pressure excursions were not directly related to low air-cylinder pressure; negative-excursions were not confined to times late in the use period, where low cylinder pressure would occur. Although a few of the 57 measurements involved the

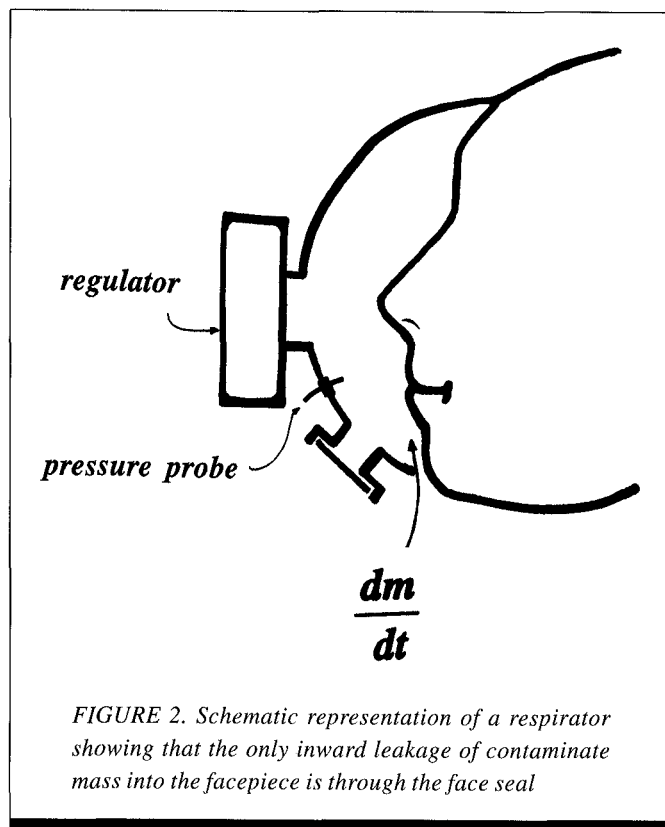


FIGURE 2. Schematic representation of a respirator showing that the only inward leakage of contaminate mass into the facepiece is through the face seal

same firefighter, each of the four negative excursions were associated with a different firefighter. Also, each of the four episodes of negative-pressure excursion were associated with a different SCBA unit.

#### DEVELOPMENT AND APPLICATION OF ANALYTICAL MODEL

In an attempt to understand the significance of the negative-pressure excursions just described, an analytical model to estimate how inward leakage into the facepiece is related to facepiece pressure was developed. The authors began by considering the respirator shown schematically in Figure 2. The instantaneous mass leakage rate into the facepiece can be expressed as:

$$\frac{dm}{dt} = C \frac{dv}{dt} = CQ \quad (1)$$

where,

- $m$  = contaminant mass entering facepiece through face seal
- $C$  = ambient contaminant mass concentration
- $v$  = volume leaking into facepiece
- $Q$  = volumetric leak rate
- $t$  = time.

Inherent in the above relationship is the simplifying assumption that the contaminant concentration entering the

facepiece through face-seal leakage is equal to the ambient contaminant concentration outside the facepiece. That is, the face-seal leak penetration, defined as the ratio of these two concentrations, is unity. This is valid for typical gases and vapors, and a reasonable approximation for respirable aerosols.<sup>(16,17)</sup> (The significance of any error introduced by this assumption is minimized in the final result, Equation 11, because the error would affect both the numerator and denominator of the right side in similar ways.)

The volumetric leakage into the facepiece  $Q$  can be expressed as a function of facepiece pressure as follows:<sup>(16,18,19)</sup>

$$Q = K p^\lambda$$

where  $p$  is the magnitude of the pressure differential between inside and outside the respirator facepiece, and  $K$  and  $\lambda$  are constants determined by the geometry of the leak path. The constant  $K$  is primarily determined by the size of the leak opening;  $\lambda$  is a constant between  $\frac{1}{2}$  and 1, depending on the geometry of the leak site.

Flow through a capillary is characterized by  $\lambda = 1$ , and at the other extreme,  $\lambda = \frac{1}{2}$  is characteristic of flow through a hole in a thin membrane. The large variation typically associated with face-seal leakage from one individual to another and from one fitting to another is associated with large variation in the constant  $K$ .

Equations 1 and 2 can be combined as

$$\frac{dm}{dt} = C K p^\lambda \quad (3)$$

which can be integrated to give the contaminant mass that entered the facepiece at time  $T$ :

$$m = \int_0^T C K p^\lambda \delta(p) dt \quad (4)$$

where  $\delta(p)$  is defined such that

$$\begin{aligned} \delta(p) &= 1 \text{ if facepiece pressure is negative} \\ &= 0 \text{ if facepiece pressure is positive.} \end{aligned} \quad (5)$$

Thus, the above integral is non-zero only during those times when the pressure inside the facepiece is less than that outside. This is equivalent to assuming that contaminant enters the facepiece only when the facepiece pressure is negative.

By definition of the WPF, the following can be written

$$\frac{1}{\text{WPF}} \equiv \frac{C_i}{C_o} = \frac{m_i/V}{m_o/V} = \frac{m_i}{m_o} = \frac{m_i}{C_o V} = \frac{m}{CV} \quad (6)$$

where,

WPF = workplace protection factor

$C_i$  = contaminant mass concentration inspired with respirator worn

$C_o$  = contaminant mass concentration inspired if no respirator worn

$V$  = inspired volume

$m_i$  = contaminant mass inspired with respirator worn

$m_o$  = contaminant mass inspired without respirator worn

$m$  = contaminant mass entering the facepiece

In Equation 6 the approximation is made that the inspired mass,  $m_i$ , equals the mass entering the facepiece,  $m$ . However, due to dead-space effects, there is a possibility that these two masses may differ slightly. (If that difference had been accounted for in Equations 7 through 9, it would not affect Equations 10 or 11 because it would appear in both the denominator and numerator of those equations.) Combining Equations 4 and 6 gives an expression for the WPF as a function of the facepiece pressure, the inspired volume, and the unknown constant  $K$ .

$$\frac{1}{\text{WPF}} = \frac{1}{V} \int K p^\lambda \delta(p) dt \quad (7)$$

This relationship is, by itself, not useable for direct calculation of WPFs because of the unknown constant  $K$ . It can, however, serve as a link between what is known about WPF values of negative-pressure respirators and positive-pressure respirator WPF values, when both utilize the same facepiece. To that end, the authors considered a respirator being used in a negative-pressure mode, and then visualized that same respirator being used in a positive-pressure mode, by the same individual in exactly the same conditions. The negative-pressure respirator could be, for example, an SCBA with the regulator operated in the negative-pressure mode, while the positive-pressure respirator could be the same SCBA operated in the positive-pressure mode. Equation 7 could then be written for each respirator as follows, using the subscripts  $(-)$  and  $(+)$  to indicate the negative and positive modes, respectively:

$$\frac{1}{\text{WPF}_-} = \frac{1}{V_-} \int_0^T K p_-^\lambda \delta(p_-) dt \quad (8)$$

$$\frac{1}{\text{WPF}_+} = \frac{1}{V_+} \int_0^T K p_+^\lambda \delta(p_+) dt \quad (9)$$

which can then be combined to yield

$$\text{WPF}_+ = \text{WPF}_- \frac{V_+ \int_0^T p_-^\lambda \delta(p_-) dt}{V_- \int_0^T p_+^\lambda \delta(p_+) dt} \quad (10)$$

This result establishes the relationship between the WPFs of a positive-pressure respirator and the WPF of its negative-pressure counterpart utilizing the same facepiece. Thus, knowledge of the performance of a negative-pressure respirator can be used to estimate the performance of a positive-pressure version of that respirator.

The integral over  $p_+$  is, of course, evaluated using the pressure data previously obtained with working firefighters in the Firesmoke study. The negative-pressure integral was

determined by measuring  $p_-$  in a negative pressure air-purifying respirator mounted on a laboratory breathing machine. By estimating the work rates of the firefighters during Firesmoke and operating the laboratory breathing machine at that same rate, the ratio  $V_+/V_-$  reduces to unity and is eliminated from Equation 10 to yield the following relationship, the basic working equation of this analysis.

$$WPF_+ = WPF_- \frac{\int_0^T p_-^\lambda \delta(p_-) dt}{\int_0^T p_+^\lambda \delta(p_+) dt} \quad (11)$$

During the course of Firesmoke, no direct measurements of respiratory flow rates were obtained. Because of the remote location of firefighters at the fire scene, direct observations of firefighter activities by NIOSH researchers were not always possible, and monitoring of heart rate was not practical. For the purpose of this analysis, and based on a general knowledge of the firefighting tasks undertaken during the study, the respiratory demands of the four firefighters experiencing negative-pressure excursions were estimated to be characterized by a minute-volume of 80 L/min. This estimate is considered to be sufficiently accurate for the WPF estimates to be made in this analysis; however, if future studies are undertaken, the development of techniques to measure instantaneous inspiration rate directly would be of value.

Inspection of Equation 11 shows that, to the first approximation, the error in computing  $WPF_+$  will be directly proportional to the error in estimating the inspired volume. That is, if the inspired volume of the firefighter at the time of overbreathing had been overestimated by, say, 20%, the breathing machine (used to measure  $V_-$ ) would have been operated at a 20% higher rate, the measured pressure  $p_-$  would be 20% greater (since the filter of the negative-pressure respirator exhibits a linear relationship between pressure and flow), and the calculated value of  $WPF_+$  would, therefore, be 20% higher. The authors consider the estimated minute-volume of 80 L/min to be a conservative estimate.  $WPF_+$  is more likely to have been underestimated than overestimated.

The range of error associated with the estimate of the inspirator rate at the time of overbreathing is not unbounded. It is limited on the lower end, since overbreathing is unlikely at low inspiration rates. It is limited on the upper end by the physiological limitations of the respirator wearer. The range of error associated with the estimate of inspiration rate is judged to be  $\pm 30\%$ .

For the purpose of this analysis, the parameter  $\lambda$  is set at  $\lambda = 2/3$ . This value is the lower, more conservative limit of the range of typical values determined in informal measurements in this laboratory. It is also consistent with the range of  $\lambda$  reported by Hinds<sup>(16)</sup> for artificially induced face-seal leaks. Since the possible range of values for  $\lambda$  is known to be limited to the range of  $1/2$  to 1, any error in the estimate of  $\lambda$  is thereby limited and is not a source of significant error in the analysis that follows. (Through trial computations, it has been determined that  $\lambda = 1/2$  yielded the lowest, most

conservative estimate of APF in the analysis that follows. Selecting  $\lambda = 1/2$  would have yielded an estimate of the APF approximately 80% of that for  $\lambda = 2/3$ .)

## RESULTS

The two integrals of Equation 11 were calculated using the facepiece pressure data obtained in the previous Firesmoke study for the positive-pressure respirator, and using the pressure data of a negative pressure air-purifying respirator measured on a breathing machine. The ratios of the two integrals for the four trials with negative excursions equal  $WPF_+/WPF_-$  and were computed to be 1451, 10283, 566, 8066.

The following question is addressed to complete the analysis: for firefighters experiencing negative-pressure excursions, what would the WPF have been if the firefighter had been wearing a negative-pressure respirator with the same facepiece? If the WPF was known for the negative mode, Equation 11 could be used to compute the WPF for the positive mode. However, the individual WPF is not known. Nevertheless, it is known that the individual is a member of a population of workers and something also is known about the distribution of negative pressure WPF values for that population. The assigned protection factor for a negative pressure, full-facepiece respirator is 50<sup>4</sup>; that is, the 5th percentile for the population of workers is 50. The WPF values for a population of workers are typically log-normally distributed with typical geometric standard deviation of 3 or more.<sup>(20,21)</sup> A geometric standard deviation of 3 was assumed. (It can be shown that, in the analysis to follow, this is a more conservative assumption than larger values.) Therefore, there are estimates of the WPF probability distribution for the firefighters if they had been used in a negative-pressure respirator. Equation 11 can be used to understand how that probability distribution would change, if the respirator were to change from a negative mode to a positive mode. To see this, it is best to express Equation 11 as follows:

$$\log WPF_+ = \log WPF_- + \log D \quad (12)$$

where

$$D = \frac{\int_0^T p_-^\lambda \delta(p_-) dt}{\int_0^T p_+^\lambda \delta(p_+) dt} \quad (13)$$

As indicated above, the values of  $\log WPF_-$  are normally distributed and, for each of the four firefighters, the term  $\log D$  is a constant—a constant in the sense that it is not a function of face-fit, and does not change from donning to donning. Thus, the probability distribution function for  $WPF_+$  is identical in shape to that for  $WPF_-$  but displaced to the right by an amount equal to  $\log D$ , as shown schematically in Figure 3 for each of the four firefighters experiencing negative-pressure excursions.



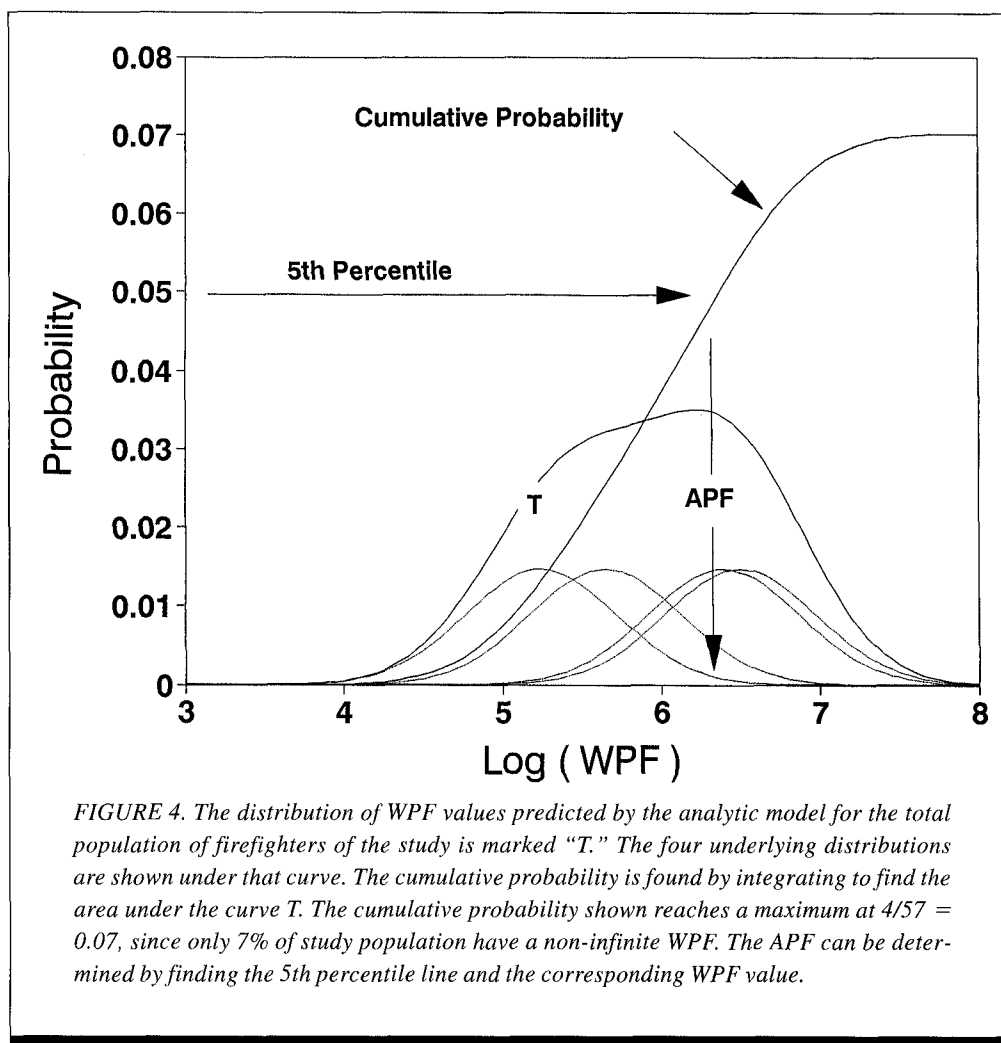


FIGURE 4. The distribution of WPF values predicted by the analytic model for the total population of firefighters of the study is marked "T." The four underlying distributions are shown under that curve. The cumulative probability is found by integrating to find the area under the curve T. The cumulative probability shown reaches a maximum at  $4/57 = 0.07$ , since only 7% of study population have a non-infinite WPF. The APF can be determined by finding the 5th percentile line and the corresponding WPF value.

firefighters can be expressed in terms of the probability distribution functions of the four subpopulations associated with momentary negative-pressure excursions.

Figure 4 shows the results of applying this approach to the 4 of 57 firefighters with negative-pressure excursions. The four normal-shaped distributions at the bottom of the figure result from a displacement of the negative-pressure distribution to the right by an amount equal to  $\log D$ , and by multiplying each by  $1/57$ . The finite portion of the distribution for the total population of firefighters is simply the sum of these four, and is shown in the center of the figure labeled "T." The infinite portion (which has probability  $53/57$ ) is far past the right of the figure and is not involved in the estimation of the fifth percentile. The curve "T" is then integrated to find the cumulative probability. The resulting curve is shown in the figure, and gives the percentage of firefighters with a WPF value less than a particular WPF value. The fifth percentile (the APF) can then be read directly from the curve, and is seen to be approximately  $2.3 \times 10^6$  ( $10^{6.36} = 2.3 \times 10^6$ ). Thus, this second approach yields, as did the first, an estimate of the APF more than two orders of magnitude greater than the value of  $1 \times 10^4$  currently established for positive-pressure SCBA.

The above result is the authors' best estimate of the assigned protection factor, APF, for positive-pressure SCBA used in the fire service. The result is, however, based on a number of approximations and assumptions. The accuracy of this result is limited by (1) the small number of firefighters studied, (2) the significant uncertainty in the general understanding of the performance of negative pressure full-facepiece respirators, and (3) the approximations made in developing the analytical model. Because of the resulting uncertainty the authors do not suggest raising the APF above  $1 \times 10^4$  based on this single study. It is only concluded that the results of this study are consistent with the current NIOSH APF for positive-pressure SCBA.

## SUMMARY AND OBSERVATIONS

An analytical model (Equation 10) has been presented that can be used to characterize the performance of a wide variety of

positive-pressure respirators. The model is applicable to any positive-pressure respirator with a tight-fitting facepiece. It could, for example, be applied to the evaluation of (1) powered, air-purifying respirators, (2) continuous flow air-line respirators, (3) positive pressure air-line respirators, or (4) positive-pressure SCBA.

As an example of the utility of the analytical model, the performance of positive-pressure SCBA was estimated using data generated in a previous NIOSH study. The results of that exercise are consistent with the high APF of  $1 \times 10^4$  currently established for positive-pressure SCBA.

In spite of the fact that the model estimates the APF to be two orders of magnitude greater than the current APF of  $1 \times 10^4$ , the authors do not suggest increasing the APF. The limitations imposed by the assumptions and approximations necessary in this analysis make any stronger conclusion imprudent. The most serious limitation of these results is associated with the limited number of firefighters, fire scenarios, and SCBA studied. However, with the availability of pressure-sampling hardware and the analytical model presented here, future studies of this nature can be undertaken without major effort. Such studies should be encouraged so that the performance of SCBA can be better characterized.

The second most important limitation of these results is uncertainty associated with the understanding of the performance of negative pressure full-facepiece respirators. The distribution of WPF values for negative pressure full-facepiece respirators is input for the model used here and, therefore, its accuracy is critical to the accuracy of the model results. There have been only a limited number of WPF studies of negative pressure full-face respirators, and, therefore, significant uncertainty exists in the understanding of the workplace performance of these respirators. The results of this analysis should be updated as understanding is increased by future WPF studies.

The third most important limitation of these results is the uncertainty in how well the SCBA used here represent SCBA after they have been in service for a period of time. These SCBA were all new, and great care was taken by both NIOSH and the respirator manufacturer to assure that the regulators were precisely adjusted for proper performance. This is, of course, consistent with the definition of "workplace protection factor," which specifies a properly functioning and properly used respirator. Nevertheless, it would be informative and useful if future studies were conducted with used SCBA after typical use and maintenance.

The SCBA used in this study were of a newer design certified by the manufacturer to comply with the requirement of NFPA 1981 (1987 edition). Many SCBA used in general industry and in the fire service comply only with the NIOSH certification requirements, which do not require as high a maximum inhalation flow rate as does NFPA 1981. Thus, the NIOSH-certified respirator may have a reduced ability to maintain a positive facepiece pressure at high work rates. The results of this study, therefore, do not necessarily apply to NIOSH certified positive-pressure SCBA that do not meet the requirements of NFPA 1981.

## REFERENCES

1. Noonan, G.P., J.A. Stobbe, P.R. Keane, L.D. Reed, and R.T. McCarthy: Firesmoke: A Field Evaluation of Self-Contained Breathing Apparatus. [Unpublished manuscript] Gary P. Noonan, CDC/NCEH, 4770 Buford Hwy, NE, Atlanta, GA 30341-3714.
2. National Fire Protection Association: *Standard 1981 on Open-Circuit Self-Contained Breathing Apparatus for Fire Fighters*. Quincy, MA: National Fire Protection Association, 1987.
3. Bollinger, N.J. and R.H. Schutz: *NIOSH Guide to Industrial Respiratory Protection*. [DHHS (NIOSH) Publication No. 87-116] Cincinnati, OH: National Institute for Occupational Safety and Health, 1987.
4. National Institute for Occupational Safety and Health: *NIOSH Respirator Decision Logic*. [DHHS (NIOSH) Publication No. 87-108] Cincinnati, OH: National Institute for Occupational Safety and Health, 1987.
5. "OSHA Safety and Health Standards for General Industry," *Code of Federal Regulations* Title 29, Part 1910.156(f)(2), 1992.
6. "NIOSH Certification Regulations" *Code of Federal Regulations*, Title 30, Part 11, Subpart H, 1989.
7. Myhre, L.G., R.D. Holden, F.W. Baumgardner, and D. Tucker: *Physiological Limits of Firefighters*. [Report No. ESL-TR-79-06] Air Force Engineering and Services Center, Tyndall Air Force Base, Florida, 1979.
8. Dahlback, G.O. and L. Novak: Do Pressure-demand Breathing Systems Safeguard Against Inward Leakage? *Am. Ind. Hyg. Assoc. J.* 44:336-340 (1983).
9. Held, B.J.: Effectiveness of Self-contained Breathing Apparatus in a Fire Environment. *J. ISRP* 1:9-27 (1983).
10. Dahlback, G.O. and U.I. Balldin: Physiological Effects of Pressure Demand Masks during Heavy Exercise. *Am. Ind. Hyg. Assoc. J.* 45:177-181 (1984).
11. Bentley, R.A., G.J. Bostock, D.J. Longson and M.W. Roff: Determination of the Quantitative Fit Factors of Various Types of Respiratory Protective Equipment. *J. ISRP* 2:313-337 (1984).
12. Stengel, J.W. and R. Rodrigues: Machine Testing of Self-contained Breathing Apparatus at a High Work Rate Typical of Firefighting. *J. ISRP* 2:362-368 (1984).
13. Myers, W.R., S.W. Lenhart, D.L. Campbell and G. Provost: Letter to the Editor. *Am. Ind. Hyg. Assoc. J.* 44:B25-B26 (1983).
14. Guy, H.P.: Letter to the Editor. *Am. Ind. Hyg. Assoc. J.* 46:B22-B24 (1985).
15. Hyatt, E.C.: Respirator Protection Factors. [Report No. LA-6084-MS] Los Alamos National Laboratory, Los Alamos, New Mexico, 1976.
16. Hinds, W.C. and G. Kraske: Performance of Dust Respirators with Facial Seal Leaks: I. Experimental. *Am. Ind. Hyg. Assoc. J.* 48:836-841 (1987).
17. Hinds, W.C. and P. Bellin: Performance of Dust Respirator with Facial Seal Leaks: II. Predictive Model. *Am. Ind. Hyg. Assoc. J.* 48:842-847 (1987).
18. Williams, F.T.: An Analytical Method for Respirator Performance Prediction Utilizing the Quantitative Fit Test (QNFT). *J. ISRP* 1(3):109-125 (1983).
19. Kreith, F. and R. Eisenstadt: Pressure Drop and Flow Characteristics of Short Capillary Tubes at Low Reynolds Numbers. *Trans. ASME* 79:1070 (1957).
20. Tannahill, S.N., R.J. Willey, and M.H. Jackson: Workplace Protection Factors of HSE Approved Negative-Pressure Full-Facepiece Dust Respirators During Asbestos Stripping: Preliminary Findings. *Ann. Occup. Hyg.* 34(6):547-522 (1990).
21. Pally, B.G., J. Gamble, P. Hewett, M. Peterson, and J.B. Hudnall: WPF Study of Half- and Full-Facepiece Particulate Air-Purifying Respirators at a Lead-Acid Battery Manufacturing Facility. [Unpublished manuscript] Barry Pally, NIOSH/DSR, 944 Chestnut Ridge Rd, Morgantown, WV 26505-2888.