

Determination of the Quantitative Fit Factors of Various Types of Respiratory Protective Equipment

R. A. Bentley, G. J. Bostock, D. J. Longson, and M. W. Roff
Health and Safety Executive
Research and Laboratory Services Division
Sheffield, England

Abstract

The quantitative fit factors (QFF) of five types of open circuit self-contained breathing apparatus (SCBA), two types of powered air-purifying respirators (PAPR) and an air-fed helmet have been determined whilst worn by twenty subjects exercising on a treadmill. The QFF ranged from 23,800 to greater than 1,000,000 for the SCBA, 120 to 100,000 for the PAPRs and 14 to 5,000 for the air-fed helmet. A study was also made of the correlation between the use of sulphur hexafluoride, argon, and sodium chloride tracer elements.

Introduction

The current methods of determining face seal leakage of respiratory protective equipment (RPE) are in need of revision or are currently being revised. The British Standard BS 4667: part 2: 1974 for instance requires that the inward leakage of the facepiece of an open circuit self-contained breathing apparatus (SCBA) be measured under negative pressure demand conditions, utilizing argon as a tracer gas detected by a mass spectrometer while the subject exercises on a treadmill. Modern SCBA are frequently worn under positive pressure demand conditions and it is desirable that total inward leakage of the external atmosphere into the apparatus is measured under these conditions as well as the negative demand mode.

Total inward leakage is here defined as the contaminated air inhaled by the subject expressed as a proportion of the total air breathed by the subject. For instance, if a subject wearing an SCBA breathes at 30 litres per minute, and a leak of 0.03 litres per minute enters his facepiece, an inward leakage of 0.1% or 1000 ppm is registered. In practice all that is required is to directly measure the contamination inside the mask and express it as a ratio compared with the challenge atmosphere concentration outside.

Quantitative Fit Factor (QFF) is an index of performance of RPE representing the protection

which the RPE affords to the user. The QFF is the ratio of the challenge concentration to the respired concentration and is thus simply the inverse of the total inward leakage. In the example above, the QFF is 1000. Thus the wearer would have to work for 1000 times as long to receive the equivalent dosage of contamination than had the RPE not been worn.

The first part of this paper describes the equipment used and the use of sulphur hexafluoride (SF_6) as a tracer gas whereby quantitative fit factors (QFF) of the order of 1,000,000 may be measured while the apparatus is worn by an exercising subject.

The second part of this paper describes the equipment used and the use of sodium chloride aerosol to determine the QFF's of Powered Air Purifying Respirators (PAPRs) while worn by exercising subjects. The current British Standard BS 2091: 1969 utilizes a sodium chloride aerosol but the face seal leakage is measured on a sedentary subject.

The third part describes the use of the same equipment to determine the QFF of an air fed helmet, while worn by an exercising subject.

The fourth part is a study of the correlation between the tracer elements SF_6 , sodium chloride, and argon. This was determined by using a

facemask fitted with an open port to simulate leakage while being worn by exercising subjects.

All the experiments described in this paper were carried out on the same twenty volunteers

from the South Yorkshire Fire Brigade who were experienced in the use of SCBA. (The anthropometric data showing facial dimensions is shown in Table 16.)

Self-Contained Breathing Apparatus (SCBA)

Materials and Apparatus

The five self contained breathing apparatus were all of the open circuit positive pressure breathing types. Four of them could be used in either negative demand mode or positive pressure mode, while one was positive pressure only. Prior to the tests all the sets were checked on a breathing simulator for compliance with the Clauses of the British Standard BS 4667: Part 2 relating to breathing resistance before use. Each facepiece was fitted with three sampling ports. Two entered the inner mask and were positioned at mouth level; these were used to sample the air and measure the pressure in the inner mask cavity. The third was fitted at eye level and was used to measure pressures in the outer cavity.

Quantitative Test Fit Equipment

A chamber, 2.0 m long, 2.1 m high, and 1.1 m wide, was constructed of clear rigid plastic sheet attached in a gas tight manner to a mild steel frame. The rear of the chamber was sealed by means of a removable polythene sheet to allow access. The chamber utilized a treadmill as the floor so that the subjects were able to exercise whilst wearing the breathing apparatus.

The treadmill was inclined at an angle to the horizontal of 5 degrees and the speed set at 5.8 km/h to give the desired work load.

A 150-mm diameter pipe passed through the front of the chamber and was positioned such that air at approximately 0.2 m/s was directed at the head and over the body of a subject walking on the treadmill. The inlet to this pipe was connected to the exhaust fan situated in the lower rear of the left hand wall. The air inside the chamber was thus recirculated.

The pure tracer gas was admitted into the chamber immediately in front of the exhaust fan so that good mixing took place before being presented to the man. A small recirculating fan was

positioned at the front of the chamber near the floor to assist in the mixing of the atmosphere in the chamber.

Once the required concentration of tracer in the chamber had been reached, the flow of pure tracer was considerably reduced to just maintain the concentration. A 2% sulphur hexafluoride (SF_6) in air concentration was used as a challenge atmosphere in the exercise.

A sampling system was installed at head, waist, and knee height to check the concentration of the challenge atmosphere.

The level of SF_6 in the chamber air was measured by means of a "Gow Mac" thermal conductivity meter, clean compressed air being used as the reference. This instrument gave a linear response to an increase in SF_6 concentration over the range of 0 to 5%. The output from the meter was recorded on one of the channels of a twin channel potentiometric chart recorder.

The concentration of SF_6 inside the facepiece was measured by means of an Analytical Instruments "Leakmeter" electron capture device. The instrument was adjusted to give full scale deflection for approximately 1 ppm of SF_6 . This gave a lower detection limit of 0.01 ppm of SF_6 corresponding to an inward leakage of 0.00005% of the challenge atmosphere. The limit of sensitivity was dependent on the interference to the instrumentation due to changing oxygen levels in the expired breath.

The output from the "Leakmeter" was displayed on the second channel of the chart recorder. In order to prevent interference from the carbon dioxide and water vapor in the subjects exhaled breath, both the chamber and the facepiece samples were passed through soda lime and calcium chloride.

The air sample was extracted from the facepiece at the rate of approximately 1 litre/min by means of reciprocating diaphragm pump. A 'T' piece was attached to the sampling nozzle of the "Leakmeter" so that the sample was passed over the nozzle. The instrument was not affected by

changes in sampling rate, within the range 0.5 to 5 litre/min, caused by pressure changes in the facepiece.

The sample connection to the facepiece was made by a threaded brass port sealed into the face blank. A short length of 2 mm diameter rigid plastic tube was inserted into the port and passed through the orinasal mask so that the sample could be extracted from the wearer's breathing zone. In order not to adversely affect the wearer's ability to move his head, the connection between the brass port and the sampling pump was made by flexible 4 mm diameter plastic tubing.

Whenever SF₆ is used as a tracer, the gas must be certified pure and free of contamination by SF₄ and S₂F₁₀. As an additional safeguard, the input gas may be passed through soda lime. Slutsky et al. used an 80% SF₆/20% O₂ mixture in experiments to investigate the pressure-flow characteristic of the human lung. The SF₆ tracer concentration used in this series of experiments was sufficiently low that if a subject suffered a massive inward leakage into the mask, his safety would not be jeopardized. Since the TLV of SF₆ has been set at 1,000 ppm an inward leakage of 5% of the external atmosphere could be tolerated without exceeding the TLV.

Test Procedure

Each subject donned the apparatus in a room adjacent to the test chamber, to avoid the ingress of SF₆ into the system. He then checked the facemask for fit, with the sampling ports closed, using the procedure normally followed by the Fire Brigade, the facemask was comfortably fitted on to the face, the cylinder valve was turned off and the air remaining in the circuit exhausted by normal breathing thus pulling the mask on to the face. If the wearer was satisfied with the fit, then the cylinder valve was turned on and the apparatus turned to the positive pressure mode.

The subject was informed that he was allowed to adjust the facemask straps during the exercise if he felt this was necessary but that he would not be instructed to do so by the supervisor. The three mask sampling ports were then connected to the appropriate sampling lines. The subject remained outside the test chamber for 2 minutes to establish a zero level for the SF₆ detector. After this time he entered the test chamber, which was sealed behind him. He then walked on

the treadmill for 2 to 3 minutes. During this time the SF₆ level in the test chamber was increased to the nominal 2% SF₆/air ratio.

Whilst still walking on the treadmill the test subject performed a set series of exercises each part lasting for 2 minutes. These were as follows:

a) Moving his head from side to side at a frequency of approximately five times per minute as though inspecting the wall of a tunnel through which he was walking.

b) Moving his head up and down as though inspecting the floor and ceiling as in (a).

c) With the head held stationary, reciting the alphabet out loud as though communicating with a colleague.

d) Walking with no head movement.

e) A repeat of exercise (d) but with the demand valve adjusted so as to operate in the negative demand mode.

In the case of the apparatus which could not be switched to the negative demand mode exercise (e) was omitted. The negative demand measurement was made after all the positive pressure measurements had been completed as a check on the 'goodness of fit' of the mask.

At the end of this period of time the treadmill was stopped, the subject returned the apparatus to the positive pressure mode and left the chamber. He then remained in fresh air for a further 2 to 3 minutes until the zero level was re-established.

During the whole of the exercises, the levels of SF₆ in the facepiece and in the chamber were continuously monitored, in addition continuous measurements were made of the pressure within the inner and outer cavities of the facemask.

Pressure Measurements

Transient pressures within the facepieces of between + 10 mbar and - 20 mbar were recorded using micromanometers (Furness Controls) with a frequency response greater than 100 Hz. The tubes connecting the micromanometers to the sampling ports were long, so a frequency response of 50 Hz is probably a more realistic figure.

The data was recorded on to magnetic tape using a 4 channel tape recorder (Racal Store 4) by means of frequency modulation. Bessel filters were used to prevent any overshoot in the recorded signal. The bandwidth of the tape recordings was 0-300 Hz. The signal from the leak detector was recorded simultaneously along with the pressures.

Leakage Results and Discussion

The results obtained for the total inward leakage of the external atmosphere into each facemask for all the subjects and for each apparatus are shown in Tables 1 to 5. A summary of the maximum, minimum, and mean leakages and quantitative fit factors for each apparatus is given in Table 6.

One of the subjects (SH) had about 3 days beard growth when the measurements on the SCBA were made. This caused some face seal leakage with apparatus 3 and 4, but produced very large leakage figures with apparatus 5.

The quantitative fit factor for this man wearing apparatus 5 and looking up and down was as low as 83; his overall average QFF of the exercises being 330. The results for SH were ignored for the fit factor determinations on SCBA in Table 6, but demonstrate clearly the need for the wearer to be clean shaven, even when using positive pressure apparatus.

The results in Tables 1 to 5 show that the total inward leakages for individual exercises range

from less than 1 ppm to 42 ppm (although SH produced a leakage of 12,000 ppm) when worn in the positive pressure mode and from less than 1 ppm to about 22,000 ppm when used in the negative demand mode. On four occasions, the masks had been fitted so as to give inward leakages in excess of the limits required by BS 4667: Part 2, but it is interesting to note that each of these poor fits still produced inward leakages of less than 2 ppm in the positive pressure mode.

The total inward leakages for the mean of each subject's four positive pressure mode exercises (Table 6) range from less than 1 ppm to 18.5 ppm (QFF from greater than 1,000,000 to 54,000).

Pressure Measurement Results

A breakdown of the occurrence of negative pressure within the facepiece by apparatus and exercise is given in Table 7.

It should be noted that the recording apparatus was of fast response and was capable of recording very sharp spikes of short duration. The

Table 1. Total inward leakage apparatus No. 1.

Subject	Average leakage ppm during exercise					Negative demand	Minute volume litres BTPS
	Side to side	Up and down	Talking	Walking	Average		
RC	—	—	—	—	—	9	63
BS	—	—	—	—	—	190	53
KD	—	—	—	—	—	43	44
AG	—	—	—	—	—	190	37
SC	—	—	—	—	—	10	34
SM	—	—	—	—	—	80	28
TH	—	—	—	—	—	8.5	41
RF	—	1.5	9.5	—	3.0	52	37
BJ	—	—	4.0	—	1.5	400	37
DG	1.5	1.5	2.5	1.5	2.0	545	39
EC	1.0	1.0	5.5	1.0	2.0	330	37
DS	—	—	—	—	—	11	47
CH	—	—	—	—	—	40	52
SH^a	1.5	1.5	2.0	1.5	1.5	50	34
GM	—	—	1.0	1.0	1.0	23	44
NK	—	—	—	—	—	58	42
AM	1.0	1.5	1.0	1.5	1.5	24	37
BC	2.0	2.5	2.0	2.0	2.0	22,000	47
CN	1.0	1.0	3.0	1.0	1.5	44	37
DC	3.0	3.0	3.5	3.0	3.0	180	33
Average	0.5	0.6	1.7	0.6	1.0	1,214	41

^a Unshaven.

— No measurable leakage, less than 0.5 ppm.

Table 2. Total inward leakage apparatus No. 2.

Subject	Average leakage ppm during exercise					Negative demand	Minute volume litres BTPS
	Side to side	Up and down	Talking	Walking	Average		
RC	—	—	1.0	—	—	60	63
B S	—	—	—	—	—	11	53
KD	—	—	—	—	—	16	44
AG	—	—	—	—	—	14	37
S C	—	—	—	—	—	12	34
SM	—	—	—	—	—	1.0	28
TH	—	—	—	—	—	—	41
RF	—	—	—	—	—	1.0	37
BJ	—	—	—	—	—	1.0	37
DG	—	—	—	—	—	—	39
EC	—	—	—	—	—	—	37
DS	—	—	—	—	—	—	47
CH	—	—	—	—	—	1.0	52
SH^a	—	—	—	—	—	1.0	34
GM	—	—	—	—	—	1.0	44
NK	—	—	—	—	—	—	42
AM	—	—	—	—	—	—	37
BC						2.5	47
CN	—	—	—	—	—	5,250	37
DC	—	—	—	—	—	—	33
Average	—	—	—	—	—	—	41

^a Unshaven.

— No measurable leakage, less than 0.5 ppm.

Table 3. Total inward leakage apparatus No. 3.

Subject	Average leakage ppm during exercise					Negative demand	Minute volume litres BTPS
	Side to side	Up and down	Talking	Walking	Average		
RC	—	—	—	—	—	—	63
BS	—	—	—	—	—	—	53
KD	—	—	—	—	—	8.0	44
AG	—	38	—	—	10.0	16	37
SC	—	—	—	—	—	1.0	34
SM	—	—	—	—	—	6.0	28
TH	—	—	—	—	—	6.5	41
RF	—	—	3.0	—	1.0	—	37
BJ	—	—	—	—	—	67.0	37
DG	—	—	—	—	—	—	39
EC	—	—	—	—	—	4.0	37
DS						—	47
CH	—	—	—	—	—	5.5	52
SH^a	—	150	—	—	38.0	—	34
GM	—	—	—	—	—	2.5	44
NK	—	—	—	—	—	4.5	42
AM	—	—	—	—	—	—	37
BC	—	—	—	—	—	600	47
CN	—	—	—	7.0	2.0	5.5	37
DC	—	—	—	—	—	9.0	33
Average	—	9.4	—	0.4	2.6	36.8	41

^a Unshaven.

— No measurable leakage, less than 0.5 ppm.

Table 4. Total inward leakage apparatus No. 4.

Subject	Average leakage ppm during exercise					Negative demand	Minute volume litres BTPS
	Side to side	Up and down	Talking	Walking	Average		
RC	—	—	—	—	—	7.0	63
BS	—	—	—	—	—	11	53
KD	—	—	—	—	—	19.0	44
AG	—	—	—	—	—	23.0	37
SC	—	—	—	—	—	18.0	34
SM	—	—	—	—	—	21.0	28
TH	—	—	—	—	—	11.0	41
RF	—	2.5	14.0	4.0	5.0	20.0	37
BJ	—	—	—	—	—	10.0	37
DG	1.0	1.0	—	—	1.0	14.0	39
EC	—	—	—	—	—	12.5	37
DS	—	—	—	—	—	7.5	47
CH	—	—	—	—	—	6.0	52
SH^a	—	65	—	2.0	17.0	5.5	34
GM	—	—	—	—	—	8.5	44
NK	—	—	—	—	—	4.0	42
AM	—	—	—	—	—	18.5	37
BC	—	—	—	—	—	200	47
CN	—	—	—	—	—	18.0	37
DC	—	—	—	—	—	40.0	33
Average	—	3.4	0.7	0.3	1.2	23.5	41

^aUnshaven.
— No measurable leakage, less than 0.5 ppm.

Table 5. Total inward leakage apparatus No. 5.

Subject	Average leakage ppm during exercise					Negative demand	Minute volume litres BTPS
	Side to side	Up and down	Talking	Walking	Average		
RC	—	—	—	—	—	—	63
BS	—	—	—	—	—	—	53
KD	—	—	—	—	—	—	44
AG	—	7.0	—	—	2.0	—	37
SC	—	—	—	—	—	—	34
SM	—	—	—	1.5	1.0	—	28
TH	—	—	—	—	—	—	41
RF	—	—	6.5	—	2.0	—	37
BJ	—	—	—	—	—	—	37
DG	—	—	—	—	—	—	39
EC	—	42.0	31.0	—	18.5	—	37
DS	—	2.0	—	—	1.0	—	47
CH	—	—	—	—	—	—	52
SH^a	35	12,000	20	20	3,010	—	34
GM	—	—	—	—	—	—	44
NK	—	—	—	—	—	—	42
AM	—	—	—	—	—	—	37
BC	—	17.0	—	—	4.5	—	47
CN	7.0	9.5	7.5	—	6.0	—	37
DC	—	1.5	—	13.0	4.0	—	33
Average	2.1	604	3.3	1.7	152.5	—	41

^aUnshaven.
— No measurable leakage, less than 0.5 ppm.

Table 6. Leakages and quantitative fit factors for SCBA (excluding SH).

Apparatus	Mean leakages (ppm)			QFF of mean leakages		
	Min	Max	Mean	Max	Min	Mean
1	<0.5	3.0	1.0	> 1,000,000	330,000	1,000,000
2	<0.5	0.5	0.5	> 1,000,000	>1,000,000	>1,000,000
3	<0.5	10	0.7	>1,000,000	100,000	>1,000,000
4	<0.5	5	<0.5	>1,000,000	200,000	> 1,000,000
5	<0.5	185	2.1	> 1,000,000	54,000	500,000

Table 7. Self-contained breathing apparatus. (Pressure measurements and occurrence of leaks.)

Breakdown by apparatus (400 tests)				:	Breakdown by apparatus excluding talking (300 tests)		
Apparatus No.	Instances of negative pressure in the inner or outer cavities	Instances of negative pressure in the outer cavity	Instances of leaks	:	Instances of negative pressure in the inner or outer cavities	Instances of negative pressure in the outer cavity	Instances of leaks
				:			
1	17	15	36	:	2	2	25
2	43	28	3	:	25	10	1
3	46	33	9	:	28	21	7
4	39	39	10	:	19	19	7
5	28	26	27	:	15	14	18
Total	173	141	85	:	89	66	58
Breakdown by exercise				:	Breakdown by exercise excluding talking		
Side to side	22	16	15	:	22	16	15
Up and down	30	23	24	:	30	23	24
Talking	84	75	27	:	—	—	—
Walking	37	27	19	:	37	27	19
Total	173	141	85	:	89	66	58

negative pressures mentioned are sharp spikes of up to 100 msec duration and would probably be unnoticed by the wearer of the apparatus.

An exercise has been counted if the pressure became negative at any time during the particular exercise, be it during one inhalation or every inhalation in the exercise.

Instances of negative pressure inside the facemask in either the inner or outer cavities were recorded on occasion in 173 of the 400 exercises. All twenty men at some time in the experiment showed instances of negative pressures.

If the pressures in the outer cavity alone are considered, since the outer seal must break to cause a leakage of the external atmosphere which is swept into the inner cavity, then 17 men

showed instances of negative pressure in 141 exercises.

Talking proved to be the exercise which had the highest frequency of occurrence and the lowest level of negative pressures. The lowest recorded was -18 mbar in the inner cavity and -16 mbar in the outer.

If talking is excluded and the other three exercises are examined separately (Table 7) then 89 out of the remaining 300 exercises showed negative pressure in the inner or outer cavities. Of these, 34 were less than 1 mbar negative, 46 between 1 and 2 mbar and 9 more than 2 mbar negative (mostly occurring in the inner cavity).

For the outer cavity, excluding talking, negative pressure occurred in 66 exercises out of 300

(Table 7) of which 56 were less than 1 mbar negative, 7 were between 1 and 2 mbar, and only 3 were more than 2 mbar negative. All of the last 3 mentioned were by SH, the unshaven subject. The lowest levels of negative pressure observed excluding talking were -3.3 mbar in the inner cavity and -3.0 mbar in the outer cavity by SH in the same breath. If SH is excluded -2.0 mbar was the lowest recorded in the inner cavity by several subjects and -1.7 mbar in the outer cavity.

Observation of Negative Pressures and Leakages

Leakage into the facemask was detected in 85 exercises out of 400 as shown in Table 7. These leakages were generally small, only 48 of them raised the mean leakage during the exercise above 0.5 ppm, and consequently are not seen in

Tables 1 to 5. The 85 exercises are divided as follows:

On 36 occasions when leakage occurred, the pressure remained positive in both cavities throughout the entire exercise. The mean leakages were typically less than 1 ppm, maximum 17 ppm. The leaks tended to be single leakage spikes on an otherwise flat trace.

On 10 occasions, the pressure in the outer cavity only remained positive throughout the exercise but negative pressures were observed in the inner cavity. The leakages were generally higher, typically mean leakages of 7 ppm with a maximum mean leakage of 38 ppm (example shown in Fig.3).

On only 10 occasions could leakage peaks be matched to a specific negative pressure spike (example shown in Fig. 2). During these 10 exercises the mean leakage was small, typically less than 1 ppm, maximum 6 ppm.

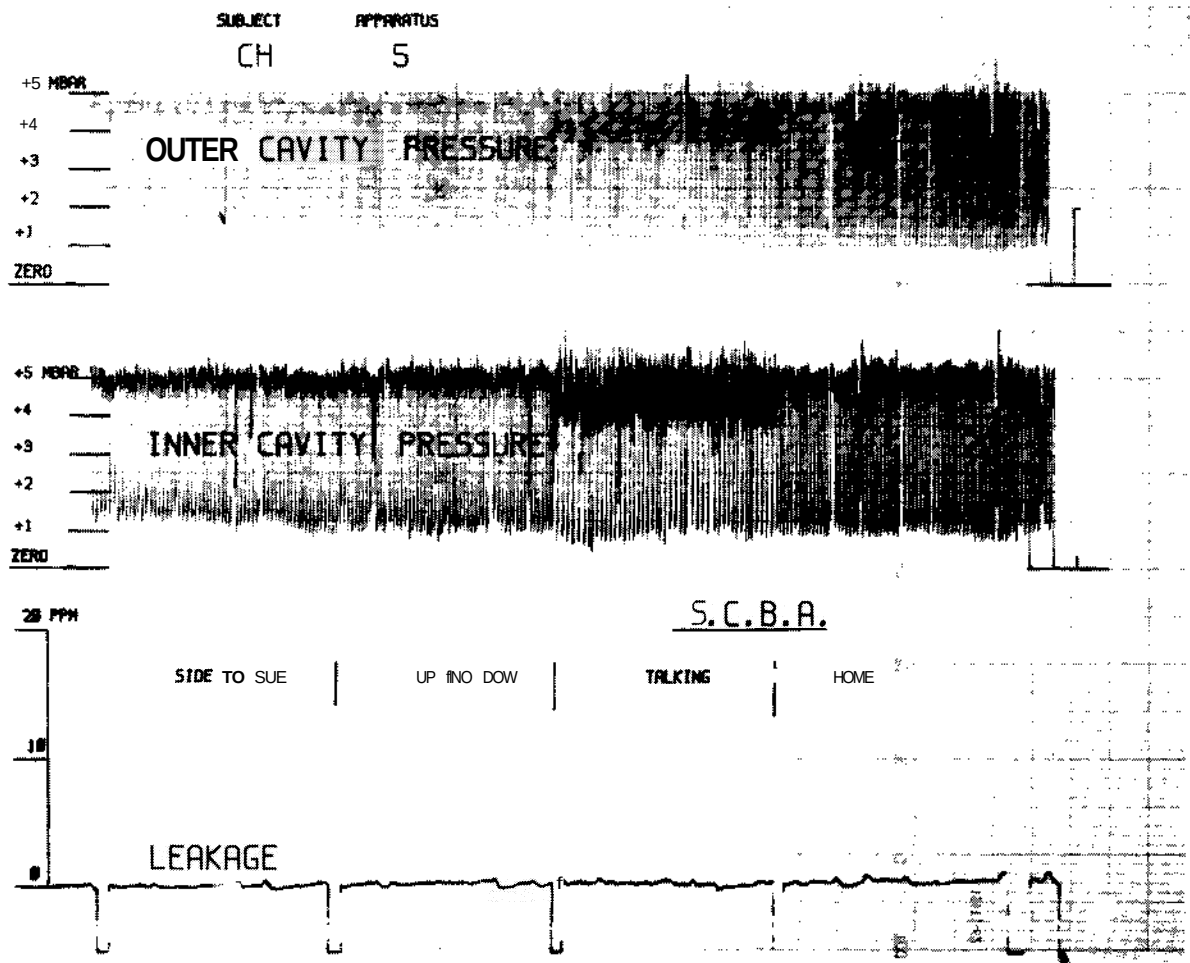


Figure 1.

On 29 occasions there was a negative pressure spike in the outer cavity and a leakage detected, but the leakage could not be matched to a particular negative pressure spike.

A breakdown of leakage by exercise and apparatus is shown in Table 7. Talking did not account for the most leaks, although a breakdown excluding the talking exercise is given for completeness.

Examples

Examples of results for individual wearings of self-contained breathing apparatus are shown in Figs. 1, 2, and 3.

Figure 1 shows subject CH wearing apparatus 5. Positive pressure is maintained during all of the four two minute exercises, and no leakage is detected.

Figure 2 shows subject EC wearing apparatus 1. The first two exercises show positive pres-

sure and no leakage. The talking exercise shows large leakages which coincide with negative pressures in both inner and outer cavities of the mask. The largest leakage does not correspond to the most negative pressure spike. The leakage of the talking exercise overall is 5.5 ppm. It is impossible to quote a peak leakage figure accurately, because the response of the leak detector is slow relative to the pressure transducers.

Figure 3 shows subject AG wearing apparatus 3. This shows a leakage into the facemask when the pressure in the outer cavity remained positive. The pressure in the inner cavity became slightly negative during a couple of breaths. This occurred during the up and down head movement, in which the mean leakage was 38 ppm. The subject had fitted the mask rather loosely, and during the test felt the need to adjust the straps. This he did in accordance with his instructions without knowledge of the presence of a leak. Upon tightening his straps, all leakage ceased.

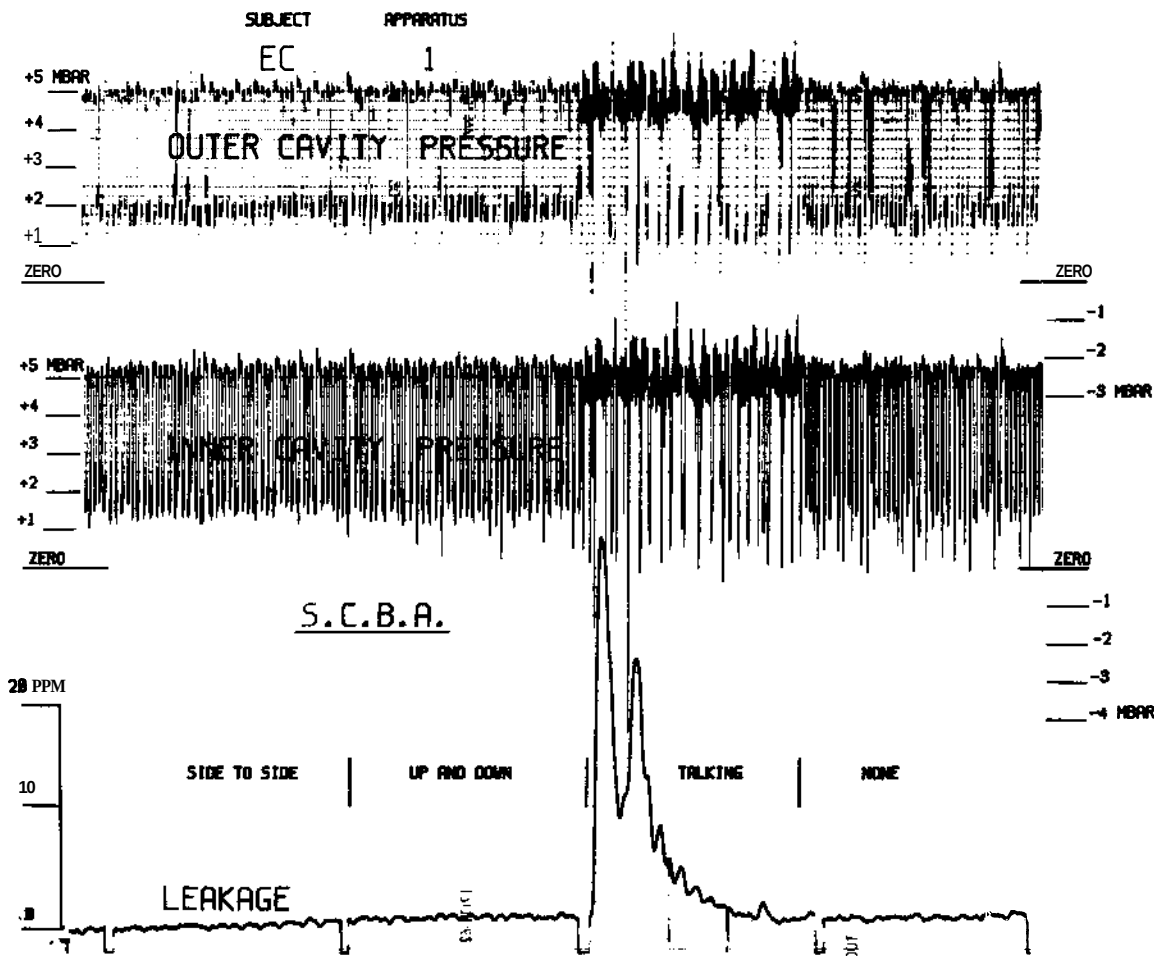


Figure 2.

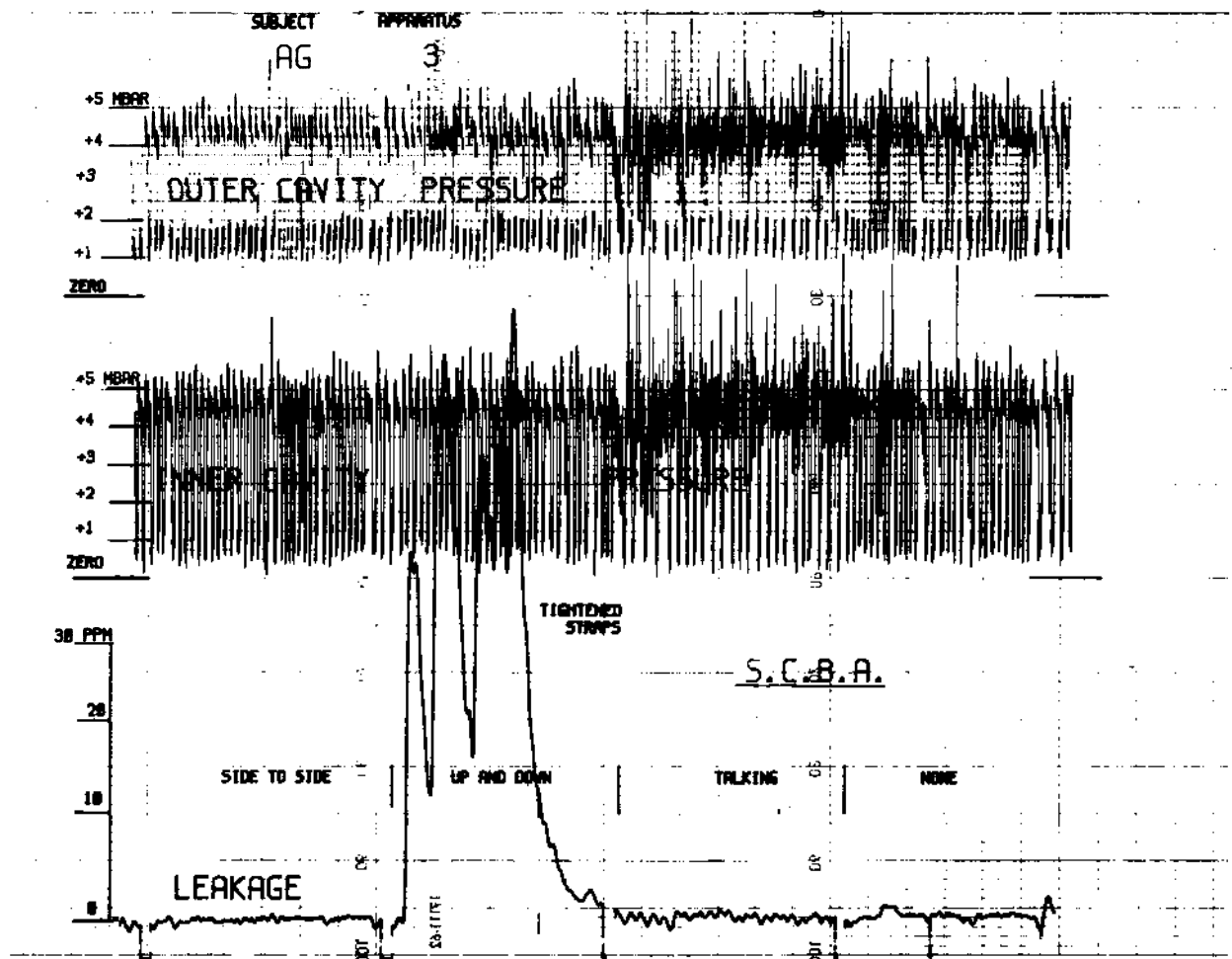


Figure 3.

Powered-Air Purifying Respirators (PAPRs)

Materials and Apparatus

Two types of PAPR, each fitted with either a full facemask or a half mask were checked for performance and filter penetration according to BS 4558: 1970 before use. Each facepiece was fitted with two ports at mouth level so that samples of the air breathed and the pressure within the facepiece could be measured during use.

Quantitative Fit Test (QFF) Equipment

The same chamber was used as in the SCBA experiments with the following modifications. The inlet pipe of 150 mm diameter was connected to a fan capable of delivering about 5000 litre/min

of air. A 2% sodium chloride solution was atomized within the airstream to give the required aerosol concentration in the chamber. The inlet to the fan was positioned in fresh air. The lower rear wall of the chamber was fitted with a similar fan to extract air from the chamber at a rate slightly less than the input fan. This fan exhausted through 150 mm diameter tubing to the external atmosphere away from the input to the inlet fan. A small recirculating fan was positioned at the front of the chamber near the floor to assist in the mixing of the atmosphere in the chamber.

The sodium chloride aerosol was generated using an atomizer as shown in BS 3928: 1969 operating at a pressure of 100 psi and passing 100 litre/min of air. The sodium chloride aerosol concentration produced was approximately 6 mg m^{-3}

which enabled leakages of less than 10 ppm to be estimated using a flame photometer. The accuracy of the results quoted in the tables is ± 5 ppm.

The sample was drawn from the facemask at a flow rate of 5 litre/min by means of a rotary vane pump through flexible plastic tubing. The pump discharged into a 20 mm diameter tube through which clean air flowed at 10 litre/min to the flame photometer. The resulting dilution was necessary as the minimum flow rate for the photometer to operate reliably was 15 litre/min. The output from the photometer was recorded by means of a potentiometric recorder.

Test Procedure

Each subject donned the apparatus in the room adjacent to the test chamber. When a satisfactory fit had been obtained and with the air supply on, the sampling and pressure measuring

lines were connected to the ports in the facepiece. The subject then entered the chamber with the sodium chloride aerosol generator off and walked on the treadmill until the zero of the apparatus was established (about 3 minutes). The aerosol generator was then turned on and the subject continued to walk for a further 2 minutes during which time the salt cloud stabilized. He then carried out the set exercises as detailed previously, (a) to (d). These exercises were followed by a further 2 minutes walk, without head movement with the air supply to the facepiece turned off. At the end of this period of time the power to the respirator was turned on, the treadmill was stopped and the subject remained in the chamber until the salt concentration within the chamber was established.

The concentration of salt within the respirator facepiece was continuously monitored during the tests.

Table 8. Inward leakage of apparatus No. 6 (full-face mask) powered air-purifying respirator.

Subject	Average leakage ppm during exercise						Minute volume litres BTPS
	Side to side	Up and down	Talking	Walking	Average	Power off	
RC	5	5	5	5	5	5	63
BS	5	5	5	5	5	5	53
KD	5	5	5	5	5	5	44
AG	30	25	50	30	35	35	37
SC	55	55	55	55	55	95 ^a	34
SM	15	5	20	5	10	15	28
TH	5	5	5	5	5	5	41
RF	5	5	15	10	10	5	37
BJ	5	20	20	5	10	5	37
DG	45	15	240	10	80	10	39
EC	5	5	5	5	5	5	37
DS	5	5	5	5	5	15	47
CH	5	5	5	5	5	20	52
SH	10	5	15	5	10	15	34
GM	10	5	10	10	10	10	44
NK	5	10	10	5	10	20	42
AM	10	5	10	5	10	15	37
BC	5	40	10	5	15	265	47
CN	5	5	35	5	10	19,100 ^b	37
DC	5	5	5	5	5	5	33
Average							41
Geometric mean					10		
Geometric standard deviation					2.3		

^a Apparatus fault.

^b Loose coupling.

Leakage Results and Discussion

The total inward leakage results are shown in Tables 8 to 11 for each PAPR. It has been suggested (R. A. da Roza et al., 1983) that the magnitude of respirator inward leakage follows a log-normal model. Probability plots of the total inward leakage (TIL) of apparatus No. 7 are shown in Fig. 4(a) and (b). As can be seen, a log-normal model gives a fair fit in the case of the full mask, but not a good fit for a half-mask. These results include the effect of the constant filter penetration which is independent of the subject. If the penetration is subtracted from each result, and the variable face seal leakage (FSL) only is considered, the probability plots become as shown in Fig. 4(c) and (d). The fit is little different for the full mask, but in the case of the half-mask, the fit has improved. The results for apparatus 7 support the log-normal model and the results for mean penetration are quoted using the geometric mean FSL plus the constant penetration.

For apparatus 6, there is no detectable penetration to allow for. The probability plots are

shown in Fig. 5(a) and (b). The measured leakages are very close to the detectable limit (5 ppm) and consequently, the probability plot is distorted at the lower end. There is insufficient detail in the results to make any meaningful comment on the fit of a log-normal distribution to the data. However, the log-normal model is still an improvement over the normal model and log-normal statistics are used for apparatus 6 also. A summary and the QFF's are shown in Table 12.

The individual exercise results (Tables 8 to 11) show the leakage to range from less than 10 ppm (QFF greater than 100,000) to 8,200 ppm (QFF = 120) when worn with the power on and less than 10 ppm (QFF greater than 100,000) to 30,500 ppm (QFF = 33) with the power off.

The results obtained show that the mean leakages (Table 12) ranged from 10 ppm (QFF = 100,000) to 390 ppm (QFF = 2,500).

Pressure Measurement Results

Instances of negative pressure inside the mask were recorded on occasions for all 20 men.

Table 9. Inward leakage of apparatus No. 6 (half-mask) powered air-purifying respirator.

Subject	Average leakage ppm during exercise						Minute volume litres BTPS
	Side to side	Up and down	Talking	Walking	Average	Power off	
RC	5	5	510	60	145	4,350	63
BS	5	5	35	5	15	180	53
KD	5	10	15	5	10	85	44
AG	5	5	5	5	5	115	37
SC	5	15	5	5	10	160	34
SM	5	5	10	5	5	2,400	28
TH	5	5	20	5	10	90	41
RF	5	5	5	5	5	10	37
BJ	5	5	10	10	10	220	37
DG	45	85	105	20	65	45	39
EC	10	5	5	5	5	15	37
DS	5	5	5	5	5	25	47
CH	5	10	10	5	10	30	52
SH	5	5	20	5	10	30	34
GM	10	15	2,800	10	710	3,700	44
NK	5	5	5	5	5	30	42
AM	5	5	90	5	25	1,600	37
BC	5	5	10	5	5	95	47
CN	5	5	5	5	5	190	37
DC	5	5	5	5	5	100	33
Average							41
Geometric mean					12		
Geometric standard deviation					3.8		

Table 10. Inward leakage of apparatus No. 7 (full-face mask) powered air-purifying respirator.

Subject	Average leakage ppm during exercise						Minute volume litres BTPS
	Side to side	Up and down	Talking	Walking	Average	Power off	
RC	20	20	8,200	30	2,070	75	63
BS	20	20	5,780	45	1,465	75	53
KD	30	25	2,500	35	650	55	44
AG	30	25	1,000	30	270	105	37
SC	25	25	55	35	35	55	34
SM	25	25	575	30	165	30	28
TH	15	15	1,600	15	410	20	41
RF	20	20	2,000	20	515	30	37
BJ	25	25	3,550	25	905	15	37
DG	20	40	4,550	125	1,165	20	39
EC	20	20	1,500	30	395	25	37
DS	25	20	3,200	25	820	30	47
CH	25	25	35	25	30	60	52
SH	45	35	3,400	30	880	115	34
GM	40	45	4,300	30	1,100	80	44
NK	25	20	1,200	25	320	40	42
AM	25	25	470	25	135	25	37
BC	35	35	1,300	35	350	40	47
CN	30	30	765	30	215	50	37
DC	30	30	1,580	45	420	160	33
Average							41
Geometric mean					390		
Geometric standard deviation					3.1		

Table 11. Inward leakage of apparatus No. 7 (half mask) powered air purifying respirator.

Subject	Average leakage ppm during exercise						Minute volume litres BTPS
	Side to side	Up and down	Talking	Walking	Average	Power off	
RC	35	35	120	45	60	20,000	63
BS	60	60	695	60	220	20	53
KD	50	50	80	50	60	40	44
AG	85	75	95	70	80	170	37
SC	45	65	50	45	50	125	34
SM	80	65	2,800	80	755	30,500	28
TH	35	35	65	35	45	15	41
RF	40	40	50	35	40	1,970	37
BJ	50	45	145	45	70	50	37
DG	80	100	225	45	115	1,550	39
EC	45	45	720	55	215	160	37
DS	70	60	150	45	80	1,400	47
CH	50	130	80	60	80	16,700	52
SH	60	60	80	65	65	40	34
GM	70	75	110	65	80	50	44
NK	55	40	90	35	55	3,700	42
AM	50	45	45	40	45	10,600	37
BC	40	40	80	40	50	475	47
CN	55	55	60	50	55	85	37
DC	55	55	95	55	65	35	33
Average							41
Geometric mean					70		
Geometric standard deviation					3.2		

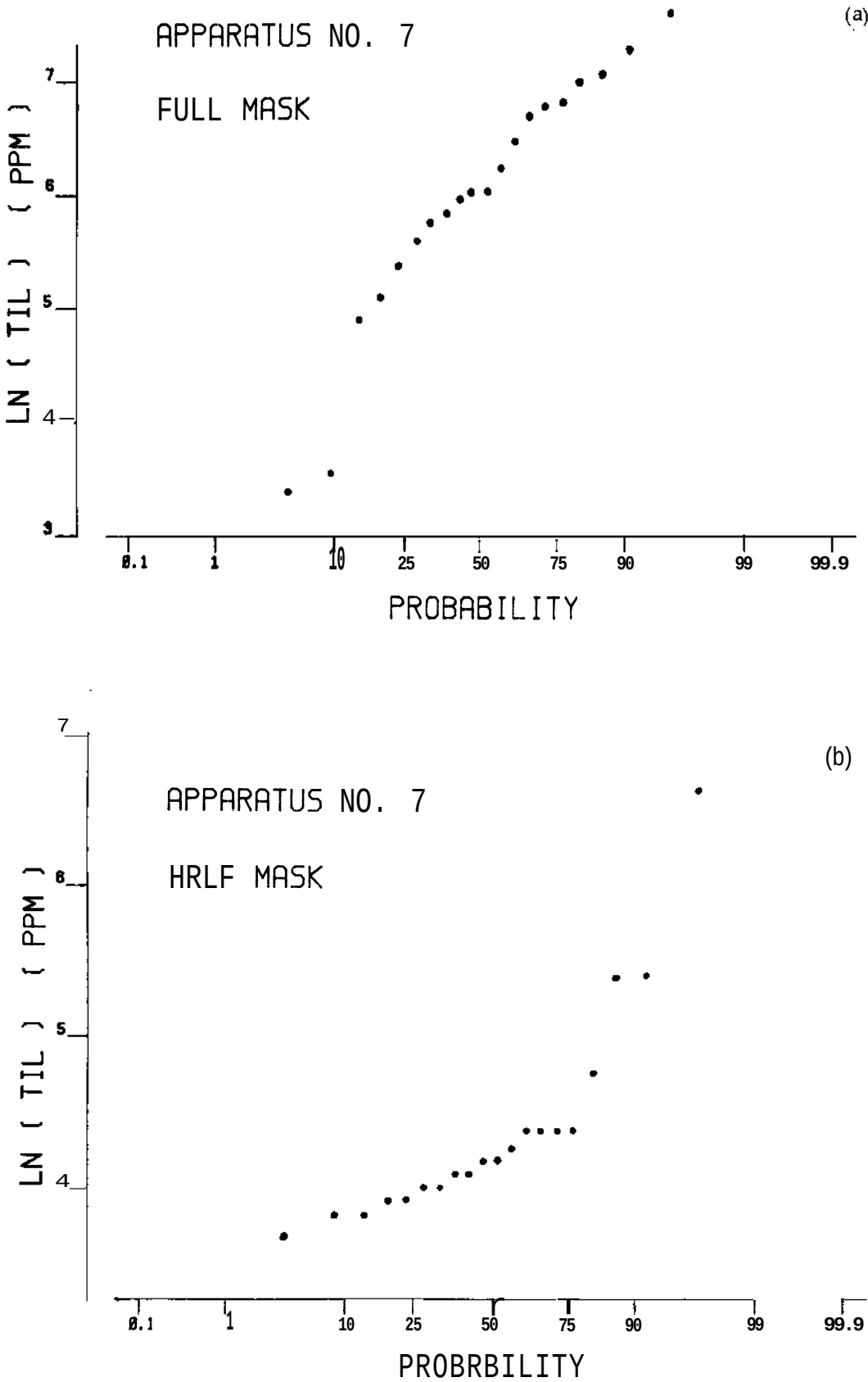
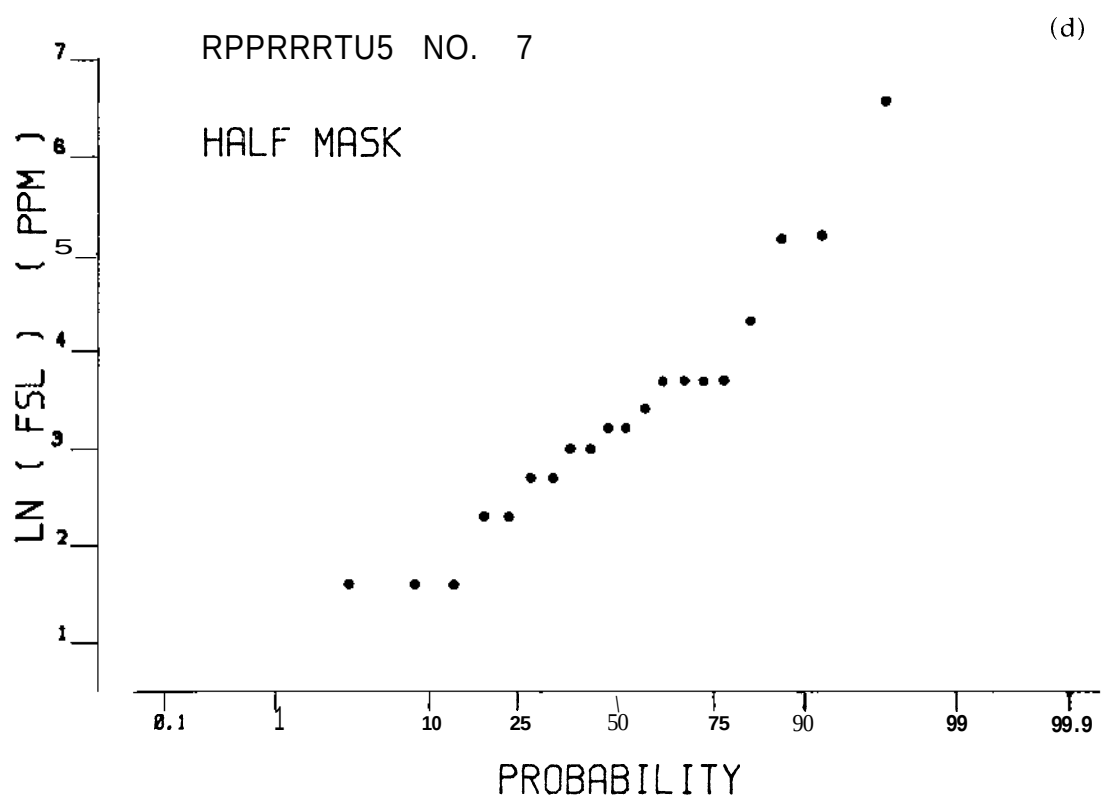
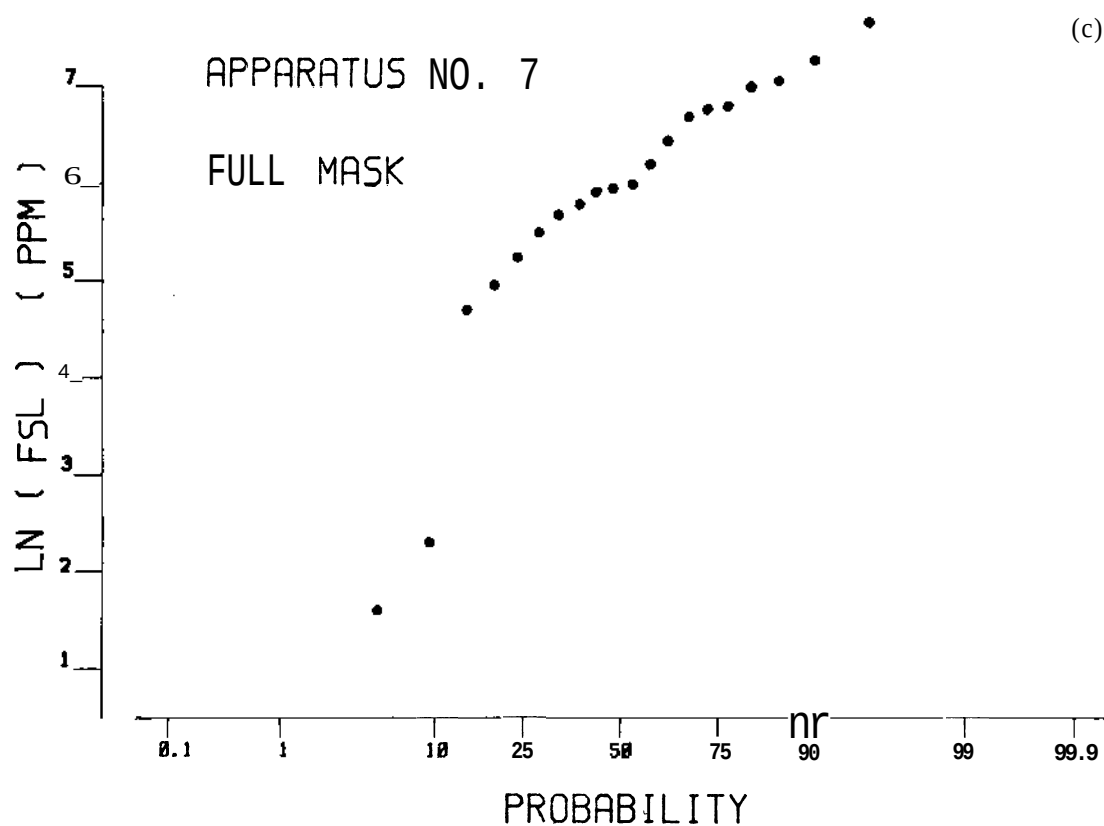


Figure 4.



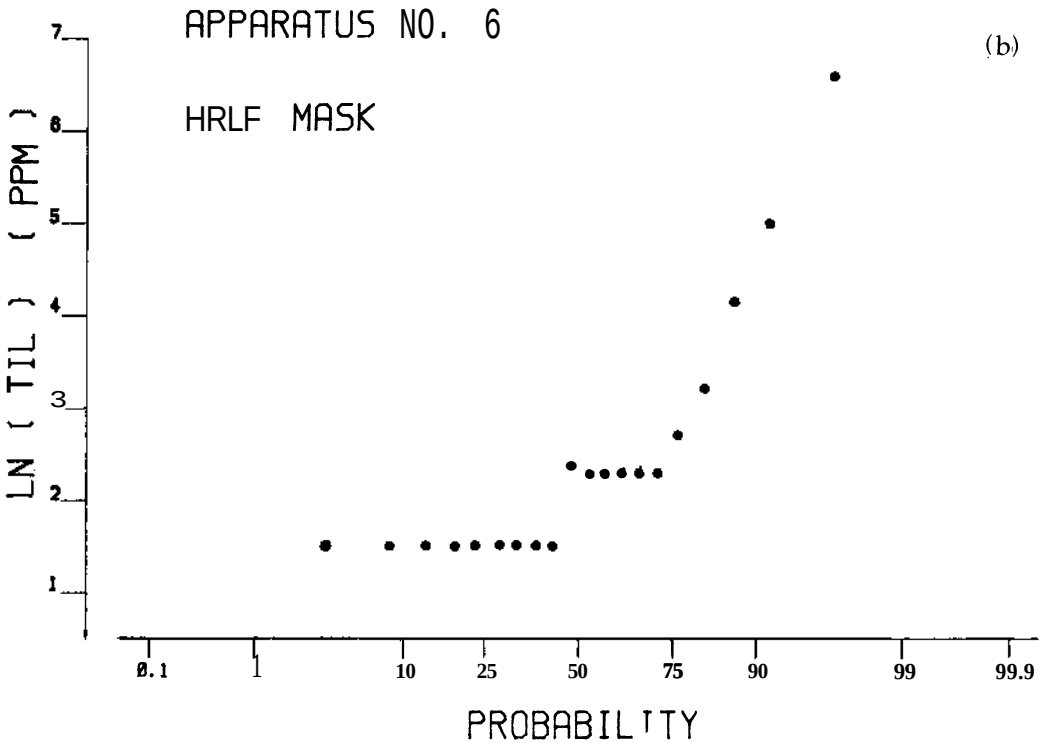
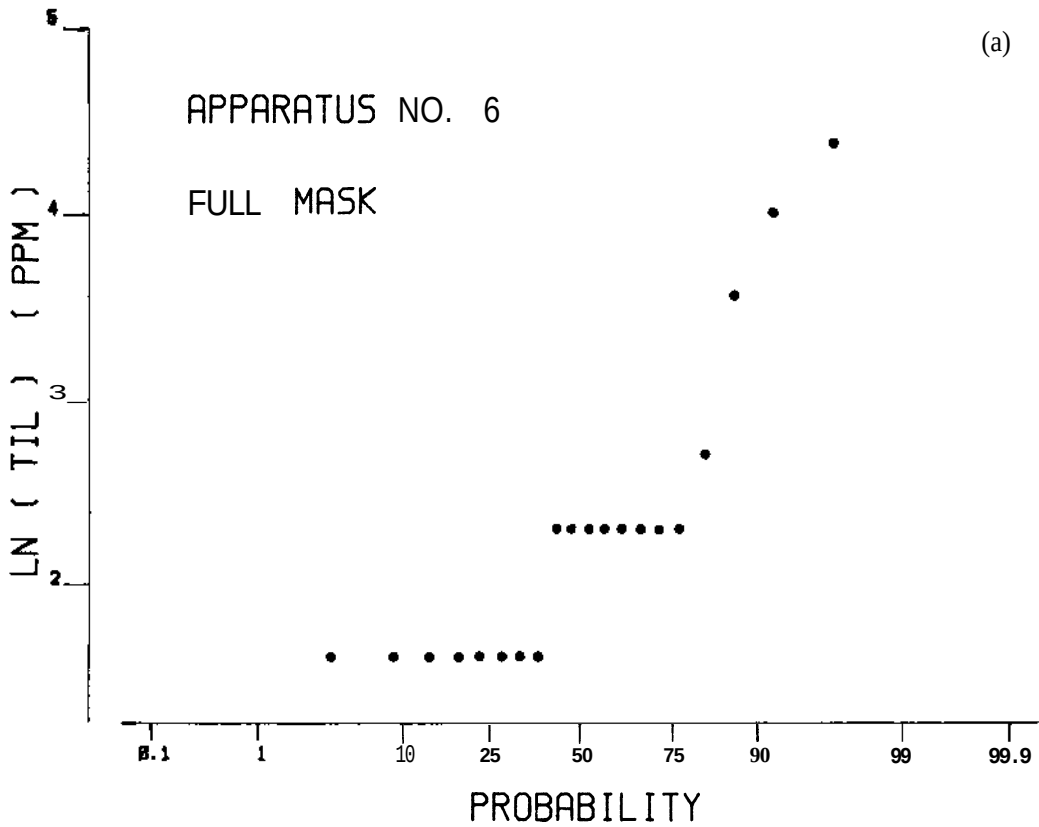


Figure 5.

Table 12. Leakages and quantitative fit factors for the PAPR's.

Apparatus	Mask mode	Mean leakage (ppm)		Mean (geometric)	Std. dev. (geometric)	QFF of mean leakage		
		Min	Max			Max	Min	Mean
6	Full	5	80	10	2.3	100,000	12,500	100,000
	Half	5	710	12	3.8	100,000	1,400	83,000
7	Full	30	2070	390	3.1	33,000	480	2,500
	Half	40	755	70	3.2	25,000	1,300	14,000

Table 13. Power assisted respirators. (Pressure measurements and occurrence of leaks.)

Breakdown by exercise (320 tests)			:	Breakdown by exercise excluding talking (240 tests)	
Apparatus No.	Instances of negative pressure	Instances of leaks	:	Instance of negative pressure	Instances of leaks
6 Full mask	31	40 (40)	:	11	25 (25)
6 Half mask	46	38 (38)	:	27	28 (28)
7 Full mask	19	80 (43)	:	4	60 (24)
7 Half mask	20	80 (52)	:	1	60 (34)
Total	116	238 (173)	:	43	173 (111)
Exercise			:		
Side to side	12	58 (40)	:	12	58 (40)
Up and down	12	62 (38)	:	12	62 (38)
Talking	73	65 (62)	:	—	—
Walking	19	53 (33)	:	19	53 (33)
Total	116	238 (173)	:	43	173 (111)

Figures in brackets indicate face seal leakage results only.

Negative pressures were observed in 116 of the 320 exercises (20 men, 4 apparatus, 4 exercises). A breakdown of the results by exercise and apparatus is given in Table 13.

The majority of instances of negative pressure occurred during the talking exercise. Seventy-three out of 80 tests were negative in this exercise. Typically, pressures fell to -4 mbar to -5 mbar during inspiration in the talking exercise.

If the talking exercise is excluded, then only 43 out of 240 exercises showed negative pressure. These were usually single breaths with a pressure of about -1 mbar during an otherwise positive pressure exercise.

Observation of Negative Pressures and Leakages

Inward leakages were observed in 238 exercises out of 320. This includes apparatus 7, which

for both full and half-masks, showed a constant filter penetration. The figures in Table 13 in brackets indicate the observation of a leakage spike on top of the continuous filter penetration, i.e., a face seal leakage. If this face seal leakage only is considered then leakage was observed in 173 out of 320 exercises. The occurrence of leakages do not show a predominance in the talking exercise, although the figures are included in Table 13 for completeness. The largest leakages, however, occurred during the talking exercise.

Of the 173 exercises in which face seal leakages were observed, 91 occurred whilst positive pressure was maintained at all times during the exercises, 58 could be correlated with the occurrence of negative pressure in the facepiece and 24 showed leakage in an exercise in which negative pressures were also observed, but during a different part of the exercise, i.e., pressure was positive during the occurrence of a leak.

Of the 91 exercises in which a leak occurred but positive pressure was maintained, only 29

were large enough to raise the mean face seal leakage above 10 ppm, and 2 above 50 ppm. These 2 were 100 ppm (CH apparatus, 7 half-masks up and down) and 1500 ppm (EC apparatus, 6 half-masks talking).

Of the 58 exercises in which negative pressure could be matched to a leakage, 49 occurred in the talking exercise, giving large leakages (1000's of ppm). The other 9 were small leakages (maximum 60 ppm) occurring during the other exercises.

Of the other 24 uncorrelated leaks, 11 raised the mean leakage above 10 ppm, and 5 above 50 ppm. The largest leakage was 240 ppm. This is a similar result to the 91 cases where positive pressure was maintained throughout the exercise.

Examples

Examples of results for individual wearings of powered respirators are shown in Figs. 6, 7, and 8.

Figure 6 shows subject KD wearing apparatus No. 6 with full mask. It shows positive pressures without any inward leakage except for the talking exercise, during which pressures of -3 mbar to -4 mbar were recorded and a small leak observed.

Figure 7 shows subject RC wearing apparatus No. 6 with half mask. This shows large leakages correlated with negative pressures during the last two exercises.

Figure 8 shows subject RC wearing apparatus No. 7 with half mask. Note the continuous leakage of about 40 ppm due to filter penetration. Negative pressures and leakages are correlated in the talking exercise, giving a mean leakage of 120 ppm. Face seal leakage spikes are seen in the first two exercises, which are uncorrelated with negative pressures.

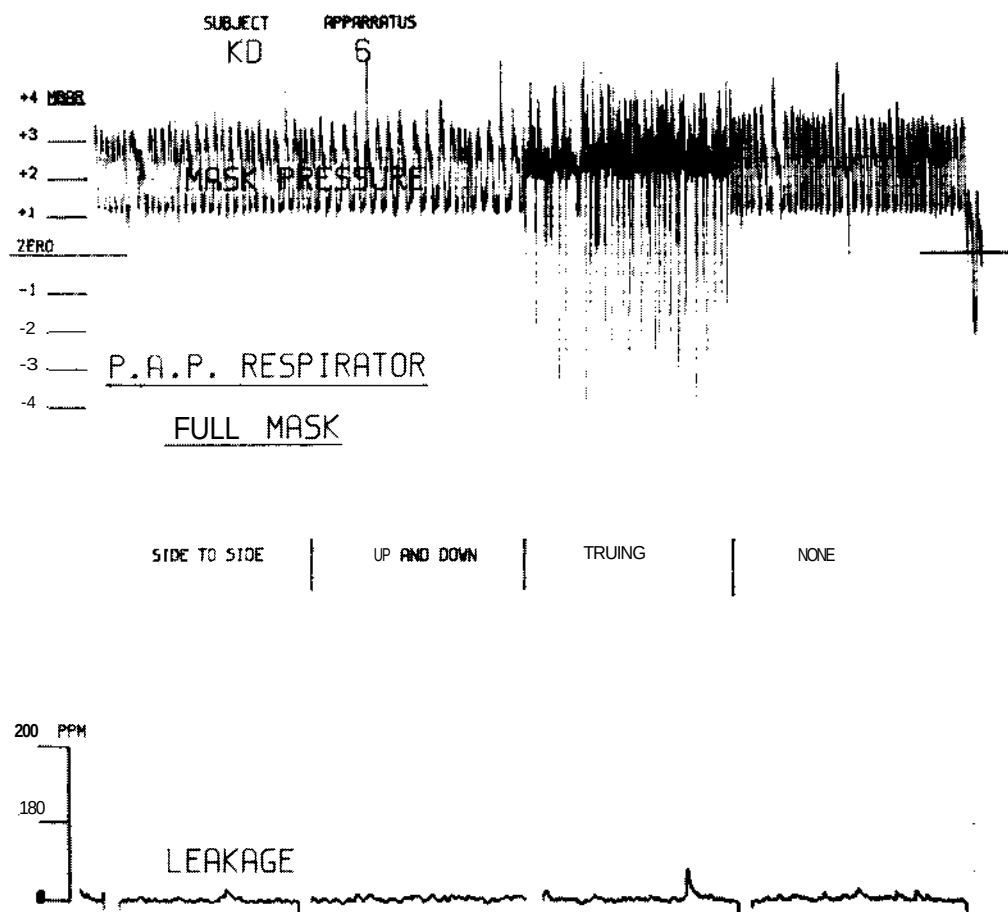


Figure 6.

FIG 5

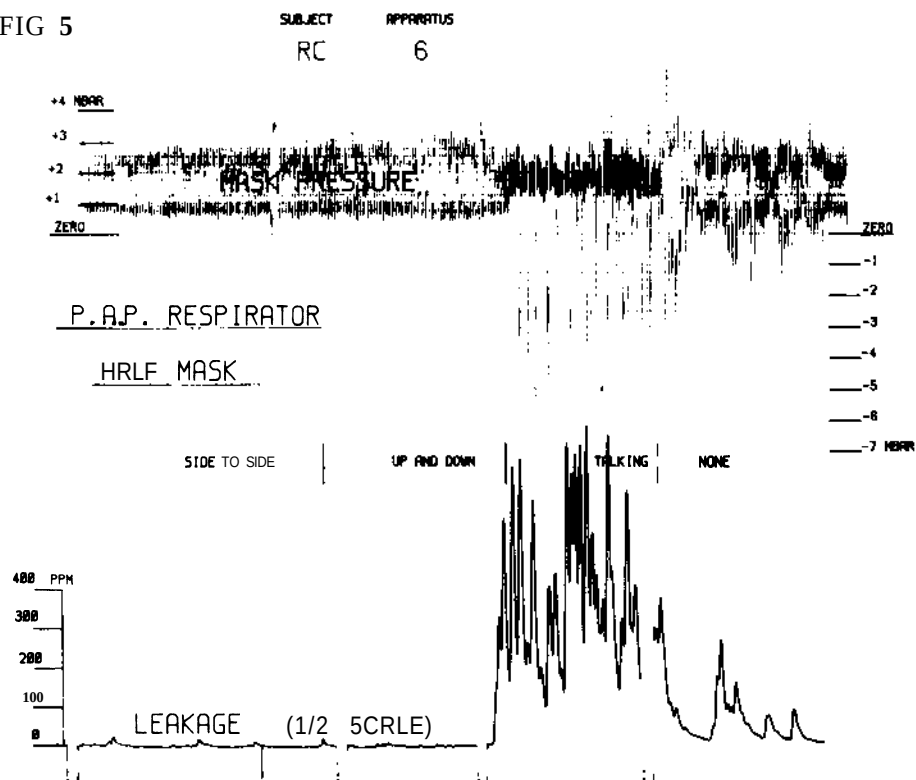


Figure 7.

FIG 6

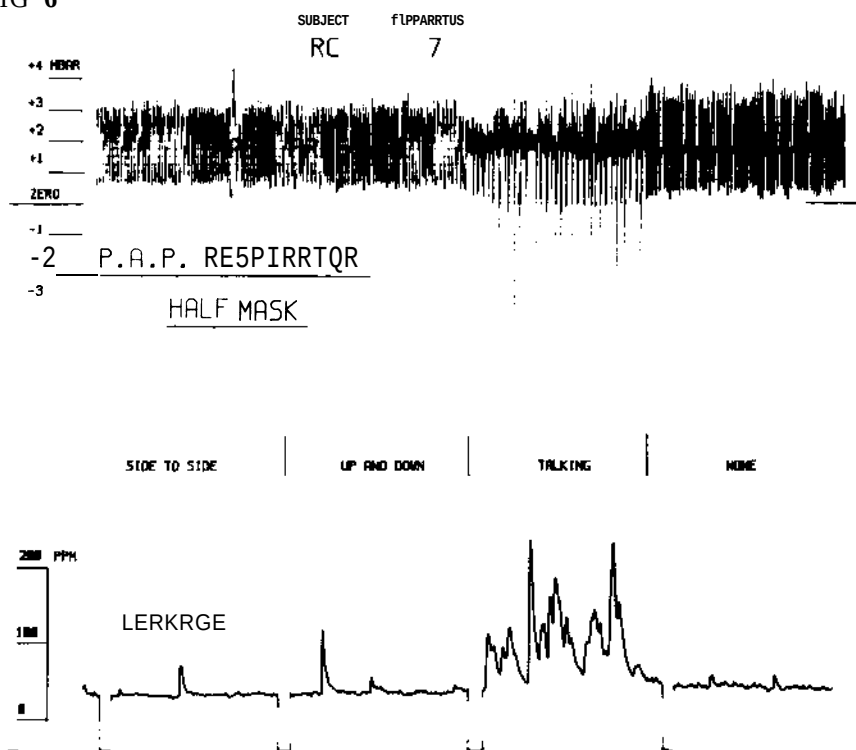


Figure 8.

Air-Fed Helmet

Materials and Apparatus

The air-fed helmet is similar to the self contained power assisted helmet known as the "Air-stream" the difference being that air is supplied to the helmet via an airline connected to a source of breathable air.

The helmet was checked for condition and the flow rate of air determined at the minimum required supply pressure of 3 bar. This was found to be 170 litres per minute. This pressure was then used throughout the tests. The visor of the helmet was fitted with a sampling port at mouth level.

Quantitative Fit Factor (QFF) Equipment

The chamber was used with the sodium chloride aerosol admitted as in the PAPR experiments to give a chamber concentration of 6 mg m^{-3} sodium chloride. The sampling line for the sodium chloride photometer was connected directly to the sampling port on the visor. The sample was drawn from the helmet at a flow rate of 5 litre/min through a flexible plastic tube and mixed with clean air at a flow rate of 10 litre/min to give a flow of 15 litre/min to the flame photometer.

Test Procedure

The subject donned the helmet, the air supply was connected and turned on and adjusted to 3 bar. The subject entered the chamber and walked for about 1 minute, during which time the zero levels were established and then for a further 2 minutes during which the atomizer was switched on and the aerosol concentration allowed to stabilize. The subject then performed the set exercises, as detailed previously (a) to (d). The concentration of sodium chloride from within the helmet was continuously recorded throughout the exercises. At the end of the exercises the subject stepped off the mill which was then stopped. He then remained standing on the mill and lifted the visor, the air supply was turned off, and sampling was continued in order to measure chamber concentration.

Results and Discussion

The results for the leakage into the helmet are shown in Table 14. There was a wide spread of leakage figures, with the highest produced when talking, probably due to the high peak inspiration flow.

The results fit a log-normal distribution as shown in the probability plot in Fig. 9. The geometric mean of the average inward leakages is 0.55% (geometric std. dev. = 2.9) giving a mean QFF of 180 and range from 1250 to 29. If the results obtained from the talking exercise are separated, the geometric mean QFF obtained over the other exercises improves to 970 and range from 5,000 to 43. Note that the values given in Table 14 are percentages rather than parts per million.

Correlation Study

The methods commonly used in the British Standards Specifications for the estimation of face seal or total inward leakage utilize tracer elements in either particulate aerosol or gaseous form. BS 2091: 1969 for instance uses sodium chloride aerosol while BS 4667: 1974 uses argon gas as a tracer. As we have shown in the estimation of quantitative fit factors for SCBA used in the positive pressure mode, SF_6 offers, in our opinion, a much more sensitive, accurate, and less expensive method for total inward leakage estimation.

It was felt that some attempt should be made to show whether or not a correlation existed in the use of these tracer elements.

Materials and Apparatus

One of the facemasks and apparatus used in the SCBA experiments was used in this study. The port in the outer cavity was left open to the external atmosphere to act as a permanent leak into the mask. One of the sampling ports entering the inner mask was used to collect a sample, by means of a 'T' piece, for the analysis of argon and SF_6 , the other to collect a sample for sodium chloride determination. As there was no continuous flow of clean air through the facepiece, sampling during exhalation could cause condensation and

Table 14. Inward leakage of apparatus No. 8 (air-fed helmet).

Subject	Average leakage percent during exercise					Minute volume litres BTPS
	Side to side	Up and down	Talking	Walking	Average	
RC	0.02	0.06	1.48	0.02	0.43	63
BS	2.30	2.05	7.10	2.30	3.40	53
KD	0.01	0.05	0.51	0.08	0.16	44
AG	0.92	0.43	3.55	0.48	1.35	37
SC	0.04	0.12	0.42	0.01	0.15	34
SM	0.01	0.01	0.60	0.02	0.16	28
TH	0.17	0.47	3.45	0.47	1.14	41
RF	1.85	2.15	6.50	3.00	3.40	37
BJ	0.74	1.76	1.64	0.23	1.09	37
DG	0.03	0.02	3.95	0.02	1.01	39
EC	0.01	0.03	0.78	0.03	0.21	37
DS	0.05	0.05	3.90	0.15	1.05	47
CH	0.04	0.06	0.14	0.06	0.08	52
SH	0.01	0.01	0.74	0.06	0.21	34
GM	0.18	2.85	2.85	0.15	1.50	44
NK	0.01	0.01	1.59	0.04	0.41	42
AM	0.01	0.06	2.70	0.18	0.75	37
BC	0.01	0.01	2.15	0.02	0.55	47
CN	0.07	0.40	1.13	0.40	0.50	37
DC	0.02	0.02	1.55	0.02	0.40	33
Average						41
Geometric mean					0.55	
Geometric standard deviation					2.9	

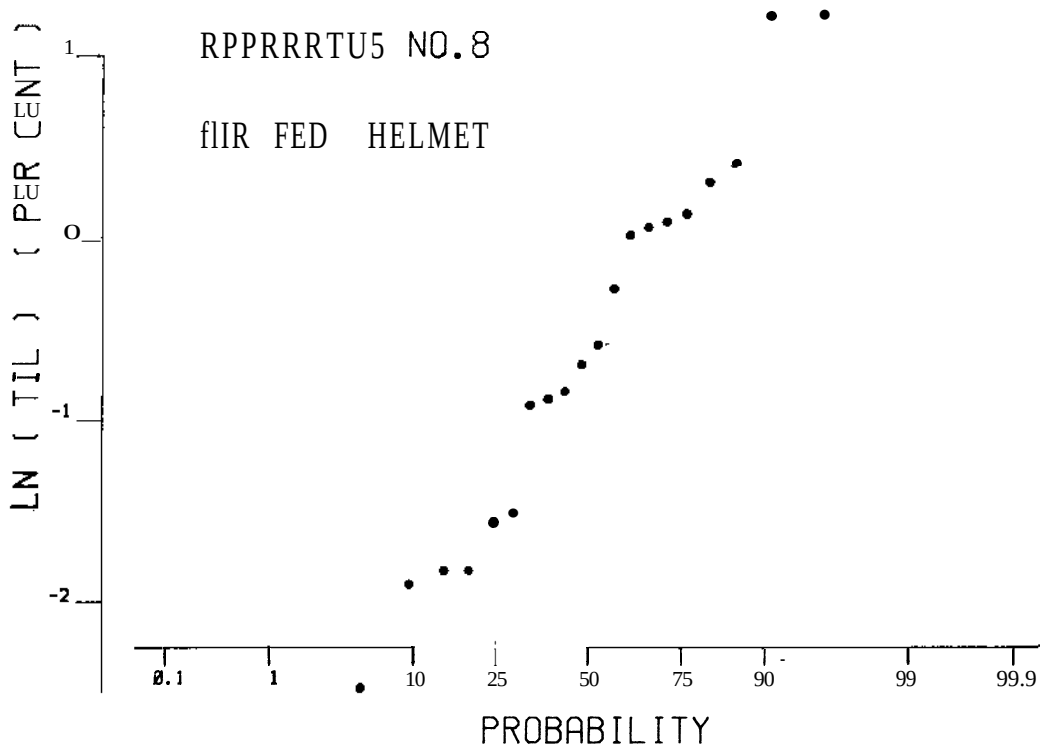


Figure 9.

hence loss of aerosol in the sodium chloride sampling line. Clean dry air was therefore added at the sampling port by means of a further 'T' piece. The airflow was 2.5 litre/min so with the rotary pump set to deliver 5 litre/min, the sample drawn from the facepiece was also 2.5 litre/min.

Quantitative Fit Factor (QFF) Equipment

The chamber, set up as in the PAPR experiments, was used with the sodium chloride aerosol generated and admitted into the airstream as before. The SF₆ was admitted, via a port in the ducting, at a controlled rate immediately before the inlet fan to ensure good mixing. The amount of argon normally present in the atmosphere was sufficient as a tracer test gas for the argon estimation. The concentration of the tracers in the chamber was therefore maintained at about 6 mg m⁻³ sodium chloride, 50 ppm SF₆ and 9,400 ppm argon. These concentrations were sufficient to detect an inward leakage of about 100 ppm or 0.01%.

Each subject wore the SCBA in the negative demand mode and breathed an oxygen/nitrogen mixture containing about 0.04 percent argon.

The sodium chloride was estimated as before by means of the flame photometer. An allowance had to be made for the reduced sample flow and also for the depleted aerosol concentration during exhalation. The recommended factor in BS 6016: 1980 of 0.6 was applied to allow for losses in the respiratory tract.

The sample from the other port was passed through a drying tube and then divided into two samples. One of these samples was passed to the SF₆ detector, the other to a quadrupole mass spectrometer for the argon estimation.

Test Procedure

The subject donned the facemask and apparatus in the room adjacent to the chamber and turned the apparatus to positive pressure supply. The sampling lines were connected and the subject entered the chamber; he walked for 2 to 3 minutes on positive pressure while the various zero levels were established and the chamber concentration of the tracers stabilized. The apparatus was turned to the negative demand mode and the set exercises carried out as previously described (a) to (d). The concentration of argon, SF₆, and

sodium chloride from within the facepiece were continuously recorded during the tests. At the end of this time the apparatus was turned to the positive pressure mode and the zero levels re-established. The subject then stopped walking and the treadmill was stopped. The facepiece was removed and he remained in the chamber until the concentrations of the tracer elements with the chamber were determined.

Results and Discussion

The percentage leakage of each tracer element for each man during all the exercises is shown in Table 15. From the results it can be seen that the leakage through the open port was of the order of 1% but varied somewhat according to the subject's breathing rate and whether or not there was any face seal leakage. This was apparent on some occasions, e.g., RF and BC during the head up and down movement. During these exercises the leakage was sufficiently large so as to cause the sulphur hexafluoride and sodium chloride detectors to be overloaded. These results were ignored in the subsequent analysis.

When a paired 't' test was performed on the twenty side to side leakage results and the eighteen up and down leakage results it was found that there was no significant difference between the values for the leakage obtained by the argon and sulphur hexafluoride techniques. There was, however, a significant difference between the two sets of recorded leakages for the talking exercise. Experience gained since these experiments were performed has shown that when reciting the alphabet the breathing pattern is sufficiently changed to decrease the mean expired oxygen concentration. This in turn decreases the output from the sulphur hexafluoride detector. When related to the test conditions during these experiments, the change in breathing pattern would have caused the reading to be depressed by 0.06-0.09%. If this correction is applied to the leakage recorded by the sulphur hexafluoride technique during the talking exercise, then the difference between the argon and sulphur hexafluoride results becomes insignificant.

Similarly there is a slight but significant difference in the leakage results recorded by the argon and sulphur hexafluoride techniques during the final walking exercise. Most of this difference can be attributed to a carry over of the oxygen depletion effect caused by the rhythmic recital of

Table 15. Inward leakage of mask No. 1 correlation exercise.

Subject		Leakage percent during exercise					Standard deviation (SD)
		Side to side	Up and down	Talking	Walking	Average	
RC	Argon	0.85	0.80	0.60	0.80	0.75	0.11
	SF ₆	0.75	0.70	0.40	0.70	0.65	0.16
	NaCl	1.35	1.20	0.65	1.20	1.10	0.31
BS	Argon	0.85	0.80	0.55	1.00	0.80	0.19
	SF ₆	0.85	0.85	0.50	0.90	0.80	0.18
	NaCl	0.75	0.70	0.55	0.90	0.75	0.14
KD	Argon	1.00	0.85	0.55	1.05	0.85	0.23
	SF ₆	1.10	1.00	0.55	1.10	0.95	0.26
	NaCl	1.05	0.90	0.55	1.05	0.90	0.24
AG	Argon	1.05	0.95	0.95	0.90	0.95	0.06
	SF ₆	0.95	0.90	0.90	0.75	0.90	0.09
	NaCl	1.05	1.00	0.80	0.90	0.95	0.11
SC	Argon	1.30	1.30	1.00	1.15	1.20	0.14
	SF ₆	1.30	1.45	1.05	1.25	1.25	0.16
	NaCl	1.70	1.95	1.35	1.45	1.60	0.27
SM	Argon	1.00	0.95	0.45	1.00	0.85	0.27
	SF ₆	1.10	1.05	0.35	0.90	0.85	0.34
	NaCl	1.60	1.35	0.50	1.40	1.20	0.49
TH	Argon	0.75	0.70	0.50	0.85	0.70	0.15
	SF ₆	0.75	0.70	0.45	0.80	0.70	0.16
	NaCl	1.60	1.30	0.55	1.15	1.15	0.44
RF	Argon	1.45	(4.75)	1.00	1.10	1.20	0.24
	SF ₆	1.55	*	0.70	1.05	1.10	0.43
	NaCl	2.45	*	0.60	1.35	1.45	0.93
BJ	Argon	1.15	1.15	0.60	1.15	1.00	0.28
	SF ₆	1.15	1.10	0.55	1.10	1.00	0.28
	NaCl	1.00	0.95	0.55	0.55	0.75	0.25
DG	Argon	1.05	0.95	0.65	0.95	0.90	0.17
	SF ₆	1.10	1.00	0.55	0.95	0.90	0.24
	NaCl	1.80	1.65	0.80	1.45	1.45	0.44
EC	Argon	1.00	0.95	0.85	1.00	0.95	0.07
	SF ₆	0.90	0.90	0.60	0.90	0.85	0.15
	NaCl	1.40	1.15	0.30	1.60	1.10	0.57
DS	Argon	1.10	1.05	0.70	1.05	1.00	0.18
	SF ₆	1.10	1.10	0.65	1.00	0.95	0.21
	NaCl	1.50	1.40	0.85	1.10	1.20	0.30
CH	Argon	1.00	0.90	0.75	0.95	0.90	0.11
	SF ₆	1.00	0.95	0.75	1.00	0.95	0.12
	NaCl	1.70	1.50	0.90	1.40	1.40	0.34
SH	Argon	0.90	1.35	0.65	0.85	0.95	0.30
	SF ₆	0.85	1.25	0.65	0.75	0.90	0.26
	NaCl	1.05	1.65	0.75	1.05	1.15	0.38
GM	Argon	0.80	0.60	0.50	0.70	0.65	0.13
	SF ₆	0.70	0.65	0.40	0.65	0.60	0.14
	NaCl	0.35	0.35	0.35	0.35	0.35	0.00
NK	Argon	0.90	0.85	0.60	0.80	0.80	0.13
	SF ₆	0.80	0.85	0.50	0.75	0.75	0.16
	NaCl	1.25	1.10	0.30	0.80	0.85	0.42

Table 15. (Continued)

Subject		Leakage percent during exercise					Standard deviation (SD)
		Side to side	Up and down	Talking	Walking	Average	
AM	Argon	0.90	0.90	0.60	0.70	0.80	0.15
	SF₆	0.85	0.85	0.20	0.70	0.65	0.31
	NaCl	1.25	1.35	0.35	0.75	0.95	0.46
BC	Argon	0.95	(5.25)	0.70	1.05	0.90	0.18
	SF₆	1.10	*	0.60	1.05	0.90	0.28
	NaCl	1.15	*	0.80	1.00	1.00	0.18
CN	Argon	1.70	1.05	0.85	1.10	1.20	0.37
	SF₆	1.90	1.10	0.80	1.10	1.25	0.47
	NaCl	2.50	1.10	0.75	1.30	1.40	0.76
DC	Argon	1.20	1.20	0.75	0.90	1.00	0.23
	SF₆	1.30	1.30	0.65	1.00	1.05	0.31
	NaCl	1.30	1.45	0.65	1.30	1.20	0.36
Mean		1.05	0.95	0.70	0.95	0.90	
SD	Argon	0.23	0.20	0.17	0.14	0.15	
Mean		1.05	1.00	0.60	0.90	0.90	
SD	SF₆	0.29	0.21	0.20	0.17	0.18	
Mean		1.40	1.25	0.65	1.10	1.10	
SD	NaCl	0.51	0.38	0.25	0.32	0.30	

* Leakage beyond range of instruments.

() Not included in means.

Table 16. Anthropometric data of the firemen.

Subject	Face length (nasion-menton)	Face width (bizygomatic diameter)	Lip length
	mm	mm	mm
RC	137	159	54
BS	125	151	65
RD	133	145	51
AG	118	148	50
SC	116	148	56
SM	129	146	51
TH	135	149	52
RF	121	142	49
BJ	122	145	52
DG	132	141	50
EC	123	148	51
DS	—	—	—
CH	127	152	54
SH	112	147	58
GM	—	—	—
NK	124	147	58
AM	130	155	59
BC	—	—	—
CN	120	151	48
DC	128	141	47

the alphabet during the preceding exercise. These results suggest that a stabilization period, during which leakage is not recorded, should be left between exercises if the leakage for a particular exercise is required, if the mean leakage relating to a series of exercises is required then stabilization periods are unnecessary. It is also suggested that the recital of the alphabet is not the most appropriate method to simulate the wearers normal speech as it tends to induce rhythmic speech patterns.

The application of the paired "t" test to the sodium chloride technique results shows that there is a significant difference when compared with the argon and the sulphur hexafluoride results for all the exercises except talking. The factor employed in these calculations to allow for aerosol losses within the respiratory tract was 0.6. This factor is specified in British Standard 6016: 1980

and has been verified in further unpublished work by the authors. However, the leakage results obtained during these experiments suggest that the factor should be nearer 0.8.

Recent work has now shown that this value can be explained by a dead space effect within the facepiece whereby the probe continues to sample inhaled air during the initial portion of the exhalation cycle. The magnitude of this dead space effect will depend on the subject's breathing pattern and will tend to decrease as the tidal volume increases. The factor will therefore tend to vary between different subjects and this was observed in the recorded results. There is no dead space effect with the two other tracers as they are not absorbed by the body so that the inhaled and exhaled concentrations are equal. Further work to quantify this dead space effect is proceeding.

Acknowledgments

The authors are indebted to the Chief Fire Officer and the volunteers of the South Yorkshire Fire Brigade who assisted in these experiments.

References

1. BS 4667 Part 2: June 1974. Specification for Breathing Apparatus Part 2 Open-circuit breathing apparatus.
2. BS 2091 1969. Specification for Respirators for Protection Against Harmful Dusts, Gases, and Scheduled Agricultural Chemicals.
3. Slutsky, A. S., J. M. Drazen, C. F. O'Cain, and R. H. Ingram, Jr., Alveolar pressure-airflow characteristics in humans breathing air He O₂ and SF₆ O₂, *J. Appl. Phys.* 57(4) (1981).
4. BS 4558 1970. Specification for Positive Pressure, Powered Dust Respirators.
5. BS 3928 1969. Methods for sodium flame test for air filters (other than for air supply to i.c. engines and compressors).
6. Roza da, R. A., C. A. Cadena Fix, G. J. Carlson, K. E. Hardis, and B. J. Held, Reproducibility of Respirator Fit as Measured by Quantitative Fitting Tests, *Am. Ind. Hyg. Assoc. J.* 44(11): 788-794 (1983).
7. BS 6016 1980. Specification for Filtering Facepiece Dust Respirators.