

# Physiological Studies of Respiratory Protective Equipment (RPE) For Escape and Rescue

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Paper presented to the second International Conference of the International Society for Respiratory Protection  
York, England: September 2-5th, 1985

## ABSTRACT

September 3rd, 1985

Session 1:

Physiology and Ergonomics

Respiratory protective equipment (RPE) worn during escape or rescue procedures is likely to subject the wearer to a more severe physiological burden than devices worn under other conditions because of the extreme physical exertion and environmental conditions encountered.

The physiologically relevant factors for wearers of RPE under these conditions are described. These included volume and rate of air supply, weight and bulk of the apparatus, breathing resistance, ambient conditions and the condition of the inhaled atmosphere (temperature, humidity and contaminant gases).

The potential effects of these factors are summarized and recommendations suggested for reducing their physiological impact on the user of RPE during escape and rescue from difficult surroundings.

## Physiological studies of respiratory protective equipment for escape and rescue.

RPE used in emergencies presents a much greater physiological burden on the wearer of such apparatus than devices worn in other situations by virtue of the

extreme conditions likely to be encountered. The equipment may have to sustain life under a range of conditions, such as entrapment in a burning building, escape from holds of tankers, legs of oil production platforms and industrial complexes, carrying out an unconscious person from a narrow coalface and other activities where hard physical demands are placed on the wearer, e.g. firefighting.

Respiration, blood circulation and muscular movement may already be in an elevated state in these circumstances. The added burden of mask dead space, restricted breathing and vision, physical bulk and weight of the apparatus, interference with body heat loss, etc., must be allowed for in the setting of standards, design and use of RPE for escape and rescue purposes.

Some studies of the physiological effects of self-rescue apparatus and the heavier cylinder-based systems have been carried out in the past (Raven et al., 1977, Louhevaara, 1984). However, there is clearly a need for further studies of men wearing heavy apparatus during fires and mines rescue and during escape from confined environments, where there is an immediate danger to life and where escape requires a high expenditure of energy. It is important to realize that the oxygen uptake of the wearer in such conditions is likely to be much higher than that estimated under laboratory conditions from the additional weight of

the apparatus alone.

RPE needs to be able to cope with these levels of energy expenditure and to have an adequate air or oxygen supply to meet that need. I intend to summarize some of the more important factors related to RPE, which are relevant physiologically, how these can combine to affect the performance of the wearer and to suggest how some of these effects can best be ameliorated.

## Physiologically relevant factors for wearer of RPE

### 1. Volume of air in cylinder

For a given task of known duration the wearer of RPE needs to have a sufficient air supply with a safety margin. The volume of air and its rate of supply should be adequate for all expected (near maximum) levels of exertion. The expected work duration must be known in relation to the nominal duration of the equipment. The latter may be based on a test minute volume of 40 liters/minute whereas the wearer's actual minute volume may be double that in practice. For an 1800 liter cylinder this could mean a difference in effective working duration (allowing for a 10 minute safety margin) of  $35 - 12.5 = 22.5$  minutes.

i.e.  $1800/40 - 10 = 35$  minutes at  
minute volume of 40 l/min  
 $1800/80 - 10 = 12.5$  minutes at  
minute volume of 80 l/min

Those responsible for providing equipment for escape and rescue purposes should ensure that the air supply is going to be sufficient for the task, especially for personnel who have to escape along a fixed escape route under severe conditions e.g. climbing a 100m vertical ladder in smoke and heat.

Under these severe conditions air supply to the facemask or mouthpiece must be adequate up to at least 250 and probably 300 liters/minute, while maintaining a positive pressure in the facemask where relevant. Physically fit individuals should be able to breathe for several minutes at these high volumes and flow rates, which can often be encountered in men escaping from oil production platform legs or firemen erecting and climbing ladders, carrying hoses or bodies.

## 2. Weight and bulk of equipment

The principal contribution to the weight of a self-contained air-supplying respirator is the air cylinder, a typical apparatus weighing between 15 and 20 kg. The physiological impact of this extra weight depends on the activity being performed and how the weight is distributed about the body. It is commonly thought that this extra weight (usually back-mounted) is equivalent, in terms of extra energy expenditure, to additional body weight. Walking on the level or up an incline is indeed likely to increase energy expenditure by about 30% for a 20 kg load, which is equivalent to the percentage increase in body weight for a 70 kg man (Durin and Passmore, 1967).

However, more complex activities, such as crawling, climbing and other maneuvers involving awkward postures, can give rise to a disproportionate increase of energy expenditure. This may be manifest as an increased oxygen uptake and minute volume or, if the work done is near maximal, a prolonged time to complete the task at the same rate of expenditure. Climbing a ladder with restricted openings, for example, throws a

considerable extra load onto the upper body muscles, especially the arms and other muscles concerned with maintaining posture. Local muscular fatigue can therefore be an additional problem and a bulkier or awkwardly positioned apparatus may give rise to a greater than expected work load.

RPE weight is recognized as being the biggest factor in reducing endurance time in firemen, by over 20% in some cases (Raven et al, 1977). As well as increases in heart rate, cardiac output, oxygen uptake and minute volume, fatigue may become a problem, especially in the less physically fit. Lightening the load or redistributing it to the hips would help alleviate the extra physiological strain.

## 3. Resistance to breathing

Some breathing resistance is inevitable in RPE, given the presence of valves, tubing and in some cases positive (static) mask pressure. A positive pressure apparatus will reduce the inspiratory resistance but increase the expiratory resistance because of static mask pressure and expiratory valve opening pressure. The wearer's acceptability of the resistances associated with breathing through any form of RPE depends on many interacting factors but resistance does give rise to many subjective complaints. However, one needs to ask whether an acceptable breathing resistance should be based on either subjective comfort or physiological change. Acceptable levels ranging from 2-20 mbar (cmH<sub>2</sub>O) at various flow rates have been quoted at different times in the literature (Love, 1983).

The range of values depends to a large extent on the apparatus used, the activity being performed, the length of time it is worn, the environment, whether the resistance is primarily inspiratory or expiratory, the degree of training and motivation of the wearer

and many other factors relating to comfort.

Breathing resistance can be graded according to the following categories:

- A. Physiologically first detectable
- B. Subjectively first noticeable
- C. Noticeable but still well tolerated
- D. Only just tolerable

Most standards applied to breathing resistance would cover values, which fall under category C and cover the range quoted above. A pressure swing of 20 mbar for total breathing resistance was quoted by Bentley et al (1973) as being acceptable by 90% of a working group of men during a simulated escape procedure. In contrast a positive pressure set worn by men working at 80% VO<sub>2</sub> max led to pressure swings of about 25 mbar, which probably contributed to 50% of wearers being unable to complete the 10 minute exercise (Raven et al., 1982).

## 4. Ambient conditions

The temperature and relative humidity of air inspired from an apparatus may be critical to the heat balance of the body in hot and humid ambient conditions. Inhaled air at 10-15°C provides optimal cooling conditions, if it is dry, and a compressed air set should fulfil these conditions. However, a compressed oxygen set recycles the exhaled air, which during CO<sub>2</sub> removal reaches temperatures between 40-50°C and humidities close to 100%. Such high temperatures and humidities may significantly reduce the effectiveness of the wearers to carry out their tasks, especially if the respiratory tract is the only remaining avenue for bodily heat loss. Safe working times therefore have to be reduced.

Additional factors affecting heat loss in some circumstances are the presence of protective clothing as worn by firefighters, and full facemasks which further reduce the area available for evaporative heat loss, partly compensated for in apparatus providing a cool airflow

over the face. Twenty percent of total heat loss can occur through the head. Sweating and other factors can reduce the protection afforded by the facesal in some individuals. This may result in the effective protection given by a positive pressure breathing apparatus being reduced to that of a lung-governed demand set (Stojack and Raven, 1984).

### 5. Contaminant Gases

The main gases of physiological interest for wearers of self-contained sets are carbon dioxide and carbon monoxide.  $\text{CO}_2$  is naturally produced during metabolism (up to 5 liters per minute during hard work) and may also be present in the immediate environment because of combustion processes. Whatever its source, if it is not removed immediately from the breathing zone of the wearer, which may include a large dead space, **hyperventilation** and discomfort (headache, **breathlessness**) may result. Any level of inspired  $\text{CO}_2$  between 1 and 10% will increase ventilation but discomfort may not be experienced until the concentration rises above about 3%, depending on the work load, apparatus worn, etc. (Love et al., 1979).

Carbon monoxide on the other hand is only produced in small amounts internally, although concentrations of up to 10% may be circulating in the blood because of prior smoking. CO is a constant danger in any environment where there is incomplete combustion, a recent explosion **and/or** poor ventilation. Since small amounts inhaled can be quickly disabling, good facesal of masks is essential, otherwise increased **carboxyhemoglobin**, decreased oxygen carrying capacity of the blood and hence reduced endurance will result.

The effect of the above factors can be summarized thus. The increased weight due to RPE causes extra energy expenditure, strain on the cardiovascular system and increased oxygen uptake and  $\text{CO}_2$  production. The addition of breathing

resistance will increase the work of breathing, which may result in a changed breathing pattern, typically **hypoventilation** and  $\text{CO}_2$  retention. The resultant effect of these factors will also depend on ambient and inspired air conditions, temperature, humidity and contaminant gases. The individual, consciously or subconsciously, may choose to allow an increased work of breathing, which will cause discomfort, or allow  $\text{CO}_2$  retention.

Work capacity will inevitably be reduced. It may be further affected by the ambient temperature and humidity, other working conditions, the time available for escape or rescue, physical fitness of the individual and his or her emotional state at the time.

It is recommended that, in order to reduce the physiological impact of self-contained breathing apparatus during escape and rescue situations, the following actions need to be considered as possible means of reducing the physiological impact of RPE on users.

1. Reduce weight of gas cylinders.
2. Redesign body harness.
3. Redistribute load on body (in with 2).
4. Improve air supply.
5. Increase oxygen level of inspired air (30-70%).
6. Provide (or maintain) cool inhaled air.
7. Improve physical fitness of wearers.

In conclusion, it is clear that RPE for escape and rescue can have a significant impact on normal physiology. Some of the physiological effects have been well studied. Shortcomings of existing RPE for particular needs should be assessed, with particular regard to reducing the weight (by cylinder redesign), and/or redistributing the load (possibly by harness redesign) and optimizing its cooling characteristics in hot environments to allow improved working or escape times.

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