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Deployment of Self-Contained Self Rescuers in Coal Mines

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ABSTRACT

Field trials at three New South Wales and one Queensland coal mines were carried out to gather data on oxygen "run out" times of Self-Contained Self Rescuers (SCSRs), time taken to escape from the mine, distances travelled and the average heart rate of subjects wearing SCSR. The study has led to a method of predicting the duration of oxygen supply from a SCSR as a function of the wearer's body weight, physical fitness and the prevailing environmental conditions. Escapeway design, planning for emergencies, familiarity with SCSR and experiential escape training are critical to control panic and maximise the likelihood of survival of a person attempting to escape in an emergency involving fire or explosion.

INTRODUCTION

The filter self rescuers (FSRs) currently approved for underground use in Australia are not designed to function in an oxygen deficient environment and accordingly cannot be relied upon to save lives, particularly in situations where there has been a fire or explosion in a mine. The function of FSRs is to remove low concentrations of carbon monoxide (up to 1.5%) from the inhaled air (Strang and Mackenzie-Wood, 1990). FSRs do not produce any oxygen. In order to escape from an irrespirable atmosphere to a respirable zone, a miner must be provided continuously with sufficient oxygen.

In the light of the recent fatalities experienced in the Australian coal mining industry, such as the 1994 Moura No.2 disaster in which 11 lives were lost underground, there was a general consensus for the need to legislate SCSR to replace FSRs. The recommendations of the Moura No.2 inquiry included the following extract:

"..... development and introduction of oxygen based escape systems from underground coal mines, a means to maximise the likelihood of survival, in the event of fires or explosion".

In Australia, SCSR are used for special purposes, for example when working in gas outburst prone mining conditions, and in recent years SCSR have replaced the FSR under these conditions. In the State of New South Wales, an exemption is required if a colliery wishes to replace the FSR as compulsory equipment to be worn by each person who wishes to proceed underground. The exemption will only be granted if the mine manager can demonstrate that each person is provided with full protection through the changed arrangements. The deployment of SCSR in Queensland as approved standard units came into effect in January 1998 (The Moura Task Group 4, 1996).

This paper discusses a study, which was conducted to develop procedures for an introduction of the SCSR into Australian coal mines (Mackenzie-Wood et al, 1997). The other study objectives were:

1. To evaluate the influence of personal factors such as age, weight, physical fitness on individual's oxygen requirements to escape from and underground place of work to a place of safety.
2. To evaluate the capability and comfort of SCSR.
3. To derive a method of predicting an individual's oxygen requirements to escape from and underground place of work to a place of safety.

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SELF-CONTAINED SELF RESCUERS (SCSR)

There are two types of SCSRs available commercially, compressed and chemically produced oxygen. The compressed oxygen type supplies oxygen to the wearer on demand from a cylinder of high pressure oxygen, the carbon dioxide in the exhaled breath is removed by a soda lime or alkali canister. The chemically produced oxygen type uses a chemical, potassium superoxide (KO_2) that reacts with the moisture in the wearer's breath to produce oxygen and potassium hydroxide. The potassium hydroxide then chemically removes (scrubs) carbon dioxide. Both reactions are exothermic, causing the canister to become hot. Heat exchangers made of wire mesh are usually fitted in the breathing tube to reduce the inhalation temperature.

Coal mining industries in NSW and Queensland require that SCSRs comply with Australian Standard (AS) criteria where applicable. Compressed oxygen SCSRs must meet the requirements of AS 1716 - 1994 and the duration is determined when the criteria for inhalation temperature, breathing resistance, inhaled CO_2 and oxygen cylinder pressure is exceeded.

Currently there is no Australian Standard for chemically produced oxygen SCSRs, the standard used for assessment is the British and European Standard BS/EN 401: 1993. The criteria for determining duration in this standard is:

Maximum inhalation temperature	$\leq 55^\circ C$
Exhalation/inhalation resistance	$\leq 1.3kPa$
Inhaled CO_2	$\leq 1.5\%$

Manufacturers currently favour the chemical oxygen type. Chemically based SCSRs require little maintenance due to the absence of gauges, pressure reducers, lung demand valves and other moving parts. However, powdering of the KO_2 granules may occur with vibration caused by carrying or transporting the SCSR. This may cause a path of low resistance through the chemical bed leading to a premature breakthrough and build up of CO_2 in the wearer's breathing circuit.

The Portal-Pack™ Self-Contained Self Rescuer was selected for the project because it was the only unit of 60 minutes duration that had met the requirements of BS/EN 401:1993 (based on the NSW Department of Mineral Resources Tests) and had been approved for use in NSW underground coal mines. The Portal-Pack is a single-use, self-contained closed-circuit breathing apparatus (Fig. 1).



Fig.1 - Portal-pack™ self-contained self rescuer

Its operation is completely independent of the surrounding atmosphere. Once properly donned, the SCSR can assist a miner to escape from an area containing smoke, toxic gases or an oxygen deficient atmosphere. Its operating life during escape depends on the demands of the user. Two chemical sources within the unit release the life sustaining oxygen.

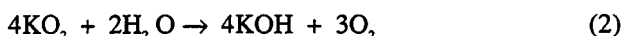
The initial source of oxygen is from a cylinder containing the chemical Sodium Chlorate (NaClO_3), commonly known as the "chlorate candle". Its function is to provide an immediate source of oxygen to fill the system including the breathing bag. When the breathing tube is pulled at the time of donning the apparatus, a primer cap initiates the chemical reaction which "burns" the chlorate to produce oxygen according to Equation 1.



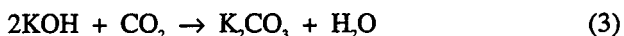
Over the first two to three minutes, the chlorate candle produces roughly 10 litres of oxygen. The released oxygen partially fills the breathing bag. Once the individual commences to breathe into the unit the chemical reaction of the wearer's breath and the potassium superoxide will produce more oxygen continuously. If the "Chlorate Candle" fails to initiate, the unit can still be used and the breathing bag became fully inflated by the end of seven minutes.

The second source of oxygen is a canister containing potassium superoxide (KO_2). This chemical consists of coarse granules held in place by baffles contained in the canister. The chemical reaction between moisture in the exhaled breath and the KO_2 liberates the oxygen. The Portal-Pack contains about 600 gm of KO_2 , which produces approximately 140 litres of oxygen.

The chemical reaction is given in Equation 2:



In addition to this, a second reaction takes place between the potassium hydroxide and the carbon dioxide in the external breath to combine and retain CO_2 according to the following Equation 3.



The above reactions are self-regulating. The harder the wearer works the more oxygen is generated and the more CO_2 is removed. The basic operation of the unit is depicted in Fig. 2.

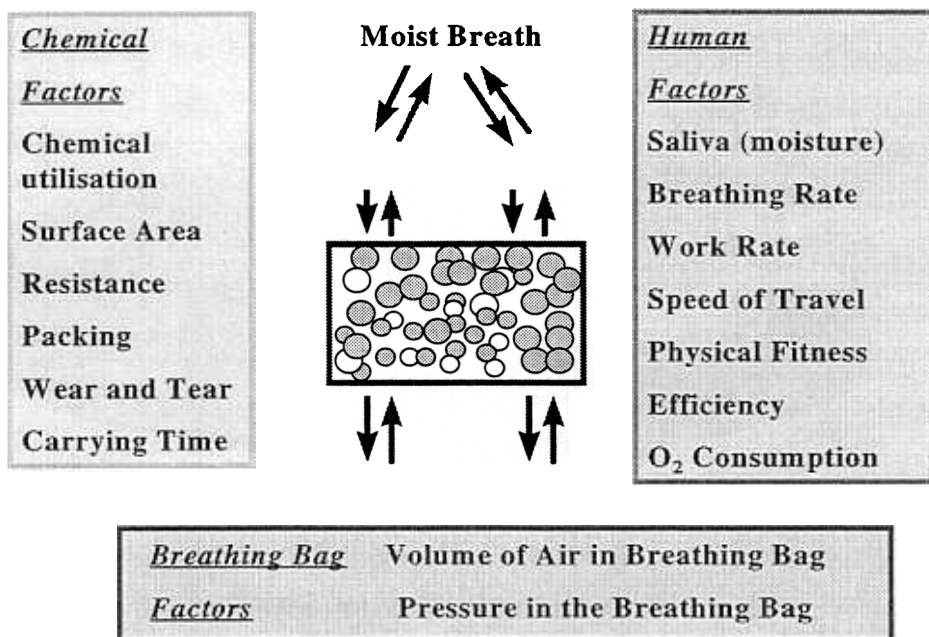


Fig. 2 - Operation of SCSR

The duration of a SCSR is the time taken for the oxygen supply to run out and is indicated by the complete collapse of the breathing bag. The duration of a SCSR was expressed in Equation 4.

$$\text{SCSR Duration (minutes)} = \frac{\text{Useable Oxygen (litres)}}{\text{Oxygen Consumption (litres / minute)}} \cong \frac{100}{V\dot{O}_2} \quad (4)$$

Initially, the wearer is likely to experience increased breathing resistance. As the chemical becomes exhausted, carbon dioxide (CO₂) builds up within the circuit and the wearer may develop a headache or light headedness.

MINE SIMULATED ESCAPE TRIALS

The objectives of the underground investigations were to gather in-mine data on escape times, distances travelled and average heart rates and to develop a technique to predict how much oxygen was actually needed for an average miner to escape from an underground mine. Underground simulated escape trials were conducted at South Bulli, Elouera and Myuna Collieries located in NSW and Crinum Colliery in Queensland. The mines were selected to represent the variety of conditions that are normally encountered in the actual escapeways of Australian coal mines. The escape routes were selected by the mine and based on the following requirements:

1. a distance which would require the volunteers to walk for a minimum of one hour, and
2. an established escapeway to simulate typical underground escape route conditions.

Attempts were made to ensure that the profiles of the volunteers represented those of the current workforce in Australian underground coal mines. Prior to participating in the field trials, all the volunteers were assessed by an occupational physician to identify those with significant medical conditions or those who may have problems walking out of the mine because of significant musculoskeletal problems. None of the volunteers were considered "unfit" to participate in the study.

The age distribution of the 37 subjects from South Bulli, Elouera, Myuna and Crinum Collieries is shown in Fig. 3, where 81% of all the subjects were between 30 and 49 years old. The minimum and maximum ages of the subjects was 27 and 57 years old with an overall average age of 40.7 years.

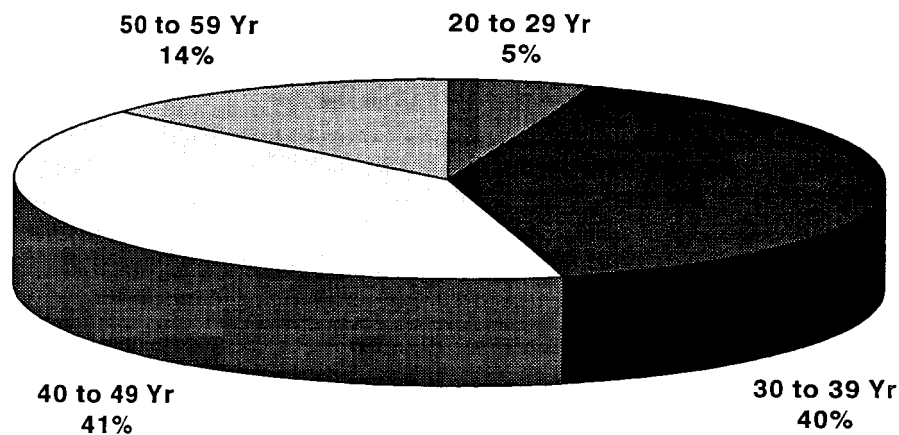


Fig. 3 - Age Distribution of the 37 Subjects

The weight distribution of the 37 subjects is illustrated in Fig. 4, where 87% of the subjects weighed between 70 and 99 kg. The minimum and maximum weight of all the subjects are 66 and 130 kg with an average of 85.5 kg. The weight and age

distributions of the selected volunteers represented the profiles of the current workforce employed in NSW and Queensland.

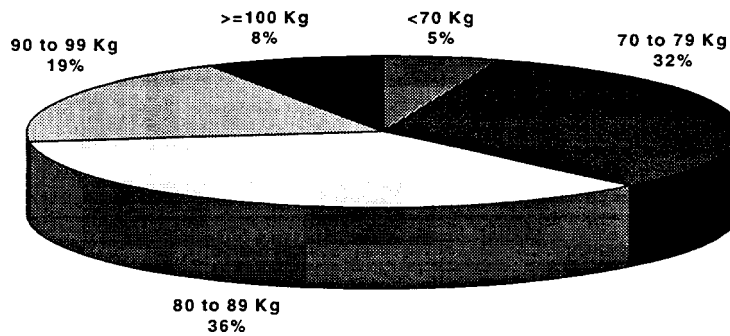


Fig.4 - Weight distribution of the 37 subjects

FIELD TRIALS

Prior to wearing the SCSR each volunteer participated in a training program. At the conclusion of training all volunteers had to correctly don and wear training SCSR. Training was conducted by demonstration, lecture and video.

The content of the training program included information and instruction on the following:

1. components and principles of operation of the SCSR;
2. donning procedures;
3. expectations while wearing;
4. recognition of oxygen “run out”; and
5. symptoms of carbon dioxide retention and oxygen deficiency.

During the simulated escape trials, the 37 volunteers walked along the escape route at their respective mines on Day 1 carrying the SCSRs on their belts. The walk was repeated on Day 2 with the same subjects wearing the SCSRs. As the route in each mine had been identified by the mine as an established escapeway, the physical conditions were realistic with uneven ground, roadway water, overcasts to climb over, low roof conditions, inclines, pit furniture to negotiate and warm conditions. Each mine escapeway was different. The walking pace on each day was kept at a constant rate of about 2 km/hr. The heart rates of each subject was recorded by a Polar Vantage NV™. The heart rates for one of the subjects is reproduced in Fig. 5.

At the end of Day 2 each SCSR’s breathing bag was monitored by an observer to enable the oxygen “run out” time to be determined. Normally, the end of the trial could be defined for each individual as the point of complete collapse of the breathing bag, which may be accompanied by increased breathing resistance. If carbon dioxide builds up in the breathing circuit headache and light headedness may also occur. This is most likely to be caused by inhaled concentrations of CO₂ of 2-3%. The duration of the SCSR was taken from the time the individual started to breathe oxygen via the SCSR, ending with the complete collapse of the breathing bag.

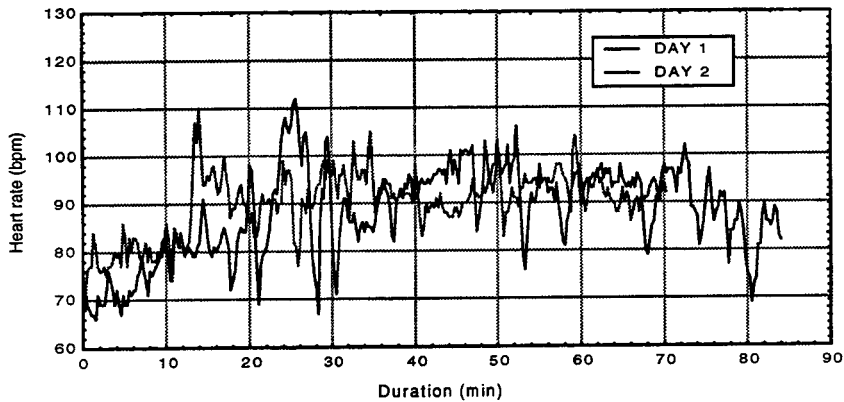


Fig.5 - Heart Rates versus duration for subject

DISCUSSIONS OF RESULTS

Performance and comfort of the SCSRs

All the 37 volunteers were asked to complete a questionnaire designed to assess the performance and comfort of the SCSRs.

The following conclusions could be drawn from the questionnaire.

- (i) All the subjects felt they could don and wear the SCSRs in an emergency;
- (ii) 95% felt the SCSRs would protect them in oxygen deficient or toxic atmospheres;
- (iii) 46% felt the SCSRs were uncomfortable to wear around the head and neck;
- (iv) 84% would not like to carry the SCSR for a complete normal working shift;
- (v) 89% found the nose clips uncomfortable but appreciated the need for a tight nasal seal to prevent the ingress of irrespirable atmospheres;
- (vi) 38% felt the temperature of the inhaled air was comfortable to breathe and 54% found the air hot but tolerable; and
- (vii) 19% found breathing comfortable and 56% found breathing resistance noticeable but tolerable.

All volunteers were advised to carry gloves or rags to place between the canister and the chest wall, despite this precaution a small number of subjects had observable evidence of superficial skin scalding.

Oxygen "run out" time

The oxygen "run out" time distributions for the 37 subjects are shown in Fig. 6. In 60% of individuals, the duration of the SCSR equalled or exceeded the 60 minute nominal duration time of the SCSR. Of all the subjects, 11% has duration greater than 70 minutes and 8% less than 50 minutes. One individual ran out of oxygen in 45 minutes.

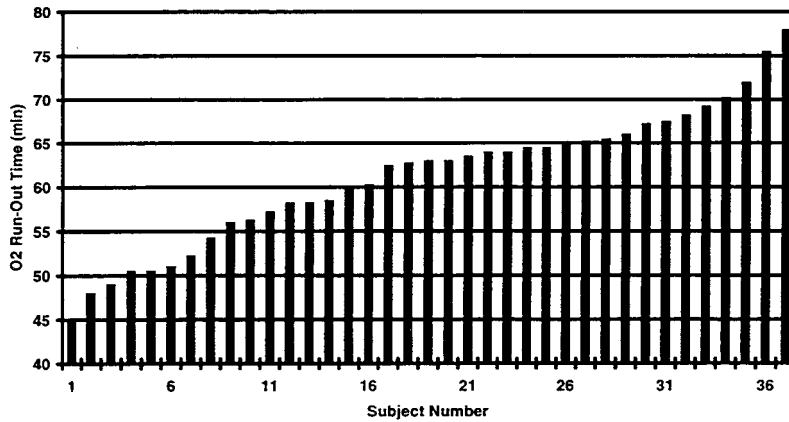


Fig.6 - Oxygen "run out" time distribution of the 37 subjects

Predicting oxygen consumption

Various studies in USA (Bernard, Kamon and Stein, 1979; Berry, et al., 1983; Buskirk, Nicholas and Hodgson., 1975) have linked the oxygen consumption ($\dot{V}O_2$) to average heart rate (HR) and the body weight (W) as per the following equations.

$$\text{PSU Model} \quad \dot{V}O_2 = \frac{HR - 66}{36}$$

$$\text{Foster Model} \quad \dot{V}O_2 = 0.024HR - 1.54$$

$$\text{NIOSH Model} \quad \dot{V}O_2 = \frac{W(HR - 61.25)}{3230}$$

Using the above three equations, Day 1 average heart rates and the body weights of the 28 subjects, from the South Bulli, Elouera and Myuna trials, the average oxygen consumption rate and hence oxygen "run out" time for each subject was estimated. The results predicted by the three models as well as the observed are presented in Fig. 7. The three models generally underestimated the average $\dot{V}O_2$ and hence overestimated the oxygen "run out" time for average heart rates under 120 bpm (fitter individuals). For heart rates above 120 bpm the predictions were inconsistent. There is a strong possibility that the above models were developed under conditions which were different from the Australian simulated field trials in this study.

In order to achieve better prediction capability for oxygen consumption, pre-trial and field data were statistically analysed. The data was examined to determine if there were any significant relationships between $\dot{V}O_2$ and average heart rate, age, weight, smoking habits, drinking habits, physical fitness estimates based upon bicycle ergometer tests, exercise habits, previous breathing apparatus experience and other factors.

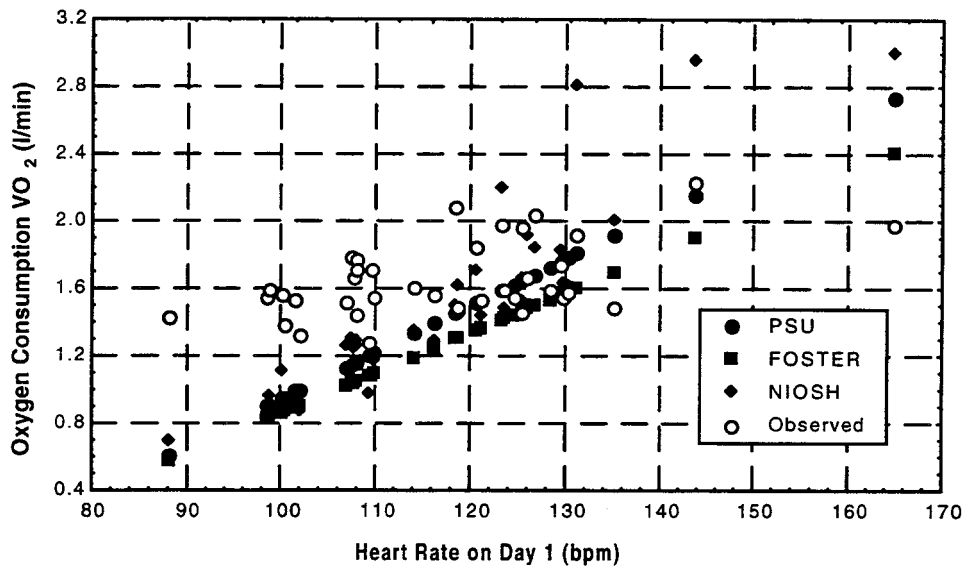


Fig.7 - Predicted versus Observed $\dot{V}O_2$

Fig. 8 shows that there is a tendency for lower average heart rates and body weights to be associated with lower values for $\dot{V}O_2$. Higher exercise rating, greater than a score of 5, was generally associated with lower $\dot{V}O_2$. The coefficient of correlation between observed $\dot{V}O_2$ and weight is 0.78. This suggests a strong linear relationship between observed $\dot{V}O_2$ and weight, in other words weight is a good predictor of $\dot{V}O_2$. In practice, a correlation coefficient over 0.7 shows a strong linear relationship between the variables, 0.3-0.7 is moderate and less than 0.3 is considered as a weak association.

The associations between $\dot{V}O_2$ and other measured variables could be described in statistical terms as follows:

- (a) There was a strong association between $\dot{V}O_2$ with body weight;
- (b) Exercise rating (habits) was moderately associated with $\dot{V}O_2$
- (c) A weak association existed between $\dot{V}O_2$ and both cigarette use and alcohol consumption; and
- (d) The association between $\dot{V}O_2$ and age was very weak.

It was observed that the average heart rates for each of the 37 subjects were not the same on Day 1 and Day 2. In fact the average heart rate was slightly higher on Day 2 in 60% of the subjects. The correlation coefficient of average heart rate on Day 1 and Day 2 was found to be 0.79.

Both the compiled medical data and the simulated escape field data were statistically analysed. Based on the mine simulated escape trials from the first three mines, the Equation (4) was developed as

$$\dot{V}O_2 = \frac{7.5W + HR}{500} + 0.043 \quad (4)$$

A comparison of prediction of $\dot{V}O_2$ on the fourth mines' (Crinum) trials using the previous three models as well as Equation (4) is depicted in Fig. 10, indicating that the Equation (4) gives the best predictive values. All the four mine data were finally used to produce the Equation (5) referred to as the "University Of Wollongong (UOW) model".

$$\dot{V}O_2 = \frac{6.0W + 1.5HR}{500} + 0.332 \quad (5)$$

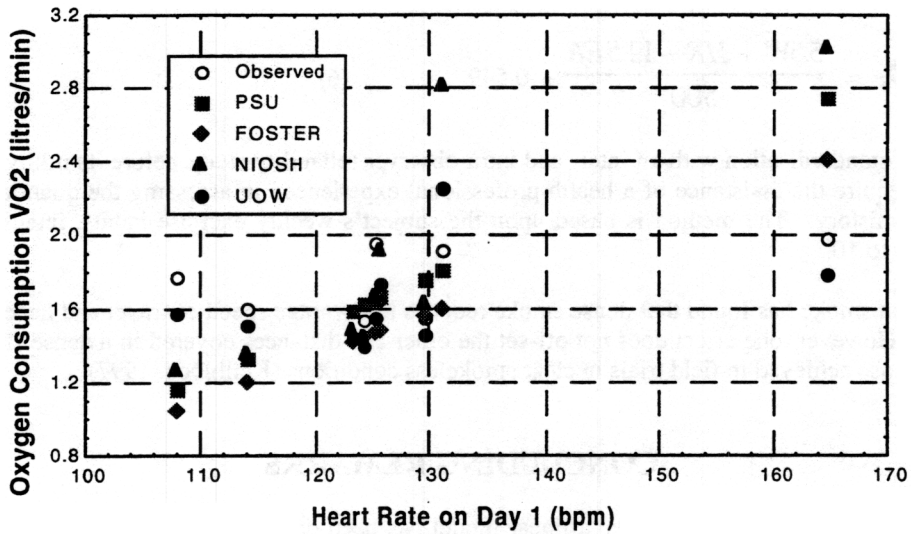


Fig.10 - Comparison of four predictive models

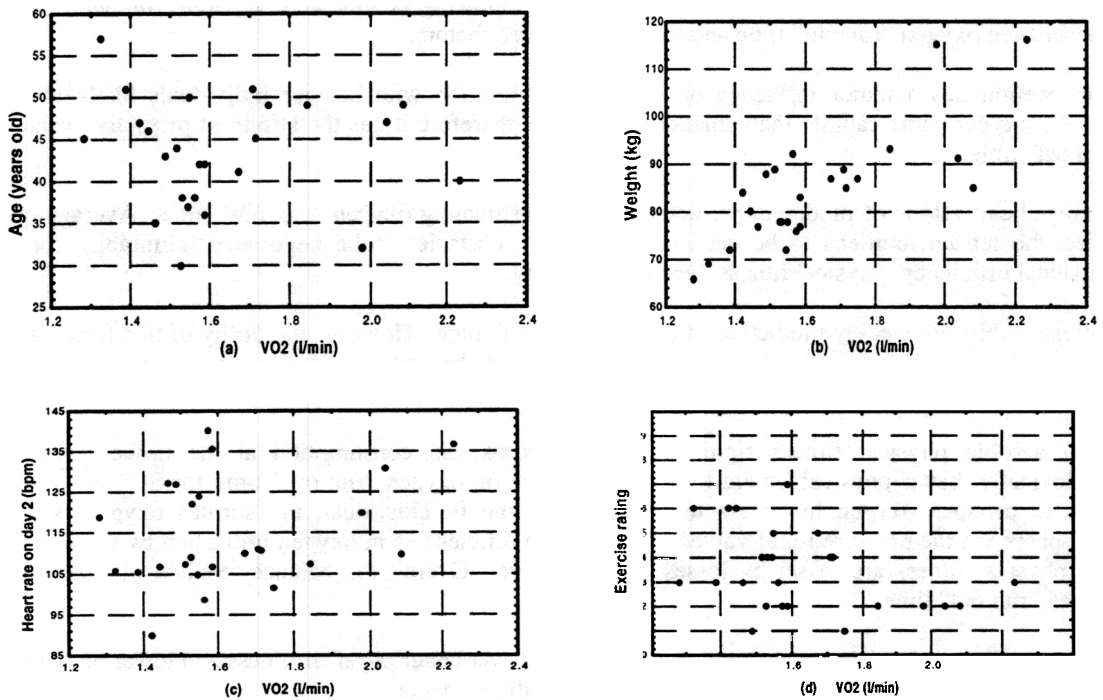


Fig. 8 - Scattergram of $\dot{V}O_2$ versus age, weight, heart rate and exercise ratio

The above predictive UOW model relates oxygen consumption ($\dot{V}O_2$) with average heart rate (HR) and body weight (W) and is based upon a representative group of Australian male underground coal miners. This model appears to be of better

predictive value than the previous models, therefore a better estimate of oxygen consumption and hence predicted oxygen “run out” time. The above predictive model is recommended for use by Australian collieries. The model is simple and requires minimal technology. It requires a device to measure average heart rate during a simulated escape in an established escapeway, an accurate set of bathroom scales and a calculator.

Equation (6) relates oxygen consumption ($\dot{V}O_2$) with average heart rate (HR), body weight (W) and exercise rating (ER) of an individual .

$$\dot{V}O_2 = \frac{5.5W + HR - 11.5ER}{500} + 0.549 \quad (6)$$

Equation (6) requires standardisation with an inter- and intra-observer reliability study before its utility can be established. The method would require the assistance of a health professional experienced in assessing the quantity and quality of an individual’s exercise history. The method is based upon the subject’s weekly exercise habits, intensity of exercise and scored on a scale of 1 to 10.

South African work on smoke has found that dense smoke reduces the average speed of travel and hence the breathing rate of the SCSR wearer. However, one effect does not off-set the other and distances covered in a dense smoke were found to be a low as 60% of those achieved in field trials in clear smokeless conditions (Keilblock, 1997).

CONCLUDING REMARKS

Using results from field simulated escape trials, a linear model has been developed to predict oxygen “run out” times of SCSR. While oxygen consumption is related to the amount of work performed, this study has demonstrated that personal factors can influence the amount of oxygen consumed while wearing a SCSR. Considerable physiological research has established that fitter and younger persons tend to utilise oxygen more efficiently in the body’s microscopic tissues. This results in less oxygen being consumed per unit of work. The following factors were apparent following analysis of the relationships between oxygen “run out” time and individual related factors:

1. Body weight has a major influence on oxygen consumption with heavier individuals likely to consume the SCSR’s oxygen more rapidly than smaller individuals, therefore it has the strongest predictive value for oxygen “run out” time.
2. Average heart rate is of moderate predictive value in estimating oxygen “run out” time. Average heart rate can reflect the terrain, burdens to be carried, roof height, obstacles to be negotiated (climbing), speed of travel, individual efficiency, physical fitness, heat and humidity.
3. Exercise habits are weakly predictive of oxygen “run out” time. However the utility of this factor is of uncertain value at this stage due to the need for interpretation of the exercise history and a scoring system which is subjective.
4. Better aerobic physical fitness significantly reduces oxygen consumption at the tissue level. However paradoxically, better physical fitness has little influence on oxygen “run out” time for SCSRs. As the SCSR is likely to produce oxygen in excess to the needs of the fit individual, the surplus oxygen is discharged to atmosphere via the pressure relief valve. Therefore the efficiencies in oxygen utilisation by the tissues associated with physical fitness are offset by losses to atmosphere. Overall the balance resulted in a minimal effect on oxygen “run out” time.
5. Age had a slight influence on oxygen consumption, however better physical fitness and lower body mass modified the amount consumed. Therefore age is of dubious predictive value.
6. Previous experience in wearing breathing apparatus appeared to have no significant value in predicting oxygen “run out” time.
7. Habitual consumption of alcohol and cigarettes may slightly increase $\dot{V}O_2$ and this would be modified by both physical fitness and body mass, therefore has negligible predictive value.

In life threatening underground incidents, as occurs following an explosion or during a fire, individuals are likely to walk quickly or run as a consequence of panic. As a result oxygen may be consumed more quickly or the chemical used less efficiently. Consequently there is a risk the duration of the SCSR will be reduced. It is this factor which will reduce oxygen "run out" time more significantly. Therefore if the rate of travel is controlled anxiety is unlikely to have a significant effect upon oxygen consumption. Anxiety may result in the release of hormones into the circulation (the fight and fright reaction) and subsequently increase the individual's heart rate. However unless large muscles, such as those used in walking and running are working or exercising there is unlikely to be a parallel increase in oxygen consumption in the tissues.

ACKNOWLEDGMENTS

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