PREDICTING THE DURATION OF SELF-CONTAINED SELF-RECUERS

Paul Mackenzie-Wood
Mines Rescue Service NSW

I Tague
Joint Coal Board

E Baafi, N Aziz, Y Sun
University of Wollongong

SUMMARY

Field trials at various New South Wales (NSW) and Queensland (Qld) 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 SCSRs. This project 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.

BACKGROUND

In view of recent mine disasters in the coal mining industry in Australia, there is a need to develop strategies to enable the introduction of Self-Contained Self Rescuers (SCSRs) into underground mines. These strategies must be part of an overall strategy to maximise the likelihood of survival of a person attempting to escape in an emergency involving fire or explosion. In order to fulfil this aim the project set out to gather field data in order to develop methodology to predict how much oxygen is actually needed by an individual to escape from an underground mine. The project team considered the effects of personal and environmental factors upon the duration of SCSRs, escape times, distances travelled and average heart rates. The study was an opportunity to assess the capability and comfort of SCSRs. In order to facilitate the introduction of SCSRs, training issues relating to SCSRs were also identified. The results of this research should assist mines to develop a practical system for escape planning which accounts for relevant issues pertaining to the use of SCSRs.

SELF-CONTAINED SELF-RESCUER

The SCSR in this project uses a chemical, potassium superoxide (KO_2), which reacts with the wearers breath to produce oxygen (O_2) and absorb carbon dioxide (CO_2). A SCSR works in a closed circuit whereby the wearer exhales back through the chemical into a breathing bag for re-use. As oxygen is produced, any excess to an individual's requirement is released to the atmosphere via a pressure relief valve situated in the breathing bag. MSA Portal-Pack SCSRs with a nominal duration of 60 minutes were used in the trials. Approximately 100 litres of oxygen is available to the wearer. If oxygen consumption, or the rate at which the wearer consumes oxygen, is VO_2 (litres/min) then the duration of a SCSR (oxygen "run out" time) in minutes is as follows:

$$\text{SCSR Duration (minutes)} = \frac{\text{Useable Oxygen (litres)}}{\text{Oxygen Consumption (litres / minute)}} \cong \frac{100}{\text{VO2}}$$

PHYSIOLOGY

Astrand and others have demonstrated that oxygen consumption increases with the intensity of the work being performed. Physiologically this is evident as an increase in heart rate. By measuring heart rate during exercise (work) the amount of work being performed or oxygen being consumed can be estimated. This physiological model underpins the methodology used in this project.

Various studies in USA (Bernard et al, 1979; Berry et al, 1983; Buskirk et al, 1975) have linked the oxygen consumption (VO_2) to average heart rate (HR) and the body weight (W) as per the following equations:

PSU Model	$VO_2 = (HR - 66) / 36$	(1)
Foster Model	$VO_2 = 0.24HR - 1.54$	(2)
NIOSH Model	$VO_2 = W(HR - 61.25) / 3230$	(3)

where VO_2 = volume of oxygen consumed in litres per minutes

HR = average heart rate, beats per minute

W = weight, kg

FIELD TRIALS

Underground trials were carried out at three NSW and one QLD mine under simulated escape conditions to:

- predict the individual oxygen needs using published formulae
- measure the duration of oxygen supply and
- evaluate the wearer comfort and operational performance of SCSR's.

In all 37 volunteer male subjects underwent a health and fitness assessment to document demographic data, to estimate fitness levels and assess individuals for contraindications to participate in the trials. All volunteers were used in the trials and were required to walk out of the mine on each of two successive days at a walking rate of 3 km/hr:

- on day 1 the SCSR was carried on their belt and
- on day 2 the SCSR was donned and worn until its oxygen exhausted.

The exhaustion of the oxygen supply was identified as the point of complete collapse of the breathing bag and this oxygen "run out" time was recorded. A distribution for the "run-out" time is shown in Fig 1.

The majority of volunteers were inexperienced in the use of SCSRs or other breathing apparatus.

During the field trials, each volunteer's average heart rate was recorded using a Polar Vantage Heart Monitor NV™. The data was later downloaded into a Polar software computer program for statistical analysis.

Results and Discussion

All volunteers completed a subjective assessment of the comfort and operational efficiency of the SCSR. Most wearers reported some discomfort which did not impede their capability to escape.

US Bureau of Mines studies indicated there would likely be an increase in average heart rate of 15% on day 2. The relationship between the heart rates found was established using linear regression analysis and is given by equation (4) below, where HR_1 is the average heart rate on Day 1 at HR_2 is the average heart rate of Day 2.

- $HR_2 = 0.73HR_1 + 31$ (4)

Oxygen "run out" time was observed for each individual on day 2. Consequently oxygen consumption was calculated for each individual. Based upon manufacturer's data it was assumed that 100 litres of oxygen was available to each individual. Using average heart rate data on day 1 the oxygen "run out" time for day 2 was estimated using the three models represented by equations (1), (2) and (3).

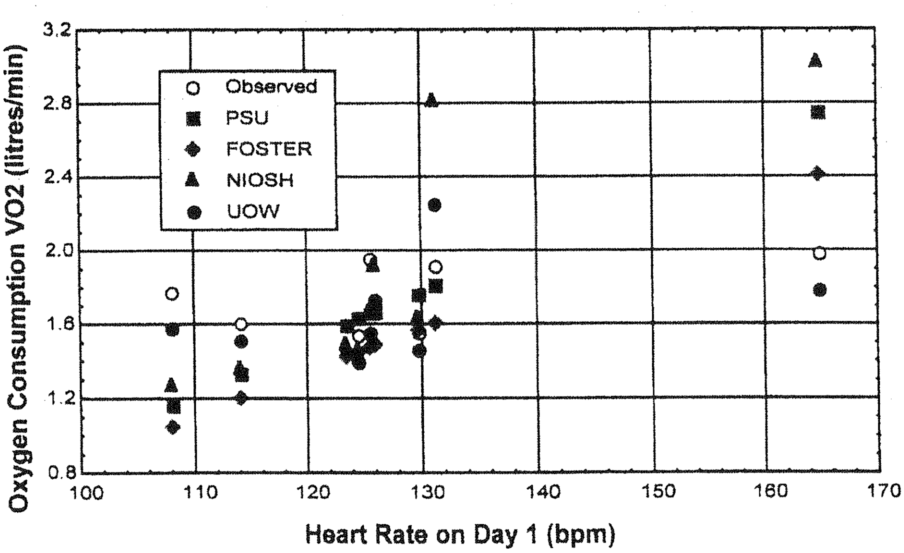

Figure 1 : Comparison of Four Predictive Models

Using Day 1 average heart rates and the weights of the 37 subjects, the average oxygen consumption rate of each subject was estimated. The three models generally underestimated the average VO_2 for average heart rates under 120 bpm and inconsistent at heart rates above 120 bpm. There is a strong possibility that the above models were developed under conditions which were different from the field simulated trials.

The association between VO_2 and other measured variables such as body weight, age, fitness rating and experience was analysed using linear regression analysis. The associations found could be described as follows:

- strong association of VO_2 with body weight;
- moderate association of VO_2 with exercise rating;
- very weak association of VO_2 with age.

Further analysis using multiple regression techniques led to the development of a further model based on the following formula:

$$VO_2 = \frac{6.0W + 1.5HR}{500} + 0.332 \qquad (5)$$

The above formula is the basis of the University of Wollongong (UOW) model. The four formulae for average heart rate vs VO_2 was compared using data from the final colliery trial and the results are given in Fig 2. The UOW model (5) came closest to predicting oxygen "run out" times.

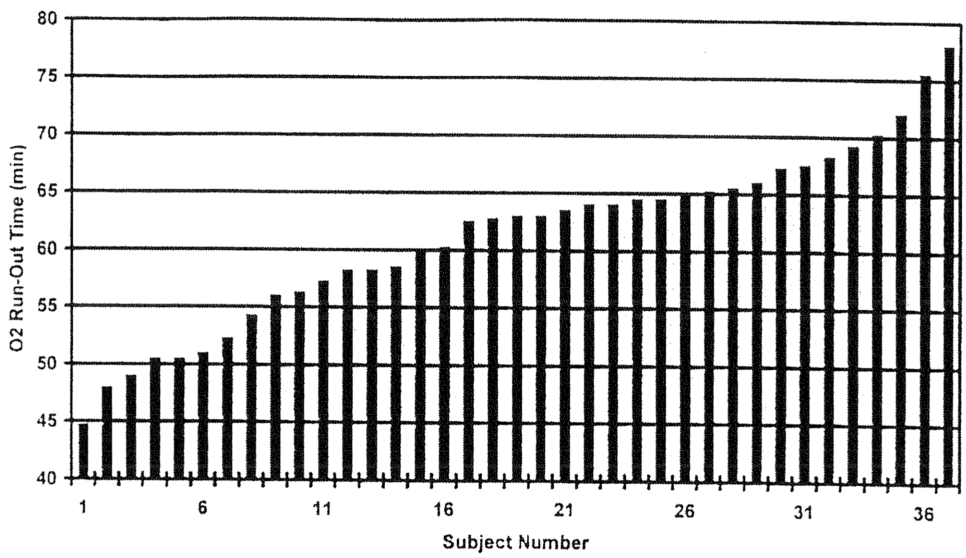

Figure 2 : Distribution of Oxygen "Run-Out" Times

EFFECT OF HEAT AND HUMIDITY

The second stage of the project was conducted in a hot and humid chamber to study the effect of heat and humidity on oxygen "run out" time. Six volunteer male subjects experienced in the use of SCSR underwent a health and fitness assessment for the reasons mentioned in the previous trial.

Each subject was required to walk on a treadmill wearing full underground apparel on three separate occasions 24 hours apart. The treadmill speed was held constant at 4 Kph in a hot and humid chamber maintained at 22°C on days 1 and 2, with relative humidity of 50-75%. The subjects were tested in the same order on each day. The temperature and humidity was selected as representative of underground conditions to be encountered following an incident. The temperature and humidity were increased to 32°C and 100% respectively on day 3, to simulate heat and humidity conditions in an atmosphere in the vicinity of an underground fire or post explosion situation.

As in the field trials, the heart rate was recorded continuously. On each day the criteria for stopping the tests were either the collapse of the SCSR breathing bag, or the subject's heart rate exceeding 85% of its predicted maximum or signs and symptoms of heat related stress.

Results and Discussion

On completion of the test on day 1 the UOW model was used to predict oxygen "run out" time for day 2 and day 3. Oxygen "run out" time was observed on day 2. On day 3 all subjects were stopped when 85% of the predicted heart rate was exceeded and therefore oxygen "run out" time was derived by extrapolation. Using the UOW formula extrapolated results indicated the duration of the SCSR was not significantly reduced in extreme heat and humidity.

Evidence from the literature suggests that the greater portion of the increase in average heart rate in hot and humid environments is more likely to reflect the body's attempts to keep its core temperature from rising too high, thus preventing heat related illness. From the practical perspective the duration of availability of oxygen should not be affected by the hot and humid conditions likely to be encountered in escape from mines by individuals wearing a SCSR.

MEASUREMENT OF OXYGEN CONSUMPTION WHILE WEARING A SCSR

In the third stage of the project 6 volunteers walked on a treadmill at 5 Kph breathing through a SCSR in a closed circuit. The concentration of oxygen and carbon dioxide for the inhaled and exhaled air were monitored.
Criteria to stop the test were:

- the unit ran out of oxygen
- the subject desired to terminate the trial
- the subject showed overt signs of exercise strain (heart rate greater than 90% of cardiac reserve) or the inhaled carbon dioxide over 3%.

Results and Discussions
The volume of oxygen "useable" by the wearer is crucial in escaping as well as predicting oxygen "run out" time. The average volume of "useable" oxygen was found to be 99 litres. In view of this finding and its concurrence with the manufacturer's advice it appears reasonable to assume 100 litres O_2 will be "useable" by the wearer for the purposes of predicting oxygen "run out" time.
The rate of production of oxygen is dependent upon the quantity of moisture and carbon dioxide in the wearer's breath and the system is designed to produce oxygen in excess of the individual's needs. As oxygen exceeds the individual's needs, the pressure within the breathing bag exceeds the opening pressure of the relief valve and so oxygen is released to the atmosphere. Potentially 140 litres of oxygen was available to the wearer therefore the quantity of oxygen released to atmosphere, via the pressure relief valve, averaged 41 litres. It may be that fitter individuals consumed less oxygen from the SCSR but lost more to the atmosphere via the pressure relief valve.

DISCUSSION

The UOW model predicts the oxygen "run out" time for sub-maximal exertion in clear conditions. If exertion was close to maximal, physical fitness would become a significant factor. Research in the USA (Shearer) indicates heavy panting would minimise the dwell time between the exhaled breath and the chemical pellets causing oxygen "run out" to occur before exhaustion of the potassium superoxide is achieved. This would indicate a controlled escape speed at sub-maximal exertion would increase the distance travelled during an escape.
South African work in smoke (Keilblock) has found that dense smoke reduces the speed of travel and hence the breathing rate of the wearer. However, one effect does not off-set the other and distances covered in dense smoke were found to be as little as 60% of those achieved in trials in clear conditions.

CONCLUSION

Compiled medical data and the simulated escape field data were statistically analysed to produce the following UOW prediction model.

$$VO_2 = \frac{6.0W + 1.5HR}{500} + 0.332 \qquad (5)$$

This predictive UOW model relates oxygen consumption (VO_2) with average heart rate (HR) and body mass (W) is based upon a representative group of Australian male underground coal miners. This model appears to be of better predictive value than the previous overseas models, therefore a better estimate of oxygen consumption and hence predicted oxygen "run out" time.
Table 1 which is based upon the UOW model can be used to predict oxygen "run out" time of a SCSR of 60 minutes nominal duration. This table indicates that people with a body weight in excess of 100 kg will not achieve the nominal duration for a SCSR. People in this category would need to control their speed of travel to minimise heart rate and maximise duration of the SCSR and hence distance travelled.
"Changeover" stations containing SCSRs may need to be located in all designated escapeways at specified distances from all working places. These specified distances can be calculated by estimating the duration of SCSRs from Table 1 based upon the body weights and the average heart rate of the individuals measured during a simulated escape at a realistic controlled speed. When locating "changeover" stations, consideration must be given to environmental conditions that may include dense smoke and also correspond to the 95 percentile estimate of a persons weight and fitness rating according to international practice.

REFERENCES

1. Astrand and Rodahl, 1986, Textbook of Work Physiology, McGraw-Hill, 3rd Ed
2. Bernard, T.E., Kamon, E. and Stein, R.L., 1979, Interrelationships of Respiratory Variables of Coal Miners during Work, Ergonomics, Vol. 22, No. 10, pp 1097-1104
3. Berry, D.R., Doyle, D.M., Kamon, E. and Mitchell, D.W., 1983, Escapetime Studies in Underground Coal Mines, Foster-Miller Associates Inc and US Bureau of Mines, Contract No. J0199118, 49 pp
4. Buskirk, E.R., Nicholas, W.C. and Hodgsdon, J.L., 1975, Measurement of Work Metabolism, Use of Cardiorespiratory Parameters for Estimating Metabolic Heat Production in Hot Environments, National Institute for Occupational Safety and Health, Cincinnati, Ohio, Contract No. HSM 99-72-70, 35 pp
5. Keilblock, J., 1997, Personal Communication, MiningTek CSIR, South Africa
6. Shearer, S., 1996, Personal Communication, CSE Corp, United States

ACKNOWLEDGEMENTS

The assistance of Dr N Taylor, Dept of Biomedical Science, University of Wollongong, in the design and supervision of laboratory tests is gratefully acknowledged.

The support of ACARP, Mines Rescue Service NSW, Dept Civil and Mining Engineering (University of Wollongong), Joint Coal Board, participating mines and volunteers.

Table 1 : Estimate of Oxygen "Run-Out" Times of a SCSR with a 60 Minute Nominal Duration

Weight (kg)	55	60	65	70	75	80	85	90	95	100	105	110	115	120	125	130	135	140	145	150
Average Heart Rate (bpm)	**Greater than 60 minutes duration**								**Less than 60 minutes duration**											
80	81	77	74	71	68	65	63	61	58	56	55	53	51	50	48	47	46	44	43	42
85	80	77	73	70	67	65	62	60	58	56	54	52	51	49	48	47	45	44	43	42
90	79	76	72	69	67	64	62	59	57	55	54	52	50	49	48	46	45	44	43	42
95	78	75	72	69	66	63	61	59	57	55	53	52	50	49	47	46	45	44	42	41
100	77	74	71	68	65	63	61	58	56	55	53	51	50	48	47	46	44	43	42	41
105	77	73	70	67	65	62	60	58	56	54	52	51	49	48	47	45	44	43	42	41
110	76	72	69	67	64	62	59	57	55	54	52	50	49	48	46	45	44	43	42	41
115	75	72	69	66	63	61	59	57	55	53	52	50	49	47	46	45	44	42	41	40
120	74	71	68	65	63	61	58	56	55	53	51	50	48	47	46	45	43	42	41	40
125	73	70	67	65	62	60	58	56	54	52	51	49	48	47	45	44	43	42	41	40
130	72	69	67	64	62	59	57	55	54	52	50	49	48	46	45	44	43	42	41	40
135	72	69	66	63	61	59	57	55	53	52	50	49	47	46	45	44	42	41	40	39
140	71	68	65	63	61	58	56	55	53	51	50	48	47	46	44	43	42	41	40	39
145	70	67	65	62	60	58	56	54	52	51	49	48	47	45	44	43	42	41	40	39
150	69	67	64	62	59	57	55	54	52	50	49	48	46	45	44	43	42	41	40	39
155	69	66	63	61	59	57	55	53	52	50	49	47	46	45	44	43	41	40	39	39
160	68	65	63	61	58	56	55	53	51	50	48	47	46	44	43	42	41	40	39	38
165	67	65	62	60	58	56	54	52	51	49	48	47	45	44	43	42	41	40	39	38
170	67	64	62	59	57	55	54	52	50	49	48	46	45	44	43	42	41	40	39	38
175	66	63	61	59	57	55	53	52	50	49	47	46	45	44	42	42	40	39	39	38
180	65	63	61	58	56	55	53	51	50	48	47	46	44	43	42	41	40	39	38	37

$$VO_2 = (6.0W + 1.5HR)/500 + 0.332$$