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VARIABILITY IN PROTECTION AFFORDED BY HALF-MASK RESPIRATORS AGAINST STYRENE EXPOSURE IN THE FIELD

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Concentrations of styrene were measured in the breathing zone and inside the facepiece of air-purifying half-mask respirators of 13 workers for three to six 1-hr periods while they were engaged in the production of fiberglass-reinforced products. These data were used to estimate the protection afforded by the respirators. In arriving at these estimates, it was necessary to correct the concentration measured inside the mask for pulmonary retention of styrene by the workers. Workers were classified as sprayers or as other production line workers not directly carrying out spraying operations. An analysis of variance showed no evidence of differences in the level of protection afforded by the respirators between the two job classes. A second analysis of variance showed that protection varied between workers as well as for a single worker during different wearing periods. The geometric standard deviation (GSD) between workers was 1.92, the common within-worker GSD was 2.93, and the total GSD was 3.51. One-half of a population of wearers with similar protection would be expected to experience long-term average workplace protection factors in excess of 44 and one-half below that value. The observation of between-worker and within-worker variability in protection indicates that both sources of variability have to be taken into account in the specification of maximum use concentrations.

Selection of the proper respirator for a work environment is based, in part, on the assigned protection factor (APF) for each respirator type. The APF is defined as "a measure of the minimum anticipated workplace level of respiratory protection that would be provided by a properly functioning respirator to a large percentage of properly fitted and trained users."[1] The workplace protection factor (WPF) is defined as "a measure of the actual protection provided in the workplace under the conditions of that workplace by a properly functioning respirator when correctly worn and used."[1] However, there are little data on the level of protection that respirators actually provide when used in the work environment. A small number of protection factor studies have been conducted in the workplace for powered air-purifying respirators, negative pressure half-mask respirators, and disposable half-mask respirators.[2–5] More information is available on respiratory protection assessed under laboratory conditions ranging from quantitative fit tests to simulated work environments. Most studies to date, of either kind, have addressed respiratory protection for aerosols or particulates rather than for gases or vapors.

The protection afforded by an air-purifying respirator is determined by two major factors. One is the fit of the respirator around the face seal and the second is the efficiency of the cartridge in removing the contaminant from the airstream. Fit is influenced by the ability of the respirator to conform to individual facial structure and to maintain the facial seal during work activities. Cartridge efficiency and service life are compound-specific for gases and vapors and are also influenced by environmental conditions such as temperature and humidity.[6] Cartridge efficiency and service life have been extensively studied for many organic solvents.[7]

This study was aimed at developing further data on the variability of WPFs for gases and vapors. In particular, the authors were interested in investigating a suggestion made by Nicas[8] that the variability in the respirator protection should be regarded as having both a respirator-specific and a person-specific component which, if true, has implications for how the APF should be defined and interpreted. This objective required a study design that involved multiple determinations of WPF values on each member of a group of workers engaged in similar tasks. Cartridge breakthrough was avoided by using a new pair of cartridges for each measurement period and limiting the measurement period to 1 hr. Therefore, this study focused on the issue of variability in protection associated principally with fit-related factors.

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EXPERIMENTAL SETTING AND METHODS

The study took place at a plant that manufactures fiberglass-reinforced bathtubs and shower stalls. A spray layup procedure is used to apply polyester resin and fiberglass to male molds, which move slowly on an assembly line. Study participants either operated spray guns (sprayers) or performed other duties on the assembly line (nonsprayers). In general, the nonspraying jobs involved a lesser range of physical movements than those observed among the sprayers. Possible differences in fit based on job activity are addressed in the statistical analysis of the data. Half-mask air-purifying respirators had not been previously used in the plant, although normal practice was for all workers in the assembly area to wear charcoal-impregnated dust-mist disposable respirators.

The study protocol included the requirement that sampling would have minimal interference with the assembly line and that the employees would continue to perform their usual job responsibilities when participating in the study. The study was presented and explained to the employees, and they had an opportunity to ask questions. Those who did not have facial hair that would interfere with the respirator face seal were given the chance to participate. Participation was strictly voluntary and participants were able to discontinue their participation at any time without penalty. All who elected to participate in the study were given medical examinations that assessed their pulmonary and cardiovascular fitness to wear negative pressure half-mask respirators in this work environment. Irritant smoke was used, according to ANSI Z88.2, to fit-test participants for the correct respirator size.[9] At this time employees were also trained on how to properly don their respirator and how to conduct negative and positive pressure respirator fit checks. It was suggested that workers carry out such checks from time to time. Odor was not discussed as a qualitative index of fit. The workers were very attentive and cooperative at this point and throughout the study.

Probed North Safety Equipment (Cranston, R.I.) negative pressure air-purifying half-mask respirators (model 7709) equipped with organic vapor cartridges (North N7500-1) were used for this study. The probes were installed by the manufacturer as routinely done for quantitative fit-testing. Charcoal sorbent tubes were attached to the probe with a short piece of Viton® tubing and attached to the outside of the mask. Styrene concentrations outside the facepiece were measured in the participant's breathing zone. The sampling trains were assembled and checked for tightness and integrity in an uncontaminated room separated from the assembly area. Pre- and post-calibrations with a bubble flow meter were also done in this room immediately before and after each sampling period.

Respirators with sampling trains were donned on the assembly line floor just prior to sampling to minimize work interruptions. At this time observers assisted with all negative and positive pressure fit checks to ensure proper fit. There were two observers working with a maximum of five participants at any given time. Respirators were not readjusted during the 1-hr sampling period. New cartridges were used for each period. Sample blanks for each sampling period were opened at the time the sampling trains were assembled, then capped and transported with the samples from the end of the measurement period until analysis.

Air samples were collected on SKC #225-01 100/50 mg lot 120 charcoal sorbent tubes (SKC, Inc., Eighty Four, Pa.). Inside and outside the respirator air samples were collected simultaneously at 0.420 and 0.050 Lpm, respectively. The low styrene concentrations inside the respirator dictated the higher flow rate for collecting inside air samples. Use of a variable flow dual sampling manifold (SKC 224-26-02) permitted the participants to use a single personal sampling pump (Gilian HFS 513 UT, Gilian Instrument Corp., Wayne, N.J.). Inside-outside sample pairs were collected for each participant at three to six randomly selected times for a period of approximately 1 hr on 6 different days. Sampling periods always started at the beginning of the shift or immediately after a rest or meal break. This prevented interruptions of the assembly line and had the effect of minimizing the contribution of styrene from exhaled breath to the measured styrene concentration inside the respirator, as discussed further below. One hour was chosen as being typical of uninterrupted respirator use. In addition, this sampling time ensured that each participant performed the same task through each test period.

The simultaneous occurrence of low styrene concentrations and high humidity inside the respirator led to some concern over both collection and desorption efficiencies for the inside samples. The work of Andersson et al.,[10] carried out with roughly similar sampling parameters, indicated that collection efficiency was unlikely to be a problem for styrene. It was clear, however, that laboratory work was necessary to adequately define desorption efficiency. The low amounts of styrene expected to be collected on the charcoal for the inside respirator samples precluded use of the direct-load desorption efficiency determination method described in National Institute for Occupational Safety and Health (NIOSH) analytical method 1501 for aromatic hydrocarbons.[11] The phase equilibrium method,[12] in which CS_2 containing styrene is added to the charcoal and allowed to reach equilibrium, was used instead. Desorbtion efficiencies varied from a low of 20% at 1 μg of styrene recovered to 92% at 1000 μg. The loadings of the field samples at the low end of the range were about 20 μg where the desorption efficiency was about 60%.[13] The data were corrected to account for desorption efficiency.

Analysis of samples and field blanks closely followed NIOSH analytical method 1501.[11] Two flame ionization detector-equipped gas chromatographs (GCs) were used to analyze the samples for styrene. Initially a Varian Associates (Walnut Creek, Calif.) 3700 GC equipped with a Vista CDS-401 terminal and an 8000 autosampler were used. The 2 m × 2 mm I.D. column was packed with 10% carbowax 1540, 80/120 mesh chromosorb W.HP. Temperatures for the column, injector, and detector were: 128, 220, and 240°C, respectively. The retention time was 1.9 min with a nitrogen carrier flow rate of approximately 20 mL/min. A Hewlett-Packard (Avondale, Pa.) 5880A GC with a control terminal and a 7673 A autosampler was also used. The autosampler rack was cooled to approximately 10°C. The glass column, 2 m × 2 mm I.D., was packed with 3% carbopack B, 80/120 mesh SP-1500. Temperatures for the column, injector, and detector were 190, 220, and 230°C, respectively. The retention time of 6.2 min resulted from an helium carrier gas flow rate of 30 mL/min.[13]

FRAMEWORK FOR ANALYSIS

An operational definition of the workplace protection factor for a specific individual is the ratio of the time-weighted average (TWA) concentration in the breathing zone, C_o, divided by the TWA concentration inside the mask during inhalation, C_i. (The concentration inside the mask during inhalation is, in principle if not in practice, the most direct measure of leakage because it is less contaminated from styrene in expired air.) The inverse of the WPF is termed the penetration denoted by **p** (i.e., $\mathbf{p} = C_i/C_o$). From an analytical point of view, the authors found it preferable to analyze the data in terms of penetration rather than WPF. Previous work has shown WPF distributions to be approximately lognormal,[2,5,14] which implies that **p** is lognormally distributed as well. The authors followed conventional practice in assuming lognormality which, when **p** is used, results in the additive relationship $\ln(C_i) = \ln(\mathbf{p}) + \ln(C_o)$. The results of this analysis will be recast in terms of WPF in the Discussion section.

The situation is complicated by the fact that the TWA concentration measured inside the mask, C_m, is equal to the TWA concentration inside the mask during inhalation, C_i, only under special circumstances. In general, $C_m = [1/2][C_i + C_e]$, where C_e is the concentration in exhaled air. Clearly, $C_m = C_i$ only if $C_e = C_i$, that is all of the inhaled chemical is exhaled or if there is a pre-existing body burden of the chemical that is being excreted via the lungs and the equality holds by chance. C_m could be greater than C_i if prior exposures resulted in a sufficiently large C_e, in which case the true penetration would be overestimated. The other extreme is when the chemical is completely retained, $C_e = 0$, in which case $C_m = 1/2[C_i]$ and the true penetration would be underestimated by a factor of two. For styrene, Ramsey and Andersen[15] express C_e as a function of C_i and C_a, the latter being the concentration of styrene in alveolar air. Their relationship is $C_e = \alpha C_i + (1 - \alpha)C_a$, where the parameter α equals 0.3. The alveolar concentration, C_a, in turn, is assumed to be directly proportional to the concentration of styrene in arterial blood, the constant of proportionality being approximately 0.02. In short, the exact relation between C_m and C_i depends on the properties of the chemical and the exposure history both prior to and during the time when the mask is in place. In the Results section the probable influence of prior exposure in the present study will be addressed by assessing the differences in penetration as a function of measurement period, i.e., whether measurements began at the beginning of the shift, after lunch, or after the break.

As indicated previously, the authors' focus was on the variability of the penetration that is caused by fit rather than cartridge breakthrough. Also the principal area of interest was in the partitioning of this variability between factors that appear to influence the fit of all workers in common versus those associated with the fit on individual workers. Hence, an analysis of variance model as discussed by Nicas[8] and similar to that used previously to partition the variability in benzene exposures between personal and common environmental factors was utilized.[16]

This model is shown in Figure 1, in which the distributions in the middle of the figure represent the distributions of the penetration values experienced by individual workers upon repeated wearings of the same properly fitted respirator. The distributions are depicted by their statistical frequency functions. It is assumed that each worker's distribution has a different mean value, but that the variance is the same. The distribution at the bottom of the figure represents the variability in mean penetration across the population of wearers. The distribution at the top is that of the penetration value experienced by a randomly selected worker on a random wearing of the respirator. The relation between these three frequency functions is given by the expression:

$$h(\mathbf{p}) = \int_0^1 f(\mathbf{p}|\mu)\, g(\mu) d\mu \qquad (1)$$

where, working from the bottom to the top of Figure 1, $g(\mu)$ is the distribution of individual means, $f(\mathbf{p}|\mu)$ is the distribution of an individual's penetration values given his or her mean, and $h(\mathbf{p})$ is the total distribution, or the distribution of penetration values experienced by randomly selected workers during random periods of respirator use.

Table I shows the parameters of these distributions when f, g, and, consequently, h are assumed to be lognormal. As usual

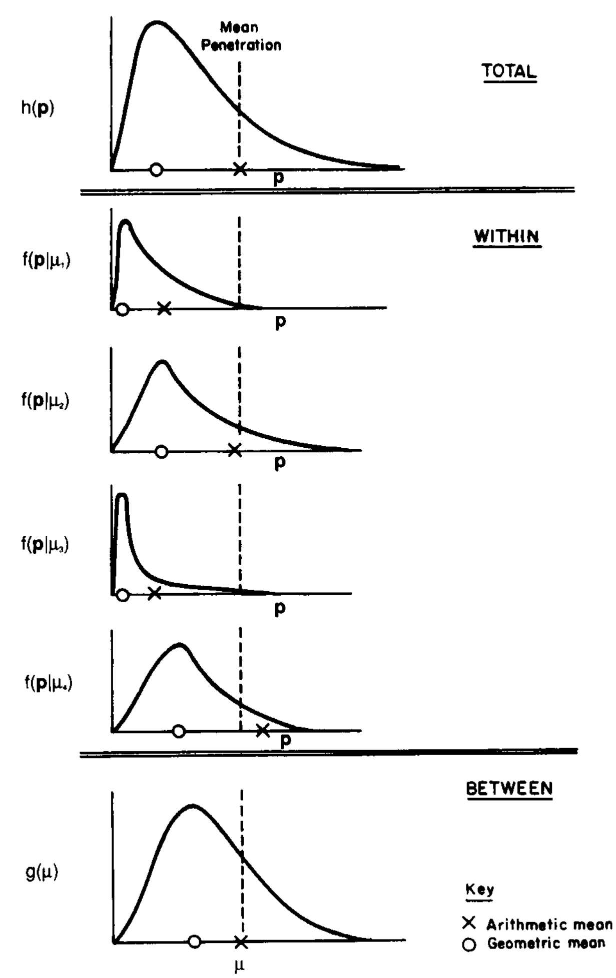

*FIGURE 1. Frequency functions comprising a lognormal model for respirator penetration, **p**, or mean penetration, μ*

with lognormal distributions, there are several sets of equivalent parameters that are used interchangeably. Specification of the full model, i.e., all three distributions, requires estimates of three of these parameters, most commonly the within and between variances of the logarithms of the **p** values, σ_b^2 and σ_w^2, and the mean value, μ_t, of the logarithms of the **p** values arising from the total distribution, h(**p**). The "within" and "between" nomenclature, common to analysis of variance applications, refers to variability in **p** for a particular individual from wearing to wearing and the variability associated with differences amongst individuals, respectively. As indicated in Table I, the total variance is the sum of these two components, $\sigma_t^2 = \sigma_b^2 + \sigma_w^2$.

TABLE I. Parameters of the Lognormal Distribution

Parameter	*f(p|μ)*	*g(μ)*	*h(p)*
Mean of the logarithms of **p**	—	μ_b	μ_t
Geometric means	—	$GM_b = e^{\mu_b}$	$GM_t = e^{\mu_t}$
Variance of logarithms of **p**	σ_w^2	σ_b^2	$\sigma_t^2 = \sigma_b^2 + \sigma_w^2$
Geometric standard deviation	$GSD_w = e^{\sigma_w}$	$GSD_b = e^{\sigma_b}$	$GSD_t = e^{\sqrt{\sigma_b^2 + \sigma_w^2}}$

If there were no differences in the distribution of **p** values between individuals, $\sigma_b = 0$, $g(\mu) = c$, and the distribution f(**p**\|c) would describe the variability of **p** values on repeated wearings of the respirator for everyone. The opposite extreme is that everyone has a different, but invariant, value of **p** in which case $f(\mathbf{p}|\mu_i) = \mu_i$ and $h(\mathbf{p}) = g(\mu)$. In practice, both sources of variability are expected to be found, which produces a situation in which variation in **p** is caused by both differences amongst individuals and by differences common to all wearers.

Another source of variability is that contributed by the procedures for sample collection and analysis. This issue was investigated only in the context of desorption efficiency, and this factor did not contribute substantially to the overall variance. However, the issue of collection efficiency in the high humidity environment inside the mask may be of particular concern for compounds other than styrene. In general, these effects are likely to appear as components of the within variability and increase it above that associated with fit factors alone. Although there is no evidence that factors unrelated to fit influence the within variance appreciably, it should be kept in mind that they do make a contribution to the overall variability of the data. Similarly, the between variance is susceptible to contributions from factors unrelated to fit and difficult to quantify, for example, personal differences in the retention or metabolism of styrene.

RESULTS

Before reporting the results, it is necessary to consider the potential effect of prior exposure and pulmonary retention of styrene on the relation between the average concentration measured inside the mask and the average concentration during inhalation, the latter being the more appropriate theoretical measure of leakage into the respirator. To explore the implications of these issues on the forgoing results, the model of styrene absorption and distribution developed by Ramsey and Andersen[15] was used. It was found that, if there was no pre-existing body burden of styrene, then for the first hour that a worker was exposed to a mean concentration C_i inside the mask during inhalation, the measured concentration would be $C_m = 0.69\ C_i$. That is, if C_m is used to calculate **p**, the penetration would be underestimated by about 30%. This result pertains to those cases in the field study where the measurement of C_m was made during the hour following the beginning of the shift.

Assuming that an individual had been working for several hours in the same environment using a charcoal-impregnated dust-mist disposable respirator, as was the practice in this workplace, the highest body burden at the beginning of a WPF measurement period for the half-mask respirators would have occurred just following the break (15 min in the break area, a low-styrene environment). The body burdens of styrene just after lunch (30 min) would be expected to be greater than at the beginning of the shift, but less than after the break. Because the authors were not equipped to measure these levels directly, the penetration data were subjected to an unbalanced, two-way analysis of variance (individual values versus exposure interval) to ascertain if there was any discernable effect on the estimates of penetration that could be attributed to exposure before the measurement period. The resulting F value was 0.171 with (2,30) degrees of freedom, which yields a corresponding probability of 0.84 of observing this value under the null hypothesis that no difference exists in penetration values that can be associated with the measurement period. The authors concluded that there was no evidence of styrene in the exhaled breath because of prior exposure that was sufficient to affect the penetration estimates. Presumably, this was caused by the rapid decrease of styrene in expired air after the cessation of exposure and/or the protection offered by the charcoal-impregnated dust-mist respirators. Hence, all measured values inside the respirator, C_i, were multiplied by 1.4 to correct for pulmonary retention only, as discussed in the previous paragraph, and these corrected values were used in all subsequent calculations.

Three to six penetration values were determined for each of the 13 study participants. Table II shows the penetration values and the inside and outside concentration values from which they were derived. The penetration data are also displayed as a histogram in Figure 2, together with the h(**p**) and g(μ) distributions estimated from the data, as discussed below. The ordinate of this figure pertains to the histogram with the frequency functions scaled to have approximately the same integrated area at each value of **p** or μ. Clearly, the histogram is right-skewed, which is consistent with the lognormal assumption, but the number of observations are not sufficient to allow a more rigorous goodness-of-fit test of the lognormal assumption.

One might be inclined to consider two of the data points shown in Figure 2 to be outliers warranting removal from the data set. These points correspond to data from Worker 9, Sample 1, with $C_i = 3.53$, $C_o = 11.90$, and $\mathbf{p} = 0.2965$ and Worker 13, Sample 3, with $C_i = 215.17$, $C_o = 597.45$, and $\mathbf{p} = 0.3601$. Both of these penetration values are larger than the remainder of the data set by approximately a factor of ten. Though it is possible that these results are a result of sampling or analytical irregularities, a critical review of all sampling and analytical procedures revealed no anomalies that would justify removal of these points from the data set.

Because sprayers and nonsprayers carried out a different range of body movements during work, there was reason to expect that the penetration values might be different for the two groups. To investigate this issue a nested analysis of variance was used. The null hypothesis is that there was no difference in penetration values between the two groups. There were six sprayers and seven nonsprayers with 28 and 35 observations of **p**, respectively. The geometric mean for the sprayer group was 0.015, as contrasted with 0.011 for the nonsprayers. The F statistic resulting from the analysis of variance was 0.705, with a corresponding probability of observing this value under the null hypothesis of 0.576. This result indicates no evidence of a significant difference in the measured values of penetration between sprayers and nonsprayers.

Having found no difference in the penetration data caused by job classification, the data for the sprayers and nonsprayers were treated as equivalent and combined in carrying out the parameter estimation for the full model. This resulted in a GSD_t estimate of 3.51, with $GSD_b = 1.92$, and $GSD_w = 2.93$. Based on the variances of the logarithms, 73% of the variability in fit was common to the entire group, that is caused by differences in fit on different wearings as contrasted with consistent differences in fit between individuals. This does not imply, however, that differences in fit between individuals were small, as evidenced by the GSD_b value of 1.91.

TABLE II. C_i (mg/m^3)/C_o (mg/m^3) = Penetration for 13 Workers[A]

			Sample Number					
Worker	*Job*		*1*	*2*	*3*	*4*	*5*	*6*
1	Nonsprayer	C_o	324.95	265.35	281.39	251.10	210.91	
		C_i	1.22	1.79	1.72	2.28	2.52	
		p	0.0037	0.0068	0.0061	0.0091	0.0119	
2	Nonsprayer	C_o	350.43	223.20	192.79	285.57	243.27	238.31
		C_i	1.69	1.57	8.12	1.36	1.48	2.09
		p	0.0048	0.0070	0.0421	0.0048	0.0061	0.0088
3	Nonsprayer	C_o	311.14	195.11	187.39	527.27		
		C_i	2.28	1.51	1.54	2.28		
		p	0.0073	0.0077	0.0082	0.0043		
4	Nonsprayer	C_o	253.78	488.56	382.64	475.26	666.87	
		C_i	3.15	49.32	0.39	4.03	7.39	
		p	0.0124	0.1010	0.0010	0.0085	0.0111	
5	Nonsprayer	C_o	224.87	499.89	470.68	562.56	255.83	
		C_i	2.45	22.86	40.38	84.25	7.94	
		p	0.0109	0.0457	0.0858	0.1498	0.0310	
6	Nonsprayer	C_o	281.30	550.56	368.53	535.57	545.12	
		C_i	5.05	1.19	2.32	11.59	3.30	
		p	0.0180	0.0022	0.0063	0.0216	0.0061	
7	Nonsprayer	C_o	189.92	242.41	330.49	366.99	327.96	
		C_i	2.11	1.11	1.89	17.44	8.43	
		p	0.0111	0.0046	0.0057	0.0475	0.0257	
8	Sprayer	C_o	456.25	569.29	689.86			
		C_i	0.80	11.27	4.77			
		p	0.0017	0.0198	0.0069			
9	Sprayer	C_o	11.90	456.55	761.78	611.27	650.39	
		C_i	3.53	23.21	4.27	1.43	14.94	
		p	0.2965	0.0508	0.0056	0.0023	0.0230	
10	Sprayer	C_o	640.15	436.12	204.48	585.44	585.98	
		C_i	16.09	3.04	1.20	13.19	16.98	
		p	0.0251	0.0070	0.0059	0.0225	0.0290	
11	Sprayer	C_o	453.57	392.06	360.01	672.16	450.33	
		C_i	2.60	2.17	4.79	3.70	2.34	
		p	0.0057	0.0055	0.0133	0.0055	0.0052	
12	Sprayer	C_o	497.27	502.62	560.17	680.94	568.44	
		C_i	3.51	14.94	10.72	39.48	9.31	
		p	0.0071	0.0298	0.0191	0.0580	0.0164	
13	Sprayer	C_o	389.89	437.73	597.45	631.65	556.29	
		C_i	6.57	10.60	215.17	4.86	12.73	
		p	0.0168	0.0242	0.3601	0.0077	0.0229	

[A]Note: C_i values corrected for pulmonary retention as discussed in text.

Also shown in Figure 2 are h(**p**) and g(μ) for the parameter estimates given above. The geometric mean of the between distribution was estimated to be 0.0226. This is the median value of g(μ), which implies that half of a population of wearers would have a mean penetration in excess of that value and half below. Because of the reciprocal relation between **p** and WPF and the properties of the median, this means that about one-half of wearers will have a long-term average WPF in excess of 44 and one-half below that value. The geometric mean of the total distribution, h(**p**), is estimated to be 0.0127 (WPF = 79). Again, this is the median penetration value (or WPF) of the distribution of values that pertain to a randomly selected worker on a randomly selected wearing period. These results suggest, as one would expect, that these respirators are more protective against styrene than the disposable respirators assessed by Cohen[5] in protecting against mercury vapor.

DISCUSSION

Because $C_i = \mathbf{p} * C_o$ and the statistical structure of **p** is now postulated for this particular exposure situation, it is possible to address the issue of maximum use concentrations, that is, the environmental concentration values, C_o, for which the inside concentration, C_i, remains within acceptable limits. Although the authors are not formally proposing the following criteria, the use of the model can be illustrated by supposing that acceptability is defined in terms of:

1. constraining C_i to be below the American Conference of Governmental Industrial Hygienists (ACGIH) STEL for styrene on 95% of wearing periods for a population of respirator wearers.
2. constraining the long-term average C_i to be below the ACGIH 8-hr TLV® for styrene for 99% of a population of wearers.

Assuming that the 1-hr penetration distributions are valid for both the 15-min and the 8-hr periods, it is then possible to calculate the limiting value of C_o that would constrain the 1-hr C_i values to meet the foregoing criteria. For a lognormally distributed variable, the value x' exceeded by 100α percent of the distribution is given by:

$$x' = GM(GSD)^{z'} \quad (2)$$

where z' is the $(1 - \alpha)$ percentile of the standard normal distribution. Utilizing this relation in the case of the STEL criterion, the relevant distribution is h(**p**) because it pertains to a randomly selected worker during a randomly selected wearing period. The STEL is 100 ppm, which leads to the following calculation:

$$\mathbf{p}_{95} = (0.0127)(3.51)^{1.645} = 0.100 \quad (3)$$

where 0.0127 and 3.51 are the GM and GSD of h(**p**). It follows that

$$C_o = 100\ \text{ppm}/0.100 = 1000\ \text{ppm} \quad (4)$$

that is, if C_o is constant at a value of 1000 ppm, then the TWA inside concentration C_i will be less than 100 ppm on 95% of 15-min wearing periods for the exposed population. This does not mean, however, that each individual will experience the same protection, because the calculation is based on h(**p**), which does not take account of individual differences. The situation becomes more complex if one wishes to determine the distribution of C_i in circumstances in which C_o is not constant, but is itself a statistical variable describing the exposure of a population of wearers.

The same calculation is required to meet the second criterion, but in this case the appropriate distribution is $g(\mu)$ because this concerns the mean penetration value experienced by the worker population. The TLV is 50 ppm, which leads to:

$$\mathbf{p}_{99} = (0.0226)(1.91)^{2.326} = 0.102 \quad (5)$$

where 0.0226 and 1.91 are now the GM and GSD of $g(\mu)$. Then:

$$C_o = 50\ \text{ppm}/0.102 = 488\ \text{ppm} \quad (6)$$

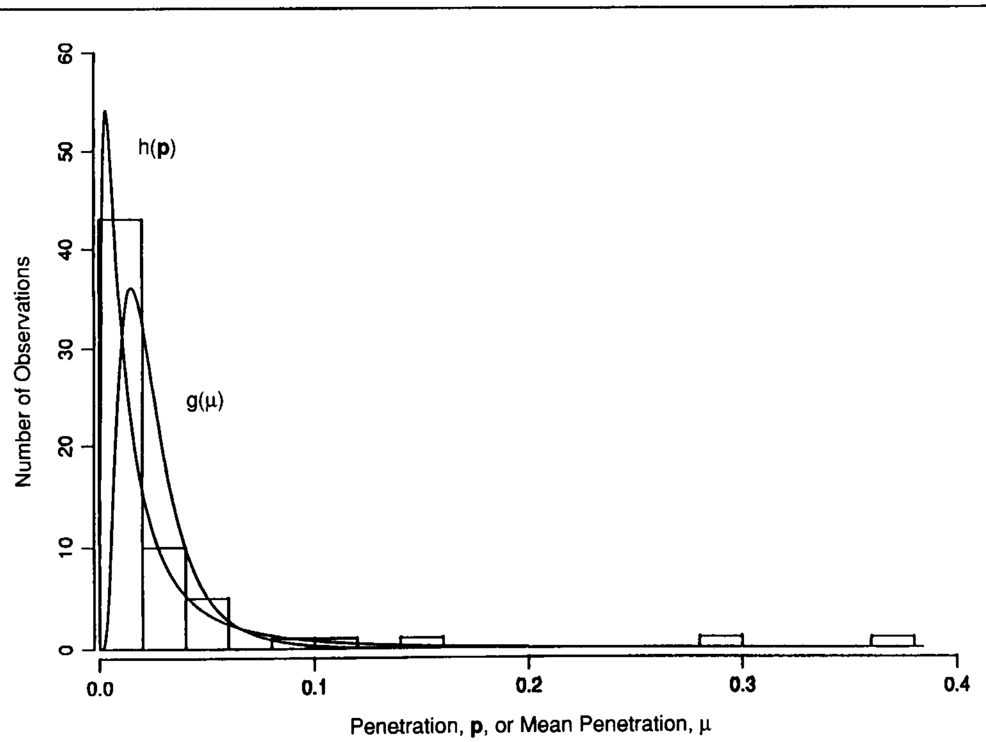

*FIGURE 2. Histogram of observed penetration values and the frequency functions h(**p**) and g(μ) estimated from these data*

Clearly, if C_o is constrained to be below 488 ppm, both criteria are satisfied. If these criteria were to be used to rigorously define an assigned protection factor, it can be seen that the value that would emerge is roughly ten, which is consistent with current practice for the respirators used in this study. The major point, however, is that, whatever particular criteria of acceptability are adopted, the results of this study indicate that differences between individuals, as well as between different wearings, must be taken into consideration in setting maximum use concentrations. It is worth repeating, for example, that even though Criterion 1 is met on 95% of wearings, it may well be that a few individuals will experience the majority of the 5% of fit-related overexposure events.

In carrying out this study, several technical problems arose that will need special attention in the future. The issue of collection and desorption efficiencies of gases and vapors on sampling media in the low concentration–high humidity environment inside the facepiece, although manageable in the case of styrene, is likely to be a more troublesome problem in general. Also, the effect of prior exposure and pulmonary retention requires serious study if reliable WPF values are to be determined from field data. From experience, measurements of expired air concentrations on each individual at the beginning and the end of the measurement period are believed to be the most direct means of obtaining valid field data. Although dermal exposure to styrene was not believed to have affected these results, because of its irritating properties to the skin and the consequent care of workers in avoiding such exposure, it is an issue that must be considered and can be a significant problem for other chemicals.

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