Evaluating methods of training of mineworkers for hot inspired air when wearing self-rescuers

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Staff of Mines Rescue Service Limited
Mansfield Training Centre
Leeming Lane South
Mansfield Woodhouse
Mansfield
Nottinghamshire NG19 9AQ

in association with

Dr A P Booth
Senior Occupational Physician
RPS Business Healthcare
Leeming Lane South
Mansfield Woodhouse
Nottinghamshire NG19 9AQ

HSE defined a need for an improved training methodology for escape respiratory protective devices, essentially to provide a realistic experience of the hot air breathing effects of a device operating in a high carbon monoxide content mine atmosphere. Information was also sought by HSE on the tolerability and ultimately endurance limits associated with the extended wearing of an escape respiratory protective device producing a significant heat burden. This information would collectively help address HSE’s duty to offer advice to mine managers on escape respiratory protective systems selection and use, including where escape will entail conditions of high heat and humidity. The research work was addressed in two phases; involving (i) thermo-chemical modelling of filter self-rescuers and the development of a hot air simulation device, suitable for both research and training purposes, and (ii) a range of physiological trials which identified significant thermal physiological benefits from adopting a staged evacuation process in conjunction with safe havens.

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EXECUTIVE SUMMARY

Background

Modern underground coal mines are planned in a manner to produce very high annual production levels. This in turn dictates that coal face and retreat panel dimensions are made as large as possible. Coal panels of >3km length at firling (face commissioning) are not unusual. However an inherent consequence of high production rates and rapid development is that the complex of underground roadways must be located progressively further from the shafts. Most working sections in underground coal mines therefore involve significant travelling time, possibly as much as 90 minutes depending on the mode of transport available and mine layout. This lateral extension of mine workings, coupled with great depth and waste heat from equipment results in increasingly difficult mine environmental conditions. The return airways of retreat coal faces are particularly severe conditions in which to work. Equally, these same environmental conditions can present significant heat stress to mineworkers if they must quickly evacuate the mine.

HSE commissioned earlier research with Mines Rescue Service and RPS Business Healthcare (then Business Healthcare) to examine the heat strain that might arise if the mine workforce was required to undertake a lengthy evacuation wearing escape respiratory protective devices. These studies, reported in HSE Research Report 180, indicated that there are potentially serious heat strain risks if a long evacuation must be contemplated in severe conditions of heat and humidity. The prospect of mineworkers having to retreat through a coal face and along a return roadway, possibly 3km or more in length, in order to escape a developing fire in an intake airway presents arguably one of the most demanding of fire scenarios in an underground coal mine.

In response, HSE has invoked a number of measures to address the thermal physiological impacts associated with evacuation from deep, hot, laterally extended mines. The principal response has been to evaluate the design and application of safe havens as part of a staged evacuation strategy, together with undertaking research within this project on addressing the training needs of wearers of self-rescuers and evaluating their physiological impact. The design of safe havens has been considered by an industry-HSE expert group, resulting in a guidance document "Guidance and Information on the role and design of Safe Havens in arrangements for escape from mines". The work conducted within this research project complements directly this guidance.

In the event of a mine fire or mine explosion, the mine ventilation system can become polluted with harmful gases very quickly. In such situations miners may be in various states of disarray and injury, and effective arrangements must be in place for both self-escape and aided-escape. Of particular importance is a requirement to provide suitable respiratory protection as mineworkers pass through atmospheres that may not support life. Each mineworker is supplied with an escape respiratory protective device (RPD), which is worn on the person and regarded as an essential safety device. Regular training is provided at a mine in the donning and use of whatever type of RPD is used, since this has been shown to have a major influence on the successful deployment of such devices in an emergency.

However, one recognised significant limitation of current training in regard to the use of escape respiratory protective devices is that the training does not offer any provision to experience the hot air burden and breathing impacts associated with their use. Both catalytic filter self-rescuers (FSRs) and oxygen providing self-contained self-rescuers (SCSRs) are associated with noticeable heat whilst they operate. In the case of the filter self-rescuer, the heat arises directly from the conversion of highly toxic carbon monoxide to carbon dioxide, and the heat can be particularly “fierce” at high carbon monoxide levels. However, the FSR is a robust device and is considered a suitable escape respiratory protective device for UK coal mines, where mine ventilation standards are generally very high. The self-contained self-rescuer, which supplies a limited supply of oxygen for use within an isolated breathing circuit, produces less heat but incurs significant breathing resistance towards the end of the
device’s useful operating life. Mineworkers generally have no notion however of either the heat or breathing resistance that they may experience in wearing either type of device in an emergency situation. Making progress towards understanding the training needs here has been one of the central objectives of the research.

Research Needs

HSE defined a need for an improved training methodology for escape respiratory protective devices, essentially to provide a realistic experience of the hot air breathing effects of a device operating in a high carbon monoxide content challenge atmosphere. Information was also sought by HSE on the tolerability and ultimately endurance limits associated with the extended wearing of an escape respiratory protective device producing a significant heat burden. This information would collectively help address HSE's duty to offer advice to mine managers on escape respiratory protective systems selection and use, including where escape will entail conditions of high heat and humidity.

In summary, HSE project aims included:

- A requirement to provide a realistic simulation of both breathing resistance and the heating effects that occur when wearing self-rescuers.
- The development of a programmable simulator or device which mimics the performance of various types of self-rescuer (if feasible).
- A requirement to assess the applicability of the developed training device to satisfy relevant statutory provisions and to provide the basis of a device that can be used by industry.
- Undertaking wearing trials under various climatic conditions, thereby establishing tolerability and indicative endurance limits.
- Determining what role recovery, cooling and rehydration have in a staged evacuation process.

Programme of Work

The research was organised into two separate but linked phases of work:

Phase 1:

The development of a hot air device which provides a simulation of the breathing behaviour of a W95 filter self-rescuer operating in a carbon monoxide contaminated atmosphere. This work involved thermo-chemical modelling of generic FSR behaviour in specific challenge atmospheres together with the construction and testing of suitable prototype hot air simulation devices for use in Phase 2. Consideration was also given to how the hot air simulation device could be used as the basis of an industry training device.

Phase 2:

This involved undertaking a range of baseline and high temperature physiological endurance tests to examine how well mineworkers accommodate the hot air breathing effects of a filter self-rescuer whilst making a long duration evacuation. This, importantly, also included consideration of the physiological benefits of cooling and rehydration within a staged evacuation process. HSE Research Ethics Committee approval (ETHCOM/REG/04/08) was granted for a programme of physiological tests to evaluate long duration wearing of a hot air FSR simulator device.
Research Outputs and Findings

Phase 1:

Initial studies within Phase 1 confirmed a need to better understand the operating characteristics of a generic FSR when operating in mine atmospheres containing carbon monoxide (CO). To this effect, thermo-chemical modelling of a catalytic FSR was undertaken to appreciate the range of inspired air conditions that could be presented to the user from CO challenge atmospheres of 0.5% (5,000ppm) to 1.5% (15,000ppm). This information would provide insight on the respiratory thermal burden imposed on the wearer and to what extent these conditions could be safely replicated in a training simulation device.

The thermo-chemical modelling identified that the air from a FSR at high CO concentrations would be extremely dry and hot. Indeed, it was not possible to reconcile the temperatures predicted by modelling with the breathing simulator temperature limits prescribed by BS EN 404 1993 and the revised standard BS EN 404:2005: Respiratory protective devices for self-rescue. Filter self-rescuer from carbon monoxide with mouthpiece assembly. It was identified that there were differences in the modelled temperatures of a generic FSR and the inhalation temperature limits specified by BS EN 404. Appraising the BS EN 404 test conditions, the inhalation temperature limits of 90°C dry bulb, 50°C wet bulb were considered to be consistent with a maximum carbon monoxide concentration of 1%. For a CO challenge atmosphere of 1.5%, the thermo-chemical analysis suggested that inspired air temperature limits would be exceeded in a human subject. At a more fundamental level, the possibility is raised that the assumptions made in the EN 404 breathing circuit design for the exhaled air temperature being maintained at 37°C may warrant further examination.

Review of the modelled inspired air conditions presented by a generic FSR suggested that it would not be admissible to reproduce the full range of conditions within a training device. Whilst an escape respiratory protective device is engineered to provide a high degree of protection in dangerous circumstances, a training device must be safe to use and should not result in intolerable discomfort or injury. Medical opinion directed that it would not be acceptable to develop a training device, or long duration research device, which incurred a risk of respiratory tract desiccation or other burn injury potential. Advice was offered that any training device should provide an adequately humidified inspired air characteristic.

A scoping review was undertaken to confirm which approach should be used to providing a hot air device that would simulate the behaviour of a FSR operating in a nominal 0.5% CO content. Initial studies suggested the use of a chemical cartridge carbon dioxide absorbent using proprietary “reactive plastic cartridge” (RPC) technology. 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. This approach offered a drop-in cartridge replacement capability with precise control over breathing resistance, absorbent utilisation and hence minimum duration.

Prototype long duration hot air devices were constructed using RPC technology. An extensive appraisal of the potential risks arising from the use of a chemical cartridge hot air device was undertaken. This considered chemical agent toxicity impacts, the ergonomic design of the cartridge body support and mouthpiece arrangement, the effects of dead space, and, the tolerability of breathing hot air for long durations. The risk appraisal is presented in full as an Annex. Further to the initial device design and modelling, it was agreed that HSE’s laboratory agent HSL would undertake safety testing and characterisation of the prototype hot air device using a breathing simulator. This testing confirmed that the device produced a highly humidified air stream with peak inspired air temperatures within tolerability limits at the anticipated breathing rates. The device was subject to medically supervised wearing to confirm it suitability. A sufficient number of hot air devices were then manufactured for use in the physiological trials. Consideration was also given to possible future use of the device as a training device, with discussions held with interested manufacturers. It was evident
from observations made during the trials that a smaller version could provide the basis of a shorter duration device suitable for training purposes.

**Phase 2:**

Earlier research identified that there are significant potential thermal physiological impacts associated with evacuation and escape from deep, hot mines. During simulated evacuations reported in HSE RR 180, body core temperature was observed to rise progressively, and consistently, to reach or exceed safety guidelines (>38.5°C). The natural instinct of mineworkers in an emergency situation is to ‘run’ and get to safety as fast as possible. However, there may be a need to consider the requirement for thermal physiological safety limits for use in mine/tunnel risk assessments and escape planning guidelines, or alternatively, suitable strategies and support technologies have to be developed to deal with the heat. This latter approach is exemplified by the use of safe havens (underground refuges) within a staged evacuation process. Here safe havens are a central component of mustering and emergency decision making actions, and offer a place where the mine workforce can await rescue or exchange respiratory protective devices, rest and continue their evacuation.

It was evident that safe travelling distance in severe conditions of heat and humidity can only be extended if there is some additional means of cooling available, exercise intensity is reduced and dehydration is prevented. This suggested three key scenarios for evaluation:

1. A baseline physiological response where the subject exercises without rest, additional cooling or rehydration whilst wearing an escape respiratory protective device. This reflects a situation where mine workers commence the evacuation and do not stop until they reach safety.

2. Periodic rest under ambient test conditions whilst wearing an escape respiratory protective device. This is equivalent to a situation where the mineworker paces his evacuation and stops for periodic rests (“breathers”) along the escape route.

3. Periodic rest under ambient test conditions, but with an ability to remove the escape respiratory protective device whilst resting and to freely consume water. This is equivalent to mineworkers being able to rest and recover within a safe haven before continuing their evacuation.

Four test protocols were devised to evaluate these scenarios. In broad terms, if evacuating personnel are unable to cool significantly in the prevailing roadway conditions, then a travelling distance of around 2 km would be consistent with the body core temperature reaching a zone associated with rapidly increasing probability of heat exhaustion. One important finding was that a staged evacuation process involving cycles of moderate pace walking followed by a comparable period of rest has the potential to constrain body core temperature within acceptable limits. In effect, a cycle of exercise and rest ensures the overall level of metabolic heat production is controlled. Providing the roadway ventilation air cooling power is sufficient, it should in principle be possible to limit maximum body core temperature excursions.

The physiological tests provided a clear indication of the benefits of a staged exercise-rest cycle against uninterrupted exercise. The relative distances achieved (or estimated) for each case may be gauged from figure overleaf. It is estimated that the test subject, who was physically fit but unacclimated, could have exceeded a distance of 4.0km in a staged evacuation involving cyclical rest and rehydration, versus 2.1km to reach a body core temperature of 39°C for uninterrupted exercise. The application of staged evacuation strategies, involving periodic rest and recovery, requires further consideration with Mines Inspectorate and mine operators to identify any changes in practice and recommended guidance.
Figure: Comparison of distances achieved under uninterrupted exercise and cyclical exercise-rest

Given the limited size of the physiological test programme, it was not possible to experimentally determine the influence of rehydration and heat acclimation status (acclimatisation). In this regard, estimations of the impact of hydration status and other factors were gauged by reference to the scientific literature.
Evaluating methods of training of mineworkers for hot inspired air when wearing self-rescuers
1. **INTRODUCTION AND RESEARCH OBJECTIVES**

Previous HSE research undertaken by Mines Rescue Service Limited and RPS Business Healthcare, (reported in Research Report 180, http://www.hse.gov.uk/research/rrhtm/rr180.htm) identified significant potential thermal physiological impacts associated with evacuation and escape from deep, hot mines. This report dealt with climatic chamber testing of mines rescue workers wearing a variety of filter self-rescuers (FSR) and self contained self-rescuers (SCSR) in a series of medically supervised tests under hot and humid conditions. During the simulated evacuations, body core temperature was observed to rise progressively, and consistently, to reach or exceed safety guidelines (>38.5°C). The trial key results included:

- In a range of fully saturated atmospheres between 27°C and 37°C all test subjects were withdrawn inside one hour of entering the chamber;
- In some subjects, an increase in body core temperature of 2°C was observed after 30 minutes of exercise;
- During the tests, exceedance of body core temperature limit (38.5°C) was the predominant reason for withdrawal;
- Subjects self-paced themselves at between 2 to 4 km/h but in all cases, body core temperature continued to rise during periods of exercise;
- Only limited cooling took place during rest periods;
- The average total distance covered during the test runs was 1448m;
- The maximum distance covered was 2350m;
- The minimum distance covered was 590m;
- Total distance covered was influenced strongly by chamber temperature;
- Observed run-out times for SCSR varied (MSA SSR 30/100) from 10 to 25 minutes with equivalent distance covered of between 560m and 1400m;
- The mean travel speed for the subject group was 3.3 km/h.

The work and findings within Research Report 180 raised a number of unresolved questions. Specifically, HSE and mine operators required further guidance on how mine escape strategy could be better tailored to address the potential difficulties of escape in very hot and humid conditions. The Health and Safety Commission’s Guidance document on escape from mines [2001]* cites elevated risks situations to include:

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


Escape strategies need to address a wide range of operational situations and scenarios, including mines with deep, distant workings, where gradients and high heat stress conditions can greatly impede evacuation. This situation is observed increasingly as mines become more capital and energy intensive, are driven deeper and operate with long travelling distances to the production areas. The prospect of mineworkers having to retreat through a coal face and along a return roadway, possibly 3km or more in length, in order to escape a developing fire in an intake airway presents arguably one of the most demanding of fire scenarios in an underground coal mine. One incontrovertible fact is an expectation on the part of mine escape planners, that mineworkers have the physical and mental capacities required for self-rescue under these circumstances, and that they would be able to cope with wearing an escape respiratory protective device for a relatively long period, including when the device was presenting a significant heat burden to the mouth and respiratory tract. In many regards, this expectation was not consistent with the breathing apparatus safe wearing duration limits used by the
industry to protect the wellbeing of rescue staff under these circumstances. In some scenarios, mines rescue team travel distance can be affected by severe climatic conditions.

In response, HSE has invoked a number of measures to address the significant thermal physiological impacts associated with evacuation from deep, hot, laterally extended mines. The principal response has been to evaluate the design and application of safe havens as part of a staged evacuation strategy, together with undertaking research within this project on addressing the training needs of wearers of self-rescuers and evaluating their physiological impact. The design of safe havens was considered by an industry-HSE expert group and the output of this group is a guidance document "Guidance and Information on the role and design of Safe Havens in arrangements for escape from mines". At the time of writing, this guidance had been agreed by the Mining Industry Committee and is to be published. The work conducted within this research project complements directly this guidance.

There are currently no physiological heat stress safety limits prescribed for the mining industry, although guidance has been published on precautionary measures and environmental temperature ‘action’ levels. In general, there may be a need to consider the requirement for thermal physiological safety limits for use in mine/tunnel risk assessments and escape planning guidelines, or alternatively, suitable strategies and support technologies have to be developed to deal with the heat. This latter approach is exemplified by the use of safe havens (underground refuges) within a staged evacuation process. Here safe havens are a central component of mustering and emergency decision making actions, and offer a place where the mine workforce can await rescue or exchange respiratory protective devices, rest and continue their evacuation. Refuge-based strategies are commonplace in metalliferous mining. However their adaptation to coal mines continues to require very careful consideration.

There is equally, a need to provide a more realistic training experience of wearing escape respiratory protective devices under adverse conditions. The principal standard for respiratory protective devices for self-rescue in the UK, BS EN 404, does not incorporate adequate assessment of thermal physiological impacts or the assessment of feasibility of long duration wearing. There is a requirement for the mine workforce to have access to a realistic simulation of the breathing and heating effects from wearing the self-rescuers used in the mining industry. As a specific requirement, there is a need to improve training methodology for escape respiratory protective devices, as a minimum accounting for the W95 (or equivalent) filter self-rescuer (FSR). The work within RR180 went some way to addressing these issues, but did not result in a satisfactory training device (the hot air FSR device had deficiencies it terms of maximum attainable temperature, its variability and duration of heat effects). The scale of UK mining operations suggested that a limited number of suitable hot air training simulators or devices, if made available, would meet industry training needs.

**Background on Training and Use of Mining Industry Escape Respiratory Protective Devices**

During events following an underground fire or explosion, survival is critically dependent on the effectiveness of respiratory protective systems. Within UK mines, the principal escape respiratory protective device is the filter self-rescuer, which provides a degree of protection against poisoning from products of combustion by catalytically oxidising the carbon monoxide present. Self-rescuers were introduced into British coal mines following the Michael Colliery disaster on 9 September 1967.

There are several types of escape respiratory protective device available, each having differing modes of operation, i.e. chemical oxygen producing devices providing a short-term isolated breathing system (self contained self rescuers 'SCSR'), or, mixed catalyst - absorbent based chemical filter self rescuers ('FSR'). The one common quality is they both heat up in use (the latter when operating in a carbon monoxide challenge atmosphere). The inspired air temperature can reach uncomfortable levels and in recognition of this, a limited 'hot air' training experience was provided to every person required to go underground as part of their initial training in the use of self-rescuers. This facility was provided on a
voluntary basis i.e., there was no compulsion on mineworkers to undertake the 'hot air' training, but most did. The hot air training units provided a short duration experience of the hot air impacts of using a filter self-rescuer in a high CO content challenge atmosphere. However since 1993 no units have been commercially produced.

In 1995, the new Escape and Rescue from Mines regulations (ERM) identified a number of provisions. This includes Regulation 10, which deals with the mine owner’s duty to provide suitable self-rescuers for all persons going underground in a mine, including the company’s own employees and visitors, such as Mines Inspectors. Regulation 10, ACoP 56, includes a provision to provide a facility for hot-air training - "Where appropriate (i.e. for filter self-rescuers), both initial and refresher training will need to include the option of hot air experience". In Appendix 4, under Initial Training, part 2 states this should consist of three parts "namely: drill, wearing activity and hot air experience". Part 10 states "five yearly refresher training should include the opportunity to undertake the hot air experience if the trainee has not already done it or wishes to repeat it." Part 6 gives detail on the hot air experience stating "Where filter respirator self-rescuers are provided, trainees should have an opportunity to experience breathing hot air by wearing a hot air training model ... for about 15 minutes, or by an extended wearing of a normal self-rescuer resulting in an increase in 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......".

There are two issues to address within Part 6 of the ACoP. Firstly, a normal self-rescuer, no matter how long it is worn for, will not heat up or increase in resistance since it is not exposed to carbon monoxide and no chemical reaction occurs. Secondly, it could be unwise to attempt to simulate increased heat conditions by wearing a self-rescuer in underground hot and humid climatic conditions. Arguably, the only safe and effective way a mineworker can experience realistic 'hot air' training in the use of an escape respiratory protective device is to use a simulator. Anecdotal evidence on the hot air breathing impacts and the importance of hot air training in the use of filter self-rescuers can be gauged from the circumstances of the explosion at Moura No.2 coal mine, Australia on 7 August 1994, when 10 of the 21 miners underground at the time of the first explosion escaped wearing FSRs. All reported the "intensity of the heat generated by the self-rescuers". Unfortunately 11 miners lost their lives and in the inquiry that followed, the adequacy of FSR was questioned in light of the availability of alternative types of escape breathing apparatus and in the context of being part of an overall escape strategy. Within the UK, the Escape and Rescue from Mines regulations 1995 is probably unique legislation in that it encourages mine managers to seek the advice of a Mines Inspector, if they are in doubt as to the suitability of a self-rescue; viz. Reg.10 - ACoP 46. Provision of a hot air simulator is regarded as a prerequisite to allow further research into the tolerability and suitability of self-rescuers that may be worn in hot and humid conditions. The reported research addresses this statutory gap.

**HSE Research Requirements and Objectives**

HSE defined a need for an improved training methodology for escape respiratory protective devices, essentially to provide a realistic experience of the hot air breathing effects of a device operating in a high carbon monoxide content challenge atmosphere. Information was also sought by HSE on the tolerability and ultimately endurance limits associated with the extended wearing of an escape respiratory protective device producing a significant heat burden. The above information would collectively help address HSE's duty to offer advice to mine managers on escape respiratory protective systems selection and use, including where escape will entail conditions of high heat and humidity. As part of these investigations, there was a requirement to examine whether cooling and rehydration (possibly within safe havens) was feasible and could be utilised as a possible intervention response to reduce heat stress potential during evacuation. It was anticipated the research undertaken could result in a requirement for amendment of BS EN 404: 1993, section 6.3 (Practical performance tests) to reflect improved knowledge on training methodology. Appropriate recommendations and discussions would need to be undertaken in conjunction with relevant UK and European Working Group representatives.
In summary, HSE project aims included:

- A requirement to provide a realistic simulation of both breathing resistance and the heating effects that occur when wearing self-rescuers.
- The development of a programmable simulator or device which mimics the performance of various types of self-rescuer (if feasible).
- A requirement to assess the applicability of the developed training device to satisfy relevant statutory provisions and to provide the basis of a device that can be used by industry.
- Undertaking wearing trials under various climatic conditions, thereby establishing tolerability and indicative endurance limits.
- Determining what role recovery, cooling and rehydration have in a staged evacuation process.

In terms of the submission to HSE Ethics Committee, the relevant phase of the research was principally that associated with establishing tolerability of the FSR simulator under typical escape scenarios. These endurance tests could extend to two hours or more and would involve heat stress, with the tests undertaken in elevated heat and humidity conditions. As noted earlier, precursor research was undertaken which also involved a submission to the Ethics Committee (for the work within HSE Research Report RR180). This research, as a subsidiary task, undertook development and testing of a hot air self-rescuer training device. Unfortunately, the device developed within the scope of RR180 did not simulate in a satisfactory manner the hot air behaviour of a filter self-rescuer during extended wearing circumstances, particularly under conditions of high heat and humidity. The graph below, reproduced from RR180, indicates that the device offered a useful hot air experience that generally lasted for less than 10-15 minutes.

As such, only qualified data was derived within RR180 on the tolerability of wearing filter self-rescuers. Furthermore, there was also no work undertaken to establish the significance of resting and rehydration as a means of controlling body core temperature. Both of these issues were addressed in the subsequent research project reported here.
2. DESCRIPTION OF KEY RESEARCH TASKS

The work was conducted in two phases, summarised as follows:

**Phase 1:**
Development of a hot air device which models breathing behaviour of a W95 filter self-rescuer (FSR) operating in a carbon monoxide (CO) contaminated atmosphere. This work involved thermo-chemical modelling of generic FSR behaviour in specific challenge atmospheres together with the construction and testing of suitable prototype hot air simulation devices for use in Phase 2.

**Programme of work:**
1. Dialogue was conducted with industry experts and manufacturers to ascertain the inspired air characteristics for a W95 FSR when operating with 0.5% (5,000ppm) mine atmosphere carbon monoxide (CO) content in representative mine climatic conditions.
2. Supporting thermo-chemical modelling of a generic catalytic FSR was undertaken to appreciate the range of inspired air conditions that could be presented to the user from specific challenge atmospheres. This information would also provide some insight on the respiratory thermal burden imposed on the wearer.
3. A scoping review was undertaken to confirm which approach should be used to providing a hot air device that would simulate the behaviour of a FSR operating in a nominal 0.5% CO content. Initial studies and work undertaken with HSE RR180 suggested the use of a chemical cartridge carbon dioxide absorbent using proprietary “reactive plastic cartridge” (RPC) technology. This was considered the best approach to engineering a portable, wearable device to provide a “hot air breathing experience” for use during the physiological test programme and possibly for training purposes.
4. Undertake a full appraisal of the potential risks arising from the use of a chemical cartridge hot air device. It was agreed that HSE’s laboratory agent HSL would undertake safety testing and characterisation of the prototype hot air device using a breathing simulator.
5. Manufacture a sufficient number of hot air devices for use in the physiological trials phase. Consideration was also given to possible future use of the device as a training device.

**Phase 2:**
This involved undertaking a range of baseline and high temperature physiological endurance tests to examine how well mineworkers accommodate the hot air breathing effects of a filter self-rescuer whilst making a long duration evacuation. This included consideration of the physiological benefits of cooling and rehydration within a staged evacuation process. HSE Ethics Committee approval (ETHCOM/REG/04/08) was granted for a programme of physiological tests to evaluate long duration wearing of a hot air FSR simulator device.

**Programme of work:**
1. Careful consideration to be given to the trial programme design and how statistical significance might be obtained consistent with the limited research project budget. This would include consideration of extrapolation of the research findings to the wider mine workforce.
2. A cohort size of 8 subjects was selected, drawn from the pool of available volunteers, all of whom were employees of Mines Rescue Service Ltd. The cohort group was maintained throughout the trial programme.
3. A suitable means of exercising the subjects within the specified range of environmental conditions was to be devised. Electrical safety requirements dictated the use of mechanical,
self-paced treadmills and battery-powered monitoring equipment which would be unconditionally safe where chamber conditions lead to a condensing atmosphere.

4. The trials employed a recently completed environmental training facility at Rawdon Mines Rescue Station. The environmental chamber could be operated with either sensibly static air conditions or with a modest ventilation air flow, of the order of 0.5m/s. The latter operating mode was used throughout the trials.

5. A range of pilot tests and comparative baseline tests was undertaken. All subjects were medically checked and supervised throughout the trials, supported by continuous recordings of heart rate and body core temperature.

6. The test sequence followed the protocol approved by HSE’s Research Ethics Committee. This comprised baseline and high temperature tests. Where feasible, the pilot trials were incorporated with the baseline tests in order to reduce the overall number of tests. Each subject was used as their own control to provide a baseline reference.

7. HSE considered it important that as wide a range of observations as possible be obtained on factors impacting on staged evacuation physiological response and that indicative observations and data would still be considered useful.

8. The subjects would exercise at a maximum effective temperature of 32°C and would be permitted to self-regulate their pace on the treadmill, even though this introduced a further uncontrolled variable.
Phase 1: Development of hot air simulation device and thermal modelling

Essentially the modelling work was progressed in two stages. The initial thermal modelling research concerned the behaviour of a generic catalytic filter self-rescuer (FSR), to determine inspired air conditions when operating in various mine atmospheres/CO concentrations. Three specific input conditions of temperature and humidity were assumed:

- 20°C/60% Relative Humidity
- 29°C/95% Relative Humidity
- 37°C/95% Relative Humidity

with an initial 0.5% carbon monoxide concentration. Then further analysis was undertaken for carbon monoxide concentrations of 1% and 1.5% respectively in order to determine inspired air conditions presented by the self-rescuer under 'severe' conditions of use.

The thermal modelling of a generic FSR pointed to any such device being potentially "unwearable" at 1.5% CO concentration for a sustained period of wearing, particularly at high lung ventilation rates. In essence, there is a fundamental difference between the modelled data for a generic FSR complete with heat exchanger operating in a CO challenge atmosphere and the test condition limits specified in EN 404 (which are specified at 0.25% and 1.5% CO respectively). A discussion on the lack of reconciliation with EN 404 is given which suggests that assumptions made in the EN 404 test apparatus may be flawed. This matter requires further consideration. A summary of the modelled FSR data is given in Annex 3.

The hot air cartridge device was modelled under the same prevailing mine/test chamber atmospheric conditions (20°C/60%RH, 29°C/95%RH and 37°C/95%RH), together with a range of exercise conditions, noting that 'sensible' estimates of respiratory conditions and carbon dioxide production rates etc. were made. The range of modelled inspired air conditions potentially presented by the hot air cartridge is given in Annex 4. In addition to modelling of the hot air device, thermal characteristics were measured by HSL using a breathing machine. An extensive risk appraisal was produced in support. Further details are given in Annex 1, Annex 2 and Annex 4.

A number of prototype hot air devices were assembled for the physiological trials. The devices functioned as expected, presenting a tolerable but significant heat burden to the wearers.
3. THERMAL MODELLING OF GENERIC FILTER SELF-RESCUER

The objective of this component of the work programme was to gauge how the inspired air characteristics of a generic filter self-rescuer behave as a function of challenge atmosphere ambient psychrometric conditions and carbon monoxide concentration. The thermal modelling data derived would then provide cardinal point specification detail for the hot air simulation device. The term “generic” here applies to any FSR which employs catalytic processes to oxidise the carbon monoxide. In this regard the heating rate is relatively independent of device design. The heating rate is fixed in that the standard enthalpy change of combustion of carbon monoxide is a physical constant, 283 kJ/mol, irrespective of catalyst type used. The other aspect of “generic” design is the heat exchanger used in FSR devices to cool the post-oxidation stage gases. Providing the heat exchanger has adequate mass and interfacial area (as for example imparted by copper wire wool) then there would be relatively small differences between heat exchanger designs.

The thermal modelling results are reproduced in Annex 3. Inspection of the output data confirms significant differences in the modelled temperatures of a generic FSR and the inhalation temperature limits of 90°C dry bulb, 50°C wet bulb imposed by EN 404. It was not possible to reconcile the differences between the modelled results at 1.5% carbon monoxide and the aforementioned limits. It is observed that the modelled operation of a filter self-rescuer at high lung ventilation rates and at 1.5% carbon monoxide concentration is associated with very high heating rates. The heat exchanger within the FSR will permit a useful removal of heat. However, it was considered that there was rather limited scope to improve upon the heat exchanger used within the W95. Other than minor heat losses through the device case (and breathing tube if employed) there remains only one mechanism for cooling; namely employing the latent heat of evaporation of water in the respiratory tract. It is however speculated that this mechanism may well be compromised when ‘overloaded’ with excessively hot air for extended periods.

It can be gauged from Table 3.1 below that any device wearer who tries to accomplish strenuous work (and therefore incurs a high lung ventilation rate) in a high CO content atmosphere will observe a very high heating rate, possibly in excess of 300Watts. It is not unrealistic to envisage a scenario where the inspired air characteristics at the mouth and naso-pharyngeal region could become intolerable. Anecdotal evidence has already been cited in respect of the Moura Mine disaster, Australia. Personal communications with Deutsche Steinkohle AG (DSK), Germany confirm that after an explosion at the Stolzenbach Mine, Borken in 1988 that many of the 51 fatalities had removed their filter self-rescuers. The reason for the removal was speculated to be excessive inhalation temperature.

| Table 3.1: Estimated heating rates arising from CO oxidation within a generic FSR |
|------------------------|-----|-----|-----|
| Lung ventilation rate, Litres/min.: | 20  | 43  | 100 |
| CO concentration: | 0.5% | 0.5% | 0.5% |
| Heating rate*: | 21.2W | 45.5W | 105.9W |
| CO concentration: | 1% | 1% | 1% |
| Heating rate*: | 42.4W | 91.0W | 211.8W |
| CO concentration: | 1.5% | 1.5% | 1.5% |
| Heating rate*: | 65.5W | 136.6W | 317.7W |

*Heating associated with catalytic conversion of CO within FSR
Notwithstanding the observations from the Moura and Stolzenbach Mine incidents, filter self-rescuers are considered a robust, reliable technology by industry and which is capable of offering excellent protection from toxic products of combustion including carbon monoxide at moderate concentrations. The issue here is entirely a question over the tolerability of the device at high CO concentrations (of the order of 1.5%, 15,000 ppm). As a further point for consideration, Japanese work undertaken to establish tolerability limits for breathing hot air (Takahashi et al 1999) established that a maximum wet bulb temperature of 53°C could be tolerated and hot dry air to 90°C. However subjects in these trials exercised only for 5 minutes and at moderate work rates. The Japanese researchers identify an assumption that the tolerance limits are predicated entirely on the respiratory tract not becoming desiccated and issue a cautionary note:

"If, however, an apparatus produces hot and dry air sufficient to dry out the normally wet surfaces of the mouth and respiratory tract, the dry-bulb temperature of the inhaled gas will better approximate the temperature of the mouth and respiratory tract".

This latter condition, if sustained, may be associated with thermal injury potential. The heat transfer analysis from Takahashi et al (1999) also points to a nett measured heating rate to the body of up to 140W under the experimental conditions cited. This is considered significant. It was not possible to identify literature which confirms tolerance under these conditions for say 1-2 hours and beyond. It would be helpful if the physiological evidence could be obtained against which the BS EN 404 limits of temperature and humidity tolerability (90°C DB, 50°C WB) are premised for the classified minimum test duration of 120 minutes for FSR-4BR devices (such as the W95).

**Reconciliation with BS EN 404 1993**

It is identified that there are differences in the modelled temperatures of a generic FSR and the inhalation temperature limits of 90°C dry bulb, 50°C wet bulb imposed by EN 404. It was not possible to reconcile the differences between the modelled results at 1.5% carbon monoxide and the aforementioned limits. Appraising the EN 404 test conditions, the inhalation temperature limits of 90°C dry bulb, 50°C wet bulb are considered to be consistent with a maximum carbon monoxide concentration of circa 1%. For a test challenge atmosphere of 1.5%, the thermo-chemical analysis suggests that these inspired air temperature limits might be exceeded. It is not clear how these differences can be reconciled but three points were raised for consideration:

- With regard to BS EN 404 1993, s. 6.4.1, one key issue is how fast the ‘fast-response thermocouple’ is in practice. It is assumed that each cycle of the breathing machine is followed precisely and faithfully with negligible thermal time constants. Otherwise the temperature will reflect some ‘integrated’ intermediate value between the peak temperature seen in the inspired air stroke, and the ‘trough’ seen in the expired air stroke.
- The test arrangement in BS EN 404 Fig. 1a does not state how heat losses are prevented or accounted for, arising from the inter-connecting ducts and the breathing machine. These heat losses could moderate the extremities of temperature cited in the modelled work.
- At a more fundamental level, the possibility was raised that the assumptions made in the EN 404 breathing circuit design for the exhaled air temperature being maintained at 37°C may warrant further examination.

In reading BS EN 404 1993, s. 6.4.1, Table 6, there is a specification that the exhalation air shall be maintained at 37°C ±0.5°C, 95-100% RH. There is also a requirement that the exhalation air is checked to comply with the given figure. A reasonable interpretation of the standard is that the exhalation air shall be maintained at 37°C ±0.5°C under all conditions. It is noted that the exhalation air from the humidifier circuit is returned to the heat exchanger of the FSR, where it usefully cools the airstream which has emerged from the carbon monoxide catalyst stage. If this interpretation of the standard is consistent, then there is a mechanism for reconciling the figures expected from modelling of a human subject wearing the FSR.
With further reference to line 6 of the thermal modelling results, tabulated in Table 1 of Annex 3. Inspection of line 6 confirms that it is not considered possible within respiratory tract cooling mechanisms for the exhaled air to be maintained below 38°C for a carbon monoxide challenge atmosphere concentration much above 0.5%. The capacity for mucosal evaporation to maintain wet bulb temperatures below 38°C is lost at higher carbon monoxide concentrations, where the heat balance with the inspired air dictates that a higher exhalation temperature must result. In extremis, we note an exhalation temperature of ~54°C WB results. This is quite different from the maintained exhalation air conditions of 37°C ±0.5°C, 95-100% RH cited in BS EN 404 1993. The nett consequence is that in a human test situation, the exhaled air will have a somewhat lower capacity to cool the hot air arriving from the catalyst. In contrast, if the EN 404 test conditions enforce a lower exhalation air temperature, this will have significantly greater capacity to moderate inspired air temperatures.

It is asserted that EN 404 inhalation temperature limits of 90°C dry bulb, 50°C wet bulb can only be consistent with a maximum carbon monoxide concentration of circa 1%.

It is noted that BS EN 404 1993 was replaced by BS EN 404:2005: Respiratory protective devices for self-rescue. Filter self-rescuer from carbon monoxide with mouthpiece assembly. However, it is pointed out that current mining industry FSRs were assessed against BS EN 404 1993.
4. HOT AIR SIMULATION DEVICE: DESIGN, MODELLING AND TESTING

Hot Air Device Based on CO₂ Absorption

A review of the technical options for a hot air device is given in HSE Research Report 180. Other than the use of a carbon dioxide absorbent chemical cartridge, the only other option considered as the basis of a long duration hot air device was an electrically heated device. The latter alternative involving an electrically heated analogue of FSR behaviour was rejected due to limitations imposed on wearer mobility. The use of proprietary soda lime absorbent cartridge technology (“reactive plastic cartridge”, RPC) described in Annex 1 was selected as the basis of the hot air device. 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%.

As discussed in HSE Research Report 180, the approach to providing a hot air simulation of a FSR operating in a CO challenge atmosphere was to use a calcium hydroxide absorbent cartridge in a simple ‘pendulum’ breathing circuit (i.e. the inspired and expired air pass through the same circuit elements). The conceptual arrangement can be gauged from Figure 4.1 below.

Figure 4.1: Conceptual form of hot air device using CO₂ absorbent canister
This arrangement provides a simple, robust breathing circuit where the calcium hydroxide cartridge behaves as a recuperative heat exchanger to preheat the inspired air stream. It is noted that the heat liberated by a FSR is largely dependent on ventilation rate and CO concentration, whilst the heat from the hot air simulation device is a function of CO₂ exhalation rate (VCO₂). However, on balance it was considered to provide a suitable analogue to a FSR for constrained exercise work rates and constrained input psychrometric conditions to the device.

The primary constituents of soda lime include calcium hydroxide - Ca(OH)₂ (about 70-80%), water - H₂O (about 16 to 20%), sodium hydroxide - NaOH (about 1-2%), and potassium hydroxide - KOH (about >0-1%). The cartridges employed used mixed alkali hydroxides, with calcium hydroxide comprising 92.3% molar proportion, with the remainder constituted by sodium and potassium hydroxides. Water is an important part of the reaction which takes place to bind the CO₂. The general description of the reaction is as follows. The complete reaction is still not fully understood.

\[
\begin{align*}
    \text{H}_2\text{O} + \text{CO}_2 & \rightarrow \text{H}_2\text{CO}_3 \\
    \text{NaOH} + \text{H}_2\text{CO}_3 & \rightarrow \text{NaHCO}_3 + \text{H}_2\text{O} \\
    2\text{NaHCO}_3 + \text{Ca(OH)}_2 & \rightarrow 2\text{NaOH} + \text{CaCO}_3 + \text{H}_2\text{O}
\end{align*}
\]

Firstly, the gaseous CO₂ reacts with water to form carbonic acid - H₂CO₃. Then, the NaOH reacts with the carbonic acid to produce Na₂CO₃ and H₂O. The Na₂CO₃ reacts with the Ca(OH)₂ which has been dissociated into calcium and hydroxide ions (Ca++ and OH-) to produce CaCO₃ (calcium carbonate). The CO₂ is now in a relatively stable state. There is a nett production of three H₂O molecules for every molecule of CO₂ absorbed together with exothermic heat. The weighted heat evolution for the absorption of 1 mole of carbon dioxide is calculated at 57.43 kJoules. The free evolution of water in the reaction is important in that in helps ensure the inspired air drawn through such a cartridge is both heated and humidified.

**Hot Air Device Modelling**

The overall objective here was to produce a simple analytical model which would permit the hot air device airflow behaviour to be predicted with a sensible level of accuracy for various use conditions. The modelling work was verified by testing on a breathing simulator. This work was undertaken by HSL. Whilst the modelling work produced a good descriptive model of device behaviour and the influence of primary respiratory and environmental parameters, the thermal characteristic of the practical chemical cartridge device was shown to be relatively complex.

Device behaviour was modelled under the following ambient environmental conditions. These conditions represented the range of conditions in which the device might be used.

- **Training Use**: 20°C @ 60%RH
- **Endurance Trial Use**: 29°C @ 95%RH
- **Upper Limit of Use**: 37°C @ 95%RH

After initial sizing calculations, two cartridge sizes were sourced, with a weight of absorbent of 900g and 1.2 kg respectively, and 831 and 897 individual flow channels in their designs. The layered disposition of the reagent and flow channels within the cartridge can be seen in Figure 4.2 overleaf.
The analysis was complicated by the fact that it is difficult to quantify the impacts of varying mine floor conditions, obstructions and potentially low visibility on the metabolic work rate associated with self-paced walking during an escape or evacuation. Literature on bipedal locomotion mechanics and energy consumption under various stress conditions (e.g. soft floor, heavy boots and limited height clearance) was examined to offer some insight into the additional energy debit expended during exercise under adverse conditions, and allowances made. Estimates were used for design centre figures for the test population in regard to lung ventilation rate (VE), respiratory exchange ratio, peak flow rates and impacts of dead space volume and breathing resistance on limiting subject potential performance. Estimates were also used for the population mean $\text{VCO}_2$ at specific sub-maximal regimes/work rates. For the purpose of calculation, a lung ventilation rate of 43 litres per minute and respiratory exchange ratio of unity was assumed. This corresponds to 2 litres of carbon dioxide per minute or 10.7 moles produced in 2 hours.

The behaviour of the reactive plastic cartridge in a recuperative heat exchanger configuration was modelled under typical training, laboratory and limit psychrometric conditions of use. Work was also undertaken to model the flow properties through the cartridge device. This was required, in part, to ensure that device breathing resistance was tolerable and did not unduly limit subject potential performance. At a VE of 43 litres per minute STPD, approximate peak flows of around 170 litres per minute BTPS could be anticipated. The flow regime within the prototype cartridge/housing was considered to be complex. The analysis is presented in Annex 4. It is noted that the predicted pressure drop through the candidate RPC cartridge is acceptable against respiratory breathing resistance limit guidelines. Discussions with Micropore Inc. indicate that the manufacturer has not yet been able to develop an adequate analytical flow model and uses practical pressure drop testing to characterise individual cartridge designs.

Based on the various assumptions above, the hot air device was estimated have a rate of heat evolution of carbon dioxide absorption which will be approximately twice that of carbon monoxide oxidation. Essentially, the heat liberated within the hot air device will be equivalent to that liberated in a catalytic filter self-rescuer at a carbon monoxide concentration of 1%. The results of the thermal modelling are given in Annex 4.
Hot Air Device Risk Assessment

In view of the unproven design of the hot air device and the long wearing durations anticipated, it was considered necessary that the risk assessment included laboratory testing and qualification of the device behaviour together with a medically-supervised pilot wearing trial. The primary risk issues of wearing the hot air device were considered to be as follows:

(a) establishing that the hydroxide reagents used within the device did not present unacceptable risks from inspired particulate or toxicity impacts.
(b) ensuring that the ergonomic design of the cartridge body support and mouthpiece arrangement was appropriate to the nett weight, possibly as much as 1500g, taken together with the possibility of a long wearing period for the device.
(c) ensuring that any dead space in the hot air device did not lead to rebreathing and a potential to cause oxygen deficiency.
(d) assessing the tolerability of breathing hot air for long durations and the possibility of respiratory tract desiccation or other burn injury potential.

Issues (c)-(d) were considered the most difficult to resolve. The risk assessment concerning thermal respiratory and dead space related issues is reproduced in full in Annexes 1 and 2. Under controlled conditions of use the device dead space was confirmed to be high but not excessive. This is reflected in maximum inspired carbon dioxide levels of 1% when evaluated on a breathing simulator. The issue of respiratory tract desiccation was also been revised in the light of HSL's breathing simulator tests. Here it was demonstrated that the inspired air from the device was in all cases of very high relative humidity, >90%. This was not anticipated from earlier device modelling and suggests that the absorption of carbon dioxide on the reagent matrix is associated with a significant reciprocal evolution of free water.

One approach adopted in the risk assessment was to relate the extended wearing of the prototype device to the limit conditions for certified closed circuit breathing apparatus. Within BS EN 145:1997 (section 6.28.5) it is specified that the temperature of the inhaled gas, irrespective of humidity level, shall not exceed 45°C over a two-hour test duration and 50 l/min breathing rate. This limit temperature is lower than that observed in the breathing simulator tests of the prototype device (at least during the initial part of their operation). However, offsetting this, breathing rates would be lower during the self-paced walking exercise of the physiological trials. Investigations were also conducted to ascertain the maximum inhalation temperatures of various closed-circuit apparatus types in use. Here, it was evident that approved apparatus (for example BG 174) can reach 47°C at a breathing rate of 30 l/min and ambient temperature of 30°C.

There are clearly a number of issues concerning "endurance" wearing of a hot air device which required medical opinion. This included the respiratory tract desiccation mechanisms and the possibility of progressive deoxygenation due to the device dead space. The risk assessment confirmed that the risks to the wearer were low providing the use of the hot air device was medically supervised.
Testing of Prototype Device - Results

Development and assessment of the hot air device progressed via modelling, prototype design and verification testing. The thermal modelling of the inspired air characteristic of the proposed hot air device was verified by testing. This testing involved the device being attached to a pendulum breathing simulator at HSL. A small matrix of tests was undertaken to characterise the hot air device behaviour at nominal ventilation rates of 35 L/min and 60 L/min for a test period of 120 min. Two cartridge types were tested; one of 152 mm length and the other of 195 mm length. The test results and observations made by HSL are summarised as follows:

- The breathing resistance of the cartridges was at worst of the order of \( \pm 20 \text{mm H}_2\text{O} \) and was reasonably consistent for the duration of the test (2 hours). This level of resistance should not burden the wearer unduly.

- The level of rebreathed carbon dioxide was generally less than 1% for the major part of the test, only reaching 1% towards the end of the test. This is an acceptable level of carbon dioxide as evidenced by the majority of respiratory standards having this level of rebreathed carbon dioxide as a limit.

- Oxygen levels are not of concern as ambient air is drawn through the device and carbon dioxide levels are adequately controlled.

- Inspired air temperature is partly dependent on the breathing rate of the wearer. Tests at a lower breathing rate (35 l/min) produced lower temperatures than tests at a higher breathing rate (60 l/min). Under ambient conditions, lower breathing rates gave peak temperatures of the order of 45°C. At the higher rate, peak temperatures approached 50°C. The peak occurred after approximately 15 minutes and then reduced by some 10 to 15 degrees over the remainder of the test. This temperature pattern was observed for all tests, regardless of canister size or environmental conditions of test.

- When tested at a higher external temperature and humidity (37°C and 95% RH), peak temperatures were a few degrees higher at the lower breathing rate but were of the order of 55°C at the higher breathing rate.

- The relative humidity of the inhaled air was high under all conditions of test, exceeding 90% in all cases. This is due to the nature of the chemical reaction involved.

- Two sizes of cartridge were tested; 152mm and 195mm in length. From the results, there appeared to be little significant difference in performance and hence the smaller, lighter cartridge is recommended.

- In order to use a cartridge as a potential training device to simulate hot wearing, it is recommended that the breathing rate be restricted (by selecting conditions of use) to <35 l/min in order to maintain the inhaled air temperature below 45°C. A short length of corrugated breathing hose to the cartridge holder will help reduce the peak inhaled air temperature by providing some heat loss to the ambient environment.
Medically Supervised Wearing Trial of Hot Air Device

The prototype hot air device was evaluated for the possibility of hypoxia potentiation under the supervision of the study physician. A medically supervised wearing trial of the hot air device was conducted with test observations as follows:

- The wearing trial of the prototype hot air device was conducted with the subject sitting at rest using a 152mm cartridge. The lower plenum chamber was used to retain the cartridge, which incurred a small additional increase in dead space.

- A pulse oximeter was used to monitor oxygen saturation, %SpO₂. The pulse oximeter was checked by the study physician to confirm the readings were consistent prior to use. The instrument had a specified accuracy of \( \pm 2\%\text{ SpO}_2\) over the range 70-100%.

- Heat from the device, which is principally a function of CO₂ exhalation rate (VCO₂), was slow to build up, taking of the order of 10 minutes. This was considered to be consistent with the high cartridge mass, low test breathing minute volume and corresponding VCO₂. The inhaled air was judged to be well-humidified and readily tolerated. The device will deliver higher temperatures when the subject exercises. The breathing resistance was considered to be low and acceptable.

- During the period of extended deep breathing, there was no discernable reduction in oxygen saturation reading. During this test phase, the tidal volume exceeded the dead space volume by a large margin.

- During the final phase of the test, breathing was deliberately changed to very shallow, low tidal volume breathing to check for any reduction in oxygen saturation reading, %SpO₂.

- During the period of constrained shallow breathing, there was an observed reduction in oxygen saturation reading to 78%. This is consistent with the tidal volume being of comparable magnitude to the dead space and the CO₂ stimulus response being lowered due to the cartridge absorbent action.

- Medical opinion was that quiet breathing at rest would not be typical of the physiological test conditions, where a somewhat higher breathing rate and tidal volume would be observed. The hypoxia stimulus would also at some point induce an autonomous reaction to increase breathing rate and breathing depth. The risk appraisal in Annex 2 considers these matters further. As a precaution, spot checks were made during the pilot trials to confirm that oxygen saturation was maintained at a normal level for subjects.

- The heat exchange process within the cartridge appeared to be largely confined to the upper 30% of the cartridge. A training device of shorter duration could reasonably employ a cartridge of smaller mass/dead space, consistent with ensuring adequate gas flow residence time. There was no significant residue of saliva or condensate and the in line air filter had significant residual capacity at the end of the test.
Use of Prototype as a Training Device

A meeting was held with MSA regarding the possible use of the prototype device as the basis of a training aid. The discussions covered the range of technical options available to provide a hot air experience simulating the behaviour of a filter self-rescuer (operating in a CO challenge atmosphere).

It was noted that MSA had investigated an electrically heated device to simulate the behaviour of self-contained self-rescuers, required for the South African market. A related fixed infrastructure training simulator developed for the mining industry in Asturias, Spain was also discussed as a further option. However, on balance it was agreed that the chemical cartridge approach, as proposed, was arguably the best approach to providing a training device. Apart from portability benefits, the heat of evolution associated with CO₂ absorption was inherently limited and the inspired air had a high relative humidity. These were considered important safety features in a training model.

The design objectives, thermal behaviour and safety issues associated with granular reagent and reactive plastic cartridge type devices were contrasted. It was proposed that a small reactive plastic cartridge could provide the basis of a short duration training device (~20 minutes) with attendant low variability in characteristics.
5. PHYSIOLOGICAL TRIALS

Phase 2 of the research programme was concerned with the physiological trials phase. Within the scope of finite experimental resources, it was considered that maximum value would derive from focusing the research approach as follows:

- Demonstrate uncompensable heat gain during sustained exercise under the tests conditions.
- Demonstrate cooling potential within an exercise-rest cycle.
- Evaluate the ability of repeated exercise-rest cycles as a means to avoid excessive cumulative heat storage.
- Evaluate the limitations of a staged evacuate-rest and recovery cycle approach at higher heat stress levels.
- Evaluate the impacts of hydration status, acclimation etc. by reference to a supporting review of the scientific literature.

**Test Protocols and Escape Scenarios**

It is evident from HSE RR 180 and other data that safe travelling distance can only be extended if there is some additional means of cooling available, exercise intensity is reduced and dehydration is prevented. This suggests four scenarios for evaluation:

i  A baseline physiological response where the subject exercises without rest, additional cooling or rehydration whilst wearing an escape respiratory protective device.

ii Periodic rest under ambient test conditions whilst wearing an escape respiratory protective device.

iii Periodic rest under ambient test conditions, but with an ability to remove the escape respiratory protective device whilst resting and to freely consume water.

iv Periodic rest and fluid replenishment conducted at a lower ambient temperature or humidity than the ambient test conditions (for example as would be obtained within a climate-controlled safe haven, if such existed).

Trial run D290507-08-N corresponds to the first scenario. Each of the other three scenarios is capable in principle of achieving some cooling and therefore an extension in safe travelling distance. For cooling to take place within scenarios ii and iii, wet-bulb temperature must be <34°C, although as discussed in Section 6, there is a rapid diminution in air cooling power for wet-bulb temperature >31°C.

The ability to quantify the benefits from fluid replenishment during a simulated evacuation was not considered feasible within a small test matrix. It was therefore decided that the impact of hydration status would be gauged qualitatively by way of reference to the scientific literature. Section 7 discusses various factors which impact upon individual heat stress response. Equally, it was not considered feasible to gauge experimentally the impact of cooling in a separate microclimate.
Arguably, the most important scenarios were considered to be ii and iii above. The first of these relates to the simple process of an escaping mineworker taking a periodic rest in the mine roadway, and then when rested, continuing in a staged evacuation process. This scenario dictates the mineworker must continue to wear the escape respiratory protective device provided, and would not be given any relief from the respiratory heat burden, or opportunity to consume drinking water until fresh air was reached. Scenario iii corresponds with a staged evacuation using safe havens which are provided with breathable air, but where the air within the safe haven does not have significantly greater air cooling power than the mine ventilation air. (In practice, safe haven designs are supplied with a high volume flow rate compressed air source which is engineered to be as cool and dry as possible).

In this regard, scenarios ii and iii above were considered important; since they are consistent with current mine escape practice and provision. Four test protocols, A-D were devised. The focus of test protocols “A” and “B” was to address scenario ii, whilst test protocol “C” addressed scenario iii. The protocols are summarised as follows.

**Protocol “A”**
- Commence treadmill exercise with hot air device, nominally 25 minutes
- Rest, seated, for 15 minutes with hot air device worn
- Recomence treadmill exercise, with hot air device worn, for 25 minutes (or period at discretion of study physician)
- Hot air device removed, rest for 15 minutes, seated
- Completion of test run

**Protocol “B”**
- As for protocol ‘A’, but conducted at a 2°C higher chamber temperature

**Protocol “C”**
- Exercise with hot air device (initially 25 minutes) followed by rest and recovery (seated) for 15 minutes. Hot air device removed during rest period and free drinking encouraged
- Cycle repeated. This is equivalent to rest and recovery taking place in a safe haven with comparable psychrometric conditions to the mine roadway.
- Nominal 32°C $T_{WB}/T_{DB}$

**Protocol “D”**
- Continuous self-paced exercise, without rest, until withdrawal criterion reached.

**Trial Supporting Arrangements**

The trial medical supervision arrangements, withdrawal criteria and physiological instrumentation were in common with the arrangements reported in HSE RR 180. Annex 6 provides a review of physiological measurement issues and techniques. Data management procedures were also similar to those used in HSE RR 180, other than data protection measures, which were extended to prevent the possible identification of the test subjects.

Dr Andrew Booth, Study Physician, medically checked the test subjects and supervised all trials and post-trial recovery. Again, procedures were in common with those defined in HSE RR 180.
**Trial Results**

Some 22 individual test runs were undertaken:

- 4 pilot runs
- 8 runs using protocol “A”
- 2 runs using protocol “B”
- 7 runs using protocol “C”
- 1 run using protocol “D”

The graphical output of each test run is given in Annex 5 in terms of body core temperature (channel 1, °C), heart rate (channel 13, bpm) and treadmill odometer pulse output (channel 14). In each case, the x-axis shows elapsed time in hours together with the periods of exercise and rest being defined. The environmental chamber wet-bulb, dry-bulb temperatures and estimated relative humidity are also indicated in Annex 5.

The generalised characteristic for body core temperature response is given in Figure 5.1. The observed mean rates of body heating and body cooling are given in Table 5.1. Maximum heating and cooling rates were also estimated using regression analysis from the “linear” segments of the heating and cooling components of the cycle and are presented in Table 5.2. The distance walked and average speed for each cycle of exercise, together with the total aggregated for the trial run, are given in Table 5.3.
Figure 5.1: Generalised characteristic of physiological trials with heat gain (T1, T3, T5, T7) and cooling (T2, T4, T6, T8) and exercise periods (男子) followed by rest periods
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<th>T3 (°C/hr)</th>
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| Minimum Rate  | 1.69       | -1.13      | 1.47       | -1.42      | 2.02       | -1.80      |            |            |
| Average Rate  | 2.73       | -1.68      | 2.87       | -2.46      | 2.89       | -2.16      | 2.86       | -2.04      |
| Maximum Rate  | 4.61       | -2.51      | 4.69       | -4.37      | 3.85       | -2.93      |            |            |

**Table 5.1:** Rates of change of subject body core temperature over complete exercise and rest cycles

Determined using simple average

(refer to Figure 5.1 for further clarification)
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<tr>
<th>TEST NO.</th>
<th>T1 (°C/hr)</th>
<th>T2 (°C/hr)</th>
<th>T3 (°C/hr)</th>
<th>T4 (°C/hr)</th>
<th>T5 (°C/hr)</th>
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| Minimum | 1.71 | -1.37 | 1.58 | -1.39 | 2.20 | -1.63 |
| Average | 3.19 | -2.19 | 3.24 | -3.12 | 3.17 | -2.59 | 3.06 | -2.14 |
| Maximum | 4.96 | -3.89 | 5.84 | -5.80 | 4.81 | -4.27 |

**Table 5.2:** Rates of change of subject body core temperature over “linear” segments of exercise and rest cycles
Determined using linear regression
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<th>EXERCISE PERIOD 3</th>
<th>EXERCISE PERIOD 4</th>
<th>EXERCISE TOTAL</th>
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<td>4.00</td>
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</table>

| Minimum Speed | 3.59 | 3.55 | 3.92 |     | 3.66 |
| Average Speed | 4.05 | 4.06 | 4.19 | 4.09| 4.07 |
| Maximum Speed | 4.33 | 4.56 | 4.61 |     | 4.45 |

**Table 5.3:** Distance and walking speed data for exercise cycles
6. **DISCUSSION OF PHYSIOLOGICAL TRIAL RESULTS**

**General Observations**

**Figure 5.1** indicates the generalised body core temperature characteristic observed throughout the physiological trials. Periods of significant heat storage and cooling were associated with exercise-rest cycles. As a general observation, uncompensable heat gain took place after several minutes of exercise. This behaviour was also observed in the trials reported within HSE RR180. It is postulated that the initial delay in core body temperature rise on commencing exercise is associated with heat storage effects, as the individual’s cardio-vascular system attempts to respond to the heat stress. This results in the onset of thermoregulatory breakdown being progressive, taking place over several minutes. After this, for a constant work rate, the rate of core body temperature rise appears to be linear. Trial run D290507-08-N shows the resultant response to continuous self-paced exercise without rest. It is observed that body core temperature increases in a linear manner with elapsed time.

The response to uncompensable heat gain may be explained by use of the heat balance equation. The concept of the heat balance equation is useful for providing an understanding of how internal body temperature is maintained and in explaining the thermoregulatory breakdown characteristic. The interrelationship between metabolic heat production, work and cooling effects is shown graphically below.

![Figure 6.1: Factors associated with metabolic heat production and environmental cooling](image)

All heat balance equations have the same underlying concept: heat generation within the body, heat transfer, and heat storage. Equations 1 and 2 below show the conceptual heat balance equation where metabolic rate (M) provides energy enabling the body to perform mechanical work (W). The remainder of the energy is given off as heat (M-W). The ways that heat transfer can be achieved involve evaporation, sweating and respiratory (E), radiation (R), convection (C) and conduction (K). The resultant heat production and loss provide the storage (S), where in heat balance, S = zero.

\[ M - W = E + R + C + K + S \]  \[1\]

and when S=0

\[ M - W - E - R - C - K = 0 \]  \[2\]
Heat produced is in proportion to the work rate (metabolic rate). Core temperature in a steady state is dependent upon work rate, while under severe environmental conditions thermoregulation fails. Heat loss is small in saturated atmospheres, especially at >34°C. Assuming constant biomechanical efficiency, the rate of core body temperature rise is a function of work rate. At a fixed work rate, core body temperature continues to rise linearly, once initial heat compensation effects have been overwhelmed. This simple linear model appears to explain core body behavior once thermoregulatory breakdown is established.

**Comparison with HSE RR180**

The characteristic behavior of body core temperature in response to uncompensable heat gain was observed to be similar in both sets of trials. Consideration was given to the possible pooling of the data sets between HSE RR180 and that reported. However, the experimental controls between both sets of trials were not considered sufficiently consistent to allow the data sets to be combined. By way of example, the treadmill work rates, cohort groups, psychrometric test conditions and respiratory heat burden were different between each set of trials. In particular, it is noted that no sensible cooling was observed in HSE RR180 compared with the reported work. Given the environmental test facility used in HSE RR180 was decommissioned and was no longer available, no further checks could be made between the respective facilities. Comparison of the psychrometric conditions was as follows:

**Table 6.1: Comparison of test conditions with HSE RR 180**

<table>
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<tr>
<th>Environmental Chamber</th>
<th>HSE RR 180</th>
<th>Current</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air velocity</td>
<td>Negligible</td>
<td>0.5 – 1.0 ms⁻¹</td>
</tr>
<tr>
<td>Range of T_db</td>
<td>27°C – 37°C</td>
<td>30°C – 33°C</td>
</tr>
<tr>
<td>Air Relative Humidity</td>
<td>Fully saturated</td>
<td>est. 96% RH</td>
</tr>
<tr>
<td>Vertical temp. stratification</td>
<td>Pronounced (6°C-8°C)</td>
<td>Well controlled &gt;0.5m</td>
</tr>
</tbody>
</table>

It is speculated that the more severe conditions incurred under HSE RR180 resulted in the test chamber having very limited or negligible air cooling power.

**Discussion on a Body Core Temperature Limit**

A combination of environmental conditions and exercise intensity can prevent thermal equilibrium, such that exhaustion from heat strain eventually occurs. Uncompensable heat stress occurs where the required evaporative cooling exceeds the evaporative cooling possible under the ambient psychrometric conditions. During uncompensable heat stress, steady state core temperature cannot be achieved and body temperature continues to rise until exhaustion occurs. Evaporative cooling is impaired, skin temperature increases causing the blood vessels in the skin to dilate. The resulting displacement of blood causes cardiovascular strain and instability, which accounts for the occurrence of exhaustion at relatively low core temperatures. Somewhat higher core temperatures can be tolerated during compensable heat stress, where exhaustion is usually associated with dehydration or substrate depletion. Knowledge is incomplete about the quantitative relationships between physiological indices and morbidity from heat strain. Core temperature provides the most reliable physiological index to predict the incidence of exhaustion from heat strain (Sawka and Pandolf 2001, Sawka et al 1992, Montain et al 1994). A
discussion on individual heat stress response and safety guidelines is given in HSE RR180, and factors influencing response to heat stress are considered further in Section 7.

For emergency planning purposes there is a requirement for a body core temperature upper limit or maximum temperature rise to be defined. As noted in Section 7, there is no single temperature above which evacuating personnel are "at risk". For heat-acclimated subjects exercising in uncompensable heat stress, Kraning (1997) observed a relationship between core temperature and the cumulative occurrence of exhaustion from heat strain as shown in Figure 6.2 below.

![Figure 6.2: Observed cumulative occurrence of exhaustion from heat strain (Kraning 1997, Sawka and Pandolf 2001)](image)

There was a continuum from circa 38°C to 40°C, between which all casualties were recorded. The selection of a body core temperature upper limit of 38°C would suggest a 1°C increase from resting normothermal conditions under a euhydrated state. For design purposes this would provide a high degree of protection, including those who have elevated skin temperature associated with their work, or who are moderately dehydrated. This matter however requires further consideration.

**Estimation of Safe Travelling Distance Without Rest and Recovery**

As discussed elsewhere, there is no threshold for body core temperature, or specific rise in temperature from rest, which is associated with the onset of heat exhaustion. If the combination of environmental conditions and exercise intensity result in significant uncompensable heat stress, then eventually without rest and recovery the body will succumb to heat strain. Trial run D290507-08-N and data reported within HSE RR 180 confirm that uncompensable heat storage resulted from the self-paced exercise under the prevailing conditions.

Inspection of D290507-08-N shows that after an initial period where the body responds to the heat stress by increasing peripheral circulation, the body core temperature characteristic increases linearly with time, consistent with a sensibly constant walking pace and hence work rate. It is reasonable to assume that without the intervention of the study physician to terminate the trial, the body core temperature would have continued to increase in this manner.

For the purposes of illustration, the estimated distance associated with body core temperature rises of 1°C, 1.5°C and 2°C were estimated for the test cohort as given in Table 6.2. With respect to Table 5.1, the initial transient delay in the rise of body core temperature on commencing exercise leads to an average rate of rise of 2.73°C/hr during heat storage phase T1. If this initial delay is discounted and the linear
segment of T1 is used, then this produces a slightly higher rate of rise of 3.19°C/hr, refer to Table 5.2. It is noted that the average rate of rise is based on protocols with a range of effective temperatures of 30°C – 33°C. The assumption for mean walking pace is 4.07 km/hr, refer to Table 5.3.

Table 6.2: Estimated distances for specific increases in body core temperature (without rest)

<table>
<thead>
<tr>
<th>Temperature Rise ΔT, °C</th>
<th>ΔT = 1°C</th>
<th>ΔT = 1.5°C</th>
<th>ΔT = 2.0°C</th>
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<td>Assumed rate of rise of core temperature °C/hr</td>
<td>2.73</td>
<td>2.73</td>
<td>2.73</td>
</tr>
<tr>
<td>Estimated Distance, m</td>
<td>1468</td>
<td>2202</td>
<td>2936</td>
</tr>
<tr>
<td>Assumed rate of rise of core temperature °C/hr</td>
<td>3.19</td>
<td>3.19</td>
<td>3.19</td>
</tr>
<tr>
<td>Estimated Distance, m</td>
<td>1256</td>
<td>1884</td>
<td>2512</td>
</tr>
<tr>
<td>Mean walking pace, km/hr</td>
<td>4.07</td>
<td>4.07</td>
<td>4.07</td>
</tr>
</tbody>
</table>

Inspection of Table 6.2 indicates a travelling distance of 1.9 – 2.2 km is consistent with a rise in body core temperature of 1.5°C. This is higher than the corresponding figure of 1.45 km observed in HSE RR 180. The difference is attributed to higher mean heat stress levels and treadmill resistance in HSE RR 180.

In broad terms, if evacuating personnel are unable to cool significantly in the prevailing roadway conditions, then a travelling distance of around 2 km would be consistent with the body core temperature reaching a zone associated with rapidly increasing probability of heat exhaustion.

Estimation of Safe Travelling Distance with Cyclical Rest and Recovery

Evaluation of the data associated with test protocol ‘C’ indicates that a staged evacuation process involving cycles of moderate pace walking followed by a comparable period of rest has the potential to constrain body core temperature within acceptable limits. In effect, a cycle of exercise and rest introduces the concept of diversity. By switching between the exercise intensity associated with walking to the lower resting (cooling) metabolic rate in a cyclical fashion, the overall level of metabolic heat production is reduced in a controlled manner. Providing exercise is of limited duration and intensity, and the air cooling power is sufficient, then it should in principle be possible to limit maximum body core temperature excursions.

The maximum exercise period that can be safely accomplished in uncompensable conditions is largely a function of exercise intensity, and hence heat storage rate. The corresponding amount of time that must be assigned to cooling is then largely a function of air cooling power, and hence wet-bulb temperature. The discussion in a following section confirms the cooling period must be extended significantly at high wet-bulb temperatures.
Practical limitations dictated that a restricted number of test permutations could be evaluated. The study physician developed an exercise-rest/cooling cycle which was observed to provide a constrained range of body core temperature in the test cohort; although as expected there was significant individual variation in response. There was also a progressive reduction in the nett cooling observed over consecutive exercise-rest cycles. The physiological basis for this requires further investigation, although it was noted that “cardiac drift” (progressive elevation in heart rate at a given exercise intensity) was not significant.

Test C100507-02-N provides a clear indication of the benefits of a staged exercise-rest cycle against uninterrupted exercise. The relative distances achieved (or estimated) for each case may be gauged from Figure 6.3 below.

It is estimated that the test subject, who was physically fit but unacclimated, could have exceeded a distance of 4.0km in a staged evacuation involving cyclical rest and rehydration, versus 2.1km to reach a body core temperature of 39°C for uninterrupted exercise.

![Figure 6.3](image)

**Figure 6.3:** Comparison of distances achieved under uninterrupted exercise and cyclical exercise-rest (test run C100507-02-N)

**Cooling Capacity Available During Periods of Rest**

The ability of the chamber air to cool the subjects can be gauged from the Air Cooling Power (ACP) and Modified Air Cooling Power (ACPM) indices. Heat stress indices are discussed further in Section 7. The ACP index is based on principles of heat transfer and from the results of wind tunnel experiments. McPherson (1992, 1993) modified the ACP index to incorporate a thermoregulatory model with the heat
transfer equations, which better accounts for the influence of clothing ensemble. The ACP and ACPM scales are shown overleaf (Pickering and Tuck 1997).
It can be appreciated from the ACPM scale that clothing ensemble effects are significant. The clothing worn by the test subjects would correspond to a sub-set between the “light clothing” and “unclothed” categories. It is noted that the scales assume the mean radiant temperature of the surroundings to be equal to the dry-bulb temperature and a wet-bulb depression of 2°C and 5°C respectively. No data for ACP and ACPM could be determined for wet-bulb temperature depressions of <1°C.

In order for there to be nett cooling, the air cooling power must exceed the metabolic heat generated by the subject. The rate of cooling will then be a function of psychrometric conditions, air velocity and clothing ensemble. Considering the above indices, it is clear that air cooling power diminishes rapidly for wet-bulb temperatures >31°C. In practical terms, a rapidly increasing period of cooling is required as wet-bulb temperatures exceed 30°C-31°C.

**Hot Air Device Heat Burden**

A limited analysis of the trial data was undertaken to assess the thermal physiological impact from wearing the hot air device. It is also noted that the study physician used an agreed sign protocol to allow the test volunteers to indicate the relative tolerability of the hot air device throughout each test run. The subjects provided a subjective assessment during the trials and were debriefed by the physician after the post-test recovery period. As general observations, the air presented by the hot air device was well tolerated during rest periods, but some subjects found the device on the limit of tolerability after exercising. The reported discomfort was mainly confined to the breathing tube-mouthpiece interface area, where the inspired air was at peak temperature. No significant discomfort was reported in the thoracic tract.

In test protocols “A” and “B”, wearing of the hot air device was continued during the initial rest period, and discontinued at commencement of the second rest period. In this regard, cooling segment T2 is influenced by the resting heat burden from the hot air device, whilst cooling segment T4 is not associated with any respiratory heat burden. Comparison of the difference in gradients in T2 and T4, viz. differences
in rates of body cooling, permits the influence of the hot air device to be gauged. Inspection of the cooling characteristics within segments T2 and T4 confirms rates of cooling as tabulated in Table 6.3.

<table>
<thead>
<tr>
<th></th>
<th>Average rate of cooling with hot air device worn, °C/hr</th>
<th>Average rate of cooling with no respiratory heat burden, °C/hr</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average cooling rate</td>
<td>-1.58</td>
<td>-2.47</td>
</tr>
<tr>
<td>(refer to Table 1)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maximum rate of cooling</td>
<td>-1.96</td>
<td>-3.29</td>
</tr>
<tr>
<td>(refer to Table 2)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Table 6.3**: Comparison of rates of cooling with and without hot air device being worn

The cooling rate data derived from Table 5.1 refers to the average cooling rate observed over the complete period associated with any observable cooling. The cooling rate data derived from Table 5.2 reflects the maximum, short-term cooling rate observed at higher body core temperatures.

Inspection of Table 6.3 indicates that average cooling rates of ~1.6°C/hr improve to ~2.5°C/hr if the subject is allowed to remove the respiratory heat burden incurred by the hot air device. Similarly, peak cooling rates improve from ~2°C/hr to ~3.3°C/hr. During protocols ‘A’ and ‘B’, there was no scope to rehydrate during the trial run. Hence the difference in cooling rates is attributed entirely to the removal of the respiratory heat burden.

At a practical level, the benefits of being able to remove an escape respiratory protective device in a safe haven, all other matters being equal, include a potentially significant reduction in the time for body core temperature to recover to normothermal levels. This could translate into a reduced time to complete the evacuation to safety.

**Energy Cost of Walking and Treadmill Set-up**

In the physiological trials, a key factor was recognised to be the exercise work rate, and how well this reflected the average exercise intensity associated with undertaking an evacuation under adverse conditions. The determination of a representative figure for work rate associated with self-paced walking during an escape or evacuation is complicated by a number of factors, including: the impacts of varying mine floor conditions, obstructions and low visibility. Literature on bipedal locomotion mechanics and energy consumption under various stress conditions (e.g. soft floor, heavy boots and limited height clearance) was examined to offer some insight into the additional energy debit expended during exercise under adverse conditions. Pearce et al (1983) identified differences between the energy cost of floor and treadmill walking. Bunc and Dlouha (1997) found U-shaped curves of coefficient of energy cost of walking versus speed, with a minimum at speeds of about 4 km/h. Lejeune et al (1998) determined that walking on sand requires 1.6–2.5 times more mechanical work than does walking on a hard surface at the same speed.

Taking the above matters into consideration, it was judged that any exercise intensity proposed for the treadmill would be arbitrary and would in any case be a function of the self-paced walking speed. However, it was also considered necessary to ensure that the exercise work rate was not too low, since thermal strain could then be under-estimated. The experimental approach adopted was to vary the grade of the mechanical treadmills and then have a group of subjects confirm the setting which provided the most
natural walking gait, with minimum reaction required against the treadmill frame. Here it was determined that a horizontal (0% grade) setting required excessive reaction, necessitating a postural change to compensate. On balance, the subjects considered a grade setting of 8% (4.6 degrees) on the treadmills to be optimal, resulting in a comfortable, natural gait which required very little reaction from the treadmill bars. The following simplified estimate for energy expenditure during walking was used [ACSM 2000]:

Walking energy expenditure: \( \text{VO}_2 = 3.5 + 1.7(\text{speed}) + 0.3(\text{speed})(\%\text{gradient}) \)

\( \text{VO}_2 \) in ml.kg\(^{-1}\).min\(^{-1}\), and speed in km.h\(^{-1}\)

Exercise can be expressed as multiples of resting metabolism, defined as the current energy expenditure rate divided by the basal metabolic rate. The metabolic equivalent standard value of 1 MET is 3.5 ml.kg.min\(^{-1}\) is often used for estimation, although it is influenced by thyroid status, post exercise, obesity, and if subject to disease. Based on ACSM (2000) estimates of energy requirements in METs for horizontal and grade walking, the energy requirement was estimated to be of the order of 5.6 - 6.0 MET for a mean speed of 4 km/h and 8% grade. The corresponding figure for a horizontal treadmill is 2.9 METs.

In approximate terms, the energy expenditure in using the treadmills was considered to be equivalent to walking along a horizontal mine tunnel with very soft, rough floor conditions present. This treadmill arrangement was maintained for all tests.
7. DISCUSSION OF HEAT EXHAUSTION AND MITIGATION STRATEGIES

Introduction

The experimental programme within HSE contract 6042, together with earlier work undertaken by MRSL/RPS on behalf of HSE, has been able to address a number of issues concerning the potential for heat exhaustion during evacuation. However, there are a number of issues which could not be addressed effectively in the programme. These included the influence of hydration status and the effectiveness of rehydration to mitigate heat stress potential. In order to consider these matters, a review of scientific literature was carried out. This was contrasted with the programme experimental observations and an estimation made of the impacts of various mitigation strategies.

The following reviews key findings from the scientific literature in regard to:

- Heat related illness in mining, and in particular what limit conditions/measures are applied internationally to reduce heat exhaustion.
- The impacts of dehydration on exercise performance and thermoregulatory response.
- Rehydration effectiveness, particularly over the relatively short time frames anticipated.
- The impact acclimation has in terms of the thermoregulatory response where uncompensable heat gain occurs.
- Whether self-pacing is effective as a strategy to contain heat strain within acceptable limits.
- The impacts that pre-cooling, and conversely pre-warming, have on thermal strain when operating in hot humid conditions.
- How eye irritation from the smoke of a developing fire might compound the already severe thermal effects present.

A wide range of literature was consulted and a summary of key points is presented at the conclusion of this section. However, the experimental observations made within the programme are consistent with the general findings reported in the literature.

Heat Related Illness and Impairment

Heat-related illnesses are widely recognised and are summarised below:
Table 7.1: Heat exposure effects

<table>
<thead>
<tr>
<th>Effects</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat cramps</td>
<td>This occurs due to salt depletion due to excessive sweating. These are the first signs that the body is having difficulty with increased temperature.</td>
</tr>
<tr>
<td>Heat exhaustion</td>
<td>It is more serious than heat cramps. It is due to salt and water depletion occurring due to excessive sweating. This occurs when a person is exposed to high temperature for a longer period or the body may become dehydrated and temperature regulation may begin to fail. The symptoms include headache, nausea, exhaustion, weakness, dizziness, faintness, mental confusion etc.</td>
</tr>
<tr>
<td>Heat syncope</td>
<td>Due to vasodilation and excessive sweating there is circulatory and vasomotor instability.</td>
</tr>
<tr>
<td>Heat stroke</td>
<td>Under the most extreme conditions, the body temperature regulation fails. Subject may become mentally confused and aggressive. There is very little perspiration. Requirement for emergency medical attention. Without care, will die in a matter of hours.</td>
</tr>
</tbody>
</table>

Heat stroke in underground miners is almost exclusively observed in South African mines, although the incidence has declined significantly in recent years. For the period 1956–1961, the incidence of heat stroke was reported to be 0.24/1,000/year (Wyndham 1965). In 1993 the incidence was reported to be 0.0468/1,000/year (Kielblock and Schutte, 1993). The risk of heat stroke is greatly increased at wet-bulb temperatures above 32°C. Stanton (2004) cites 1990 year heat stroke risk factors increasing tenfold from 0.6/1,000/year at 32°C wet-bulb to 6/1,000/year at 35°C wet-bulb. Further discussion on the probability of heat stroke developing is given by Wyndham and Heyns (1973).

Clinical distinctions between heat stroke, heat exhaustion and heat cramps are given by Donaghue et al (2000). Heat stroke is often fatal and is distinguished from the less severe condition of heat exhaustion by way of tissue damage caused by severe or prolonged elevation in body temperature. Heat stroke is distinguished from heat exhaustion by disturbances of the central nervous system, usually prolonged unconsciousness, often preceded by confusion, ataxia, or convulsions. The core temperature is typically over 40°C at onset whereas this is very rarely the case in heat exhaustion. Core temperature on presentation of heat exhaustion does not generally exceed 38.5°C. Sawka et al (1992) confirm that there is no specific threshold body core temperature above which exhaustion will suddenly occur. Exhaustion from strain occurs over a range of core temperatures. Heat exhaustion is caused by the inability of the circulatory system to simultaneously supply sufficient blood flow to the skin to achieve adequate heat loss and to supply the vital organs and exercising skeletal muscles. It is usually due to hypovolaemia resulting from varying degrees of water and salt loss. People with heat exhaustion may develop fatigue, headache, dizziness, anorexia, nausea, vomiting, shortness of breath, or syncope whilst confusion, ataxia, prolonged unconsciousness, or convulsions are strongly suggestive of heat stroke. Heat cramps are painful involuntary contractions of skeletal muscle associated with work in hot conditions. The limbs are usually involved and the spasms typically last a few minutes during which the affected part is incapacitated. The underlying mechanism is not fully understood, and there is conflict as to the role of dehydration and salt depletion. Physiological mechanisms responsible for exhaustion from heat strain are considered further by Brück and Olschewski 1987, Febbraio et al 1994, Fink et al 1975, Gonzalez et al 1978, Hargreaves et al 1996, Johnson and Proppe 1996, Montain et al 1994, Rowell 1983, Young et al 1995.
It is clear that the range of wet-bulb temperatures between 31°C and 35°C is associated with a rapidly increasing probability of significant heat-related disorders. Donaghue et al (2000) examined the underground thermal conditions associated with the occurrence of heat exhaustion at a deep Australian underground metalliferous mine in a one year prospective study. This included assessment of the incidence, clinical state, personal risk factors, haematology, and biochemistry of heat exhaustion. The incidence of heat exhaustion observed over a year was 43.0 cases /million man-hours. Studies on heat illness in other countries (Donaghue 2004) indicate much lower incidence rates of heat illness. In US underground mining, heat incidence incidence rates range from 0.00275/million man-hours for coal, to 0.168/million man-hours for metal mines.

In the above Australian study, few cases of heat exhaustion (<5%) occurred below the following limit conditions; psychrometric wet bulb temperature <25.0°C, dry bulb temperature <33.8°C, air velocity >1.56 m/s, air cooling power >248 W/m². Significantly more cases of heat-related illness occurred on the first shift, and during the day shift, than would have been expected. Loss of acclimatisation was considered unlikely to explain the excess of cases occurring on the first day shift. Fluid intake was judged to be clearly inadequate and was probably associated with recreational activities and alcohol consumption. Estimated fluid intake was much less than the maximum gastrointestinal absorption rate of 1.4–1.8 l/h. In terms of clinical observations, heat exhaustion in underground miners was associated with dehydration, neutrophil leukocytosis, eosinopenia, metabolic acidosis, increased glucose and ferritin, and a mild rise in creatine kinase, aspartate transaminase, and lactate dehydrogenase. Heat cramps were associated with dehydration but not hyponatraemia.

Heat stress has been associated with higher accident rates and reduced work efficiency in mining (Howes and Nixon 1997, Kielblock 2001, Pickering and Tuck 1997). A number of studies have shown that heat stress has a negative effect on both physical performance and cognitive performance (Bennet et al 1995, Pilcher and Nadler 2002, 2003). There is an inference by a number of researchers that working in heat, when accompanied by dehydration, affects safety performance either directly or indirectly. Dehydration and hyperthermia have both been found to independently impair mental performance and especially attention overload.

Mental and physical decrements in performance have been observed with dehydration levels as low as 2% of total body water, with pronounced effects at 4% (Brake and Bates 2001). Bates and Matthew (1996) cite further observations:

- Dehydration of 1 to 2% of body weight results in a 6 to 7% reduction in physical work rate.
- Dehydration of 3 to 4% of body weight results in a 22% to 50% reduction in work rate, for “moderate” and “hot” environments respectively.
- Mental performance (mental function, visuomotor skills and arithmetic tests) begins to decrease at 2% dehydration and thereafter is proportional to the degree of further dehydration.

The influence of dehydration and rehydration as a mitigation strategy are considered further in subsequent sections.
Impact of Dehydration

Powell and Bethea (2005) completed an extensive review of the literature concerning dehydration. A noted conclusion was that hydration status of workers is pivotal to their ability to thermoregulate and for their wellbeing when working in hot environments. Powell and Bethea reviewed the physiological costs of dehydration (hypohydration) and a range of effects on health, performance and physical ability. Due to vasodilation, heart rate increases during heat stress compared to the same work rate undertaken in neutral conditions. Thermoregulatory requirements override the cardiovascular requirements resulting in thermally induced increase in heart rate. Blood flow to the skin and muscles is reduced and the capacity for effective heat loss from the deep body is reduced. If no action is taken to address the onset of dehydration, the final outcome will be an increase in core temperature. Deep body temperature is consistently higher in dehydrated subjects compared to those subjects who are euhydrated (Cheung and McLellan, 1998).

Dehydration magnifies the core temperature responses to exercise in both temperate and hot environments and this effect is observed with a fluid deficit as small as 1% of body weight (Ekblom et al 1970). As the water deficit increases, there is a corresponding elevation of core temperature relative to the euhydrated condition during exercise stress. The magnitude of additional core temperature elevation ranges from 0.1°C to 0.23°C for every percentage of body weight lost. Figure 7.1 shows the increase determined from four studies.

![Figure 7.1: Influence of degree of dehydration on elevation of body core temperature during exercise from 4 studies (a)-(d)](image)


Dehydration elevates core temperature response and negates the core temperature advantage conferred by heat acclimation. Figure 7.2 illustrates the effect of relatively severe dehydration (5% body weight loss) on core temperature responses in the same persons when unacclimated and when acclimated to heat (Sawka et al 1983). It is noted that heat acclimation lowered the core temperature response of euhydrated subjects. However, similar body core temperature responses were observed in hypohydrated subjects regardless of their acclimation state. The core temperature penalty induced by dehydration is seen to be greater in heat-acclimated than unacclimated persons.
Sawka et al (1992) studied whether exhaustion from heat strain occurred at the same body temperature when subjects are euhydrated and hypohydrated respectively, and whether aerobic fitness influences the body temperature at which exhaustion occurs. Their findings were that hypohydration reduced the core temperature that could be tolerated; aerobic fitness, per se, did not influence the magnitude of heat strain that could be tolerated; and exhaustion was rarely associated with a body core temperature <38°C but always occurred before a temperature of 40°C was reached.

The foregoing observations confirm the critical importance of industry advice and measures to prevent dehydration in the underground workplace. Urine specific gravity and individually associated urine colour are considered useful in informing the underground workforce as to the fluid intake required to prevent dehydration. A urine specific gravity of <1.015 on going underground and of <1.025 on surfacing might be expected to reduce the incidence of heat exhaustion. Comparison of urine colour with photographs of urine samples known to be of these specific gravities avoids the need for specific gravity testing and is more practical. Urine colour has been shown to correlate well with specific gravity and dehydration measured by changes in body mass (Armstrong et al 1995, 1998). Powell and Bethea (2005) support the use of urine colour interpretation where no other physiological determination is possible but cite caution over the influence of certain foodstuffs on urine colour. The Fantus Test of urinary chloride (Cross 1989) has also been proposed as a pre-shift check and indication of propensity to heat exhaustion.

The development of appropriate guidance and underground potable water supplies has improved the hydration status of underground workers. Szlyk et al (1989) comment that a 2% body mass loss is accepted as a threshold for thirst stimulation. Above a dehydration of 3%, there is an increase in heart rate and a depressed sweating sensitivity. Malchaire et al (2000) suggest that 3% dehydration level should be the maximum dehydration limit for industrial workers. Malchaire et al (2000) also identify that average rehydration rates are 60% for hot working conditions in coal mines with 4 to 6 h exposure. The mean rehydration rate was independent of total sweat production.
Impact of Self-Pacing

A fundamental question is raised as to whether self-pacing of work rate has the ability to maintain an acceptable body core temperature. There is also a question over the incidence of fatigue under thermal stress where extended shifts are worked. Brake and Bates (2001) investigated fatigue levels in mineworkers working extended (10 - 12.5h) shifts in hot conditions. Workers did experience fatigue, which was largely observed in the first half of the shift. The cohort group was non-dehydrating, acclimatised workers who were well informed about the impacts of working in heat and there was evidence that the workers were employing self-pacing strategies to control work rate. The observation of self-pacing is consistent with a number of other studies in industrial settings (Brake and Bates 2001).

Kay and Marino (2003), Tatterson et al (2000) and Marino et al (2000) suggest comparable behaviour in endurance sports. A hypothesis is advanced by these researchers that during self-paced exercise, athletes select a power output (work rate) which allows them to maintain a core body temperature below a critical limit. It is speculated that the central nervous system can subconsciously direct a reduction in exercise intensity or cessation of activity in order to reduce the rate of rise of core temperature. However, it is argued that there is one important distinction between endurance racing and underground escape conditions. There is likely to be a somewhat higher heat stress potential underground and which may result in an uncompensable response even for relatively moderate work rates. Lind (1963) suggests that exercise rates below a ‘prescriptive zone’, where rectal temperature increases with increasing climatic stress for a given work intensity, a reduction in work intensity may maintain and control the rectal temperature. The transition into the prescriptive zone at a particular work rate and effective temperature can be observed from Figure 7.3.

![Figure 7.3: Uncompensable “prescriptive zone” characteristic](image)

There is also evidence that self-pacing produces excessive deep body core temperature when environmental conditions exceed 33.5°C wet-bulb (Soule et al 1978). Nag et al (1997) suggest the acceptable limits for human exposure in heat corresponding to 31.5 and 36.5°C BET at a work intensity of 60% VO2max are 80-85 min and 40-45 min respectively to reach a body core temperature of 38 to 38.2°C. González et al (1999) investigated whether fatigue during exercise in uncompensable hot environments occurred at the same critical level of hyperthermia when the initial value and the rate of increase in body temperature were altered. Time to exhaustion was inversely related to the initial body temperature; 63 ± 3, 46 ± 3, and 28 ± 2 min with initial body core temperature of ~36, 37, and 38°C, respectively. With different rates of heat storage all subjects reached exhaustion at a similar body core
temperature, but with significantly different skin temperature. Time to exhaustion in hot environments is inversely related to the initial body core temperature and directly related to the rate of heat storage.

Goldman et al (1965) provided an insight into the tolerance times of unacclimated volunteers at rest in a variety of severe hot, humid environmental conditions. The tolerance time (and uncompensable heat gain) was shown to have a strong correlation with Oxford (Wet-Dry, WD) index, which is highly weighted by wet-bulb temperature. Above a WD of 35.5°C, the uncompensable zone of thermoregulation is reached and no regulation of body temperature is possible. The corresponding effective temperature threshold for loss of thermoregulation was of the order of 37°C, with tolerance time reduced to less than 100min at 38°C effective temperature.

_in these tests acclimatisation status was not shown to have any influence on tolerance time, rates of sweat production, final skin temperature, or the rates of increase in heart rate or rectal temperature. It is noted that whilst the Oxford (Wet-Dry) index has not found general use, it was developed and used by Lind to calculate tolerance times (safe wearing times) of mines rescue personnel whilst wearing breathing apparatus (Graveling et al 1998).

Impact of Acclimation

The influence of acclimation on the ability to tolerate hot, humid conditions could not be gauged from the experimental protocol (all subjects were not heat acclimated). However, studies on acclimation point to a conclusion that after short-term acclimation to humid heat, workers appear to be able to defend and maintain a body core temperature around a lower setpoint temperature. In effect, heat acclimation has the potential to significantly reduce resting body core temperature. Buono et al (1998) have reviewed several acclimation studies and confirm that acclimation produces a potential reduction in resting rectal temperature of between 0.3-0.5°C. The reduction in resting core temperature from acclimation is shared by primates (Sato et al 1990). In terms of the research carried out, it is anticipated that the lowering of resting core temperature derived from acclimation could attenuate the final body core temperature observed during the protocol. The heat storage associated with uncompensable heat gain in severe conditions is however common to both acclimated and non-acclimated subjects. Gonzalez et al (1997), commenting on several military studies, suggest that significant evaporative cooling by sweating can delay the rise in body core temperature. However average rates of core temperature rise before acclimation and after heat acclimation were generally similar. Final skin temperatures pre- and post-acclimation were also not significantly different in these studies.

On the basis of the reported studies, it is believed that acclimation would confer at least an initial advantage of lower resting body core temperature to the test subjects. However, this would also depend on their hydration status.

Impact of Heat Index Used

A question is raised as to whether the UK mining industry’s climate index is sufficiently representative and whether measurements based on the index confer adequate protection under conditions of severe heat stress. The effective temperature index continues to satisfy the practical requirements of the mining industry in the UK and Europe. However, the effective temperature scale employed has limitations; it does not include a work rate component and the appropriateness of the scale is questioned in severe hot-humid climates (Lind and Hellon 1957, Brebner et al 1958).

There are six factors influencing individual capacity for heat exchange with the environment; these are dry-bulb temperature, wet-bulb temperature, virgin strata temperature (or other radiant heat source), air flow rate, metabolic rate (work rate) and clothing ensemble (Eissing 1995). Clothing ensemble can have
a significant influence on thermal strain and due to this sensitivity, heat stress indices need to account for clothing ensemble.

An extensive literature review of the development of empirical scales relating physiological and subjective responses to climate together with indices based on mathematical analysis of heat exchange is given by Graveling et al (1988). Heat stress assessment methodology is also examined at length in Bethea and Parsons (2002). A further review of the effective temperature index is given by Hanson and Graveling (1997), who argued that despite its limitations its use should continue in the UK mining industry. Smith (1952) suggested that the effective temperature scale has acceptable accuracy up to 31-32°C effective temperature.

There are other indices which arguably better account for variation in work rate and low air velocities. The Air Cooling Power (ACP) or Modified Air Cooling Power (ACPM) is one such index (Pickering and Tuck 1997, McPherson 1992, McPherson1993), although it is more complex to apply than effective temperature and it has not been used to any significant extent outside of South Africa. Brake and Bates (2002) cite the rational heat stress index Thermal Work Limit (TWL) as being suited to self-paced underground working and that it provides adequate protection for mineworkers.

**Impact of Mine Regulations**

The coal mine regulations in regard to climatic conditions differ significantly. Statutory limit values are applied in Germany and there are recommended action levels in the UK. In Australia and South Africa the limit values are higher. Consideration was given in particular to German regulations to identify what if any additional protection is provided.

It is observed that German regulations place no restrictions for working hours for dry-bulb temperatures up to 28°C or effective temperatures up to 25°C. At higher dry-bulb or effective temperatures, shift lengths are reduced to 6 or 5 hours. Above 30°C effective temperature, work underground is allowed under controlled circumstances and is forbidden at effective temperatures above 32°C (Schlotte 1999). Beyond this limit only members of mine rescue teams are allowed to work in accordance with safe working duration tables. Additional rests and pauses also have to be incorporated, depending on the level of climatic stress.

Kalkowsky and Kampmann (2006) describe the additional precautionary measures to prevent heat stress in the German coal mining industry. Prior to commencing work at a climatic stress level of effective temperature >29°C, mineworkers must not be integrated into any system of piece working for at least 14 days. This time is assigned for adaptation, with >2.5 h to be worked daily within this climate. The same applies for a mineworker that has not worked in this climatic regime for more than 6 months. Mineworkers younger than 21 y and older than 50 y require approval from an occupational physician after a medical check-up to be allowed to work in this climatic regime. In climatically restricted areas a mineworker may only work if there are no health concerns arising from a medical check-up by an occupational physician. Conditions leading to restrictions for working in heat include high blood pressure (without or with medication), obesity, chronic lung disease, cardiovascular disease and a low degree of fitness as determined by a bicycle ergometry test. Medical check-ups are repeated at least every 2 years. Mineworkers who have worked more than 80 shifts a year at BET>29°C, and mineworkers younger than 21 y or older than 50 y, must pass a medical check-up every year. A shorter interval for the check-up may be set at the discretion of the occupational physician. After a period of sick-leave, a mineworker must pass a medical check-up before returning to work and the occupational physician will make an estimation as to whether the sick-leave may have been due to climatic stress.
The precautionary approach reflected in these measures is considered justified by Kalkowsky and Kampmann (2006). The percentage of shifts in hot working conditions in German coal mines has increased to more than 50% during the last decade. A study on physiological strain of mineworkers confirmed a mean heart rate of 102.8 beats/min, mean rectal temperature of 37.7°C, mean sweat loss per shift 3,436 g and mean sweat rate of 494 g/h. Rehydration during the shift at high climatic stress was <60% of sweat losses and remains an issue. With respect to water balance, water deficit was observed to reach more than 2 kg at the end of the shift. This deficit has to be compensated before commencement of the next working shift. Kalkowsky and Kampmann (2006) commenting on a different study at hot working places in coal mines found that approximately 10% of miners accumulated an increasing water deficit throughout the working week and restored their body mass only during the weekend.

The recommendations made by Kalkowsky and Kampmann (2006) are reflected in current HSE guidance and recommendations (e.g. HSE Mining Industry Committee, Occupational Health in Mines Sub-committee, Guidance: Prevention of heat illness in mines, 14p, http://www.hse.gov.uk/pubns/mines07.pdf). These include:

- Miners should be informed of measures to maintain a satisfactory level of hydration.
- Relying on the thirst response is generally inadequate. Pre-emptive measures and regular on-the-job drinks are essential.
- Drinking water should be made freely available in hot working areas and for unexpectedly heavy work.
- The practice of self-pacing of work should be encouraged.

The Institute of Occupational Medicine, Edinburgh, a recognised expert body, was involved in both the development of the HSE guidance and in confirming that guidance limits were at appropriate levels (Hanson and Graveling 1997, Hanson et al 2000).

Impact of Pre-cooling

Mine climate control strategies which constrain the physiological strain at underground workplaces have obvious benefits. The body core temperature at the start of a long and difficult evacuation would be advantageously lower. The benefits of pre-cooling (and conversely the disbenefits of pre-warming) are examined here. A major advantage of pre-cooling is related to the artificially enhanced capacity for heat storage. The body’s capacity to store heat is limited and directly related to exercise intensity, body size, and metabolic heat production. The environmental conditions impact on the heat storage capacity particularly when ambient conditions are hot and humid. Nielsen (1996) showed that the rate of rise in body temperature is increased dramatically when ambient temperature is > 35°C and relative humidity is >60%. Booth et al (1997), Lee and Haymes (1995) and Kay et al (1999) confirmed that rate of heat storage (W/m²) in three different studies were significantly increased in the pre-cooled condition compared with control conditions.

Kay et al (2000) examined the effect that pre-cooling the skin without a concomitant reduction in core temperature has on subsequent self-paced cycling exercise performance under warm humid (31°C and 60% relative humidity) conditions. The results indicated that skin pre-cooling in the absence of an observed reduction in rectal temperature was still effective in reducing thermal strain and increased the distance cycled in 30 min under warm humid conditions. However there is a significant delay in rectal temperature characteristic compared with other measurement sites (Lee 2000).

Marino (2000) has reviewed the physiological benefits of body pre-cooling on subsequent exercise. The current body of evidence suggests that whole body pre-cooling is able to increase capacity for prolonged
exercise at various ambient temperatures. It is clear that pre-cooling does allow a greater rate of heat storage, with the effect of reducing the rate of rise in core temperature a decisive advantage. In most cases, pre-cooled subjects are also able to sustain higher exercise intensity than controls, but this may not be associated with any apparent metabolic or cardiovascular advantages. The effects of pre-cooling are observed for up to 30-40 min. Studies by Webborn et al (2005) indicate that both pre-cooling and cooling during intermittent sprint exercise in the heat reduce thermal strain in tetraplegic athletes (who have an increased risk of heat strain and consequently heat illness relative to able-bodied individuals).

In terms of induced cooling, there are questions as to the extent that the vasomotor response to cold may compromise the capacity for microclimate cooling to reduce thermoregulatory strain. Cheuvront et al (2003) examined the hypothesis that intermittent, regional cooling would abate this response and improve heat loss when compared with constant microclimate cooling during exercise heat stress. Compared with a no cooling control, constant microclimate cooling reduced significantly changes in rectal temperature (by 1.2°C) and heart rate (by 60 beats/min). Intermittent regional cooling regimens also provided a similar reduction in exercise heat strain and were 164–215% more efficient than constant microclimate cooling because of greater heat flux over a smaller body surface area. Providing peripheral blood flow is maintained, there is reasonable evidence that hand immersion and cooling can be effective in mitigating heat strain (Grahn et al 2005). However, regional cooling effectiveness may be relatively test condition specific. Studies by Young et al (1987) indicated that cooling arms during upper body exercise provided no significant thermoregulatory advantage, whilst cooling the thigh surfaces during lower body exercise provided an advantage. Shvartz (1976) showed that a cooling arrangement occupying as little as 2.2% of the body surface can achieve rates of cooling of >60W/m².

**There remains a degree of uncertainty regarding the most effective means of rapidly cooling hyperthermia associated with heat stroke.** To date, ice water immersion is considered a clinical gold standard for treating hyperthermia and heat stroke. Aside from conventional cooling methods, such as ice packs or ice water immersion, adjunctive cooling modalities have been evaluated. Some of these cooling methods include water spray, warm air spray, face fanning, rotary blade downdraft, whole-body liquid cooling garments, head cooling units, cooling vests, ice packs or towels, cold water immersion, and ice water immersion (Clapp et al 2001, Clements et al 2002, Costrini 1990, Desruelle and Candas 2000, Germain et al 1987, Weiner and Khogali 1980).

**Impact of Fluid Ingestion**

Earlier discussion has confirmed the role dehydration has in exacerbating heat strain. There is a requirement to maintain a euhydrated state, or at worst a mildly dehydrated state, if heat strain is to be minimised. This begs the question as to how well fluid is absorbed, particularly over relatively short time periods, and whether indeed deliberate hyperhydration (from moderate over-consumption of fluid) offers any thermoregulatory benefits.

The underlying mechanisms responsible for the premature development of fatigue in the heat include metabolic, cardiovascular and central nervous system perturbations, together with elevated core temperature. Fluid ingestion is one of three strategies that have been shown to be successful in enhancing the performance of endurance exercise in the heat, with the other interventions being pre-cooling and acclimatisation (Kay and Marino 2000). However subsequent studies (Kay and Marino 2003) showed that complete fluid replacement during exercise of 1 h did not provide a heat sink sufficient to attenuate thermoregulatory strain over no fluid replacement. The findings indicate that the ingestion of fluids replacing 100% of sweat losses has no effect on 1 h of self-paced cycling performance or thermoregulation in moderate and warm conditions.
Marino et al (2004) investigated the effect of active pre-warming combined with three regimens of fluid ingestion; (1) fluid replacement equal to sweat rate, (2) fluid replacement equal to half the sweat rate, and (3) no fluid replacement. The results indicated that fluid ingestion equal to sweat rate had no added benefit over fluid ingestion equal to half the sweat rate in determining time to fatigue over 40 min of sub-maximal exercise in warm humid conditions. However fluid restriction accelerated the rate of increase in rectal temperature after 40 min of exercise, thereby reducing the time to fatigue.

The gastrointestinal tract (GI tract) readily meets the fluid and nutrient requirements of mild to moderately severe exercise. Gastric emptying rate can keep pace with sweating rate up to 2.0 l/h. Thus it is concluded that for the great majority of situations requiring even heavy (70–80% VO$_2$max) and prolonged (1-2 h) work, the GI system is built for exercise (Fordtran and Saltin 1967). The capacity to perform this amount of exercise, without detrimental effects, also includes the colon.

On the other hand, when heavy exercise becomes prolonged, performed in the heat, and the overall stress is exacerbated by dehydration, GI symptoms emerge, gut-barrier function can become impaired. During severe exercise, splanchnic blood flow is markedly reduced and intestinal permeability can increase. When severe exercise is performed in the heat, splanchnic blood flow may further decline, gastric emptying and intestinal absorption reportedly decrease, cutaneous blood flow is reduced, and sweating rate decreases. When exercise in the heat is accompanied by dehydration (>3.0% body weight), circulatory and thermal functions are further impaired and the gut may be subjected to the combined effects of ischaemia, hypoxia, and hyperthermia. Under these conditions, gut-barrier function may be compromised (Gisolfi 2000). Neufèr et al (1989) reported impaired gastric function when subjects had elevated rectal temperature and were hypohydrated. However rates of gastric emptying were similar when exercising at 18°C and 35°C when the subjects were euhydrated.

The literature on the benefits of hyperhydration (increased total body water) as against euhydration is not equivocal in regard to tolerance and cardiovascular strain during uncompensable exercise-heat stress. Latzka et al (1998) reported that pre-exercise glycerol hyperhydration provided no meaningful physiological advantage over water hyperhydration and that hyperhydration per se only provides the advantage (over euhydration) of delaying hypohydration during uncompensable exercise-heat stress. Sawka et al (1998) suggest data supporting the notion that hyperhydration reduces physiologic strain during exercise heat stress is not robust. McLellan et al (1999) suggest hydration status has less effect on tolerance time while wearing protective clothing as the severity of uncompensable heat stress increases.

Taken on balance, the literature would appear to suggest that there is limited, if any thermoregulatory benefit from hyperhydration interventions. The literature does however confirm a requirement to maintain the body’s hydration close to the euhydrated state when subject to prolonged heat stress.

Impact of Eye Irritation from Smoke

A further critical issue affecting the success of escape is the irritant effects of smoke. Irritant effects are produced by all fire atmospheres and can be severe even in the early stages of fire development. The degree of eye irritation, as an immediate effect, is dependent only on the concentration of the irritant. However, the ability of smoke to impair escape is often grossly underestimated. Chemically induced sensory irritation results from stimulation of the free nerve endings of the trigeminal nerve in the mucosas of the eye and the nose (Nielsen 1991). The nerve endings in the cornea are stimulated, which causes pain, reflex blinking and tearing. Severe irritation may lead to subsequent eye damage. In extremis, affected individuals are forced to shut their eyes to alleviate the irritant effects, impairing any escape attempt.
Kissell and Litton (1992) undertook conveyor belt fire tests and examined the subjective irritant response to smoke. The CO concentration and subjective response to the smoke were noted as follows. The observations on sensory irritation were confirmed by Rasbash (1975) and Jin (1981).

<table>
<thead>
<tr>
<th>CO concentration</th>
<th>Reaction</th>
</tr>
</thead>
<tbody>
<tr>
<td>up to 40 ppm</td>
<td>Mild discomfort. Breathing laboured and eyes mildly irritated.</td>
</tr>
<tr>
<td>80 ppm</td>
<td>Hard to breathe. Eyes stung.</td>
</tr>
<tr>
<td>160 ppm</td>
<td>Very difficult to breathe. Severe eye irritation. Could barely see.</td>
</tr>
</tbody>
</table>

Under the specific test conditions it was observed that severe sensory irritation could take place at CO levels that did not represent an immediate carboxyhaemoglobin danger. The minimum acceptable smoke visibility was also reached before the critical maximum carbon monoxide value. Smoke is hence considered a key factor in escape from mine fires. In particular, if a fire is in the early growth stage, escaping miners will meet with visibility problems before any other. Methods to guide miners through dense smoke may contribute greatly to saving lives during mine fires. This also directs that reliable eye protection is made available. However, even if reliable eye protection can be provided, under conditions of low or zero visibility, speed of travel is materially impaired and may be less than 25% of that possible when visibility is normal (Kriel et al 1995).
Summary of Key Points:

**Heat exhaustion**
- Risk of heat-related disorders increases significantly between 31°C and 35°C BET.
- Risk of heat stroke increases tenfold between 32°C and 35°C T\_WB.
- Core temperature on presentation of heat exhaustion does not generally exceed 38.5°C.
- Few cases of heat exhaustion will occur if T\_WB <25° C, T\_DB <34°C, air speed >1.5 m/s, air cooling power >250 W/m².
- Mental performance and judgment can be significantly affected by heat.

**Impact of dehydration**
- Water deficit (hypohydration) can range from ~1% to 8%.
- Dehydration magnifies the body core temperature response in hot environments.
- Effects are detectable for fluid deficits as small as 1%.
- Physical work potential grossly impaired at >4% dehydration.
- As water deficit increases, there is a progressive increase in core temperature (compared with euhydrated state) during exercise stress.
- The magnitude of additional core temperature elevation ranges from 0.1°C to 0.23°C per % body weight loss.
- Dehydration can negate the core temperature advantages conferred by acclimation.
- At a dehydration level of 5%, core temperature responses of unacclimated and acclimated persons are similar.
- A maximum dehydration limit of 3% is suggested for industrial workers.
- Urine colour is a useful indicator of hydration status (with reservations).

**Impact of self-pacing**
- There is some evidence that central nervous system of athletes can moderate the rate of rise and maintain core temperature within critical limits.
- Experienced mineworkers generally employ self-pacing strategies to help cope with heat.
- However, severe climatic conditions that can occur underground may overwhelm any self-pacing strategy.
- Heat storage will generally occur if exercise is conducted at high wet bulb temperatures.
- Time to exhaustion is inversely related to the initial body core temperature and directly related to the rate of heat storage.
**Impact of acclimation**

- Heat acclimation is likely to confer one important advantage - a lowering of resting body core temperature of the order of 0.3-0.5°C.
- The use of acclimated subjects in the exercise protocol may have presented, at least initially, a lower body core temperature response compared with non-acclimated subjects.
- The benefits of acclimation a rapidly negated by increasing levels of dehydration.

**Impact of heat index used**

- The effective temperature index has limitations, particularly in severe hot humid climates.
- On balance however, the continued use of effective temperature in the mining industry is recommended.

**Impact of mine regulations**

- German regulations and practice confer the highest degree of protection against heat-related illness.
- UK industry depends on voluntary guidance codes. The preventive measures contained in this codes are representative of good practice.

**Impact of pre-cooling**

- The current body of evidence suggests that pre-cooling allows a greater rate of heat storage. This is a decisive advantage.
- Conversely, any pre-warming will reduce the heat storage potential.
- Intermittent regional cooling can be as effective as constant microclimate cooling.
- Cooling rates of >60 W/m² are feasible.

**Impact of fluid ingestion**

- Under normal circumstances the GI tract can absorb fluid at a very high rate.
- However as the body reacts to prolonged heat stress and dehydration the gut-barrier function can be compromised.
- Moderate over-drinking (or hyperhydration) confers limited value as a heat strain mitigation strategy.

**Impact of eye irritation**

- For ethical reasons, it was not possible to have subjects endure prolonged eye irritation.
- The potential of smoke to impair escape may be grossly underestimated.
- Reliable eye protection should be provided.
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1. General

A prototype long duration hot air simulation device was designed for use in the physiological trials phase of the research. A second use as an escape respiratory protective training model was also proposed. These notes were prepared in support of a medical risk assessment for the hot air device.

2. Hot air simulation device – description and breathing simulator test results

Design

The approach to providing a hot air simulation of a filter self-rescuer (FSR) operating in a CO challenge atmosphere was to use a calcium hydroxide absorbent cartridge in a simple ‘pendulum’ breathing circuit (i.e. the inspired and expired air pass through the same circuit elements). This provides a simple, robust breathing circuit where the calcium hydroxide cartridge behaves as a recuperative heat exchanger to preheat the inspired air stream. The conceptual arrangement for the device is given in Figure 1, although the practical device employs a short flexible breathing hose to connect the mouthpiece to the canister, offering some similarity with a self-contained self-rescuer (SCSR). One further aspect of the device design is the use of a “reactive plastic cartridge” (RPC) absorbent technology. This provides the possibility of a high reagent utilisation factor, low breathing resistance, low particulate make and consistent behaviour. Further details of RPC technology are appended to this Annex and the cross-sectional form of the selected RPC cartridge is given in Figure 2.

It is noted that the heat liberated by a FSR is largely dependent on ventilation rate and CO concentration, whilst the hot air simulation is linked closely to the CO₂ exhalation rate (VCO₂). The relative humidity of the inspired air of a hot air simulation device will also be somewhat higher than a FSR which includes a drying stage. However, on balance the calcium hydroxide absorbent heating effect is considered to provide a suitable analogue for a constrained range of exercise work rates and environmental conditions of use.

Modelling Results

Development of the hot air device was progressed via modelling, prototype design and verification testing. The behaviour of a reactive plastic cartridge in a recuperative heat exchanger configuration was modelled under typical training, laboratory and limit conditions of use, as follows:

- **Training Use**: nominally 20°C @ ~60%RH
- **Endurance Trial Use**: 29°C + 33°C BET (basic effective temperature) @ ~95%RH
- **Upper Limit Temperature for Use**: 37°C BET @ 95%RH

The overall objective here was to produce a simple analytical model which would permit the hot air device behaviour to be predicted with a sensible level of accuracy for various use conditions. Estimates of
population mean VCO₂ for particular work rates were used as a design centre figure for estimating the properties of the hot air device under given psychrometric conditions. The analysis was complicated by difficulty in quantifying the metabolic work rate associated with self-paced walking during an escape or evacuation and the impacts of varying mine floor conditions, obstructions, anxiety and (potentially) low visibility. Literature on bipedal locomotion mechanics and energy consumption under various stress conditions (e.g. soft floor, heavy boots and limited height clearance) was examined to offer some insight into the additional energy debit expended during exercise under adverse conditions.

Information was also sought on population means for minute volume, peak flow rates and impacts of dead space volume (mouthpiece and RPC canister) and breathing resistance on limiting subject potential performance. The flow type/regime through the device was also investigated and device breathing resistance estimates arrived at. This analysis work indicated that the predicted pressure drop through the candidate RPC cartridge would be acceptable against respiratory breathing resistance limit guidelines (Bentley et al 1973, Love RG et al 1977).

The modelled thermal characteristic of the hot air device was also considered to be generally satisfactory, providing the breathing rate and subject metabolic rate were constrained to “low-medium” work rates. The modelling work confirmed that it would be appropriate to undertake a range of validation tests using a breathing simulator. Subsequent arrangements were made for HSL to undertake the test work to characterise the behaviour of the proposed hot air device on behalf of HSE.

Testing of Prototype Device - Results

This work was undertaken by HSL. Two cartridge types were tested; one of 152 mm length and the other of 195 mm length. The test setup involved a breathing simulator used within an environmental chamber, where specific temperature and humidity conditions could be maintained. The hot air device thermal characteristics were determined at ventilation rates of 35 l/min and 60 l/min for a test period of up to 180 min. The tests additionally determined pressure drop (breathing resistance), and inspired O₂ and CO₂ concentration levels. The results (with some minor data interpolation) and observations supplied by HSL are summarised as follows:

- The measured thermal characteristic, inspired O₂ and CO₂ levels for the two cartridge types are given in Figures 3, 4 and 5. The inspired O₂ measurements may be unreliable due to instrumentation problems, and as such are included only as an indication.

- The breathing resistance of the cartridges was at worst of the order of ± 20mm H₂O and was reasonably consistent for the duration of the test (2 hours). This level of resistance should not burden the wearer unduly.

- The level of rebreathed carbon dioxide was generally less than 1% for the major part of the test, only reaching 1% towards the end of the test. This is an acceptable level of carbon dioxide as evidenced by the majority of respiratory standards having this level of rebreathed carbon dioxide as a limit.

- Inspired air temperature is partly dependent on the breathing rate of the wearer. Tests at a lower breathing rate (35 l/min) produced lower temperatures than tests at a higher breathing rate (60 l/min). Under ambient conditions, lower breathing rates gave peak temperatures of the order of 45°C. At the higher rate, peak temperatures approached 50°C. The peak occurred after approximately 15 minutes and then reduced by some 10 to 15 degrees over the remainder of the test. This temperature pattern was observed for all tests, regardless of canister size or environmental conditions of test.
When tested at a higher external temperature and humidity (37°C and 95% RH), peak temperatures were a few degrees higher at the lower breathing rate but were of the order of 55°C at the higher breathing rate.

The relative humidity of the inhaled air was high under all conditions of test, exceeding 90% in all cases. This is due to the nature of the chemical reaction involved.

Two sizes of cartridge were tested: 152mm and 195mm in length. From the results, there appeared to be little significant difference in performance and hence the smaller, lighter cartridge was recommended.

In order to use a cartridge as a potential training device to simulate hot wearing, it was recommended that the breathing rate be restricted (by selecting conditions of use) to <35 l/min in order to maintain the inhaled air temperature below 45°C. A short length of corrugated breathing hose to the cartridge holder would also help reduce the peak inhaled air temperature by providing some heat loss to the ambient environment.

3. Risk appraisal of using the hot air device

Given the absorbent reagent was to be close-coupled to the respiratory tract, it was necessary to evaluate any relevant thermal limits and reagent exposure limits. The risk appraisal of the hot air device encompasses four main issues:

(i) Establishing that the hydroxide reagents used within the device do not present unacceptable risks from inspired particulate or toxicity impacts.

(ii) Ensuring that the ergonomic design of the cartridge body support and mouthpiece arrangement was appropriate to the net weight, possibly as much as 1500g, taken together with the possibility of a long wearing period for the device.

(iii) Ensuring that any dead space in the hot air device does not lead to excessive rebreathing with a potential to cause oxygen deficiency.

(iv) Ensuring the tolerability of breathing hot air for long durations and that there is the smallest possible risk of respiratory tract desiccation or other burn injury potential.

(i) Risk from inspired particulate or toxicity impacts

Establishing that the hydroxide reagents used within the device do not present unacceptable risks from inspired particulate or toxicity impacts requires reference to chemical material data sheets in conjunction with design control measures (particulate filtration). In terms of reagent safety assessment, EH 40/2005 indicates an exposure limit (8 hour TWA reference period) of 5 mg/m³ for calcium hydroxide particulate (93% of the active reagent), with lower limits for sodium hydroxide and potassium hydroxide, the other reagents. Micropore Inc. (www.extendair.com), makers of the proposed reactive cartridge technology, provide a data sheet to meet the Hazard Communications (HAZCOM) regulations covered by Part 1910.1200 of Title 29 of the Code of Federal Regulations (29 CFR 1910.1200), designed to provide information on chemical risks. This provided corroborative information. It was estimated that particulate levels from the RPC device would be very low, partly confirmed from experience of use in closed circuit breathing apparatus and anaesthesiology circuits. As a precautionary measure, an air filter was incorporated between the canister and mouthpiece.
(ii) **Risk from inappropriate ergonomic design**

The overall weight of the hot air device is circa 1500g. It was identified that a close-coupled design, such as in used in current industry FSRs, could not be adapted to accommodate this weight. The load on any head straps and mouthpiece would be excessive, particularly for sustained periods of wearing. The proposed approach was to support the canister with a wide-web neck strap and couple the device to the mouthpiece with a flexible breathing hose. This arrangement is commonly adopted in SCSRs. Attention is also required concerning the management of saliva and condensate build-up associated with all mouthpiece designs. One further requirement was to ensure that the thermal action of the cartridge did not result in skin burns where the cartridge lies on the chest. This was addressed by adding a suitable insulating pad to the canister.

(iii) **Risk from excessive dead space and potential to cause oxygen deficiency**

The principal disadvantage with pendulum breathing circuits is the inherently high associated dead space. The respiratory stimulus from CO₂ enrichment (hypercapnia response) would be reduced due to the action of the CO₂ absorbent. Figure 4 indicates that measured rebreathed CO₂ levels were <1.5% for all test conditions. However due to device dead space, oxygen deficiency potential needed to be assessed further. This is considered in Annex 2. Figure 5 confirms that oxygen deficiency is not an issue for a breathing rate of 60 l/min with either cartridge type. The subsequent single measurement at 35 l/min indicates a potential instrument problem. Attention was required to ensure shallow breathing with small attendant tidal volumes does not cause any respiratory distress. In every case of use, test subjects were advised and monitored to ensure they took slow, deep breaths through the device whilst at rest. Stannard and Russ (1948) note that at rest there is a respiratory compensation to mask dead volume by an increase in tidal volume. As points of note it is observed that male, resting state tidal volume is ~500-600ml. Tidal volume should increase to 1200ml and more during exercise. The dead space of a practical hot air device was approximately 500ml; the cartridge having an intrinsic channel dead space of 280ml, the mouthpiece and cartridge plenum 100ml-120ml and the flexible breathing hose 100ml. The literature on dead space impact on physical performance suggests a potential reduction of 19% in performance if exercise is intense (80% VO₂max) for an external dead space volume of 380ml (Johnson et al 2000). The carbon dioxide (CO₂) absorbent will in practice reduce the effective dead space in regard to the hypercapnia (CO₂ induced respiratory stimulus) response.

Oxygen deficiency onset is dependent on a number of factors; magnitude of the deficiency, exposure time, work rate, breathing rate, age and health status, and physiological acclimatisation. As a precautionary measure, pilot subject testing runs involved checks of blood oxygen saturation level using a clinical grade finger pulse oximeter (97-98% normal, 90% onset of measurable impairment). It was also considered advisable to evaluate comments from test subjects and their experiences of wearing any respiratory device with significant dead space. Johnson et al (2000) reviewed feedback from subjects after wearing modified high dead space volume respirators. Subjects wearing masks with relatively high dead volumes generally withdrew before the onset of volitional fatigue. Dyspnoea was the main reason for termination. Several subjects reported that they encountered breathing difficulties immediately after being fitted, while seated, with higher dead volume masks. Several subjects also complained of headaches and dizziness during test conditions containing high dead volumes. As noted, test subjects were encouraged to increase the depth of their breathing at rest in order to maximise their respiration tidal volume.

(iv) **Risk of respiratory tract injury from breathing hot air for an extended duration**

Respiratory tract heat burden and desiccation issues were perhaps the most difficult medical risk issue to pin down. Whilst the risk assessment methodology needed to consider all feasible psychrometric conditions that might be presented to the device, information from published studies reported only
breathing dry air or breathing saturated air. Consideration of breathing hot dry air applies to the use of a FSR in high CO content challenge atmospheres, whilst the breathing of moderately hot humid air applies to closed circuit breathing apparatus and the hot air simulator under consideration. Insensible evaporative water loss from the respiratory tract is typically ~400 ml/day (~15 ml/hr at rest). In prolonged exercise, respiratory water loss can be 100 ml/hr. The modelling of respiratory water loss from using a FSR (at 0.5%-1.5% CO) indicates a somewhat higher value of between 120-180 ml/hr. This poses questions as to whether an extended period of breathing hot dry air could lead to the possibility of (i) airway desiccation, (ii) tracheal mucosal/epithelial inflammation and damage, or (iii) airflow-induced bronchoconstriction (AIB).

The issue of respiratory tract desiccation arising from the use of the proposed hot air device was reviewed in the light of HSL's breathing simulator tests. Here it was demonstrated that the inspired air from the device was in all cases of very high relative humidity, greater than 90%. This was not anticipated from earlier device modelling and resulted from the absorption of carbon dioxide in the reagent matrix being associated with a significant reciprocal evolution of free water (where three H2O molecules are produced for every molecule of CO2 absorbed).

Analysis of heat and water transport processes in the respiratory tract is generally a difficult task (Yong Gang et al 2006). Flow is complex and the thermal boundary conditions and onset of thermal damage are influenced by individual physiology, involving factors such as blood perfusion rates. Whilst there are numerous numerical simulations of skin burn injury, the early stages of thermal damage to the upper respiratory tract are less well considered. Finite difference analyses are typically used in heat transfer modelling. Thermal damage evaluation can use Henriques model approaches to predict the time for thermal injury to occur (Yong Gang et al 2006, Henriques and Moritz 1947). Several modelling simulations of regional pulmonary heat transfer were identified but it was not clear how these models help to quantify statistically relevant tolerance limits for breathing hot air. It was considered that the only sensible way to gauge tolerance limits was to review the limited scope of experimental work in this field.

As technical points, Japanese work to establish tolerability limits for breathing hot air (Takahashi et al 1999) was reviewed. This work established that a maximum wet bulb temperature of 53°C was tolerated and hot dry air to 90°C. However in these tests subjects exercised only for 5 minutes and at moderate work rates. Griffin and Atherton (1972) comment on physiological aspects of FSR design including breathing of hot air. Reference is made by Griffin and Atherton to early work, Killick (1932), who carried out investigations on tolerability limits for breathing both dry and saturated air whilst subjects were resting or walking (6.4-7.2 km/hr). The maximum temperatures that all test subjects could tolerate was 93°C (dry air) and 54°C (saturated air). Related work was conducted by HSL in the 1970s at Doncaster Mines Rescue Station to characterise the thermal tolerance limits for individuals breathing hot, dry air. It is believed that the limits cited in BS EN 404 are premised on this work and the earlier experiments of Killick. Baxter et al (1998) have examined critical parameters for human survival in regard to volcanic pyroclastic flow events where a further interpretation is offered on Killick’s findings regarding the limit of tolerance for breathing saturated air, which is cited as 60°C. Reviewing the literature, there is a degree of consistency suggesting an upper limit temperature for breathing hot saturated air of 53°C. What is not qualified is whether extended breathing durations at this temperature is associated with morbidity.

One further approach adopted in the risk assessment was to relate the effects of extended wearing of the prototype device to test limits specified for certified closed circuit breathing apparatus and escape respiratory protective devices. Within BS EN 145:1997 (section 6.28.5) it is specified that the temperature of the inhaled gas, irrespective of humidity level, shall not exceed 45°C over a two-hour test duration and 50 l/min breathing rate. Regarding FSR testing, BS EN 404:2005 cites limits of temperature and humidity (90°C DB, 50°C WB) consistent with a minimum test duration of 120 minutes for FSR-4BR devices (such as the W95). Investigations have also been made to ascertain the measured inhalation temperatures.
of various closed-circuit apparatus types in use. Here, it is evident that approved apparatus (for example BG 174) can eventually reach 47°C at a breathing rate of 30 l/min and ambient temperature of 30°C. Reference is made to Figure 6 (Eisenbarth and Schuler 2005).

4. Guidance on proposed use of hot air device

There are clearly a number of issues arising concerning "endurance" wearing of a hot air device which require medical opinion. These include:

- the possible impacts of hypohydration/dehydration on respiratory tract desiccation mechanisms
- establishing guidance on avoiding airway desiccation, tracheal mucosal/epithelial inflammation/damage and possibly airflow-induced bronchoconstriction (AIB)
- hot air device dead space, and the possibility of progressive deoxygenation.

In support of these issues the associated scientific literature was reviewed and supported by validation testing. The inspired air temperature generated by the two canister types was observed to be partly dependent on the breathing rate of the wearer. Tests at a lower breathing rate (35 l/min) produced lower temperatures than tests at a higher breathing rate (60 l/min). The lower breathing rate gave peak temperatures of the order of 45°C.

Providing use of the device can be controlled in a manner that does not result in breathing rates exceeding ~35 l/min then the resulting inspired air temperatures will not exceed the requirements of BS EN 145:1997 or BS EN 404:2005.
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Acceptable levels for breathing resistance of respiratory apparatus  

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2nd Int. Mines Rescue Conf., Sydney, 5-11 Nov. 2005

Griffin OG, Atherton E (1972)  
The physiological requirements for self-rescuers related to the performance of existing apparatus  

Henriques FC, Moritz AR (1947)  
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Stannard J N, Russ EM (1948)  
Estimation of critical dead space in respiratory protective devices  

Acceptability of elevated breathing gas temperature and humidity in relation to ventilation rate.  

Theoretical evaluation of burns to the human respiratory tract due to inhalation of hot gas in the early stage of fires  
Burns 32, pp 436-446, 2006
**Figure 1:** Conceptual form of hot air simulation device

**Figure 2:** Cross-section of candidate CO$_2$ absorbent reactive plastic cartridge technology
Figure 3: Inspired air temperature of cartridges
Figure 4: Rebreathed CO₂ concentration of cartridges
Figure 5: Inspired O₂ concentration of cartridges
Figure 6: Inspired air temperature characteristic of BG174 and BG4 closed circuit apparatus
Extract from HSE Research Report RR180 “Use of Self-Rescuers in Hot and Humid Mines”

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 CO$_2$ 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 CO$_2$ 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 CO$_2$ 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.

![RPC technology, key features](image)

Figure 2.15: Reactive plastic cartridge (RPC) technology, key features
Annex 2

Risk Appraisal Supplement

1. General

Part I of the hot air device risk appraisal focuses on the respiratory thermal characteristics of the device. This supplement provides an overview of the anticipated air composition within the device and as presented to the wearer under conditions of shallow breathing.

The risk appraisal identifies that the high device dead space combined with the removal of CO₂ potentially causing a significant reduction in blood oxygen saturation level under conditions of constrained shallow breathing. Medical opinion is that the device does not present a measurable reduction in blood oxygen saturation level whilst the test subject is either exercising at moderate intensity, or breathes slowly and deeply whilst wearing the device at rest. All subjects were medically supervised and monitored to ensure their safety. It was also recommended that any hot air training device based on the use of a CO₂ absorbent canister should be designed to offer a total dead space significantly less than the resting respiratory tidal volume. This is considered feasible in a short duration training device.

2. Hot air simulation device – description of anticipated initial air composition within the hot air device under conditions of constrained shallow breathing

The following is an overview of the initial air composition anticipated within the prototype hot air unit under conditions of quiet, shallow breathing. The hot air unit is shown assembled in Figure 1 and in component form in Figure 2. Under circumstances when the device dead space is comparable to tidal volume, little fresh air is admitted to the cartridge on each breath. In a medically supervised pilot wearing trial of the hot air device, a reduction in blood oxygen saturation level was observed during behaviourally constrained shallow breathing.

The following assessment, which uses various approximations and simplifications, points to the device causing a progressive reduction in the partial pressure of the oxygen content in the inspired air, which is anticipated over a relatively small number of breathing cycles. Further medical assessment was undertaken by the study physician to determine how ventilation stability is restored under conditions of a progressive reduction in blood oxygen saturation level.

Assumptions on quiet breathing without cartridge

When a subject is relaxed and exhibiting quiet, shallow breathing then the following is assumed:

- Ventilatory minute volume is circa 7.5 litres/min.
- Ventilatory frequency is circa 12 breaths/min.
- Corresponding depth of breathing, tidal volume is 0.625 litres.
- Resting uptake of O₂ is circa 0.3 litres/min.
Resting discharge of CO\textsubscript{2} is 0.24 litres/min consistent with a respiratory quotient of 0.8.

Exhaled air composition is 17\% O\textsubscript{2}, 3.2\% CO\textsubscript{2} and 3.8\% water vapour (35°C, 95\% RH) with the remainder nitrogen and inert gases.

Normal dry air at STP (101.325 kPa and 0°C) comprises 20.95\% O\textsubscript{2}, 78.08\% N\textsubscript{2}, 0.0314\% CO\textsubscript{2}, 0.93\% Ar and trace gases.

**Effects of wearing cartridge device**

When a subject dons the hot air device and constrains breathing to quiet, shallow breathing then the following assumptions are made:

- The dead space of the prototype device comprises 0.28 litre (cartridge) + 0.12 litres (upper plenum) + 0.1 litre (flexible breathing hose) = 0.5 litre. Figure 3 shows the proposed prototype canister arrangement.
- For the purposes of analysis, assume a second lower plenum is used to retain the reactive plastic cartridge (as used in medically supervised breathing trial). This adds 0.12 litre dead space.
- Therefore total device dead space = 0.625 litre.
- The device dead space is comparable to tidal volume.
- The device dead space may be modelled as shown in Figure 4.
- Laminar plug flow occurs throughout the breathing cycle.
- The CO\textsubscript{2} absorbent cartridge exhibits negligible slippage.

A simplified estimation of the behaviour of the device and the intermediate atmospheric compositions is as follows. For simplicity, let us assume the wearer has inhaled and then manages to don the device instantaneously. Again, it is assumed that the device dead space is equal to the tidal volume. After exhaling into the device, the following approximate conditions are anticipated at the end of the first exhalation stroke whilst wearing the device:

<table>
<thead>
<tr>
<th>Approximate air composition upstream of cartridge (in breathing hose and upper plenum zone)</th>
<th>Approximate air composition in cartridge and lower plenum zone</th>
</tr>
</thead>
<tbody>
<tr>
<td>17% O\textsubscript{2}</td>
<td>17.67% O\textsubscript{2}</td>
</tr>
<tr>
<td>3.2% CO\textsubscript{2}</td>
<td>0% CO\textsubscript{2}</td>
</tr>
<tr>
<td>3.8% H\textsubscript{2}O (water vapour)</td>
<td>3.8% H\textsubscript{2}O (water vapour)</td>
</tr>
<tr>
<td>76.0% N\textsubscript{2} + inert gases</td>
<td>78.53% N\textsubscript{2} + inert gases</td>
</tr>
</tbody>
</table>

The mean gas concentrations within the device are then approximately as follows:

17.43\% O\textsubscript{2}
1.14\% CO\textsubscript{2}
3.8\% H\textsubscript{2}O (water vapour)
77.63\% N\textsubscript{2} + inert gases
Prior to commencement of the next inspiration stroke it is observed that the air within the cartridge is oxygen deficient. The mean CO\textsubscript{2} concentration is relatively high but is not considered sufficient to invoke a hypercapnaic response.

Assuming a consistent initial uptake of circa 0.020 litre O\textsubscript{2} per breath under sustained shallow breathing with 0.6 litre tidal volume, then the next exhalation stroke would witness a slightly lower decrement in oxygen concentration compared with the initial breath. The actual reduction depends on how much of the accessible body oxygen store is available for gas exchange. The relationship between tidal volume and total lung capacity is given in Figure 5. The male total lung capacity is of the order of 6 litres. However, accessible oxygen stores within the lung are quite modest, as indicated in Figure 6.

The behaviour in the following stages, where successive breaths are taken through the device, is less deterministic. The actual behaviour will depend partly on the flow regime through the device and fresh air entry and make-up for the CO\textsubscript{2} absorbed by the cartridge. The flow model is considered later.

No data could be determined for respiratory gas exchange, O\textsubscript{2} uptake and CO\textsubscript{2} discharge on a breath by breath basis when re-breathing oxygen deficient air. However, it is anticipated that further rebreathing of the cartridge air will rapidly lower the O\textsubscript{2} concentration/partial pressure.

The above observations are broadly consistent with the observations of testing the device under behaviourally constrained conditions of shallow breathing. Here a progressive reduction in blood oxygen saturation level was observed, which was immediately corrected when the subject recommenced deep breathing, bringing fresh air again to the lungs.

3. Further discussion on respiratory response to breathing oxygen deficient air

The foregoing analysis suggests that the air within the hot air device will become progressively deoxygenated during constrained shallow breathing. This is attributable to the large device dead space, removal of exhaled CO\textsubscript{2} and the anticipated flow regime through the device. This section examines the physiological mechanisms of respiratory response to progressive deoxygenation within the lung. At this point hypoxia is distinguished from hypoxaemia. Hypoxaemia is an abnormally low partial pressure of oxygen (PO\textsubscript{2}) in the arterial blood. These comments are of necessity a very limited overview of the complex physiological control processes associated with respiration. The intention was to provide a broad appreciation of the anticipated respiratory response, towards assessing whether the device was unconditionally safe (or otherwise).

Firstly, it is identified that the partial pressure of CO\textsubscript{2} in the inspired air will remain relatively high. This is an important issue. The scientific literature [Corne et al 2003] confirms that acute hypocapnia can cause a subject to become unconscious before developing any hypoxic drive. The possible removal of the chemical drive to breathe due to hypocapnia was examined by the study physician but was not considered an issue with the current device. However, the action of the CO\textsubscript{2} absorbent moderates the rebreathed CO\textsubscript{2} concentration to under half that observed in an identical dead space without an absorbent being present.

The next question to address is the flow regime through the hot air device. James (1976) reviewed the literature on the physiological effect of respirator dead space. Rebreathing a fraction of the exhaled CO\textsubscript{2} leads to an increase in depth and frequency of breathing. Typically, the increase in tidal volume ranges from 50% to 90% of the respirator dead space volume. The type of flow through a respirator influences the manner of air change within a device. Flow can either be well-mixed or plug flow (no mixing), or some state between these physical extremes of mixing. In plug flow, the device can be conceptualised as a long tube with an opening at one end and the mouth at the other. As air enters the tube it pushes the
plug of dead space air along the tube, without mixing, into the mouth. A sharp boundary exists between the external/incoming air and the dead space air. The simple configuration of the hot air device, taken together with the flow straightening properties of the cartridge suggests that plug flow will predominate under quiet, resting breathing conditions. A further analysis is provided by Hinds and Bellin (1993) who have modelled the flow regime for a variety of flow types and respirator dead space to tidal volume ratios.

Given that the flow regime will discourage fresh air make up under constrained small tidal volume breathing conditions, there is an imperative requirement to determine how low the inspired oxygen concentration must fall prior to autonomous mechanisms being invoked to stabilise ventilation. The clinical features of a significant insult to simple asphyxiants are broadly observed to be as follows [Tan and Wang 2005]. A decrease in the fraction of inspired oxygen from ambient, (i.e., 21%) to 15% brings acute effects of hypoxia within minutes of exposure to a simple asphyxiant. This results in autonomic stimulation (e.g., tachycardia, tachypnea, and dyspnea) and cerebral hypoxia (e.g., ataxia, dizziness, lack of coordination, and confusion). It is anticipated however that the progressive reduction in oxygen partial pressure should permit the respiratory system to respond and defend a certain level of hypoxia where breathing frequency and breathing depth will be increased autonomously. This is considered further as follows by selective reference to the literature. It is noted that plant risk assessments of significant releases of an asphyxiant agent often make use of the fatality factor, \( F_i \) specified as a function of the lowest sustained oxygen concentration of exposure. The relationship is given in Figure 7.

Early work by Weil et el [1970] assessed the ventilatory response to progressive isocapnic hypoxia in normal subjects. The relationships between ventilation, alveolar oxygen tension, carbon dioxide tension and minute ventilation are given in Figure 8, A and B. The alveolar oxygen tension-minute ventilation curves for a group of 10 normal subjects are given in C, with a least squares fit in D. It can be appreciated that a relatively low oxygen tension must be obtained prior to the respiration rate responding under a normal carbon dioxide tension. This work also showed the profound effect that hypocapnia can have in suppressing the hypoxic ventilatory drive, qualified further by Corne et al [2003]. Zhang and Robbins [2000] also confirmed that under isocapnic conditions, the ventilation rate response is not significantly influenced by the type of protocol, shown in Figure 9. A further assessment is given by Tenney et al [1963], where the response to hypoxia is shown in Figure 10 at sea level and high altitude, together with the significant influence of alveolar carbon dioxide tension.

Caruana-Montaldo et [2000] discuss the respiratory control mechanisms in terms of physiology. The carotid body responds to both oxygen tension and hydrogen ion concentration. The intensity of the response of the glomus cells varies according to the severity of the arterial hypoxaemia or acidosis in a nonlinear manner. The greatest increase is seen in response to hypoxaemia, especially when \( \text{PaO}_2 \) falls to <70 mm Hg, as shown in Figure 11, at which point the firing frequency and, subsequently, minute ventilation (\( V_e \)) increase in an accelerated fashion. This increase in \( V_e \) is manifested primarily by an increase in the depth of breathing (tidal volume) rather than by an increased respiratory rate. In mammals, the carotid bodies are responsible for about 90% of the ventilatory response to hypoxaemia; the remaining 10% is from the aortic bodies.

Whilst the respiratory response to transient hypoxia requires further consideration, the main conclusion was that at slightly elevated carbon dioxide tensions/partial pressures, there should be a pronounced increase in minute ventilation (principally through an increase in tidal volume) at a defensible level of hypoxia.
4. **Recommendations on the use of chemical cartridge hot air devices**

The risk appraisal, supported by medically supervised testing, has identified that a device with high dead space combined with the removal of CO₂ can potentially induce a significant reduction in blood oxygen saturation level under conditions of constrained shallow breathing. This represents the worst case scenario. Further issues include quantifying triggering thresholds and autonomous mechanisms to stabilise ventilation, the relationship between minute ventilation and arterial oxyhaemoglobin saturation level, together with the variation in hypoxic sensitivity of subjects.

Medical opinion is that the device does not present a measurable reduction in blood oxygen saturation level whilst the test subject is either exercising at moderate intensity, or breathes deeply whilst wearing the device at rest. In each case the respiratory tidal volume will significantly exceed the device dead space. All subjects were medically supervised and monitored whilst using the hot air device to ensure their safety.

The above findings recommend that any hot air training device based on the use of a CO₂ absorbent canister should be designed so as to offer a total dead space significantly less than the resting adult respiratory tidal volume. This is considered feasible in a training device designed to produce a short duration hot air experience, using either granular reagent or reactive plastic cartridge technology.

**References**


James RH (1976) Breathing resistance and dead space in respiratory protective devices, NIOSH, Cincinnati, Ohio, HEW Publication No. (NIOSH) 77-161, 33 pages (1976)


Figure 1: Prototype hot air unit in typical wearing position

Figure 2: Components of prototype hot air unit
Revision to plenum:
Central section of end plate and internal moulding removed, as required.
Purpose to provide cartridge retention with minimum additional dead space.

Figure 3: Proposed adaptation of RPC canister to reduce dead space
Figure 4: Modelling of dead space within prototype hot air unit

Figure 5: Relationship of tidal volume to total lung capacity
**Figure 6:** Oxygen and carbon dioxide stores within the body

- Oxygen stores:
  
  \[(ERV + RV) \times F_{\text{ACO}_2} = 2700 \times 0.15 = 405 \text{ ml STPD}\]
  
  or
  
  \[= 18 \text{ mmol}\]

- Carbon dioxide stores:
  
  \[(ERV + RV) \times F_{\text{ACO}_2} = 2700 \times 0.056 = 151 \text{ ml STPD}\]
  
  or
  
  \[= 8 \text{ mmol}\]

- Blood:
  
  \[(2C_{\text{SCO}} + 3C_{\text{CO}_2})\]
  
  \[(400 + 450) = 850 \text{ ml STPD}\]
  
  or
  
  \[= 38 \text{ mmol}\]

- ECV is 13 l and ICV is 26 l
  
  \[\text{ECV: } (13 \times 24 \text{ mM}) = 312 \text{ mmol bicarbonate}\]

- Myoglobin & tissues: 7 mmol

**Figure 7:** Fatality factor Fi versus lowest % oxygen exposure

\[F = 10^{0.76(8.8 - \%O_2)}\]

\[F = 0\]
Figure 8: Ventilatory response to progressive isocapnic hypoxia in normal subjects

Figure 9: Ventilatory response to isocapnic hypoxia for three test protocols
Figure 10: Ventilatory response to hypoxia and influence of alveolar CO₂ tension

Figure 11: Generalised intensity of response of carotid body to arterial O₂ tension
Annex 3

Results of FSR Thermal Modelling

The results of thermo-chemical modelling of a generic FSR device are tabulated below together with explanatory notes.

Table 1

<table>
<thead>
<tr>
<th>(1) Temperature, ambient, °C</th>
<th>20</th>
<th>29</th>
<th>37</th>
<th>20</th>
<th>29</th>
<th>37</th>
</tr>
</thead>
<tbody>
<tr>
<td>(2) Relative humidity, ambient, %</td>
<td>60</td>
<td>95</td>
<td>95</td>
<td>60</td>
<td>95</td>
<td>95</td>
</tr>
<tr>
<td>(3) Carbon monoxide concentration, %</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
<td>1.5</td>
<td>1.5</td>
<td>1.5</td>
</tr>
<tr>
<td>(4) Temp, °C after oxidation of CO to CO₂</td>
<td>68.7</td>
<td>77.3</td>
<td>85.1</td>
<td>167.6</td>
<td>175.9</td>
<td>183.4</td>
</tr>
<tr>
<td>(5) Corresponding relative humidity, %</td>
<td>4.76</td>
<td>8.99</td>
<td>10.28</td>
<td>0.188</td>
<td>0.419</td>
<td>0.552</td>
</tr>
<tr>
<td>(6) Temp, °C after cooling by evaporation</td>
<td>38.0</td>
<td>38.0</td>
<td>43.5</td>
<td>45.4</td>
<td>50.5</td>
<td>54.1</td>
</tr>
<tr>
<td>(7) Corresponding relative humidity, %</td>
<td>52.61</td>
<td>97.54</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>(8) Temperature, °C after heat exchange</td>
<td>53.3</td>
<td>57.7</td>
<td>64.3</td>
<td>105.4</td>
<td>112.2</td>
<td>117.6</td>
</tr>
<tr>
<td>(9) Relative humidity of inspired air after heat exchange, %</td>
<td>10.35</td>
<td>21.26</td>
<td>24.59</td>
<td>1.145</td>
<td>2.467</td>
<td>3.241</td>
</tr>
<tr>
<td>(10) Molar ratio, Water evap./ CO removed</td>
<td>4.136</td>
<td>5.337</td>
<td>5.705</td>
<td>5.665</td>
<td>5.875</td>
<td>6.094</td>
</tr>
<tr>
<td>(11) &quot;Tracheal&quot; evaporation requirement, mL/hour</td>
<td>122</td>
<td>158</td>
<td>169</td>
<td>167</td>
<td>174</td>
<td>180</td>
</tr>
<tr>
<td>(12) Estimated residual oxygen content of inspired air</td>
<td>19.7</td>
<td>19.4</td>
<td>18.9</td>
<td>18.2</td>
<td>17.9</td>
<td>17.4</td>
</tr>
</tbody>
</table>

Consequences of restricting evaporative temperatures to 38 °C (under EN 404):

| (13) Temp, °C after cooling by evaporation | 38.0 | 38.0 | 38.0 | 38.0 | 38.0 | 38.0 |
| (14) Temperature, °C after heat exchange | 53.3 | 57.7 | 61.5 | 102.3 | 106.6 | 110.4 |
| (15) Heat absorption deficit, Watts | 0 | 0 | 38.4 | 53.1 | 102.2 | 142.2 |

Explanatory Notes to Table 1

Reference is made to Figure 1 overleaf, which shows a cross-section of a generic FSR. Ambient conditions (1-3), conditions immediately after the oxidation stage (4-5) and after the heat exchanger stage (8-9) are identified in Figure 1 and relate to the corresponding lines above.
Lines 1 to 3 above define the relevant ambient conditions

Over the relevant temperature range (say, 20°C to 200°C) the specific heat, $C_p$ of individual constituent gases does not change significantly; however the (molar) $C_p$ values for the different constituent gases vary significantly, from 4.978 cal/mole for Argon to 9.026 cal/mole for Carbon dioxide. Temperature changes are therefore a function of gas composition in addition to heat input from CO oxidation. This effect has been factored into the derivation of the figures quoted above.

In addition to the CO$_2$ produced via the oxidation of CO, an exhaled addition of 4.65% CO$_2$ has been assumed throughout, to define the composition of the exhaled gas as required above for temperature derivations. This concentration of CO$_2$ corresponds to a lung ventilation rate of 43 Litres/minute and pulse rate of 150/minute and which reconciles in all respects with the data provided previously.

Line 4 gives the temperatures immediately after the oxidation of CO to CO$_2$; the input water (steam) is unchanged but the relative humidity falls to low values as a consequence of the considerable increase in gas temperature.

Line 6 gives the temperature of the exhaled gas, assuming:

- Cooling to 38°C via evaporation of ‘tracheal’ water, or
- Cooling to the lowest temperature possible, defined as that temperature at which the exhaled gas becomes water saturated (100% relative humidity) at which point further evaporation / cooling becomes impossible.

Temperatures above 38°C imply that significant further cooling is required to lower the internal body temperature. Clearly, deep body temperatures in excess of 40°C and certainly 50°C cannot be sustained for long, if they can be sustained at all. However, this is the province of medical opinion.
Lines 8 and 9 give the resultant temperature /relative humidity occasioned by heat exchange between the (hot) inhaled gas and the (cooled) exhaled gas, assuming perfect heat exchange i.e. zero temperature difference between the two gas streams; a close approach to this condition might be achieved with a fine metal wire heat exchanger. These temperatures are those that would actually be experienced; the relative humidity is in all cases low. For monoxide concentrations of 1.5% the inspired air is for practical purposes dry and would be perceived as such; and at least for the removal of 1.5% CO, the temperatures seem daunting.

Line 10 gives the ‘tracheal’ evaporation requirements to effect the cooling consistent with line 6; the worst value (6.094) corresponds to the evaporation of ~360 ml of ‘tracheal’ water over a period of ~2hours; again the province of medical opinion as to related impacts.

Lines 13 to 15 quantify the effects of maintaining an evaporative heat sink temperature of 38°C; in reality this can only be achieved by additional cooling by some form of heat transfer. To put this heat transfer in context line 15 gives the additional cooling required, predicated on a breathing rate of 43 Litres / minute (as previously). In a ‘broncho-tracheal’ context such heat transfer is not possible, since there exists no temperature difference if the trachea is assumed to be maintained at 38°C. In a laboratory apparatus the dissipation of 30 to 140 Watts might be realistic.

Line 14 gives the revised temperatures (consequent on maintaining the heat sink at 38°C) after heat exchange; there is a significant reduction in the higher temperatures but no reconciliation with a maximum temperature of ~90°C without some form of supplementary heat loss.

The revised assumptions on constraining the exhalation air temperature (by unspecified means) do not lead to a reconciliation between the modelled inspired air conditions presented by a generic filter self-rescuer and the inhalation temperature limits of 90°C dry bulb, 50°C wet bulb imposed by EN 404.
Annex 4

Results of Hot Air Device Modelling

The results of thermo-chemical modelling of the hot air device are tabulated below together with explanatory notes. The second part of the Annex is an analysis of pressure drop within the hot air device.

Table 1

<table>
<thead>
<tr>
<th>WORK RATE:</th>
<th>Moderate</th>
<th>High</th>
<th>Extreme</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pulse rate, beats / min.:</td>
<td>100</td>
<td>150</td>
<td>175+</td>
</tr>
<tr>
<td>Lung ventilation rate, Litres / min.:</td>
<td>20</td>
<td>43</td>
<td>100</td>
</tr>
<tr>
<td>O₂ abstraction rate, Litres / min.:</td>
<td>1.0</td>
<td>2.0</td>
<td>4.0</td>
</tr>
<tr>
<td>CO₂ exhalation rate, Litres / min.:</td>
<td>0.5</td>
<td>1.5</td>
<td>4.5</td>
</tr>
<tr>
<td>O₂ debit:</td>
<td>5.0%</td>
<td>4.65%</td>
<td>4.0%</td>
</tr>
<tr>
<td>CO₂ addition:</td>
<td>2.5%</td>
<td>3.49%</td>
<td>4.5%</td>
</tr>
<tr>
<td>Temp. °C, post CO₂ absorption with heat exchange, for 20 / 65% RH ambient</td>
<td>45.3</td>
<td>54.6</td>
<td>63.8</td>
</tr>
<tr>
<td>RH of inhaled gas at the quoted temp:</td>
<td>14.4%</td>
<td>9.1%</td>
<td>5.9%</td>
</tr>
<tr>
<td>Equiv. CO removal at 20°C / 65% ambient</td>
<td>0.32%</td>
<td>0.53%</td>
<td>0.71%</td>
</tr>
<tr>
<td>Equiv. CO removal at 29°C / 95% ambient:</td>
<td>0.28%</td>
<td>0.44%</td>
<td>0.61%</td>
</tr>
<tr>
<td>Equiv CO removal at 37°C / 95% ambient</td>
<td>0.14%</td>
<td>0.32%</td>
<td>0.49%</td>
</tr>
<tr>
<td>Temp. °C, post CO₂ absorption with heat exchange, for 29 / 95% RH ambient</td>
<td>54.2</td>
<td>63.5</td>
<td>72.7</td>
</tr>
<tr>
<td>RH of inhaled gas at the quoted temp:</td>
<td>25.1%</td>
<td>16.3%</td>
<td>10.9%</td>
</tr>
<tr>
<td>Equiv. CO removal at 20°C / 65% ambient:</td>
<td>0.52%</td>
<td>0.70%</td>
<td>0.88%</td>
</tr>
<tr>
<td>Equiv. CO removal at 29°C / 95% ambient:</td>
<td>0.44%</td>
<td>0.61%</td>
<td>0.83%</td>
</tr>
<tr>
<td>Equiv. CO removal at 37°C / 95% ambient:</td>
<td>0.31%</td>
<td>0.49%</td>
<td>0.66%</td>
</tr>
<tr>
<td>Temp. °C, post CO₂ absorption with heat exchange, for 37 / 95% RH ambient</td>
<td>62.1</td>
<td>71.4</td>
<td>80.5</td>
</tr>
<tr>
<td>RH of inhaled gas at the quoted temp:</td>
<td>29.9%</td>
<td>18.0%</td>
<td>12.3%</td>
</tr>
<tr>
<td>Equiv. CO removal at 20°C / 65% ambient:</td>
<td>0.67%</td>
<td>0.85%</td>
<td>1.03%</td>
</tr>
<tr>
<td>Equiv. CO removal at 29°C / 95% ambient:</td>
<td>0.58%</td>
<td>0.75%</td>
<td>0.92%</td>
</tr>
<tr>
<td>Equiv. CO removal at 37°C / 95% ambient:</td>
<td>0.46%</td>
<td>0.63%</td>
<td>0.80%</td>
</tr>
</tbody>
</table>
Explanatory Notes to Table 1

1. Thermal behaviour is characterised for three work rates; “moderate”, “high” and “extreme”. Associated respiratory assumptions are given in Table 1.

2. The modelled inspired air temperatures are then given for three sets of environmental conditions; 20°C/65% RH, 29°C/95% RH and 37°C/95% RH.

3. The equivalent carbon monoxide concentration level to generate comparable heat in a FSR is given for the three sets of environmental conditions.

Analysis of pressure drops through calcium hydroxide RPC cartridge

Based on the proposed RPC cartridge type, an analysis has been made of the pressure drops that may be reasonably incurred in breathing through the cartridge. The analysis accounts for air flow behaviour through the cartridge per se, but does not include the effects of any HEPA filtration media or the impacts of saliva build up on device breathing resistance. The latter two issues must be determined experimentally.

Concerning the RPC channel geometry; the cross section is assumed to be rectangular, 2.74 mm x 0.813 mm; length, L = 152 mm. The number of channels is taken as 773.

The total CSA =17.22 cm²; the hydraulic diameter of each channel, d, (defined as 4x CSA / length of circumference) =1.254 mm.

Assuming a (worst case) tidal volume of 2 litres, and 60 breaths/minute gives a corresponding maximum flow rate of ~ 8 litres/sec. (assuming an approximately sinusoidal variation in flow rate); the corresponding maximum inhaled/exhaled velocity is 4.65 metres/sec. There are two distinct pressure drops associated with this flow velocity, viz:

(i) The pressure drop consequent on the conversion of potential energy (pressure) to kinetic energy (velocity), and which would be observed in a frictionless duct; such a pressure drop could be largely recovered in an evasee, but in the present context an evasee is not possible.

(ii) The pressure drop consequent on the fluid friction of a (real) gas with the channel walls; here, potential energy (pressure) is converted to internal energy (heat) which is also irrecoverable.

Dry air at 50°C is assumed; the first pressure drop (velocity) is given by \( P = \rho \cdot V \cdot V \cdot 2 \), where \( \rho \) and \( V \) are the density and velocity respectively, in MKS units; \( P \) is here in Pascals and is 11.6 Pascal in this instance (i.e. very low).

The second (fluid friction) pressure drop is a function of the roughness of the channel walls, gas velocity and Reynolds number, Re; since the channel walls appear pretty smooth, a roughness corresponding to a CLA of .002mm has been assumed; Re is then given by:

\[
Re = \frac{\rho \cdot V \cdot d}{\mu}
\]

where \( \mu \) is the viscosity and the other symbols are defined above; the viscosity of dry air is a (weakly) increasing function of temperature; established data are available; as defined above, for air at 50°C, \( Re = 324 \); since fluid flow is invariably laminar up to \( Re=2000 \), gas/air flow through the calcium hydroxide matrix will therefore be laminar at all times. For laminar flow, the pressure drop is given by the Hagen-Poiseuille equation, viz:

\[
P = 64 \cdot \mu \cdot V \cdot L / (d^2)
\]
In MKS units, P is in Pascals and in this example P=276.6 Pa. Adding to this pressure the velocity pressure of 11.6 Pa gives a total pressure drop of 288.2 Pa; the pressure swing is twice this figure i.e. 576.4 Pa, equivalent to ~5.8cm water gauge. Notwithstanding the obvious simplifications in the calculations above, this figure is sufficiently clear of an assumed maximum tolerable pressure swing guideline of ~17cm water gauge to establish that pressure drop through the hydroxide matrix is not considered a problem, particularly in view of the arguably extreme example chosen; these numbers also reconcile with user experience to date.
Annex 5

Results of Physiological Trials
<table>
<thead>
<tr>
<th>TRIAL NO.</th>
<th>$T_{DB}$, °C</th>
<th>$T_{WB}$, °C</th>
<th>RH (est.), %</th>
</tr>
</thead>
<tbody>
<tr>
<td>A010307-01-N</td>
<td>31.0</td>
<td>30.5</td>
<td></td>
</tr>
<tr>
<td>A010307-02-F</td>
<td>31.0</td>
<td>30.5</td>
<td></td>
</tr>
<tr>
<td>A080307-03-F</td>
<td>30.0</td>
<td>29.5</td>
<td></td>
</tr>
<tr>
<td>A080307-04-N</td>
<td>30.0</td>
<td>29.5</td>
<td></td>
</tr>
<tr>
<td>A080307-05-N</td>
<td>30.0</td>
<td>29.5</td>
<td></td>
</tr>
<tr>
<td>A080307-06-F</td>
<td>30.0</td>
<td>29.5</td>
<td></td>
</tr>
<tr>
<td>A120307-07-F</td>
<td>30.0</td>
<td>29.5</td>
<td></td>
</tr>
<tr>
<td>A120307-08-N</td>
<td>30.0</td>
<td>29.5</td>
<td></td>
</tr>
<tr>
<td>B050407-02-N</td>
<td>32.0</td>
<td>31.5</td>
<td></td>
</tr>
<tr>
<td>B050407-06-F</td>
<td>32.0</td>
<td>31.5</td>
<td></td>
</tr>
<tr>
<td>C080507-07-F</td>
<td>32.0</td>
<td>31.5</td>
<td></td>
</tr>
<tr>
<td>C080507-08-N</td>
<td>32.0</td>
<td>31.5</td>
<td></td>
</tr>
<tr>
<td>C100507-01-N</td>
<td>31.0</td>
<td>30.5</td>
<td></td>
</tr>
<tr>
<td>C100507-02-N</td>
<td>32.0</td>
<td>31.5</td>
<td></td>
</tr>
<tr>
<td>C100507-03-F</td>
<td>31.0</td>
<td>30.5</td>
<td></td>
</tr>
<tr>
<td>C100507-06-F</td>
<td>32.0</td>
<td>31.5</td>
<td></td>
</tr>
<tr>
<td>C290507-07-F</td>
<td>33.0</td>
<td>32.5</td>
<td></td>
</tr>
<tr>
<td>D290507-08-N</td>
<td>33.0</td>
<td>32.5</td>
<td></td>
</tr>
</tbody>
</table>

Table 1: Summary of trial environmental conditions
1. General

Thermal measurement techniques and standards, sources of error, attainable accuracy and application considerations are reviewed as follows. The section concludes with a brief discussion on ECG electrode behaviour for stress testing applications.

2. Thermal physiological measurement standards – ISO 9886:2004

ISO 9886:2004 identifies and contrasts measurement techniques for indicators of body core temperature, together with identifying suggested body core temperature limits (derived from particular methods of measurement).

The identified measurement techniques for body core temperature within ISO 9886:2004 are as follows:

- oesophagus: oesophageal temperature ($t_{es}$);
- rectum: rectal temperature ($t_{re}$);
- gastro-intestinal tract: intra-abdominal temperature ($t_{ab}$);
- mouth: oral temperature ($t_{or}$);
- tympanum: tympanic temperature ($t_{ty}$);
- auditory canal: auditory canal temperature ($t_{ac}$);
- body fluid: urine temperature ($t_{ur}$).

The relative merits of these methods are cited in Table A.1 from ISO 9886:2004 below. This table considers implementation complexity, continuous or discontinuous measurement capability and test subject hazards and discomfort ratings:

<table>
<thead>
<tr>
<th>Method</th>
<th>1 Instrument complexity</th>
<th>2 Technical requirement</th>
<th>3 Continuity of the measurement</th>
<th>4 Work interference</th>
<th>5 Annoyance</th>
<th>6 Health hazard</th>
<th>7 Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t_{es}$</td>
<td>2</td>
<td>2</td>
<td>C</td>
<td>1</td>
<td>3</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>$t_{re}$</td>
<td>1</td>
<td>0</td>
<td>C</td>
<td>0</td>
<td>2</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>$t_{ab}$</td>
<td>2</td>
<td>1</td>
<td>C</td>
<td>0</td>
<td>2</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>$t_{or}$ (transducer)</td>
<td>2</td>
<td>2</td>
<td>C</td>
<td>1</td>
<td>3</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>$t_{ty}$ (IR-device)</td>
<td>1</td>
<td>1</td>
<td>D</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>$t_{ac}$</td>
<td>1</td>
<td>1</td>
<td>C</td>
<td>1</td>
<td>3</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>$t_{ur}$</td>
<td>1</td>
<td>0</td>
<td>D</td>
<td>0</td>
<td>2</td>
<td>2</td>
<td>0</td>
</tr>
</tbody>
</table>

- WR: Pulse a
- Rate b
- ECG c

<table>
<thead>
<tr>
<th>Method</th>
<th>1 Instrument complexity</th>
<th>2 Technical requirement</th>
<th>3 Continuity of the measurement</th>
<th>4 Work interference</th>
<th>5 Annoyance</th>
<th>6 Health hazard</th>
<th>7 Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t_{es}$</td>
<td>1</td>
<td>1</td>
<td>C</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>$t_{re}$</td>
<td>1</td>
<td>0</td>
<td>D</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>$t_{ab}$</td>
<td>1</td>
<td>0</td>
<td>C</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>$t_{or}$ (contact)</td>
<td>1</td>
<td>1</td>
<td>C</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>$t_{ac}$</td>
<td>1</td>
<td>0</td>
<td>D</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>3</td>
</tr>
</tbody>
</table>

a This refers to the recording of the pulse rate at the wrist.
b This refers to the recording of the pulse rate deduced from an electrocardiographic signal analysis.
c This refers to the continuous recording of the electrocardiographic signal.
d Other requirements must be set to obtain accurate values.

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3. Body core temperature measurement methods and attainable accuracy

Given that ear-based measurements were a favoured method for making determinations of body core temperature, the attainable accuracy of ear-based measurements was appraised with reference to recent research and relevant tests standards. This concerns both infra-red and thermistor based measurements made in the aural canal. A subsequent section examines the issues of modelling accuracy using an arterial heat balance analysis, together with considerations of variability in local perfusion rates and method of measurement.

It is of central importance that test and measurement instrumentation provides reliable data of sufficient stability, within appropriate limits of accuracy. The essential problem of every measuring instrument is that what appears at the input of the measuring instrument might be significantly different from the real condition of a measurand. Namely, it is assumed that a measurand is stable, repeatable, and relatively unsusceptible to environmental influences. All these requirements are difficult to assure in a biological system and gross measurement errors can be introduced.

It is expected that a measuring device will deliver the true value of a measurand. In general we are interested in the accuracy of measurements. Accuracy is the closeness of the agreement between the measurement result and the true value of a measurand. The measurement result, typically obtained as the average value of several measurements, differs from the true value due to the systematic error of measurement, for which it has to be numerically corrected or physically compensated. Correction is the negative value of the systematic error. Due to random physical influential quantities, the scattering of individual measurements is represented by random errors. Random errors cannot be compensated or corrected. Therefore they are included as one of the components into the uncertainty of measurement. In general, the total uncertainty of measurement comprises many components. Some of them may be evaluated from the statistical distribution of the results of series of measurements and can be characterised by the experimental standard deviations. Other components, which can also be characterised by standard deviations, are evaluated from assumed probability distributions, based on experience or other information. Further definition and explanation can be found in a guide to the expression of uncertainty (International Organization for Standardization 1995).

For aural canal and specifically infrared ear thermometers (IRETs), we are faced with several measurement uncertainty issues. The first issue is the basic problem of radiation thermometry in general. A second problem concerns the traceability and calibration requirements for an IRET. The third problem deals with practical application of an IRET. These problems are related to each other. Deriving an adequate qualification of the contribution of these issues requires knowledge of metrological aspects in radiation thermometry linked with medical requirements and practice. Pušnik et al (2004) assessed the measurement uncertainty of infrared ear thermometers against the requirements of relevant standards (ASTM Standards 1998, CEN 2003). Practical problems in the use of these thermometers were also considered. The deviations in reading may be influenced by the age of patients, their physical condition, physiological variations in normal body temperature, place where the readings are taken, in which ear, positioning in the ear channel, obstructions in the ear channel (impacted cerumen), etc. The deviations comprise a combination of several influences. Following a general approach in conformity assessment (International Organization for Standardization 1998), Pušnik et al derived maximum permissible errors for instruments under test. Following the findings in calibration of several infrared ear thermometers, a recommendation was made that these instruments should be used with care and only as indicative measuring devices. In the case where an accurate temperature of a human body has to be determined, other more reliable methods were recommended, such as measurements with thermistors or classical thermometers.
4. Application of arterial heat balance compensation methods

To advance the understanding of the attainable accuracy of body core temperature measurement, consideration was given to the issues affecting accuracy for skin-based measurements, temporal artery and other heat balance based methods. One favoured method for correcting the measured temperature for the cooling effect at the skin is to use the Arterial Heat Balance (AHB). In this method, an equation may be derived by equating the heat supplied to the tissue by arterial blood flow = \( wc (T_c - T_s) \), with the heat loss at the skin to the ambient = \( hA (T_s - T_a) \), which results in the AHB equation:

\[
T_c = \left( 1 + \frac{h}{pc} \right) (T_s - T_a) + T_a
\]

where \( T_c \) = core arterial temperature, \( T_s \) = skin temperature (viz. at the temporal artery), \( T_a \) = ambient temperature, \( h \) = heat transfer coefficient, \( p \) = \( w/A \) = blood perfusion rate per unit area at the skin, and \( c \) = specific heat of blood. The AHB method can be used anywhere in or on the body to compute source arterial temperature from local skin temperature \( T_s \), if local ambient temperature \( T_a \) and the values of the parameters are known. The objective is to make \( h/pc \) as small as possible so that any uncertainty in \( T_c \) is as small as possible.

Important properties of the AHB model can be immediately ascertained for certain cases:

- If \( h = 0 \), which means the heat loss is zero, then \( T_c = T_s \), i.e. skin temperature is the same as core temperature.
- If \( p = \infty \), which means the perfusion is infinite, then \( T_c = T_s \).
- If \( T_a = T_c \), which means that ambient temperature is near core temperature, then \( T_c = T_s \).

The AHB equation is general for steady state conditions, although it may be modified to include nonlinearities and other second order effects to improve accuracy. It can be applied to various thermometry methods to assess errors as follows:

1. **Ear thermometry:** The heat loss coefficient \( h \) is variable depending on the direction the sensor is pointed when the probe is inserted. Deep tissue near the tympanic membrane is well insulated by the cavity effect, thus producing a low value of \( h \) and an accurate temperature. Superficial external ear tissue is more exposed, and will produce \( h \) values an order of magnitude greater. The perfusion rate \( p \) is very low in the ear tissue, thus amplifying the effect of variations in \( h \). The result is a variable measurement, which produces differences of more than 1°C depending on where the (infrared) sensor is pointed or located.

2. **Oral thermometry:** Measurements in the oral cavity are heavily influenced by evaporation, which influences \( h \), changing by orders of magnitude depending on air motion, local dew point, and precisely where the thermometer probe is placed. However the perfusion rate \( p \) is very high in the oral cavity, tending to reduce the inaccuracy caused by high and variable \( h \). A study by Tandberg and Sklar (1983) showed that increased respirations reduce oral temperature by about 1°C per 25 resp/minute.

3. **Rectal thermometry:** The heat loss factor \( h \) is determined by the insertion depth, and can be variable. The perfusion rate \( p \) is very low except under heavy exercise conditions. There is the added time lag error due to low perfusion of a large tissue mass, which can be many hours for adults. Mathematically, the AHB equation would be derived for unsteady state conditions to include heat storage.

4. **Temporal artery thermometry:** Providing the temporal artery is accurately located (by physically scanning the area), the heat loss coefficient \( h \) has only small variations depending on local skin properties (except for perspiration). The perfusion rate \( p \) is very high. The result is largely independent of technique. Perspiration is managed by extending the physical scan to a spot on the neck behind the earlobe, thus recording the temperature at this site as the peak if the temporal artery is
cooled by perspiration. This method has been demonstrated to provide corrected readings which are comparable to pulmonary artery catheter temperatures.

Carroll et al (2003) have investigated the validation of pulmonary artery thermistor measurements versus temporal artery, rectal and oral measurements, together with perfusion values. Their investigations indicate the high potential accuracy of temporal artery measurement, always providing a physical scan of the skin area is feasible.

5. Skin temperature measurements

ISO 9886:2004 considers the use of mean skin temperature. For the determination of the mean skin temperature from local temperatures measured at different body locations, many weighting schemes have been proposed, using a number of measuring points ranging from 1 to 14. In order for the measurements to be made in a systematic way and the results to be more comparable, three weighting schemes, with 4, 8 or 14 measuring points, are proposed within ISO 9886:2004. Table B.1 and Figure B.1 reproduced from ISO 9886:2004 shows the location of the 14 local temperature sites.

\[ T_{sk} = \sum \frac{1}{n} \cdot \text{weight} \]

\( T_{sk} \) is calculated by weighting each of the local temperatures with a coefficient corresponding to the relative surface of the body area that each measuring point represents. Table B.1 gives the weighting coefficients to be used for the three schemes. In conditions close to thermal neutrality and in cold environments, weighting schemes with 8 or 14 points are recommended. In warm or hot conditions, the weighting scheme using 4 points can be chosen, except in the case of a highly asymmetrical radiation.

<table>
<thead>
<tr>
<th>Sites</th>
<th>4 points</th>
<th>8 points</th>
<th>14 points</th>
</tr>
</thead>
<tbody>
<tr>
<td>forehead</td>
<td>0.07</td>
<td>1/14</td>
<td></td>
</tr>
<tr>
<td>neck</td>
<td>0.29</td>
<td>1/14</td>
<td></td>
</tr>
<tr>
<td>right scapula</td>
<td>0.29</td>
<td>0.175</td>
<td>1/14</td>
</tr>
<tr>
<td>left upper chest</td>
<td>0.175</td>
<td>1/14</td>
<td></td>
</tr>
<tr>
<td>right arm in upper location</td>
<td>0.07</td>
<td>1/14</td>
<td></td>
</tr>
<tr>
<td>left arm in lower location</td>
<td>0.07</td>
<td>1/14</td>
<td></td>
</tr>
<tr>
<td>left hand</td>
<td>0.16</td>
<td>0.05</td>
<td>1/14</td>
</tr>
<tr>
<td>right abdomen</td>
<td></td>
<td>1/14</td>
<td></td>
</tr>
<tr>
<td>left paravertebral</td>
<td></td>
<td>1/14</td>
<td></td>
</tr>
<tr>
<td>right anterior thigh</td>
<td>0.19</td>
<td>1/14</td>
<td></td>
</tr>
<tr>
<td>left posterior thigh</td>
<td>0.2</td>
<td>1/14</td>
<td></td>
</tr>
<tr>
<td>right shin</td>
<td>0.29</td>
<td></td>
<td>1/14</td>
</tr>
<tr>
<td>left calf</td>
<td>0.2</td>
<td></td>
<td>1/14</td>
</tr>
<tr>
<td>right instep</td>
<td></td>
<td></td>
<td>1/14</td>
</tr>
</tbody>
</table>

The practical difficulties in implementing an arrangement even for measuring 4 points can be significant. There is also evidence that where there is a significant radiative heat component (for example in firefighting activities), then correlation of skin temperature with body core temperature can be highly variable. Within investigations conducted by thermal physiology consultants, Optimal Performance Limited (2004), on behalf of the UK Government’s Office of the Deputy Prime Minister, skin temperatures were recorded at the neck, scapula and hand but showed a variable and generally inadequate correlation with body core temperature.
Given the practical difficulties of implementing a suitable, rapid deployment operational arrangement for determining skin temperatures at multiple sites, researchers are examining non-conventional skin temperature measurement methods. A summary is given below.

With the outbreak of SARS in Indo-China, there have been extensive searches for thermometers which could be used for rapid non-invasive screening for fever. Significant interest has been expressed at airports in the feasibility of using infra-red imaging systems, so as to permit rapid, non-invasive screening. Pompei and Pompei (2004) have examined the variables which must be considered to provide a reliable detection system.

An IR camera (or any remote IR radiometer) must contend with two sources of measurement uncertainty; the radiometer uncertainty and the physiological uncertainty. The analysis below only deals with the physiological uncertainty. Examination of specifications of available devices suggests that absolute accuracies for IR imagers are limited to about ±1°C. Spot radiometers designed for medical applications can achieve absolute accuracies of 0.2°C. Based on a calculation method using the probability theorem that the variance of a uniformly distributed variable is equal to its range squared divided by 12, uncertainties were enumerated in statistical terms. Table 2 below, reproduced from Pompei and Pompei (2004) tabulates radiometer temperature reading uncertainties due to several physiological variables. Within the limitations of this analysis, it is clear that the development of a high accuracy radiometric screening device is technically challenging. Further consideration is given in proceedings of Thermosense XXVI (2004).

<table>
<thead>
<tr>
<th>Physiological Variable</th>
<th>Est. Range</th>
<th>Estimated standard deviation of temperature uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Remote IR</td>
</tr>
<tr>
<td>Skin emissivity</td>
<td>0.97 ± 0.02</td>
<td>0.31°C</td>
</tr>
<tr>
<td>Skin ambient temperature</td>
<td>±5°C</td>
<td>0.58°C</td>
</tr>
<tr>
<td>Variable perfusion on face</td>
<td>±1°C</td>
<td>0.58°C</td>
</tr>
<tr>
<td>Perspiration on the face</td>
<td>±1°C</td>
<td>0.58°C</td>
</tr>
<tr>
<td>95% confidence interval of errors due to identifiable skin physiological variables</td>
<td></td>
<td>2.09°C</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.21°C</td>
</tr>
</tbody>
</table>
6. Safe upper limits of body core temperature and measurement capability

ISO 9886:2004 suggests body core temperature limits as follows for occupational exposures in hot environments (not clinical or laboratory settings, where wider limits may be acceptable). Limit values will depend upon the rate of increase of core temperature and the types of physiological measurement used. In the case of slow heat storage (that is, increase by about 1°C in more than 1h), the limit must be set at an increase of 1.0°C or 38.0°C whichever comes first, in the following cases:

- if body core temperature is measured intermittently, whatever the technique used;
- for auditory canal temperature and tympanic temperature, because the constant correct positioning of the transducer is uncertain;
- in the absence of competent medical personnel;
- when no other physiological parameter is measured.

In case of rapid heat storage (increase by about 1°C in less than 1h), the same limits apply in the same conditions as well as when rectal or intra-abdominal temperature are used, as they rise at a lower rate than the temperature of the thermoregulation centres. In other conditions and in particular when oesophageal temperature as well as heart rate is monitored continuously, higher limit values can be tolerated, such as an increase of 1.4 °C or 38.5°C, whichever comes first.

Stable temperatures above 38.5°C may be tolerated providing the following conditions are observed:

- The subjects have been medically screened.
- They are acclimatised to heat through repeated exposure to that environment and to the particular work task.
- Continuous medical surveillance is provided and emergency resources are readily available.
- Oesophageal temperature is continuously monitored.
- Other physiological parameters, in particular heart rate, are monitored simultaneously.
- The exposure can be stopped as soon as intolerance symptoms, such as sensations of exhaustion, dizziness, or nausea appear.
- The worker is allowed to leave the work situation as he or she pleases.

Any increase of the core temperature above 39.0°C is not recommended. The above precautionary limits may be contrasted with two heat exposure survey results from mining industries in the UK and Australia, where environmental conditions can exceed those considered acceptable under industrial occupational health standards (ACGIH 1998). Hanson et al (2000) determined the following for the mines surveyed:

- Environmental conditions at the three hot mines showed only small differences at comparable measurement locations.
- The majority of effective temperatures measured at workplaces were within a range of 26º-32ºC.
- At a small number of workplaces, effective temperature reached 40ºC.
- Mean core body temperature increased by 0.04°C per ºC increase in BET.
- Core body temperature measurements exceeded 38ºC for 13% of the measurements recorded, and exceeded 38.5ºC in 7% of the measurements recorded.
Brake (2002) surveyed hot Australian mines, where average environmental conditions were measured as 30.9ºC WBGT, std dev 2ºC within a range of 25.7º - 35.2ºC. Measurements of maximum body core temperature indicated that acclimated mineworkers measured on average 38.3ºC, std dev 0.4ºC, with a maximum temperature rise of 1.4ºC, std dev 0.4ºC and maximum heat storage of 431kJ, st dev 163kJ.

7. Temperature instrument selection issues

It is clear from the above reviews and argument that the application and measurement of body core temperature instruments in a non-clinical setting is not straightforward. Significant sources of potential error and variability are noted. Favoured measurement approaches, based largely on practicability of implementation include the following:

- aural canal thermistors,
- temporal artery thermistors, and
- ingestible pill technologies.

Whilst the scientific literature reports widely the use of pill-based gastric temperature sensors, infrared tympanic and temporal artery based measurements, all of these are considered to be highly dependent on experimental technique or the individual’s physiology. Ingestible pill technologies are proven research tools but are not acceptable to all test subjects. Alternative simpler, practical, non-invasive approaches are favoured. It is also necessary to consider how straightforward it is to deploy the instrumentation, and the degree of repeatability. Intra-individual variances in absolute temperature can result from sensor placement or application technique, and there may be a warm-up period, where the indicated temperature/rate is unreliable.

On balance, the use of 2-point calibrated aural canal thermistors housed within a thermally insulated housing was considered to offer moderate though acceptable accuracy together with a straightforward application method.

8. Heart rate monitoring in stress testing environments

There are numerous real-time reading heart rate monitors available, some of which offer clinical grade performance. The preferred approach, at least in principle, was to use the heart rate and body core temperature monitoring and data logging facilities as used and reported in HSE Research Report 180. The benefits of this arrangement were that the heart rate, core temperature and treadmill odometer readings were taken in synchronisation, and were data logged and stored as a single text file (for export into statistical packages etc. for subsequent analysis). This arrangement also permitted the physiological vital signs to be displayed in real-time on a portable computer. However, a recognised deficiency in the earlier measurement scheme was the intermittent nature of the heart rate recordings, attributed to ECG electrode and movement artefact problems. For this reason, consideration was given to sourcing specialised ECG electrodes.

In order for ECG/heart rate monitoring signals to pass from the body to the electrode, an electrically conductive path between the skin and electrode must be established. The conductive ability of this path is referred to as electrode impedance or contact impedance. High impedance decreases the conduction of the ECG signal. The major factors affecting electrode impedance are: (i) the quantity and quality of gel between the electrode and the skin and (ii) the degree to which the outer layer of the epidermis (the stratum corneum) has been bridged by the conductive gel. Proper site preparation (as described below) will produce contact impedances of 10 kohms or less in 90% of subjects (Patterson 1978), noting that <5 kohms is a target value. Improper site preparation will usually produce contact impedances as high as 100kohms to 200 kohms. An ideal skin preparation consists of four steps:

- Abrasive removal of part of the stratum corneum to allow the electrical signals to travel to the electrode.
Scratching the stratum granulosum to reduce motion potentials generated in this layer.
Defatting/deoiling of the skin to permit the adhesive base on the electrode to grip the skin.
Assuring the presence and sufficiency of conductive gel.

Until recently, movement of the electrode gel under the electrode was thought to be the primary cause of motion artifact. However, studies have revealed that this effect in many cases is small (Tam and Webster 1977, Odman and Oberg 1982) The electrode gel does, however, significantly affect the transmission of signals from the skin to the electrode. The lack of sufficient electrode gel, possibly due to sweat leaching or evaporation, results in 50 Hz mains pickup from the very high electrode impedance presented. Sweating can also produce ECG electrical disturbance by shorting electrode pairs.

Mindful of the above observations, care was taken to source ECG electrodes which were specifically designed for stress testing application, where significant movement and sweat rates could be expected. However despite favourable initial heart rate recordings, subsequent tests were highly variable. It is questioned whether it is feasible to design long duration ECG electrodes for stress testing. The stress testing electrodes, along with details of the temperature sensor and environmental chamber are given below.
Figure 3: Environmental chamber, temperature sensor and heart rate monitoring arrangement
References

ACGIH (1998), Heat stress in TLV’s and BEIs: Threshold limit values for chemical substances and physical agents, ACGIH, Cincinnati, OH, USA, 1998, pp 170-182


Evaluating methods of training of mineworkers for hot inspired air when wearing self-rescuers

HSE defined a need for an improved training methodology for escape respiratory protective devices, essentially to provide a realistic experience of the hot air breathing effects of a device operating in a high carbon monoxide content mine atmosphere. Information was also sought by HSE on the tolerability and ultimately endurance limits associated with the extended wearing of an escape respiratory protective device producing a significant heat burden. This information would collectively help address HSE’s duty to offer advice to mine managers on escape respiratory protective systems selection and use, including where escape will entail conditions of high heat and humidity. The research work was addressed in two phases; involving (i) thermo-chemical modelling of filter self-rescuers and the development of a hot air simulation device, suitable for both research and training purposes, and (ii) a range of physiological trials which identified significant thermal physiological benefits from adopting a staged evacuation process in conjunction with safe havens.

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