

ACCEPTABLE BREATHING RESISTANCE FOR RESPIRATOR USE

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Resistance to breathing is a factor common to all forms of respiratory protective device ranging from the simple dust respirator to the more complex self-contained closed circuit breathing apparatus. All types of apparatus have some form of filter, absorbent, gas reservoir or valve system, which imposes a resistance to breathing. This resistance, which may be of the flow resistive, elastic or threshold type, is a necessary consequence of the presence of components essential to the efficient functioning of the equipment.

Physiologists in conjunction with manufacturers of apparatus must agree on what resistance is compatible with wearer acceptability and correct operation of the equipment under normal conditions of use. There has been considerable research, particularly during and since the Second World War, to establish acceptable levels of breathing resistance, most of this based on filter types of apparatus for military use, which impose primarily a resistance to airflow during inspiration. It is probably from work done on this type of device that many of the national and international standards for upper limits of breathing resistance have been derived.

The increasing use of filter and other respirators has meant that breathing resistance must be made acceptable to a much broader range of users than was previously the case, particularly with the introduction of more stringent health and safety regulations in many countries. For example, it is pointless setting the same standard, which may be quite acceptable for a fit young soldier, but which an older man, such as a coal miner who may be suffering from shortness of breath, cannot tolerate.

At a British symposium nearly 20 years ago maximum levels of inspiratory flow resistance for respirators used at rest and under varying conditions of exercise were suggested (COTES, 1962) (Table 1). The principle on which these were based was that the maximum allowable resistance should decrease with severity of exercise: 5 cm H₂O at 85 l/min at rest falling to 0.7 cm H₂O at 85 l/min during maximal exercise. These levels were considered unlikely to affect performance in normal subjects. Assuming an approximately linear relationship between airflow and resistance through a filter, these resistances are equivalent to about 2 cm H₂O at the peak inspiratory flow expected at each condition of exercise, a value which many would consider very low in relation to most forms of breathing apparatus, particularly at the higher flow rates.

It was also pointed out that the physiological cost associated with respirator wear, although measurable, was usually a very small proportion of the total respiratory or total body mechanical capacity for work. Limitations to performance were likely to be mostly of psychological origin, which could be practically overcome with training (SHEPHARD, 1962).

COOPER (1962) related the rate of external respiratory work done against external resistance to the minute volume breathed up to a limit of about 100 l/min. Both Cooper and Senneck in other papers to the same symposium discussed the establishment of an acceptable resistance and also an ideal resistance, which was arbitrarily defined as half the acceptable level. SENNECK (1962) summarized the available evidence and compared the various standards proposed at the symposium (Table 2).

Since this time there have been several studies concerning the definition of tolerable or acceptable levels of breathing resistance in the U.K. (e.g., BENTLEY et. al., 1973; BENNETT et. al., 1962; FREEDMAN AND CAMPBELL, 1970), which differed considerably in their approach to the problem and the range of resistances studied.

It is therefore important to define what is meant by acceptable, when referring to an acceptable breathing resistance. Depending on other prevailing conditions a breathing resistance can be described according to the following categories: that which is

1. physiologically first detectable;
2. subjectively first noticeable;
3. noticeable but still well tolerated;
4. only just tolerable.

The definition of the boundaries between these categories depends in practice on several factors.

1. Whether the apparatus contains tubing, filters, valves, etc. and whether it is connected to the respiratory system by means of a full facemask, half-mask, mouthpiece only or hood enclosing the whole head.
2. Level of activity carried out. For example, the wearer of a self-contained closed circuit breathing apparatus may be required to undertake a wide range of tasks from walking to heavy lifting in underground mines rescue operations, in which case allowance must be made for breathing resistance at very high flow rates. On the other hand many forms of respirators and externally supplied breathing apparatus may only be used under conditions of rest or light work and accordingly different standards of resistance may apply.
3. Length of time worn will partly be related to (2) above but some devices may be designed to last for a limited period, owing to exhaustion of air supply or chemical absorbent, in which case a different resistance may be acceptable to that for a device worn for a whole shift.
4. Ambient conditions, particularly temperature and humidity, may not only influence general comfort and tolerance of additional stress but also high humidity may cause a gradual increase in inspiratory resistance in some chemical absorbent systems. In addition moisture from expired air may increase dust clogging in devices such as valveless filtering facepieces.
5. Inspiratory or expiratory resistance. It is generally recognized that expiratory resistance is subjectively more unpleasant than inspiratory (SILVERMAN et al., 1945), probably because expiration is predominantly a passive process and the production of a positive intrathoracic pressure may affect return of blood to the heart.

6. Familiarity, training, motivation, etc. In certain workplaces respiratory protection will be constantly required thus ensuring sufficient familiarity and motivation. In others infrequent use of emergency or escape apparatus may require regular training to familiarize potential wearers with any discomfort likely to be experienced during use. However, in such situations one assumes that the wearers would be sufficiently motivated to ignore an otherwise noticeable obstruction to breathing. On the other hand, telling a coalminer that wearing a dust mask regularly may reduce his chance of contracting pneumoconiosis in 20 years time may not be a very persuasive motivating factor.
7. Other factors affecting general comfort of equipment in relation to resistance, e.g., mask dead space, which may increase inhaled carbon dioxide levels thus stimulating ventilation. The maximum expected CO₂ concentration will need to be allowed for in assessing levels of acceptable breathing resistance.
8. Presence of respiratory disorder. Some workers may have some degree of chronic lung disease, which, while not severely limiting to normal work, may limit the capacity to breathe comfortably through a respirator. It could be argued that such people should not be employed where respiratory protection is required and that consideration of workers with these conditions would be unduly restrictive to development of protective equipment.
9. Manufacturer's ability to meet defined 'acceptable' levels of resistance. Many standards for breathing resistance are based on the levels which are present in currently available apparatus, whereas attempts should be made to base such standards on physiological criteria.

As a result of all these factors it may be difficult to define an acceptable breathing resistance from published data unless evidence has been derived specifically from an apparatus worn under its normal conditions of use. Nevertheless, there is abundant evidence in the literature, much of a purely research or academic nature, which can and has been used to define levels of acceptable resistance. The work of SILVERMAN *et al.* (1943, 1945) and COOPER (1960) is still widely quoted as the basis for many of the current standards of breathing resistance.

As previously outlined, breathing resistance has been divided into four categories of acceptability.

1. Physiologically first detectable.

The resistance which causes physiological changes, e.g., reduced minute volume, may occur at a lower level than that at which subjects become aware of its presence. This was noted by MCKERROW (1955), who determined that a non-linear resistance of 1 cm H₂O at 100 l/min (6.8 cm H₂O at 300 l/min) inserted in a low resistance M.B.C. (maximum breathing capacity) apparatus significantly reduced M.B.C., although this was below the level of resistance described (HART, 1943) as being subjectively noticeable. For all practical purposes, however, it would be very difficult to reduce the resistance of breathing apparatus much below this level, which must therefore be considered as representing the lower limit of acceptability.

2. First subjectively noticeable.

Studies carried out at rest have established that an inspiratory resistive load would be detected in the first few breaths 50% of the time, if it exceeded 0.59 cm H₂O l/sec (BENNETT et al., 1962; WILEY AND ZECHMAN, 1966; AITKEN, 1969), which corresponds to about 25% of the normal non-elastic load to breathing. Slightly higher values (about 0.87 cm H₂O l/sec) have been observed in healthy subjects (DAVIS, 1967) and also in asthmatics (BURKI et al., 1978). It has been found that the threshold of detection for added inspiratory resistances is a constant function of the ratio of the added resistance to the normal subject's initial pulmonary resistance (BURKI et al., 1978), believed to be due to the 'inappropriateness' of the particular volume change in relation to the developed pressure change (CAMPBELL and HOWELL, 1963), thoracic joint and muscle receptors possibly being involved in this detection.

Detectable levels of elastic loads, i.e., breathing from and/or into a closed container similarly represent between 10 and 20% of the normal elastance of the pulmonary system, but may be considerably higher in subjects with certain lung diseases. However, investigations have only been carried out on inspiratory loading and in practice such loads would rarely be met (CAMPBELL et al., 1961).

3. Noticeable but tolerable.

This is probably the most difficult area to define but is the most important as far as breathing apparatus is concerned, since most have breathing resistances which fall within this range. What is acceptable by a wearer of an apparatus depends so much on the secondary factors already described that it may not be possible to give absolute values for acceptability. However, it is possible from past studies to draw certain conclusions as to what determines an acceptable resistance.

A breathing resistance, which is noticeable or even uncomfortable, although tolerable for the normal wearing period of an apparatus, will almost certainly be of the same order of magnitude as the pulmonary resistance itself. The cost of breathing without an added resistance may range from about 2% of total body work at rest up to 10% or more during very heavy exercise. The extent to which an external resistance adds to that cost may play a considerable part in determining the acceptable value of breathing resistance particularly at high workloads. A change in the physiological state is therefore implied by the presence of such resistances, e.g., reductions in ventilation, breathing frequency or tidal volume, and possibly changes in oxygen uptake and increases in alveolar and arterial P_{CO2} (e.g., LOVE et al., 1977). No doubt these will be enlarged upon by the next speaker. Alteration of one or more of these parameters may not give rise to feelings of discomfort sufficient to limit performance but they should be taken into account in long term wearing of breathing apparatus.

A comparison of three masks worn by subjects walking for 5 minutes at three grades on a treadmill showed clearly that there was a relationship between both pulse rate increases and recovery oxygen consumption, and resistance values and subjective responses, especially at the higher workloads (THOMPSON and SHARKEY, 1966) (Table 3). Mask 1 was stated to be considerably more comfortable to work with than the other two masks. At the highest flow likely to have been encountered during the hardest workload (about 150 l/min) the inspiratory pressure drop in the mask with the highest resistance would have been about 15 cm H₂O.

In contrast, a comprehensive investigation of the effects of a resistance of 5 cm H₂O I/sec during inspiration and expiration, separately and combined, (GEE et al., 1968) demonstrated that minute ventilation could be significantly reduced (by nearly 20% at the hardest workload) without significant changes in oxygen uptake, diffusing capacity and heart rate. Pressure swings of up to 30 cm H₂O were experienced during each phase of respiration yet no discomfort was reported by the subjects who wore the resistances for between 4 and 7 minutes depending on the workload. The authors concluded that such resistances should not limit the work capacity for everyday tasks. Both these studies could, however, be criticized as being of too short a duration for a reliable assessment to have been made.

In other studies physiological changes did not seem to be related to the degree of discomfort experienced by the subject (HANSON et al., 1965; TABAKIN et al., 1965) .

Another study (DEMEDTS and ANTHONISEN, 1973) demonstrated that an alinear resistance, which approximately doubled the internal work of breathing, did not reduce tolerance of hard exercise but gave rise to dyspnoea at high workloads of 5 minutes duration.

We have specifically investigated the tolerance of mineworkers to a wide range of inspiratory alinear resistances (4 - 35 cm H₂O at 100 l/min) under a range of workloads for 30 minute periods on a treadmill (BENTLEY et al., 1973) (Fig. 1). The proportion of subjects noting discomfort was correlated with the peak inspiratory pressure and also with the inspiratory work done per litre of air breathed, which also has the dimensions of pressure. The degree of discomfort in breathing (dyspnoea) was considered to be a function of the 'negative' intrathoracic pressure. We suggested that an inspiratory resistance would be acceptable by 90% of mineworkers if the pressure drop did not exceed 14 cm H₂O measured during steady flow (Fig. 2). We further stipulated that the total resistance of an apparatus with low expiratory resistance (valve only) would be acceptable if the total pressure swing measured at the mouth did not exceed 17 cm H₂O. This value is equivalent to 20 cm H₂O when measured by a sine wave pump under laboratory conditions, since this allows for the slight flattening of the normal breathing pattern that occurs when a resistance is present. We have also confirmed the acceptability of such pressure swings by a group of older miners aged up to 64 (LOVE et al., 1977) .

We have recently carried out a study of the acceptability of carbon monoxide filter self-rescuers in a group of coalminers, who wore them for an hour under conditions simulating use during an emergency escape from a mine (JOHNSTON et al., 1979). The inspiratory resistance of these devices was, on average, 10.5 cm H₂O at 110 l/min, although the resistance in some cases increased by several cms H₂O during the exercise (Table 4). It is apparent that only one subject noticed the resistance under both normal and hot, humid conditions (26°C, 90% RH). When another group of men went through a simulated coalface and underground roadway either stooping or crawling, i.e., much harder work, 3 out of 7 men noticed the resistance, although none complained that it was too uncomfortable. Therefore, the inspiratory resistance of this device, while quite acceptable by the majority under expected conditions of use (minute volume = 30-35 l/min), would be noticeable by a proportion of men during much harder work, when the pressure drop would be expected to be in excess of 14-15 cm H₂O at the highest flow rate.

Our earlier work appeared to confirm the general principles on which the standards suggested by SILVERMAN et al. (1945) and COOPER (1960) were based. Cooper's acceptable limit on total breathing resistance (up to 50% being expiratory) was equivalent to a pressure drop of 25 cm H₂O, compared with about 13 cm H₂O derived from Silverman's work. Cooper suggested that an ideal value should be half of his own standard, i.e., close to that of Silverman, but acceptable values of resistance probably lie somewhere within this range (e.g., BENTLEY et al., 1973) depending on other conditions. Subsequently other European workers have recommended limits based on Cooper's method and concluded that filter devices were suitable for workloads not exceeding 90W, considered to be moderate work. Closed circuit self-contained breathing apparatus allowed prolonged hard work to be carried out but open circuit apparatus was most suitable for very hard work not exceeding about 30 minutes duration (CHRETIEN et al., 1973). Similar recommendations have been made that respirators should not be worn during work greater than 50% V_{O2} max (maximum aerobic capacity), at which level the pressure drop should not exceed 2 cm H₂O and during light work (30% V_{O2} max) when it should not exceed 3.3 cm H₂O (COMTE et al., 1975). However, even wearers of disposable filtering facepieces, with inspiratory and expiratory resistances of 2 cm H₂O at 85 l/min, may complain of difficulty in breathing during hard work even though the pressure swing during each phase of respiration is unlikely to exceed 2 cm H₂O.

In a survey of underground workers at two British coalmines we have found that about 30% of regular wearers of NCB approved dust respirators (inspiratory and expiratory resistance = 1.5 - 1.9 and 0.8 - 1.0 cm H₂O respectively at 85 l/min), complained that they had difficulty in breathing, when working in a dust respirator, about the same number as complained in a group who no longer wore respirators.

4. Only just tolerable.

This description refers to the levels of breathing resistance which are restricted by the upper limits of physiological adaptation. I won't discuss this at any length except to say that the limit of tolerable inspiratory resistance, reproducible within individuals at rest, has been found to be 283 cm H₂O/l/sec on average for flow resistive (viscous) resistance (FREEDMAN and CAMPBELL, 1970). This could be considered as indicating the upper limits of human performance at rest.

What factors may account for this limit? An intrathoracic pressure swing of about 100 cm H₂O was not exceeded at the limiting resistance used at rest and during exercise in one study (CERRETELLI et al., 1970). On the other hand an upper limit to inspiratory resistance was found to be dependent on a minimum exhalation time of about 0.7 sec, a value to be found at exhausting levels of exercise (CRAIG et al., 1970; JOHNSON and BERLIN, 1974).

A resistance which increased internal respiratory work by 4 - 5 times, caused intolerable dyspnoea at submaximal loads and severely limited performance. The reduction in minute ventilation appeared to be closely related to the individual's CO₂ responsiveness during unobstructed breathing (DEMEDTS and ANTHONISEN, 1973).

JOHNSON (1976) has also discussed the limitations of performance as affected by work rate and hence the length of time work is performed. During moderate workloads the performance may be limited by the rise in body temperature but at high workloads exhalation time characterizes a very definite voluntary end point. This is paralleled by the rapid rise in the oxygen cost of ventilation at high loads, which will be considerably enhanced by the presence of any resistance to airflow. A typical mask may have doubled the inspiratory resistance of the human lung at rest but the respiratory work, already 8-10% of total body work during hard exercise, may increase to 15% or greater in the presence of the external resistance.

In practice it is unlikely that such levels of resistance will be met except at near exhausting levels of exercise but the possibility should be borne in mind when formulating standards and defining conditions of use of certain types of apparatus.

Breathing resistance and current standards

How does the evidence available in the literature on acceptable levels of breathing resistance compare with the various national standards which are currently available? There is a growing tendency to harmonize standards within Europe and wider national groupings with the aim of achieving a standard based on an agreed physiologically acceptable maximum value, which should not be exceeded by any apparatus under any conditions of use.

Standards for inspiratory and expiratory levels of resistance of many different kinds of apparatus are far from being universally agreed upon. Inter-country comparisons are also complicated by the fact that resistances may be measured and expressed at different airflows, which cannot be directly compared with other values owing to the non-linear nature of most resistances.

It may be more scientifically correct to limit resistance in terms of the extra respiratory work imposed on the body as a proportion of energy expenditure, ventilation or some other indicator of total body activity but it is more practicable to define a resistance as a pressure drop at one or more flowrates or by means of a single value which must not be exceeded under normal conditions of use, as tested in the laboratory.

Within CEN (European Committee for Standardisation) agreement has been reached that from a physiological point of view the maximum allowable resistance (inspiratory + expiratory) should give rise to a pressure swing not greater than 20 cm H₂O, although there is still some disagreement over the maximum values of inspiratory and expiratory resistances. Upper limits of 10 cm H₂O have been suggested for each phase of respiration but at an as yet unspecified flow rate. On the basis of published evidence these would appear to be acceptable limits, although in practice much apparatus will have considerably lower resistances than these under normal conditions of test and work.

CONCLUSION

I will summarise my review of past and recent research in this field by briefly listing areas of work where sufficient data exist for us to draw some basic conclusions to what constitutes acceptable breathing resistance.

Allowable breathing resistance in any form of breathing apparatus or respirator should not be any greater than that which is designed 'noticeable but well tolerated' during the hardest work likely to be experienced by wearers of such apparatus. Under most conditions this corresponds to a pressure swing within the range 12-17 cm H₂O for total breathing resistance and between 6 and 14 cm H₂O for inspiratory resistance, the higher values being acceptable for apparatus with minimum expiratory resistance. However, devices such as lower grade dust respirators, which are often worn on a voluntary basis, should have as low a resistance as possible, the pressure drop preferably not exceeding 2-5 cm H₂O under conditions of hard work.

FUTURE WORK

There is, of course, further work to be done in this field, in spite of the large amount of data already available.

At present there are insufficient data to define an accurate relationship between acceptable breathing resistance and work rate and duration. This would, of course, be of immense use to all users and manufacturers of respiratory protective equipment. This ideal, although possible to achieve under strictly defined conditions, may need to be considerably modified in practice, when different types of apparatus are worn for very different jobs by different workers in different ambient conditions.

Therefore we need to know what is the equivalent between breathing through a particular resistance for a long time at a low work load and for a short time at a higher work load. For example, different peak pressures will be reached during each type of exercise and the limit of tolerance of the resistance will not be based on the same criteria in each case. In the first case a constantly reduced minute volume, increased alveolar CO₂ level and a lengthened inspiratory time may eventually upset the physiological/biochemical balance, whereas in the second case the excessive peak pressure, respiratory work done or minimum exhalation time may indicate this limit. A comprehensive research project aimed at investigating the range of breathing resistance acceptable for periods of, say, 10 minutes to 4 hours may be needed to answer these problems.

Future research into acceptable breathing resistance will also need to concentrate on examination of its acceptability under conditions as close as possible to those encountered in the actual apparatus during normal use. Personal observations suggest, for example, that the same resistance represented to the wearer via a facemask may be considerably less acceptable than via a mouthpiece. Although this may be due to several factors, such as mouth versus nose breathing, different amount of facial contact, dead space effects, extra elastic as well as flow resistance, workers used to breathing through mouthpieces appeared to favour facemasks in a recent study of British mines rescue workers.

In general, standards for acceptable breathing resistance for respirators and other forms of respiratory protective equipment should be determined according to physiological and/or subjective criteria. These should only be modified if in practice manufacturers find that it is technologically impracticable to meet them. Inevitably many so-called 'physiologically' based standards are merely 'rubber-stamping' of conditions which can be met in certain current apparatus. Nevertheless close cooperation between research workers and manufacturers is required if realistic standards are to be met.

How can this work be coordinated internationally? Through international forums such as this and through international standardization committees the subject can be brought before a wide and representative body of people who should be in a position to decide what work needs to be done. It is likely that large scale research of this kind will be carried out within countries with the largest interest in the field of manufacturing, where there is a greater incentive to fit the apparatus to acceptable human limits.

I do not see any great increase in international coordination of actual research work. National legislation may well stimulate research within nations. Incentives for manufacturers in one country to sell equipment which meets the specifications of other countries may stimulate work in the former. Otherwise I see Government organizations such as NIOSH and its equivalent in Britain and elsewhere providing the stimulus to further research in this and other fields.

It is almost inevitable that some minimum level of breathing resistance will be present in most respiratory protective devices and acceptable levels will usually be a compromise between the physiologically or subjectively acceptable value and the manufacturer's ability to reduce resistance without losing protection.

The concept of protection should, of course, not be lost sight of in the aim of reducing breathing resistance, since that is the primary function of respirators and breathing apparatus. Nevertheless, in the practical situation it may be advisable to recommend the lower limits of acceptable breathing resistance, which have been derived mostly from laboratory studies, in order to allow for the complicating additional factors which influence comfort, when apparatus is worn at the workplace.

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TABLE 1

SUGGESTED MAXIMUM INSPIRATORY FLOW RESISTANCE FOR RESPIRATORS
TO BE USED IN DIFFERENT SITUATIONS

Conditions	Inspiratory flow resistance (cm H ₂ O at 85 /min)
Rest	5.0
Light to moderate exercise	2.5
Heavy exercise	1.0
Maximal exercise	0.7

TABLE 2

INSPIRATORY WORK RATES (kgm/min) EQUIVALENT TO VARIOUS
SUGGESTED STANDARDS FOR RESISTANCE IN 1962

Minute Volume (1)	SMRE ideal	MOP dust filter*	COTES		COOPER ideal	Service Respirator+
			Laminar	Turbulent		
10	0.08	0.06	0.15	(0.05)	0.63	0.22
30	0.51	0.50	0.66	0.62	1.88	1.98
50	1.5	1.4	0.7	1.1	3.1	5.5
100	7.4	5.5	(2.0)	6.4	6.3	22.0

* 1.9 cm H₂O at 85 l/min.

+ 8 cm H₂O at 90 l/min.

[Fran Senneck (1962), with permission]

TABLE 3

CHARACTERISTICS OF AN ACCEPTABLE MASK AND TWO MASKS
WHICH WERE DIFFICULT TO BREATHE THROUGH

MASK		RESISTANCE AT 85 l/min		RESISTANCE AT 170 l/min	
		Inspiratory	Expiratory	Inspiratory	Expiratory
		(cm H ₂ O)		(cm H ₂ O)	
'ACCEPTABLE'	I	3.8	2.3	9.3	5.8
	II	5.8	1.8	13.1	4.8
'UNACCEPTABLE'	III	7.5	1.6	17.3	3.3

TABLE 4

FILTER SELF-RESCUER WEARING TRIALS

Exercise	Inspiratory Resistance (cm H ₂ O @ 110 l/min)			No. of men noticing resistance	Heart rate (beats/min)
	Initial	Final	Maximum		
1. Treadmill: 3 mph 5% grade					
(a) Normal ambient	10.6	11.2	12.2	1/8	117
(b) Hot humid	10.6	15.2	30.2	1/8	126
2. Gallery *					
(Warm humid)	10.2	14.1	17.2	3/7	148

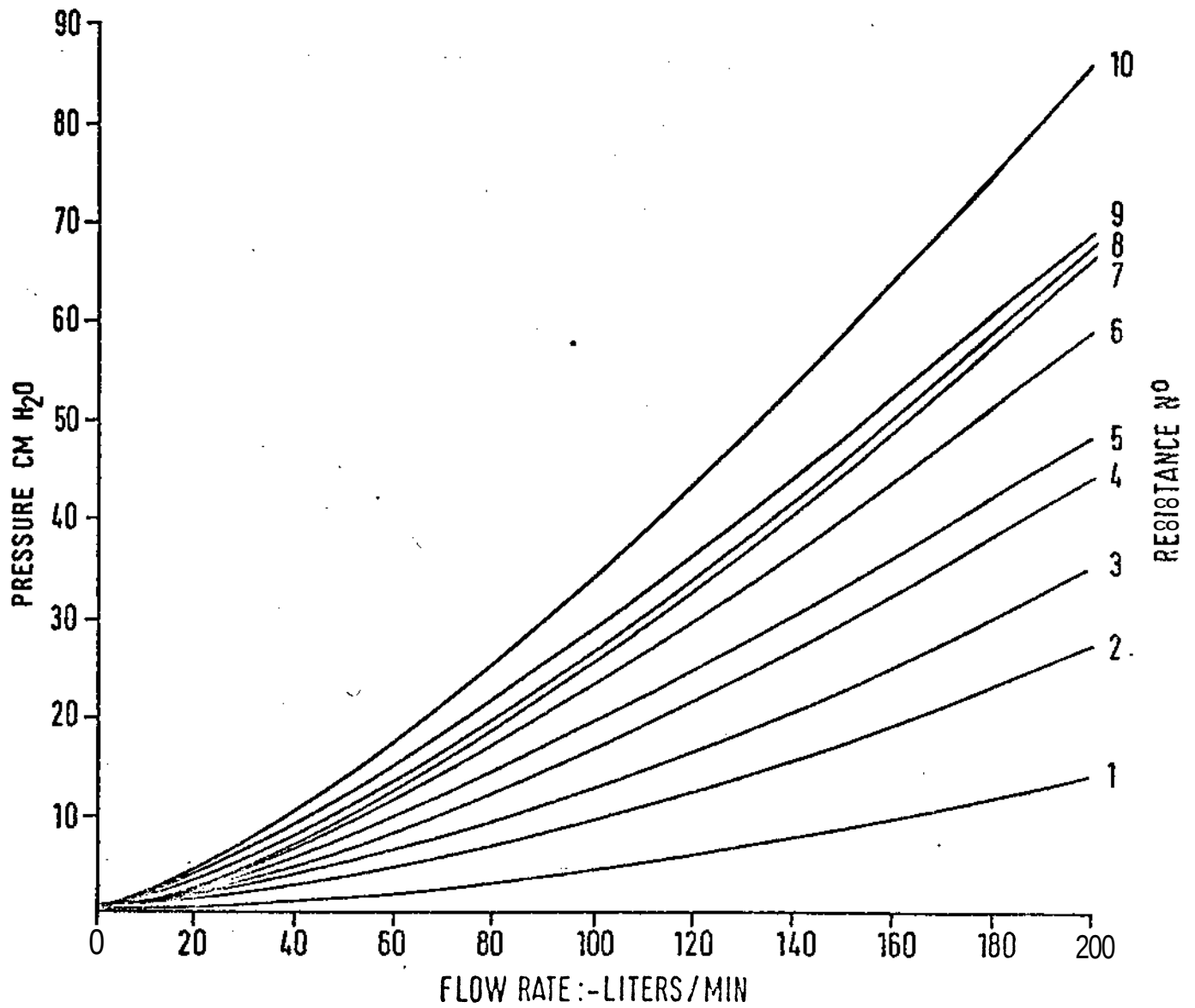
* Circuit simulating coal-face and underground roadways necessitating mostly crawling and stooped walking.

LEGENDS

FIG. 1 Pressure-flow curves of ten resistances.

FIG. 2 Proportion of men experiencing discomfort related to the
inspiratory work done per litre of air breathed. Only 10%
of subjects should ~~experience discomfort~~ if the inspiratory
work does not exceed 0.14 kgm/l, which is equivalent to a
pressure of 14 cm H₂O.

FIG. 1



Pressure-flow curves for resistance RI-RIO

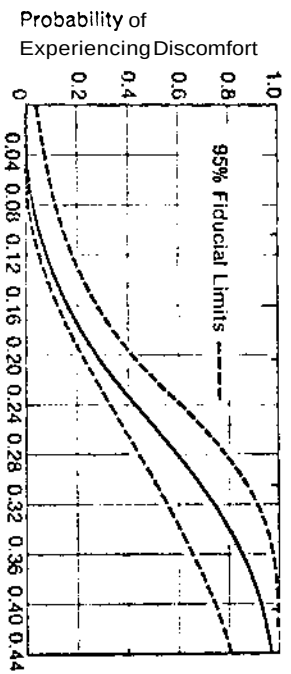


FIGURE 2