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INFLUENCE OF FACEMASK DESIGN ON OPERATIONAL PERFORMANCE

O. G. Griffin and D. J. Longson
Safety in Mines Research Establishment,
Department of Trade and Industry, Sheffield, England

FACEMASK LEAKAGE

The increasing use of full facemasks with respiratory apparatus emphasizes the need for accurate methods of evaluating facemask efficiency. All facemasks leak to some extent; the leakage is past the peripheral seal and is governed by the fit of the mask, which can be adversely affected by facial hair and movement of the head and facial muscles.

Inward Leakage

Recent methods of evaluating facemask efficiency employ either an aerosol or a halogenated hydrocarbon gas in the atmosphere surrounding the mask. The aerosol methods, which include the use of sodium chloride (refs. 1 and 2), uranine (ref. 3), and bacterial spores (refs. 4 and 5), are not, in general, considered suitable for the rapid determination of inward leakage of gas into a full facemask. The sodium chloride aerosol method in particular suffers from the disadvantage that particles are absorbed in the respiratory tract and that the subject must breathe regularly, and there might therefore be difficulties in applying the method while the subject is exercising. Halogenated hydrocarbons such as dichlorodifluoromethane (freon 12) (ref. 6) have the disadvantage of being mildly toxic so that the concentration in the test gas atmosphere must be kept relatively low; the sensitivity of the method might therefore be limited.

A dynamic method developed at the Safety in Mines Research Establishment determines accurately the leakage of the external atmosphere into the mask while the subject is performing various exercises. In this method the subject, wearing the facemask complete with breathing tubes, is enclosed in a transparent plastic hood large enough for him to move his head while wearing the mask (fig. 24.1). Pure argon is fed into the top of the hood from a regulated cylinder supply. Argon is used as the atmosphere in the hood because it is physiologically inert, inexpensive, and available in a pure form.

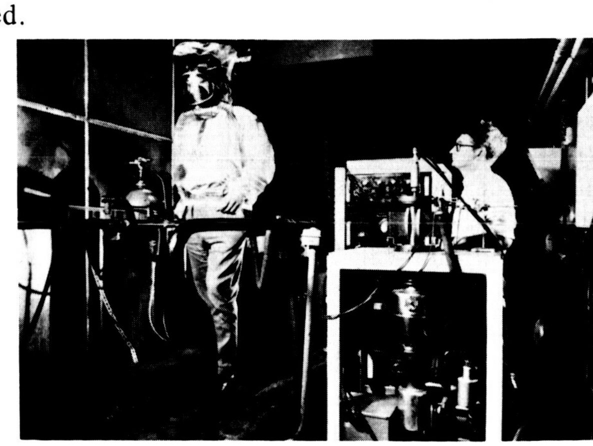

Figure 24.1 *Test equipment.*

The subject inhales medical quality oxygen supplied from a cylinder fitted with a pressure reducer and a lung-governed demand valve, so that the wearer can draw as much oxygen as he needs. The oxygen breathing tube is fitted with a sampling port. A spirometer measures the volume of oxygen used.

The facemask is fitted with two nonreturn valves, controlling the direction of flow of oxygen in the two breathing tubes. The exhaled gas passes through the second breathing tube into a sampling bladder fitted with a sampling port, and then passes to atmosphere.

The amount of argon in the exhaled gas is determined by means of an MS10 mass spectrometer. This instrument is capable of detecting at least 10 ppm of argon in the exhaled breath. A multiway tap is connected to the spectrometer and the various sampling ports. Sampling is by means of a small suction pump. With the mass spectrometer tuned to mass number 40, the principal number of argon, and the multiway tap positioned to sample the wearer's oxygen supply, a trace is obtained on the mass spectrometer recorder that corresponds to the concentration of argon in the oxygen supply; this is usually less than 50 ppm. The tap is then repositioned to enable the exhaled breath in the sampling bladder to be sampled. A second trace is obtained on the recorder corresponding to the concentration of argon in the exhaled breath. The difference between the two gives a measure of the rate of flow of argon leaking into the mask.

In each test the subject walks at 6.4 km/h (4 mph) on a treadmill inclined at 2.5° (fig. 24.1), and carries out slowly, at his own pace, a prearranged series of head movements.

This method has been used to determine the inward leakage rate into various facemasks in two series of experiments. The first series was with 29 clean-shaven subjects wearing two types of facemask. The second series was with 12 unshaven subjects wearing three types of facemask.

Experimental Results with Clean-Shaven Subjects Wearing Two Types of Facemask. The two masks tested were of the plain-seal and pneumatic-seal types. The inward leakage rate of each type of mask was determined for 29 clean-shaven subjects. The subjects (SMRE staff) fitted the facemasks themselves and checked for gross leakage by gripping the breathing tubes and trying to inhale. When leakage was apparent the mask was readjusted. No attempt was made to refit a mask during a test even when leakage became apparent. Tables 24.1 and 24.2 show the results obtained with the plain-seal mask and the pneumatic-seal mask. One subject, whose results are marked with an asterisk in table 24.1, had a visible gap between the mask and face that could not be improved. The leakage is expressed in the conventional way—that is, concentration of argon appearing in the exhaled breath.

The subject whose results are marked with an asterisk in table 24.2 could not be fitted satisfactorily with a facemask; although no gap was

Table 24.1 *Leakage with plain-seal mask.*

Subject number	Minute volume l min BTPS	Leakage : ppm				
		Head steady	Head side to side	Head up and down	Head steady talking	Mean of the exercises
1	46·0	411	316	282	300	327
2	30·7	414	376	387	379	389
3	32·0	2090	1855	1722	836	1626
4†	-	-	-	-	-	-
5	40·1	128	107	92	86	103
6	48·2	3859	1760	11863	4512	5499
7	33·9	461	442	366	392	415
8	37·7	88	67	67	67	72
9	38·4	251	196	8467	-	2971
10	38·7	4734	6545	137	185	2900
11	36·6	980	1684	1113	602	1095
12	39·0	220	191	196	198	201
13	34·6	104	83	410	99	174
14	35·8	109	88	92	76	91
15	40·7	81	72	9458	129	2435
16	41·0	110	81	84	96	93
17	36·2	108	87	77	102	94
18	45·5	102	76	4397	1368	1468
19	40·8	429	433	481	533	469
20	47·8	834	482	182	99	399
21	44·2	131	94	95	113	108
22	38·1	111	192	1040	112	364
23	36·6	136	99	9637	460	2583
24	45·9	95	73	67	74	77
25	45·1	21364	16009	46253	61600	36307
26	38·6	168	522	772	245	427
27	43·8	725	651	630	648	664
28	39·0	149	130	28341	219	7210
29	39·0	792	963	1418	982	1039

†Visible gap between mask and face

Table 24.2 *Leakage with pneumatic-seal mask.*

Subject number	Minute volume l/min BTPS	Leakage : ppm				
		Head steady	Head side to side	Head up and down	Head steady talking	Mean of the exercises
1	43·6	155	125	127	151	140
2	23·6	82	35	42	50	52
3	35·4	50	50	50	30	45
4	30·7	90	39	35	25	47
5	25·1	194	146	125	117	146
6	46·2	57	40	46	56	50
7	38·7	241	100	85	222	162
8	40·2	82	77	74	100	83
9	40·0	96	40	33	59	57
10	35·3	84	52	50	43	57
11	49·2	155	125	125	125	140
12	39·8	105	94	85	100	96
13†	-	-	-	-	-	-
14	38·3	534	359	82	52	257
15	46·2	154	138	150	150	148
16	44·7	180	105	110	176	143
17	46·4	188	136	119	150	148
18	43·3	65	35	42	50	48
19	41·1	146	125	119	237	157
20	43·6	132	45	80	90	87
21	49·2	47	42	40	60	47
22	43·4	69	75	71	52	67
23	50·4	35	42	50	50	44
24	44·2	75	75	75	75	75
25	32·4	49	90	172	271	146
26	40·6	32	25	25	25	27
27	38·4	140	130	67	255	148
28	34·5	62	217	142	250	168
29	34·7	86	64	64	86	75

†Badly fitting mask

visible between the mask and the face, leakage could be felt in the suction test and repeat fittings made no improvement.

The method described above allows facemask leakages of the order of 0.001 percent to be detected. Also, the leakage may be measured while the subject is carrying out various exercises.

The results obtained using this method confirm the superiority of the pneumatic-seal type of mask compared to the plain-seal type. It is likely that the fit of the plain-seal mask can be improved by very careful adjustment by the subject or fitter. In exceptional cases, however, there may be subjects who, because of facial characteristics, cannot be satisfactorily fitted with either type of facemask.

Experimental Results with Unshaven Subjects Wearing Three Types of Facemask. These tests were conducted on 12 volunteers from the City of Manchester Fire Brigade. Two of the subjects normally wore a substantial beard (fig. 24.2(a)). The other 10 men had beard growths ranging from 15 days to one month. Three facemask leakage tests were carried out on each man: unshaven, beard shaved but sideburns left to below the ear lobe, and clean-shaven. The results of these tests are shown in tables 24.3, 24.4 and 24.5.

Some of the men retained moustaches, but these were always small enough to be completely contained within the masks. The two men who were normally bearded chose not to be completely clean-shaven but retained much smaller beards (fig. 24.2(b)), supposedly small enough to lie within the sealing rim of the mask.

The three facemasks used in the tests were of the plain-seal, revert-seal, and pneumatic-seal types. Each man wore the same mask for each of the three tests. Additional tests, in which the pneumatic-seal mask was worn by the subjects in the clean-shaven condition, were made with the subjects who wore the plain and revert-seal masks.

As before the subjects fitted the facemasks themselves and checked for gross leakage by gripping the breathing tubes and trying to inhale. When leakage was apparent the mask was readjusted. No attempt was made to refit a mask during a test even when leakage became apparent.

From this series of experiments, it is concluded that when the subject has

A full beard: Beard growth substantially increases the inward leakage rate of all the facemasks used in the tests.

Sideburns only: Results show considerable variation. Modest sideburns (fig. 24.2(d)) that lie outside the facemask seal cause leakage rates similar to those obtained in the clean-shaven condition. Large bushy sideburns (fig. 24.2(c)), sufficiently large and bushy to lie between the facemask seal and the face, are likely to cause a substantial increase in leakage rate.

In all cases, when the subject was clean-shaven the pneumatic-seal mask gave a low leakage figure while the revert-seal and plain-seal masks showed considerable variation in the leakage rate. In the case of the two men who retained small beards, the beards were trimmed under the chin so that no hair was across the mask seal before a fairly good fit could be obtained (fig. 24.2(b)). The leakage rate, however, was still noticeably higher than with the clean-shaven subjects.

Discussion. When facemasks are worn in some toxic atmospheres a certain amount of leakage may be tolerable. It is important to remember, however, that this tolerable leakage will be less when the facemask is used with closed-circuit breathing apparatus than when it is worn with any other type of respiratory apparatus because the toxic gas leaking in with each breath may accumulate in the air in the closed circuit. In practice, the concentration of gas breathed in by the wearer will rapidly increase to an equilibrium value, which in the case of carbon monoxide would increase the concentration in the facemask by approximately 2.5 times the concentration that otherwise would have been breathed.

Figure 24.2 *Types of beard growth investigated.*

Table 24.3 *Summary of facemask leakage results in ppm, obtained with the plain- and revert-seal facemasks, and when cleanshaven, the pneumatic-seal facemask.*

Subject	Minute volume l/min BTPS	Type of mask	Leakage : ppm Full beard	Sideburns only	Clean-shaven	Pneumatic type. Clean-shaven
R.S.	49·7	Revert	6,710	1,900	2,580	25
G.H.	56·7	Revert	13,220	10,140	20	25
B.P.	48·6	Plain	190*	25	25	25
L.J.	48·0	Plain	390	30	255	15
Average	50·7		5,130	3,020	720	22

*Beard growth not substantial

These results clearly demonstrate the superiority of the pneumatic-seal facemask. The manufacture of the plain-seal type has recently been discontinued in the United Kingdon; however, many plain-seal facemasks are still in regular use in industry. Since it appears that all facemasks leak, care must be taken in the choice of facemask and particular care must be exercised before facemasks are used in highly toxic atmospheres. Also it is important to remember that facial hair, when present between the face and the facemask seal, will substantially increase the facemask leakage.

Outward Leakage

Since inward leakage occurs in all the masks examined, outward leakage is also likely to occur when there is a positive pressure in the facemask. When facemasks are used with closed-circuit breathing apparatus, which normally supply oxygen to breathe, the outward leakage of oxygen may be sufficient to create a flammability hazard (ref. 7).

The outward oxygen leakage from full facemasks has been measured in a series of tests. Four types of mask were investigated, each considered suitable for use with closed-circuit breathing apparatus: plain-seal, revert-seal, pneumatic-seal, and water-filled pneumatic seal.

The leakage rate of each of the above facemasks was determined while the masks were being worn by four subjects of differing facial shapes and sizes. All the facemasks examined were supplied with two short breathing tubes fitted to a connecting piece at the front of the mask, and opening into the mask. Inside the facemask, each subject wore a noseclip and mouthpiece. The mouthpiece was joined to one of the breathing tubes by tubing that passed out through the connecting piece. Such an arrangement allowed inspiration and expiration independent of the air in the facemask. The second breathing tube was connected to an air line and maintained the pressure in the mask at a selected value, measured with a water manometer. The flow of air through this line at the selected pressure was measured by a flowmeter and was equal to the leakage rate out of the mask. The average values of the four subjects with each type of mask are shown in figure 24.3.

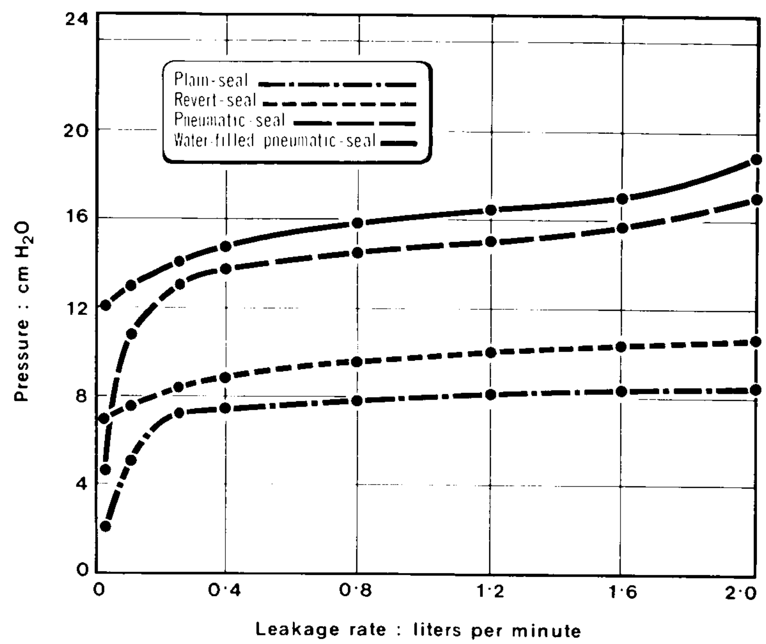

Figure 24.3 *Outward leakage rate from full facemask.*

In general, the pressures in a mask are determined by the breathing apparatus, and in particular by the relief valve. With an automatic relief valve the pressure in the mask depends largely on the opening pressure of the valve. With a manually operated relief valve the position is rather more complicated, since the wearer's use of the relief valve depends on his subjective response to breathing resistance.

When the pressure in the facemask approaches about 12 cm H_2O (1.2 kN/m^2) it is to be expected that the wearer will have difficulty in breathing out and he will become aware of the need to operate his relief valve. However, figure 24.3 indicates that when plain- or revert-seal facemasks are worn in conjunction with the apparatus, there may be a substantial outward leakage at the mask that prevents such a build-up of pressure. In practice, it has been confirmed that some wearers of these masks, when preoccupied with work, do not feel the need to operate the relief valve; large outward leakage occurs, and the pressure in the mask on exhalation remains fairly constant at about 9 cm H_2O (0.9 kN/m^2). Less leakage occurs with wearers who use their relief valves, but the amount is still considerable. Pressure is reduced to about 4 cm H_2O (0.4 kN/m^2); this then increases to nearly 9 cm H_2O (0.9 kN/m^2) before the relief valves are used again. Outward mask leakage from either type of pneumatic-seal facemask is substantially less than plain- or revert-seal types.

Another series of experiments was carried out to examine the ignition hazard associated with mask leakage. A full plain-seal facemask was fitted to a dummy head, and hair cuttings were placed around the edges of the mask. A controlled flow of oxygen was allowed to escape around the edges of the mask and attempts were made to ignite the hair cuttings; a glowing splint held near to the rim of the mask was used as the source of ignition. When the leakage rate exceeded 0.25 liters/min the hair cuttings were ignited rapidly and the rim of the mask was also ignited. Figure 24.3 shows that the leakage is probably harmless when the pressure in pneumatic-seal masks is less than 12 cm H_2O (1.2 kN/m^2).

Table 24.4 *Summary of facemask leakage results in ppm, obtained with the pneumatic-seal facemask when worn by the two subjects with substantial beard growth.*

Subject	Minute volume l/min BTPS	Leakage : ppm		
		Full beard	Reduced beard with sideburns	Smaller beard within mask. No sideburns
L.R.	41·5	30,670	27,570	320
E.R.	51·1	11,730	55	225
Average	46·3	21,200	13,810	270

This work confirms the need for care in the choice of facemasks, the importance of correctly fitting the facemask to the wearer and the advisability of using breathing apparatus supplied with a well-designed automatic relief valve.

Table 24.5 *Summary of facemask leakage results in ppm, obtained with six subjects wearing the pneumatic-seal facemask.*

Subject	Minute volume l/min BTPS	Leakage : ppm		
		Full beard	Sideburns only	Clean-shaven
M.B.	51·0	3,790	310	70
H.L.	57·0	470	25	20
F.M.	47·9	–†	790	25
L.R.	44·5	600	195	35
G.P.	42·8	5,130	35	30
B.B.	51·2	4,880	35	95
Average	49·1	2,970	235	45

†Substantial sideburns but no beard

FACEMASK DEAD SPACE

The term "dead space" when applied to a facemask may mean either the "geometric" dead space, which is the volume between the mask and the wearer's face, or the "effective" dead space, which is a measure of the exhaled breath rebreathed by the wearer. A measure of the geometric dead space can be determined by measuring the volume of water required to fill the space between a mask and a dummy head. Determination of the effective dead space, which is a more realistic measurement, requires a more complicated technique. The facepiece, complete with valves and breathing tubes, is fitted onto a dummy head in a leak-tight manner. The expiratory and inspiratory ports of a (two-cylinder) breathing simulator are connected via a T-piece to the dummy head's throat. On expiration, the breathing simulator delivers a known mixture of carbon dioxide and air (usually 5 percent carbon dioxide) into the facepiece and out through the expiration breathing tube to the atmosphere. On inspiration, laboratory air is drawn through the inspiration breathing tube and facepiece into the breathing simulator; part of the inhaled air will thus be supplied from previously exhaled air in the dead space. The inhaled, exhaled, and laboratory air are analyzed for their carbon dioxide contents. The effective dead space of the facepiece is then given by $V(x - a)/(y - a)$, where V is the volume per stroke of the breathing simulator and x, y, and a, are the percentage of carbon dioxide in the inhaled, the exhaled, and the laboratory air, respectively. By this means, the effective dead space of the facepieces may be measured at different tidal volumes and respiration rates.

This method has been applied to six commercially available facemasks. The effective dead spaces were measured at tidal volumes of 1, 2, and 3 liters and at respiration rates of 10, 20, and 30 rpm for each tidal volume. The facemasks used were:

A. A British pneumatic-seal mask of recent design, fitted with an inner nose cup and a self-demisting arrangement. This arrangement is such that on inhalation air is drawn through a duct, which directs the air over the surface of the visor before entering the nose cup through nonreturn valves. The exhaled breath passes direct from the nose cup and out of the exhalation breathing tube.

B. A mask similar in design to mask (A) but made by a different British manufacturer.

C. A British pneumatic-seal facemask molded to the shape of a face and having separate eye lenses, an inner nose cup, and self-demisting arrangement.

D. An earlier wide-vision facemask of British manufacture, of the plain-seal type, not fitted with a nose cup or demisting arrangement.

E. A Finnish revert-seal facemask with combined inhalation and exhalation valve, fitted with an inner nose cup and self-demisting arrangement.

F. A German revert-seal facemask fitted with an inner nose cup, but without self-demisting arrangement. The visor is fitted internally with a mechanical wiper blade operated externally by hand for demisting.

Figure 24.4 shows the effective dead space of all the masks fitted with inhalation and exhalation valves in the "as worn" condition.

Figure 24.5 shows the effective dead space of two of the pneumatic-seal types of facemasks (masks A and B) (a) as normally worn, i.e., demisting, (b) fitted with nose cup but with the demisting arrangement closed, and (c) without nose cup.

It was found that the respiration rate at each tidal volume had little effect on the effective dead space (usually less than 5 percent of the mean); the graphs are therefore a plot of the mean of the respirations at each tidal volume.

The recent British Standard (ref. 8) states that the carbon dioxide concentration breathed by the wearer must not exceed an average of 1 percent. It follows that to satisfy this requirement the facemask dead space should not be greater than 400 cm^3 at 2 liter tidal volume. Since this concentration in closed-circuit breathing apparatus may include a contribution from the slip of the purifier in addition to the dead space in the complete apparatus, it is recommended that the effective facemask dead space should be less than 300 cm^3.

The pneumatic-seal type of facemask was shown superior to other types as far as face-seal leakage is concerned. This work on dead space has shown that the pneumatic-seal type has a low dead space, particularly when an inner nose cup is fitted. The value of the nose cup is clearly apparent in figure 24.5.

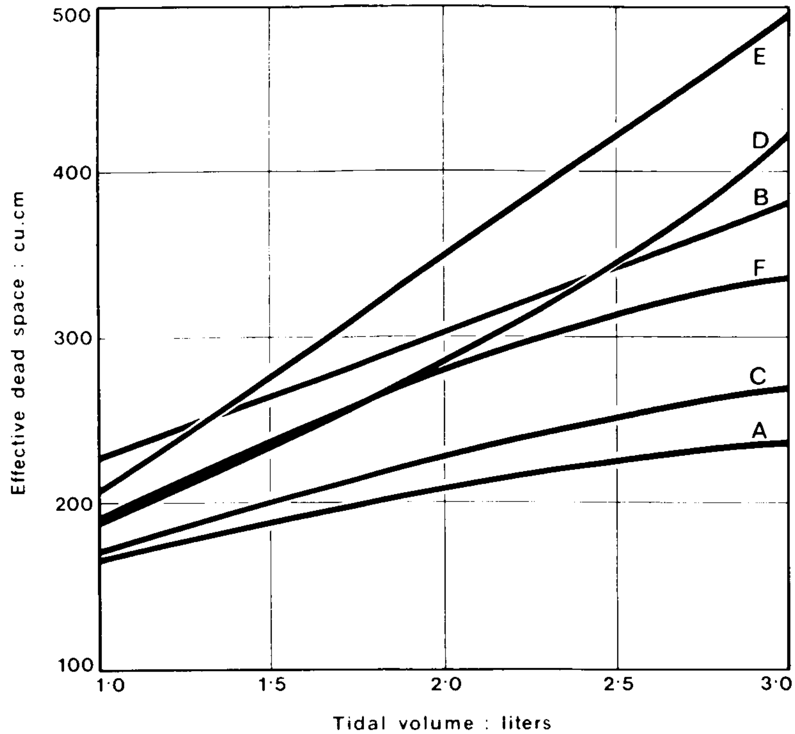

Figure 24.4 *Effective dead space of six facemasks.*

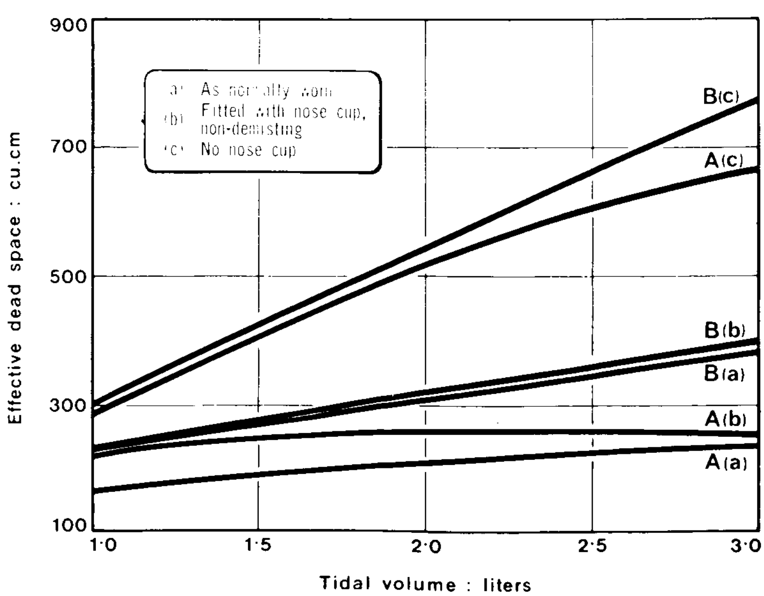

Figure 24.5 *Effective dead space of facemasks A and B.*

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