

Measurements of Workplace Protection Factors of Six Negative Pressure Half-Masks

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Abstract

Workplace protection factors (WPFs) for six negative pressure half mask respirators (two disposable filtering facepieces and four half-masks fitted with filters) were determined in four metallurgy factories. These WPFs were determined by the simultaneous measurement of the concentrations inside and outside the respirators. Thirty workers tested successively each of the respirators (for a total of 180 tests). Each test lasted one hour. Simultaneously an estimate of the **workers'** metabolic rate was determined. At the end of each set of measurements of the WPF, a subjective questionnaire on comfort was filled out by the workers. No significant difference was pointed out between the WPFs of the different masks tested although they had been selected in order to be representative of the different products available on the market. Linear relationships were found between the log transformed data of the concentration inside the masks and both the log transformed data of the outside concentration and answers to the questionnaire. No linear relationship was evidenced taking in account the workers' metabolic rate or face dimensions. This kind of correlation analysis was performed for each mask and each experimental site. After a classification of the outside concentrations into five classes according to their values, the corresponding WPFs were found to be higher for the dustiest atmospheres.

Introduction

In the field of respiratory protection, the French occupational risk prevention policy has generally preferred the use of collective means such as ventilation processes rather than the wearing of individual respiratory protection devices. In most firms the custom is that a respirator must be worn only during limited periods, which

correspond to well defined tasks where pollutants are produced in a manner which precludes the use of collective means of protection (that tacit rule obviously does not apply to special working conditions such as inert or dangerous gaseous atmospheres).

In studies of individual respiratory protection, emphasis is put on research and development of standardization methods, and on the assessment of the efficiency of respirators in laboratory rather than in the field.

Yet in the past years, our laboratory was asked to assess the efficiency of a negative pressure respirator used in a pigment factory since it seemed that the in-situ efficiency was well below that obtained from tests using the laboratory standard method (Hery et al., 1991). The results of that first measurement campaign encouraged the authors of this current study to repeat it on a more ambitious scale in order to study what type of efficiency could be expected in current industrial working conditions. The results of this larger study are presented here.

Numerous studies have been devoted to determining the efficiency of respirators in the laboratory. Many parameters have been examined in order to determine the set of tests to use in order to evaluate "fit factors."

Oestenstad et al. (1990a, 1990b) developed and applied a technique using fluorescent tracers for the identification of face seal leak sites on half-mask respirators worn either by a mannequin or human subjects. Their work demonstrated the role played by certain parameters, such as facial dimensions, in the development of leaks.

Brueck et al. (1992) investigated the lack of respirator integrity in the exhalation valves, which constitute a possible pathway for airborne contaminants. They showed in particular that cleaning of exhalation valves significantly reduced the risk of leak formation.

The influence of particle size was studied by several authors. Holton et al. (1987) studied the influence of parameters such as sampling probe location and the shape of the leak holes. Myers et al. (1988), in a paper devoted to sampling biases in half-facepiece respirators, confirmed previous results which demonstrated the influence of probe location, probe depth, leak sites, breathing patterns and facepiece designs. More recently Myers et al. (1991) investigated the influence of leak size, particle size, physical state (gaseous or particulate) of the test material, and tidal volume on the face seal leakage.

These kinds of rather fundamental studies were used for the elaboration of practical methods for the assessment of the efficiency of respirators. For example, Holton and Willeke (1987) inferred from the work described by Holton et al. (1987) that the particle size distribution has a quantitative influence on fit tests performed in order to assess the efficiency of respiratory devices. Other fundamental results were put into practice by Hinds and Bellin (1988) who developed a model which predicts the actual penetration inside a given respirator based on fit testing measurements, aerosol size distribution, and the work rate.

However, the assessment of respirator efficiency in the workplace has not been described at great length in the open literature, where most studies seem to be devoted to powered-air purifying respirators. Myers and Peach (1983) conducted laboratory and field (during silica bagging operations) evaluations of three types of respiratory equipment. The protection factors measured in the field were well below the expected value of the protection factors measured in laboratory tests. A similar study was performed at a lead smelter by Myers et al. (1984) and resulted in the same conclusions. Lenhart and Campbell (1984) compared the efficiency for two types of half-masks: one negative pressure and one powered-air purifying respirator. They concluded that protection factors (APFs) of 10 and 50 were appropriate for the negative pressure respirator and the powered-air purifying respirator, respectively.

Reed et al. (1987) conducted a similar study by measuring the workplace protection factors of a disposable negative pressure half-mask. They confirmed the main result recorded in the previous studies (Myers and Peach, 1983; Myers et al., 1984; Lenhart and Campbell, 1984): the protection provided by respirators in actual working conditions is well below the protection expected on the basis of laboratory experiments.

In addition to the previously cited studies, the American Industrial Hygiene Association's Respirator Technical Committee (1985), proposed a standardized terminology for use in this field. We adopted their terminology in this paper. It must be pointed out that the use of the Working Protection Factor (WPF) term is somewhat inappropriate because the French habits do not include the use of fitting tests.

Objectives

The aim of the study was to simultaneously determine:

- The workplace protection factors (WPF) for six negative pressure **half-mask** respirators (disposable and reusable type) worn by workers performing various tasks in **different** factories.
- An estimate of the workers' metabolic rate while wearing the mask. This estimation

was performed by observing task- and head-motions (Meyer et al., 1991).

At the end of each experimental measurement of the WPF, workers were asked to complete a questionnaire in order to assess the comfort of the mask they had just worn.

Experimental Methods

Principles

In order to determine the WPF, simultaneous measurements of potential exposure (outside the mask) and actual exposure (inside the mask) had to be taken.

Outside sampling was accomplished using the well-known technique of clipping a cassette to the collar of the work clothes near the breathing zone. This cassette was connected by silicone rubber tubing to an air sampling pump operating at a flow rate of 1 L/min in order to collect the inhalable fraction of the airborne **particulate** matter. The cassette was in closed-face configuration with a 4.1 mm diameter inlet.

Inside sampling was done by means of an inlet sampling probe inserted through the mask at a location situated between the nose and the mouth. A second cassette was connected directly to this probe, without any intermediate tubing in order to avoid problems associated with the settling of sampled dust. The cassette was in turn connected to a second pump, also operating at 1 L/min. The design of the probe and its fixing through the respirator is shown in Figure 1.

The **mask/probe** and probe/cassette junctions were examined in the laboratory to ensure that there were no potential leaks. The influence of the weight of the cassette on faceseal leakage was also studied by comparing results obtained from laboratory tests on both human subjects and on a mannequin wearing masks with and without cassette. It was found that the weight of the cassette (about 20 g) was low enough that it did not induce leakage. The volume of the cassette is

small enough that it does not reduce the **wearer's** field of vision any more than occurs when wearing a mask without a cassette.

All this checking cannot protect from incidents likely to occur under actual working conditions, such as the sampling tubing getting caught and pulling on the respirator; the guarantee against these incidents was provided by a constant observation of the workers during the experiments.

Sampling inside the mask takes place in a water-saturated atmosphere. As a consequence, a significant quantity of water condenses on the filter. It was necessary to account for this in two ways:

- The pump must be able to handle the increased pressure drop across the filter without any change in the decrease flow rate. In order to avoid any excessive increase of this pressure drop, sampling duration was limited to approximately one hour. As a check on the constancy of the pump, flow rates were measured at the beginning and at the end of each test. Pre- and post-calibration were performed with the filter used in each test in line (e.g., with the wet filter for the post calibration). Owing to the limited duration of each test, no significant change of the flow was observed, in spite of the water sampled.
- The moisture might dissolve a fraction of the sampled dust, thereby lowering the quantity of pollutants measured inside the mask. In order to avoid this problem, only worksites with environments containing pollutants insoluble in water (e.g., inorganic pigments or metals) were chosen.

- Two disposable FFP2 filtering half masks (#1 and #2).
- Three half masks provided with P2 filters (#3 to #5).
- One half mask provided with P3 filters (#6).

The specifications of these respirators are shown in Table 1. All of these devices have been tested in the latest exhaustive assessment campaign performed in the INRS (Institut National de Recherche et de Sécurité, 1987). During that campaign, most negative pressure respirators available on the French market were tested for approval by a specialized laboratory of the INRS.

A brief summary of the main specifications of these kinds of respirators (filtering half masks and P2 and P3 filters) according to the French standards (AFNOR, 1983a; AFNOR, 1983b; AFNOR, 1983c) is given in Table 2. The Total Inward Leakage (TIL) is reckoned from the concentration measured simultaneously inside (Cins) and outside (Cout) the respirator: $TIL = Cins / Cout$. The TIL is the inverse of the Protection Factor (often called

Nominal Protection Factor—NPF—when determined according to laboratory standards). Each TIL value given in Table 1 is the mean of the measurements of Cins/Cout, performed during the wearing of the mask by ten subjects in the laboratory according to the French standard (AFNOR, 1983a). Since European standards have undergone alterations since that time, the classification of those devices might be somewhat different according to the new standards. These specific materials were chosen in order to be able to compare devices of appreciably different performance levels. All devices tested were consistent with the new European standards.

Choice of Experimental Sites and Subjects

A preliminary group of a dozen factories where respiratory protective devices are commonly used was selected. A study of potential exposure levels was made in each of these factories in order to check whether the actual conditions met with the experimental requirements needed: the workers

Table 1. Characteristics of the six masks tested during the study.

Mask	Characteristics	Total Inward Leakage	Nominal Protection Factor	Remarks
# 1	Disposable FFP2	2.7 %	37	Expiratory valve
# 2	Disposable FFP2	5.0 %	20	
# 3	Half - mask fitted with P2 filter	0.8 %	125	
# 4	Half - mask fitted with P2 filter	5.9 %	17	
# 5	Half - mask fitted with P2 filters	7.8 %	13	Two filters
# 6	Half - mask fitted with P3 filter	0.5 %	200	

Table 2. Specifications of the respirators tested in the study according to the French standards.

	Permeability (to NaCl at a flow-rate of 95 L/min)	Clogging to dolomite (400 mg/m ³) (at a flow-rate of 95 L/min)	Breathing resistance (at a flow-rate of 95 L/min)	Breathing resistance (at a flow-rate of 30 L/min)	Total Inward Leakage (test with NaCl)
Filtering facepieces Type 2	6%	5mb	2.4mb	0.7mb	10%
Half-masks fitted with P2 filters)	6%	5mb	2.4mb	0.7mb	10%
Half-masks fitted with P3 filter(s)	0.05%	This test is not performed	4.2mb	1.2mb	0.5%

had to be exposed to insoluble pollutants, of which the chemical analysis was easy to perform with a good sensitivity. The working conditions in these factories had to allow us a good development of the experimentation with a minor risk of incident such as the tubing getting caught and pulling on the respirator. All these requirements were checked by the means of a preliminary measurement campaign of the exposure performed in the dozen factories selected. The potential subjects were simultaneously informed of the aim of the measurements and were requested to take part in the assessment of mask efficiency. Four factories were found to be suitable for the development of the actual study.

From this first campaign of measurements, a group of 30 workers (25 men and 5 women, all of the women being employed in factory B) from those four factories was selected for the actual study:

- 6 (#1 to #6) in factory A (pigment manufacture).
- 7 (#7 to #13) in factory B (lead-acid battery plant).
- 7 (#14 to #20) in factory C (fire-proof additive manufacture).
- 10 (#21 to #30) in factory D (lead smelter).

The 30 workers were volunteers. They had been previously informed about the method used in the study and the requirements the enquiry

would involve for them. They had been informed, too, of the presence of an INRS agent for each test whose role was to avoid any technical problem and to make sure that the respirator was properly worn.

The men were asked to take particular care in shaving (nobody had a beard or moustache), and all subjects were given a brief reminding training on the fitting and use of the respirators. That training insisted especially on the detection of the lack of tightness to the face and the necessity of a good application of the respirator on the face. The INRS agent helped each worker during the fitting of the respirator and the sampling equipment before the beginning of the test; good setting of the respirator could thus be checked. No fit testing involving saccharin or irritant smoke was performed; these methods are not used in France, mainly, as we set out in our introduction text, because of the particular status of the personal respiratory protection in France, which is considered makeshift and is refused by all major trade-unions which on principle only accept collective protective equipment.

Facial dimensions of the workers were measured including:

- Bitragion-subnasale arc.
- Bizygomatic breadth.
- Lip width.

Development of the Test

Each subject was requested to wear successively each of the masks for one hour, in order to determine the WPF of each device. Of the 180 tests executed (30 subjects x 6 masks), four were rejected because of analytical mishaps. The INRS team was present for three days in each factory, i.e., each worker performed two tests per day in order to reach the total of six masks at the end of the measurement campaign. The workers were assigned each mask in random order.

The workers were constantly observed all along each test by a member of the INRS team in order to ensure that the mask was properly worn throughout the testing, and to avoid incidents such as the accidental disconnection of the tubing, etc. With the obvious exception of the tightness of the mask, the INRS observer could modify the configuration of the experimental device when requested by the worker.

A physiologist estimated the metabolic rate of each worker by observing him for one or two ten minute periods during each test. Consequently the total number of estimation of metabolic values is 180.

At the end of each test, the workers were asked to complete a brief questionnaire which included the following questions:

- a: Would you estimate the comfort of the respirator you just wore? (1: very comfortable → 10: very uncomfortable)
- b: Did you **suffer** from vision constraint? (1: none → 6: unbearable)
- c: Did you suffer from breathing constraint? (1: none → 6: unbearable);
- d: Was that respirator easy to put on? (1: very easy → 6: very difficult)
- e: Was that respirator easy to keep in place? (1: very easy → 6: very difficult)
- f: How long do you think you could wear this respirator easily if you had to? (h min)
- g: At which level do you estimate the efficiency of the protection provided? (1: not efficient at all → 10: very efficient)
- h: Considering the respirator globally, how would you characterize it? (0: unbearable → 10: a success)

Intermediate qualifying adjectives were proposed to the workers in order to help them to place their estimation between the ends of the scale.

Particle Size Distribution Measurements

Area samples were collected using **Marple** cascade impactors at a flow-rate of 2 L/min in conformity with the **designer's** specifications (Rubow et al., 1987).

Material

WPF Estimation

- Dust was collected on quartz fiber filters (Whatman QMA 1851037) contained in 37 mm diameter cassettes (Millipore M000037AO).
- Sampling pumps were Gilian HFS 113. They were calibrated by means of a **Gilibrator** with the filter used in the test in line.
- Metals were analyzed by atomic absorption spectroscopy (flame or graphite furnace), or by direct current or inductively coupled plasma spectroscopy after dissolving sampled dust in inorganic acids (generally a mixture of hydrogen fluoride and nitric acid). The analytical method was chosen as a function of the quantity of dust collected on the filters; most inside samples

were analysed by graphite furnace atomic absorption. The analytical methods used were those indicated in a French standard (AFNOR, 1992) or were directly inspired by it when they did not exist.

It should be noted that the filters were not extracted from the cassette before dissolving, but that acids were introduced directly into that cassette. This technique is used in order to avoid the loss of dust which may have settled on the inner walls (Demange et al., 1990). All analytical results were blank corrected from the reagent pollution.

Moreover, blank filters were prepared simultaneously to the filters used in the tests, brought in the test atmosphere, but not sampled. They were

analyzed the same way as were the filters sampled during the tests. The results obtained confirmed that the content of pollutants of these blank filters corresponded with the pollution brought by the reagents (which was very low).

Particle Size Distribution Measurement

Marple cascade impactors (298 Sierra Instruments) with Mylar substrates, coated with silicone grease (Dow Corning 316 silicone release spray) were used. Analytical techniques were the same as those used for the sampling filters.

Results

The sampling data collected in the course of this study (inside and outside the respirators, and the corresponding WPFs) are shown in the appendix at the end of this paper.

Influence of the Sampling Methods

Any possible bias due to the **difference** between the sampling velocities inside and outside the mask was assessed. The results, shown in Table 3, demonstrate that there appears to be no significant difference between the different values. For more than 90% of the pairs, the difference between the results is less than 10%. No tests were performed in factory A.

Testing of Data Collected

In general, it is well-known that most occupational hygiene measurements series follow a

lognormal distribution function, provided that the measurements are homogeneous. Since the thirty measurements performed on each of the masks were carried out in four different factories, it was important to examine the experimental data series (outside and inside concentrations for each mask) in order to determine what type of distribution function was observed. As expected the log transformed data were better approximated by a normal distribution than were the raw data. Therefore the logarithmically transformed data were used in the statistical analysis. An example of the normal probability plot of outside concentrations in which mask 1 was tested is given in Figure 2.

The same tests were also performed on the questionnaire data: the best approximation was provided by the normal distribution.

Table 3. Comparison of the sampling efficiency of the inlets used inside and outside the masks.

Factory	Sample size	Range of x	Mean Value of x	95 % Confidence Limit of x	Number of x values < 0,90 or > 1,10
B	8	0.97 - 1.05	1.01	0.98 - 1.04	0
C	9	0.94 - 1.07	1.01	0.97 - 1.05	0
D	14	0.91 - 1.46	1.03	0.90 - 1.16	2 (1.11 - 1.46)

$$\times = \frac{\text{Concentration of sample taken in the cassette fitted with the 2 mm inlet}}{\text{Concentration of sample taken in the cassette in closed face configuration}}$$

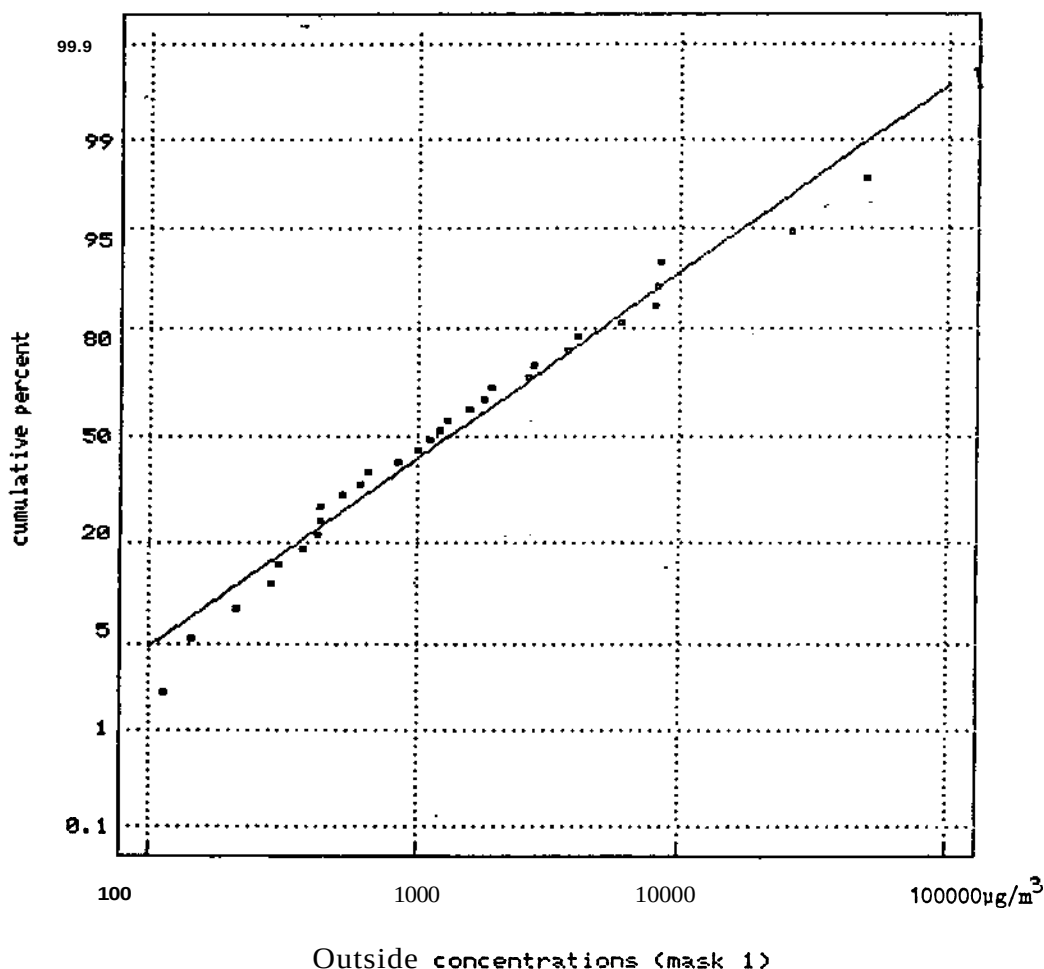


Figure 2. Normal probability plot of log-transformed outside concentration data (mask #4).

Comparison of Mask Efficiency

In order to assess the validity of the comparison of the efficiency of the six masks tested during the study, the series of outside concentrations data for each mask had to be compared for each pair of masks (mask 1 vs mask 2, mask 1 vs mask 3, etc.). Fifteen two-sample analyses (variances) were made, and in no case were the variances found to be statistically different. Comparison is then justified.

WPFs were estimated based on a comparison of outside and inside concentrations. For the six masks, the best approximation of normal distribution was achieved from the log transformed data. Fifteen two-sample analyses showed that there was no significant difference between the WPFs of the six masks.

Range of WPFs, their geometric mean, geometric standard deviation, two-sided 95% confidence interval limits about the mean and the 5th percentile are shown in Table 4. Because of deviation from normality at the extremes of the distribution, this 5th percentile was not calculated from the geometric mean and the geometric standard deviation, but using the software **Statgraphics**.

Mask Efficiency: Linear Regression Analysis

In this part an attempt was made to determine the main parameters having an influence on the efficiency of the respirators. In other words, the purpose of this treatment was to point out the parameters which influenced the value of the concentration of pollutant sampled inside the respirators.

Table 4. Workplace Protection Factors of the six masks tested.

Mask	Sample size	Workplace Protection Factors				
		Range	Geometric Mean	95 % Confidence Limit on Mean	Geometric Standard Deviation	5th percentile
# 1	30	2 - 490	11	5- 13	3.9	1.7
#2	29	2 - 90	9	6 - 14	3.2	1.9
#3	29	2 - 700	13	8 - 21	3.3	2.3
#4	29	2 - 115	8	5-13	3.2	1.8
#5	30	2 - 65	12	7 - 19	3.7	1.7
#6	29	2 - 30	13	8 - 21	3.6	2.4

For each mask, dust concentration inside the mask was evaluated as a function of dust concentration measured outside. Linear relationships ($P < 0.05$) were found between the log transformed data with correlation coefficients (r^2) for the regressions ranging from 0.18 to 0.41.

The influence of other parameters such as the workers' metabolic rate, facial dimensions and answers to the questionnaires was also studied. ANOVA results showed a correlation between some of these factors and inside concentration variations. The correlation coefficients were significantly improved by the interaction of some of these factors. A summary of the main influences of these factors and the corresponding correlation coefficients are given in Table 5 (with all parameters at $P < 0.05$).

As the WPFs of the different masks do not differ significantly, it is justified to consider that some data collected in a factory (e.g., all outside concentration measurements for the six masks in factory B), can be considered as forming a homogeneous family. From this point of view, the statistical treatment which has been performed before taking each mask as a reference can also be performed taking each factory as a reference. Again, the log transformed data (inside or outside concentrations) best approximates a normal distribution.

Consequently, dust concentration inside the mask was evaluated once more as a function of dust concentration measured outside, not for each mask this time, but for the series of data constituted from all of the results collected in each

Table 5. Correlation analysis between inside concentration and other parameters collected during the workplace protection factor determinations (Reference: mask).

Mask	First Coefficient of Correlation (r^2) (Independent Variable : log Outside Concentration)	Second Coefficient of Correlation (r^2)	Independent Variables : log Outside Concentration and answers to questions
#1	0.18	0.25	c
#2	0.41	0.51	c, f
#3	0.27	0.38	f, h
#4	0.20	0.23	f
#5	0.32	0.32	-----
#6	0.26	0.45	a, c.

a : would you estimate the comfort of the respirator you just wore (1 : very comfortable $\Rightarrow$ 10 : very uncomfortable)

c : did you suffer from breathing constraint ? (1 : none $\Rightarrow$ 6 : unbearable)

f : how long do you think you could wear this respirator if you had to? (x h y min)

h : at which level do you estimate the efficiency of the protection provided? (1 : not efficient at all $\Rightarrow$ 10 : very efficient)

factory. Linear relationships ($P < 0.05$) were found between the log-transformed inside and outside concentrations with correlation coefficients (r^2) ranging from 0.17 to 0.51, according to the different factories. As previously in the case of the masks taken as references, the influence of questionnaire answers, facial dimensions and workers' metabolic rates were also taken into account. A new linear regression analysis was performed in order to determine which of these parameters had a significant influence on the values of the pollutant concentration measured inside the mask. Only answers to the questionnaire appeared to have a significant influence in three factories, with new

correlation coefficients (r^2) growing from 0.34 to 0.36 in factory A, from 0.34 to 0.50 in factory C and from 0.17 to 0.20 in factory D. These results are summarized in Table 6 (given that all parameters are at $P < 0.05$).

Influence of Particle Size Distribution

The correlation coefficient (r^2) between the log transformed outside and inside concentrations were lower in factory D than in other factories (for example 0.17 against 0.51 in factory C), and the influence of the other parameters appeared weak.

Table 6. Correlation analysis between inside concentration and other parameters collected during the workplace protection factor determinations (Reference: factory).

Factory	First Coefficient of Correlation (r^2) (Independent Variable : log Outside Concentration)	Second Coefficient of Correlation (r^2)	Independent Variables : log Outside Concentration and answers to questions
A	0.34	0.36	f, h
B	0.51	0.51	
C	0.34	0.50	f, h
D	0.17	0.20	c

c : did you suffer from breathing constraint ? (1 : none $\Rightarrow$ 6 : unbearable)

f : how long do you think you could wear this respirator if you had to? (x h y mm)

h : at which level do you estimate the efficiency of the protection provided? (1 : not efficient at all $\Rightarrow$ 10 : very efficient)

The study of the particle size distribution of the airborne dust showed that three workers were exposed to a coarser dust than the others (the mean aerodynamic mass median diameters were ranging from 6 to 10 μm for the three workers and about 2 μm for the others). In that factory there were in fact two different workshops. The first, in which three workers had been selected, was devoted to the recovery of precious metals from a dusty matte. The second, which employed the seven remaining workers, was a plant that specialized in primary lead smelting. That process is well known for producing fine dust, which is consistent with the mean aerodynamic mass median diameters found. These particle size data are presented in Table 7.

The values collected for the three workers were excluded, and the correlation coefficient (r^2) was recalculated. As a result, the coefficient increased from 0.17 ($P < 0.05$) to 0.27 ($P < 0.05$), nearer to the values calculated from the data collected in the other factories. However, no normal or lognormal distribution could be found for the eighteen samples taken on the three workers, and no regression analysis could therefore be performed.

Influence of Outside Concentration on Masks' Efficiency

Since the WPFs of the six masks do not differ significantly, it was decided to consider the entire data set, and to investigate whether the efficiency of the masks was influenced by the outside concentration. In order to do so, the data of the outside concentrations measured were classed in five classes according to their value: the first class is made up of the data below 0.315 mg/m^3 , the second with data from 0.315 to 1 mg/m^3 , and so on with limits of 3.15 mg/m^3 and 10 mg/m^3 , the fifth class being made up of values over 10 mg/m^3 . These limit values were chosen in order to make up classes consistent with the lognormal distribution of the data.

For each of these five classes, the geometric mean of the corresponding WPFs was reckoned. These WPF geometric means and their two-sided 95% confidence interval limits are shown in Table 8. Logarithmic values were chosen so that the treatment would be consistent with the statistical treatments previously performed in the current study, but in this instance they have no real

Table 7. Particle size data of the working atmosphere dust collected in the two different workshops of factory D.

Particle size range (μm)	Percentage of the collected mass (lead smelting workshop)	Percentage of the collected mass (precious metals workshop)	Percentage of the collected mass (precious metals workshop)
<0.11	0	0	0
0.11-0.14	5.12	3.31	3.07
0.14-0.17	5.11	3.3	3.07
0.17-0.21	5.12	3.3	3.07
0.21-0.25	5.11	3.15	3.04
0.25-0.31	5.09	2.43	2.91
0.31-0.38	4.95	1.05	2.41
0.38-0.47	4.65	0.04	1.49
0.47-0.58	4.17	0	0.62
0.58-0.72	3.66	0	0.19
0.72-0.88	2.95	0	0.12
0.88-1.08	2.11	0	0.13
1.08-1.33	1.64	0.04	0.24
1.33-1.64	1.31	0.23	1.02
1.64-2.02	0.89	0.67	2.41
2.02-2.48	0.72	0.46	3.12
2.48-3.05	0.93	0.08	2.55
3.05-3.75	1.61	0	1.32
3.75-4.62	2.36	0	0.59
4.62-5.68	2.58	0	1.27
5.68-6.99	2.53	5.79	4.98
6.99-8.60	3.02	7.42	8.03
8.60-10.57	4.67	1.64	6.26
10.57-13.01	6.56	0	5.21
13.01-16.00	6.78	0	10.08
16.00-19.68	5.39	3.7	14.8
19.68-24.22	3.89	27.48	11.13
24.22-29.79	2.88	28.63	4.53
29.79-36.65	2.26	5.8	1.6
>36.65	1.94	1.28	0.74
	mammd= 2.08 μm	mammd= 9.76 μm	mammd= 5.86 μm
mammd=mean	aerodynamic	mass median	diameter

Table 8. Influence of outside concentration on workplace protection factor.

Range of outside Concentrations (mg/m ³)	Sample size	Workplace Protection Factors	
		Geometric Mean	95 % Confidence Limit on Mean
0 - 0.315	22	4	3 - 6
0.315 - 1.0	59	6	5 - 8
1.0 - 3.15	44	10	8 - 13
3.15-10.0	24	26	19 - 38
> 10.0	25	55	35 - 87

statistical meaning, since no **lognormal** distribution is possible when the data are divided into five such classes.

As shown in Table 8, the WPFs are seen to increase dramatically as a function of the outside concentration. Such results have already been observed by other authors (Moore and Smith, 1976; Tannahill et al., 1990), but no satisfactory explanation has been given.

In the current study, as in most others, the amount of dust sampled inside the masks was relatively small. Therefore, some of the lowest

concentrations measured were near the detection limit. However, for more than half the data in the first class (i.e., actually some data of which the value is included between 0.15 and 0.315 mg/m³), the analytical signal was strong enough that, even when sampling error and analytical confidence intervals (which can be as high as +50% of the analytical value) are taken into account, the WPFs still did not reach the same level as they did in the fourth and fifth classes (outside concentrations greater than 3.5 mg/m³). Therefore, this discrepancy cannot entirely be explained by sampling errors and analytical imprecision.

Discussion

One major result obtained from this study is that no significant **difference** was found between the WPFs of the different masks tested. If the mean values of WPFs are considered, the positions established from laboratory tests are roughly respected (see Table 1), but the range is drastically reduced. Once again it is shown that actual WPFs cannot be inferred from laboratory tests.

The variation of WPFs as a function of the outside concentrations are also noteworthy. Given the theoretical principles of filtration, it is not

surprising in itself that masks are relatively more efficient when exposed to high concentrations (even if, of course, the amount of pollutant inside the respirator goes on increasing). Nevertheless, the **difference** in the level of **efficiency** is surprising.

The presence of pollutant inside the respirators is due to the penetration of dust through the filter, but more especially to the lack of tightness of the mask to the face of the worker. In a recent paper, Myers et al. (1991) measured the penetra-

tion of aerosols through fixed-diameter capillaries in order to represent the face seal leaks of a respirator. This representation, which has been previously chosen by Holton et al. (1987), suggests that the phenomena involved in face seal leaks have something to do with filtration.

From this comparison with the filtration, although the increase in breathing resistance in higher dust concentrations may cause an increase of face seal leakage, these face seal leakages might increase in a minor proportion than the dust concentration.

The observation that respirators are more efficient in higher dust concentrations might be due to differences in the particle size distribution found in different environments. Atmospheres with a weak concentration of dust may contain smaller particles than atmospheres with higher dust contents. Holton et al. (1987), Myers et al. (1991), and Ruuskanen et al. (1988) have shown the effect of particle size on penetration inside masks. Although these results have been got during experiments performed on mannequins and not humans, it can be interesting to compare our findings with theirs. In general, their findings show that the maximum penetration is observed for particles on the order of $1\text{ }\mu\text{m}$ (with some exceptions for Myers et al.). This penetration decreases for particles of greater diameters. In the current study, the mean aerodynamic mass median diameters measured with **Marple** impactors were generally found to be between 5 and $10\text{ }\mu\text{m}$, except in the case of seven workers in factory D, where it was approximately $2\text{ }\mu\text{m}$. It should, however, be noted that these particle size measurements were all performed for concentrations greater than 1 mg/m^3 . No data for particle size distribution are available below that concentration, although 50% of the outside concentration measurements fall into this category. It is therefore not possible to determine whether or not the external concentration and the particle size were related.

One can thus conclude that the influence of outside concentration should be studied in the

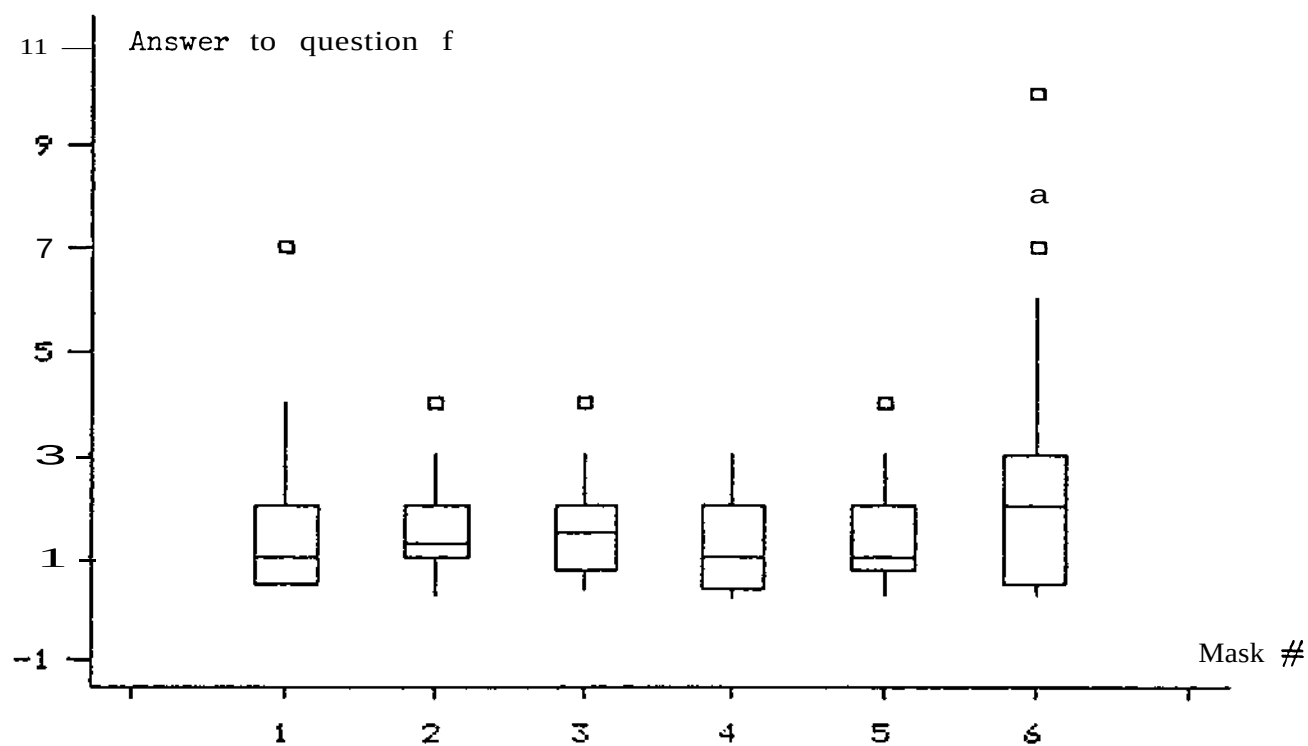
laboratory, where the particle size distribution can be controlled.

A recent Dutch document (Veenstra et al., 1991) proposes values for Assigned Protection Factors (APFs) for half-masks fitted with dust filters: these values equal 10 for P3 and 6 for P2. Compared to our results, these values seem realistic only for outside concentrations superior to 3 mg/m^3 , but are probably too severe for concentrations over 10 mg/m^3 . Nevertheless, it must be kept in mind that our study was performed under somewhat ideal conditions (for France) for the wearing of masks: the wearing duration was limited, special care had been taken for shaving, and the workers were constantly surveyed to ensure that they were wearing the masks correctly. However, no fit testings had been performed before the tests, and it is not possible to ensure that the workers had been provided with all the means necessary to the checking of a good fitting.

The regression analysis showed that the data correlation coefficients (r^2) increased when the answers to the questionnaire were taken into account. However parameters such as the facial dimensions of the subjects and their metabolic rate did not seem very important.

The answers to the questionnaire indicated that the workers believe that they can wear negative pressure half-masks in a satisfactory way only for a limited period. They generally agreed to a one-hour duration. When longer exposure times are foreseen, it would be preferable to provide the workers with alternative respiratory protection devices for use in place of negative pressure masks.

This limit in the duration of wearing is shown in Figures 3 and 4. In Figure 3, it appears that all the masks are considered the same way by the workers (30 answers for each mask). The differences are more significant when the wearing duration is related with the individual answers (see Figure 4).



Question f : How long do you think you could wear this respirator if you had to : 4 min

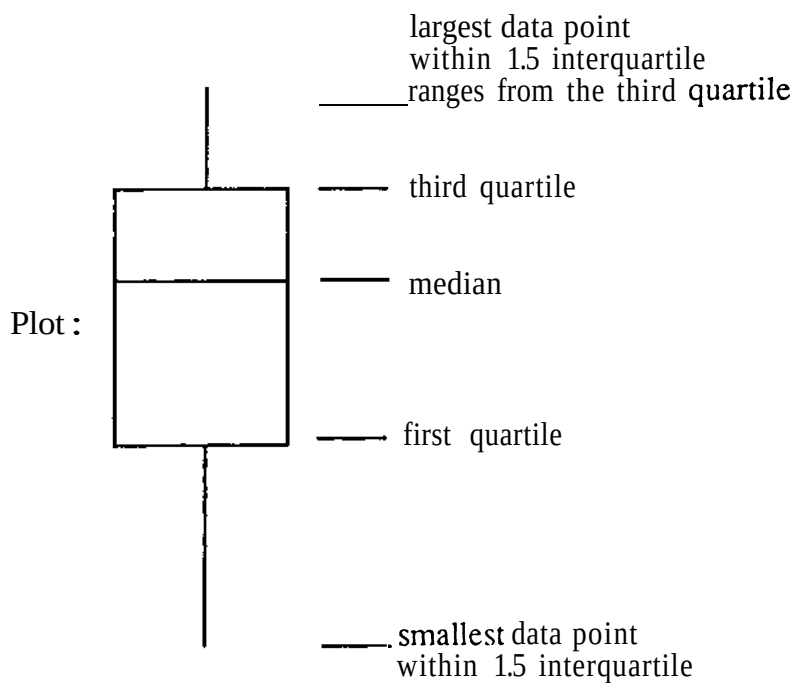


Figure 3. Duration of easy wearing related to different masks.

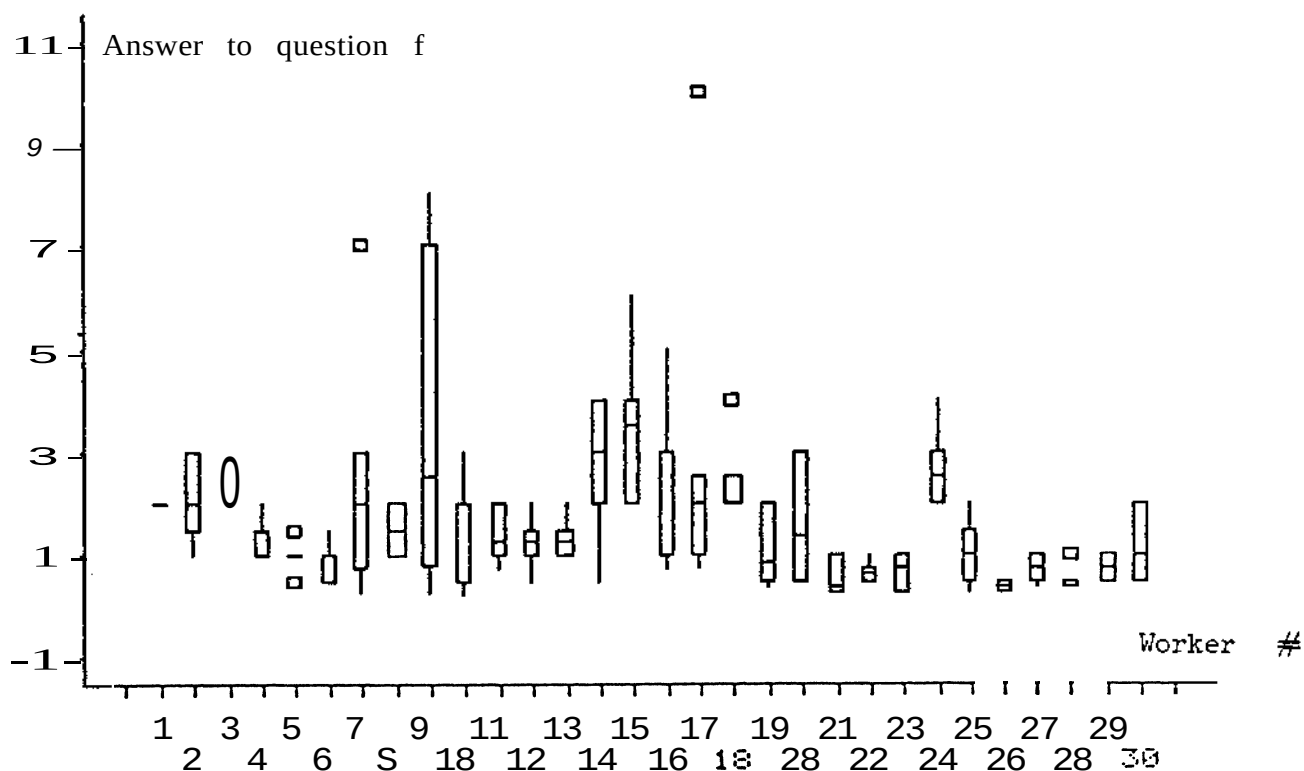


Figure 4. Duration of easy wearing related to each subject. Question F = How long do you think you could wear this respirator easily if you had to? h min.

Conclusion

Two general conclusions can be drawn from the results presented above:

- Negative pressure respirators can be very useful in protecting workers from environments containing high quantities of inert dust. However, confirming previous results, the protection factor might be somewhat weaker in less polluted areas. No a priori conclusions should be drawn on the actual efficiency of the devices. WPFs should be systematically determined before a respirator is put to extended use in a factory, especially if workers are likely to be exposed to dangerous dust.
- No significant **difference** was found between the efficiency of the masks studied; yet the models tested were very different

regarding shape, filtration principle, and cost. Given the importance of comfort parameters and the weak differences in efficiency found between the various models tested in this study, workers should be given the choice of which type of respirator they will have to wear. They should have at their disposal several models of respirators, amongst which they can choose. These models should of course be selected from a list of materials, all consistent with the standards requirements. The use of respirators implies that a program must be set up in the factory including workers training and apparatus maintenance.

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Appendix

The following tables show the sampling data collected in the course of this study (inside and outside the respirators, and the corresponding WPFs).

Table 9. Outside and inside concentrations measured during the tests of mask #1 and corresponding WPFs.

	Workers	Inside concentration ($\mu\text{g}/\text{m}^3$)	Outside Concentration ($\mu\text{g}/\text{m}^3$)	WPF
Factory A	#1	4080	232	18
Factory A	#2	110	54	2
Factory A	#3	1560	61	26
Factory A	#4	1010	131	8
Factory A	#5	8150	438	19
Factory A	#6	1110	200	6
Factory B	#7	49730	250	199
Factory B	#8	290	143	2
Factory B	#9	2750	87	32
Factory B	#10	210	32	7
Factory B	#11	26000	164	159
Factory B	#12	140	38	4
Factory B	#13	300	219	2
Factory C	#14	1930	412	5
Factory C	#15	2620	132	20
Factory C	#16	3690	144	26
Factory C	#17	8110	251	32
Factory C	#18	8390	407	21
Factory C	#19	5900	24	246
Factory C	#20	1780	144	12
Factory D	#21	440	130	3
Factory D	#22	380	30	13
Factory D	#23	620	30	21
Factory D	#24	530	35	15
Factory D	#25	430	45	10
Factory D	#26	440	255	2
Factory D	#27	1220	420	3
Factory D	#28	1300	n.a	n.a
Factory D	#29	660	195	3
Factory D	#30	840	175	5

Table 10. Outside and inside concentrations measured during the tests of mask #2 and corresponding WPFs.

	Workers	Inside Concentration ($\mu\text{g}/\text{m}^3$)	Outside Concentration ($\mu\text{g}/\text{m}^3$)	WPF
Factory A	#1	2740	178	15
Factory A	#2	460	126	4
Factory A	#3	4670	349	13
Factory A	#4	750	182	4
Factory A	#5	430	107	4
Factory A	#6	600	61	10
Factory B	#7	28530	557	51
Factory B	#8	2470	32	77
Factory B	#9	15030	420	36
Factory B	#10	180	72	2
Factory B	#11	4240	83	51
Factory B	#12	170	91	2
Factory B	#13	390	25	15
Factory C	#14	19540	950	21
Factory C	#15	23780	1329	18
Factory C	#16	6860	335	20
Factory C	#17	16440	3196	5
Factory C	#18	6520	72	91
Factory C	#19	1050	132	8
Factory C	#20	3810	96	40
Factory D	#21	490	95	5
Factory D	#22	2260	480	5
Factory D	#23	490	45	11
Factory D	#24	350	175	2
Factory D	#25	1110	450	2
Factory D	#26	750	300	3
Factory D	#27	2860	510	6
Factory D	#28	240	20	12
Factory D	#29	610	235	3
Factory D	#30	630	325	2

Table 11. Outside and inside concentrations measured during the tests of mask #3 and corresponding WPFs.

	Workers	Inside Concentration ($\mu\text{g}/\text{m}^3$)	Outside Concentration ($\mu\text{g}/\text{m}^3$)	WPF
Factory A	#1	3700	282	13
Factory A	#2	1930	68	28
Factory A	#3	1420	133	11
Factory A	#4	1140	89	13
Factory A	#5	350	35	10
Factory A	#6	390	25	16
Factory B	#7	17600	279	63
Factory B	#8	650	55	12
Factory B	#9	2370	205	12
Factory B	#10	280	36	8
Factory B	#11	11840	331	36
Factory B	#12	200	39	5
Factory B	#13	890	39	23
Factory C	#14	22450	32	702
Factory C	#15	6020	120	50
Factory C	#16	3030	n.a	n.a
Factory C	#17	2680	431	6
Factory C	#18	20300	742	27
Factory C	#19	160	12	13
Factory C	#20	970	36	27
Factory D	#21	780	20	39
Factory D	#22	1330	240	6
Factory D	#23	2260	165	14
Factory D	#24	410	15	27
Factory D	#25	430	185	2
Factory D	#26	480	260	2
Factory D	#27	1020	140	7
Factory D	#28	480	170	3
Factory D	#29	560	200	3
Factory D	#30	430	90	5

Table 12. Outside and inside concentrations measured during the tests of mask #4 and corresponding WPFs.

	Workers	Inside Concentration ($\mu\text{g}/\text{m}^3$)	Outside Concentration ($\mu\text{g}/\text{m}^3$)	WPF
Factory A	#1	2700	245	11
Factory A	#2	290	130	2
Factory A	#3	550	66	8
Factory A	#4	600	88	7
Factory A	#5	500	81	6
Factory A	#6	580	167	3
Factory B	#7	3460	136	25
Factory B	#8	1070	68	16
Factory B	#9	13450	1497	9
Factory B	#10	160	61	3
Factory B	#11	2620	60	44
Factory B	#12	200	51	4
Factory B	#13	260	58	4
Factory C	#14	5410	n.a	n.a
Factory C	#15	2100	144	15
Factory C	#16	4930	215	23
Factory C	#17	11960	407	29
Factory C	#18	18600	156	119
Factory C	#19	710	84	8
Factory C	#20	690	12	58
Factory D	#21	750	240	3
Factory D	#22	1340	170	8
Factory D	#23	300	170	2
Factory D	#24	5980	80	75
Factory D	#25	500	285	2
Factory D	#26	540	135	4
Factory D	#27	470	90	5
Factory D	#28	310	150	2
Factory D	#29	1020	155	7
Factory D	#30	680	175	4

Table 13. Outside and inside concentrations measured during the tests of mask #5 and corresponding WPFs.

	Worker	Outside Concentration ($\mu\text{g}/\text{m}^3$)	Inside Concentration ($\mu\text{g}/\text{m}^3$)	WPF
Factory A	#1	2660	1004	3
Factory A	#2	240	142	2
Factory A	#3	1860	70	27
Factory A	#4	1000	50	20
Factory A	#5	1430	182	8
Factory A	#6	1530	251	6
Factory B	#7	35750	420	85
Factory B	#8	350	38	9
Factory B	#9	9660	417	23
Factory B	#10	140	77	2
Factory B	#11	36470	1332	27
Factory B	#12	280	4	69
Factory B	#13	380	356	2
Factory C	#14	27750	1298	21
Factory C	#15	4800	395	12
Factory C	#16	2210	96	23
Factory C	#17	12440	72	173
Factory C	#18	25820	539	48
Factory C	#19	5170	108	48
Factory C	#20	2300	36	64
Factory D	#21	390	235	2
Factory D	#22	1180	85	14
Factory D	#23	340	95	4
Factory D	#24	360	70	5
Factory D	#25	720	115	6
Factory D	#26	580	250	2
Factory D	#27	990	120	8
Factory D	#28	3900	330	12
Factory D	#29	1310	145	9
Factory D	#30	1270	85	15

Table 14. Outside and inside concentrations measured during the tests of mask #6 and corresponding WPFs.

	Worker	Outside Concentration ($\mu\text{g}/\text{m}^3$)	Inside Concentration ($\mu\text{g}/\text{m}^3$)	WPF
Factory A	#1	810	44	18
Factory A	#2	1080	393	3
Factory A	#3	460	54	8
Factory A	#4	870	40	22
Factory A	#5	1020	183	6
Factory A	#6	1540	273	6
Factory B	#7	47310	468	101
Factory B	#8	620	79	8
Factory B	#9	1390	n.a	n.a
Factory B	#10	200	14	14
Factory B	#11	4690	179	26
Factory B	#12	170	73	2
Factory B	#13	330	102	3
Factory C	#14	28770	158	182
Factory C	#15	27700	503	55
Factory C	#16	10670	204	52
Factory C	#17	3340	96	35
Factory C	#18	19270	227	85
Factory C	#19	15010	108	139
Factory C	#20	830	156	5
Factory D	#21	1950	230	8
Factory D	#22	3800	1005	4
Factory D	#23	1000	130	8
Factory D	#24	760	145	5
Factory D	#25	820	250	3
Factory D	#26	1150	550	2
Factory D	#27	1000	150	7
Factory D	#28	3940	315	12
Factory D	#29	1060	150	7
Factory D	#30	910	30	30