
Asbestos Fibre Sampling through a Facepiece Visor to Measure Workplace Protection Factor

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ABSTRACT

Background: In France, the occupational limit value for asbestos (WHO definition + fine asbestos fibres) was reduced from 100 f/L to 10f/L, as analysed by analytical transmission electron microscopy, on 1st July 2015. This reduction associated with the change in analytical method to evaluate exposure to asbestos fibers in July 2012 required occupational assessment of the efficacy of respiratory protective devices used by operators during asbestos removal.

Objective: The preliminary work for this sampling campaign was to develop a CE-certified prototype standard facepiece integrating asbestos fibre sampling in line with standard XP X 43-269 (2012).

Methods: Numerical simulations and tests with live subjects and dummy heads were performed to verify the performance parameters of each model of modified mask including sampling in the visor (2 supplied air and 2 powered assisted RPDs).

Results: This article presents the results of the laboratory tests through which this way of sampling inside the facepiece was validated.

Conclusion: All the models of modified mask developed are appropriate for use in occupational settings in the limited framework of the INRS study.

Keywords: asbestos, sampling inside mask, PAPR, supplied air respirator, protection factor.

INTRODUCTION

The French regulations with regard to asbestos-related risks stipulate that operators responsible for removing asbestos-containing material must be trained on how to fit Respiratory Protective Equipment (RPE), and that RPE appropriate for the level of dusts expected to be generated during the removal operation be provided by the employer. Three levels of dust ambient concentration have been defined. Level 1 corresponds to dust levels between 0 and 100 f/L; level 2 covers dust levels between 100 and 6,000 f/L; and level 3 corresponds to dust levels between 6,000 and 25,000 f/L. Beyond the upper limit of level 3, additional preventive measures must be applied to reduce dust levels to below 25,000 f/L. The French regulations also require that dust levels be measured according to sampling standards XP X 43-269 (2012) and NF X 43-050 (1996), and that the concentration of asbestos fibres be determined by analytical transmission electron microscopy.

The results of toxicological studies (Afsset (2009)) induced the French authorities to reduce the occupational limit value for asbestos fibres from 100 f/L to 10 f/L as of 1st July 2015. In parallel to this change for the prevention of occupational risks, INRS performed a study aiming to verify the respiratory protection of Respiratory Protective Devices (RPD) used by operators performing asbestos removal in level 2 and 3 construction sites.

Four devices were tested, two powered air purifying respirators and two supplied air respirators. These models were selected as they are commonly used on construction sites where asbestos removal is performed. In addition to the specifications required for their certification, these devices were specifically designed for use during asbestos removal, and therefore present enhanced aerodynamic performance compared to other devices. The French regulations stipulate that respiratory protection to be used with asbestos exposure must meet the following requirements:

- Filtering RPD with assisted TM3P with full-face mask (classification derived from standard EN 12942:1998 and its amendments) continuous positive pressure must be ensured inside the mask with a minimum flow rate of 160 L/min;
- Class 4 supplied air RPD with a supply of compressed breathing gas at continuous flow with full-face mask (defined and identified according to standard BS EN 14594:2005) with a minimum flow rate of 300 L/min, or air flow defined on-demand combined with positive pressure to allow a flow rate greater than 300 L/min to be maintained.

The first step of this project to evaluate protection factors in the workplace was to develop modified RPDs in laboratory which would include a system for sampling asbestos fibres inside the facepiece. It is the aim of this paper.

Several campaigns to assess the protection factor afforded by powered air or supplied air RPD in occupational conditions can be found in the literature. Depending on the chemical nature of the pollutant being assessed, various sampling strategies were adopted, generally involving filter-based sampling followed by assay of the pollutant (e.g. metallic particles by atomic absorption spectrometry (Myers (1984), Hee (1983)) or Particle induced X-ray emission (PIXE) (Nelson (2001), Janssen (2008))). The sampling performed inside the facepieces tested in the context of these studies (powered air helmet for the first two references and supplied air hood for the other two) was done via a sampling line integrated through an airtight connection into the head-gear's visor, or by placing a cartridge inside the helmet or hood. In the absence of an interior half mask, sampling can be performed as close as possible to the airways of the person wearing the RPD. Field studies of asbestos exposure are rare, and those that exist date from the end of the 1990s (Riala (1998), Villa (1994)). The sampling modes used in these studies were similar to those mentioned above. Nevertheless, none of the articles indicated whether, after modification, the masks still complied with the relevant standards for protection against asbestos exposure.

Myers and co-workers (Myers (1988); Myers (1991)) showed that, with regard to the representativity of the samples taken inside respiratory masks, the main biases were related to the following:

- Localisation of the sampling zone (probe) in relation to the air flow inside the visor
- Leaks and their positions
- Interactions between the subject's breathing mode (through mouth or nose) and the position of the sampling probe

The studies which led to these conclusions investigated negative pressure masks, inside which the air flow will be conditioned by the wearer's breathing. In addition, the level of negative pressure maintained will be affected by any leakage between the mask and the face.

The study described in this paper concentrated on developing a sampling system for asbestos fibres for use inside positive pressure masks. With powered air masks, flow rates of greater than 160 L/min are found, while rates of greater than 300 L/min can be recorded with supplied air masks. The devices assessed during this study were therefore positive pressure devices in good working order and used in line with the manufacturer's recommendations. The presence of leaks between the facepiece and the wearer's face, their extent and positions, as well as the effect of intense air circulation within the mask required new tests to be performed to develop a sampling system for use in these masks.

METHODS

Prototype Modified Mask

The final objective of the project is to determine the workplace protection factors of the masks studied. Then it was essential that the way of sampling inside the mask developed in the present study be performed in line with the protocol recommended for personal sampling outside the RPD, both from the point of view of flow rate and of the sampling support. This protocol has been described in the French standard XP X 43-269 (2012) It recommends the use of a 3- or 4-stage, 37-mm diameter open antistatic cartridge at a sampling flow rate of 3 L/min ($\pm 10\%$).

The other constraints for this sampling were as follows:

- sampling had to be representative of what the operator inhales;
- integration of the cartridge had to cause as little physical or visual discomfort as possible;
- sampling had to be perturbed as little as possible (calm air flow around the sampling point);
- the site of sampling had to be the same on the different models of full masks tested so as to guarantee similar test conditions between models;
- the level of CO₂ had to remain low, i.e., a half mask had to be maintained;
- CE certification in accordance with the requirements of PPE directive 89/686/EEC for the design of RPE had to be maintained after modification: each batch of masks modified by the integration of the sampling system had to be certified according to the same reference tests as the unmodified masks.

These requirements represented major constraints. Because of the bulk of the 37-mm open sampling cartridge and the variability of mask design, it was integrated into the upper part of the visor of respiratory masks. The sampler was centred to reduce visual distortion as much as possible.

The modified mask to allow sampling of asbestos fibres is composed of two parts. The first is a mask with a pierced visor allowing integration of an airtight Rd40-type threaded connection. The second is a standardised asbestos fibre sampling cartridge which was modified for integration into the connection

in the mask. To be robust and airtight, the modified sampling cartridge was made up of three elements, which were interconnected using tape (Figure 1). The three elements were as follows:

1. a 37-mm diameter, 4-stage antistatic sampling cartridge for asbestos fibres, as required by the Air quality in workplaces French standard (XP X 43-269: 2012)
2. an elbow adapter for this cartridge to allow its connection via a sampling channel to a personal sampling pump
3. an Rd40 connection to allow integration of the sampling system into the visor of the modified respiratory mask fitted with an Rd40 connector

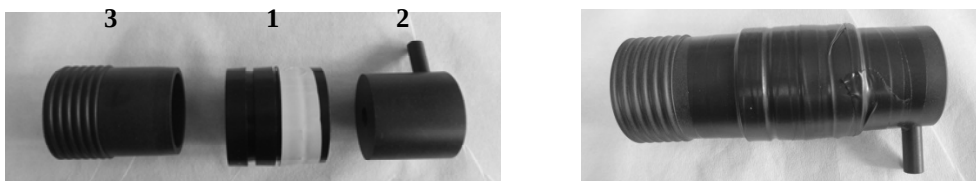


Figure 1: Modified Cartridge before and after Assembly:

1. a 37-mm diameter, 4-stage antistatic sampling cartridge for asbestos fibres
2. an elbow adapter for this cartridge to allow its connection to a personal sampling pump
3. an Rd40 connection to allow integration of the sampling system into the visor

The final prototype modified masks integrating a sampling cartridge appropriate for asbestos fibres is presented in Figure 2.



Figure 2: Modified mask to allow sampling of asbestos fibres.

This prototype was then used by each of the partner manufacturers to produce limited series of modified masks for testing in occupational conditions. Each model of mask studied was certified in line with PPE directive 89/686/EEC.

Efficacy of the Sampling System by Numerical Simulation

Numerical simulations were performed to carefully examine the risks of deposits forming in the sampling system. The aim of this numerical study was to assess whether the fraction of fibres deposited upstream of the sampling filter, in part No. 3 of the modified cartridge, which forms a sleeve (Figure 1), affected the quality of sampling on the filter.

The system was simplified by selecting three hypotheses. First, the air flow configuration inside the mask was assumed to correspond to an air flow of 300 L/min. Two scenarios were tested: the first with an inactive sampling pump and the second with the sampling pump switched on at 3 L/min. Second, the aerodynamic behaviour of the fibres was considered to mimic that of rigid spheres with the same aerodynamic diameter. Third, electrostatic effects and rebound on the walls of the sampler were ignored, which represents the worst case. Based on these hypotheses, the transport equation for the particle concentration can be reduced to a convection diffusion equation, as proposed by Zaichik (2004).

The results of these numerical studies made it possible to calculate theoretical amounts of particles deposited first on the walls of the sleeve for various particle sizes and secondly on the sampling filter.

For the deposit on the filter, the calculations showed that when the pump is switched on, the flow deposited was very close to the reference value corresponding to an ideal sampler with low heterogeneity. With a deactivated pump, at best the local deposit reached one-tenth of the mean values attained in the activated pump configuration.

For the fraction deposited on the walls of the sampling system upstream of the filter in the part named “sleeve”, the results of the numerical simulation were compared to the case of an ideal sampler. The amount of particles deposited normalised relative to the total flow measured with an ideal sampler is represented in Table I.

Table I. Predictions of the Fraction of Fibres Deposited on the Filter and on the Walls of the Sampling System Compared to an Ideal Sampler Determined by Numerical Simulations

Aerodynamic diameter of fibres	Activated sampling pump		Inactivated sampling pump	
	Deposit on filter (#.s ⁻¹)	Deposit on walls of sampler (#.s ⁻¹)	Deposit on filter (#.s ⁻¹)	Deposit on walls of sampler (#.s ⁻¹)
100 nm	99.8%	1.2%	1.8%	1.0%
500 nm	99.6%	0.9%	1.8%	0.8%
1 µm	98.8%	0.9%	1.8%	0.7%
2 µm	99.0%	1.2%	2.0%	1.0%

The results of the numerical simulation show that, in the worst case, the sampling device collects 98.8% of the real concentration present inside the mask. In the limits of the hypotheses applied to simplify calculations, the deposit on the walls of the sampling system was marginal compared to the amount deposited on the filter.

These first numerical results suggest that this system integrated into the visor of the RPE allows fibres present in the visor to be sampled with an efficacy close to that of an ideal sampler.

Representativity of Sampling

While the certification tests performed on modified masks guaranteed their air-tightness and robustness, they could not ensure that measurements made inside the mask were representative of the fibre concentrations inhaled by operators. Therefore, tests were performed in the laboratory before starting occupational campaigns to study the following:

- The performance of modified masks compared with that of non-modified masks
- The representativity of sampling in the visor compared to sampling in the half mask, which is closer to the wearer's airways.

These tests were performed inside a booth where a stable concentration of polydisperse NaCl aerosol was generated by nebulization from a 1% mass NaCl solution. The polydisperse aerosol generated presents a total number concentration of $2.10^6 \text{ \#/cm}^3$ and a size distribution determined by Fast Mobility Particle Sizer (TSI) with a geometric mean diameter of 52 nm ($\sigma_g = 1.82$). Inside the booth tests were carried out on live subjects walking on a treadmill or on a dummy head associated with a breathing machine.

During experiments, the RPD was used in normal working conditions, i.e.:

- Ventilator switched on, fully charged battery and new filters fitted to devices with powered air,
- Breathing air was supplied at a pressure exceeding 4 bars (in general 6 to 7 bars) for supplied air devices.

The **first series of tests** consisted in comparing the performances of the four models of unmodified and modified masks on six subjects walking slowly on a treadmill in the booth. Comparisons were made by calculating the ratio of test aerosol concentrations between the inside and the outside of the facepiece.

The concentration inside the facepiece (C_i) was measured using a TSI adapter linked to a tube sampling the aerosol between the nose and the mouth. In the case of modified masks, the sampling line including the modified cartridge and personal sampling pump was activated, as indicated in Figure 3. The outside concentration of particles (C_o) is located in the subject's respiratory area outside the RPD but shifted to the right at the opposite to the exhaust air flow. Alternated measurements between the inside and the outside of the RPD were carried out with the same instrument to determine protection level expressed by the ratio C_o/C_i .

Particle concentrations were measured with two devices: an FMPS (TSI) which provides a granulometric distribution within the range 6–560 nm by analysing electrical current, and a GRIMM 1.108 photometer which can measure the concentrations of particles with diameters greater than 250 nm.

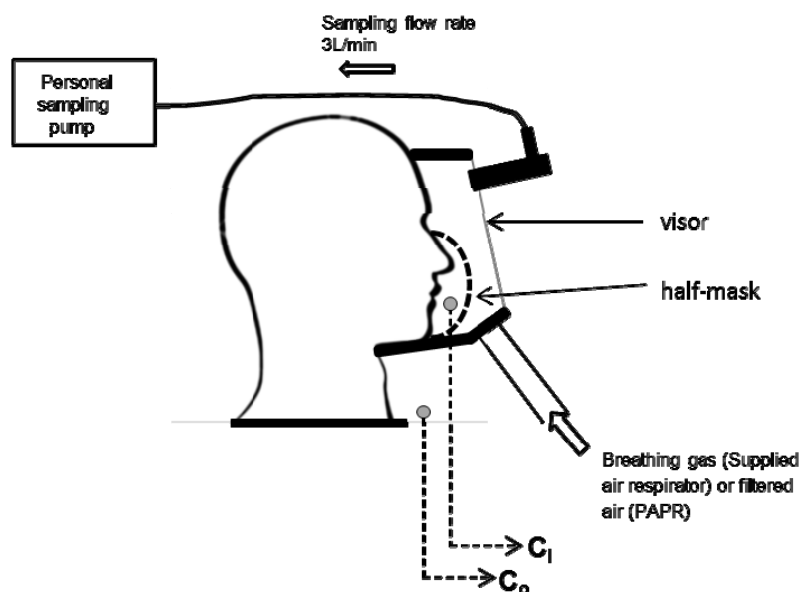


Figure 3: Experimental setup for laboratory assessment of the performances of respiratory masks following integration of the sampling device into the visor (C_0 : outside mask particle concentration; C_i : inside mask particle concentration).

The **second series of tests** aimed to determine how the localisation of the sampling device inside the respiratory mask affected the ratio of concentrations outside and inside the mask. A sampling device placed in the visor, as planned in the specifications for sampling of asbestos fibres (route 2), was compared to a device placed in the half mask at the level of the operator's mouth (route 1) (Figure 4). These tests were performed on a dummy head associated with a breathing machine running various breathing patterns. There is no filter on the breathing machine but each test includes a blank inside the mask to evaluate the residual inside mask concentration when no particles are generated outside. The FMPS analyser was not available for these tests (undergoing maintenance), it was replaced by a condensation nucleus counter covering the full granulometric range from 20 nm to 2 μ m. For compatibility with this counter, the sampling cartridge was empty (contained no filter) during these tests. The positive pressure inside the mask at the two sampling points was measured (P'_1 at the level of the airways and P'_2 in the visor) (Keller PD41X differential pressure sensor 0-50 mbar). These measurements were made at the same time as the concentration measurements, but at the opposite point, i.e.: P'_1 was measured at the same time as C_{i2} , and P'_2 was measured simultaneously to C_{i1} .

The breathing patterns simulated by the breathing machine were defined based on the reference parameters indicated in standard EN ISO 8996 (February 2005). Patterns were numbered from 1 to 5 and correspond to the five classes of activity-induced metabolism: from resting to very intense activity. The parameters defining the sinusoidal breathing patterns are indicated in Table II.

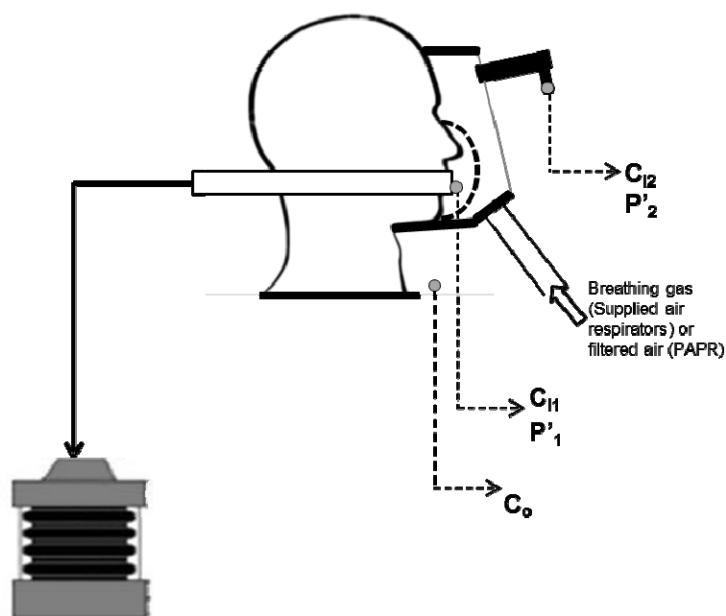


Figure 4: Experimental setup for the comparison of samples taken inside the mask in the visor (concentration C_{i2} and pressure P'_{2}) and at the level of the airways (concentration C_{i1} and pressure P'_{1}) on a dummy head.

Table II. Sinusoidal Breathing Patterns Simulated by the Breathing Machine

Level of Work Activity	Mean Ventilatory Flow (L/Min)	Breathing Pattern No.	Peak Inhalation Flow (L/Min)
rest	13	1	41
low intensity work	18	2	57
moderate intensity work	27	3	84
high intensity work	36	4	113
very high intensity work	45	5	141

To test the representativity of the sampling in the visor in suboptimal conditions, three mask positions were tested for the powered air purifying respirators models:

- a normal, correctly adjusted position,
- a position with a calibrated leak at forehead level in the right side of the head (6-mm external diameter tube),
- a position with a calibrated leak at chin level in the right side of the head on the opposite side to the filtered air inlet (6-mm external diameter tube).

RESULTS AND DISCUSSION

Air-tightness of the Modified Masks

The results of the first series of tests showed that, whatever the subject and the model of respiratory mask tested, the performances of masks modified by the integration of 37-mm cartridge-based sampling at 3 L/min into the visor were the same as those of unmodified masks. Figure 5 illustrates this conclusion based on the concentrations measured by the GRIMM photometer. The data obtained with the FMPS give similar results.

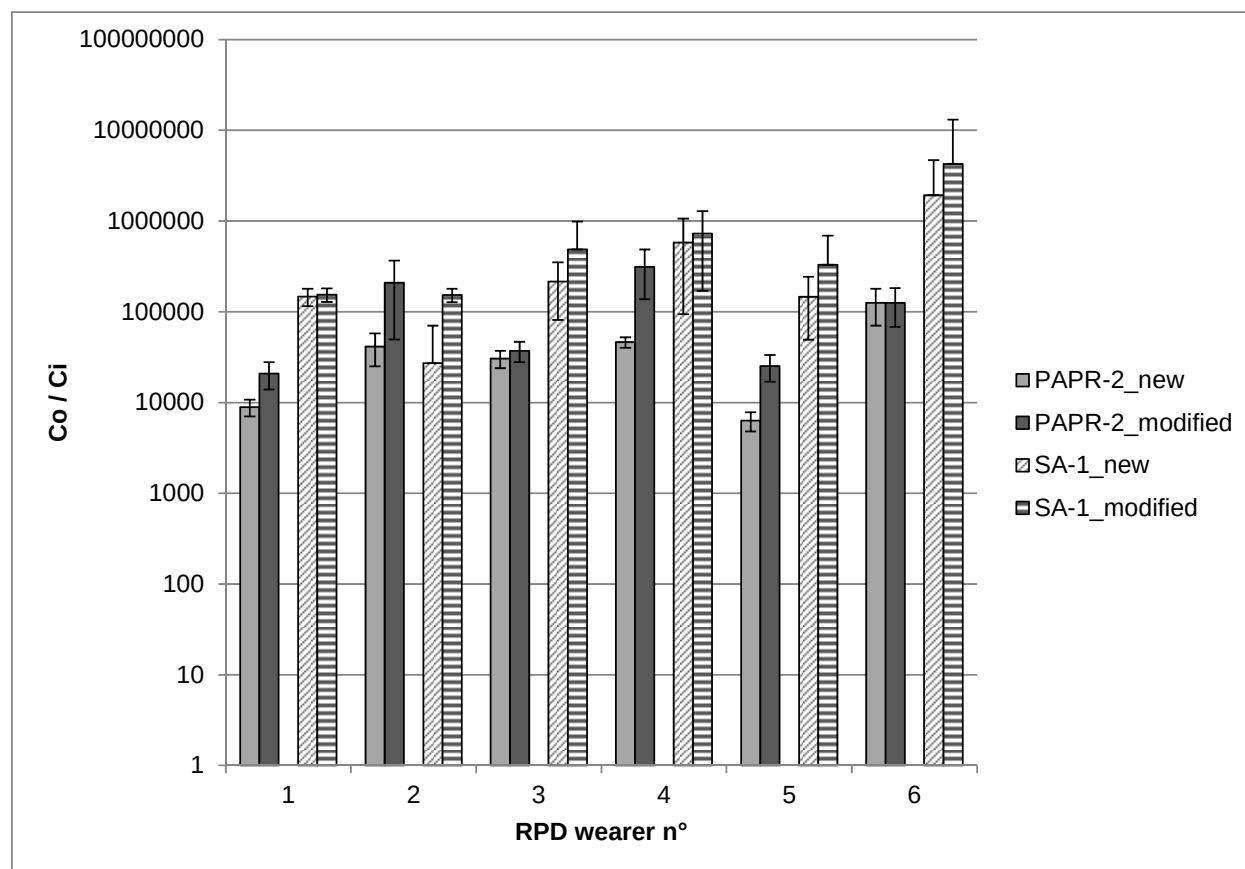


Figure 5: Comparison of concentration ratios between the outside (C_o) and the inside (C_i) of the mask for new masks and modified masks, 6 subject and 2 mask models (a powered air purifying respirator model: PAPR-2 and a supplied air model: SA-1).

The data on C_o/C_i concentration ratios can be divided into two series, the first for measurements made with unmodified masks and the second for measurements made with modified masks. Each series consisted of 23 values. Statistical comparison of these two series is done by the Kolmogorov-Smirnov test. The results indicated that there is no significant difference between modified and unmodified masks at the 95% confidence interval with a maximal gap between both distributions (D_{max}) equal to 0.217, which is lower than the maximal accepted gap with this confidence level ($D_{0.05}$ ($N=23$)) equal to 0.2749. The performances of the mask modified by integration in the visor of a 37-mm diameter sampling cartridge connected to a functioning sampling pump set for a flow rate of 3 L/min were no different from those with new masks.

Comparison of Sampling in the Visor and in the Half Mask

The second series of tests compared the two sampling routes (route 1 in the half mask and route 2 in the visor) based on measurements of the C_o/C_{i1} and C_o/C_{i2} ratios with C_o the outside concentration and C_{i1} and C_{i2} the inside mask concentrations respectively in the half mask and in the visor. One of the supplied air RPD studied was a device with continuous flow (SA-1), which can be manually regulated between a minimal flow rate ($Q_{min} \sim 120$ L/min) and a maximal flow rate ($Q_{max} \sim 350$ L/min). The second supplied air RPD model works on-demand at guaranteed positive pressure or at a continuous flow rate (SA-2). During tests, all the modes of functioning of these masks were studied. For each of the modified powered air masks studied, three configurations were tested, as follows:

- The mask worn normally
- The mask with a calibrated leak at forehead level in the right side of the head
- The mask with a calibrated leak at chin level in the right side of the head on the opposite side to the filtered air inlet

Figures 6-a (for supplied air respirators) and 6-b (for powered assisted purifying respirators) present the C_o/C_i ratios measured with the condensation nucleus counter as well as the relative pressure values measured inside the visor and the half mask, for the most intense breathing pattern (n°5, Table II) for each model of modified RPD.

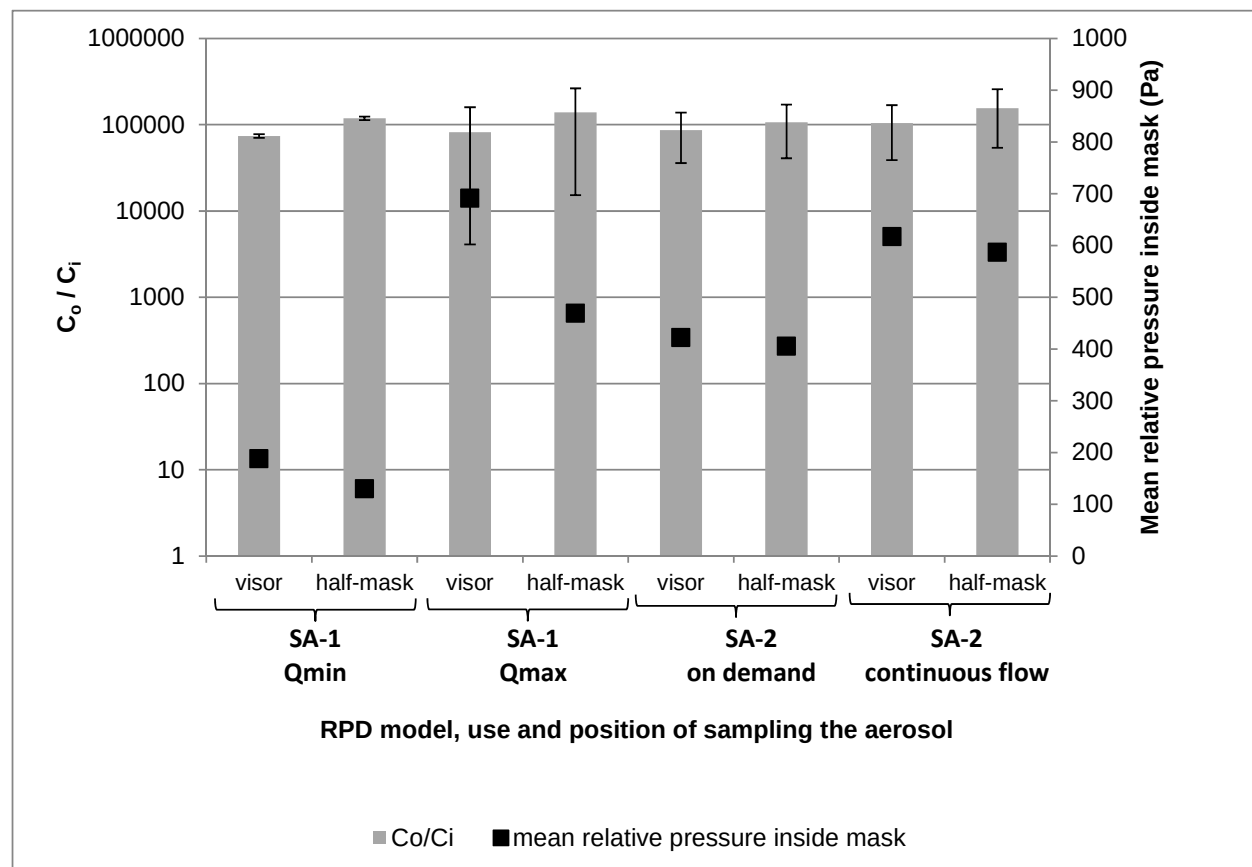


Figure 6-a: Summary of the differences in C_o/C_i concentration ratios between the half mask and the visor and associated relative pressures for supplied air respirators SA-1 and SA-2 at breathing pattern n°5.

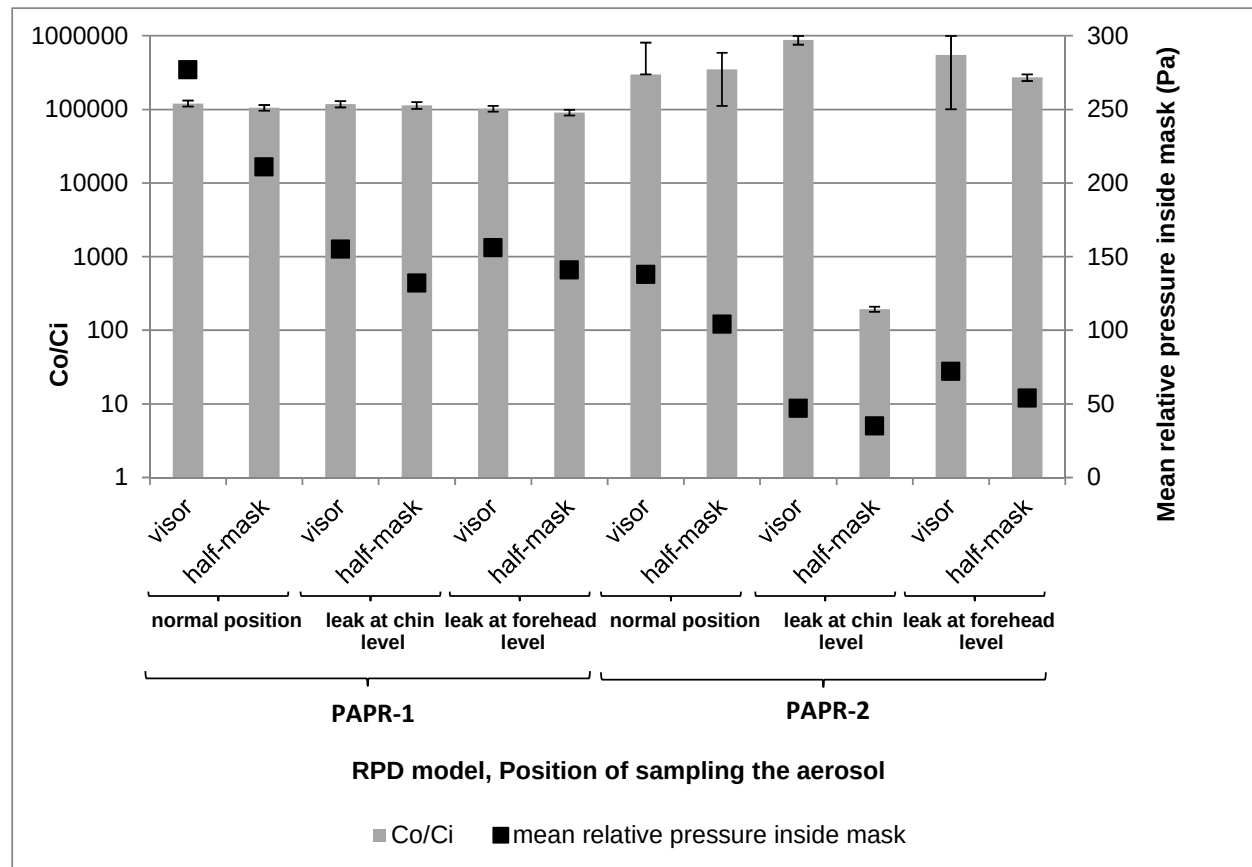


Figure 6-b: Summary of the differences in C_o/C_i concentration ratios between the half mask and the visor and associated relative pressures for powered air purifying respirators PAPR-1 and PAPR-2 at breathing pattern n°5.

For supplied air devices, the relative pressure does not vary between the visor and half mask.

For device SA-1, a slight difference in concentration ratio was visible at Q_{min} , but this difference was no longer visible at Q_{max} taking into account measurement uncertainties. Statistical analysis of the two series of values obtained at Q_{min} and Q_{max} indicated that:

- A significant difference at the 95% confidence interval exists between the two sampling routes (inhaled flow and visor) at Q_{min}
- No significant difference at the 95% confidence interval exists between the two sampling routes (inhaled flow and visor) at Q_{max} (Kolmogorov-Smirnov test, maximum difference calculated between the two distributions: $D_{max} = 0.4$, we therefore conclude: $D_{max} < D_{0.05}(N=5)$ with $D_{0.05}(N=5) = 0.563$).

For device SA-2, all the data obtained, whether in on-demand mode or in continuous flow mode, were analysed.

No significant difference at the 95% confidence interval was found between the two sampling routes (inhaled flow and visor) in the two modes of use of model SA-2 (Kolmogorov-Smirnov test,

maximum difference calculated between the two distributions: $D_{\max} = 0.2$, we therefore conclude: $D_{\max} < D_{0.05}(N=10)$ with $D_{0.05}(N=10) = 0.41$).

For the supplied air RPD models tested, the results show that sampling in the visor is representative of what the operator inhales at the 95% confidence interval, except when device SA-1 is used inappropriately, against the regulations, with a weak continuous flow of less than 300 L/min.

For the powered air RPD models, PAPR-1 and PAPR-2, the pressure measured in the visor is greater than in the half mask ($P_2 > P_1$). The difference was slight but systematically observed for all breathing patterns, and when leakage was present at the forehead or at the chin. An identical result was found for all powered air masks.

For powered air RPD model PAPR-1, similar C_o/C_i concentration ratios were measured at the level of the visor and the half mask.

In contrast, with powered air model PAPR-2, sampling in the visor was clearly not representative of what the operator inhales, in particular when leakage was present. Figure 7 details the concentration ratios obtained with mask PAPR-2 depending on how it was worn and the breathing pattern simulated by the breathing machine; Figure 8 shows the corresponding relative pressures.

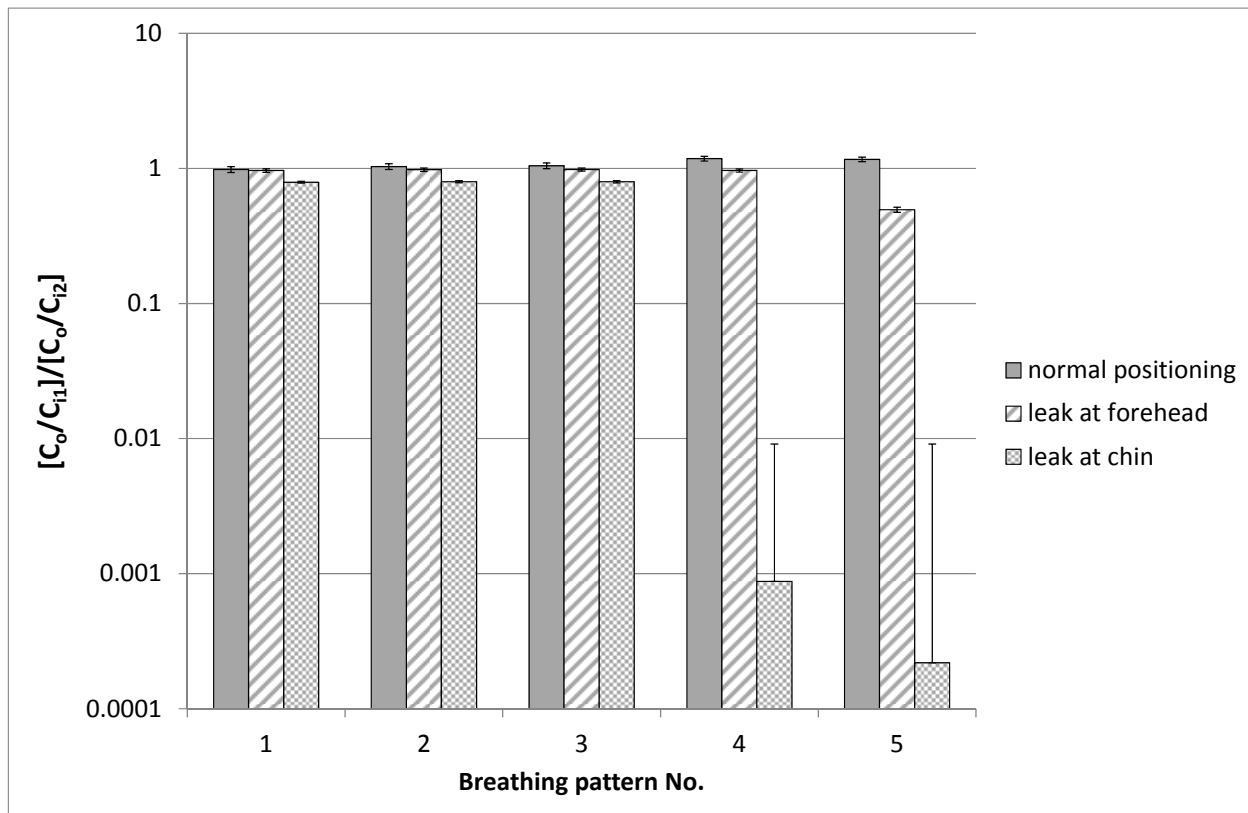


Figure 7: Ratio of C_o/C_i ratios between the inhaled flow (C_{i1}) and the visor (C_{i2}) as a function of the breathing pattern and how the mask was worn for the specific case of powered air mask PAPR-2.

The results expressed as a function of the breathing pattern indicated that differences in concentration ratio between sampling in the inhaled flux and sampling in the visor appeared when the relative pressure inside the powered air mask was low, which corresponds to the case when the mask is incorrectly fitted, allowing leakage, and associated with an intense breathing effort. Nevertheless, Meyer's work has shown that the physiological strain due to the removal of asbestos materials can be described as moderate with peak flows of less than 50 L / min (Meyer (1997)). The cases studied by means of the breathing machine (respiratory rhythms 4 and 5) constitute extreme cases. Figure 7 shows that, up to moderate respiratory rates, the flow delivered by the PAPR is sufficient to compensate for the effect of leaks between the mask and the face.

For the powered air RPD models tested, the results showed that sampling in the visor is representative of what the operator inhales at the 95% confidence interval, except when device PAPR-2 is worn in a non-airtight manner and the breathing effort is intense.

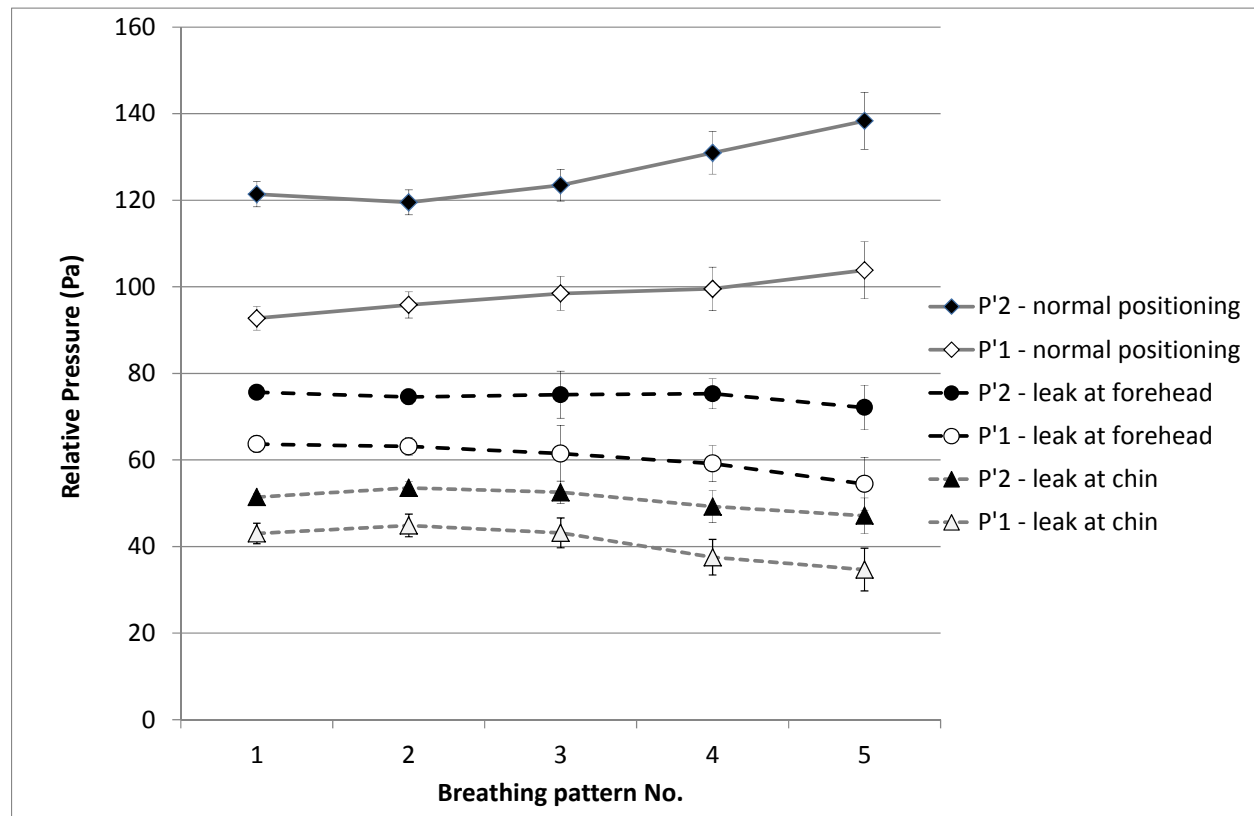


Figure 8: Relative pressure measured inside the mask in the inhaled flux (P'1) and inside the visor (P'2) for the different ways in which powered air mask PAPR-2 could be worn and as a function of the breathing pattern.

CONCLUSIONS

This work, performed prior to starting a campaign to determine the workplace protection factors for RPD used in level 2 and 3 asbestos removal operations validated the system to sample asbestos fibres placed inside respiratory masks. The system:

- complies with the standards for personal sampling of asbestos fibres,
- does not alter the performance of the mask, and
- guarantees maintenance of the CE certification of the masks upon its integration.

Within the limited scope of the laboratory tests with the dummy head, particularly with regard to the positioning of leaks and their effect on sampling within the mask, the sampling system allows samples to be taken which are representative of the concentration of pollutants in the inhaled flow if the recommendations on how to wear and use respiratory masks are correctly followed. Other sources of leakage at the interface between the mask and the face of the wearer could lead to a pressure drop in the mask and an erroneous sampling in the visor for intense breathing patterns. However, this level of physiological constraint has never been measured for these activities of asbestos removal in the workplace if they are carried out in accordance with the regulations in force

To guarantee that RPD are worn and used appropriately, for each operator who is followed during the campaign in occupational situations to assess exposure to asbestos fibres inside RPD a quantitative fit test is systematically performed with the modified masks tested.

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