CHAPTER 4

THE EFFECTS OF HEAT AND HUMIDITY ON THE DURATION OF SCSRs

4.1 Introduction

The environment in a mine may be hot and humid following a fire or explosion, therefore this stage of the project sought to determine the effects of environmental conditions on the duration of SCSRs.

The consequences of heat and humidity put significant stress on the cardiovascular system (Ludbrook, 1987; Hales, 1983; Robertshaw, 1983; Appenzeller, 1983) particularly during exercise. Because individuals are 20 to 25% efficient, 80 to 75% of their energy expenditure is wasted as heat and not used for useful external work. Assume a 20% efficiency, to perform at 200W on a bicycle ergometer, one would need to expend energy at a rate of 1,000W, and 200W would appear as heat. Heat is likely to be generated during exercise or escape in hot and humid conditions.

Heat also may be gained from the environment, through exothermic chemical reactions occurring in the SCSR canister itself, since the wearer is unable to discharge heat from exhaled breath. While wearing SCSRs and dressed in underground apparel wearing is most likely to be the most important avenue to dissipate heat.

The physiological events occurring during exposure to heat and humidity are summarised in Fig. 28. As the core (internal body) temperature increases, redistribution of blood supply starts to occur (A) through preferential opening and closing of tissue capillary channels (B). Blood is shunted away from the kidneys and gastrointestinal tract. Skin capillaries open up and blood is shunted into skin in an attempt to lose heat by evaporative cooling.

Thus during exercise in heat, skin blood flow is elevated. However, during heavier exercise there becomes a competition for blood between muscle and skin. Consequently the blood pressure falls. To counter the fall in blood pressure skin blood flow is reduced in favour of muscle blood flow. This causes a more rapid rise in core temperature. To help maintain blood pressure, the heart rate rises. In classical heat stroke, the patient is likely to have hot dry skin, rapid heart rate, low blood pressure and core (internal body) temperature over 40°C.

Heat stress does not decrease cardiac output. However, at the same \( \dot{V}O_2 \), cardiac output is greater, but during maximal exercise maximal cardiac output is reached earlier. Thus maximal cardiac output is still attained.

\(^{\dagger}\) Refer to the flowchart in Fig. 28. Discussion points have been numbered from A to C.
Fig. 28 The Oxygenation of Tissues
4.2 Objectives of the Heat and Humidity Trial

The objectives of the trial were to:

1. Observe the relative effects upon heart rate when carrying a SCSR while breathing normal room air, wearing a SCSR at room temperature breathing oxygen and wearing a SCSR in high heat and humidity breathing oxygen.

2. Predict the duration of SCSRs using average heart rate measured during exercise on a treadmill and confirm the prediction on a subsequent Day and

3. Observe the effects of heat and humidity on the duration of the oxygen supply from a SCSR.

4.3 Study Methods

Six male subjects experienced in the use of SCSR were chosen by staff at Newcastle Mines Rescue Station (NMRS). Each subject underwent a medical questionnaire and physical assessment to establish any contraindications to participate in the study. Detailed Joint Coal Board medical files were available and except for one subject a detailed assessment had been conducted in the previous twelve months as part of periodic health and fitness appraisal for mine rescue. History of the current exercise habits, normal work duties, health on the Day and physical examination were the factors considered most important in assessing suitability for the study. Each subject was aware of the hazards and potential adverse health effects of exercising in hot and humid conditions. Written informed consent was obtained from each subject.

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 four kilometres per hour. The treadmill tests were conducted 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 in "second means of egress" in many mines. On Day 3 the temperature and humidity were increased to 32°C and 100%, respectively. These environmental conditions were chosen as representative of those in an area adjacent to an underground fire.

Two observers were present throughout each test. Heart rate was recorded continuously throughout the tests using the heart rate monitor and recordings were downloaded onto a lap top computer using a transmitter-watch interface and Polar software. Average heart rate was taken from the time the exercise was commenced through to its termination at one hour on Day 1. The average heart rate was obtained from the Polar Software set to average the heart rate sampled at 15 second intervals. On Day 2 average heart rate was determined by the Polar Software and the value was taken during the period between the commencement of breathing oxygen via the SCSR and the cessation of the test when the bag collapsed.
Criteria for stopping the tests were heart rate in excess of 85% of predicted maximum (particularly on Day 3), signs or symptoms of heat related stress, oxygen supply was exhausted on Days 2 and 3 or at the discretion of the volunteers.

The heart rate on Day 1 was used to predict SCSR duration on Day 2. Predicted oxygen duration was calculated using the “University Of Wollongong” model. Each subject was supervised during the donning of the SCSR. The observer confirmed the initiation of the chlorate candle during the donning procedure. Each subject’s oxygen supply was considered exhausted when the two experienced observers were satisfied that the breathing bag had collapsed.

### 4.4 Results

Table 12 below shows the differences in average heart rate for each volunteer on each of the three Days, HR1, HR2 and HR3 respectively. On Day 1 (HR1) the SCSR was carried on the individual’s belt. On Day 2 (HR2) the SCSR was worn until oxygen was exhausted. On Day 3 (HR3) the SCSR was worn until the test was stopped, as discussed below.

Dynamic heart rate records of the subjects can be seen in Figs. 29 through 34.

The observed and predicted oxygen “run out” times for Day 2 are also given in Table 12. The predicted oxygen “run out” times were based upon the average heart rate on Day 1, using the University of Wollongong model.

### Table 12 Summary of Heat and Humidity Trials

<table>
<thead>
<tr>
<th>Subject ID</th>
<th>Age (yr)</th>
<th>Weight (kg)</th>
<th>Heart Rate on Day 1 (bpm)</th>
<th>Heart Rate on Day 2 (bpm)</th>
<th>Heart Rate on Day 3 (bpm)</th>
<th>Estimated HR3 (bpm)</th>
<th>Observed oxygen &quot;run out&quot; time on Day 2 (minutes)</th>
<th>Predicted oxygen &quot;run out&quot; time on Day 2 (minutes)</th>
<th>Predicted oxygen &quot;run out&quot; time on Day 3 (minutes)</th>
</tr>
</thead>
<tbody>
<tr>
<td>N1</td>
<td>36</td>
<td>72</td>
<td>153</td>
<td>134</td>
<td>N/A*</td>
<td>N/A</td>
<td>N/A</td>
<td>60.4</td>
<td>N/A</td>
</tr>
<tr>
<td>N2</td>
<td>41</td>
<td>83</td>
<td>133</td>
<td>130</td>
<td>134</td>
<td>143</td>
<td>48.0</td>
<td>59.6</td>
<td>56.7</td>
</tr>
<tr>
<td>N3</td>
<td>39</td>
<td>79</td>
<td>133</td>
<td>121</td>
<td>131</td>
<td>145</td>
<td>60.0</td>
<td>61.4</td>
<td>60.0</td>
</tr>
<tr>
<td>N4</td>
<td>40</td>
<td>75</td>
<td>132</td>
<td>137</td>
<td>137</td>
<td>145</td>
<td>61.0</td>
<td>61.5</td>
<td>61.5</td>
</tr>
<tr>
<td>N5</td>
<td>52</td>
<td>73</td>
<td>144</td>
<td>133</td>
<td>136</td>
<td>139</td>
<td>52.5</td>
<td>61.0</td>
<td>61.0</td>
</tr>
<tr>
<td>N6</td>
<td>39</td>
<td>97</td>
<td>133</td>
<td>121</td>
<td>125</td>
<td>145</td>
<td>45.0</td>
<td>52.8</td>
<td>51.8</td>
</tr>
</tbody>
</table>

* Note the subject N1 withdrew from the test on Day 2 prior to running out of oxygen and was not tested on Day 3.

In the interests of safety each subject was stopped at 85% of the predicted maximum heart rate on Day 3 before oxygen “run out” time was reached. As the duration of exercise was shortened the average heart rate on Day 3 was artificially low. Therefore an estimate was made of the heart rate when the oxygen supply is likely to have been exhausted. The estimated average heart rate on Day 3 was calculated from the heart rate when the subject commenced breathing oxygen and the predicted maximum heart rate.

\[
\text{Average Heart Rate} = \frac{\text{Predicted Maximum Heart Rate} + \text{Initial Heart Rate}}{2}
\] (15)
Fig. 29 Heart Rate versus Duration of Subject $N_1$

Fig. 30 Heart Rate versus Duration of Subject $N_2$
Fig. 31 Heart Rate versus Duration of Subject N₃

Fig. 32 Heart Rate versus Duration of Subject N₄
Fig. 33 Heart Rate versus Duration of Subject N₂

Fig. 34 Heart Rate versus Duration of Subject N₆
Using the University of Wollongong model the predicted average heart rate on Day 3 was used to predict the oxygen "run out" time of the SCSRs on Day 3. These predicted times are compared with the observed oxygen "run out" times of the SCSRs on Day 2, as illustrated in Table 12. As can be seen the SCSR oxygen "run out" time may have been reduced by approximately two minutes.

Table 13 Comparison of Oxygen Consumption for all Trials

<table>
<thead>
<tr>
<th>Physiological Parameter</th>
<th>NMRS Trial (n = 5)</th>
<th>Field Simulated Trial (n = 37)</th>
<th>UOW Trial (n = 6)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Absolute&lt;sup&gt;a&lt;/sup&gt;</td>
<td>Relative&lt;sup&gt;b&lt;/sup&gt;</td>
<td>Absolute</td>
</tr>
<tr>
<td>Average</td>
<td>2.0</td>
<td>24.6</td>
<td>1.7</td>
</tr>
<tr>
<td>Maximum</td>
<td>2.2</td>
<td>26.4</td>
<td>2.2</td>
</tr>
<tr>
<td>Minimum</td>
<td>1.8</td>
<td>22.9</td>
<td>1.3</td>
</tr>
</tbody>
</table>

<sup>a</sup> Absolute $\dot{V}O_2$ is the actual amount of oxygen consumed by the individual per minute;

<sup>b</sup> Relative $\dot{V}O_2$ is the amount of oxygen consumed by the individual per kg body weight per minute.

Table 13 compares the oxygen consumption on Day 2 for the volunteers in the NMRS treadmill trials, the underground field trials and the University of Wollongong treadmill trials. There appears to be a significant difference in oxygen consumption in each case. Days 1 and 2 of the NMRS trials were carried out in environmental conditions similar to the underground and University of Wollongong trials. The NMRS volunteers exercised at 4 km/hr on a treadmill, the individuals in the underground trials exercised at a rate of approximately 2 km/hr and the University of Wollongong trials at 5 km/hr. The NMRS and University cohorts also exercised continuously until the oxygen ran out, whereas the underground cohort stopped every 10 minutes for no more than 60 seconds and at natural "bottlenecks" such as waiting to climb over an overcast.

When comparing the oxygen consumption in the University of Wollongong treadmill trials, oxygen consumption was greater in the Newcastle study, which was unexpected as the treadmill speed was 1 km/hr less. The volunteers in the Wollongong University stage exercised in shorts, joggers, t-shirt or bare chested and did not have the SCSR secured onto the chest. Therefore there was a significant difference in the workload for the Wollongong volunteers.

It is estimated the load carried by underground volunteers and Newcastle volunteers would amount to approximately 15 kg, including miner's lamp, overalls, belt, safety hat, safety boots, SCSR (Day 2), and belt or harness. The individual therefore carried a load which would represent 19 to 11% of their body weight, with an average of 15%. Therefore there was a significant increase in workload and consequently increased physiological demand on the cardiovascular system. This would result in proportionately greater oxygen consumption in the underground and Newcastle trials than the University trial. Although bicycle ergometer tests were not performed on this group, they were above average fitness based upon detailed exercise histories. When
compared to the NMRS and field trials, as expected, the oxygen consumption was lower for the majority of the University group.

The influence of loss of oxygen through the pressure relief valve is thought to be appreciable when the breathing bag is accidentally squeezed, especially in confined spaces, stooping under low roof or climbing ladders. This may also partially explain the greater oxygen consumption in some of the individuals in the underground stage of the study.

The NMRS volunteers were compared with the underground cohort for other factors such as body weight, age, absolute \( \dot{V}O_2 \) and relative \( \dot{V}O_2 \) and an index of fitness based upon duration, frequency and intensity of exercise. There was no appreciable difference between the cohorts.

Three individuals had physical signs which were thought to be due to heat. These individuals had orthostatic hypotension at the termination of the exercise, with low blood pressure when standing. This was associated with a rapid heart rate. None had complained of symptoms of hyperthermia, apart from sweating and feeling hot. Dizziness and nausea were notably absent. All were coherent and responded appropriately to questions throughout the exercise.

4.5 Discussion

Wearing respirators has been shown to increase the physiological load on the individual both in cool and hot environments (Turner and Hodous, 1993). Other researchers (Kovac, 1992) demonstrated a 15% increase in average heart rate above basal while wearing SCSR. In this stage of the study the average heart rate on Day 1 was consistently higher than Day 2, as was the average heart rate in 60% of individuals on Day 1 of the field trials at the collieries. The reasons for this are not clear. This may be due to either, or a combination of, an “anxiety factor”, on Day 1 or an expression of a “learning effect” or familiarisation with the equipment on Day 2, particularly as none of the individuals regularly used a treadmill. All of the individuals had used a treadmill at the rescue station or at a gymnasium previously.

Heart rate often increases in anticipation of exercise, its mechanism through the limbic system of the brain (Durstine, 1993). Subject N3’s average heart rate was highest on Day 1 which would appear paradoxical. He appeared to tolerate heat fairly well and his result may be indicative of a better natural capacity to work in heat. In his case an “anxiety factor” may have been more operational on Day 1 than on Days 2 and 3.

The conditions on Day 3 were extreme 32°C and 100% humidity. None of the subjects were exercised until the SCSR \( \dot{O}_2 \) supply was exhausted on Day 3. The breathing bag was well inflated for all individuals when the exercise was terminated. If it is assumed that the relationship between heart rate and oxygen consumption remains valid in hot and humid conditions, then SCSR duration could be reduced as the heart rate increased with time (Table 12). This is unlikely to be true, as skin capillaries open up and skin blood flow is increased. Far less oxygen is extracted from the blood circulating through the skin as would be extracted from a comparable
volume of blood being supplied to exercising muscles. Therefore there is likely to be a negligible effect upon SCSR oxygen “run out” time.

Powers (1982) exercised five males in cool conditions (19-21°C) with a fan directed onto the subjects on Day 1 and on Day 2. The participants wore shorts and nylon shells to retard evaporation. Both rectal temperature and heart rate were higher on Day 2. They also measured oxygen uptake and suggested that oxygen uptake was only slightly affected by the shell treatment, resulting in a small but statistically insignificant ($p>0.05$) increase in $\dot{V}O_2$ when compared to the fan test. Because of the small number of subjects in their study the results maybe inconclusive.

At 85% of maximum heart rate three individuals had objective cardiovascular signs of heat related conditions, including high systolic blood pressure at the end of the test, rapid heart rate and postural hypotension. The signs persisted for some time after the test was terminated. As escape may occur in hot and humid conditions, it is recommended that those escaping recognise the potential for heat related illness. In order to prevent these conditions occurring it is recommended that escaping groups, proceed at a steady pace and stop at regular intervals to rest. These steps are more likely to conserve oxygen. It is further recommended those escaping discard unnecessary loads and clothing to reduce physiological load and assist heat losses by the evaporation of sweat. When water is available it may be used to cool the skin.

In the event of heat related illness it may not be appropriate for the first aid person to provide treatment. If the life of the person providing the first aid could be compromised, such as through running out of oxygen, then this may amount to no more than stopping the affected individual and sitting him in a safe place to be retrieved by a rescue party at a later stage. As indicated in Chapter 1 individuals may be provided with oxygen for up to five hours at rest. Therefore the survival of two individuals could depend upon what appears to be a harsh decision.

From a practical perspective, if a mine elects to use the University of Wollongong formula to predict SCSR duration in hot and humid mining conditions the predictions may underestimate oxygen “run out” times as higher heart rates will indicate oxygen consumption is greater than is likely to occur in reality. On the other hand, if the tests are conducted in main intakes in colder climatic conditions, such as winter, the University of Wollongong may overestimate SCSR duration.

4.6 Concluding Remarks

The UOW model demonstrated the duration of SCSRs is unlikely to be significantly reduced in extreme environmental conditions. The physiological evidence in the literature supports this finding. A significant proportion of the increase in heart rate in hot and humid environments is likely to reflect the body’s attempts to lose excessive heat. The possibility of developing heat related illness must be considered by those about to escape.
Mine Escape Strategies must include training to assist miners to:

- Prevent the development of heat related illness by controlling speed of travel, shedding unnecessary loads including clothing, using water to cool the skin and recognising the need to take regular rest breaks.

- Recognise the symptoms and signs of heat related illness.

- Provide first aid management for heat related illness if it occurs and does not endanger the life of the person providing the first aid.