Use of self-rescuers in hot and humid mines


RESEARCH REPORT 180
Use of self-rescuers in hot and humid mines

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The concept of self-rescue is premised on the assumption that underground mineworkers have the physical and mental capacities required for self-rescue and in-seam rescue. There is a recognised research ‘gap’ concerning the practical limitations, and ultimately personal endurance limits, associated with the extended wearing of mining industry respiratory protective devices particularly under high physiological stress conditions. This has important implications for emergency response strategies predicated on seeking to evacuate hot and humid mines. In response to these issues, a programme of research was defined, consisting of:

- a literature review
- an audit of climatic conditions
- laboratory investigations
- a programme of climatic chamber wearing trials.

The wearing trial component of the programme, which involved volunteers being subject to controlled heat stress, was reviewed by and received the approval of HSE’s Research Ethics Committee. This work has provided a wider base of fundamental knowledge on physiological response to the wearing of escape respiratory protective devices under hot and humid conditions, and contributes to available guidance on the selection and use of self-rescuers appropriate to prevailing deep mine environments in the UK.

This report and the work it describes were funded by the Health and Safety Executive (HSE). Its contents, including any opinions and/or conclusions expressed, are those of the authors alone and do not necessarily reflect HSE policy.
Acknowledgements

The authors would like to thank and acknowledge all those who contributed and took part in this project, including:

HSE’s Research Ethics Committee for reviewing the trial protocol.

MRSL brigadesmen who volunteered to take part in the climate chamber trials.  
MRSL managers for coordinating and making available test facilities.  
MRSL staff for the construction and testing of a hot air simulation unit.

Dr A.P. Booth and other Business Healthcare Limited staff for medical guidance and supervision throughout the work.

Finally, we would like to thank Mr J.A. Forster, HSE Project Officer and Mr G. Gilmour of the Health and Safety Executive, Bootle, for providing invaluable support and advice throughout the project.
Table of Contents

EXECUTIVE SUMMARY 1

INTRODUCTION 12
RESEARCH OBJECTIVES 13
DESCRIPTION OF KEY RESEARCH TASKS 13
INITIAL DISCUSSION ON HEAT STRESS ISSUES 15

SECTION 1: REVIEW OF UNDERGROUND CLIMATE CONDITIONS 22
Section 1 References 24

SECTION 2: DEVELOPMENT OF A RESPIRATORY PROTECTIVE DEVICE HOT INSPIRED AIR SIMULATION UNIT 26
PART A: REVIEW OF RPD IMPACTS AND HOT AIR SAFETY LIMITS 26
1. Physiological impact of wearing a personal respiratory protective device 26
2. Limits of tolerability for breathing hot air 28
PART B: DEVELOPMENT OF HOT INSPIRED AIR SIMULATORS 29
1. Simulation of the W95 FSR - Background data 29
2. Hot air simulation using air-liquid heat exchanger 30
3. Use of chemical reagents for a hot air simulation unit 31
4. Use of soda lime as a respiratory CO2 absorbent 32
5. MSA hot air training model self rescuer 33
6. Adaptation of the MSA hot air training model 34
7. Reactive plastic cartridges 35
8. SCSR training simulation 35
9. Options for a mining industry hot air training model 36
Section 2 References 37
Figures 2.1 - 2.17 40

SECTION 3: TRIAL DEVELOPMENT ISSUES 52
1. Trial hypothesis 52
2. Evacuation simulation, work rate and treadmill calibration 53
3. Ensuring safety of the subject 56
4. Physiological monitoring of core temperature and heart rate 57
5. Experimental protocol refinement 60
Section 3 References 62
Section 3 Annex 1: Trial protocol procedures 65
Figures 3.1 - 3.8 67
### SECTION 4: ANALYSIS OF TRIAL DATA

1. Scope and objectives of analysis 71
2. Overview of data obtained 71
3. Typical behaviour of physiological response indicators 72
4. Trial development 73
5. Statistical testing objectives 74
6. Core body temperature analytical model 75
7. Regression analysis of core body temperature data 76
8. Difference assessment - respiratory protective devices versus baseline 77
9. Analysis of treadmill speed and distance data 78
10. Analysis of core body temperature and SCSR run-out period versus chamber temperature 79
11. Summary of test subject medical information 80
12. Discussion of heart rate data and oxygen consumption models 81

Section 4 References 86
Section 4 Annex 1: Overview of statistical tests employed 89
Tables 4.1 - 4.5 93
Figures 4.1 - 4.23 99

### SECTION 5: DISCUSSION OF TRIAL RESULTS

1. Scope and development of trial objectives 112
2. Summary of trial key results 113
3. Discussion on individual heat stress response and guidelines 114

Section 5 References 119
Table 5.1 122
Figures 5.1 - 5.4 123

### SECTION 6: PHYSIOLOGIC DATA GRAPH PLOTS

125
EXECUTIVE SUMMARY

Background

During events following an underground fire and/or explosion, survival is critically dependent on the effectiveness of respiratory protective systems. Within the UK underground coal industry, the principal personal respiratory protective device is the filter self-rescuer (FSR), which provides a measure of protection against carbon monoxide poisoning. When a risk of oxygen deficiency has been identified, self-contained self-rescuers (SCSRs) should be used, possibly in conjunction with safe havens. SCSR designs are based on either compressed oxygen or chemical oxygen provision, however, all SCSR types used in UK coal mines have a chemical oxygen supply.

In order to escape following a fire, gas outburst or explosion, underground staff are trained to put on their self-rescuers and wear them until they have reached a place of safety or are instructed that it is safe to remove the device. The specific evacuation difficulties posed by deep and laterally extended coal mine workings include hot and humid environments, difficult travelling conditions, and the possible need for extended wearing durations to be endured before reaching safety. The general trend in mines is towards warmer working districts where effective temperatures above 30°C are not uncommon.

The requirements for effective arrangements for escape and rescue are identified inter alia in Regulations 10, 12 and 13 of the Escape and Rescue from Mines Regulations 1995 and the associated Approved Code of Practice and Guidance [Health and Safety Commission 1995]. ACOP section 75 specifically identifies

"that to be effective the rescue arrangements must address all the hazards identified in the risk assessment .... except where they are absent or present at minimal risk".

At the present time, mines regulations and guidance relating to acceptable limits for risk of heat stress are, at best, incomplete. Within the United Kingdom mines rescue service, a precautionary approach has been defined over a number of years for assessing hot and humid conditions and for what constitutes a safe wearing period for closed circuit breathing apparatus. A number of international incidents have been identified where otherwise healthy rescue personnel have collapsed from heat strain. Multiple fatalities were recorded in the Polish Niwka-Modrzejów coal mine incident on 24 February 1998, and the US Barrick Miekle mine on 17 October 2002. In each case, prevailing conditions involved high heat and humidity.

Whilst mineworkers generally have a high tolerance of arduous mine conditions, there are many contractors, visitors and possibly management staff who have somewhat lower levels of cardiovascular fitness and may lack heat acclimatisation. In the event of an emergency taking place towards the end of a shift, then it is likely that mineworkers would be in a partially dehydrated state. This situation will be compounded for those who have been undertaking tasks with a high work-rate. In this case, their core body temperature may be close to its maximum for the shift. The acclimatisation response to heat requires frequent exposure and is rapidly lost on leaving the hot area. In an emergency there is no opportunity to reduce physiological heat stress by resting prior to using the respiratory protective device. The requirements to undertake evacuation at a steady, paced rate may be compromised by fear and disorientation. Training can help increase this preparedness and ultimately moderate metabolic rate in an emergency situation.

Some mines have an environment consistently close to 100% air saturation. Any loss of ventilation acutely affects the body's ability to be cooled effectively. Whilst selection of rescue personnel can be undertaken to screen out illness and dehydration, a small but significant fraction of the mine workforce would at any time have increased proneness to experiencing heat strain associated with
illness. The filter self-rescuer apparatus, under high carbon monoxide concentrations, substantially increases the inhalation air temperature to the wearer, and most probably the breathing resistance, making breathing uncomfortable and adding to the thermal burden on the body. In an emergency evacuation, staged rests may help the body to thermoregulate and lose body heat. However, the motivation to escape may be such that resting is ignored. Traversing uneven or sloping mine floors, particularly drifts, will be associated with a significantly higher work-rate. Travelling up significant gradients in a return airway may present high physiological stress. The Health and Safety Commission’s Guidance document [2001] cites elevated risks situations to include:

- Single entry headings;
- Longwall faces with roadways over one kilometre long;
- Hot and humid roadways;
- Steep roadways.

Heat strain involves a complex interaction of mine environmental conditions (temperature, humidity, radiation, air velocity) metabolic heat production rate and clothing. Individual tolerance to heat can vary widely. The effective heat strain on the body will depend on these conditions. Individual response depends on age, fitness, acclimatisation, hydration, and general health. If heat cannot be lost to the environment, heat build up will occur within the body (heat storage). Mines rescue staff have maximum safe wearing times for SEFA breathing apparatus calculated from empirically derived tables. Body pre-heating associated with walking inbye has been shown to have a significant contributory effect in terms of increase in core temperature of rescue brigadesmen [Hanson and Booth 2000].

Underground clothing is likely to be standard, hot climate workwear (boots, shorts, T-shirts, helmet). However, visitors and management staff may be more likely to wear overalls. Significant clothing, such as a combination of overalls and underwear, can act as a barrier to heat dissipation and reduce the effective body surface available for evaporative cooling. This needs to be taken into account.

Experimental scenarios to simulate escape activities primarily involve walking with varying gradients and floor conditions. In practical circumstances it would be reasonable to assume that the individuals may have eye irritation from smoke and must also make their way out in low visibility conditions. Experimental circumstances cannot however cover the use of irritant smoke. In practice it would also be difficult to rule out the possibility of escaping workers offering assistance to their injured colleagues. Any intervention to partially support or assist injured colleagues could dramatically increase heat burden and individual heat stress.

The physiological wearing limits for breathing apparatus are based on a large body of experimental research, and observations of physiological response, including core body temperature and heart-rate. However, no such physiological limiting criteria are currently applied in the use of mine industry escape self-rescuers. Evacuation planning, and assumptions on distances that can be covered in emergency circumstances, are substantially predicated on manufacturers’ escape respiratory protective device test behaviour and durations against specified challenge atmospheres. In this regard, whilst UK standard BS EN 404: 1993 prescribes a detailed test methodology for filter self-rescuers, no information is given on the complex physiological interaction with the wearer in demanding conditions of heat and humidity. In part, this is a reflection of the complexity and heterogeneity of human thermal physiological response. This study has attempted to address these issues and seeks to advance the knowledge base on which coal mine evacuation risk assessments are made. The information is also intended to assist HSE in providing guidance and information on the selection and use of self-rescuers in underground mines.
Research Aims

HSE's responsibility to provide guidance and information on the selection and use of self-rescuers when asked invokes a number of potential questions:

- Do current escape arrangements, based essentially on the use of self-rescuers, adequately account for climatic conditions and travelling distances present in underground coal mines?
- Under what circumstances are manufacturers' claimed wearing durations for both FSR and SCSR self-rescuer types valid, particularly where the wearer is subjected to severe conditions of heat and humidity?
- Do unacclimatised underground personnel, such as contractors, technical representatives, managers and inspectors warrant separate consideration in regard to heat stress risks?
- Does an increasing workforce age profile, together with criteria such as body mass and cardiovascular fitness, also need to be accounted for?

In order to adequately address these issues in the context of this work, a number of experimental objectives were identified:

1. Determine whether acclimatisation and heat stress susceptibility play a significant role in self-rescuer wearing performance.
2. Account for workforce population variation of age and fitness.
3. Determine the relationship between heart-rate, core body temperature, work activity and environmental conditions.
4. Assess the impact of the additional thermal burden arising from an SCSR or FSR operating in a high CO atmosphere.
5. Establish whether a relationship can be defined between effective temperature in mines and a safe wearing time for self-rescuers.

In order to address fully the impacts of acclimatisation and the influence of age and fitness within the underground workforce would require test subjects drawn from the entire mining industry workforce. However, the requirements for a high level of medical assessment data and complete medical history led to the HSE Research Ethics Committee restricting test subjects to mines rescue brigadesmen employed by Mines Rescue Service Ltd. Notwithstanding this limitation, a significant programme of research was implemented to investigate physiological behaviour and safety limits whilst wearing mining escape respiratory protective devices.

Research Tasks

In order to provide an improved understanding of the interactions between the wearing of escape respiratory protective devices and the prevailing thermal environment, an integrated programme of research was proposed, comprising three sections as below. Essentially the research involved:-

- an examination of relevant physiological heat stress literature and underground climate conditions
- undertaking investigations towards developing an improved simulation of hot air breathing effects, and
- carrying out a programme of climatic chamber wearing trials using both filter self-rescuers and chemical self-contained self-rescuers (SCSRs) in conditions of high heat and humidity.
It is noted that the wearing trial component of the programme, which involved mines rescue volunteers being subject to controlled physiological stress, was reviewed by and subsequently received the approval of HSE’s Research Ethics Committee before any test was undertaken. The scope of the three principal research tasks was as follows:

**Task 1. Literature review and scoping review of industry practice and climate conditions**

Various emergency escape strategies were contrasted with reference being made to international practice and developments in self-escape. The general climatic conditions present in deep UK mines and representative seams were reviewed. This was a selective report of the range of conditions associated with hot and humid working environments present underground. The reader is referred to Section 1 for a review of underground climatic conditions.

**Task 2. Simulation of high temperature breathing characteristic of FSR when subject to high levels of carbon monoxide**

The research activities within this module primarily involved:

- Investigating hot air simulator configurations based on:
  - (a) heat release from soda-lime or alternative exothermic chemical agents (where heat release is a function of respiration rate/work rate), and
  - (b) intake air preheating based on an air heater-heat exchange unit design.
- Application of the hot air breathing unit(s) in the climatic chamber trials.
- Identifying possible industry options for hot air training.

It was determined that the safe limit for water-saturated hot inspired air is of the order of 50°C. Hot air simulation devices using both of the above approaches were developed and assessed. The development of a respiratory protective device hot inspired air simulation unit is described in Section 2.

**Task 3. Climatic chamber wearing trials of FSRs and SCSRs under high physiological stress conditions**

This was the largest single component of the research programme, involving a pool of 25 mines rescue volunteers, with supervision and medical guidance on experiment design and procedure provided by Business Healthcare Limited. A key issue was whether it was possible to maintain adequate thermoregulation during an underground evacuation in hot and humid conditions, whilst wearing a respiratory protective device for the escape.

A climate-controlled chamber at Selby Mines Rescue Station was utilised to develop a controlled environment of between 27°C and 37°C (100% humidity). A range of test temperatures with fully saturated atmospheres was used. Treadmills were used to develop an appropriate work rate. The hot air training apparatus resulting from Research Task 2 was used in the chamber trial programme. The climatic chamber wearing trials focussed on the deployment of a hot air training model filter self-rescuer, with a lesser number of comparative tests conducted using approved SCSR devices (MSA SSR30).

Risk assessment, experimental design and the prescribed limits for terminating the experiment were critical considerations. Physiological monitoring was employed throughout all trials, which involved continuous real-time monitoring and recording of subject heart rate and core body temperature. An experienced occupational physician supervised subjects throughout the trials. Section 3 onwards reviews the climatic chamber wearing trials and examination of associated issues.
**Trial Approach and Observations**

The effects of high inspired air temperature and breathing resistance associated with wearing both SCSRs and FSRs were observed against a range of climatic conditions. The investigation focused on determining the impacts on escape travel speed and distance and self-rescuer duration. The effects of limited visibility following an underground fire or explosion were not considered, but would be understood to greatly exacerbate disorientation, psychological stress and would substantially reduce travelling speed.

The experimental procedure involved subjects walking on a mechanical treadmill, at a self-determined pace, in specific climatic conditions whilst heart rate and core body temperature were observed. Three cases were evaluated:

- [A] no self-rescuer
- [B] wearing a hot air training FSR model, and
- [C] wearing a chemical oxygen SCSR.

The tests were conducted within a range of temperatures of 27°C to 37°C (air fully saturated) with the majority of readings taken at either 29°C or 35°C. Regression analysis techniques were applied to the results to identify any correlation between various climatic parameters and subject physiological response indicators.

The trial procedure involved two phases:

- A warm-up phase, followed by a short rest.
- A second phase where a self-rescuer was worn until the subject was withdrawn.

In the baseline test [A], the subject continued into the second phase without a self-rescuer. The withdrawal criteria were set as follows:

- End of protocol reached
- Exceedence of core body temperature limit (38.5°C)
- Exceedence of age-adjusted maximum heart rate
- SCSR run out, or
- Physician's assessment.

A general observation can be made for all subjects at the prevailing test conditions of heat and humidity. After a brief period of warm-up, all subjects exhibited a progressive increase in core body temperature whilst exercising. The characteristic of the core body temperature rise was influenced by a number of factors including work rate (energy expenditure during exercise), the individual's physiology, and the prevailing climatic stress. Other than a limited number of comparative tests undertaken with overalls, all subjects were lightly clothed (T-shirt and shorts).

It is illustrative to examine the typical physiological response of a subject, in this case undertaken at 34°C BET (air fully saturated). The graph overleaf indicates readings for core body temperature, heart rate and odometer activity from the treadmill. It can be observed that the subject at rest had a resting pulse rate of ~75 bpm and an initial core temperature of ~37°C.
The subject commenced exercise and was instructed to stop after a warm-up period of approximately 7 minutes. During the warm-up period, the subject's heart rate rose to stabilise at ~130 bpm. The core body temperature, after an initial period of compensation, rose progressively and stabilised at 37.5°C during the period of rest between the exercise phases. Heart-rate during the rest period showed a rapid recovery to ~110 bpm. There is evidence of slight cooling taking place during the rest period. On commencing the second phase of the test, heart rate increased rapidly to ~135 bpm and then increased slowly to reach a maximum of 170 bpm. Core body temperature increased steadily until the physician withdrew the subject at 38.6°C.

Neglecting heart rate monitor spikes attributed to electrode connection problems, all subjects were observed to be within safe heart rate limits. In generalising the trial observations, the primary risk factor for the test subjects was exceedence of safe core body temperature limits. It is noted that even where individuals attempted to pace themselves and reduce their energy expenditure, there was still evidence of heat gain. As an example, the figure overleaf graphs core body temperature characteristic and treadmill odometer pulse rate for a trial conducted at 29°C BET.
As a point of detail, during the second phase of the trial, the subject witnessed some discomfort from the hot air training model filter self-rescuer and compensated by progressively reducing his walking pace. Over a period of approximately 25 minutes, the subject, an experienced rescue brigadesman, reduced his walking pace by one third and substantially reduced the rate of core body heat gain. However it is noted that thermoregulation was still not achieved. This observation of progressive loss of thermoregulation during exercise held for all subjects. Related studies on the impacts of pre-warming of rescue brigadesmen by Hanson and Booth [2000] conducted by MRSL demonstrated comparable heat gain behaviour. In both of these studies the subjects were not acclimatised.

The question as to whether the escape respiratory protective devices used in mining contribute significantly to thermal burden, and hence rate of heat gain, is more difficult to answer. The method used to assess this was to statistically compare the body temperature rise characteristic observed in phase one (no self-rescuer) with that of phase two (FSR/SCSR self-rescuer worn). A variety of statistical tests were employed. The overall conclusion was that any heat gained from these devices via the thoracic cavity was secondary to that involved in exercising under the prevailing conditions of heat and humidity. However this conclusion has a significant caveat - the soda lime hot air training model used in the trials had a relatively short life and achieved modest peak temperatures, and would not be representative of a filter self-rescuer worn in a high CO concentration atmosphere for extended periods. There is anecdotal evidence from mine incidents that wearers have witnessed significant discomfort at CO concentrations of 1% and above. Investigation of the Moura No. 2 colliery explosion in Australia, 1994, confirmed the potential for intense heat to be generated by filter self-rescuers.

In regard to chemical oxygen SCSRs, heat gained from the device during use has a complex physiological response when combined with the effects of breathing pure oxygen under severe climatic conditions. Breathing pure oxygen is postulated to reduce heart rate but not to otherwise reduce significantly heat build up within the body. One important observation in the deployment of
SCSRs was that recorded run-out times were all below the nominal duration specified at 30 L/min flow rate. There was also an indication that run-out time was adversely affected by the severity of the climatic conditions. These observations were however based on a small sample set.

A review of the scientific literature was undertaken to identify tolerance limits for breathing hot inspired air. Work conducted on behalf of the Japanese mining industry experimentally determined inspired air temperature limits for a test group over a range of relative humidity and breathing rates. Essentially, tolerance is determined by the heat content of the inspired air (enthalpy). At low air humidity, dry bulb temperatures of 90°C can be tolerated. However, the maximum temperature that can be tolerated is reduced for humid air. A limiting wet bulb temperature of 53°C is observed for most subjects. The effects of dehydration on the ability of subjects to tolerate hot inspired air require further investigation.

**Summary of Trial Key Results**

The foregoing observations, taken together with the results from the various statistical analyses, can be summarised as follows:

- In a range of climatic conditions ranging from 27°C to 37°C (air fully saturated), all subjects were withdrawn inside one hour of entering the chamber. In some subjects, an increase in core body temperature of 2°C was observed after a total of 30 minutes of exercise.

- During the trials, exceedence of the core body temperature limit (38.5°C) was the predominant reason for withdrawal. In nearly all cases, the subjects’ core temperatures would have continued to rise above 38.6°C had they continued to exercise. This could have implications for emergency evacuation planning.

- None of the test subjects could be regarded as heat acclimatised, but all had levels of cardiovascular fitness meeting the statutory requirements for rescue brigadesman duties.

- Subjects self-paced themselves at between 2-4 km/h, but in all cases, core body temperature continued to rise during exercise. Only limited cooling took place during the short rest breaks. Even at the lower test chamber temperatures, restoration of normal core body temperature would probably require subjects to rest for several tens of minutes.

- There was no clear evidence that the test respiratory protective devices exacerbated thermoregulation and heat strain risk. However, the limits of tolerance for breathing hot inspired air and risk of premature removal are stressed.

- The average total distance covered during the test runs was 1448 m. This comprised the sum of the distances covered in the ‘warm-up’ and ‘escape’ phases. The maximum distance covered by any subject was 2350 m. The minimum distance covered was 590 m. The total distance covered was influenced strongly by chamber temperature.

- Based on two methods of regression analysis, the maximum distance projected for the upper and lower temperatures were as follows:

<table>
<thead>
<tr>
<th>Temperature</th>
<th>Regression Method 1</th>
<th>Regression Method 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>27°C BET</td>
<td>1945 m</td>
<td>2335 m</td>
</tr>
<tr>
<td>37°C BET</td>
<td>785 m</td>
<td>1015 m</td>
</tr>
</tbody>
</table>

It is noted that these distances apply to test subjects that had no pre-warming. Any significant pre-warming would reduce these distances.

- The mean rate of core body temperature rise observed was 0.07°C per minute within a range of 0.03 - 0.15°C per minute. (Limited scale tests in a hot US mine indicated an increase in core
temperature of 0.04°C per minute. The difference may be accounted for by the severity of climatic conditions and work rate.)

- No measurements could be made of typical metabolic rate whilst exercising on the mechanical treadmills. Estimates were obtained from scientific literature. The treadmill speed and effort incurred were considered appropriate to negotiating typical rough roadway surfaces underground.

- The observed run-out times for SCSRs varied from 10-25 minutes, with equivalent distances of between 560m and 1400m covered wearing the SCSR. Regression analysis indicates a reduction in SCSR run-out time of between 30-90 seconds for each 1 °C increase in BET. However this is based on a small data set.

- Temperature fluctuations and stratification of chamber temperature were observed. Whether thermal stratification increases individual thermal stress response is not clear.

- Only a limited subset of heart rate data was obtained, due to electrode connection problems. The mean heart rate recorded during the rescuer wearing phase was 156 bpm.

- It is reasonable to suggest that if a larger scale study of temperature sensitivity were conducted, comparable trends to breathing apparatus safe wearing times would be observed.

- Extrapolation of the findings to the general underground workforce is not straightforward. The test subject cohort utilised was not acclimatised. The regular underground workforce at UK deep mines would be acclimatised. However, the test subjects were considered representative of otherwise fit but unacclimatised mine staff and visitors.

- The mean speed of egress for the subject group was 3.3 km/h. This is also the most efficient walking speed when wearing heavy footwear. The analysis did not include assessment of the impacts of low visibility on speed of egress.

**Application of the Research Work**

One of the key issues of planning escape or rescue of casualties in long tunnels, without access to fresh air zones, is the ability to determine the margins of safety, under prevailing conditions, to extricate personnel without unacceptable risk. Critical parameters in this regard are the oxygen costs of the escape or rescue and the physiological strain resulting from hot, humid atmospheres, possibly compounded by low visibility. The emphasis of this study has been the qualification of thermal endurance limits. The limited tolerance of subjects to hot and humid conditions identified by this research may require reappraisal of escape and rescue assumptions used in mine and tunnel emergency planning.

Areas of potential focus include forced evacuation through return airways of coalfaces, or, seeking to evacuate blind headings ventilated by ducting. In order to minimise explosion risk in an emergency, electricity is isolated and underground transport systems are unavailable. In certain scenarios, such as fires in the intake side of production units, escape through return airways on foot may be the only option available. The energy intensity of modern coalfaces, taken together with water evaporation and coal/strata heat contributions, can substantially increase the return air effective temperature. Similarly, air returned along a single entry heading imposes an increasing level of climatic stress. The research findings suggest that the risks associated with these emergency scenarios may warrant reappraisal.

Development of guidelines that protect the whole mine workforce, whether they work regularly or infrequently underground, is not straightforward. Furthermore, the protection of persons who are most heat intolerant could possibly entail adopting conservative and restrictive heat stress limits. A few pointers are noted in this regard. Assessment of heat stroke in the South African gold mining industry by Stewart [1982] suggests that occupational incidence of heat stroke increased for ages >40. Kielblock et al [1982], commenting on the same industry, cite annual incidence rate of heat stroke
morbidity and mortality increasing rapidly for wet-bulb temperature $>$34°C. In terms of the relationship between BET and productivity, Pickering and Tuck [1997] state that adverse effects on work efficiency commence at a BET of 27°C, and productivity declines noticeably at BETs $>$30°C.

Predictive safety models, such as ISO 7933 [1989], are used to predict the safe group response (i.e. 38 °C maximum core body temperature) for 95-99% of the population. When actual workplaces in the mining industry have been evaluated, it has been shown that many workplaces significantly exceed the ISO modelled safety limits [Havenith 1997]. However, at these workplaces, few heat related problems were encountered. Havenith [1997] conjectures that underground workers are fitter than the general population and are also acclimatised, resulting in lower strain for the same climatic stress. However, the benefits of acclimatisation are greatly diminished if members of the workforce are subject to hypohydration (significant body fluid deficit). In this case, the response of unacclimated and heat-acclimated personnel who are hypohydrated is broadly similar. This reinforces the critical requirement for underground staff to have ready access to drinking water, and for drinks to be taken at regular intervals in hot and humid conditions. This unfortunately, is not an option in a prolonged escape.

**Further Work**

The research programme has highlighted a number of critical issues and requirements, which suggest further research may be appropriate:

1. The test observations were all associated with unacclimatised personnel. There is a specific need to reproduce the tests using physically fit, acclimatised mine personnel. The concerns of HSE's Research Ethics Committee have been noted. In order to respond to these concerns, an approach could utilise part-time brigadesmen who are normally employed at the mine. A medical examination could be arranged for the test date. The part-time brigadesmen could then be selected as being reasonably representative of the mine workforce.

2. The metabolic rate of subjects using the treadmills was not measured. It would be useful to confirm the typical metabolic rate using laboratory calorimetric methods. Metabolic rate has a fundamental impact on heat stress response and escape oxygen cost (SCSR run-out time).

3. The application of safe havens has been progressed at a number of UK underground mines. Safe havens may provide a suitable location to rest and recover within a staged evacuation procedure. There is a need to determine how safe haven microclimate influences cooling. This could impact on the design, location and use of safe havens.

4. There is a requirement for an SCSR oxygen consumption prediction model specifically for use in high heat and humidity. The observations of SCSR run-out time, based on a small data set, provide some limited evidence to suggest a relationship between run-out time and climatic stress. A tailored extension to the work programme could specifically address this issue.

5. Acclimation of personnel is influenced by hydration state. It would be valuable to determine if the ability to recover and rehydrate, by making drinking water available, possibly at safe havens, materially reduces heat stress risks. This issue is also of critical importance to mines rescue staff.

6. Current test standards for escape respiratory protective devices do not account for dehydration and wearer discomfort. There is a requirement to reappraise FSR/SCSR thermal behaviour to assess whether standards should be revised in order to provide a better estimation of wearing duration limits.

7. A further requirement is to determine under what climatic conditions mineworkers are able to walk for a nominal 2 hours whilst wearing a FSR and maintain thermoregulation.

8. There could be some benefit in contrasting safe wearing times for various types of breathing apparatus, in physiological response and risk terms, with safe endurance limits for escape.
respiratory protective devices. An objective could be to determine whether a generalised wearing
time model could be developed to help industry apply breathing apparatus and respiratory
protective devices in thermally stressful environments.

9. It is recommended that thermal physiological limits are formally incorporated in mine/tunnel risk
assessment and escape planning. This recommendation also applies to a wider range of
industries, which impose stressful conditions of heat and humidity during specific activities (e.g.
entry and maintenance activities within confined spaces).

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1. INTRODUCTION

The concept of self-rescue is premised on the assumption that underground mineworkers will have the physical and mental capacities required for self-rescue and in-seam rescue. There is a recognised research ‘gap’ concerning the practical limitations, and ultimately personal endurance limits, associated with the extended wearing of mining industry respiratory protective devices under high physiological stress conditions. This has implications for those who have responsibility for the design of emergency response strategies predicated on seeking to directly evacuate hot and humid mines. There are a number of related issues to be considered when preparing an emergency preparedness strategy:

- Is it possible to devise mine-wide escape strategies, which account for the limitations of respiratory protective devices?
- What are the impacts of seeking to evacuate the mine where there are long walking distances, adverse gradients and high heat and humidity conditions?
- Is it possible to provide effective and realistic training, accurately simulating the respirator’s heat release under high carbon monoxide conditions?
- How can the use of self-rescuers be integrated with safe havens?
- What additional support technologies are required to aid escape, and can they be put to effective use in an emergency situation?

Throughout the UK underground mining industry, the primary response to a major emergency is to evacuate the mine. In the case of fire or explosion, the filter self-rescuer (FSR) provides some protection against carbon monoxide poisoning. It is a requirement of mine owners and mine managers to determine the most appropriate means of evacuation support and training. There must be an appropriate response to the assessed risks at the mine and the atmosphere present after a fire or explosion. This includes the need to consider the selection of self-rescuers and the possible provision of safe havens. Managers may also wish to seek advice from the Health & Safety Executive (HSE). The Escape & Rescue from Mines Regulations 1995, Reg 10 ACOP 46, states that “Managers should seek the advice of a Mines Inspector if they are in any doubt as to the suitability of a type of self-rescuer.

In order to provide an improved understanding of the interactions between the wearing of escape respiratory protective devices and the prevailing thermal environment, an integrated programme of research was proposed. Essentially this involved:-

- a re-examination of relevant physiological heat stress literature
- consideration of the underground climate conditions encountered
- undertaking investigations towards developing an improved simulation of hot air breathing effects, and
• carrying out a programme of climatic chamber wearing trials using both filter self-rescuers and chemical self-contained self-rescuers (SCSRs) in conditions of high heat and humidity.

The wearing trial component of the programme, which involved volunteers being subject to controlled physiological stress, was reviewed by and subsequently received the approval of HSE’s Research Ethics Committee (ref. ETHCOM/EG/01/16, 27-11-2001). Any requirements for information on the submission to HSE’s Research Ethics Committee were to be addressed to Dr RG Rawbone, Medical Secretary of the Committee.

2. RESEARCH OBJECTIVES

The primary objectives of the work were:

• to improve knowledge and guidance on the selection and use of self-rescuers appropriate to prevailing deep mine environments in the UK.

• to help identify escape strategies which may be suitable for distant working, low visibility and high heat stress conditions.

Statutory Instruments, 1995, Number 2870, Health and Safety, The Escape and Rescue from Mines Regulations, 1995, Regulation 10, ‘Arrangements for Escape’, prescribes a duty on the owner of every mine to provide suitable self-rescuers for all persons going below ground, and where necessary, safe havens or facilities for the exchange and recharge of self-rescuers. The associated Approved Code of Practice and Guidance (ACOP) to The Escape and Rescue from Mines Regulations specifies that managers should seek the advice of a Mines Inspector if they are in any doubt as to the suitability of a type of self-rescuer (L 71, s 46). The ACOP (s 49 et seq) also specifies that the selection of self-rescuer, and the need to consider the provision of a safe haven, will need to take account of the results of the risk assessment and the atmosphere present after an incident. The ACOP places an additional duty on mine owners to ensure, where appropriate, that all persons routinely working below ground include the option of hot air experience in initial training and, by election, in five yearly refresher training.

The above legislative requirements and guidance place a significant duty on mine owners and mine managers to determine the most appropriate means of evacuation support and training. The central objective of the research programme was to systematically address these issues and provide additional information to complement guidance given in HSC Deep Mined Coal Industry Advisory Committee document ‘Guidance and Information on Escape and Rescue from Mines’, [2001].

3. DESCRIPTION OF KEY RESEARCH TASKS

The research comprised three integrated modules of work which collectively:-

• involved a re-examination of relevant physiological heat stress literature and industry conditions

• undertaking investigations towards developing an improved simulation of hot air breathing effects, and

• carrying out a programme of climatic chamber wearing trials using both filter self-rescuers and chemical SCSRs.

The activities within the respective research modules are summarised as follows:
RESEARCH MODULE 1: **Literature review and scoping review of industry practice and climate conditions**

This component of the work programme primarily involved reviews of literature in this field. Various emergency escape strategies were contrasted with reference being made to international practice and developments in self-escape. A second component of the literature review examined relevant aspects of heat stress and the use and testing of respiratory protective devices under hot and humid conditions. The general climatic conditions present in deep UK mines and representative seams were also reviewed. This was not a comprehensive survey, but rather, a selective report of the range of conditions associated with hot and humid working environments present underground.

RESEARCH MODULE 2: **Simulation of high temperature breathing characteristic of FSR when subject to high levels of carbon monoxide**

There is a legal duty to be able to provide training experience of the hot air breathing characteristic of a filter self-rescuer. It is clearly not permissible for subjects to experience the use of FSRs using an atmosphere containing high levels of carbon monoxide and alternative means of simulating the hot air characteristic must be found. The research activities within this module included:

- Reviewing the inhalation temperature behaviour of the FSR, with reference to manufacturers’ EN404:1993 test data (as available).
- Examining training requirements and associated safety and practicability issues.
- Investigating hot air simulator configurations based on:
  - Heat release from soda-lime or alternative exothermic chemical agents (where heat release is a function of respiration rate/work rate), and
  - Intake air preheating based on an air heater-heat exchange unit design.
- Application of the hot air breathing unit(s) in the climatic chamber trials.
- Identifying possible industry options for hot air training.

RESEARCH MODULE 3: **Climatic chamber wearing trials of FSRs and SCSRs under high physiological stress conditions**

This was the largest component of the research programme, involving a pool of 25 volunteers, with medical supervision and medical guidance on experiment design and procedure provided by Business Healthcare Limited. A key issue addressed was whether it was possible to maintain adequate thermoregulation during an underground evacuation in hot and humid conditions, whilst wearing an escape respiratory protective device. The filter self-rescuer apparatus, under high carbon monoxide concentrations, substantially increases the inhalation air temperature to the wearer, increasing the thermal burden on the body. However, thermoregulatory stress response is dependent on a number of individual characteristics including heat acclimatisation status. The form of clothing may also have a significant impact. Within the wearing trial programme, it was recognised that consideration should be given to the following:

- Ensuring subjects presented, as far as possible, a representative range of ages, body weights and cardio-vascular fitness levels.
- The need to represent the requirement of seeking egress from long headings.
- Incorporating consideration of escape involving adverse gradients in conditions of high heat and humidity, possibly involving staff without acclimatisation.
- That the additional heat burden from the respiratory protective device was accounted for in any wearing trials.
A climate-controlled chamber at Selby Mines Rescue Station was used to develop a controlled saturated environment of between 27°C and 37°C (100% humidity). This provided a range of test temperatures with fully saturated atmospheres. Treadmills were utilised to develop an appropriate work rate. The hot air training apparatus resulting from Research Module 2 was used in the chamber trial programme. The climatic chamber wearing trials focussed on the deployment of the MSA W95-FSR filter self-rescuers, with a lesser number of comparative tests conducted using approved SCSR devices (MSA SSR30).

Risk assessment, experimental design and the prescribed limits for terminating the experiment were critical considerations. Physiological monitoring was employed throughout all trials, which involved continuous real-time monitoring and recording of subject heart rate and core body temperature. Physiological withdrawal criteria were set at 38.5°C core temperature measured via aural measurement and a heart rate in excess of 180 beats per minute. An experienced occupational physician supervised subjects throughout the trials. As noted earlier, the experimental protocol received the approval of HSE’s Research Ethics Review Committee.

4. INITIAL DISCUSSION ON HEAT STRESS ISSUES

In order to help devise a representative physiological test regime, consideration was given to various aspects of underground working, heat stress measurement and disorders, and individual thermal stress response. An initial discussion on heat stress issues is given here, although it is noted that further comment is made at other points in the report. Since the bulk of the research programme is essentially concerned with investigation of thermoregulatory breakdown, it is also useful to provide a simple description of the model of thermoregulation in man, together with listing factors which impact on heat stress.

4.1 Workplace Issues

Whilst mineworkers generally have a high tolerance of arduous mine conditions, there are many contractors, visitors and possibly management staff who have somewhat lower levels of cardiovascular fitness and may lack heat acclimatisation. In the event of an emergency taking place towards the end of a shift, then it is likely that men would be in a partially dehydrated state. This situation will be compounded for men who have been undertaking tasks with a high work-rate. In this case, their core body temperature may be close to its maximum for the shift. The acclimatisation response to heat requires frequent exposure and is rapidly lost on leaving the hot area. In an emergency there is no opportunity to reduce physiological heat stress by resting prior to using the respiratory protective device. The requirements to undertake evacuation at a steady, paced rate may be compromised by fear and disorientation. Training can help increase this preparedness and ultimately moderate metabolic rate in an emergency situation.

Some mines have an environment consistently close to 100% air saturation. Any loss of ventilation acutely affects the body’s ability to be cooled effectively. Whilst selection of rescue personnel can be undertaken to screen out illness and dehydration, a small but significant fraction of the mine workforce would at any time have increased proneness to experiencing heat strain associated with illness. The filter self-rescuer apparatus, under high carbon monoxide concentrations, substantially increases the inhalation air temperature to the wearer, and most probably the breathing resistance, making breathing uncomfortable and adding to the thermal burden on the body. In an emergency evacuation, staged rests may help the body to thermoregulate and lose body heat. However, the motivation to escape may be such that resting is ignored. Travelling uneven or sloping mine floors, particularly drifts, will be associated with a significantly higher work-rate. Travelling up significant gradients in a return airway may present high physiological stress. The Health and Safety Commission’s Guidance document [2001] cites elevated risks situations to include:
- Single entry headings;
- Longwall faces with roadways over one kilometre long;
- Hot and humid roadways;
- Steep roadways.

Heat strain involves a complex interaction of mine environmental conditions (temperature, humidity, radiation, air velocity) metabolic heat production rate and clothing. Individual tolerance to heat can vary widely. The effective heat strain on the body will depend on these conditions. Individual response depends on age, fitness, acclimatisation, hydration, and general health. If heat cannot be lost to the environment, heat build up will occur within the body (heat storage). Mines rescue staff have maximum safe wearing times for SEFA breathing apparatus calculated from empirically derived tables. Body pre-heating associated with walking inbye has been shown to have a significant contributory effect in terms of increase in core temperature of rescue brigadesmen [Hanson and Booth 2000].

In terms of selection of subjects for climatic chamber endurance tests, the cohort should be reasonably representative of the workforce population, including less heat tolerant individuals. A hypothesis was advanced that cooling from the respiratory tract would be reversed (i.e. heat gain) or greatly reduced when the filter self-rescuer is operated in a high carbon monoxide concentration environment. The risk of heat exhaustion is linked to a number of individual characteristics. The body-mass index (BMI) calculated as BMI=weight/height² has a significant correlation with heat exhaustion risk. Accordingly, subjects with high BMI needed to be considered (BMI greater than 30). Similarly, it was also necessary to consider whether subjects representative of older workforce members should be included.

Underground clothing is likely to be standard, hot climate workwear (boots, shorts, T-shirts, helmet). However, visitors and management staff may be more likely to wear overalls. Significant clothing, such as a combination of overalls and underwear, can act as a barrier to heat dissipation and reduce the effective body surface available for evaporative cooling. This needs to be taken into account.

Experimental scenarios to simulate escape activities primarily involve walking with varying gradients and floor conditions. In practical circumstances it would be reasonable to assume that the individuals may have eye irritation from smoke and must also make their way out in low visibility conditions. Experimental circumstances cannot however cover the use of irritant smoke. In practice it would also be difficult to rule out the possibility of escaping workers offering assistance to their injured colleagues. Any intervention to partially support or assist injured colleagues could dramatically increase heat burden and individual heat stress.

4.2 Factors involved in human heat stress

There is a wide range of factors that have an impact on human heat stress response, but which can be summarised as follows [Schneider 1999, Zenz et al 1994]:

**External Factors:**
- Air temperature and humidity
- Temperature of solid surroundings (radiant energy)
- Temperature of the skin
- Air motion
- Type of clothing worn
- Time exposed
- Work factors (load, weight of equipment, pace)
Human Factors:
- Age, sex, race
- Size (mass, surface area)
- Degree of muscle activity
- Health status and individual fitness
- State of acclimatisation
- Psychological factors (incentives, rewards, discipline).

4.3 Heat Disorders and Health Effects

The human body has a limited capacity to adjust to extremes of temperature and humidity. The following summarises principal heat-related illnesses:

Heat stroke occurs when the body's system of temperature regulation fails and body temperature rises to critical levels due to uncompensated heat storage. This condition is associated with highly variable factors, and its occurrence is difficult to predict. Heat stroke is a medical emergency. The medical outcome of an episode of heat stroke depends on the victim's physical fitness and the timing and effectiveness of first aid treatment. The primary signs and symptoms of heat stroke are confusion, irrational behaviour, and loss of consciousness, convulsions, a lack of sweating, hot dry skin, and an abnormally high body temperature, e.g., a rectal temperature of 41°C.

Heat exhaustion - the symptoms of heat exhaustion include headache, nausea, vertigo, weakness, thirst, and giddiness, and have some similarity with the symptoms of heat stroke. The condition responds readily to prompt treatment. Fainting associated with heat exhaustion represents a significant hazard where the subject may be operating machinery or controlling an operation that should not be left unattended.

Heat cramps are associated with performing hard physical labour in a hot environment. The cramps are attributed to an electrolyte imbalance caused by sweating and lack of water replenishment. Since sweat is a hypotonic solution (±0.3% NaCl), excess salt can build up in the body if the water lost through sweating is not replaced. Thirst cannot be relied on as a guide to the need for water; water must be taken every 15 to 20 minutes in hot environments.

Heat collapse - in heat collapse, the brain does not receive enough oxygen due to blood pooling at the extremities. As a result, the exposed individual may lose consciousness. This reaction is similar to that of heat exhaustion and does not affect the body's heat balance. However, the onset of heat collapse is rapid and unpredictable. To prevent heat collapse, the worker should be progressively acclimatised to the hot environment.

Heat rashes are the most common problem in hot work environments. Prickly heat is manifested as red papules which usually appear in areas where clothing is restrictive. Prickly heat is associated with skin that is persistently wetted by unevaporated sweat. In most cases, heat rashes will disappear when the affected individual returns to a cool environment.

Heat fatigue - one factor that predisposes an individual to heat fatigue is lack of acclimatisation. The signs and symptoms of heat fatigue include impaired performance of skilled sensorimotor, mental, or vigilance-based tasks. Mitigation of heat fatigue requires removal or reduction of the heat stress.

The following host factors are reported to increase risk of heat stroke:

- Lack of acclimatisation
- Obesity
- Poor physical fitness
- Fatigue
- Sleep deprivation
- Febrile illness
- Dehydration
- Acute and convalescent infections
- Immunisation reactions
- Conditions effecting sweating
- Skin disease (heat rash, sunburn)
- Drugs (alcohol, antihypertensives, caffeine)
- Past history of heat injury
- Past history of residence in areas with greater atmospheric cooling power
- Chronic disease (diabetes, thyroid, cardiovascular)
- Neurological lesions (hypothalamus, brainstem, cervical chord)
- Post surgery
- Recent food intake
- Sustained muscle metabolism.

4.4 Thermoregulation

Although the thermoregulatory mechanisms in man have not been fully explained, there is convincing evidence concerning the role of the hypothalamus as the temperature-regulating centre, which mediates heat loss through increased blood flow to the skin and sweating. Minard [1973] proposed a model for the thermoregulatory system controlling body temperature under conditions of heat stress. Minard structured the model as an analogue of an electrical engineering closed loop control system employing negative feedback proportional control. Whilst an electrical feedback system has limits as an analogy, it does permit primary physiological responses to be modelled quantitatively to a first order.

Feedback in the model is negative since the error signal is the difference between the input, the set point of the thermostat (37.0°C for the hypothalamus and 34.0°C for the skin), and the output, core body or skin temperature. It is reasonable to use a proportional control model because the central drive and effector responses (blood flows and sweat rate) are proportional to the error signal. In the absence of a heat load, the central drive is zero, output and input being equal. The model predicts that when equilibrium is reached under a given heat load, core temperature and mean skin temperature (output of the system) will stabilise at a level above the set point by an amount proportional to the load. The deviation from the set point is called the ‘load error’, and the effectiveness of the controller in temperature regulation depends on its sensitivity to the error signal, or gain. The gain factor is high in individuals with high heat tolerance, and increases with acclimatisation.

4.5 Heat storage

Heat storage is a change in the body’s heat content. The rate of heat storage is the difference between heat production/gain and heat loss, and can be determined from simultaneous measurements of metabolism by indirect calorimetry and heat gain or loss by direct calorimetry. Since heat storage in the tissues changes their temperature, the amount of heat stored is the product of body mass, the body’s mean specific heat, and a suitable mean body temperature. The body’s mean specific heat depends on its composition, especially the proportion of fat, and is about 3.39 kJkg⁻¹°C⁻¹ for a typical body composition of 16% bone, 10% fat, and 74% lean soft tissue.

The human body maintains a basic minimum rate of heat production of about 75 Watts, and about 120 Watts when awake but sedentary. As bodily activity increases, the rate of oxidation of food, with its attendant release of energy, must increase. Metabolic enthalpies (heat energy liberated in the body per g combusted nutrient) in kJ.g⁻¹ per food type are; protein 17, fat 39 and carbohydrate 17.5 kJ.g⁻¹.
The level of heat production for light work is of the order of 190 Watts, with the extreme value exceeding 700 Watts for heavy work.

Borudulin et al [2001] have reviewed heat exposure metrics and modelled the respective contributions of breathing, convection, radiation and sweat evaporation. At a metabolic rate of 165 Wm\(^2\) and dry/wet bulb temperatures of 28°C/25°C, the contribution to cooling is typically as follows:

<table>
<thead>
<tr>
<th>Mode</th>
<th>Contribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Breathing</td>
<td>8%</td>
</tr>
<tr>
<td>Convection</td>
<td>16.5%</td>
</tr>
<tr>
<td>Radiation</td>
<td>5.5%</td>
</tr>
<tr>
<td>Sweating</td>
<td>70%</td>
</tr>
</tbody>
</table>

It is noted that a description of a first order linear model of heat storage, which takes place when thermoregulation has failed, is provided in the statistical analysis of trial results. This is based on a classical heat balance equation approach. It is shown that there is reasonable agreement between the model and the empirical core body temperature gradient data with elapsed physical activity time.

### 4.6 Effects of Clothing

Clothing an individual wears modifies thermal comfort and stability considerably. In hot environments or during heavy work, the body relies critically on heat loss through the evaporation of sweat. Clothes become a barrier to the evaporation of perspiration from the skin, and sweat evaporated from wet clothing is much less effective in removing heat from the body than moisture evaporated directly from the skin. The impact of garment sets used in the mining industry, represented as a ratio of surface area available for heat exchange by convection is cited as follows [McPherson 1992]:

<table>
<thead>
<tr>
<th>Garment Set</th>
<th>Ratio of Surface Area</th>
</tr>
</thead>
<tbody>
<tr>
<td>No clothes</td>
<td>1.0</td>
</tr>
<tr>
<td>Shorts</td>
<td>0.95</td>
</tr>
<tr>
<td>Shorts and T-shirt</td>
<td>0.90</td>
</tr>
<tr>
<td>Long overalls</td>
<td>0.78</td>
</tr>
</tbody>
</table>

It is unlikely (and inadvisable) that workers would attempt to remove clothing during an emergency whilst wearing a filter self-rescuer. The risk of dislodging the self-rescuer and disturbing the mouth or nose seal would be high.

With impermeable clothing, direct heat loss by sweat evaporation is not possible. Additionally, any weight carried adds to the metabolic rate of workers, increasing the amount of heat the body produces. The net effect is potentially severe heat stress. Heat transfer through clothing is a function of the thermal resistance of the clothing and the temperature and humidity differential between the inner and outer surfaces. Thermal resistance of clothing is expressed in terms of "clo" units. One clo is defined as the equivalent to normal indoor clothing and is the clothing insulation required to keep a resting subject indefinitely comfortable within a standard test environment. The biophysics of clothing has become increasingly significant in recent years, using an interdisciplinary approach (physiology, psychology, physics, clothing design, and textile science) to relate human work efficiency and comfort to a specific task in particular environments. Example standards relating to protective clothing and equipment include the US National Fire Protection Association (NFPA) Technical Committee on Fire Service Protective Clothing and Equipment, and the American Society for Testing and Materials (ASTM) F23 Committee on Protective Clothing. Hanson [1999], Havenith [1999] and Parsons [1999] provide further reviews of standards.

NIOSH studies of workers wearing chemical protective clothing and firefighters' ensembles have indicated that heat stress is a serious consideration [US Department of Labor, 2002]. Significant physiological stress was observed, even at low work intensities (30% of maximum work capacity involving level walking at 5.4 km/hr) in a thermally benign environment (23°C and 55% RH). With
the chemical protective ensemble, worker tolerance time was reduced by 56% as compared to light work clothing only. Elevated rectal temperatures (in excess of 39.0°C) were observed in three of the nine subjects. With the heavier firefighters' ensemble, tolerance time was reduced by 84% as compared to light work clothing only and heart rates averaged 25-50 beats per minute higher than with the lightweight work clothing. At higher work intensities (60% of maximum), tolerance time was decreased by as much as 96%.

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Respiratory Protection Information, Chapter 5 - Respirator Use Under Special Conditions
(http://www.osha-slc.gov/SLTC/respiratory_advisor/oshfiles/resp_5.html)

The progression towards deeper, more extended workings in mature mining industries can generally be associated with an increasing difficulty in maintaining tolerable working conditions. This is particularly the case where there is high productive capacity plant installed and reliance placed solely on conventional ventilation methods. This section of the report provides a general overview of climatic conditions underground, as reported by a number of historical UK surveys, and from selective data drawn from more recent surveys. There also exists a significant amount of related literature attributable to other national mining industries but this is not reported here.

Allen [1976] reported the results of a UK national survey of thermal conditions (effective temperature American, ETA) observed at longwall districts and headings at statutory measurement points. For 241 collieries, 710 headings were surveyed, where:

- 13.1% had a maximum ETA of 24-27°C, and
- 2.7% a maximum ETA of >27°C.

The respective figures for longwall districts were 10.2% and 3.7%.

A smaller survey of individual workplaces undertaken by Graves et al [1981] indicated:

- 14.9% of development headings had an ETA of 24-27°C with
- 4.6% having an ETA of >27°C.

Figures for longwalls were 25.6% and 5.3% respectively.

A slightly later study by Graveling and Nicholl [1983] concentrated on machine operator workplaces in headings and gate ends, where mean peak ETAs were observed to be 29.1°C and 29.4°C respectively, with a highest effective temperature of 32.3°C recorded.

The contraction observed within the UK deep mine coal industry has resulted in some of the remaining mines having higher temperatures than those reported above. A number of recent studies have examined approaches to controlling mine climate [e.g. Shead and Tuck 1997]. These studies provide indicative data for environmental conditions at specific sites. The Industry Working Group established to examine aspects of hot and humid conditions, as reported by a Leeming and Fifoot [2001], observed specific conditions as follows:
## Heat measurements for working places

Heat measurements for working places are also reported at meetings of the Environmental Advisory Committee convened by HM Inspectorate of Mines. The table below, reproduced from the minutes of the meeting of the 13th November 2001, lists those working places which exceeded 30°C within a period of 6 months:

<table>
<thead>
<tr>
<th>Underground Location</th>
<th>Dry Bulb Temperature, °C</th>
<th>Wet Bulb Temperature, °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Site A: Development</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inbye</td>
<td>36</td>
<td>28.5</td>
</tr>
<tr>
<td>Outbye</td>
<td>39</td>
<td>29</td>
</tr>
<tr>
<td>Site B: Longwall Face</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Return Gate, Outbye</td>
<td>38</td>
<td>34</td>
</tr>
<tr>
<td>Site C: Longwall Face</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mid Face</td>
<td>33</td>
<td>31</td>
</tr>
<tr>
<td>Site D: Longwall Face</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Return Gate, Outbye</td>
<td>33</td>
<td>27</td>
</tr>
<tr>
<td>Site E: Development</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Face</td>
<td>31</td>
<td>24</td>
</tr>
<tr>
<td>Outbye</td>
<td>33</td>
<td>28</td>
</tr>
<tr>
<td>Site F: Development</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Face</td>
<td>36</td>
<td>31</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Mine</th>
<th>Working Place</th>
<th>ET(A) °C</th>
<th>May 01</th>
<th>June 01</th>
<th>July 01</th>
<th>Aug 01</th>
<th>Sept 01</th>
<th>Oct 01</th>
</tr>
</thead>
<tbody>
<tr>
<td>Harworth</td>
<td>22’s T/Gate D</td>
<td>35.92</td>
<td>33.56</td>
<td>31.00</td>
<td>32.24</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td></td>
<td>22’s R/Gate D</td>
<td>30.67</td>
<td>30.81</td>
<td>31.00</td>
<td>-</td>
<td>31.31</td>
<td>32.02</td>
<td></td>
</tr>
<tr>
<td></td>
<td>19’s R/Gate D</td>
<td>-</td>
<td>30.87</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td></td>
<td>17’s Face F</td>
<td>-</td>
<td>-</td>
<td>30.48</td>
<td>-</td>
<td>-</td>
<td>30.25</td>
<td></td>
</tr>
<tr>
<td>Maltby</td>
<td>T16’s</td>
<td>31.20</td>
<td>32.10</td>
<td>31.20</td>
<td>31.50</td>
<td>32.70</td>
<td>31.90</td>
<td></td>
</tr>
<tr>
<td></td>
<td>T106’s</td>
<td>-</td>
<td>-</td>
<td>33.30</td>
<td>33.00</td>
<td>32.70</td>
<td>32.80</td>
<td></td>
</tr>
<tr>
<td>Stillingfleet</td>
<td>Moreby Return D</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>31.00</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td></td>
<td>308’s T/Gate D</td>
<td>-</td>
<td>-</td>
<td>30.00</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Thoresby</td>
<td>192’s F</td>
<td>30.30</td>
<td>30.80</td>
<td>31.60</td>
<td>30.00</td>
<td>31.80</td>
<td>31.10</td>
<td></td>
</tr>
<tr>
<td></td>
<td>190’s L/Gate D</td>
<td>30.00</td>
<td>30.30</td>
<td>30.90</td>
<td>31.20</td>
<td>31.90</td>
<td>32.00</td>
<td></td>
</tr>
<tr>
<td></td>
<td>190’s R/Gate D</td>
<td>-</td>
<td>31.20</td>
<td>31.70</td>
<td>31.00</td>
<td>31.40</td>
<td>31.80</td>
<td></td>
</tr>
<tr>
<td>Welbeck</td>
<td>310’s F</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>31.90</td>
<td></td>
</tr>
<tr>
<td></td>
<td>307’s F</td>
<td>32.30</td>
<td>30.40</td>
<td>30.40</td>
<td>30.40</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td></td>
<td>312’s R/Gate D</td>
<td>-</td>
<td>-</td>
<td>31.80</td>
<td>31.10</td>
<td>32.60</td>
<td>32.40</td>
<td></td>
</tr>
<tr>
<td></td>
<td>312’s L/Gate D</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>32.80</td>
<td>32.40</td>
<td>-</td>
<td></td>
</tr>
</tbody>
</table>
The impacts of high horsepower coalface production equipment and the water utilised for cooling purposes can be gauged from a coalface heat survey taken in mid-2002, as follows. Related climatic modelling is a subject of ongoing research [ECSC 2002].

<table>
<thead>
<tr>
<th>Heat Survey Location</th>
<th>Dry Bulb Temp, °C</th>
<th>Wet Bulb Temp, °C</th>
<th>Humidity %</th>
<th>ETA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main Gate, outbye pantechnicon</td>
<td>34</td>
<td>30</td>
<td>75</td>
<td>28.0</td>
</tr>
<tr>
<td>Face, 10m from main gate</td>
<td>35</td>
<td>31</td>
<td>75.5</td>
<td>29.3</td>
</tr>
<tr>
<td>Face, mid point</td>
<td>36</td>
<td>34</td>
<td>87</td>
<td>32.8</td>
</tr>
<tr>
<td>Face, 10m from tailgate</td>
<td>38</td>
<td>36</td>
<td>88</td>
<td>35.9</td>
</tr>
<tr>
<td>Tail Gate, 10m outbye of curtain</td>
<td>38</td>
<td>37</td>
<td>94</td>
<td>37.3</td>
</tr>
</tbody>
</table>

The Institute of Occupational Medicine, in a jointly sponsored study by RJB Mining (UK) Ltd, and HSE, undertook a survey of three hot and humid mines and one cooler mine, which included measurement of core body temperature (via the aural canal) and heart rate of miners at work [Hanson et al 2000]. This study, intended as a validation study for the Code of Practice proposed by IOM for work in hot and humid conditions in coal mines, indicated the following for the mines surveyed:

1. Environmental conditions at the three hot mines showed only small differences at comparable measurement locations.
2. The majority of effective temperatures measured at workplaces were within a range of 26°-32°C.
3. At a small number of workplaces, effective temperature reached 40°C.
4. Mean core body temperature increased by 0.04°C per °C increase in BET.
5. Core body temperature measurements exceeded 38°C for 13% of the measurements recorded, and exceeded 38.5°C in 7% of the measurements recorded.

In summary, all deep laterally extended mines receive heat contributions from a variety of natural and production process sources [e.g. Pickering and Tuck 1997]. Outwith employing refrigeration, heat control options broadly comprise increased ventilation and preventing unwanted heat transfer to intake air streams, possibly involving changes to equipment siting and duty [Leeming and Fifoot 2001]. On consideration of the climatic conditions currently observed underground, and the possible exacerbation of these conditions in a developing fire situation, the range of chamber test temperatures used at Selby is considered to be appropriate.

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Leeming JR, Fifoot TJ (2001)
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Heat: sources, evaluation, determination of heat stress, and heat stress treatment

Shead P, Tuck MA (1997)
Mine climate control, both present and future, for high production faces in strata temperatures exceeding 40°C. – A case study.
This section of the report examines the work undertaken to develop a hot air simulation unit for use in the climatic chamber trials. Options available for providing hot air training on a wider industry basis are also discussed. The section is sub-divided into two parts:

A discusses the physiological impacts of wearing personal respiratory protective devices and limits of tolerability for hot inspired air

B reviews the work undertaken to examine options for a hot inspired air simulation unit.

A: REVIEW OF RPD IMPACTS AND HOT AIR SAFETY LIMITS

The requirement for a hot air simulation unit was predicated on two requirements:

- **Training Device**
  The objective is to develop or identify devices appropriate to providing wearing experience of the hot inspired air effects associated with an operating FSR or SCSR in a high CO content atmosphere. In this case, the intention is to offer the mine workforce short-term experience of any respiratory tract discomfort resulting from breathing hot air.

- **Hot Air Burden During Trials**
  The inspired air from a filter self-rescuer operating in high ambient CO concentrations will become uncomfortable. It is speculated that the additional heat burden might have a statistically significant effect where the individual is escaping in severe climatic conditions, say basic effective temperatures greater than 35°C. Under normal circumstances, breathing heat loss from the thoracic cavity is substantially less than that from the evaporative heat loss from sweating. However, in extreme climatic conditions, possibly associated with hot and humid conditions underground where ventilation has been disrupted, then the ability to thermoregulate through the sweat mechanism could be seriously compromised. At this point, the additional heat burden from a hot filter self-rescuer would augment body heat storage and the progression to heat stress. For this reason it is argued that the heat load presented by the hot air simulation should be made as demanding as possible.

Contrasting these two requirements, a distinction is made between experiencing respiratory tract discomfort and the hot air burden contribution to thermoregulatory breakdown. As part of the assessment of risk arising from subjecting hot air device wearers to excessive inspired air temperature and heat content, preliminary studies were undertaken to establish safety limits for inhalation of hot air, together with a general review of physiological impacts.

1. **Physiological impacts of wearing a personal respiratory protective device**

There has been wide-ranging research on the physiological effects of the use of personal respiratory protection, including wearing properties and subjective assessments of discomfort. Hettinger et al [1997], in a programme of work for the European Commission, commented as follows on the need for training to ensure that respiratory protective devices are used correctly:
"The special importance of adequate training, which was often found to be insufficient in the workplace-related study, was particularly apparent with regard to faulty use and the many different manipulations performed by employees on the filtering devices. Training and regular (repeated) instruction ... must therefore be performed systematically. Only in this way can the filtering device protect the employee in the expected manner."

The need for effective induction training and follow up training has been widely accepted within the international mining industry for escape respiratory protective devices. Familiarity with the respiratory protective device is also likely to reduce the psychological strain reaction and result in a lower level of cardiovascular strain. However, there is virtually no evidence of training programmes containing simulation of the hot inspired air effects potentially associated with the wearing of these devices. A brief overview on wearer general physiological impacts is presented here.

The literature cites respiratory pressure difference, and its effect on pulmonary and cardiovascular parameters, as being an important limiting factor on performance whilst wearing filtering devices. [Steinhaus 1989, Fuerst 1983]. Dead space may also be an issue.

The increased resistance to inspiratory and expiratory flow that a respirator imposes can cause an increase in tidal volume, a decrease in breathing frequency, and a decrease in minute ventilation, with a concomitant decrease in alveolar ventilation [Deno et al 1981, Harber et al 1989, Hermansen et al 1972]. In certified respirators, these effects have been shown to be small and generally well tolerated in healthy individuals, and even in persons with impaired lung function [American Thoracic Society, 1996]. The increase in dead space associated with a respirator will tend to increase minute ventilation due to the rebreathing of expired air. This added stress, which although variable and dependent on the type of respirator and the individual, is usually not a limiting factor [Harber et al 1982, Harber et al 1991, Morgan 1983].

During submaximal exercise, the effects on work performance from wearing most respirators seem to be small. When submaximal work load was held constant, several studies showed that heart rate did not appear to be affected by a respirator [American Thoracic Society, 1996]. Other studies show, depending on the level of energy expenditure, a mean increase in working pulse rate of up to 11 beats per minute accompanied by a reduction in respiratory rate and an increase in tidal volume, with study inhalation pressure differences in the range of 2 - 24 mbar [Hettinger et al 1997].

Increased resistances and dead space can lead to decreased (by approximately 10%) maximal work performance [American Thoracic Society, 1996]. In industrial settings, Hettinger et al [1997] observed maximum inhalation pressure differences in devices in use of up to 40 mbar due to excessive respirator loading. In the UK, work by Bentley et al [1973] showed that 90% of a test population of 158 rescue brigadesmen did not experience discomfort if the pressure swing at the mouth could be kept below 17 cm H2O equivalent, and the mean inspiratory work rate did not exceed 1.37 Joules per litre (0.14 kg/l). Love et al [1976] extended this work to men over the age of 45, where it was concluded that the acceptable level of breathing resistance established for younger men could also be applied to older workers.

The attribution of heat stress due to respirator wear in physiologic studies is relatively limited, and does not generally cover devices which present a significant thermal load. In one study [Caretti 2000], five subjects completed treadmill walking trials in a warm environment (34°C dry bulb and 25°C wet bulb) with and without a respirator (a powered air-purifying respirator). Subjects wore one-piece cotton coveralls over shorts and a T-shirt for both test trials. In general, core temperatures (Tc) increased throughout heat exposure trials. However, no differences in average core temperatures, heart rates, mean skin temperature (Tsk), sweat rates, or heat storage rates were observed between the unmasked and masked tests under these conditions. The respirator thermal burden in these trials was however relatively small compared with that potentially arising from an escape respiratory protective device.
Whilst the physiological response to the wearing of SCSRs has been extensively studied using breathing machines at moderate work and temperature conditions, there is relatively limited reported research on the characteristics of SCSRs at high work rates and extreme temperatures. Takahashi et al [1997] have suggested that some SCSR designs experience a rapid increase in CO₂ when the metabolic rate of the user exceeds the absorbent capacity of the units. This can lead to ventilatory distress and early rejection of the SCSR in use for some individuals (acute hypercapnia response). Takahashi et al [2000] suggest that there is up to 20-1 range of sensitivity in individual ventilatory response to high inhaled CO₂ levels and that, accordingly, a recommendation be made for standards for SCSR CO₂ limits to be reduced to a 2% design standard, with a long-term objective of a 1% design standard.

2. Limits of Tolerability for Breathing Hot Air

The maximum tolerable temperature is a complex issue, with the heat energy content of the air being an important parameter. The total air energy, the air enthalpy, is the sum of both the heat energy of dry air and the heat content of vaporised moisture in the air. Psychrometric data in Figure 2.1 indicates that lines of constant air enthalpy follow almost exactly the line of constant wet bulb temperature. Therefore, wet bulb temperature provides a relatively accurate measurement of the heat (energy) content of air. The specific enthalpy for dry and saturated air, plotted in Figure 2.2, indicates that saturated air enthalpy increases rapidly above ~50°C.

The extent and depth of any thermal damage depends ultimately on the intensity and depth of tissue heating, the amount of energy transferred from the source and the ability of the local circulatory system to remove heat [Diller 1994, Moritz and Henriques 1947, Stoll 1967]. In submerged hot-water scald burns, for example, temperatures of 46°C can rapidly cause major damage due to intimate thermal contact. However, hot dry air, in spite of its low enthalpy will have some discomfort and may induce naso-pharyngeal spasm, leading to removal of a respiratory protective device. The issue of wearing discomfort of FSRs at very high CO ambient concentrations has, for obvious reasons, not been systematically researched.

Various researchers have investigated the effects of elevated inhalation temperature on the human body [Takahashi et al 1999]. One notable finding is that there is a close correlation between the inspired wet bulb temperature and tissue temperature in the respiratory tract. Takahashi et al [1999] have researched the relationship between thermal tolerance limits for breathable air against dry bulb, wet bulb temperature and ventilation rate. The maximum tolerable temperatures for air varying between ~20% RH and saturated air, together with the influence of ventilation rate on maximum tolerable wet bulb temperature are shown in Figure 2.3 and Figure 2.4. Takahashi et al [1999] suggest that, at least up to 90°C, dry bulb temperature has little effect on heat perception and that the maximum breathable temperature is not influenced to a practical extent by breathing rate.

This work also examined how much heat is gained by the respiratory tract from hot humid air at the limit of tolerance. Assuming an isobaric heat transfer process, and using measurements of inspired and exhaled air temperature, it has been possible to determine experimentally the heat gain. It has been shown that heat transfer from hot, saturated air at the limit of tolerability (up to ~9 kJ/min heat gain) would be a significant fraction of the work joules associated with steady walking (where work joules is a measure of the additional energy consumption over and above the basal or resting metabolic rate). It is conjectured that the additional heat burden from a respiratory protective device may reduce the net effectiveness of subjects’ efforts to deliberately restrict their walking pace to reduce thermal stress in extreme climatic conditions.

Based on communications with Health and Safety Laboratory, Sheffield and other specialists, and with reference to respiratory protective device testing standards for both personal protective
equipment and escape devices, there was agreement for a limit figure of 48-50°C, where the air is saturated or close to saturated. The maximum inspired air temperature within RPD test standards is anticipated to include a margin of safety. The temperature limit in some standards is also a function of wearing time. Example standards include US Code of Federal Regulations, Title 42, Part 84, 103(c), which permits a maximum allowable temperature for inspired air of 62°C at 15 minutes wearing time, to 46°C at 4 hours wearing time for escape only devices. UK standard BS EN404:1993 (s 5.16.3), for filter self-rescuer escape devices, identifies an inhalation air temperature limit of 90°C dry bulb and 50°C wet bulb during the minimum test duration.

The discussion on inspired air safety is continued in Part B, subsection 4, where the use of alkali based CO₂ absorbents in anaesthesia and air purification systems is reviewed.

B: DEVELOPMENT OF HOT INSPIRED AIR SIMULATORS

This section has been structured as follows:

1. Background data pertaining to W95 FSR thermal behaviour.
2. Hot air simulator using air-liquid heat exchangers.
3. Hot air simulation using chemical reagents - choice of reagent.
4. Experience of using soda lime as a respiratory carbon dioxide absorbent.
5. Description of MSA hot air training model.
6. Modification of MSA hot air training model - refillable canister.
7. Reactive plastic cartridge (RPC) CO₂ absorbent technology.
8. SCSR hot air training simulation options.
9. General comment on options for a mining industry hot air training model.

1. Simulation of the W95 FSR - Background Data

In gauging the design of a hot air filter self rescuer simulation unit, it was considered necessary to model, as far as practicable, the breathing characteristics and heat burden imposed by the W95 FSR. Specifications for the MSA-Auer W95 are summarised as follows:

- Weight (with container): 0.9 kg
- Weight (without container): 0.52 kg
- Dimensions: 14cm H, 10.2 cm W, 8.5cm H
- Duration: > 240 min
- (40 l/min, 0.25 %vol CO₂, 27g/m³ absolute humidity (≈28°C fully saturated)
- CO penetration max. < 200 ppm)

- Breathing resistance: @ 125 l/min
  - Inhalation (start): <4.5 mbar
  - Inhalation (end): <5.0 mbar
  - Exhalation: <2.3 mbar
Inhalation temperature:  <80°C  
(conditions as per duration test but with 1.5 %vol CO)

A cross sectional diagram showing the detail of the W95 is given in Figure 2.5. Inhalation temperature data was also checked regarding the findings reported by British Coal Corporation in the ECSC final research report concerning the underlying development work of the monolithic catalyst used within the filter self-rescuer [Orr, 1993]. The tests conducted by British Coal included measurement of the maximum inspired air temperature at various challenge concentrations of carbon monoxide. The results are reproduced below:

<table>
<thead>
<tr>
<th>CO challenge concentration</th>
<th>Maximum inspired air temperature, °C</th>
<th>Maximum inspired wet bulb temperature, °C</th>
<th>Relative humidity of inspired air, % measured</th>
<th>(Relative humidity of inspired air, % calculated)</th>
</tr>
</thead>
<tbody>
<tr>
<td>500ppm</td>
<td>33.1</td>
<td>26.0</td>
<td>58</td>
<td>(55.2)</td>
</tr>
<tr>
<td>1000ppm</td>
<td>34.0</td>
<td>26.0</td>
<td>55</td>
<td>(51.1)</td>
</tr>
<tr>
<td>0.25%</td>
<td>38.0</td>
<td>27.5</td>
<td>45</td>
<td>(42.7)</td>
</tr>
<tr>
<td>0.75%</td>
<td>49.8</td>
<td>35.0</td>
<td>38</td>
<td>(36.2)</td>
</tr>
<tr>
<td>1.5%</td>
<td>60.9</td>
<td>39.0</td>
<td>30</td>
<td>(25.1)</td>
</tr>
</tbody>
</table>

Source: Orr, 1993

The upper limit of 1.5% was chosen since experience in the analysis of mine atmospheres indicates that at this concentration of CO, the level of oxygen present would be below that required to support life. The maximum inspired air temperature of 61°C is contrasted with 85-90°C expected from the older 290 design of FSR under similar test conditions. These tests were nominally carried out at 30 l/min minute volume breathing rate. At higher breathing rates, the maximum inspired air temperature would increase, particularly at high challenge CO concentrations.

For comparison, brief information is given on the SSR30/100 chemical oxygen self rescuer unit, with the breathing circuit shown diagrammatically in Figure 2.6.

Weight (with container): ~2kg
Dimensions: 18cm H, 18cm W, 10cm D
Breathing resistance: 3 - 7 mbar (inhalation and exhalation)
Oxygen content: 21 %vol.

2. **Hot air simulation using air-liquid heat exchanger**

Whilst a chemical absorbent can provide a small, compact air-preheating device, there are inherent disadvantages with this approach. These include:

- Limited heating duration associated with a small volume of absorbent.
- Limited control over the inspired air temperature.
- Relatively high exhalation breathing resistance.
An alternative approach to hot air simulation systems was to employ an air-liquid heat exchanger. This approach is advocated where a controlled range of inspired air temperatures and humidity is required, particularly in a laboratory setting. However, an air-liquid heat exchanger preheating scheme is a static system, and mobility is restricted to that provided by the umbilical air breathing hose.

In order to investigate the range of inspired air temperatures available, an appropriate high-efficiency thin-walled stainless-steel heat exchanger was obtained (Figure 2.7). This incorporated a controlled source of hot water (working fluid), a closed circuit reservoir, thermostatically heated with delivery to the heat exchanger regulated by a simple variable pump and gate valve arrangement. The flow circuit is shown in Figure 2.8.

As an essential safety feature, all development work was undertaken with a breathing machine, as shown in Figure 2.9. This permitted a wide range of circulating hot water temperatures, pump pressures and flow rates to be examined without concern of inspired air temperature exceedence. This approach also obviated the need for a water trap to be installed in the breathing circuit (in case of catastrophic failure of the heat exchanger).

At typical breathing rates, a significant heat loss was observed through the umbilical air hose. The initial response to this was to incorporate thermal insulation around the air hose. With this experimental arrangement in place, inhalation temperatures in excess of 50°C could be obtained. As a further development, it would be beneficial to sense the inspired air temperature close to the mouthpiece and incorporate this within a closed loop controlled configuration. By this means, it would be possible to compensate for wide variations in breathing rate and heat loss through the umbilical air hose.

3. Use of chemical reagents for a hot air simulation unit

The general principle of a chemical hot air unit is to exploit the exothermic heat of neutralisation associated with absorption of carbon dioxide in the exhaled air stream. The reagent, if tightly packed in granular form, acts as a recuperative heat exchanger, heating the inhaled air stream to temperatures of 50°C or more.

The choice of a chemical reagent within a hot air training unit was examined. Essentially, the absorption of carbon dioxide involves the neutralisation of an intermediary product, carbonic acid, with an appropriate alkali base. The absorbent chemicals available include:

- Sodium hydroxide and potassium hydroxide.
- Superoxides of potassium and sodium.
- Lithium hydroxide.
- Barium lime.
- Soda lime.

Consideration of material toxicity and corrosivity characteristics, indicated that soda lime and possibly barium lime were most suitable for use in a unit that has close proximity to the oral and respiratory tract. The associated absorption reactions for both reagents are as follows:

**CO₂ absorption involving soda lime:**

\[ \text{H}_2\text{O} + \text{CO}_2 \leftrightarrow \text{H}_2\text{CO}_3 \leftrightarrow \text{H}^+ + \text{HCO}_3^- \]
\[ \text{NaOH} + \text{H}_2\text{CO}_3 \leftrightarrow \text{NaHCO}_3 + \text{H}_2\text{O} \]
\[ 2\text{NaHCO}_3 + \text{Ca(OH)}_2 \leftrightarrow 2\text{NaOH} + \text{CaCO}_3 + \text{H}_2\text{O} \]
The primary constituents of soda lime include calcium hydroxide - Ca(OH)$_2$ (about 70-80%), water - H$_2$O (about 16 to 20%), sodium hydroxide - NaOH (about 1-2%), and potassium hydroxide - KOH (about >0-1%). Water is an important part of the reaction which takes place to bind the CO$_2$. The general description of the reaction is as follows. Firstly, the gaseous CO$_2$ reacts with water to form carbonic acid - H$_2$CO$_3$. Then, the NaOH reacts with the carbonic acid to produce Na$_2$CO$_3$ and H$_2$O. The Na$_2$CO$_3$ reacts with the Ca(OH)$_2$ which has been dissociated into calcium and hydroxide ions (Ca$^{++}$ and OH$^-$) to produce CaCO$_3$ (calcium carbonate). The CO$_2$ is now in a relatively stable state. There is a nett production of three H$_2$O molecules for every molecule of CO$_2$ absorbed together with exothermic heat. The complete reaction is still not fully understood.

**CO$_2$ absorption involving baralyme:**

\[
\begin{align*}
\text{Ba(OH)$_2$ and 8H$_2$O + CO$_2$} & \quad \rightarrow \quad \text{BaCO$_3$ + 9H$_2$O + heat} \\
9\text{H$_2$O + 9CO$_2$} & \quad \rightarrow \quad 9\text{H$_2$CO$_3$} \\
9\text{H$_2$CO$_3$ + 9Ca(OH)$_2$} & \quad \rightarrow \quad 9\text{CaCO$_3$ + 18H$_2$O + heat}
\end{align*}
\]

Barium hydroxide and water combine with carbon dioxide to form barium carbonate, water, and heat. Water and carbon dioxide form carbonic acid. Carbonic acid and calcium hydroxide form calcium carbonate, water, and heat.

Typically during respiration, 0.82 litre of CO$_2$ is exhaled per litre of oxygen inhaled. The reagent chemistry indicates that 0.168 kg soda lime can absorb one mole of carbon dioxide (22.4 l @ STP). However, because of the channelling of expired gases through the canister, only 10 to 20 litres of CO$_2$ are absorbed in practice per 100 grams of reagent. The efficiency of CO$_2$ absorption is inversely proportional to the hardness of the soda lime. Hence the addition of silicates to prevent powdering is a compromise. Granule size and morphology are also important. Small size increases absorbent area but increases resistance to gas flow. To increase effective surface area for absorption, the granules are made porous and irregular in shape. The sieve sizes of 'Sofnolime', a commercial soda lime absorbent product made by Molecular Products Limited, Thaxted, UK are shown in Figure 2.10.

In terms of heat of neutralisation in the canister, there is no direct correlation between heat production and remaining absorbent capacity. The exothermic absorption of one mole (40g) of CO$_2$ generates one mole of H$_2$O and 57kJ of heat energy [Wissing and Kuhn, 1998].

### 4. Use of soda lime as a respiratory CO$_2$ absorbent

There is a significant application base for alkali based CO$_2$ absorbents, including:

- Low flow anaesthesia.
- Closed circuit breathing apparatus (mining and diving).
- Submersible vehicle air purification.

Of particular relevance is the experience of using soda lime in clinical settings, mainly for anaesthesia, but also for field treatment of hypothermia. This has provided a wide range of references on absorbent behaviour and breathing circuit humidification requirements and any associated respiratory hazards. A brief review is provided here.

Dosed or almost dosed anaesthesia systems have been in use since c1850. At that time, the anaesthetic agent was chloroform, administered via a dosed system, with potassium hydroxide utilised as a carbon dioxide scavenger. The first soda lime carbon dioxide absorbent canister was introduced to anaesthesia in 1917. The introduction of low solubility anaesthetic agents has increased the use of low flow anaesthesia, and there is a significant body of knowledge on the application of soda lime and baralyme as carbon dioxide absorbents [Baum et al 1993, Freys 1999, Gootjes and Lagerweij 1981,
In order to prevent dehydration damage to the respiratory tract and to maintain the function of the tracheobronchial epithelium, a water content of at least 15-20 mg H₂O/litre inspired air is advised in long-term anaesthesia [Ingelstedt 1956, Kleeman 1994]. The application of a heated, humidified air as a primary or adjunct treatment for hypothermia is well established. For field treatment of casualties, a variety of devices have been developed which exploit the heat of neutralisation from carbon dioxide absorption [Collis et al 1977, Hayward and Steinmen 1975, Lloyd 1990, Lloyd 1991].

The core organs, which constitute approximately 8% of the total body weight, contribute 56% of the heat production in basal metabolism at normothermia. Rewarming methods thus concentrate on delivering heat to the body core organs, with air rewarming being a relatively safe, effective method. Complete humidification of the inspired airstream is however necessary for maximal heat delivery [Goldberg et al 1992, Linning et al 1986]. A rewarming rate of 1 to 2.5 °C per hour is observed, depending on the delivery technique, with an endotracheal tube being more rapid than a mask. In order to prevent damage to the pharynx, the maximum temperature of the inspired air is maintained at between 42°C to 45°C.

Within the above-cited references, it is clear that soda lime absorbents can, with appropriate design controls, be used to directly heat the inspired air stream. A soda lime absorbent canister was used in the climate chamber trials to simulate the hot air effects from an FSR operating in a high CO challenge atmosphere.

5. MSA hot air training model self rescuer

Approximately a decade ago, MSA manufactured a hot air training model self-rescuer. This device is no longer available and the manufacturer has indicated that it does not anticipate future involvement in the manufacture or supply of hot air training self rescuers. The design was examined for consideration as the basis of a unit for the climate chamber trials.

The MSA device is well engineered, employing a purpose-designed reusable mouthpiece assembly into which the reagent canister is bayonet-fitted prior to hot air training being conducted. The reagent canister was intended to be a disposable unit, and was supplied pre-packed with reagents, ready to use in a hermetically sealed foil bag. The various components are shown in Figure 2.11.

The MSA canisters contained approximately 120g of 1.0 - 2.5 mm particle size soda lime (Sofnolime or equivalent) together with 50g of a solid absorbent desiccant. The reagent canister design has a fine woven mesh screen inserted between the reagent layers, and a plug of HEPA material adjacent to the mouthpiece in order to prevent dust arising from mechanical attrition of the reagent being inhaled.

The units were physically modelled on the 275 type rescuer and had a nett weight of 525g (cf 625g for the actual 275 type rescuer). A cross-sectional diagram of the assembled hot air training model is given in Figure 2.12. It is noted that the exhalation valve is sealed and is non-operational. In order to prevent the possibility of interchange with operational type valves, a different thread is used for attachment to the plastic mouthpiece.

Without access to the original design data, the specifics of thermal behaviour, breathing resistance and reagent choice can only be speculated. The solid desiccant absorbent is not considered likely to have a significant operational role (i.e. airstream dehumidification), but rather, has a role in inhibiting corrosion of the pressed steel canister over the shelf-life of the unit. General classes of solid adsorbent dessicant include; silica gels, zeolites, synthetic zeolites (molecular sieves), activated aluminas, carbons and synthetic polymers [ASHRAE 2001]. Sorption isotherms for various desiccants are given in Figure 2.13 for reference [ASHRAE 2001].
The National Coal Board specified training sessions with the MSA hot air rescuer incorporated optional exercise, but were limited to a total wearing time of 15 minutes. The units could also be fitted with temperature sensitive indicator tape (spot temperatures >40, 43, 46, 49, 54, 60, 65, 71, 77 and 82 C) to record the peak temperature of the canister in use.

6. Adaptation of the MSA hot air training model

A limited number of mouthpieces and sealed reagent canisters were obtained from within MRSL. The reagent canisters all had a use expiry date of circa 1991. A number of sealed units were opened which confirmed that whilst many of the canisters were probably still serviceable, around 15 - 20% showed evidence of significant internal corrosion and were not usable. Given that it was essential to provide consistent performance in the hot air training models used within the chamber trials, it was considered necessary to adapt the MSA design for use.

The changes to the MSA design were relatively minor. Firstly, the desiccant was dispensed with and the entire canister filled with soda lime. This was to extend its operating life. To provide a lower breathing resistance, a larger sieve size of Sofnolime (2.5 –5.0mm) was used. Again, to prevent particulate carry over into the lungs, the air filtration medium was retained in each canister. Significant corrosion of the pressed steel canister took place, and hence filling was undertaken shortly before each trial. The extent of the corrosion can be gauged from Figure 2.11, with a new canister shown inset.

Tests of inspired air temperature were conducted of the modified design under the following circumstances:

1. Treadmill walking at 37 °C, 100% humidity, 3 km/hr average speed.
2. Treadmill walking at 28 °C , 100% humidity, 3.5 km/hr average speed.
3. Treadmill walking at 20 °C, 50% humidity, 4 km/hr average speed.

The first of these tests was to establish the maximum possible temperature obtainable from the device at very high ambient temperatures with saturated air. In this case, maximum inspired air temperatures were ~50°C. The temperatures were measured by an invasive temperature probe, inserted into the centre of the airstream within the mouthpiece.

Tests 2 and 3 above were conducted to establish what heat burden could be asserted at lower environmental temperatures. Results showing the temperature rise characteristic are given in Figure 2.14. Under the specified conditions, peak temperatures of 46 °C were recorded. As an observation, the soda lime hot air training model used in the trials achieved a relatively low peak temperature, which could only be sustained for a relatively short time, circa 10 minutes. This device may not be representative of a filter self-rescuer worn in a high CO concentration atmosphere for extended periods. The duration of the hot air effect is dependent on the mass of the reagent. With a larger canister design, peak temperatures could be maintained for a longer period. Against this, the additional size and weight could impose significant discomfort on the wearer.

Excluding experimental test wearings, data was collected for 18 test runs involving hot air, filter self rescuer units. The subjects were debriefed to ascertain their views on the tolerability of wearing the hot air units. All subjects indicated that the units produced air, which was hot but not unbearable. For some individuals, the principal difficulty was the high breathing resistance associated with the device after about 10 to 15 minutes of wearing. On investigation, it was concluded that the additional breathing resistance was almost entirely arising from saliva building up in the air filter material adjacent to the mouthpiece. In spite of the higher breathing resistance observed for the device after a
period use, it was considered essential to preserve the air filtration as a safety feature, and no changes were made in this regard.

7. **Reactive plastic cartridges**

One new technology considered to have possible application in a hot air training unit is the "reactive plastic cartridge (RPC)", manufactured by Micropore Inc., USA.

These cartridges eliminate the channelling and performance variability inherent in granular systems, by binding the CO₂ absorbent within a microporous sheet material with factory-moulded channels. The sheet is then spiral wound to form cylinders of arbitrary length and diameter. This approach offers a drop-in cartridge replacement capability with precise control over breathing resistance, absorbent utilisation and hence minimum duration. Typically, an RPC technology has a mean duration repeatability of ±5% within two standard deviations. Granular system variability in duration is typically no better than ±30%.

RPC based CO₂ scrubbers have the lightest weight and smallest size for a given scrubber duration. Absorbent reagent carry over into the exhaust airstream is also reduced. Physical details are given in Figure 2.15. The graph shows the amount of CO₂ in a closed circuit breathing loop after being passed through a conventional granular canister and an equivalent RPC canister (the shaded areas represent three standard deviations around the mean performance).

One engineering issue in the use of RPC technology is in ensuring an even flow distribution across the face of the cartridge. This can be accomplished by installation of a diffusion screen or air filter. In a practical hot air training unit, the air filter material inserted prior to the mouthpiece would achieve this function.

Further research could include modelling and optimising the recuperative heat exchange behaviour and breathing resistance of the cartridge. The ability to manufacture cartridges of arbitrary aspect ratio would be of assistance in any empirical refinement process.

8. **SCSR training simulation**

The inherently high cost of self contained, self rescuer escape apparatus, particularly long duration models, discourages their use in training programmes. Some mining industries, such as the remaining French coal mines, use the SCSRs withdrawn at the end of their five-year service life for training purposes. This approach provides first-hand experience of SCSR initiation and breathing characteristics, but is only appropriate to a rolling programme of hot air wearing experience of SCSRs. The diversity of SCSR designs in use within the mining industry also means the wearing experience and training may not necessarily reflect the apparatus carried underground.

An alternative approach is to use a purpose-designed SCSR simulator at centrally or regionally located training facilities. This latter approach reflects the statutory training provisions in the mining industry of Asturias, Northern Spain. Summary details of the training approach and the simulator system developed are given here.

The mine workforce in Asturias is estimated at 6000-7000. Three principal types of SCSR are employed; Dräger Oxyboks, MSA SSR 30, and Fenzy Biocell 1. A limited number of underground incidents have occurred where individuals had some difficulty in donning and using their SCSR effectively. Consequently, a decision was made by the Spanish authorities to provide all mineworkers with a realistic simulated experience of wearing an SCSR under various exercise conditions.
A study was undertaken by the Institute of Silicosis, Oviedo on the breathing characteristics of SCSRs whilst exercising within a range of representative treadmill gradients and speeds. This work was a precursor to the development of a purpose-designed SCSR simulator. The simulator is designed to provide a realistic experience and appreciation of temperature, humidity and breathing resistance effects. Essentially, the simulator employs a computer-cycled treadmill and SCSR mouthpiece assembly supplied with air of controlled humidity and temperature. The breathing resistance is also maintained under closed loop control.

The system provides wearing experience in two phases; a hot and humid phase, and, a hot, dry air phase. A variety of submaximal test exercises can be set up on the treadmill. Typical maximum parameter values reached during the tests are as follows:

- **Breathing resistance, symmetrical:** 6-8 mbar
- **Humidity:** 75-80% at 55°C
- **Treadmill:** 8% gradient, 4-5 km/hr
- **Hot air period:** 5 minutes (Phase 1) + 4 minutes (Phase 2)

**Figure 2.16** and **Figure 2.17** provide views of the Spanish simulator operator's console and internal engineering detail respectively.

At the end of 2000, approximately 2000 employees had been trained using the simulator, with 12 trainings per day capacity. Feedback from staff who have worn SCSRs, confirms that the simulation is challenging and realistic.

9. **Options for a mining industry hot air training model**

Statutory Instruments, 1995, Number 2870, Health and Safety, *The Escape and Rescue from Mines Regulations, 1995*, Regulation 10, ‘Arrangements for Escape’, prescribes a duty on the owner of every mine to provide suitable self rescuers for all persons going below ground. Within the same Regulation, ACOP 56-64 make reference to the training requirement. In particular, ACOP 56 states:

> “both initial and refresher training will need to include the option of hot air experience”

Appendix 4 relating to self-rescuer training in the same Regulations provides further guidance:

> **Hot air experience**

> Where filter respirator self-rescuers are provided, trainees should have an opportunity to experience breathing hot air by wearing a hot air training model of the self-rescuer for about 15 minutes or by an extended wearing of a normal self-rescuer resulting in an increase of temperature and resistance. The aim of this experience is to simulate the breathing conditions that would exist when wearing a self-rescuer in real emergency conditions underground. Training should conclude with a summary of the main training points and a check of the trainees’ understanding.”

Participation in such training has never been mandated, and arguably, this has resulted in lack of commercial incentives to develop hot air training models or simulators. With the use of filter type self rescuers now limited essentially to the UK and Germany within Europe, there is probably an insufficient market size to justify commercial development programmes.

If industry is to be provided with hot air self-rescuer training, it will require development of one or more of the following options:
1. A redesign of the MSA hot air training unit to incorporate a refillable canister design.

2. Development and manufacture of a limited number of simple air-liquid heat exchanger based units.

3. Manufacture of an SCSR simulator, possibly replicating the Institute of Silicosis design (Principality of Asturias, Spain).

In taking the cost of the components of the system into account, it is estimated that an open loop controlled air liquid heat exchanger based hot air simulation system could be assembled at a unit cost estimate of ~£3-4k. However, various safety features might have to be added and the eventual cost might be somewhat higher, particularly if product development and approval costs must be amortised. The SCSR simulator system is relatively sophisticated and would have a high cost (probably > £50k).

A practical device for use within the mining industry, proposed on the lowest cost approach, may be to have a number of stainless steel canisters made to the MSA envelope design. Given the modest numbers involved, it would be most appropriate to have these units refillable. The modified design would employ a removable stainless steel mesh base to permit the units to be filled with dedusted soda lime. No design changes are considered necessary to the proprietary MSA mouthpiece (MSA Part No. 123-0028). Design rights, availability of the MSA mouthpiece part/moulding tools are commercial issues of note here.

As an alternative to hand filling of the canisters, the use of pre-moulded plastic cartridges containing soda lime reagent, so-called‘reactive plastic cartridges’, warrants further investigation. Initial discussions were held with Micropore Inc. to define a possible requirement specification. However, again, the market size may be too small to justify manufacture of a purpose-designed product.

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Figure 2.1: Condensed Psychrometric Chart

Figure 2.2: Specific Enthalpy Components for Dry and Saturated Air
Figure 2.3: Experimentally determined limits of tolerability for various air humidity and temperatures.

Figure 2.4: Variation of tolerability limits for saturated hot air versus breathing rate.
Figure 2.5: MSA W95 Filter Self Rescuer, Cross-sectional View
Figure 2.6: MSA SSR30/100 Chemical Oxygen Self Rescuer, Cross-sectional View

1 Mouthpiece  
2 Breathing Tube  
3 Heat Exchanger  
4 Mouthpiece Plug  
5 Case  
6 Nose Clip  
7 Neckstrap  
8 Clamp  
9 Breathing Bag  
10 Protective Cover  
11 KO₂ Cannister  
12 Pressure Relief Valve  
13 Waist Belt

Inhalation
Exhalation
Figure 2.7: Air-Liquid Stainless Steel Heat Exchanger, End View

Figure 2.8: Heat Exchanger Flow Circuit
Figure 2.9: Heat Exchanger Flow Circuit and Breathing Machine
Figure 2.10: Seive Size Characteristics of ‘Sofnolime’ Soda Lime Product

Figure 2.11: MSA Hot Air Training Unit Components
(New canister shown inset)
Figure 2.12: MSA Hot Air Training Model, Cross-sectional View
Figure 2.13: Sorption Isotherms for Various Dessicant Types
Figure 2.14: Warm-up Characteristics of Modified Hot Air Training Unit
Figure 2.15: Reactive Plastic Cartridge (RPC) Technology, Key Features
Figure 2.16: Institute of Silicosis SCSR Simulator, Operator’s Console View

Figure 2.17: Institute of Silicosis SCSR Simulator, Console Internal Detail
There were a number of issues to be considered prior to the implementation of the Climatic Chamber trials in the controlled chamber at the Selby Mines Rescue Station.

- Ensuring the safety and confidentiality objectives of HSE’s Research Ethics Committee were fully accounted for.
- Investigating how to simulate the work rate involved in seeking to evacuate a mine and represent mine conditions.
- Examining how best to incorporate these issues within a simple treadmill cycle.
- Accounting for the pre-warming associated with routine work undertaken before an evacuation is initiated.
- Calibration of the treadmills and ensuring the work rate they incur was reasonably representative.
- Review of practice and measurement reliability of physiological monitoring methods.
- Selecting appropriate physiological monitoring instrumentation, which was also suited for use in saturated atmospheres.
- Establishing data telemetry and (outside chamber) real time monitoring facilities for the instrumentation functions.
- As a parallel activity, undertaking an investigation of how to simulate, with appropriate safeguards, the hot air effects of wearing a FSR in a high CO environment.
- Initiating information briefings with test volunteers and selecting subjects.
- Confirming the trial protocol and programming individual test elements therein.

Specific trial development relating to most of these issues are discussed.

1. **Trial Hypothesis**

Whilst the trials had a number of experimental objectives, there was one specific hypothesis to test:

“**In conditions of high heat and humidity, does the wearing of a filter self-rescuer, or the wearing of a self contained oxygen self-rescuer in a mine atmosphere containing a high CO content, have any noticeable effect compared with the baseline reference case, in terms of physiological stress response?**”

The test programme involved medically assessed MRSL volunteer staff, each undertaking three wearing trials:

(1) a baseline reference test run without an escape respiratory protective device
(2) a hot air filter self-rescuer training model run
(3) a wearing trial of a representative SCSR (MSA SSR30)

Within this hypothesis, there were a number of experimental influences which needed to be investigated for assessment. Some would be dependent on individual physiological responses, some were environmental variables, and some concerned the possible influence of measurement errors.
In order to arrive at results which had acceptable statistical accuracy, there were recognised benefits in having the test subject group as large as could be practically managed. The overall subject group size was nominally defined to be between 11 and 16 subjects. Furthermore, in order to reduce the number of tests within the programme, and provide for adequate statistical significance, it was decided that the initial baseline reference hot air FSR and SCSR tests, be subject to standard test conditions at a nominal temperature of 34°C (air fully saturated). These conditions are severe, but are not unrealistic, in terms of representing a mine emergency situation in a deep, laterally extended mine where ventilation has been disrupted. Further spot tests were then undertaken at temperatures ranging between 27°C and 34°C.

2. Evacuation Simulation, Work Rate and Treadmill Calibration

In devising the climatic chamber trials, an objective was to ensure, as far as practicable, that environmental conditions and work carried out by the test subjects were broadly representative of current underground conditions. Towards this, information was sought on the primary escape routes at deep, hot mines in the UK in order to establish typical gradients, and whether these could be simulated. This assessment included Harworth, Maltby, Stillingfleet, Thoresby and Welbeck. The method of assessment used was primarily inspection of mine plans and consideration of local knowledge by MRSL staff who visit these mines on training exercises.

It was not considered feasible to account fully for the physiological stresses involved in an evacuation, including possible disturbance to mine ventilation, low visibility effects, smoke irritation or variable floor conditions. It is fair to say, however, that these additional stressors would probably result in an increased effective work rate. Communication with Ms M. Hanson, Ergonomist and Heat Stress Specialist, suggested that certain standards be examined to estimate work rate/metabolic rate. UK standards include BS EN 28996:1994 (detailing methods of determining metabolic rate) and BS EN 27243:1994 (which provides ‘typical’ classifications of metabolic rate). A summary of metabolic rate categories from BS 7963:2000 was also considered relevant as follows:

<table>
<thead>
<tr>
<th>Metabolic rate class (typical activity)</th>
<th>Metabolic rate per unit area of body surface (Wm⁻²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 Resting</td>
<td>65</td>
</tr>
<tr>
<td>1 Low (e.g. walking in easily accessed areas)</td>
<td>100</td>
</tr>
<tr>
<td>2 Moderate (e.g. walking in congested areas or with limited head room)</td>
<td>165</td>
</tr>
<tr>
<td>3 High (e.g. heavy manual handling)</td>
<td>230</td>
</tr>
<tr>
<td>4 Very High (e.g. rapidly climbing stairs)</td>
<td>290</td>
</tr>
</tbody>
</table>

The above compare reasonably well with figures drawn from individual studies (based on ISO 8996, Ergonomics - Determination of Metabolic Heat Production, 1990), which suggest walking type activities have a ‘moderate’ work rate, with indicative figures as follows:

- *Walking on the level, 2 kmh⁻¹*  \(110 \text{ Wm}^{-2}\)
- *Walking on the level, 5 kmh⁻¹*  \(200 \text{ Wm}^{-2}\)

The influence of load carried on metabolic rate is significant. The following provides an indication of typical metabolic rate at two speeds and for various loads [Sawka and Kent 2001], but is not adjusted per unit area of body surface, and includes basal metabolic rate:
<table>
<thead>
<tr>
<th>Work Activity</th>
<th>Typical Metabolic Rate (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Walking on hard surface, 3.6 km/hr, no load</td>
<td>210</td>
</tr>
<tr>
<td>Walking on hard surface, 3.6 km/hr, 20-kg load</td>
<td>255</td>
</tr>
<tr>
<td>Walking on hard surface, 3.6 km/hr, 30-kg load</td>
<td>292</td>
</tr>
<tr>
<td>Walking on loose sand, 3.6 km/hr, no load</td>
<td>326</td>
</tr>
<tr>
<td>Walking on hard surface, 5.6 km/hr, no load</td>
<td>361</td>
</tr>
<tr>
<td>Walking on hard surface, 5.6 km/hr, 20-kg load</td>
<td>448</td>
</tr>
</tbody>
</table>

It is noted that rescue staff will each typically carry a load of 30 kg or more, comprising breathing equipment, lamps, tools, protective clothing, boots etc. This load leads to increased metabolic rate, oxygen demand and heat strain potential. Antekueer and Lottner [1999], in an extensive series of tests, confirmed the imperative requirement to reduce breathing apparatus weight if strain on rescue staff is to be managed effectively. Of further note in their studies was that long-duration open circuit breathing apparatus produced heart rates up to 15-20 bpm higher than for closed circuit (mines rescue) breathing apparatus, primarily due to the additional cylinder weight of the former.

Bethea and Parsons [2002] provide a useful comparative review of standards and guidelines pertaining to ergonomics of the thermal environment. They also point out that whilst measurement or estimation of metabolic heat production is a fundamental requirement, there are significant practical difficulties in making accurate estimations of metabolic heat production from activity. Estimations of metabolic rate can be subject to errors as great as 60%. The use of ISO 28996 data, empirical equations designed specifically for an activity, and indirect calorimetric measurement methods are identified as possible methods. Interviews by Bethea and Parsons with UK industry safety professionals confirm there is little expertise in the measurement of metabolic rate - (most currently use wet bulb globe temperature (WBGT) tables or American Conference of Governmental Industrial Hygienists Threshold Limit Values (ACGIH TLVs) - and that measurements taken show large variation, both between measurements of different workers doing the same task, and between different measures taken on the same worker. Acknowledging the uncertainty when using published metabolic rate estimations, consideration was given to the possible need to separately simulate both level and grade walking.

**Simulating Level Walking**

It was proposed that two treadmills be assigned to each subject. The principal treadmill used to simulate level walking was set to have minimum resistance, with the test subjects free to regulate their pace to that which was individually comfortable. It was noted that the treadmills, even on minimum resistance, had a slight grade and required some effort to overcome the irreducible frictional and other mechanical losses of a self-powered treadmill. It is speculated that this work rate was probably of the same order as the work rate associated with variable under foot and roadway clearance conditions encountered underground and when walking on the level. One alternative option would have been for test subjects to walk around the periphery of the climate chamber. However, the work rate at any particular speed would have been lower than that experienced underground. Furthermore, since the physiological monitoring equipment was hard-wired, the test subjects could not have been monitored whilst walking around the chamber. It was therefore concluded that in order to simulate level walking underground, a mechanical treadmill set to minimum resistance and inclination would be used.
Simulating Grade Walking

It was proposed that a second treadmill would be used to simulate underground gradients, as required. The primary considerations here were:-

- the nature of the gradients to be simulated and
- the calibration of the treadmill

It was determined that the treadmills were mechanically simple affairs, subject to variance in braking force, both as a function of speed and elapsed use (and possibly environmental conditions). It was also recognised that headroom limitations within the chamber would prevent the treadmills from being too greatly inclined, noting that treadmill gradient is a standard means of modifying work rate. Given the variation in roadway gradients encountered underground, and the relative mechanical crudeness of the treadmill apparatus to model them, simplifications were considered necessary. It was proposed that the second treadmill be set up to simulate a single arbitrary underground gradient. It would then be possible by varying the parts of the cycle spent on the second treadmill to approximate the distance/time of travel involved underground. Various analyses of grade walking are given in Bobbert 1960, Margaria 1976, Minetti 1995, Pivarnik and Sherman 1990, Snellen 1960, Sun et al 1996.

Consideration was then given to the means of calibration of the treadmill and setting up a particular work rate. Calibration could, in principle, make use of direct or indirect calorimetry (for greatest precision and accuracy). Alternatively, an attempt could be made to replicate tests conducted by a group of subjects on a reference treadmill or gradient walk, possibly using heart rate (HR) as the physiological metric. This approach was considered somewhat less precise.

Calorimetric methods are usually employed in controlled laboratory environments. Measurement of heat produced by the body permits a direct estimate of metabolic rate. Such measurements are performed by direct calorimetry. Direct calorimetry is complex and is not routinely performed. Indirect calorimetry methods assume that steady state metabolism is aerobic and that at moderate work, anaerobic metabolism is a small part of credit oxidation [Wasserman et al 1967]. Measuring the rate of uptake of O2 by the body provides an indirect estimate of the metabolic rate. Maximal oxygen uptake can be measured by open-circuit spirometry, or can be predicted from the peak exercise time or power output achieved during a standard maximal exercise test protocol, or can be predicted from sub-maximal exercise tests [Astrand 1960, Montoye et al 1986, Pollock et al 1980.]. The sub-maximal tests utilise heart rate responses to incremental workloads to predict VO2max and are assessed as a safer method for the general population.

On balance, the precision of calorimetric methods was not considered justified against the approximations being made to simulate the underground environment, together with the simplicity of the test apparatus. There are simplified metabolic equations for estimating energy expenditure which are considered to be useful. The concept behind the development of metabolic equations is to estimate oxygen consumption when a subject is exercising in a given mode at a particular intensity. Data from numerous studies has been used to establish statistical prediction models and equations that can be used to estimate oxygen consumption. Clearly, this is less accurate than measuring oxygen consumption directly, but does avoid the cost and complexity of using metabolic analysis instrumentation. One such set of equations is the ACSM Metabolic Calculations.

There are three components in each equation; horizontal (H), vertical (V), and resting (R), where VO2 = H + V + R.

This can be simplified to the following [ACSM 2000, Swain and Leutholtz 1997]:

<table>
<thead>
<tr>
<th>Activity</th>
<th>VO2 formula</th>
</tr>
</thead>
<tbody>
<tr>
<td>Walking</td>
<td>VO2 = 3.5 + 1.7(speed) + 0.3(speed)(%gradient)</td>
</tr>
<tr>
<td>Bench stepping</td>
<td>VO2 = 0.35(rate) + 0.025(rate)(height)</td>
</tr>
</tbody>
</table>
VO₂ in ml.kg⁻¹.min⁻¹
Speed in km.h⁻¹
Rate in steps per minute
Height in cm

An alternative method, proposed in discussions with Mr Forster, HMIM RATO, Project Officer was to select a group of test subjects and have them use a calibrated laboratory treadmill, or have them walk a defined gradient or route, with measurements taken of heart rate. These measurements, possibly in conjunction with a repeat of the tests using the same subjects on the treadmill simulator, could be used to set up an equivalent work rate. Whilst there are several potential sources of error in this method, it was considered to be practicable.

Cycle ergometry was discounted due to difficulties in relating energy expenditure to that involved in level or grade walking.

3. Ensuring Safety of the Subject

All trial phases of the study were submitted to HSE’s Research Ethics Committee for peer review and approval. The study adhered strictly to the process of informed consent, and largely followed guidelines and procedures developed for an earlier comparable trial by the study physician, Dr Andrew Booth [Hanson and Booth, 2000]. A qualitative risk assessment was undertaken. The key findings in terms of the significant risks identified and proposed monitoring and control measures were as follows:

### TRIAL RISK ASSESSMENT

<table>
<thead>
<tr>
<th>Potential Hazards</th>
<th>Potential Severity</th>
<th>Likelihood</th>
<th>Control Measures</th>
<th>Risk Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cardiovascular hazards (excessive heart rate, stroke risk)</td>
<td>High</td>
<td>Low</td>
<td>Continuous heart-rate monitoring. Supervision by occupational physician. Conservative withdrawal criteria.</td>
<td>Low</td>
</tr>
<tr>
<td>Thermoregulatory hazards (heat stress, dehydration and significant discomfort)</td>
<td>High</td>
<td>Low</td>
<td>Continuous core temperature monitoring (climate chamber trials). Supervision by occupational physician. Conservative withdrawal criteria.</td>
<td>Low</td>
</tr>
<tr>
<td>Thoracic and nasopharyngeal hazards (inhalaion of hot air)</td>
<td>Medium-High</td>
<td>Low</td>
<td>Hot inspired air devices tested to ensure peak temperatures &lt; 50°C, or devices meet appropriate EN test standards.</td>
<td>Low</td>
</tr>
<tr>
<td>Psychological stress</td>
<td>Medium-High</td>
<td>Low</td>
<td>Subject screening. Instruction and information prior to tests. Post-test debriefing and reassurance.</td>
<td>Low</td>
</tr>
<tr>
<td>Ergonomic hazards (musculo-skeletal injury including strain injuries)</td>
<td>Medium</td>
<td>Low</td>
<td>Subject selection. Trial practice, instruction and monitoring.</td>
<td>Low</td>
</tr>
<tr>
<td>Slipping, falling and trips</td>
<td>Medium</td>
<td>Low</td>
<td>Adequate illumination, familiarity with route, clearance of obstructions.</td>
<td>Low</td>
</tr>
<tr>
<td>Dental hazards (damaged teeth and dentures)</td>
<td>Low</td>
<td>Low</td>
<td>Briefing on dental precautions and failure response.</td>
<td>Low</td>
</tr>
</tbody>
</table>

Physiological monitoring of all test subjects was used throughout the trials. Heart rate and body core temperature were monitored continuously. Withdrawal criteria were specified which took into
account appropriate margins of protection and any temperature offset associated with the method of measurement (e.g. ear cavity versus rectal measurements).

The following physiological withdrawal criteria was utilised. Bethea and Parsons [2002] proposed comparable criteria.

- 38.5°C core (aural) temperature reached, or
- heart rate of 180 beats per min. /80% of age-related max. heart rate reached, or
- Physician decision (inc. other factors e.g. SCSR breathing difficulty), or
- Subject request for termination, or
- 1.5 hours elapsed travel time reached.

The key physiological withdrawal criterion was considered to be the individual’s core body temperature. The study medical staff were able to supervise this parameter continuously during the trials.

4. Physiological Monitoring of Core Temperature and Heart Rate

Prior to selecting instrumentation, a review of core body temperature measurement and heart rate monitoring was conducted. This included a site and measurement accuracy comparison with ‘gold standard’ clinical methods.

Core Body Temperature Measurement

The preferred sites for measuring core body temperature are considered to be those closest to the hypothalamus, the temperature-regulating centre. The temperature in the pulmonary artery, esophagus and bladder can be monitored to measure core values, but these sites involve invasive thermometry. Traditionally, the oral, rectal, and axillary sites have been utilised. Some clinicians consider the rectal site to be the most accurate. However, rectal measurements do not respond quickly to induced heat changes in the body. Reference is made to reviews of clinical thermometry [Holtzclaw 1998, Klein et al 1993, Milewski et al 1991, Cattaneo et al 2000].

A preferred temperature site of more recent adoption is the aural canal. True tympanic membrane temperature measurement is taken deep inside the skull, and is not subject to the errors that can affect oral, rectal, axillary and ear temperatures. There are two types of instruments available to make the measurement.

- A long thin thermocouple probe that must come in contact the tympanic membrane. There is much historical data on the efficacy of tympanic thermometry. Ferra-Love [1991] and Klein et al [1993] found pulmonary artery and tympanic measurements to be highly correlated. However, invasive tympanic methods never gained wide acceptance due to the risk of injury to the membrane.
- Infrared measurement of tympanic membrane temperature by non-contact means. This eliminates risk of injury to the tympanic membrane.

There are three types of infrared thermometers:

- tympanic
- ear
- arterial heat balance
Results of studies using (infrared) aural measurements are however conflicting, with some claiming there is a strong correlation with pulmonary artery temperature, whilst others indicate the method has high variability. Problems with technique and probe placement are areas of concern. A number of studies have been undertaken [Childs et al 1999, Erickson and Meyer 1994, Fremstad et al 1993, Imamura et al 1998, Matsukawa et al 1996, Modell et al 1998, Rohrberg et al 1997, Shibasaki et al 1998, Smith and Fehling 1996]. Tests on specific infrared instruments claim they are unreliable in clinical practice (e.g. Modell et al 1998), whilst a statistical approach to method comparison was highlighted as important by Bland and Altman 1986.

Within the trials, an objective was to eliminate the variability arising from otoscopic application technique and to get as close as possible to true tympanic thermometry. Aural canal thermistor sensors are the preferred instrument under extreme environmental condition, and are used by the military for monitoring individuals suffering from heat or cold stress. The thermistor types selected for this application were supplied within a moulded plug which fits, without discomfort, into the mid-outter part of the aural canal. In order to minimise external environmental influences on measurement accuracy, the thermistor and ear were covered in thermal insulation and then enclosed by an insulated earmuff. This arrangement was considered to be an optimal compromise between invasiveness, wearer comfort, thermal stabilisation time and core body temperature measurement precision.

The manufacturer individually calibrated the data logger channels and aural thermistors. The two point calibration results were as follows:

<table>
<thead>
<tr>
<th>Converted Thermistor Temp. Reading, °C (res. meas. error +/-0.01°C)</th>
<th>Converted Thermistor Temp. Reading, °C (res. meas. error +/-0.01°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calibration Bath Temperature: 35.70°C (max. error +/- 0.03°C)</td>
<td>Calibration Bath Temperature: 38.02°C (max. error +/- 0.03°C)</td>
</tr>
<tr>
<td>Probe No. 1 35.75</td>
<td>Probe No. 1 38.07</td>
</tr>
<tr>
<td>Probe No. 2 35.74</td>
<td>Probe No. 2 38.06</td>
</tr>
<tr>
<td>Probe No. 3 35.78</td>
<td>Probe No. 3 38.11</td>
</tr>
<tr>
<td>Probe No. 4 35.69</td>
<td>Probe No. 4 38.02</td>
</tr>
<tr>
<td>Probe No. 5 35.62</td>
<td>Probe No. 5 37.94</td>
</tr>
<tr>
<td>Probe No. 6 35.73</td>
<td>Probe No. 6 38.06</td>
</tr>
<tr>
<td>Probe No. 7 35.78</td>
<td>Probe No. 7 38.10</td>
</tr>
<tr>
<td>Probe No. 8 35.78</td>
<td>Probe No. 8 38.09</td>
</tr>
<tr>
<td>Probe No. 9 35.72</td>
<td>Probe No. 9 38.04</td>
</tr>
<tr>
<td>Probe No. 10 35.66</td>
<td>Probe No. 10 37.98</td>
</tr>
</tbody>
</table>

A number of open air thermistors were employed around the environmental chamber in order to monitor dry bulb temperature and measure temperature stratification within the chamber.

During the trial phase, a swallowable sensor pill technology ("CorTemp" measuring system supplied by HQI Technology Inc.) was identified. This technology is being used by the US National Institute for Occupational Safety and Health (NIOSH) to investigate core body temperature behaviour in underground work settings. The approach is representative of ‘intestinal’ temperature measurement, which is somewhere between esophageal and rectal measurement methods in terms of response time. Figure 3.1 shows typical response time characteristics. NASA has evaluated the sensor pill technology [Lee et al 2000], and has partially confirmed these assumptions. In Figure 3.2, taken
from the NASA evaluation report, the ‘intestinal’ data trends correspond with the swallowable sensor pill. The NASA test data confirmed variability in sensor response time, dependent on the subject. This possibly reflects the sensor clearance time from the body of 7 -45 hours within a range of subjects, and uncertainty with regard to positioning within the intestinal tract. The use of intestinal core temperature measurement is affected by the location of the sensor pill in the intestinal tract. Location is variable and uncertain and results are greatly affected by drinking while the sensor is in the stomach. It is likely that drinking cool fluids will result in recorded core body temperature measurements being lower than those measured at more conventional clinical sites.

**Using Heart Rate to Measure Exercise Intensity**

The basic physiological principle of using heart rate (HR) to measure exercise intensity is that as work rate increases, oxygen consumption (VO₂) and HR increase in a linear relationship until near maximal intensities. The relationship between HR and VO₂ is given overleaf. A key aspect is knowledge of the subject’s HRₘₐₓ.

In a physiological laboratory setting, it would be appropriate to undertake a maximal aerobic power test during which VO₂, HR and blood lactate concentration would be tracked as work intensity increased. From this laboratory test, maximal HR (HRₘₐₓ), maximal power (Watts), VO₂ₘₐₓ and lactate threshold (LT)/ heart rate (HR) can be determined (HRLT). The subject’s HR at different power outputs and percentage VO₂ can be determined.

Studies of a variety of heart rate monitors (HRMs) confirm they correlate at a level of 0.99 when compared to electrocardiography (ECG) over a range of 55-177 beats/minute and that 90% of the time measured errors are within 8 beats/minute [Laukkanen and Virtanen 1998].

<table>
<thead>
<tr>
<th>% Max VO₂</th>
<th>% Max HR</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>66</td>
</tr>
<tr>
<td>55</td>
<td>70</td>
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<tr>
<td>60</td>
<td>74</td>
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<td>70</td>
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<td>80</td>
<td>88</td>
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<td>85</td>
<td>92</td>
</tr>
<tr>
<td>90</td>
<td>96</td>
</tr>
</tbody>
</table>

**Factors affecting Heart Rate**

There is a potentially large inter-individual and intra-individual variation in heart rate, HR. Influencing factors include stress, illness, and recovery from previous work, medications and food. One phenomenon to note is ‘cardiac drift’, the increase in HR seen over time while exercising at a constant workload. Some studies suggest HR can increase by 20 beats/min during constant work rate exercise lasting 20 to 60 minutes. Ambient environmental conditions and hydration status can significantly affect cardiac drift. The presence of high heat and humidity cause cardiac drift to be more pronounced. HR, therefore, tends to be higher for a given work load in hot conditions than in cooler, dryer conditions.
Physiological Instrumentation

The physiological monitoring equipment used in these trials comprised a purpose-designed data logger (one per subject), which had a dedicated three lead ECG heart rate monitoring channel and capacity for a number of thermistors. The instrumentation for the trial was sourced from Grant Instruments/Eltek Limited.

In the pilot phase of the study, a problem was identified with the cardiac monitoring instrumentation. The study physician observed the instrument was not providing readings, which correlated adequately to real-time cardiac response. Arrangements were made to check the instrumentation against the ECG and sub-maximal cardio-vascular fitness assessment clinic instruments used by Business Healthcare Limited. These tests confirmed the initial observations. Discussions with the physiological monitor/data logger manufacturer led to changes to the statistical settings used within the instrument. These changes resolved the problem, with confirmatory checks made against ECG readings of heart rate, within the range 60 - 130 bpm. Various additional tests were also carried out to determine the sensitivity of the instrument to electrode placement and to finalise the routing and management of instrument leads on the subject.

Whilst, the instrumentation performed to specification in the trials, significant problems were experienced in maintaining proper ECG electrode contact. This was attributed to the difficulties in preventing electrode lift and gel depletion when subjects sweat profusely. The entire commercial electrode set which was evaluated showed gel leaching and detachment problems. The study medical staff made manual interpretations of pulse rate, which confirmed that all subjects were maintained within their age-adjusted heart rate limits.

The physiological data for the trials, whilst primarily intended to ensure the health and safety of subjects, was recorded against elapsed time and elapsed distance travelled on the treadmill. This permitted individual thermal stress to work rate data, distance travelled and walking speed/behaviour to be analysed. The data was recorded as primary data within the logger, with a back-up within the data trending software. In order to accomplish the elapsed distance measurement, a modified treadmill flywheel sensor had to be devised. Tests were conducted to compare the effort required to move the mechanical treadmills compared with level walking. A range of treadmill gradients was examined towards ensuring maximum representativeness.

5. Experimental Protocol Refinement

The initial phase of the experimental test programme was used for pilot testing and refinement of the trial protocol. This considered the following:

- Ensuring the programme was of manageable size and could be delivered in sensible time.
- Examining the scope of tests to offer reasonable statistical significance and scope in order to extrapolate the findings to the general workforce population.
- Examining the test variables/variations to ensure key issues were addressed first.
- Defining baseline testing and referencing requirements.
- Accounting for shift pre-warming as necessary.

The available volunteer pool population, entirely comprising MRSL staff, determined the characteristic of the cohort group. There was a requirement to represent, as far as practicable, the
range of ages, body mass index, cardio-vascular fitness and acclimatisation capability. An examination was made of the respective benefits of:

- random selection of subjects
- selection of a set of individuals which broadly span the population, and
- biasing the selection to give greater weighting to sensitive sub-groupings.

The latter approach would better account for mine staff management, contractors and visitors etc.

Even with a relatively modest number of subjects, it was recognised that the total number of tests required could become significant (to include baseline tests, different temperatures and humidity, effects of respirator type, effects of pre-warming, effects of clothing). Accordingly, the trials were structured so as to concentrate first on resolving central issues, with a ‘second tier’ of tests examining other factors such as, for example, the impact of clothing. Wearing of the industry standard W95 FSR was not carried out, since without the presence of CO, the additional physiological burden would be small, essentially a small increase in breathing resistance. Hence the emphasis was on testing with a hot air model.

The original submission to HSE’s Research Ethics Committee incorporated initial views on a test protocol, including options for accounting for shift work pre-warming. These options included simulation of walking inbye, together with a period of work involving either:

- Undertaking cycles of work and rest involving block wall building and dismantling,
- Simulation of coal face working, involving crouching, lifting and movement over irregular surfaces.

These exercises were proposed on the basis that they were reasonably representative of the underground workforce travelling to workings and mine work activities there. After discussion with the Study Physician, it was considered reasonable to introduce certain simplifications. One criterion was to ensure that the musculo-skeletal set and work rate was broadly equivalent to the intended underground work pattern. A further simplification involved assigning part of the treadmill activity as pre-heating activities, and assigning subsequent exercise to the evacuation phase following an emergency occurring. It was judged impractical to account for sweat depletion mechanisms, such as might occur towards the end of a shift in hot and humid conditions.

Initial chamber treadmill tests were conducted at 23°C (normal humidity) and then at 36°C (100% humidity) to ascertain what constituted reasonable pre-warming exercise activities, and how long subjects could be exposed to extreme temperatures before core body temperature exceeded the withdrawal criterion of 38.5-38.6°C. Even with relatively moderate work rates, it was observed that at high temperatures with the air fully saturated, the safe period in the chamber could be as little as 30 to 40 minutes. On this basis, it was not judged feasible to incorporate a high work rate component within the treadmill test procedure (designed to simulate walking up significant gradients). It was considered likely that subjects would be prematurely withdrawn from the tests due to their core body temperature exceeding safe limits.

It was agreed to restrict exercise within the trials to use of the treadmills at minimum resistance and inclination setting, broadly equivalent to moderately strenuous walking. The subjects were encouraged to pace themselves and to rest when they felt it necessary. Walking rates varied between 2 – 4 km/h.
Trials on the chamber temperature regulation system indicated that a mean maximum chamber temperature of 38°C fully saturated could be maintained. However at this temperature, the chamber was subject to a significant heat loss when doors were opened, in spite of the negligible air velocity in the chamber (<0.5 m/s). Subsequent tests showed that the target mean chamber temperature of <34°C fully saturated could be maintained with better stability. Generally, it was necessary to monitor the chamber temperature and regulate manually the chamber temperature and humidity controller.

Significant vertical stratification in temperature was noted within the chamber. Chamber temperature probe measurements were made during the tests at ceiling height (5 cm from lining), mid-torso height (left and right hand sides of treadmill row), and, close to the chamber floor (20 cm above tiled surface). Temperature and humidity measurements were confirmed by periodic Casella whirling hygrometer measurements.

The chamber temperature stratification resulted in highest local thermal stress to the head and neck. This was observed, in practical terms, by the efforts of some test subjects to lower their heads during the test runs, specifically to reduce the sensation of heat about the head. Whilst the whole peripheral cardio-vascular system and associated environmental conditions must be considered in terms of the body's overall ability to maintain thermoregulation, there is undoubtedly a complex relationship between head temperature, perception of heat and tolerability of conditions. A number of procedural modifications were evaluated in an attempt to reduce chamber temperature over-shoot and stratification. This included judiciously turning off the ceiling heat injection system and introducing modest air movement within the chamber. These measures reduced overall chamber temperature, but largely at the expense of loss of temperature control accuracy. There is an identified requirement for further investigation as to whether there is an enhanced physiological response, greater distress and possibly earlier withdrawal due to ambient temperature stratification.

The experimental arrangement used within the climate chamber trials can be readily appreciated from Figures 3.3 through Figure 3.8. A summary of the trial protocol procedures is given in Annex 1.

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Section 3: ANNEX 1

Trial Protocol Procedures

The Trial Protocol essentially involves three phases:

A. Establishing the baseline, reference response for each individual.
B. Establish response under identical circumstances, but whilst wearing a hot-air model filter self-rescuer.
C. Establish response under identical circumstances, but whilst wearing a chemical oxygen SCSR.

The trial involves establishing a baseline response, where individuals provide their own reference data set. This effectively replicates the conditions in B and C above, but without a respiratory protective device being worn. In order to reduce any systematic effects, for example initial anxiety at the first test, the three test phases A, B and C should be randomly mixed.

The trial procedure is essentially as follows:

- Ensure treadmill belt friction surface has been lubricated with silicone oil and adjusted if necessary for tracking.
- Ensure external recovery area is prepared as necessary with fans, drinks, seating etc.
- Ensure insulating cotton wool, ear protectors and relevant tapes are inside chamber (to pre-heat them).
- Sterilise aural thermistors and modified ear defender housings.
- Check portable computer and instrumentation status. Check there is sufficient residual battery life in the data loggers.
- Check aural thermistors, heart rate and odometer instrument leads and connectors.
- Bring climate chamber up to nominal temperature and humidity (34°C fully saturated).
- Wipe chamber observation windows with surfactant.
- Start Eltek 'Darca' logger software. Check data communications can be established between the loggers and portable computers.
- Check channels can be metered. Adjust graph scales and alarm points as necessary.
- Clear the previous logger data.
- Have test subjects made ready, two subjects maximum per run.
- Study physician briefs subjects on the nature of the trial, procedures, possible discomfort and confirms they may stop at any time, or, may be withdrawn by the nurse or physician.
- Confirm written consent has been obtained and records maintain subject anonymity.
• Check subjects are appropriately dressed and equipped; vest with Velcro fastenings, shorts, boots etc.

• Denature relevant chest and rib areas and fit ECG electrodes.

• Subjects enter chamber, aural canal thermistors are fitted together with insulation and earmuff.

• Subjects relax for 10 minutes to allow core-body temperature measurements to stabilise and instrumentation checks to be made. Adjust instrumentation wires as necessary.

• Subjects warm-up by walking at a steady pace for 10 minutes on treadmills (subsequently reduced to 6 minutes warm-up period). Monitor core body temperature, heart rate and odometer outputs.

• Stop subjects at appropriate mid-point. Instruct them as follows:

  • Either
    ➢ Continue walking at a steady evacuation pace (baseline test), or
    ➢ Don the SSR 30 chemical oxygen SCSR, or
    ➢ Don the hot air FSR model.

• Subjects continue until they wish to withdraw, or, are instructed by study physician to stop.

• Rapidly withdraw subject(s) to designated recovery area and monitor recovery.

• Stop data logging. Download and process data files.

• Make back-up copy of data.

• Study physician issues confidential identity code for all data files and written notes. Identity of trial subjects maintained anonymous thereafter.

• Stand down test subjects. Conduct post-test medical checks and debriefing.

• Prepare chamber for second run, if required.
Figure 3.1: Response Time Characteristic at Rectal and Esophageal Locations

Figure 3.2: Temperature Response Time Characteristic for Submaximal Exercise
Figure 3.3: Climate Chamber, Treadmills and Monitoring Instrumentation

Figure 3.4: Observation Window and Adjacent Data Acquisition Room
Figure 3.5: Portable Computers for Real-Time Data Recording and Display

Figure 3.6: Study Physician Fitting Heart Rate Monitor Electrodes
Figure 3.7: Subject Exercising with SSR30 SCSR

Figure 3.8: Subjects Exercising in High Heat and Humidity