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ASSESSING THE WORK INTENSITY OF MINE RESCUE ACTIVITIES AND ITS RELEVANCE IN APPLYING HEAT STRESS MANAGEMENT PROTOCOLS

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ABSTRACT

The metabolic heat production, as measured through indirect calorimetry, and the associated changes in core and skin temperatures of mine rescue personnel were continuously monitored during a simulated rescue in an underground mine. The purpose of the study was to target and analyze a high intensity task to supplement data already gathered on more typical light to moderate mining tasks. This data was being compiled to help design the test protocols for more rigorously controlled heat stress research being performed in a climate controlled environmental chamber and the Snellen whole-body calorimeter. The mine rescue assessment evaluated ten volunteers performing a repeated exercise working as teams of five. The exercise which lasted on average 66 minutes, involved carrying a weighted rescue-basket up an incline, installing pipe on a wall and descending the incline. The task generated an average of 538 W of metabolic heat which was sufficient to cause the average core temperature of the volunteers to increase continuously throughout the exercise from 37.31 to 38.14°C, this was despite the exercise being performed under cool environmental conditions t_{db} = 16.9°C and t_{wb} = 14.9°C. In two individuals the core temperature exceeded 38.5°C. This study shows, special consideration is required for monitoring mine rescue personnel because even in cool shallow mines, a prolonged mine rescue task could cause core temperatures to exceed recognized limits.

KEYWORDS: *Heat Stress, Mine Rescue, Core Temperature, Indirect Calorimetry*

1. INTRODUCTION

Human heat stress is primarily a function of the rate of heat gain due to the work being performed and heat lost to the surrounding environment. Mining in Canada, similar to other countries, continues to become more mechanized and automated. Because of the elimination of many manual tasks, generally speaking mining today is not as physically demanding in terms of metabolic work as it was in the past and this has the potential to reduce work induced heat effects. However, counter balancing this change is the trend to mine deeper in hotter conditions which increases the potential for environmentally induced heat effects since the deeper mine environment has a lower cooling capacity. There are also certain specific tasks, which now and for the foreseeable future, will require a significant metabolic work rate. These are some of the reasons for Canada's current interest in mitigating heat stress.

For Canadian mines, protecting the worker is always a priority. However as mines become deeper, the disproportionately escalating ventilation and potential refrigeration costs are coming under increasing scrutiny. Through the Deep Mining Research Consortium (DMRC), on behalf of the mining industry, researchers are trying to determine whether the current design/operational guidelines are appropriate to meet the specifics of their industry.

In order to determine whether the industry should continue to use the American Conference of Governmental Industrial Hygienists (ACGIH, 2001) Wet Bulb Globe Temperature (WBGT), their own psychrometric wet bulb criteria, another parameter, or a modification of any of these, the DMRC initiated a multi-year, multi-faceted research initiative. The major elements of this program were: 1) the in situ categorization of typical mining tasks through time-and-motion and energy cost analyses, 2) the replication of these tasks under temperate and extreme controlled thermal environments in a laboratory, and 3) testing the validity of an existing, new or modified indicator again in-situ, in the mining environment. Currently, the work is still at the laboratory stage. Another element of the program is an assessment of the instruments available to assess environmental parameters related to heat stress, such as the traceability of a WBGT meter's measurements (Hardcastle and Butler, 2008). Other research interest areas added through the course of the work have been the evaluation of the clothing worn by the underground workforce (Hardcastle *et al*, 2009), and the effect of intermittent work on body heat storage. The need to reassess heat stress in these areas is becoming evident through recent work involving whole-body calorimetry which indicates that heat storage, based on thermometric models may significantly underestimate body heat storage (Jay *et al*, 2007). It also shows that body heat is accumulated over time during intermittent work (Kenny *et al*, 2009) which may limit the work capacity in successive work bouts before reaching a critical body core temperature.

1.1. Mine Rescue – A High Metabolic Demand Activity

The early phases of the DMRC heat stress project (Reardon, 2007) showed that the average metabolic rates of the common mechanized mining occupations in Canadian mines ranged from 187.4 ± 77.3 W to 331.6.± 98.23 W despite short-lived, peak metabolic rates of 1080 W. Using the ACGIH (2001) ranking the work rate would be considered "Light" to "Moderate". Although important in the overall classification of mining activities, in the absence of a high metabolic average demand activity, this finding and its subsequent replication of the activities under controlled environmental conditions failed to show whether or not, the mine's heat management design and operational guidelines were appropriate. Hence, the mine rescue activity was selected to provide data of a prolonged high intensity task.

1.2. Previous Mine Rescue Studies

Despite mine rescue activities being studied in the past, in regard to avoiding heat stress, little information was found as to the actual measurement of the metabolic demands of their occupation. Lind et al (1955) mentions the use of Douglas bags to determine metabolic costs during work and rest however, no results are given. Kampmann *et al* (1994) reports, in their early mine rescue work, a single evaluation of 430 W as measured with a Gas clock from within a group of ten studied subjects. In both studies, these types of measurement would not have been continuous. In Kampmann *et al*'s later work (1996, 1997 & 1999) the focus moves towards monitoring heart rate and rectal temperatures as the indicators of potential heat strain. Similarly, the study of mine rescue activities reported by Varley (2004) used core temperature and heart rate monitoring as heat strain indicators and categorizing the work intensity was purely through visual observation. The validity of using heart rate as a heat stress indicator is questionable as it is more directly affected by work and metabolic rate. More recently, Stewart *et al* (2008) compared the physical capacity of mine rescue personnel and the demands of rescue activities through a series of simulated rescue related fitness tasks performed on surface. In this latter study, ergospirometry was used to determine each subject's aerobic capacity, VO_2 max, but not real-time oxygen consumption.

2. METHODOLOGY

2.1. Subjects

A total of ten mine rescue volunteers were used to form the standard 5-man rescue team of four "workers" and a Team Captain. They were recruited from three mining companies in the Sudbury area through the Ontario Mine's Rescue, part of Mines and Aggregates Safety and Health Association (MASHA) and each company's emergency response supervisors. All subjects were experienced mine rescue personnel who were currently participating in, and had regularly performed mine rescue training activities in the past. The mean characteristics of the male participants who consented to the study were: Age 47 ± 9 years; Height 1.78 ± 0.07 m; Weight pre-study (nude) 87.4 ± 12.1 kg; Weight dressed with equipment 109.3 ± 13.1 kg; Body fat (Brozek) 19.7 ± 3.9%; and Clothing/equipment weight 21.9 ± 1.7 kg. The post study weight of the participants was 86.6 ± 12.3 kg. Figure 1 shows some of the volunteers, fully equipped during the simulation exercise.

Figure 1: Mine Rescue Team Resting During Ramp Ascent Transporting Pipe

2.2. Experimental design

The objective of the test was to evaluate the physiological response of the mine rescue personnel performing what may be considered a strenuous task, or series of tasks, representative of that which could be expected in a true emergency. The specific, required conditions included; 1) that the test be carried out within a non-thermally stressful environment to avoid limiting the rescuer's performance; and 2) that each element of the task be of sufficient duration, in the order of five minutes, so any associated changes could be identified. The actual test performed by the subjects was designed by the Program Supervisor and an Officer of Ontario Mine Rescue. The area

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chosen for the test was an inclined ramp section of a fresh air system, primarily between the 440m and 360m Levels, of Garson Ramp Mine in Sudbury.

Over the course of three days, the test exercise was repeated five times, each time with a different Team Captain. Two mine rescue personnel were studied per test session. These subjects would be two of the four working members of the team responsible for the majority of the physical tasks. For the first two days, the volunteers were divided into two different teams of five. On the last day, a composite team was assembled to evaluate the subjects not tested on previous days.

In order to determine the metabolic heat production, the test subjects inspired ambient air while the non-test subjects inspired the recycled and reconditioned air normally supplied by their closed circuit breathing apparatus. This condition for the test subjects was required because the analytical equipment was limited to an optimal oxygen, O_2, measurement range between 0 and 28%. Initially, this was performed through a modified version of the standard breathing apparatus mask. However, this was later replaced by the half-mask designed to be used with the O_2 instrument. According to the test subjects, there was no perceived difference between the resistance of the breathing apparatus and the half-mask.

The Draeger BG4 closed circuit breathing apparatus used includes a carbon dioxide, CO_2, chemical filter that generates heat which may limit or negate dry respiratory based cooling. To compensate for this, the unit has an optional ice based air cooling system. In Ontario, the Mine Rescue personnel typically used ice in their BG4s when the air temperature is above 0ºC. The test subjects inspired mine air with typical O_2 (normoxic) and CO_2 levels, under ambient humidity and temperature conditions while the non-test subjects inspired a cooled, mildly hyperoxic “air” ($O_2 > 21\%$) scrubbed free of CO_2. The thermal effect of dry, respiratory heat losses or gains on total energy balance estimation were considered to be negligible given the relatively high metabolic requirement of mine rescue activities.

2.2.1. Experimental Protocol: The volunteers to from a five man team reported to the mine site at least 90 minutes prior to the scheduled test. During this period the subjects to be studied during that test session were measured, weighed and fitted with various physiological transducers. The test subjects then prepared to go underground dressing in appropriate undergarments, socks, coveralls, boots, belt, gloves and hard-hat, as well as a light/battery pack and their breathing apparatus (Draeger BG4) before being re-weighed.

After resting for 15 minutes, each subject's resting baseline values were established. The subjects, along with the rest of the team were transported by personnel carrier to the testing site. After the rescue exercise, the team was transported out of the mine and reweighed to establish fluid loss.

2.2.2. Rescue Exercise: The rescue exercise had seven phases. Phases 1, 4 and 7 involved lifting, carrying and setting down the rescue basket while walking up an inclined ramp from the 440L. During Phase 1, the team's load was 54.4 kg (basic equipment). In Phase 4, Figure 1, the basket was also loaded with steel piping to repair a mine service, increasing the weight to 154.8 kg. In Phase 7, the basket was loaded with 90 kg of sandbags, equivalent to the weight of a person, for a total of 141.7 kg. For Phases 1 and 4, ascending through the lower and middle ramp sections and then on to the 360L, the distance was 201 m at an average incline of 5.6°. For Phase 7, the distance increased to 254 m, ascending through the lower, middle and upper ramp sections at an average incline of 7.9°. Phases 2 and 5 involved installing a length of steel pipe, the first weighing 87.7 kg and the second 129.7 kg, at shoulder height on the wall of a mine tunnel. Phases 3 and 6 were the return trips from the 360L down through the middle and lower sections of the ramp to the 440L. The pace of the ascent or descent, the duration of each carrying element and length of the rest period between carries was set by the Team Captain based upon his observations of the team. As per normal mine rescue practice, the positions of the rescuers carrying the basket was rotated at every rest.

2.3. Measurements

2.3.1. Metabolic Heat Production: The net rate of metabolic heat production was determined through indirect calorimetry from the difference of the subject's metabolic rate and their external work. A portable Ergospirometer (Jaeger Oxycon Mobile) was used to estimate the metabolic rate from minute-by-minute average values of oxygen consumption, carbon dioxide production, the ventilation volume and respiratory exchange ratio.

2.3.2. Temperatures: Similar to Varley (2004), the deep body temperature was measured using a telemetric "pill" type temperature transducer. The "pill" was swallowed upon arrival at the mine site, which was at least 2.5 hrs before the exercise started. Skin temperatures were measured at the following 8 locations using telemetric transducer patches: upper back, chest, lower back, abdomen, triceps, bicep, quadriceps and calf. A standard weighted average was then used to estimate the mean skin temperature.

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2.3.3. Environmental Conditions: The ambient conditions of dry bulb temperature and relative humidity, were continuously measured and recorded at 1 minute intervals at six locations throughout the test area using data loggers (ACR SmartReader Plus2). These measurements defined the initial and final conditions of 4 different airflow sections of the test area. The airflow in each section was measured by mine personnel through a full traverse using a 4” Ø Biram type analog vane anemometer (Davis Instruments). Barometric pressures were recorded throughout the test area from a multifunction instrument (Nielsen-Kellerman, Kestrel 4000) to determine psychrometric wet bulb temperatures.

2.3.4. Other Measurements: The actual distances travelled (slope or level) were measured during the exercise. The incline or change in elevation was determined from mine survey data. The weight of the pipe and sand bags was also supplied by the mine.

Table 1: Average Environmental Data for the 4 Sections of the Test Area

	Temperatures		Relative Humidity	Moisture Content	Air Velocity	Evaporative Cooling
	t_{db} (ºC)	t_{wb} (ºC)	(%)	(g/kg)	(m/s)	(kJ/kg)
Lower Ramp (Above 440mL)	15.2	14.9	96.7	10.65	0.36	0.28
Middle Ramp (Below 330mL)	17.0	14.8	78.6	9.67	1.91	2.76
Pipe Hang Area (330mL)	17.5	14.8	76.4	9.67	1.62	3.14
Upper Ramp (Above 330mL)	18.1	15.1	73.7	9.69	4.25	3.91

3. RESULTS

3.1. Environmental Conditions

Table 1 summarizes the measured and calculated environmental conditions for each section of the test area. The direction of the airflow was down the ramp, into the face of the rescue team as they ascended. The air velocity was highest in the upper section of the ramp closest to an intake booster fan system at 4.25 m/s. It then decreased through the middle and lower sections as air was distributed to other areas. In the lower section, where the exercise started, the air velocity was very low at 0.36 m/s.

The temperature and relative humidity data show that, initially, the dry bulb temperature decreases and the relative humidity increases, through heat loss to the surrounding rock as the air descends the ramp. However, in the lower section of the ramp, evaporation further decreases the temperature as the moisture content of the air increases and the relative humidity climbs towards 100%. The associated psychrometric wet bulb shows a variable trend while being greatest in the upper section of ramp. The average temperature conditions of t_{db} = 16.9°C and t_{wb} = 14.9°C for the test area, with a WBGT in the order of 15.0°C, can be considered cool and insufficient to contribute to any thermal stress. However, this data also shows that the lower ramp section has minimal evaporative cooling capacity.

Table 2: Descriptive and Metabolic Data for the 7 Phases of the Rescue Exercise

Phase	Dist. Ramp/ Level (m)	Vert. Rise (m)	Avg. Grade (°)	Load (kg)	Time (min)	Travel Speed (km/h)	Oxygen Usage VO_2 (l/min)	Energy Expenditure Abs. (W)	Rel. (W/m^2)
1: Ascent	174 27	17	5.6	54.4	6.4 ± 0.9	1.6	1.4 ± 0.7	578.1 ± 250	272.5 ± 115
2: Pipe Hang				87.7	12 ± 2.5		1.12 ± 0.3	412.8 ± 145	202.5 ± 71
3: Descent	174 27	17	-5.6	25.0	9.2 ± 1.9	1.1	1.29 ± 0.4	443.3 ± 132	208.7 ± 58.7
4: Ascent	174 27	17	5.6	154.8	6.3 ± 0.5	1.7	2.22 ± 0.4	713.5 ± 162	346 ± 76
5: Pipe Hang				129.7	11.0 ± 3.5		1.23 ± 0.4	420.7 ± 148	204.9 ± 72
6: Descent	174 27	17	-5.6	54.4	8.0 ± 1.3	1.3	1.43 ± 0.8	492.1 ± 265	239.5 ± 117
7: Ascent	254	35	7.9	141.7	13 ± 4.9	1.2	2.16 ± 0.6	742.4 ± 224	359.3 ± 107

3.2. Metabolic Work

Table 2 summarizes the average duration, the oxygen consumption, metabolic work and relative energy expenditure of the subjects for each phase of the exercise, as estimated through indirect calorimetry. As expected, these results show that ascending the ramp (Phases 1, 4 & 7) required the greatest metabolic rate starting at 578 ± 250 W. This expenditure then increased with the additional loading of the rescue basket reaching a maximum of 742 ± 224 W. Descending the ramp was the second most intensive phase with the highest expenditure again correlating with the heavier rescue basket plus resuscitator. The least intensive task was installing the pipe on the wall ranging from 413 ± 145 through to 421 ± 148 W. However, based upon the ACGIH (2001) criteria, this work rate would still be categorized as the onset of “Heavy” and descending the ramp would be in the same category. Ascending the ramp, even with the standard load basket, would be considered “Very Heavy” work rate. The rate of work and duration of the ramp ascents are also sufficient to produce a time weighted average across the 66-minute exercise of 538 W, which is also “Very Heavy”.

3.3. Changes in Deep Body Temperature

Figure 2 shows the average deep body temperature of the 9 successfully monitored subjects along with their relative metabolic rate throughout the rescue simulation normalized to a 75 minute duration. These averaged “pill “ temperature results show that regardless of the variation of metabolic rate, once the core temperature starts to increase from 37.31°C, it continues to increase at a fairly consistent rate of ≈0.011°C/min throughout the rescue exercise reaching a maximum of 38.14°C, a net increase of 0.83°C. However, individual maxima reached 38.9°C, with a net increase of 1.20°C. According to the ACGIH guidelines a core temperature of 38.5°C is the limit for medically selected and acclimatized personnel to avoid excessive heat strain. Consequently, some of these subjects were already at and beyond accepted limits for continuing the activity.

Based upon the overall trend, an increasing number of the volunteers could have been at risk if the exercise continued. However, the deep body temperature data for some individuals also shows that it may have started to reach a plateau.

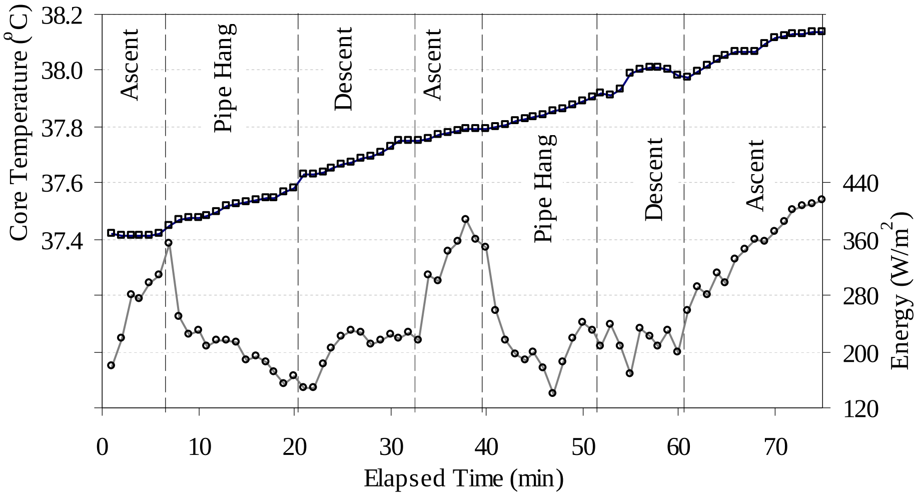

Figure 2: Average Pill Core Temperature and Energy Expenditure during the Simulated Mine Rescue Exercise

3.4. Changes in Mean Skin Temperature

Figure 3 shows the average mean skin temperature successively recorded for 9 of the 10 subjects along with their relative metabolic rate throughout the rescue simulation. Here, it can be seen that, initially, the mean skin temperature gradually drops during the first ramp ascent, pipe hanging and ramp descent cycle. The net decrease of 0.4°C during this period was, a consequence of the cooler external environment. For the remainder of the exercise, the skin temperature generally increases with a total change of 0.6°C. The rate of change of the mean skin temperature, upon starting to increase was ≈0.014°C/min, this rate was faster than that observed for the core.

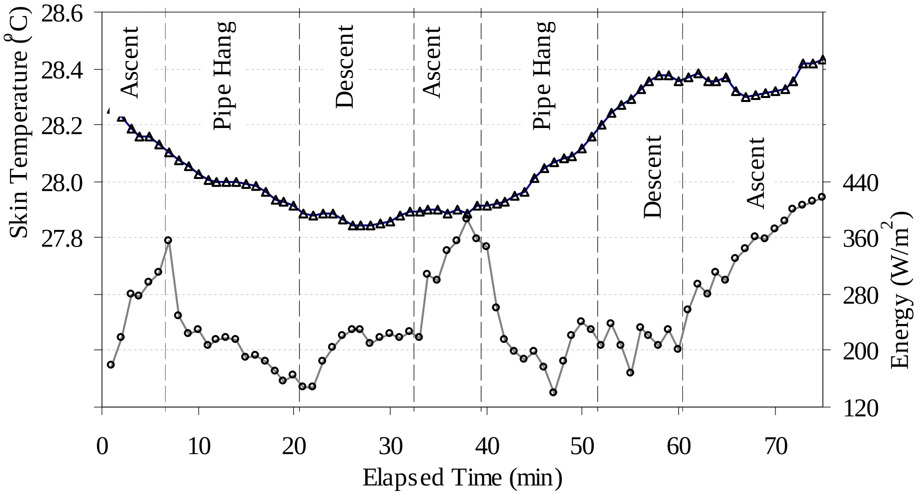

Figure 3: Average Mean Skin Temperature and Energy Expenditure during the Simulated Mine Rescue Exercise

4. DISCUSSION

As far as the authors were able to determine, this was the first time the energy expenditure of mine rescue personnel has actually been determined continuously, albeit an estimation through oxygen consumption, during a simulated mine rescue exercise. The results obtained show that mine rescue involves what could be classified as Heavy to Very Heavy metabolic demand activities. In this series of simulated emergency tasks, designed by Ontario Mine Rescue personnel to be typical of what the team could expect, the minimum and maximum energy expenditure per phase of the exercise were 413 ±

145 W, 578 ± 250 W respectively. This was significantly greater than observed for the more routine mechanized mine activities previously studied (Reardon, 2007), where 331.6 ± 98.2 W, considered moderate, was the highest average metabolic rate. The lowest rescue metabolic rate was comparable to the single 430 W measurement reported by Kampmann *et al* (1994).

The average metabolic rate, pro-rated for the duration of each phase of the rescue simulation, at 538 W was sufficient to produce an average core temperature of 38.14°C, an increase of 0.83°C. Although this average increase represents only 70% of that required to reach the regulated limit, two subjects had temperatures >38.5°C. Whether core temperatures had reached a plateau, or would continue to increase if the exercise lasted longer, is unclear.

However, if the same strenuous exercise was performed in a more environmentally stressful environment and considering, when questioned, many of the volunteers believed they had worked harder in other rescue emergencies and exercises, the potential for more rescue personnel to suffer heat stress is evident. It is also worth noting that, while performing strenuous exercise, the young and healthy are more likely to be affected by exercise (work) induced heat stroke (Chiong and Stitt, 1995). In this mine rescue simulation, it was apparent that two of the younger volunteers suffered to a greater extent.

When considering the maximum core temperature of 38.14°C and the maximum mean skin temperature of 28.43°C of the test subjects, the cardio-vascular cooling mechanism, which transports heat from the core to the skin surface appears to be working. However, whether it has reached a maximum, or could remains sufficient depends on whether or not the core temperature has stabilized. Furthermore, the difference between the skin and the ambient environment t_{db} = 16.9°C and t_{wb} = 14.9°C, indicates, that the environment has a significant potential to cool. However, by virtue of the clothing required to be worn by Mine Rescue personnel limiting heat transfer, the skin temperature eventually starts to increase which in-turn impacts core temperature. The importance of the clothing and how it promotes heat storage is the subject of another paper at this congress (Hardcastle *et al*, 2009).

5. CONCLUSIONS

This work has confirmed that mine rescue activities include tasks that are physically demanding. In this simulated exercise, which primarily consisted of carrying the rescue basket in various loaded states up and down a mine ramp, the rescue personnel were required to maintain an average metabolic rate of 538 W, which is a Very Heavy rate of work.

At this rate of work, the core temperature of all the tested subjects, as measured through a telemetric pill transducer, increased throughout the simulated exercise. The averaged core temperature increase and maximal values were, 0.83 and 38.14°C respectively. Within the group the greatest core increase and highest maximum were 1.20 and 38.89°C respectively.

These results show that prolonged mine rescue activities could cause core temperatures to exceed recognized limits even when the environment has significant potential to cool. In hotter conditions it is doubtful that this level of activity could be maintained safely without medical supervision. These results also tend to indicate that cooling may, in part, be limited by the degree and type of clothing being required for this mine activity, hence the more specific need for studies in this area.

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