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Workplace Fit of Full Face Mask Respirators— A New Approach

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Abstract

The work evaluates the practical application of a novel means of measuring facial fit and consequent indication of protection potential, of a full face mask respirator on volunteers in a workplace situation. Additionally, the same methodology was employed to measure inward leakage levels on the same volunteers whilst performing appropriate tests from European Standards (CEN Standards) so that a direct comparison could be made between these results and measurements of facial fit of the same respirator when worn in the workplace. At the same time data were gathered on breathing resistance levels and on facial dimensions of the workplace volunteers. The method uses the sampling system and the test challenge gas employed in CEN Standard tests and applies it via a hood fitted over the respirator wearer's head and the face seal of the face mask.

In the workplace situation investigated, the hood arrangement and associated instrumentation proved robust and capable of being used by wearers of full-face mask respirators. The system was able to give a real time measure of face-seal leakage and may, in some circumstances also have potential to assess performance of individual components such as exhalation valves etc. in a dynamic situation.

Levels of leakage measured in the workplace implied that the respirators were inherently well fitted and that the wearers were likely to have achieved levels of protection above that which is accepted as the pass criterion in CEN tests on such face masks. The work has also shown that in this instance, tests in European Standards are more rigorous in terms of work effort and breathing resistance load on wearers. There were some activities in the workplace which were not reproduced in the exercises in the CEN test, but there were no undue high leakage levels when these activities took place in the workplace.

Certain facial dimensions were recorded and their relationship with the Los Alamos grid is discussed. About 25% of the wearers had dimensions which placed them outside the grid and at the 'larger' end of the distribution.

In addition, an evaluation was made of a portable video visualisation system which gives a real time indication of leakage related to activity of the volunteer and movement. The system performed well and proved useful in identifying the cause of an abnormally high leakage level.

Introduction

Tests carried out in European Standards (Comite European de Normalisation or 'CEN Standards') and equivalent British Standards can show the potential of Respiratory Protective Equipment (RPE) to give protection but there is a need for information on actual workplace performance of RPE as compared to its performance under standard test conditions. Though information on the former exists, it often employs techniques not directly comparable to the latest techniques used in CEN tests. Also, exercise and work regimes are often different. It is, therefore, rarely possible to compare workplace performance directly with that achieved under CEN test conditions in the laboratory.

An important factor in determining the protection level provided by a full face mask respirator is the amount of leakage of challenge contaminant via the interface between the wearer's face and the seal of the face mask. Tests carried out in European and British Standards for full face masks (Comite European de Normalisation (CEN), EN 136:1989) measure the total leakage reaching the wearer's breathing zone; "face-seal leakage" forms a major component of this. Other sources of leakage are probably from the exhalation valve and possibly the visor. Since the Standard refers to face masks only and not the complete respirator, filter penetration is not included. The maximum value of leakage into

the breathing zone allowed in order to pass the Standard gives rise to the 'Nominal Protection Factor.'

The purpose of this work is to evaluate the practical application of a method developed in the laboratory which assesses the face-seal leakage of a full face mask respirator in a workplace situation on a number of volunteers. The method uses the test challenge gas used in CEN standards and applies it via a hood fitted over the RPE wearer's head. It goes on to compare these workplace leakage measurements with those from actual CEN test results on the same workplace volunteers wearing the same face mask. Other parameters such as breathing resistance and facial dimensions are also measured, the former to provide information to assist in formulating European standards and the latter to form part of a data-base ultimately to assist in evaluating the need for the provision of different sizes of face mask. A video visualisation system which superimposes a visual indication of mask leakage level onto a video of the subject at work is also employed. This serves to highlight actions and movements which might contribute to different levels or peaks of leakage.

The project has been cleared by the Health and Safety Executive (HSE) Research Ethics Committee.

2. Workplace Measurement Programme

2.1 General

The workplace study took place at a large chemical and polymer production plant, Id's Hillhouse International site at Thornton Cleveleys in the UK. It was the final phase of our approach to assessment of workplace performance of full face mask respirators using a method which applies sulphur hexafluoride (SF_6), the challenge gas used in leakage tests in European standards, to the face seal of a respirator while worn by regular users of such devices at work in a workplace environment. In addition, recordings of breathing resistance of the full face mask respirator were made.

The system, known as the 'PPE challenge hood,' has had considerable laboratory development and evaluation (Bancroft *et al.*, 1996, Clayton *et al.*, 1996). It consists of a hood, sealed to the rigid portion of the face mask and which fits over the wearer's head and the face seal of the mask. The hood incorporates a thin flexible latex rubber membrane (as employed in hoods used in some escape apparatus) to form an effective seal between the hood and the wearer's neck. A series of flexible supports formed in a 'crescent' shape hold the hood clear of the actual face seal to form a channel or 'halo' which passes around the circumference of the mask and which is filled with an SF_6 /air mixture. The subject is able to fit the

face mask and tighten the straps in the usual way. The arrangement is shown in Figure 1. An analysis of the laboratory development test data of face seal leakage results from tests carried out on wearers of both face masks alone and on face masks fitted with the challenge hood concluded that the hood did not significantly affect the level of face seal leakage, after allowing for the natural inter-subject and intra-subject variation in fit on the test subjects. The inward leakage of SF₆ into the wearer's breathing zone resulting from an imperfect face seal fit together with that of the challenge concentration in the hood were measured using a 'BINOS' 1004 microprocessor controlled gas analyser designed specifically to detect SF₆ by infra-red absorption. The device is manufactured by Rosemount GmbH & Co. It has two channels with four ranges per channel. The span value of the most sensitive range is 0.5 ppm is programmable. Some of the results were obtained with this scale reprogrammed to 0.1 ppm. This was achieved using a 1 ppm gas standard. In either case, scale points below full scale were obtained by dilution using a Wosthoff pump and calibration curves plotted. 'Clean air' readings were obtained using 'white spot' Nitrogen. With a hood concentration of 5000 ppm SF₆ it was possible to measure inward leakage levels well below the maximum

allowed by the European standard. Laboratory evaluation of the BINOS under various temperature and humidity conditions showed the equipment working within the manufacturer's parameters, but frequent calibration checks were carried out during use. Measurements in the breathing zone were taken via a standard 'ball probe' as used in CEN tests. This is a hollow plastic sphere about 20 mm in diameter and having a series of small holes around its circumference. The sphere is placed as near as possible to the subject's lips and connected by suitable tubing to the BINOS, the tube being sealed at the point where it passes through the mask wall.

The hood system is not intended to provide a measure of "protection factor," i.e., the ratio of contaminant outside the mask to that inside, since amongst other things, valve leakage and filter penetration are not taken into account, though a tentative estimate can be made. Its main purpose is to assess the leakage into the mask via the facial fit and thus to identify potential good or bad fit; movements which affect the fit etc. and to provide background information in order to improve or optimise a particular situation. These workplace studies were aimed at assessing the viability of the system, its robustness and application to a workplace situation,



Figure 1. Fit of hood showing crescents and lateral creases.

at the same time yielding information on a set of workplace volunteers who wear full face masks as part of their normal workplace routine.

The work aimed to carry out leakage tests on the volunteers in their workplace situation, wearing the mask/hood combination and then assess the same volunteers carrying out an inward leakage test as described in EN 136, without removing the mask/hood i.e. with the fit on the face as near as possible the same. In addition to this, so that we could be sure that each volunteer was basically suited to wearing a full face mask, we carried out a further set of inward leakage tests while another face mask of the same type and provided for this purpose was worn. This combination of tests yielded the following information:

- (i) EN 136 TEST WITH the 'spare' mask (which we have called "EN 136" results)—an indication of the basic suitability of a volunteer to wear a full face mask.
- (ii) EN 136 WITH MASK and hood (which we have called "HEN 136" results)—a comparison between EN 136 and HEN 136 results, though on different face masks.
- (iii) Workplace face seal leakage tests (which we have called "WP" results)—to give a comparison between workplace performance and that from a standard test.

During all the above leakage tests, recordings of breathing resistance were made. The system employs the SF₆ sampling probe simultaneously as a pressure sensing probe.

In total, this is a fairly ambitious programme and given the need to comply with shift patterns etc. proved to be fairly complicated to arrange and organise. Fortunately, next to the workplace site was a training room where we were able to set up our treadmill and an operational base. Thus we could transfer our sampling equipment from base to workplace or vice-versa in about 20 minutes.

The workplace volunteers were all part of the emergency response team and were either employees of ICI or of Group 4. Thus they were fully trained to wear self contained breathing apparatus with a full face mask. In addition to their emergency response duties however, part of their work involved refilling dry-powder fire extinguishers drawn from across the whole site. This took place in an unheated building, formerly a garage. At one end of this room was a smaller room housing a vacuum operated filling system which injected a charge of powder into the

extinguisher. It was this process that created any airborne dust, though the resulting dust cloud was usually of low concentration. However, in the case of a malfunction of the vacuum filling system it is possible to get a short period but relatively high burst of airborne dust. As part of general policy on the site, full face masks and the appropriate filters are now being introduced for this process.

The workplace procedure involved the extinguishers being stripped down at a bench in the main room and then being carried to the filling room about 5 metres away. After filling, the container was carried back to the bench and the whole reassembled. RPE was worn throughout the procedure and three units were serviced within a half hour period. The sampling equipment was placed on the opposite side of the room from the stripping bench so that the umbilical connecting the volunteer to the 'BINOS' instrument, used to measure SF₆ concentrations, was able to accommodate the movement of the volunteer from bench to filling room. The filling procedure involved no heavy work, other than carrying charged extinguishers, but it involved quite a lot of movement around the room, considerable bending, crouching and various head movements, many not reproduced in the exercise regime called up in EN 136.

2.2 Leakage tests

2.2.1 Fitting of hood/mask. Though each volunteer was familiar with the fitting and wearing of full face masks, there is a technique to donning one fitted with a hood. To help in this, a hood/mask was left at the site some six weeks previous to the trials in order for each person to try out and make comments. At the time of the study, no volunteer refused to wear the device and after workplace measurements there were no adverse comments about fitting the hood even though some wearers had performed a HEN 136 test and then waited for workplace trials to start, whilst still wearing the hood/mask. In some cases they could eventually have spent about two hours wearing the hood.

The technique for fitting the hood etc. was explained to each wearer before the test and observers ensured that their masks appeared to be a good fit by looking for signs such as hair under the face seal, etc. Observers were keen to ensure that the volunteers fitted the masks in the usual manner with straps tightened to their normal tension. However, there was usually no problem with these experienced wearers. Before fitting the filter, each wearer

carried out a fit-check by sealing off the inhalation port by hand and then gently inhaling. This is a method which is used to show any significant leaks, bad fit, etc. When the face mask had been fitted to the wearer's satisfaction and the straps tightened over the hood, etc. observers then ensured that the rear strap on the hood was correctly fastened. They also looked to ensure that the "crescent" arrangement which ensured the hood "halo" effect around the face seal area was present. Also, the presence of lateral creases running parallel with the face-seal line showed that there was no tension in the hood material which could inadvertently assist the seal of the face mask on the face. Figure 1 illustrates this.

After each test, the volunteer's face was examined for marks on the face which showed evidence of closeness of fit of the facemask. In most cases these were quite clear, as Figure 2 shows.

2.2.2 Face mask tests in EN 136. The inward leakage test in EN 136 requires that the test subject walks on a treadmill while carrying out various head movements, the whole system being within a chamber filled with a known concentration of a challenge gas, SF_6 . The test protocol specifies that either the

mask is fitted with a filter simulator to represent the worst case of filter resistance and weight allowed to be used with a full face mask, or that the mask is fitted with the filter with which it is intended to be used. In either case, clean air is fed to this filter or filter simulator so that when the system is worn in a challenge atmosphere of SF_6 , the only source of inward leakage experienced by the wearer is from the mask i.e., face-seal, visor, valves etc. Since our workplace trials all involved the use of a specific P3 filter for use against particles, we opted for the second arrangement.

The test exercises called up in EN 136 are as follows:

- (i) Ws—walking at 6 kilometres per hour for 2 minutes.
- (ii) S.S.—walking at 6 kilometres per hour for 2 minutes (while moving the head from side to side).
- (iii) U.D.—walking at 6 kilometres per hour for 2 minutes (while moving the head up and down).
- (iv) T—walking at 6 kilometres per hour for 2 minutes (while talking e.g., reciting the alphabet).

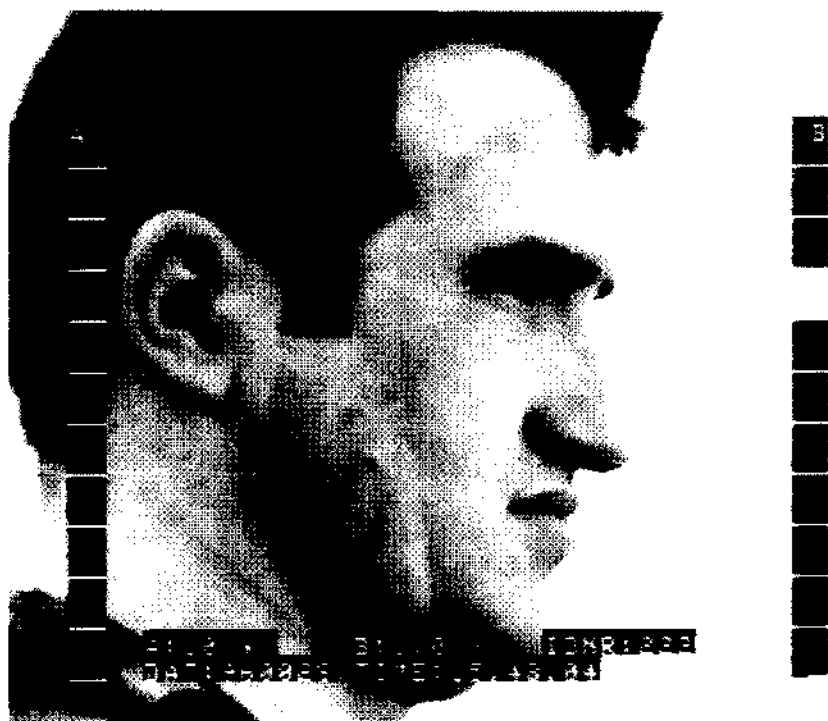


Figure 2. Face mask marking on test volunteer's face.

- (v) We—walking at 6 kilometres per hour for 2 minutes.

During this time inward leakage measurements are recorded. For the purposes of a pass/fail test in the standard the mean inward leakage over the last 100 seconds of each exercise is calculated. To pass, no exercise must yield an inward leakage greater than 0.05% for any of ten test subjects i.e., a nominal "protection factor" of 2000.

This protocol was used to assess each volunteer, using the same mask (M3) and filter. Because clean air was being supplied to the filter, we were able to estimate the minute volume of volunteers in the exercise. We recorded breathing resistance of the respirator also, which though not a part of the standard test requirement, will serve as useful data in discussions on European Standards.

Results from this set of tests are referred to as "EN 136" results. Each test subject was cleared by ICI Medical and Occupational Hygiene Services for the exercises on the treadmill and for all activities. It was noted that in general these exercises were more vigorous than those in the subsequent workplace regime.

2.2.3 Face mask/hood leakage test. This test is again an inward leakage test using the EN 136 protocol but with a number of differences. The mask used is fitted with the PPE challenge hood and the same combination is also used in the workplace measurements. Two masks were used for the majority of the tests, M5 and M6, being used on alternate wearers. A third mask, M1 was also used initially, but this was withdrawn for subsequent examination of its exhalation valve. Figure 3(a) shows a typical test in progress together with the sampling equipment.

Since the hood carries its own atmosphere of SF₆ around the face seal, as the wearer walks on the treadmill the only source of SF₆ in the wearer's breathing zone is from the face-seal when the test chamber contains clean air. Thus, in order to make a direct comparison between wearer fit in our HEN 136 tests and wearer fit in EN 136 tests, which include both face-seal and visor leakage, the chamber surrounding the treadmill is also filled with SF₆ so that valve and visor leakage can be included.

The procedure adopted was to ask the wearer to walk on the treadmill with clean air in the hood and clean air in the chamber. While walking, SF₆ was

admitted to the chamber. Any leakage now measured in the wearer's breathing zone was due to valve/visor leakage. This value was noted. As the wearer continued to walk, SF₆ was admitted to the hood and after stabilisation the new leakage level represented the total contribution of face-seal and valve/visor leakage—a measurement comparable with the inward leakage obtained for M3 from the standard EN 136 test. The wearer then reproduced the head movements previously described and the test was completed.

This additional measurement on valve leakage was useful information to have since in the workplace we only measured face-seal leakage and nothing was known about the extent of valve leakage. Using the above estimate of the magnitude of the valve leakage, we were able if we wished, to make an estimate of the total mask leakage in the later workplace tests and thus an estimate of the "protection factor" if we assumed that the filter was performing well. The usefulness of a knowledge of valve performance was demonstrated when we were able to identify a leaking exhalation valve, which was subsequently traced to a hair on the valve seat.

On completion of the exercises in the HEN 136 test, the volunteer was asked to rest with the mask in place while the sampling equipment was moved to the workplace. Ideally, to make a direct comparison between face-seal leakage from these HEN 136 tests and subsequent face-seal leakage tests in the workplace we would need to repeat the test exercises once more with clean air in the chamber and SF₆ in the hood. However, this would have needed too much of the volunteer's time, as well as being a considerable extra physical burden.

2.2.4 Workplace leakage tests. The situation in the workplace has been described in 2.1 above. Our sampling equipment was placed on the opposite side of the room from the bench where the servicing of extinguishers took place. The umbilical connecting the volunteer to the BINOS sampling equipment was able to accommodate the movement of the volunteer from the bench to the filling room. Figures 3 (b) to (e) show a general view of the workplace activities, instrumentation and volunteers.

Continuous monitoring of the inward leakage and breathing resistance of the mask during the operation then proceeded, with the visualisation technique also being used. Background levels of temperature and humidity were also recorded.

Because the wearer exhales an SF_6 /air mixture breathed in due to mask leakage, and because inevitably there is some small outward leakage from the hood, there can be an atmosphere of SF_6 around the wearer on occasions which may be rebreathed through the filter. Since no removal of SF_6 takes place in the filter this shows up as an apparent inward leakage in the wearer's breathing zone. In order to estimate the amount rebreathed via the filter we used an Electron Capture Device (ECD) which is a leak detector normally used to detect refrigerant gases but which we had calibrated and adapted to measure low levels of SF_6 with a sensitivity of 0.1 ppm. This was connected to a sample tube placed at the air inlet to the P3 filter. Thus it was possible to

note when previously exhaled SF_6 was being re-inhaled. This enabled us to correct the measurement in the mask to get a better idea of the true face-seal leakage. After some experience it became possible to make an assessment by looking at the wearer's position whether a particular peak leakage was due to this rebreathing situation. In any case, levels of total inward leakage were relatively low during the workplace exercises, so that even when the amount rebreathed was discounted, the masks appeared to be a good fit on the wearer.

2.2.5 Study protocol. The study protocol which was most practicable, given the wearer's commitment to possible emergency call out and the length

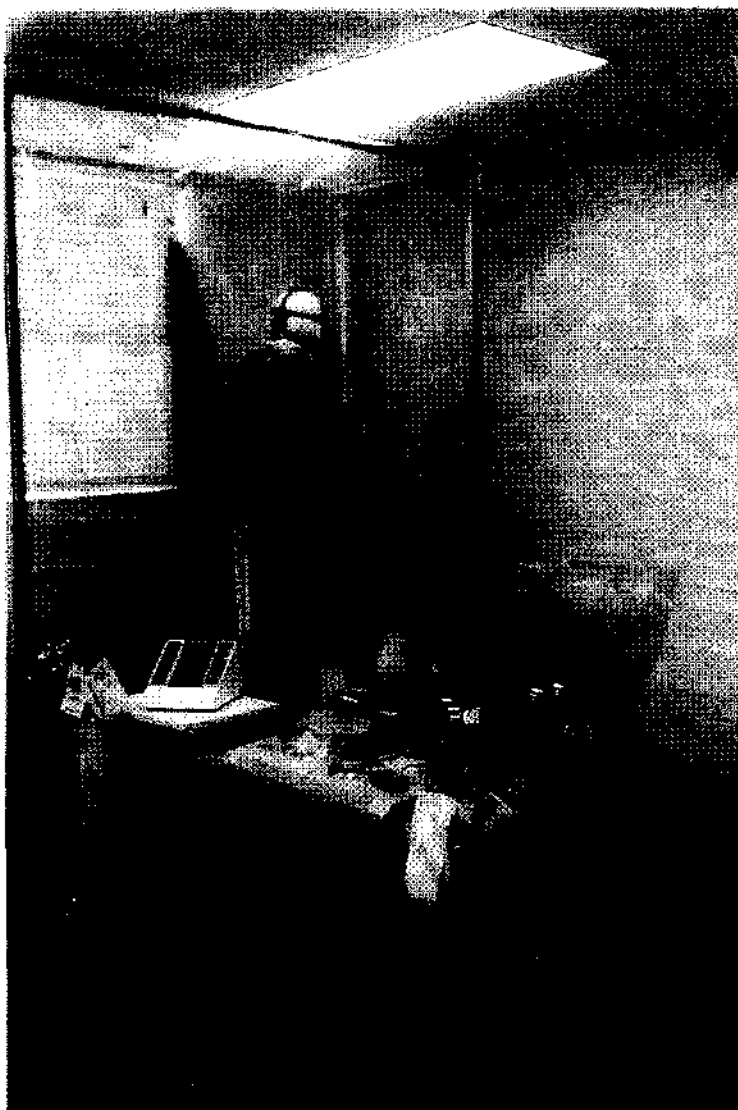


Figure 3(a). Typical HEN 136 test in progress.



Figure 3(b). Test volunteer entering extinguisher charging room.

of time involved in the study—approximately 2 hours per volunteer, was arranged as follows for each volunteer.

An assessment was first made of the basic suitability of the volunteer to wear a full face mask by measuring the inward leakage while wearing a face mask (M3) during a standard EN 136 test protocol. Thus, if a poor fit is highlighted during subsequent tests in the workplace, we are reasonably sure that the reason is not that this type of full face mask does not fit.

As soon as possible after this the test was repeated using the face mask fitted with the PPE challenge hood, providing us with the HEN 136 results. This confirms that the mask fits and, importantly, gives us a bench-mark level of inward leakage which is effectively that of the EN 136 test, the challenge being applied via the hood instead of in the chamber.

Finally, without removing this mask/hood, the sampling and measuring equipment was transferred to the volunteer's workplace where we then measured inward leakage whilst workplace operations

were carried out. By keeping the HEN 136 test and the workplace measurements in conjunction, (the order does not matter but the hood/mask combination must not be refitted between the two sets of measurements), the effect on the face seal of refitting the mask is eliminated. We can thus compare directly the leakage measured in a standard test and that in a workplace situation, on the same wearer using the same measurement system.

When a set of results for one volunteer had been completed, because our sampling equipment was now in the workplace, measurements on the next volunteer commenced here and then proceeded in reverse order—HEN 136 to EN 136. In this manner we were able to deal with about four volunteers per day.

Certain facial dimensions of volunteers were obtained using a specialised vernier calliper system. We were not able to measure all the volunteers, but the data we did obtain is recorded for possible future analysis and is discussed briefly at 3.4. The laboratory and workplace activities and data were recorded using the video visualisation system for subsequent analysis.



Figure 3(c). Dismantling extinguisher prior to recharging.

3. Discussion

3.1 Performance of hood and instrumentation

No problems were encountered throughout all the test exercises, transportation of the system etc. The BINOS infra-red analyser performed reliably after a number of journeys and repeated transfers from the laboratory base in the training room to the workplace base during the trials. The equipment needs preferably about one hour from switch-on to reach a condition where its calibration remains stable. However, the equipment is useable in a shorter time than this and could be calibrated more frequently or immediately before and after a set of readings if necessary. However, in practice if the hood/mask is being used as simply an assessment of good or bad fit, or to analyse workplace movements for those which cause leakage, then the need for accurate calibration is less important.

The umbilical system performed well, without kinking or becoming ensnared. This is due mainly to the harness arrangement worn by the volunteers, and

the simplicity of movement. The umbilical, although allowing a degree of wearer mobility, will restrict the type of workplace applications where this method is suitable. This umbilical carries more tubes than those needed for simple inward leakage measurements. As well as mask leakage, we were recording hood concentration, hood pressure and breathing resistance. The umbilical also carries feed lines of SF_6 to the hood, and the return line. If simple inward leakage "assessment of fit" were needed then only the feed line and the mask sample line would be needed, making the assumption that the hood concentration would be that of the gas feed to the hood. However, as Figure 4 shows, when inward leakage peaks there can be some reduction in challenge, due presumably to dilution by mask air escaping via the face seal into the hood. Though the effects in both the hood and the mask are virtually simultaneous, Figure 4 appears to show the hood effect occurring prior to that in the mask. This is because of the time lag in sampling from the mask compared to that when sampling from the hood. It can be seen that the hood concentration quickly



Figure 3(d). View of video, visualization monitor screen.

recovers if the mask fit returns to a low level of leakage. However, both in the laboratory development work and in the field trials we have only encountered relatively low levels of face-seal leakage. In our laboratory work we compared leakage on wearers who interchanged the mask and the mask hood combination so that we were able to assess the effect of the hood. We did not artificially increase face-seal leakage because past experience has shown us that this is not reproducible. Therefore, we were not able to assess the performance or effect of the hood on mask with high inward leakage. The same problem is evident in our workplace trials. It may be that with larger levels of leakage, constant monitor-

ing of the hood concentration may be necessary to allow for this dilution effect.

The hoods themselves proved robust and did not need replacing throughout the period of the trials. It is important to ensure that the halo around the face seal is complete and that the hood is not in tension in this area. Apart from this, wearers had no difficulty in donning the hood mask combination.

3.2 Leakage measurement

3.2.1 Inward leakage results. As described, these fall into three main categories. They are results



Figure 3(e). View of hood, respirator, and associated sampling tubes.

obtained from the European Standard tests, "EN 136," using mask M3; those obtained from identical tests but where the challenge gas is contained in the hood, "HEN 136 Results" mainly using masks M5 and M6; and workplace results, "WP Results" obtained on the same two masks without disturbing the fit. Average inward leakage results are shown in Table 1 and Figure 5. All three sets of experiments were found to be log-normally distributed as is usual with such leakage data.

EN 136 results in column 2 are a measurement of total inward leakage including all sources except that

due to filter penetration, i.e., face-seal leakage, valve/visor leakage etc. This is usually called "inward leakage." HEN 136 results, column 3, are also total inward leakage excluding filter penetration because, although the challenge for the face-seal leakage was contained in the hood, the test chamber was also filled with SF_6 in order to include any valve/visor leakage etc. and thus to give comparability with EN 136 results.

The extent of valve/visor leakage is shown in column 4, arrived at as previously described in 2.2.3, by filling the hood with clean air whilst the chamber

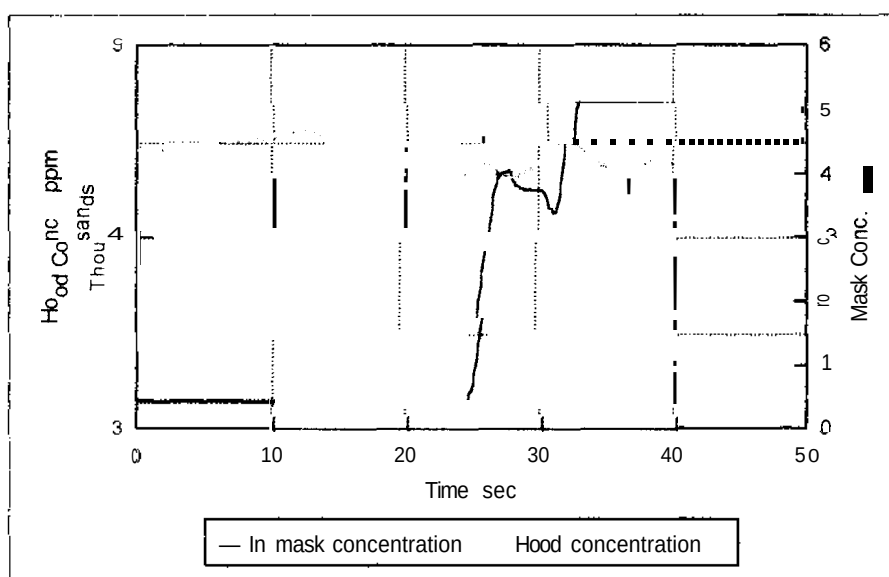


Figure 4. Effect of leak into face mask on the hood concentration.

Table 1. In-mask leakage values expressed as a percentage of challenge concentration.

Volunteer no.	Mean leakage values %				
	EN 136 Inward leakage	HEN 136 Inward leakage	Valve leaking	Derived face-seal leakage HEN 136	Workplace face-seal leakage
Col 1	Col 2	Col 3	Col 4	Col 5	Col 6
1.0000	0.0255	0.0153	0.0019	0.0134	0.0010
2.0000	0.1560	—	0.0060	—	0.0022
2 rpt	0.0045	0.0017	0.0025	-0.0008	0.0035
3.0000	—	0.2080	0.3303	-0.1215	0.0010
4.0000	0.0050	0.0023	0.0005	0.0180	0.0018
5.0000	0.0083	0.0017	0.0009	0.0008	0.0028
5 rpt	0.0073	0.0017	0.0005	0.0012	0.0013
6.0000	0.0193	0.0128	0.0036	0.0092	0.2853
7.0000	0.0120	0.0085	—	—	0.0033
8.0000	0.0044	0.0030	0.0023	0.0007	0.0014
9.0000	0.0314	0.0064	0.0055	0.0009	0.0020
10.0000	0.0077	0.0062	0.0017	0.0045	0.0001
11.0000	0.0040	0.0023	0.0072	-0.0049	0.0037
12.0000	0.0097	0.0023	0.0046	-0.0023	0.0001
13.0000	0.0072	0.0060	—	—	0.0012
14.0000	0.0049	0.0147	0.0017	0.0130	0.0016
15.0000	0.0060	0.0187	0.0011	0.0176	0.0008

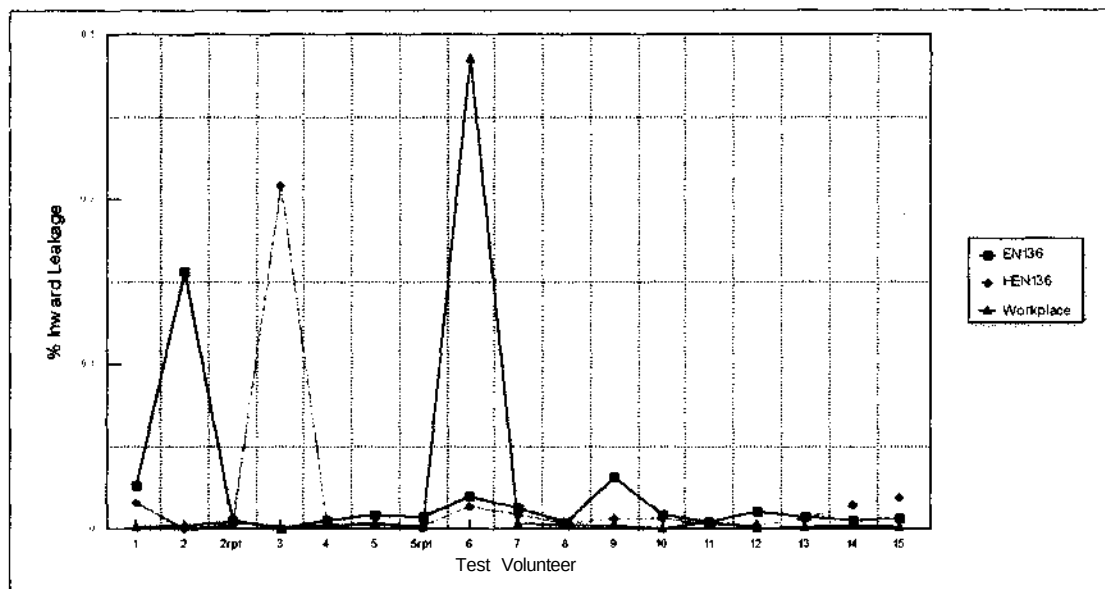


Figure 5. Average % inward leakage for EN 136, HEN 136, and the workplace.

was filled with SF_6 , prior to carrying out face-seal leakage experiments. In this condition then there is no face-seal leakage or filter leakage and all leakage measured within the mask must come from valve/visor leakage. This allows us to estimate the face seal only leakage during HEN 136 tests by subtracting this valve leakage from the inward leakage results in column 3. This is shown as 'Derived Face-Seal Leakage' in column 5. Now, face-seal leakage in HEN 136 tests can be compared with face-seal leakage occurring in the workplace.

Finally, column 6 shows the actual average face-seal leakage measured over the workplace sampling period. These figures have been corrected for pick-up of extraneous SF_6 in re-inhaled exhalate in the ambient air surrounding the mask, as described in 2.2.4.

3.2.2 EN 136 results. The results in Column 2 show that with the exceptions of volunteers No. 2 and No. 3, each wearer achieved a fit of their face mask considerably better than that of the 'pass' criterion for assessment in EN 136 tests i.e., 0.05% inward leakage. In some cases the results were an order of magnitude greater. Broadly speaking then, the results of the EN 136 test show that the volunteers are suited to wearing full face masks and that their fitting procedures etc., certainly on this occasion, were adequate.

Figures 6(a) and 6(b) show some interesting features about the fit of the mask on some of the volunteers. The leakage for volunteer No. 1 can be seen to get progressively worse with each change of action within the movements required in the test. Conversely for volunteer No. 9 the fit improves as the test proceeds. These examples show both the importance of achieving and maintaining a good fit and the effect of movement on the fit of the mask, remembering that each of these wearers is experienced in wearing a full face mask and had taken care to fit it correctly. A subsequent examination of the video for each of these wearers appears to show a good fit judged by marks on the face etc.

An examination of the records of inward leakage during the first test on volunteer No. 2 shows that leakage into the mask during the first exercises of the test were at a low value, 0.003% and that during the final exercises a similar low level of leakage was achieved. However, during the exercise involving side to side head movement the inward leakage increased considerably, to about 0.25%. Examination of the video taken at the time seemed to indicate that the clean air supply tube feeding clean air to the particle filter fitted to the mask was interfering with the fit of the mask and appeared to pull at the extremes of movement. This could be the possible cause of high inward leakage which produced an overall mean inward leakage value greater

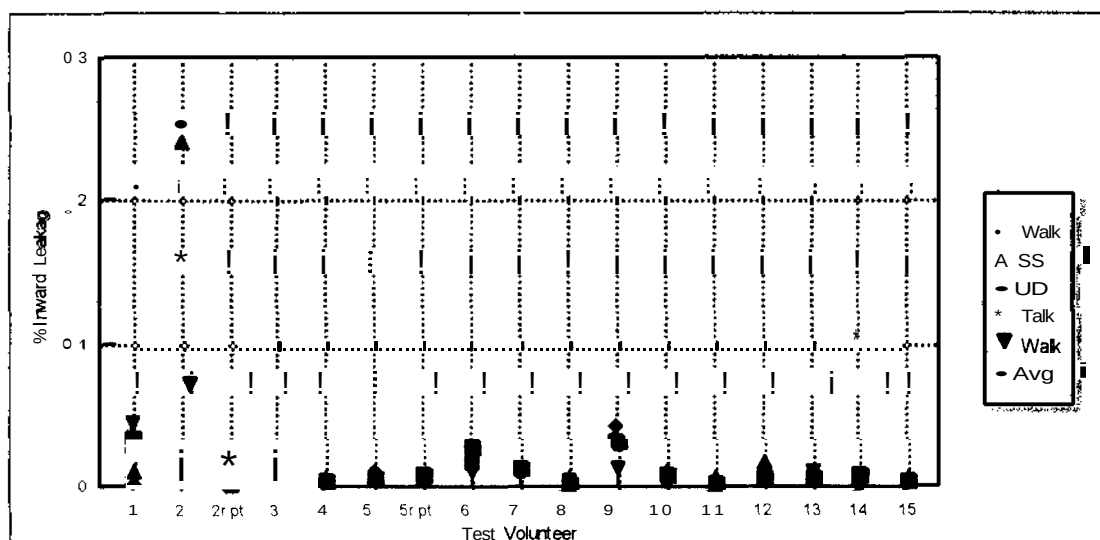


Figure 6(a). Average exercise inward leakage in the EN 136 test for each test volunteer.

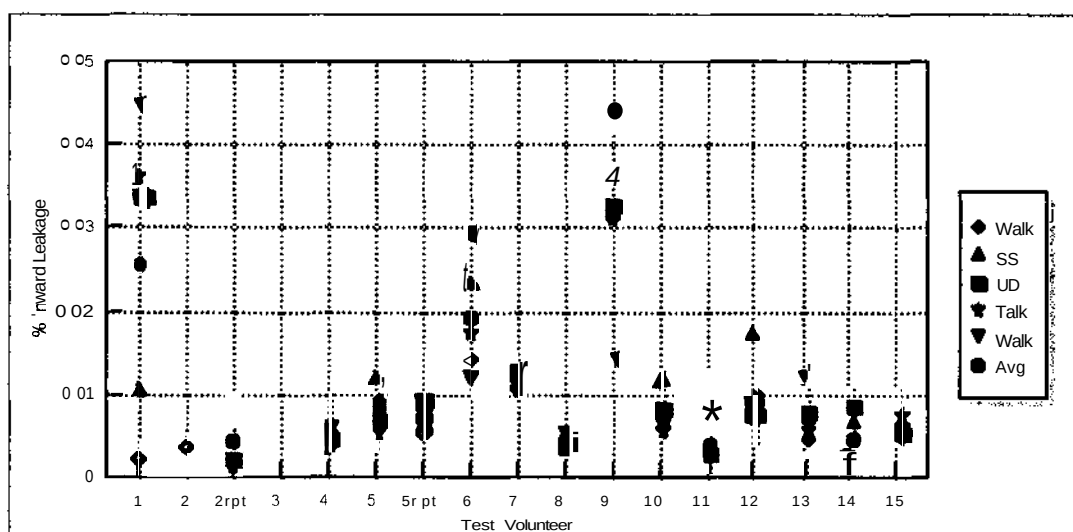


Figure 6(b). Average exercise inward leakage in the EN 136 test for each test volunteer (more detailed scale).

than 0.05%. A repeat test of volunteer No. 2 at a later date showed a much improved fit, giving a mean inward leakage of 0.0045%.

No EN 136 test was carried out for volunteer No. 3 because we encountered mechanical problems with the treadmill at the time of testing. Because of the possibility of a breakdown and to minimise usage of the treadmill at that time, it was thought best to use

the treadmill only for HEN 136 tests before subsequently proceeding to workplace measurements.

3.2.3 HEN 136 results. An examination of the HEN 136 results shows most inward leakage levels within the 0.05% requirement of the European standard test, though again, volunteers No. 2 and No. 3 were untypical. The first test on volunteer No. 2 was abandoned because of the mechanical

problem with the treadmill, mentioned previously. However, a later repeat test showed a low level of mean inward leakage of 0.0017%.

As far as volunteer No. 3 is concerned, column 4 in Table 1 shows that the valve leakage for the mask was in the order of 0.3%. This level of leakage indicates a problem, since the usual criterion for a good valve is a mean leakage of less than 0.005%. We think, therefore, that this is the likely source of high inward leakage during the HEN 136 test on volunteer No. 3.

Clearly as subsequent HEN 136 tests progress with this leaky valve, the valve itself may well reseal or function at a different leakage level because of moisture and the rapid movements typical of valve actions. This is probably why the overall leakage value in the HEN 136 test, 0.2%, is less than the value for valve leakage measured just prior to the test.

A later examination of the valve and its seating showed a hair on the valve disc. This mask was withdrawn from the trials and subsequently examined in the laboratory. An inward leakage test was carried on the same test subject used to evaluate the mask before the workplace trials commenced. The mean inward leakage was found to be 0.034%. This is an order of magnitude greater than the value measured in the pre-trial state and while it is less than the failure criterion, it is possible that this increase is due to the presence of the hair.

Figures 7(a) and 7(b) show a similar situation to that described during the EN 136 comments, regarding increasing inward leakage and exercise regime. The results for volunteer No. 3 show steadily increasing inward leakage as the exercise increases. Unfortunately no comparison can be made with the test without the hood for this volunteer. For volunteer No. 6 the reverse occurs, and the fit of the device slowly improves with exercise, although in this case all the results are better than the pass criterion of 0.05%. The results from the equivalent EN 136 test do not follow this pattern so closely. Again the same inference can be made regarding apparent fit of the mask that was made in our discussion in clause 3.2.2.

A comparison of leakage values for EN 136 and HEN 136, columns 2 and 3 of Table 1, shows that with the exception of two results, all the HEN 136 results are less than their respective EN 136 results for the same volunteer. This is shown in Figure 8 which, with the exception of the results

for volunteer No. 9, also shows such differences to be small enough such that if we use the hood results as an estimator of fit, we are going to be close to the estimate achieved using the mask alone, particularly in the light of some of the factors discussed below. However, laboratory tests prior to these field trials showed that the effect of fitting the hood on two face masks which were nearly identical was not significant, other than in fairly sedentary exercise regimes such as steady walking without head movement. Thus, in an exercise regime involving movement, the presence or not of the hood was not detectable when the variability of a fit of a mask on different wearers was present. Since the workplace activities we encountered consisted of considerable head movement, though not at the same work rate as the laboratory test, we think that the presence of the hood is not the cause of the bias.

We do know however that there is a difference between mask M3, used for all EN 136 tests and masks M5 and M6 which were both used exclusively in HEN 136 and workplace tests. We know that masks M5 and M6 are identical, from laboratory tests carried out prior to the trials. Here, wearer tests showed average inward leakages of 0.0026% and 0.0028% respectively. However, mask M3 in similar tests showed an inward leakage of 0.0070%. It is not unknown for there to be a small but finite leakage in such devices (visor bezel, exhalation valve housing, speech diaphragm etc.) which could account for this difference. This is one reason why we carefully matched masks M5 and M6 which had hoods fitted.

We think therefore it is likely that the apparent bias between EN 136 and HEN 136 results is largely due to the bias between mask M3 and masks M5 and M6.

For completeness, we did try to apply the same process of analysis that we used for laboratory trials to the leakage results in column 2 and 3. The problem with this approach is that the field tests were not carried out in the same manner as the more rigorous laboratory tests which were dedicated to the statistical analysis of the effect of the hood. Because of the nature of the trials, we were not able to interchange masks among wearers, or to interchange masks among the different test regimes, EN 136 and HEN 136. In addition to this because of time constraints, shift patterns etc. we could not do repeat tests on test subjects, other than the two

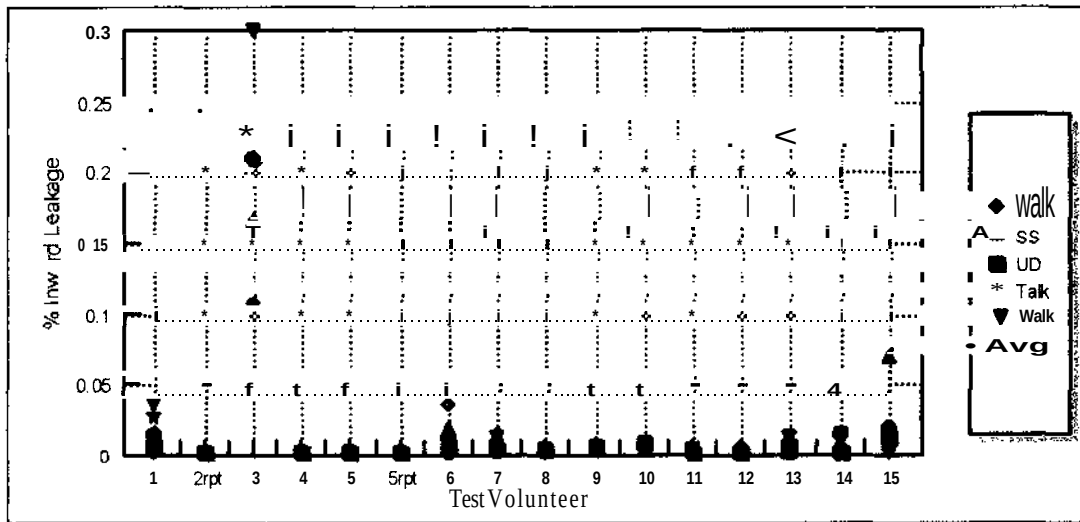


Figure 7(a). Average exercise inward leakage in the HEN 136 test for each test volunteer.

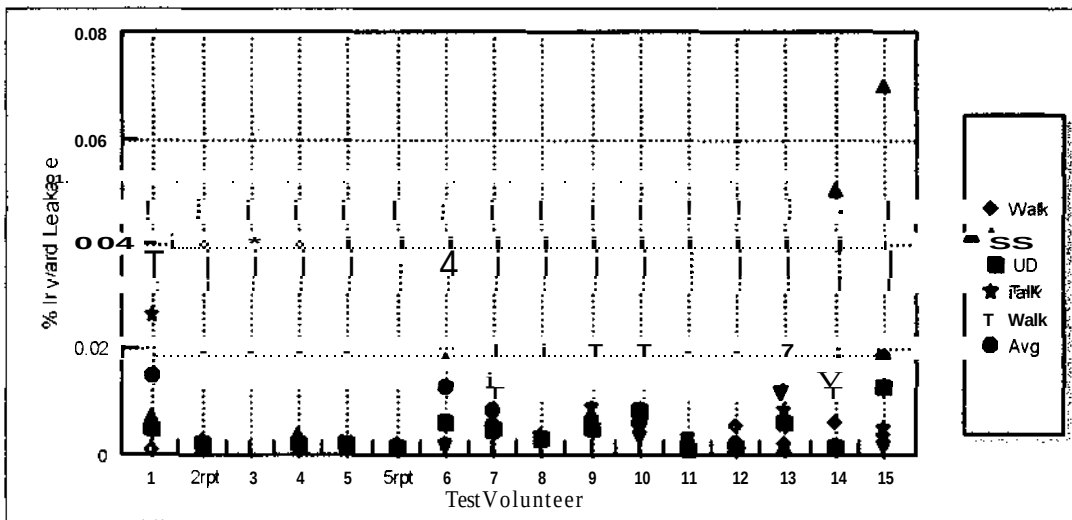


Figure 7(b). Average exercise inward leakage in the EN 136 test for each test volunteer (more detailed scale).

repeat tests which were carried out for different reasons.

The analysis that we did carry out showed, when we looked at specific test exercises within the test regime, that the ratio of EN 136/HEN 136 varied between 1.6 and 2.5, the latter results being derived from the UD exercise and being so scattered that it was not possible to detect the effect of the hood. Indeed, practical experience has shown us that in many experiments involving the refitting of a mask

on a wearer's face, factors of 2 difference in inward leakage can be encountered.

However, whatever the relationship between EN 136 results and HEN 136 results, the relationship between HEN 136 results and the subsequent workplace inward leakage measurements which immediately preceded or followed, remains because the fit of the mask and hood is the same. We can therefore draw a direct comparison between the likely performance in terms of face-seal leakage in a

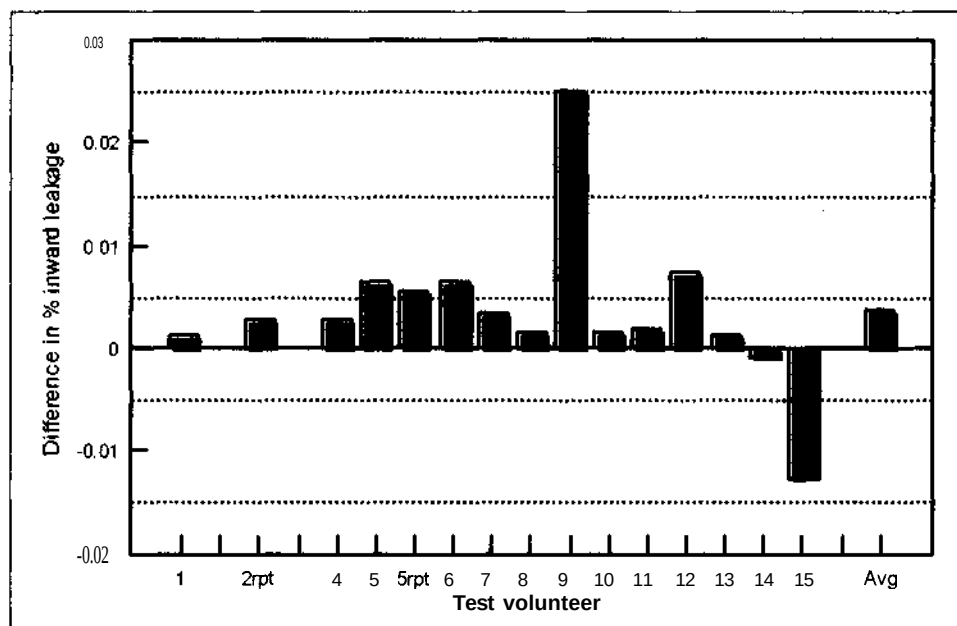


Figure 8. Difference between % inward leakage levels in EN 136 and HEN 136 (+ve values indicate that levels in EN 136 are greater).

European standard test and in the workplace if we make a correction for valve leakage.

3.2.4 Valve leakage. The purpose of the attempt to assess performance of exhalation valves is three-fold. The first reason is to give us some pointer that the valve is operating reasonably well. This is not a problem when EN 136 tests are carried out because valve leakage is included in the overall leakage measured. This is true in HEN 136 tests when we fill the test chamber with SF₆. However, when we move to the workplace situation where no valve leakage is assessed, we need to know that the valve is functioning within its parameters.

The second reason is to enable us to make the correction mentioned in 3.2.3 above, so that we can draw a comparison between HEN 136 results (face-seal leakage plus valve leakage) and workplace measurements (face-seal leakage only).

The third use of this knowledge of magnitude of valve leakage is in its contribution to our estimate of the 'protection factor' of the respirator in the workplace, covered later in 3.2.5.

However, in all these cases, because of the dynamic nature of the valve action and the fact that

it is subjected to humidified air there is no guarantee having measured this leakage that the figure remains constant, or that contamination does not work its way into the valve in a workplace situation and increase valve leakage. This is a problem in real life with all such respirators. This is born out if we compare in Table 1, valve leakage figures in column 4 with derived face-seal leakage in column 5. The negative results infer a level of valve leakage which is greater than the sum of the valve leakage and face-seal leakage, HEN 136 result, in column 3. We think that this is because the latter readings were obtained over a longer period than valve leakage was measured and thus there is the potential for the characteristics of the valve to change.

However, the hood system also has the potential to be used to actually assess the performance of individual components of the face mask, such as exhalation valves in a dynamic situation. It is unlikely that in a workplace situation this could be done by means of SF₆ leakage measurements, but it might be done by 'in-mask' leakage measurements of the actual workplace contamination reaching the wearer's breathing zone and excluding the contribution from face-seal leakage by filling the PPE Challenge hood with clean air. Also, if there was the need to investigate other sources of leakage into masks

during workplace activities, for instance due to breakthrough of gas filters, then the contribution of leakage from the fit of the mask on the wearer could be excluded using this technique.

3.2.5 Workplace measurements. The actual values of face-seal leakage experienced in the workplace are shown in column 6 of Table 1. This is the level after correction for pick up of SF_6 due to exhalate. With the exception of volunteer No. 6 the levels measured in the mask were in every case an order of magnitude less than the pass requirements of EN 136 i.e., 0.05%.

Figure 9 shows part of the workplace leakage trace for volunteer No. 6. It is not clear why the leakage is so high because the fit appeared to be correct at the start of the test, when levels of leakage were low, but they subsequently changed to the trace shown. Towards the end of the workplace measurements the leakage level fell. It is interesting to note the peaks of background pickup due to exhaled breath containing SF_6 occur at or about the times when the inward leakage in the mask shows a maximum peak.

This is a case where measurement on the volunteer started in the workplace and then progressed through to the treadmill measurements. It can be seen that by the time the first set of treadmill results (HEN 136) were taken, something had apparently changed to make the mask a better fit. There is a period of about 20 minutes between workplace and treadmill test whilst equipment is transferred from one location to the other, and it is not possible to say what happened to the fit at this time, though the wearer is asked to stay seated and asked to maintain the fit as near as possible the same.

If we had been performing the workplace measurements as part of a study of wearer suitability rather than a field assessment of the hood system, then at the first sight of large leakage peaks such as these, we would probably have stopped the test on the basis that either the wearer was not suited to wearing full face masks, or that on this occasion the fit was bad i.e., straps loose, hair in the face seal etc., or that there was a problem with our hood/measurement system. Complete removal and refitting of the latter would help to answer these problems.

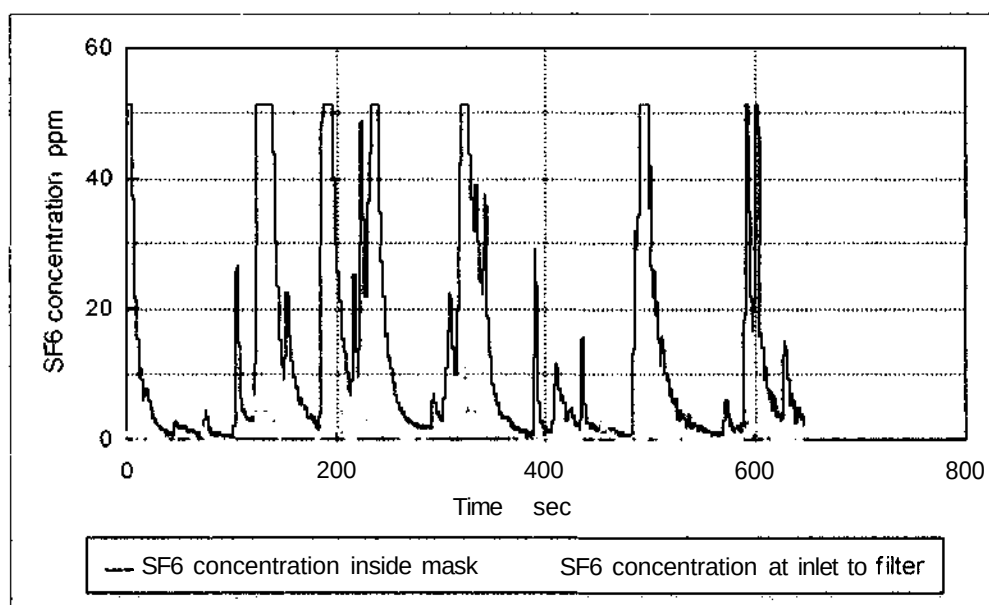


Figure 9. Extract of workplace leakage for test volunteer No. 6 showing the total SF_6 concentration inside the mask to the "pick-up" SF_6 concentration at the inlet to the filter.

However, since the airborne dust levels were low at this time, we maintained the workplace leakage test, hoping to see similar large peaks of leakage in subsequent treadmill tests which might have pointed possibly to a badly fitted mask, or perhaps to an unsuitable one in terms of size. However, the subsequent tests proved a reasonably good fit giving a mean value of 0.0128%. After observing the video, we are not able to say with certainty that the excess leakage observed in the workplace was due to activities which were not present in the following treadmill test. We were able to see that some of the high levels occurred in sedentary situations in the workplace which did have equivalence in the HEN 136 exercises when no such high peaks occurred. It seems likely therefore that this volunteer underwent a period where his mask had slipped and adjustment had been made unobserved.

If we compare the values of workplace leakage after correction for pick-up of exhalate containing SF₆ (column 6 of Table 1) with leakage in HEN 136 test (column 3), in all but two cases, one of which is the result for volunteer No. 6 just described, the workplace leakage is less than that occurring in the standard test.

A number of factors could be involved here. Firstly and probably most significantly, the workplace regime is not so strenuous as in the standard test in terms of actual work rate. In the treadmill exercise, the volunteer is unable to regulate work rate since this is governed by treadmill speed. However, the workplace activity involved more head movement than is required in the standard test. Secondly, the HEN 136 results include an element of valve leakage, not seen in workplace measurements. We have described how the current method of valve leakage is more of an indicator than a true measure of leakage, but for a guide, column 5 shows the HEN 136 figures corrected for valve leakage i.e., this is then an indication of face-seal leakage in the HEN 136 tests and as such can be compared directly with workplace face-seal leakage in column 6. Clearly there are the anomalies due to the valve leakage measurement factors mentioned in 3.2.4 which can produce negative values of face-seal leakage in column 5. However, for the ten values that are not anomalies in this way, four have workplace face-seal leakages less than that measured in HEN 136 test, five have the reverse and in one set the leakage is the same. Again the leakage values involved in both sets of exercises are in general so low that this comparison is academic. It is clear that the wearers carrying out the workplace exercises,

with the one exception quoted, have well fitted masks.

When this study was devised, we knew that there would be the likelihood of volunteers rebreathing SF₆ present in the exhalate of the mask. The sampling equipment is sensitive to small amounts of SF₆ in the air and we could not predict if the amounts rebreathed would be large. Laboratory studies had predicted that the exercises most likely to be affected by pick-up would be when the subject was bending or crouching and looking down. Air movement around the subject was also a factor. Because we did not know the extent of the problem in the workplace situation, as previously described, an ECD device was used to assess pick-up being rebreathed by sampling from a probe fitted over the inlet of the filter of the respirator. Table 2 shows the mean in-mask leakage (all sources) and the pick-up measured by the ECD. Subtracting the latter from the former gives an estimate of face-seal leakage of the mask. It can be seen that out of seventeen results, in only two is the pick-up less than the actual face-seal leakage.

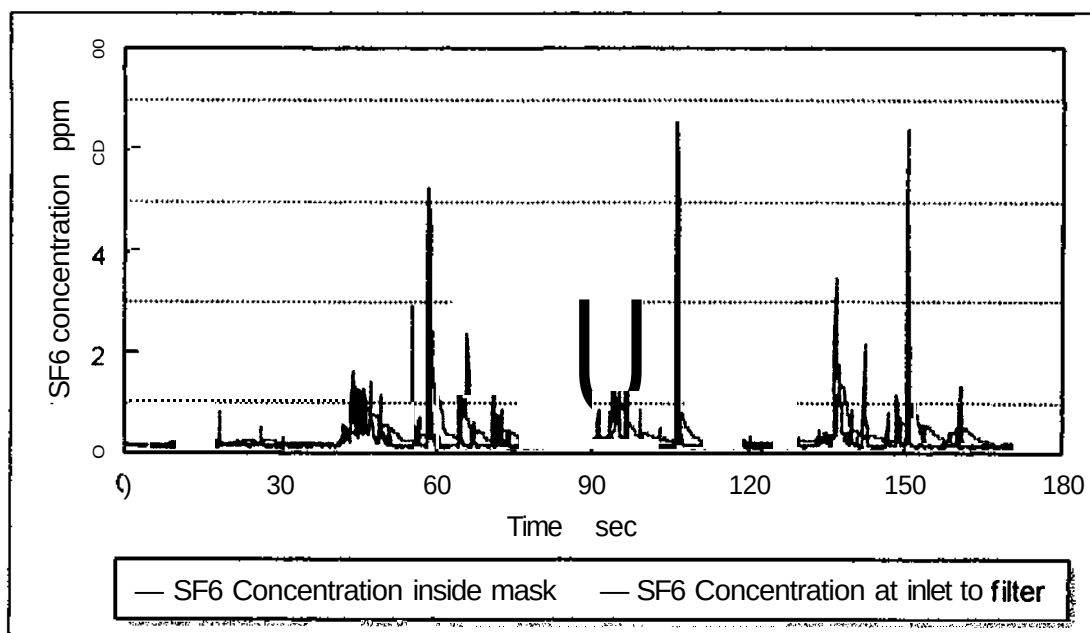
One source of problem measuring the pick-up of SF₆ is that it could easily "stream" into the filter inlet and thus the position of the sample probe could be an important factor. However when the in-mask sample is taken, this streaming has been diluted into the total volume of air breathed and the mixture has been passed around the inside of the visor and into the inner mask volume and so becomes more diffused. The overall effect is that the sample probe in the mask gives an averaged value, likely to be a lower figure than the peak measured at the inlet to the filter by the ECD probe. In addition, the different methods of assessment used by the ECD and the BINOS both tend to average any spike or peak breathing in a different way in part due to the different response times of the two systems.

Figure 10 shows an example of the total leak into the mask and the pick-up contribution for volunteer No. 6. It shows the high 'spikes' of the rebreathed SF₆ trace in green, whilst the red trace shows the total in the mask, face seal leakage which is now being mixed with pick-up.

These factors combined make it likely that we have over-compensated in our correction for pick-up. However, with the exception of volunteer No. 6, we could easily take the overall mean in the mask as a measure of the face-seal leakage without prejudicing the outcome of the workplace fit test estimations.

Table 2. Mean values of in-mask leakage in workplace.

Volunteer no.	Workplace mean leakage values %		
	Total leakage including external pick-up	External pick-up	Face-seal leakage (derived from total minus pick-up)
1.0000	0.0043	0.0033	0.0010
2.0000	0.0127	0.0105	0.0022
2 rpt	0.0086	0.0051	0.0035
3.0000	0.0023	0.0013	0.0010
4.0000	0.0025	0.0007	0.0018
5.0000	0.0080	0.0052	0.0028
5 rpt	0.0053	0.0040	0.0013
6.0000	0.3069	0.0216	0.2853
7.0000	0.0079	0.0046	0.0033
8.0000	0.0055	0.0041	0.0014
9.0000	0.0054	0.0034	0.0020
10.0000	0.0078	0.0077	0.0001
11.0000	0.0113	0.0076	0.0037
12.0000	0.0046	0.0045	0.0001
13.0000	0.0045	0.0033	0.0012
14.0000	0.0069	0.0053	0.0016
15.0000	0.0040	0.0032	0.0008

Figure 10. Typical trace of SF₆ concentration at the filter inlet and in the face mask in the workplace.

If it really is necessary to measure the rebreathed fraction in any workplace assessment, perhaps because face-seal leakage is high and hence background levels of exhalate are correspondingly high, and to obviate the need for two instruments, the second channel of the BINOS, currently used to monitor the hood concentration could be used to measure the input at the filter inlet. This means that an assumption would need to be made about the constancy of the hood concentration which could then not be monitored. Our experience on these trials shows that the concentration in the hood can remain constant within about 10%, unless a large face-seal leak occurs which can reduce the level of the challenge by forcing mask air into the hood. Again in practice the hood concentration recovers from such an event within about 20 seconds. Figure 4 illustrates this.

We mentioned in 3.2.4 a method of estimating the 'protection factor' of the device from the leakage measurements made. The protection factor is given by the quotient of ambient concentration of contaminant and the amount of contaminant measured in the facepiece. This is the same as the inverse of the total leakage into the mask, or 100%ge. total inward leakage. In these workplace trials the total leakage in the mask is the sum of leakage occurring by the three likely main routes i.e. face-seal and valve leakages and filter penetration respectively. Our workplace measurements were of face-seal leakage only but we know the approximate magnitude of valve leakage from the test described in 3.2.4 and if we assume penetration of the filter as the worst case allowed in European Standards i.e., 0.05% then we can add the three components to give us an idea of the total leakage into the mask and hence an idea of the protection factor. If the valve is operating correctly, then this component is small and we can safely take face-seal leakage as the major component of inward leakage except for that of the filter. Thus if we take the example of the first test of volunteer No. 5, with a workplace face-seal leakage of 0.0028%, a valve

leakage of 0.0009%, and assume 0.05% penetration for the filter, then we can be fairly certain that the protection factor of the device, as observed in this workplace test, is largely governed by filter penetration and would be of the order of 2000. Clearly, if filter penetration is lower than the maximum allowed by the European Standard, as many high efficiency filters often are, then this adds to the magnitude of the protection being provided by the device.

3.3 Breathing resistance

3.3.1 General. European Standard EN 132, (Comité Européen de Normalisation (CEN), EN 132:1990), defines breathing resistance as "resistance of a respiratory protective device to the flow of air during inhalation and exhalation."

For a full face mask respirator of the type used in these workplace trials, the mask and filter are the subject of different European standards. The mask, conforming with EN 136, is assessed for breathing resistance on a sinusoidal waveform breathing simulator while the filter, conforming with EN 143, (Comité Européen de Normalisation (CEN), EN 143:1990), is assessed at various constant flow rates. Table 3 shows the resistance requirements for each component.

Thus, in the absence of actual measurements on test subjects with either of these two main components or with the complete respirator, the total breathing resistance of a respirator can be estimated only by making an assumption of the resistance of the filter at a constant flow of 50 litres per minute, based on its performance at 30 litres per minute and adding this to the mask resistance, ignoring any resistance due to connections. Thus the measurement of the breathing resistance of a respirator in a practical situation during our workplace experiments and in the associated EN 136 tests on the treadmill offers useful additional information on its

Table 3. Breathing resistance requirements.

Breathing resistance mm H ₂ O		
	Full face mask (EN 136) @ 50 l/min sinusoidal flow or 160 l/min constant flow	P3 filter (EN 136) @ 95 l/min constant flow
Inhalation	25.0000	42.0000
Exhalation	30.0000	—

performance. As Table 3 shows, there is no requirement in EN 143 for exhalation resistance of the filter. This is because it is mandatory for either the filter or the mask to have an inhalation valve fitted. Thus exhalate can then only pass via the mask exhalation valve.

3.3.2 Workplace measurement of breathing resistance. In order to assess whether the tests in the EN 136 regime are actually more stringent than the load imposed on volunteers by the workplace activity we need to compare breathing resistance values for both. These are given in Table 4.

Typical average inhalation resistance peak values for each volunteer in the workplace situation are shown in Column 1 of Table 4. This is a judgement made by viewing the record from the full work cycle. These values were exceeded on what are considered to be untypical occasions. For example, volunteer No. 5 had a typical peak level of 20 mm H₂O during much of the workplace activity but on

occasions there were individual 'spikes' of inhalation resistance up to 40 mm H₂O. This could be due to factors such as a cough and resulting sharp intake of breath, a temporary kink in the sample line etc. as much as to a particular work action. For comparison, the equivalent information is shown for the inhalation resistances occurring during the EN 136 tests on the treadmill for the initial walk test (Ws) in column 3. These values include an element of resistance due to the clean-air tube which supplies the filter during the test. During the course of a test, we attempt to keep this resistance 'neutral' by feeding clean air at a low positive pressure to a reservoir at the inlet to the tube, so that the resistance of the tube is compensated. Inevitably, as breathing rates vary there is some small under-compensation and over-compensation. This is a situation inherent in the test procedure called up in EN 136. For this reason, the inhalation resistance quoted in the treadmill test is not strictly the true resistance of the mask/filter combination.

Table 4. Breathing resistance measurements.

Volunteer no.	Average peak breathing resistance mm H ₂ O					
	Workplace		EN 136			
			Ws		T	
	Inhalation	Exhalation	Inhalation	Exhalation	Inhalation	Exhalation
	Col 1	Col 2	Col 3	Col 4	Col 5	Col 6
1.0000	22.0000	5.0000	60.0000	12.0000	120.0000	20.0000
2.0000	20.0000	5.0000	45.0000	10.0000	140.0000	30.0000
2 rpt	12.0000	7.0000	38.0000	7.0000	100.0000	20.0000
3.0000	26.0000	7.0000		—		—
4.0000	25.0000	5.0000	40.0000	7.0000	150.0000	15.0000
5.00000	20.0000	5.0000	30.0000	6.0000	90.0000	10.0000
5 rpt	13.0000	8.0000	30.0000	6.0000	60.0000	13.0000
6.0000	20.0000	8.0000	80.0000	14.0000	136.0000	20.0000
7.0000	10.0000	7.0000	30.0000	6.0000	100.0000	11.0000
8.0000	20.0000	4.0000	30.0000	6.0000	100.0000	5.0000
9.0000	18.0000	5.0000	50.0000	6.0000	140.0000	20.0000
10.0000	20.0000	10.0000	35.0000	7.0000	110.0000	20.0000
11.0000	25.0000	5.0000	33.0000	5.0000	105.0000	10.0000
12.0000	13.0000	6.0000	34.0000	5.0000	83.0000	7.0000
13.0000	20.0000	5.0000	25.0000	4.0000	70.0000	6.0000
14.0000	15.0000	5.0000	26.0000	8.0000	65.0000	6.0000
15.0000	17.0000	6.0000	25.0000	7.0000	55.0000	8.0000

The Ws test was chosen for comparison with workplace results as being the one where breathing peaks were likely to be the smallest because it is the most sedentary exercise and because the volunteer is least tired. We judged that the Ws work rate, which is generally taken to approximate to a minute volume of about 30 litres per minute, appeared to be equal to or greater than the work activity viewed in the workplace. Certainly, subsequent test exercises such as walking on the treadmill whilst talking (T) often resulted in much larger breathing resistance peaks than those from the Ws tests and are shown in column 5 of Table 4. If we examine a typical breathing resistance trace taken during workplace measurements, shown in Figure 11(a) and for comparison, similar plots for the same volunteer during Ws and T exercises in the EN 136 tests at Figures 11(b) and (c), the workplace plot shows the breathing pattern to be more frequent and shallow than the others. By the time that the talking exercise has commenced, the volunteer is becoming more tired and the effect of talking is also shown in the plot.

From Table 4, it can be seen that on no occasion is the workplace inhalation resistance greater than that of the most sedentary of the EN 136 tests, Ws. It must also be remembered that once a volunteer is walking on the treadmill, the work rate is prescribed by the speed, which does not vary. Thus the volunteer must work harder as the test progresses and as tiredness grows. In the workplace however, the volunteer can adjust workrate, breathing pattern etc. to suit. There is more variation in the resistances measured on the treadmill than in the workplace which probably reflects the above factor.

Minute volume of some volunteers during treadmill exercises was occasionally obtained by measuring the flow of clean air passing into the breathing bag and air supply tube to the mask. It is crucial to keep this supply free of SF₆ and hence the system is kept at a small positive pressure relative to ambient. Such measurements of the minute volume that we were able to obtain must be treated as a guide only and have not been formally reported. Also, such estimates are further compounded because the value is changing over the test as the wearer performs different exercise and gets gradually more tired. This is particularly true of the talking exercise, when breathing patterns can become irregular. We measured the minute volume of some of the volunteers at between 60 and 70 litres per minute towards the end of their exercise regime. This

means they were breathing about 200 litres per minute at times. However, allowing for the uncertainty of the system, it seems clear from the breathing resistance values in Table 4 that treadmill tests were more stringent in terms of work rate, air consumption and inhalation resistance imposed than was the workplace regime.

As far as the workplace figures are concerned, none of the exhalation resistances recorded showed a peak above the requirements of EN 136, i.e., 30 mm H₂O, which means that the volunteer is exhaling at flow rates lower than the test condition of 50 litres per minute sinusoidal flow or about 160 litres per minute peak constant flow. The same applies to the Ws results and to all the T results except for those for volunteer No. 2. Of these latter results, volunteers No. 8, 12, 13, 14, and 15 all exhibit values similar to those in their workplace and Ws situations as well as exhibiting some of the lower values of inhalation resistance. It is possible that this is related to the physical fitness and lung capacity of these volunteers.

Because we have data of inward leakage and the breathing resistance stored, it might be possible at some later stage to see if there is a relationship between values of inward leakage and the occurrence of peaks of inhalation.

3.4 Facial dimensions

3.4.1 General. European standards require that certain facial dimensions of the test panel involved in inward leakage tests are recorded. The four dimensions identified in EN 136 and shown in Figure 12 which is reproduced from BS 7355:1990, were measured on certain of the test volunteers using specialised callipers dedicated for the purpose. The four dimensions, shown in Table 5 are:

- a) length of face (nasion-menton), LoF
- b) width of mouth, WoM
- c) depth of face, DoF
- d) width of face (bizygomatic diameter), WoF.

For comparison purposes, Figure 13 shows the data for the test volunteers used in this workplace study plotted on the Los Alamos Grid, widely publicised data which defines a range of sizes which would contribute to a meaningful test panel covering 95% of the population of the USA. It subdivides the range into a number of squares and shows the percentage of the population within each square.

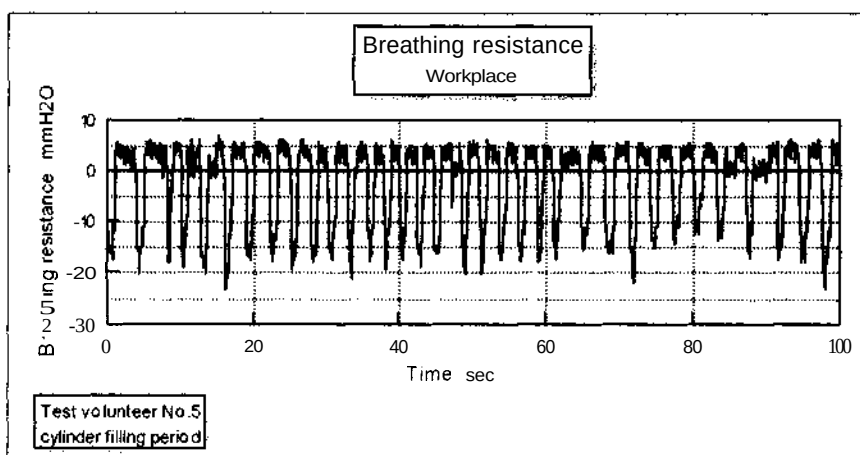


Figure 11(a)

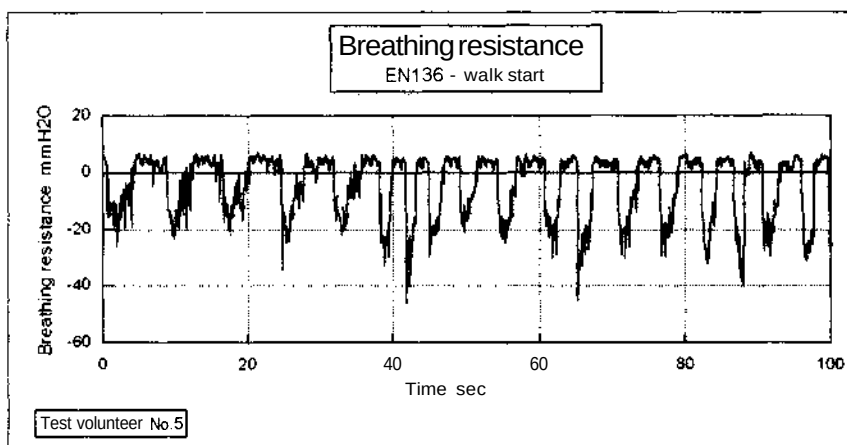


Figure 11(b)

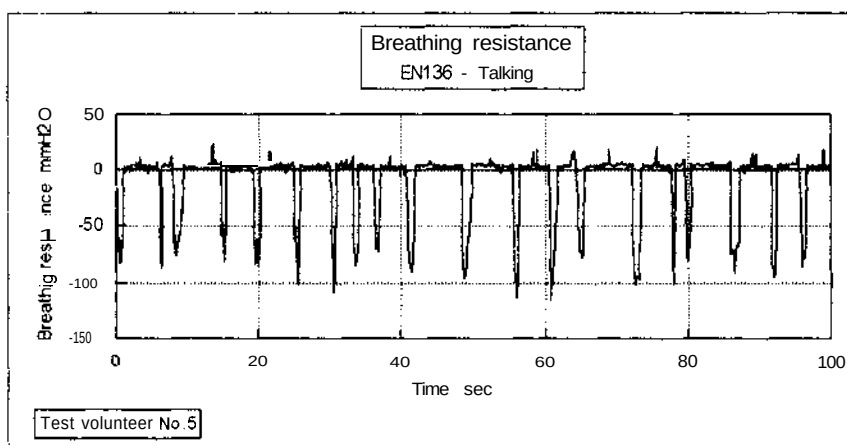


Figure 11(c)

Figure 11(a)(b)(c). Typical breathing resistance traces.

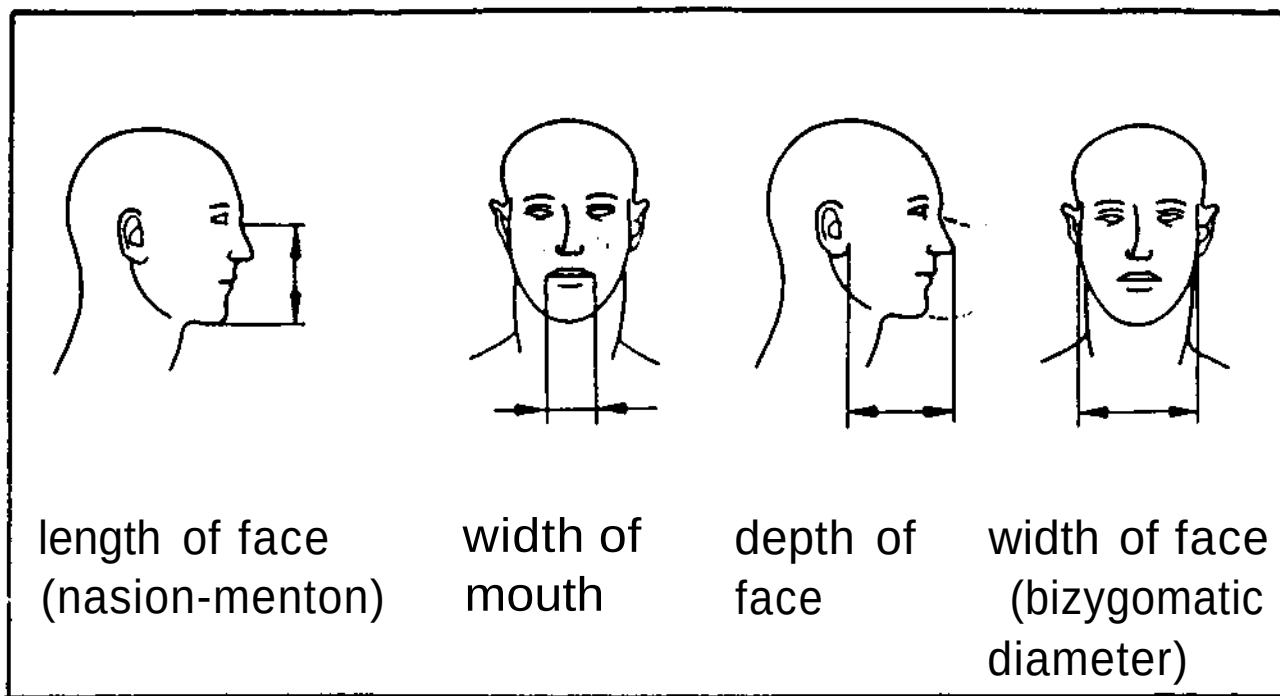


Figure 12. Facial dimensions.

Table 5. Facial dimensions of volunteers.

Volunteer no.	Length of face (mm)	Width of mouth (mm)	Depth of face (mm)	Width of face (mm)
1.0000	113.0000	46.0000	129.0000	153.0000
2.0000	123.0000	51.0000	113.0000	150.0000
5.0000	124.0000	53.0000	137.0000	140.0000
7.0000	119.0000	53.0000	128.0000	143.0000
8.0000	131.0000	55.0000	128.0000	141.0000
9.0000	150.0000	60.0000	123.0000	161.0000
10.0000	116.0000	50.0000	129.0000	134.0000
11.0000	130.0000	• 55.0000	133.0000	154.0000
12.0000	128.0000	52.0000	131.0000	140.0000
13.0000	115.0000	45.0000	116.0000	140.0000
14.0000	144.0000	56.0000	123.0000	146.0000
15.0000	119.0000	53.0000	124.0000	144.0000

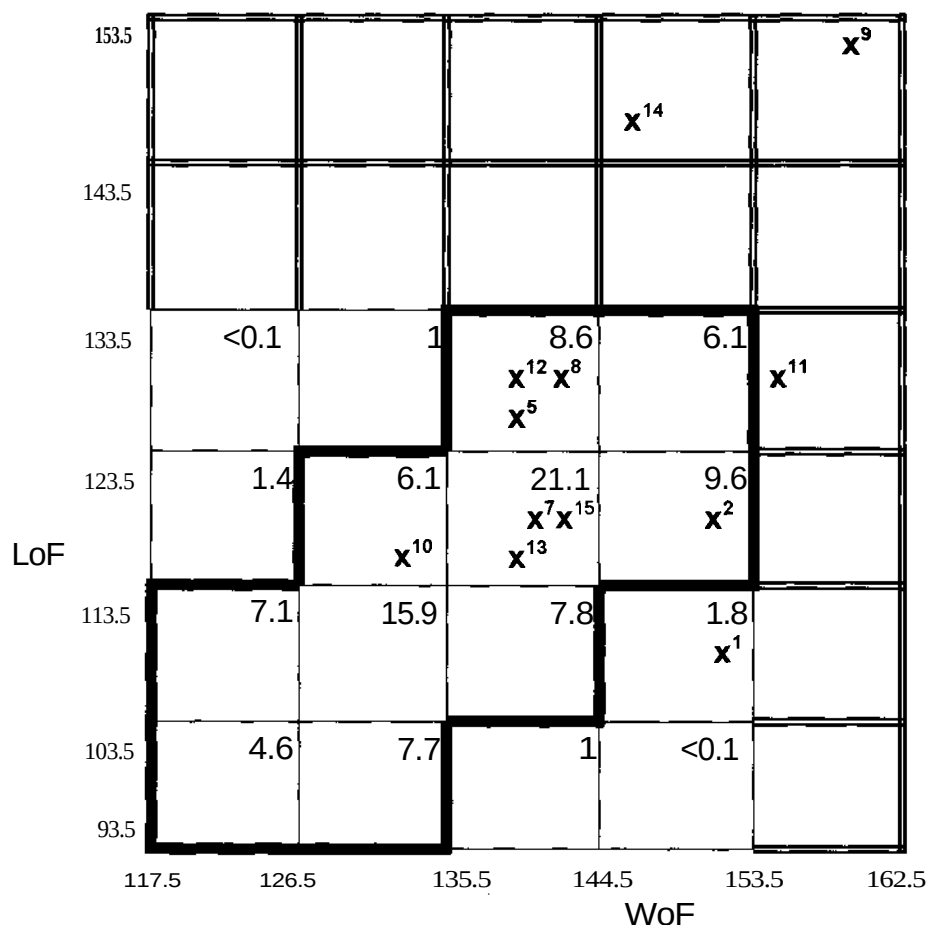


Figure 13. Los Alamos Grid showing spread of facial dimensions of volunteers X.

There are actually two grids, one comprising LoF and WoF dimensions covering full face masks and one comprising LoF and WoM dimensions covering half masks. Figure 13 is the Los Alamos Grid for the full face mask and shows that the measurements of four of the twelve test volunteers fell outside the Grid, two of them, volunteers No. 9 and No. 14 have large values of LoF and WoF. In addition, two others, Nos. 1 and 11 fall outside the Grid due to large values of WoF. Three of the population we were able to measure i.e., 25% of our measurements, occur in the grid box containing the highest percentage, 21.1%.

3.4.2 Relationship between facial dimension and inward leakage. Each of the four facial dimensions for each volunteer has been plotted against the average percentage inward leakage for the three sets of measurements EN 136, HEN 136 and the work-

place. These are shown in Figure 14(a), (b), (c), and (d).

It is possible to simplify the appearance of this data by dividing the range of facial dimensions into a convenient number of equal class intervals, in this case 5 mm for the DoF and WoM plots and 10 mm for the LoF and WoF plots, and then calculate the mean of the average percentage inward leakages which falls within each of the class intervals. This is the form shown in Figure 15(a), (b), (c) and (d).

We have not made any attempt to analyse in depth any of the results to look for particular correlations between any of the facial dimensions and particular inward leakage exercises, but a preliminary analysis using Principle Component techniques indicates that there is no correlation between the four facial dimensions and mean inward leakage for

Figure 14 (a)

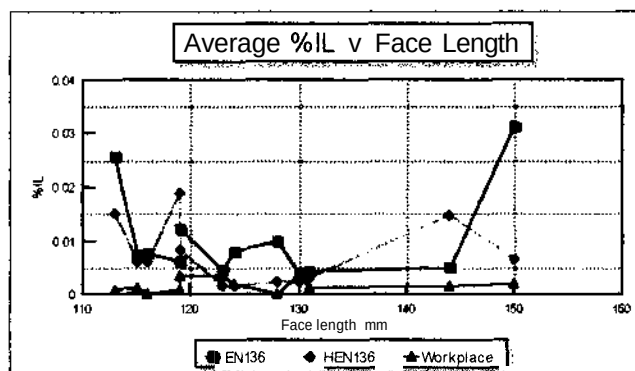


Figure 14 (b)

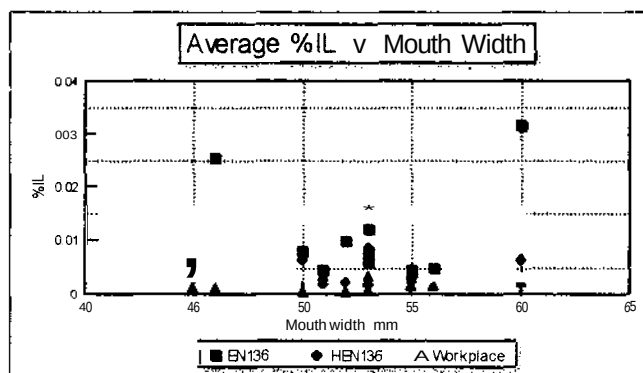


Figure 14 (c)

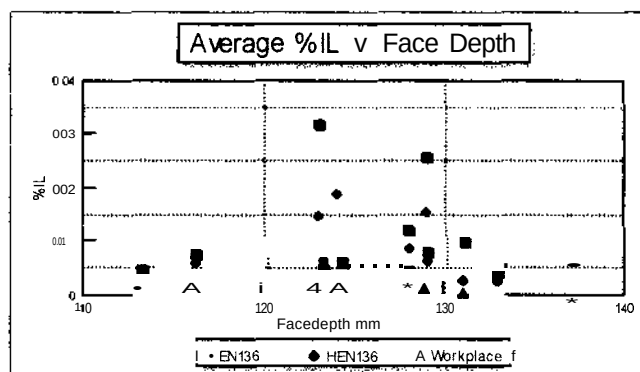


Figure 14 (d)

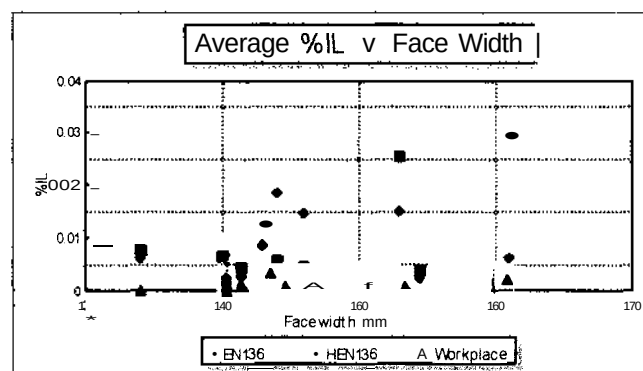


Figure 14 (a) to (d). Average % inward leakage for each facial dimension.

Figure 15 (a)

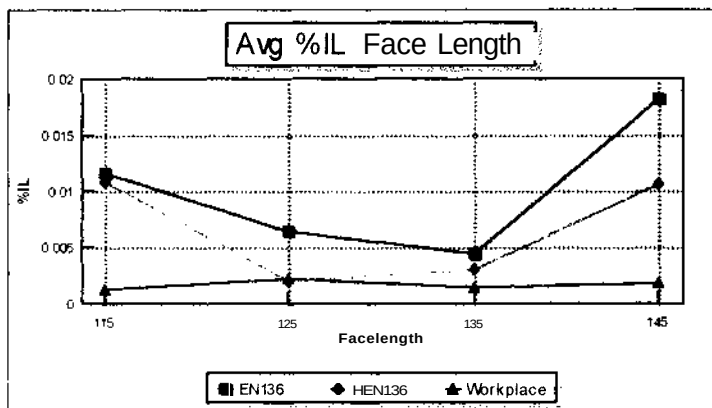


Figure 15 (b)

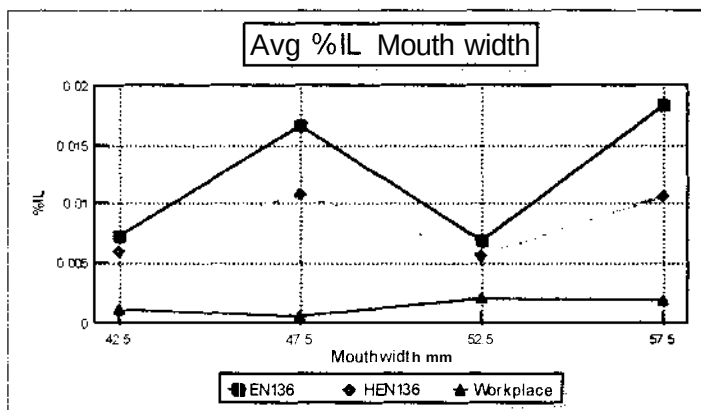


Figure 15 (c)

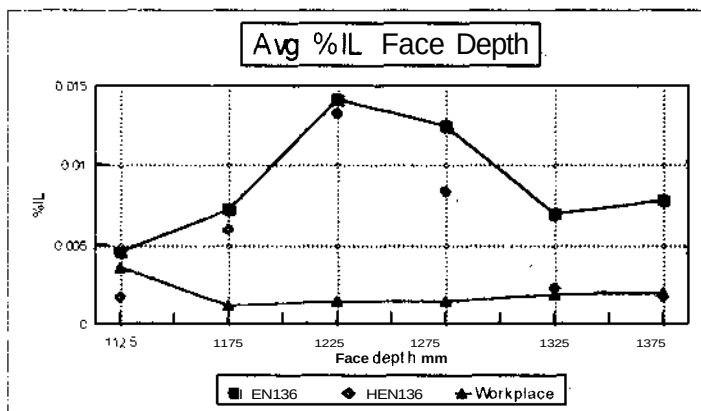


Figure 15 (d)

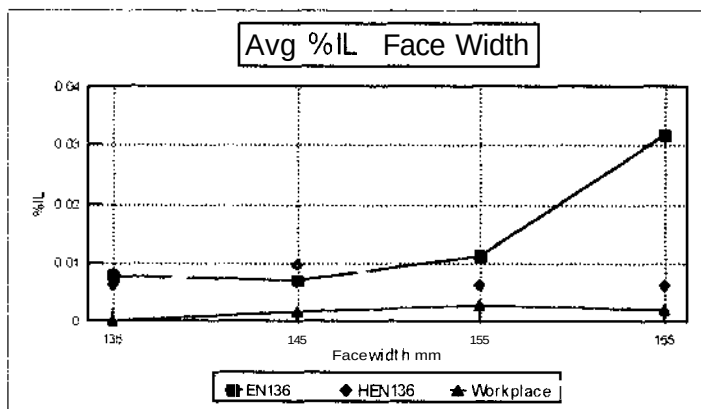


Figure 15 (a) to (d). Average % inward leakage for each facial dimension in specific class intervals.

the volunteers in any of the three test scenarios. A simple visual examination of Figure 15(a), (b), (c) and (d) shows that as we would expect, the EN 136 and HEN 136 follow broadly speaking the same peaks and troughs. It is interesting to note that in Figure 15(a) the relationship between leakage and face length reaches a peak at either extreme of facial dimension, and falls at levels of face length between these two extremes. Thus the highest leakage occurs in the shortest and longest faces while the best fit occurs on mid-range faces. Perhaps the mask was designed with this intention. Another possibility is that a particular facial parameter is more dominant when a particular exercise is performed and thus affects unduly the mean inward leakage level. For instance it is possible to postulate that LoF measurements are more important than other parameters when UD exercises are being performed so that at the extremes of movement of the head, mask slippage on the larger and smaller faces is more likely to occur. However, when we look at the relationship between facial depth and inward leakage, then here leakage is highest for the middle range of face sizes. The relationship between the various parameters involved is clearly a complex one but a possible future analysis of the relationship between actual test exercise leakage and particular facial dimension might be useful to highlight areas described above and show which parameters dominate, particularly if this data can be pooled with other data obtained from (say) other EN 136 tests. Such information

might help to support a case for different mask sizes to be produced.

Little can be gleaned from a simple examination of the workplace leakage plotted against facial dimensions because the levels of leakage are so small. Again, in the context of overall suitability to wear a full face mask, leakages were low across the whole range of facial dimensions.

3.5 Video visualisation system

3.5.1 Principle. A schematic diagram of the layout and components for the video visualisation system is shown in Figure 16. Simply, this system superimposes in real time the output from the gas analyser used to measure leakage into the face mask on to the video image of the test volunteer performing the particular workplace activity or inward leakage test. The main purpose of the system is to relate, if possible, the leakage into the mask to actions performed by the wearer. Thus, movements introducing high levels of leakage can perhaps be highlighted, with a view to changing the workplace procedure to avoid such activity.

3.5.2 Practical application. To enable the test volunteer to have sufficient freedom of movement within the workplace area, a long sample line of about 12 metres in length was required. Inevitably this sample line introduces a time lag to the system

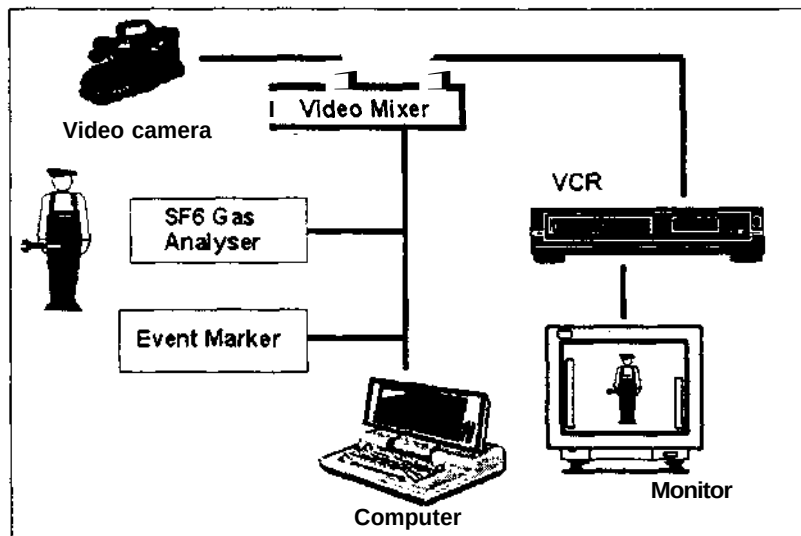


Figure 16. Schematic diagram of the Video visualization system.

between the leak occurring in the full face mask and the signal appearing on the video system. Test calibration showed that if we sampled at 1 litre per minute from the mask, the signal appeared on the video system after a nine second delay. This delay was regularly checked during the leakage exercises and remained constant.

As well as recording the output from the gas analyser as a vertical bar graph, the video visualisation system records the actual time of day. By using this recorded time and correcting for the nine second delay it is possible to relate work actions and inward leakage.

4. Conclusion

4.1 Face-seal leakage measurement system

The PPE Challenge hood system developed by the Health and Safety Laboratory (HSL), including the instrumentation for measuring SF_6 leakage, breathing resistance etc., has proved in the workplace situation investigated, to be robust and capable of being used by wearers of full face mask respirators. The whole system showed itself able to give a real time measure of face-seal leakage on wearers of full face masks and if necessary to compare this directly with the fit achieved by the same user performing tests from the European Standard. The equipment has proved to be robust, the hood system being donned and doffed by a number of wearers and being worn for up to 2 hours at a time. The method can give an estimate of an overall protection factor of the device being worn if assumptions are made for the amount of leakage entering via exhalation valves or filters. However, the system also has the potential to actually assess the performance of individual components of the face mask, such as exhalation valves and also those carried on the face mask, such as filters, in a dynamic situation.

The system used can be much simplified, if as originally intended, a simple "goodness of fit" assessment is needed. Thus if the hood is filled with a known concentration of SF_6 , then only leakage into the mask needs to be assessed. If this leakage level is low during all the activities associated with the workplace then it is likely that the wearer has fitted the mask properly and the workplace situation is not aggravating that fit. If there is gross leakage into the mask then this could be because the mask itself is

The system has a second data input channel which was used as an event marker. This produced a one volt input signal when the observer pressed a button. This signal was simultaneously recorded on the video and on the data acquisition system. This precise timing link between the video system and the logging system further aided the synchronisation of the video signal with the data logged leakage signal. Figures 1 and 2 are 'stills' from workplace videos and show leakage level in the mask on the left hand vertical bar graph and the event marker on the right hand side.

badly fitted in which case a refit of the mask should improve matters. If it does not, then the indications are that the wearer is a poor fit in that particular face mask or that size of face mask. An adjustment of the workplace activity e.g. to exclude activities such as bending or stretching, might serve to reduce leakage. The final scenario is where the leakage into the mask is around the pass/fail mark for European Standards i.e., 0.05%. If this level continually recurs during leakage tests in the workplace, it is likely that at some stage the leakage will exceed these values, especially if the level of fit reduces during long term wearing due to slackening of the straps, sweating, etc. In this case it is suggested that such wearers would either need to have a different type of face mask or need to be retrained in fitting the one they have. Again, if the video visualisation system is used in conjunction with these tests it may show that the actual workplace movements are a source of these borderline leakages and the workplace activity may be able to be modified to remove them.

The umbilical system worked well in this scenario. It can be simplified depending on the measurements being recorded. Clearly however, there will be workplace situations for which it is not suited.

4.2 Workplace measurements

The workplace measurements carried out in this particular situation showed that the wearers of full face mask respirators were inherently well fitted, with potential to achieve good levels of protection. This information gained in the workplace was also reinforced by results from actual EN 136 tests and

EN 136 style tests with the PPE hood. Again, with the exception discussed, wearers showed themselves to be good at fitting masks and achieved low levels of leakage. None of the workplace activities appeared to cause undue peaks of leakage.

4.3 European standard tests

Work has shown that the tests applied by European standards are more vigorous in terms of work effort and breathing resistance loads on wearers than in this particular workplace situation. There were some activities in the workplace such as bending or crouching low which were not reproduced in the exercises in the standard test, but there were no undue leakage levels when these activities took place in the workplace.

The facial dimensions recommended in European standards were recorded, mainly for information and comparison with an acknowledged means of assessing such data i.e., the Los Alamos Grid. About 25% of the wearers measured had dimensions

which placed them outside the grid.

4.4 Video visualisation system

The inward leakage experiments and workplace experiments were all recorded using the video visualisation system without any problem. The only drawback to the system is the imposed signal delay due to length of sample lines, time for the gas analysis to take place at the BINOS, etc. This makes the system a little less readily useable because if a peak of leakage is noted, then the movement causing it has occurred about 9 seconds earlier. This means that the tape must be rewound to that point in order to see which particular actions took place. However, this rewind can be carried out accurately due to time recording systems built in and displayed on the tape. An alternative approach might be to run the tape backwards. In this way there is a 9 second warning of an activity which caused a particular level of leakage to occur.

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