A STUDY OF HEAT STRESS EXPOSURES AND INTERVENTIONS FOR MINE RESCUE WORKERS

F. Varley
National Institute for Occupational Safety and Health
Spokane, WA

ABSTRACT

Researchers from the National Institute for Occupational Safety and Health (NIOSH), in cooperation with mine operators, conducted a study of heat stress exposures among mine rescue workers in underground mines. Mine rescue workers face extreme heat loads as they enter hot and poorly ventilated environments, particularly when they are wearing breathing apparatuses. The burden of wearing a closed-circuit breathing apparatus (CCBA), the inability to drink fluids for extended periods of time, and the potential for ventilation disruptions and fires combine to increase the risk of heat illness during a response to an emergency. In this research, ambient environmental conditions and heat strain indicators were measured using conventional ventilation monitoring tools during mine rescue training exercises. Heat strain was measured with an ingestible temperature-sensing pill that measured core temperature continuously. In addition, a heart-rate monitoring chest strap was used to indicate physical strain resulting from physical activity and heat. Both core temperature and heart rate data were trans-mitted to a remote recorder worn by a rescuer and time-stamped. Team activities were also observed to determine the contribution of work rate to a person's total heat load. The effectiveness of several engineering controls, such as cooling the air inhaled by rescuers through an apparatus, wearing cooling vests, and supplying water through the CCBA masks, were investigated. Administrative controls, such as limiting the duration of exposure and controlling the work rate through forced-rest regimens, were also evaluated. Results to date are discussed, and tools for evaluating team condition and estimating the length of time it would be safe for rescuers to work are proposed.

INTRODUCTION

Researchers from the Spokane Research Laboratory (SRL), National Institute for Occupational Safety and Health (NIOSH), in cooperation with mine operators and mine rescue associations, have conducted a study of heat stress exposure among mine rescue workers in underground mines. Mine rescue workers face extreme heat loads when they wear breathing apparatuses and enter hot and poorly ventilated environments. The burden of wearing a closed-circuit breathing apparatus (CCBA), the inability to drink fluids for extended periods of time, the high level of activity and exertion required to perform duties, and the potential for ventilation disruptions and fires combine to increase the risk of heat illness during response to an emergency (Goldstein and Kajdasz, 2000; Kampman and Gresser, 1999; Kampman et al., 1997; Mittal et al. 1991; Mine Safety and Health Administration [MSHA], 2003).

Mine rescue operations in the United States resulted in a heat-related double fatality in October 2002 when two members of a team exploring an abandoned mine slope in Nevada were lost (MSHA, 2003). In Poland in 1998, 10 mine rescuers were overcome by heat during an exploration activity and subsequent rescue attempts, resulting in six fatalities (Goldstein and Kajdasz, 2000). While these tragedies draw significant attention, they are the extreme result of exposure to the heat stress that can occur during any mine rescue work. Thermally stressful environments are known to have a negative impact on workplace safety (Ramsey et al., 1983). For each of these fatalities, numer-ous cases of undocumented heat illness are also likely to have occurred that were reversed through first aid or termination of the activity. For each case of heat illness, many cases of impairments to judgment and reaction times are probable; such impairments can cause errors that lead to catastrophic results in emergency situations.

HEAT STRESS, STRAIN, AND ILLNESS

The American Conference of Government Industrial Hygienists (ACGIH, 2001) defines heat stress as "the net heat load to which a worker may be exposed…" Heat strain is defined as "the overall physiological response resulting from heat stress." The goal of this research is to quantify the heat strain (in terms of net heat gain) experienced by mine rescuers when subjected to heat stress during their work. Heat illness is the result of excessive strain on the body and is a highly variable human response to heat stress.

Table 1. Screening criteria for heat stress exposure (WBGT in Celsius)

Work demands	Acclimatized				Unacclimatized			
	Light	Moderate	Heavy	Very heavy	Light	Moderate	Heavy	Very heavy
100% work	29.5	27.5	26		27.5	25	22.5	
75% work, 25% rest	30.5	28.5	27.5		29	26.5	24.5	
50% work, 50% rest	21.5	29.5	28.5	27.5	30	28	26.5	25
25% work, 75% rest	32.5	31	30	29.5	31	29	28	26.5

ACGIH has identified the thresholds for illness in terms of core body temperature. While these thresholds may be exceeded by some individuals without ill effect, the application of these guidelines will ensure protection of workers and teams, as a single illness affects the safety of the entire rescue team. The threshold level of core temperature associated with loss of judgment and reaction time is 38 °C (100.4 °F). At a core temperature of 38.6 °C (101.5 °F) and above, physical heat strain has begun and, if not treated, will progress to acute heat illness and eventually the life-threatening condition of heat stroke (ACGIH, 2001).

NIOSH and ACGIH provide guidelines for work in hot environments that seek to control heat strain and stress by limiting the time spent working in a hot environment

Table 1 shows the current recommendations based on wet bulb globe temperature (WBGT) index values and level of activity (ACGIH, 2001; International Organization for Standardization [ISO], 1989a; National Institute for Occupational Safety and Health [NIOSH], 1986). All rest is to be in cool environments

METHODOLOGY

In this research, ambient environmental conditions and heat strain indicators were measured on mine rescuers during mine rescue training exercises. The research described in this article was carried out between March 2002 and July 2003. Environmental monitoring was con-ducted using conventional ventilation monitoring tools. Heat strain was measured using an ingestible temperature-sensing pill that measured core temperature continuously. In addition, a heart-rate monitoring chest strap was used to monitor heart rate continuously, which was a surrogate for physical strain resulting from activity and heat. Both core temperature and heart rate data were transmitted to a remote recorder worn by a rescuer and time stamped. Activities of the teams were also observed to determine the contribution of work rate to a person's total heat load. The focus of this research was to bridge the knowledge gap between laboratory-based studies under controlled, but assumed relevant, conditions and work rates encountered in underground mines.

Environmental monitoring

Environmental conditions during mine rescue activities were monitored using conventional psychometric instruments, both digital and analog, to record ambient air temperature, natural wet bulb temperature, radiant (globe) temperature, and air speed. These data were used to calculate a WBGT heat index value for the exposure. WBGT for low radiant heat exposures such as in mines is calculated as

$$\mathrm{WBGT} = 0.7\,T_{nwb} + 0.3\,T_{globe}$$

where T_{nwb} = natural wet bulb temperature
and T_{globe} = globe temperature

(Goldstein and Kajdasz, 2000; Clayton and Clayton, 1991; Dinardi, 1988; Plog, 1996; NIOSH, 1986).

In all cases where the activity was performed underground, the radiant temperature was essentially the same as the air temperature. It is important to use the natural wet bulb temperature and not the maximum wet bulb depression. Natural wet bulb temperature is the temperature achieved due to actual air flow and not air flow forced by swinging the psychrometer. Natural wet bulb temperature is therefore a reasonable indicator of potential evaporative cooling of an individual based on ambient air velocities (Brake et al., 2001). Results are grouped by WBGT exposure.

Core temperature monitoring

The research utilized a relatively new wireless technology to monitor rescuers' core temperatures without interrupting or otherwise impeding their activities (Cutchis et al., 1988; Mittal, et al., 1991; O'Brian et al., 1997): a swallowable sensor that transmits a coded signal to an external receiver/recorder attached to the rescuer. The sensor was given to rescuers at least 2 hours before monitoring began to allow sufficient time for the sensor to move into the subject's gut. Core temperatures were recorded at intervals of at least once per minute and time stamped. All recorders were time synchronized to correlate activities with the resulting strain.

Heart rate monitoring

The same recording device received signals from an elastic chest strap worn against the skin to monitor heart rate wirelessly. A commercially available wristwatch-style monitor was also provided to allow participants to observe their condition readily.

In the general population, sustained heart-rate levels associated with excessive heat strain vary between 180 beats per minute (bpm) less the person's age (ACGIH, 2001; NIOSH, 1986) to 220 bpm minus age for cardiovascular-conditioned persons (U.S. Army, 2000). The mine rescuers observed in this study fell somewhere in these categories. Because of the variety of ages and cardiovascular conditioning found in the population of mine rescuers and the variety of often physically demanding activities they performed, it was difficult to assess heat strain by means of peak heart rate alone.

Another means of assessing heat strain is through the recovery heart rate. ACGIH sets a limit of 110 bpm for a recovery time of 1 minute (ACGIH, 2001; NIOSH, 1986). Another means of assessing recovery is to compare recovery heart rate to fully resting heart rate. Recovery heart rate was taken as the heart rate 2 minutes after resting and was compared to a baseline resting heart rate collected while the subject was wearing an apparatus but before activities were begun. A rise in this resting rate indicates accumulated strain in the person.

Activity monitoring

Observations of both team and individual activities were logged by an observer to track the contribution of metabolic heat to a person's total heat load. Activities such as walking fast, carrying loads, and working with hands above the torso all generate significant heat that rescuers must shed (ACGIH, 2001; ISO, 1990).

Another condition observed was the amount and type of clothing worn by rescuers. Clothing, as an insulator, can reduce the capability of mine ventilation to carry away heat accumulating in the body (Murray-Smith, 1987).

Observations from multiple researchers were collected first and then compared to ensure that surveys with only one observer would be consistent.

Normalizing data

When small populations are examined, an important factor is to find a means of drawing conclusions when comparing individual results. In this study, the data were first normalized individually from several different observations of the same person under varying conditions. A second method was to group individual results by similarities in environment, activity level, apparatus, and intervention. A third method was to reduce the raw core temperature data to a rate of temperature rise and then to a rate of energy absorption per unit mass and/or body size.

RESULTS AND DISCUSSION

Individual reactions to hot environments

Figure 1 is one individual's absolute results along with his heart rate data and is an example of an individual experiencing heat illness. As noted on the graphic, the person voluntarily sat down at the onset of illness and performed no further work, but the environment, at 27 °C (82 °F) WBGT, was still too hot to allow recovery, resulting in a continuing rise in core temperature until the mask was removed and active cooling was begun.

Figure 2 shows the rate of temperature rise in individuals performing similar tasks in similar environments. While there were clear variations in the absolute temperature peaks observed in individuals, the rates of temperature and energy rise were very similar for individuals within a group. The two groups here can be distinguished only by age (individual in the lower-rate group were all over 35). This observation raises a question about the role of acclimatization.

Acclimatization is the process of developing resistance to the effects of exposure to heat (and other environmental factors). It is a process requiring 5 or more days of progressive exposure and is known to be reversed within 4 days (ACGIH, 2001; Brake et al., 2001; Leveritt, 1998). South African and Australian mines have developed well-documented protocols for conditioning employees for hot work in this way. The groups studied consisted of individuals whose typical work days encompassed a range of environmental exposures, from office workers with only occasional forays into a hot mine to stope miners who spent 12-hour shifts in the heat.

We had assumed we would see a clear distinction between those workers who had had the opportunity to acclimatize and those who had not. However, the only significant difference between the potentially acclimatized individuals and others was that some, but not all, had lower-than-average starting core temperatures. Most individuals tended to gain heat at the same rate. Acclimatization would then be the ability to absorb, rather than resist, heat. Another possibility is that the climate, often controlled, in which miners spend their nonworking hours is preventing true acclimatization. Compounding the effect of the nonwork exposures are the continuous work schedules where the miners work half the days in a year. These schedules, with up to 7 days off in a row and seldom requiring more than 4 days without a break, do not promote acclimatization.

Impact of initial core temperature

As noted, while the rate of temperature rise was consistent, individuals showed considerable variation in starting core temperatures. The normal range of core temperatures is between 35.5 °C (97.0 °F) and 37.5 °C (99.6 °F) (Clayton and Clayton, 1991; Plog, 1996). The reason for this variation could be immediate health issues, such as a chronic problem, a minor ailment, medications or supplements being taken, or fatigue. Regardless of the cause, a person's initial core temperature has an immediate and absolute impact on how long that person can endure operating in a hot environment. Figure 3 depicts the length of time individuals can operate in hot environments based on initial core temperature, work rate, and rest regimen. While limiting work rates can increase the time before an individual begins to suffer from heat strain, it does not remove him or her from the position of being the weakest part of a team. A single member on a team who has an elevated temperature has the potential to limit the performance of the team. A simple check of team members' temperatures prior to putting on a breathing apparatus would identify an at-risk member.

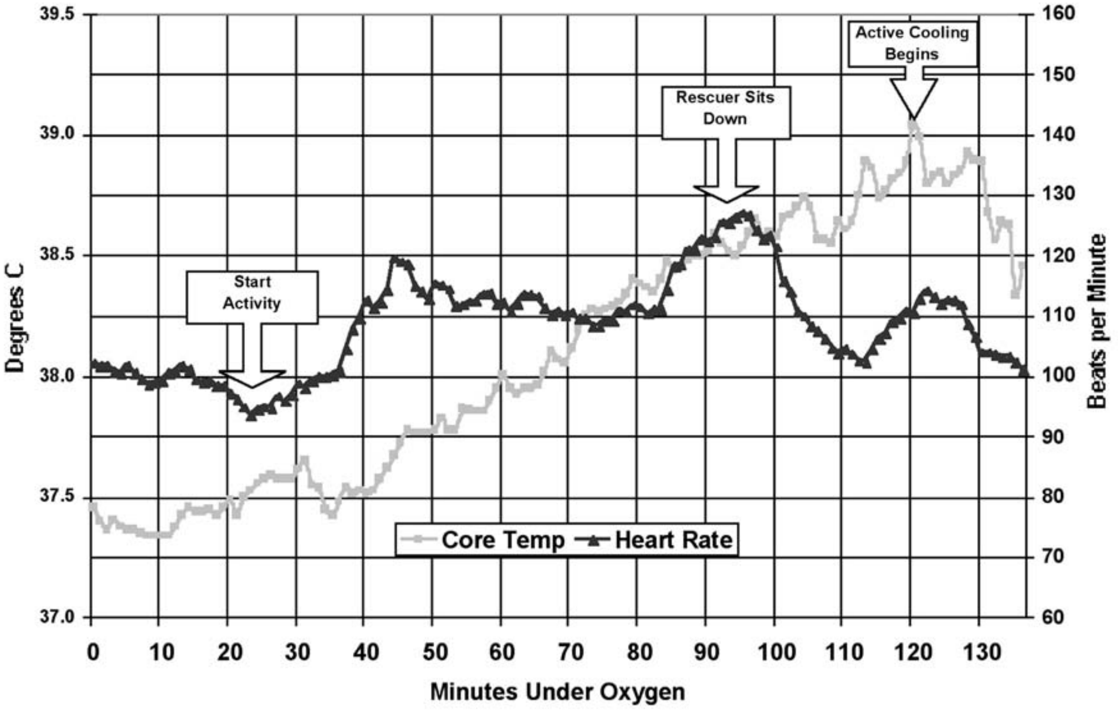

Figure 1.—Individual response to 27 °C WBGT

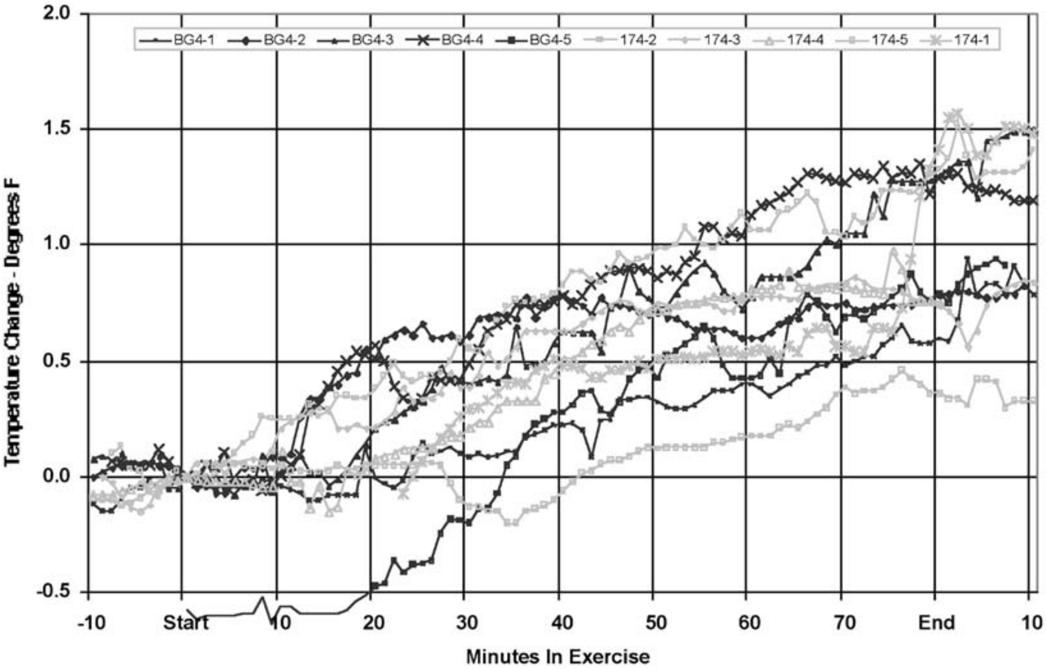

Figure 2.—Change in core temperature at 27 °C WBGT

Impact of fitness

Fitness, as measured by body mass index (BMI) has a measurable impact on a person's tolerance to rescue work in heat. BMI is determined based on a person's weight and height. That is, BMI = weight in kilograms divided by height in meters squared or 704.5 times weight in pounds divided by height in inches squared.

BMI = weight (kg) ÷ [height (m)]^2 or
BMI = 704.5 × weight (lb) ÷ [height (in)]$^{2.}$

Individual data were normalized by determining the amount of energy absorbed in watts. Figure 4 depicts results of this comparison among four groups generating varying work rates in similar environments. Of note is the relation-ship of work rate to energy absorption. While an increase in BMI results in an increase in energy absorption for the same work load, adequate rest can significantly reduce the degree to which a high BMI affects a rescuer's heat tolerance. This result is in agreement with laboratory-based tests of British mine rescuers (Kampmann and Gresser, 1999). In the study group, the average BMI was (in keeping with the general population) in the overweight range.

Impact of work rate

Throughout the study, the most significant controllable contributor to heat load was the work rate of the team. Mine rescue teams cannot choose where or under what conditions they must perform rescue operations, but they do control how they conduct these operations. The NIOSH Recom-mended Standard for Hot Work Environments and ACGIH have clear guidelines for incorporating rest into work activities (ACGIH, 2001; NIOSH, 1986). Work rates can be estimated using the guidelines in table 2, which were adapted from ACGIH.

An experiment was conducted with two groups walking in a metal mine. WBGT conditions were 27.8 °C (82 °F) with an air velocity of >100 m/s. One group of acclimatized rescuers traveled 2,000 ft down ramps and across the level in the mine, then 1,000 ft up a 10% ramp at a fast pace for 45 minutes without rest. They then rested for 15 minutes in a cool area as per the NIOSH recommendation of a regimen of 75% work/25% rest for those conditions. A second group covered the same course at the same pace with rest periods spaced throughout the activity as indicated using peak and resting heart rate as monitored by commercially available wristwatch-style monitors. The result (figure 5) clearly demonstrates that the team that rested periodically throughout the exercise absorbed much less heat while accomplishing the same amount of work. All members of the "rest-at-end" team experienced at least mild heat strain, and one individual had to be removed from the experiment (albeit under protest) due to excessive core temperature. None of the "rest-at-end" team members were prepared to resume after the 15 minutes of rest.

Table 2. Examples of metabolic rate categories

Categories	Example activities
Rest	Sitting quietly
Light	Sitting with moderate arm and leg movements Standing, working with arms in light lifting, turning Using small power tools Walking slowly on level carrying minimal weight
Moderate	Rapid and/or forceful arm movements Walking with moderate lifting or pushing Walking 6 km/hr on level carrying 3 kg load
Heavy	Hand sawing, Shoveling light material Heavy whole body motions Intermittent heavy lifting or working with hands above head Walking slowly up steep grades
Very heavy	Shoveling heavy material, near continuous heavy lifting Walking 6 km/hr up grades and/or carrying heavy load

An analysis of the heat load sources in these tests is summarized in figure 6, which depicts the average energy load for each part of the activity of walking through the mine. Sixty percent of the heat load absorbed was due to inadequate rest, 20% came from the apparatus, and only 20% could be attributed to the task itself. The increase in heat load due to wearing an apparatus, although overshadowed by the lack of rest, clearly shows that simply wearing the apparatus changes what may be a simple task on any other day. Wearing an apparatus also increases the baseline metabolic load on an individual to the point that even resting carries the equivalent heat load of light work.

INTERVENTIONS

The effectiveness of several engineering controls such as cooling the inhaled air of the apparatus, wearing frozen media cooling vests, and water-supplied CCBA masks were investigated. Administrative controls such as limiting the length of exposure and controlling work rate through forced rest regimens, were also evaluated.

Limiting duration of activity based on the environment

In the 1980's, the British Coal Board established criteria limiting the length of time of mine rescue activities based on environmental conditions and, after the 1998 disaster, the Polish Mining Institute developed independent but similar criteria (figure 7) (Goldstein and Kajdasz, 2000). A comparison of these criteria, which were developed from laboratory data, with our field survey results finds general agreement, but with several notable conditions. One is the need to determine initial resting body temperatures of mine rescuers. Both sets of criteria are reasonable for rescuers within the normal range of initial resting temperature, but could result in overexposures for those having elevated initial resting temperatures. A second, but no less significant, limitation is the need to control work rate. Periodic rest during the exercise will help ensure that a team can tolerate the planned exposure. With these conditions noted, the European recommendations can serve as a suitable starting point for emergency response planning.

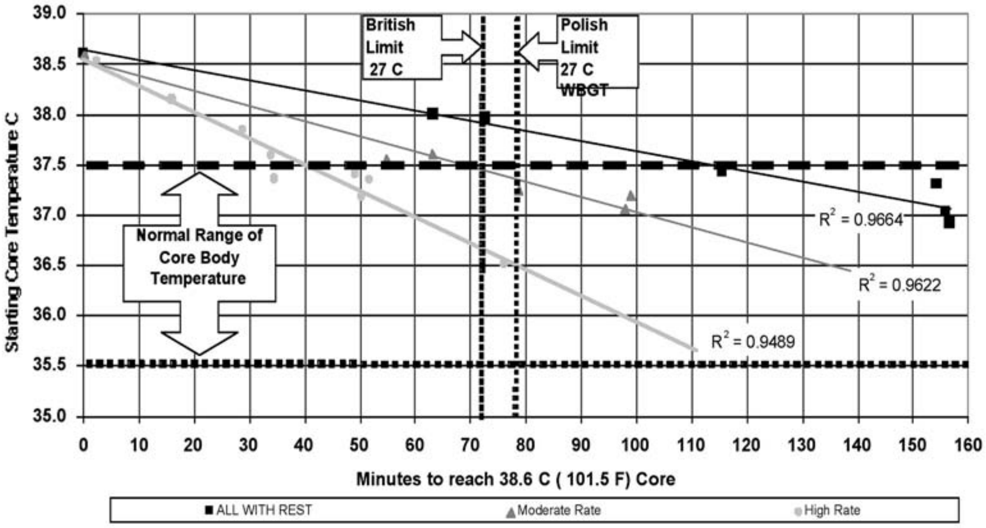

Figure 3.—Impact of starting core temperature

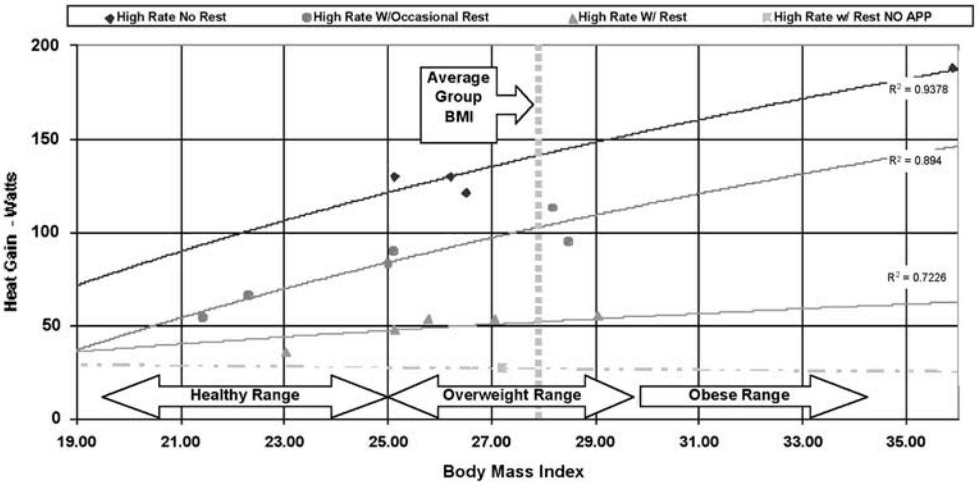

Figure 4.—Fitness effect on heat retention

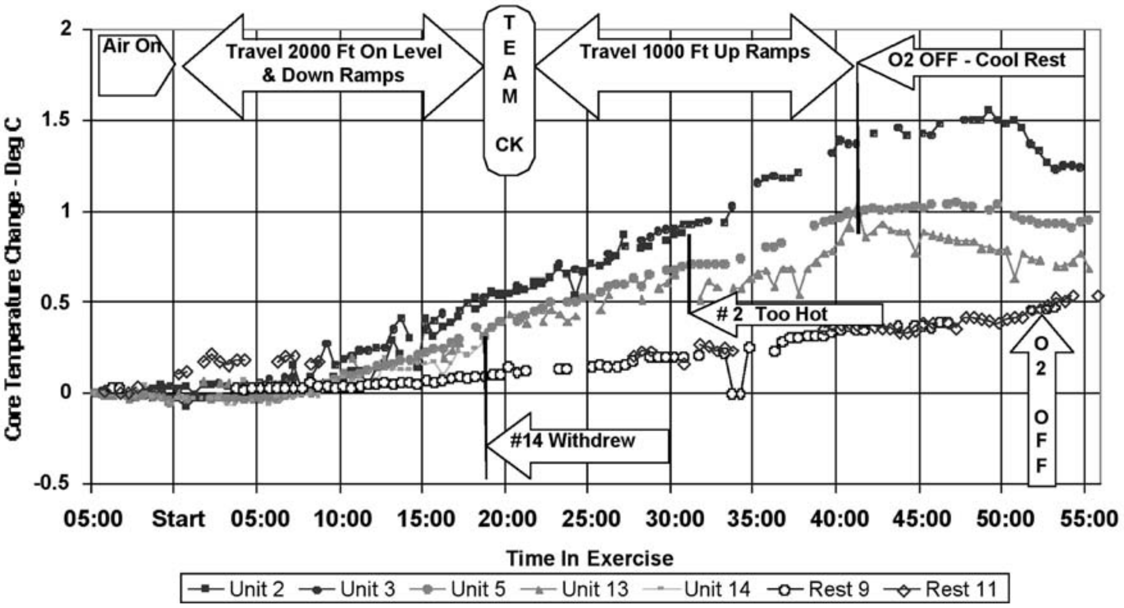

Figure 5.—Effect of forced rest regimen at 27 °C WBGT

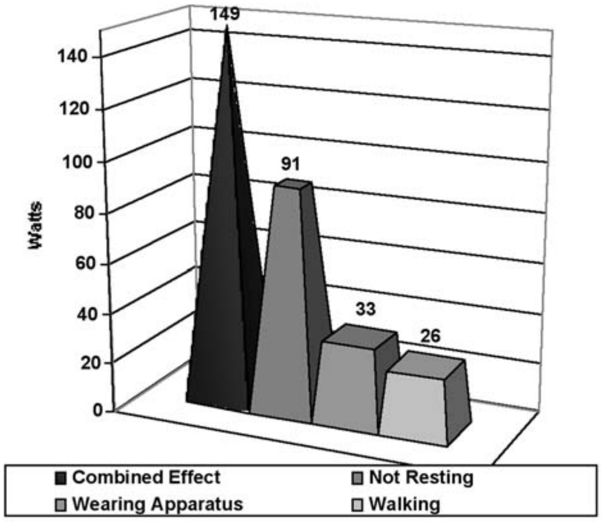

Figure 6.—Contributions to heat gain

Limiting work rate by recovery heart rate

The work rate experiment identified resting heart rate as a good tool for evaluating team condition and readiness to proceed. As demonstrated in figure 8, and increase in resting heart rate is proportional to the increase in core temperature. By limiting the rate of rise in resting heart rate, the rate of core temperature rise can be controlled and the length of operations can be maximized without risk to rescuers. Standard mine rescue operations require team checks at intervals not to exceed 20 minutes. Before putting on breathing apparatuses and at each team check, rescuers' resting heart rates should be checked. The rest period should be extended until all team members have resting heart rates no more than 10% greater than their previous check or 100 bpm, whichever is less. If any one team member can not achieve these resting heart rate levels within a reasonable amount of time, retreat should be required.

Impact of inhalation air temperature

One early evaluation was to determine if the use of an apparatus that cools the inhalation air of the CCBA provided relief from heat strain. Figure 9 depicts the mean temperature rise of two groups of individuals wearing two types of apparatus, one with and one without inhalation air cooling. Both apparatuses were worn in their NIOSH-approved configuration. No statistically significant affect on core temperature was observed between the two types. This was not unexpected, as the body's heat exchange mechanisms rely very little on respiration for heat transfer. In addition, the available cooling potential of the relatively small mass of coolant as compared to the mass of a human body limits the ability of the device to affect the core temperature of the wearer within the narrow range of operating temperatures present in the approved apparatus. This investigation did not evaluate apparatuses with required cooling media removed. The comfort provided by this enhancement was acknowledged by all participants. Regardless of the reason for the cooling system, it should be installed if required by manufacturer (MSHA, 2003).

Active cooling through water-supplied apparatus

Adequate hydration is well known as the best active defense against heat illness (Clayton and Clayton, 1991; Dinardi, 1988; Plog, 1996). All of the body's primary heat transfer functions require adequate fluid volumes for optimum performance. Heat is moved from the interior of the body to the outer surface through blood flow. Vasodilatation occurs as heart rate increases to move more heat away from sensitive organs. Without sufficient blood volume, collapse of the system can occur, resulting in inadequate blood supply to life-sustaining organs and increasing temperatures in the body core. Sweating assists in removing heat from the blood near the skin surface through evaporation. Sweating, at a peak of up to 1L/hr, can quickly deplete the body's fluid reserves (ISO, 1989b). If deficient in fluids, the body will scavenge fluids from the digestive tract. This reverse flow of fluid through the liver can introduce enzymes into the bloodstream that can increase core temperature as the body defends itself from this toxin.

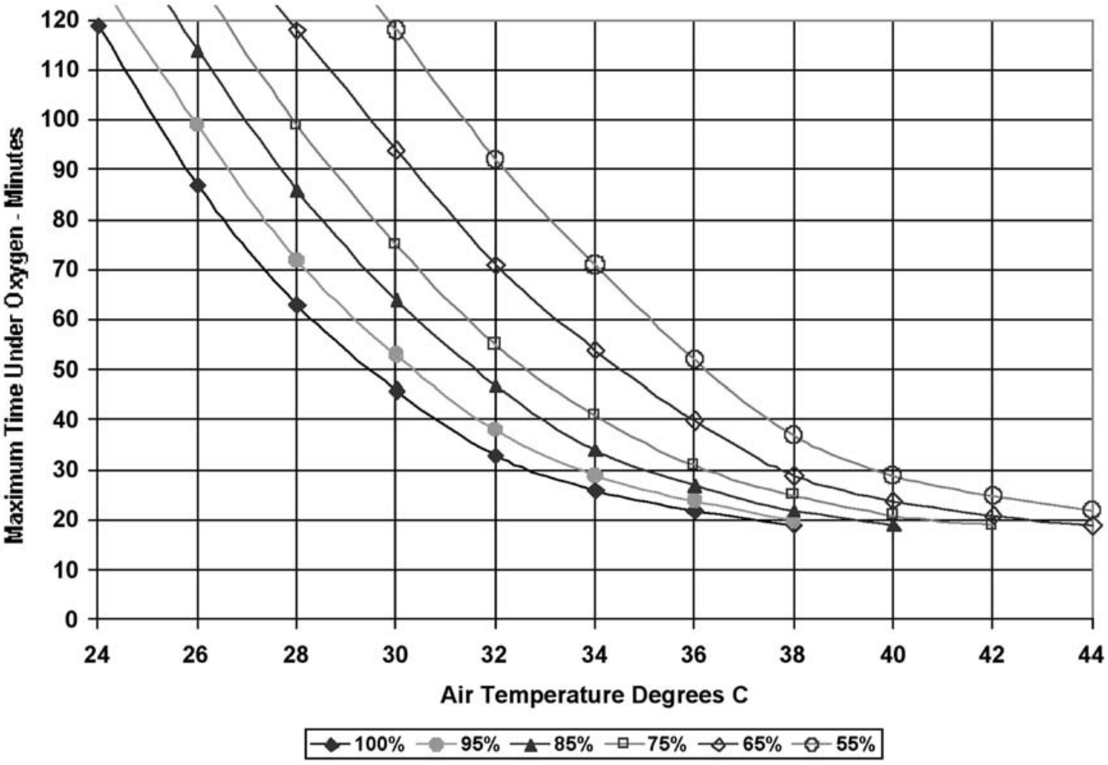

Figure 7.—Temperature- and humidity-based time limits for mine rescue (after British Coal 1990)

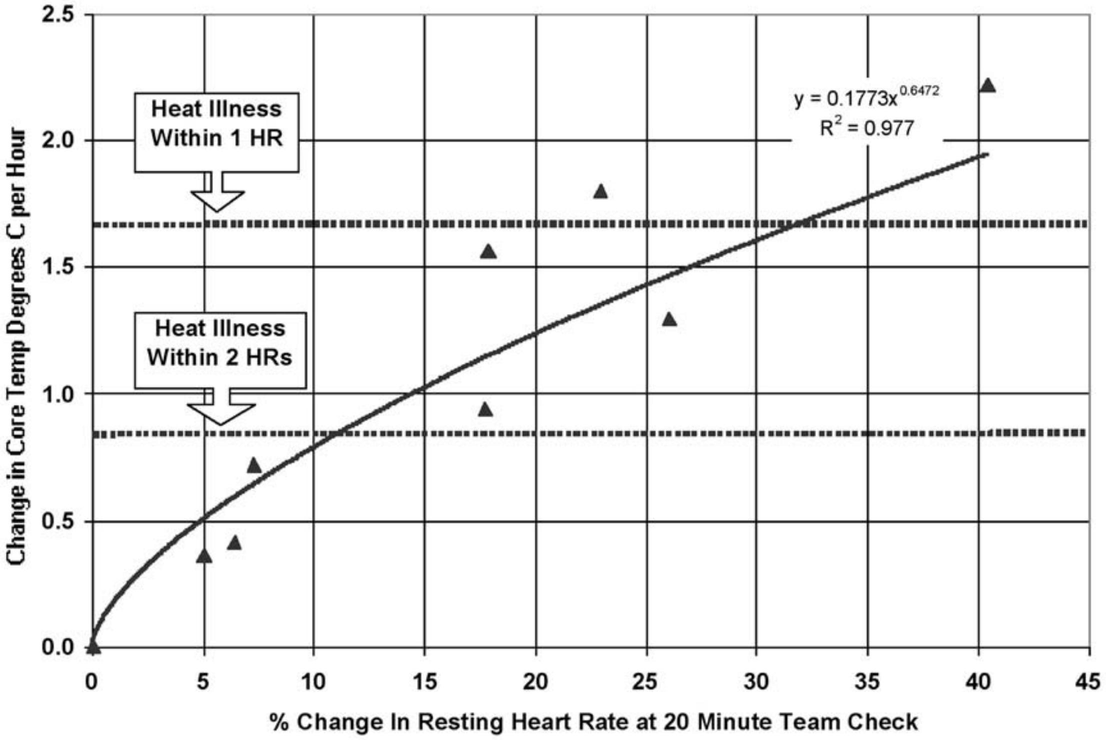

Figure 8.—Observed relationship between resting heart rate and core temperature

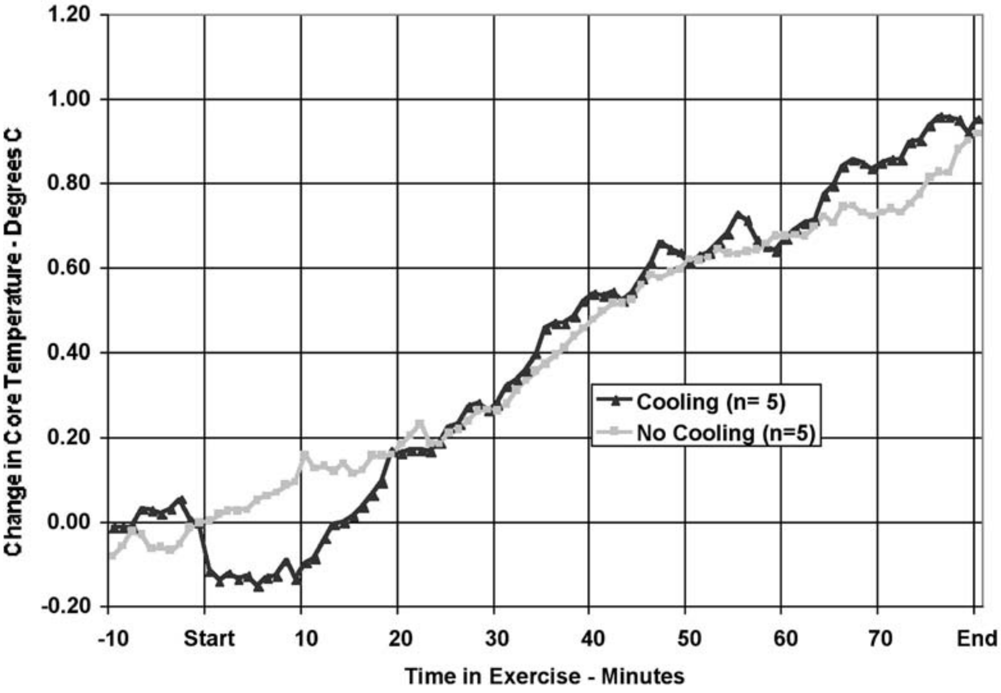

Figure 9.—Comparison of approved apparatuses

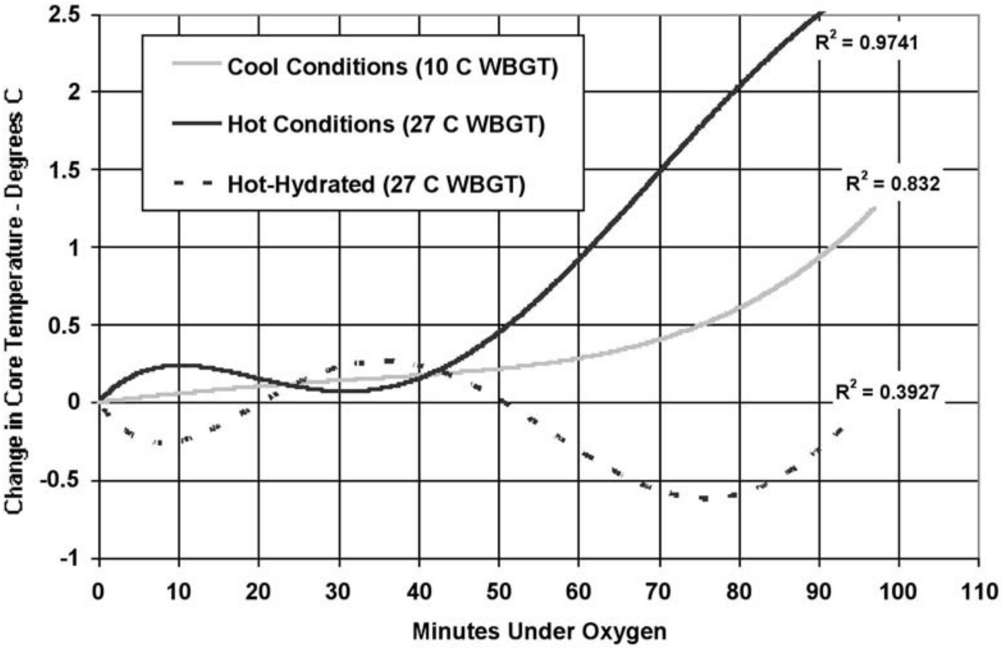

Figure 10.—Hydration effect in high-work-rate mine rescue

Despite the obvious need for adequate amounts of water, mine rescuers have no opportunity to replenish lost fluids while wearing CCBA's. Even under cool conditions (figure 10), a heating effect can be observed during extended operations. This could be a symptom of dehydration. In hotter operating environments, sweating would increase the risk of dehydration-related heat illness. To assess the value of taking in fluids, CCBA masks were modified to provide up to 2 L of drinking water to rescuers through a bite valve in the breathing cup of the mask and tested in nonhazardous training environments.

Results of a comparison of three individuals using masks with and without water in thermally stressful environments are shown in figure 11. Their core temperatures were maintained on the days they were using the hydration masks as opposed to the days used as controls. Figure 12 shows results from three other individuals who did not use hydration

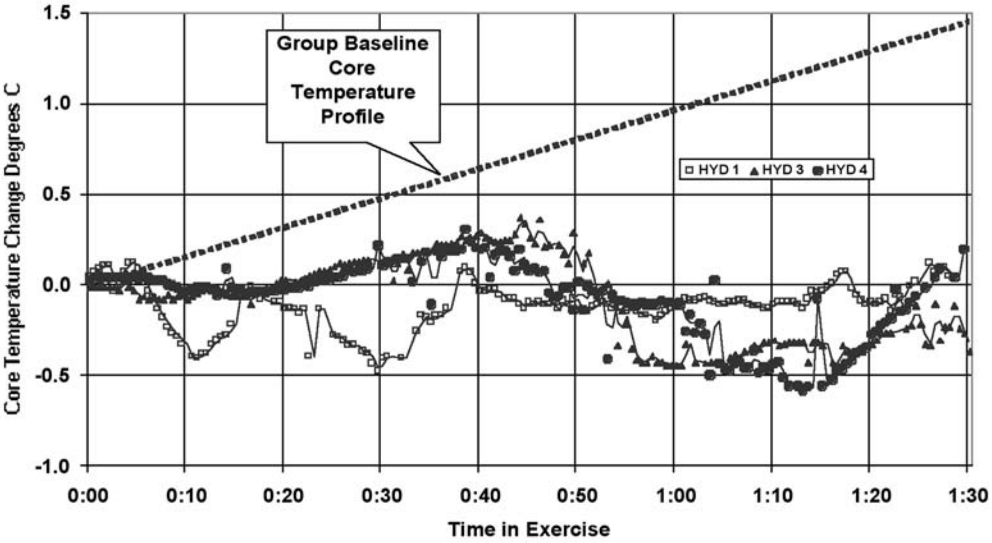

Figure 11.—Hydration effect in high-work-rate mine rescue, 27 °C WBGT

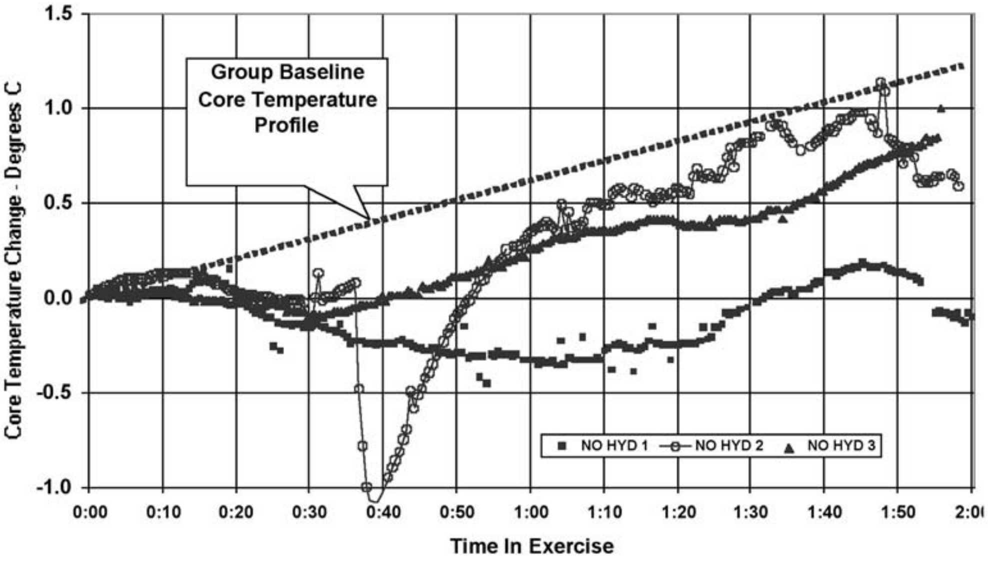

Figure 12.—Control group, hydration effect

masks; two of the three had heat gains similar to the other group's control exposure day. A third member of the control group did markedly better without hydration. These early results indicate that development of an approved water-supplied mask could be a significant tool in preventing heat illness. Further study of this intervention will proceed as opportunities become available.

Active cooling with cooling vests

The use of vests and other garments lined with material that cools by changing phase has been advanced as a means of controlling heat strain (U.S. Air Force, 1997; Chauhan, 1998; Doerr, 1988; Goldman and Kajdasz, 2000; U.S. Bureau of Mines, 1976). Phase-change vests are comprised of two basic elements: a material that melts at a temperature less than that of the human body and a method of storing the material as close to the wearer's skin as tolerable. The weight and affects on the mobility of the wearer of these garments have been of concern to end-users.

This intervention was evaluated by use of commercially available vests containing 2.5 kg of material that changes phase at 16 °C (61 °F). One-half of the team wore vests and the other half did not. Figure 13

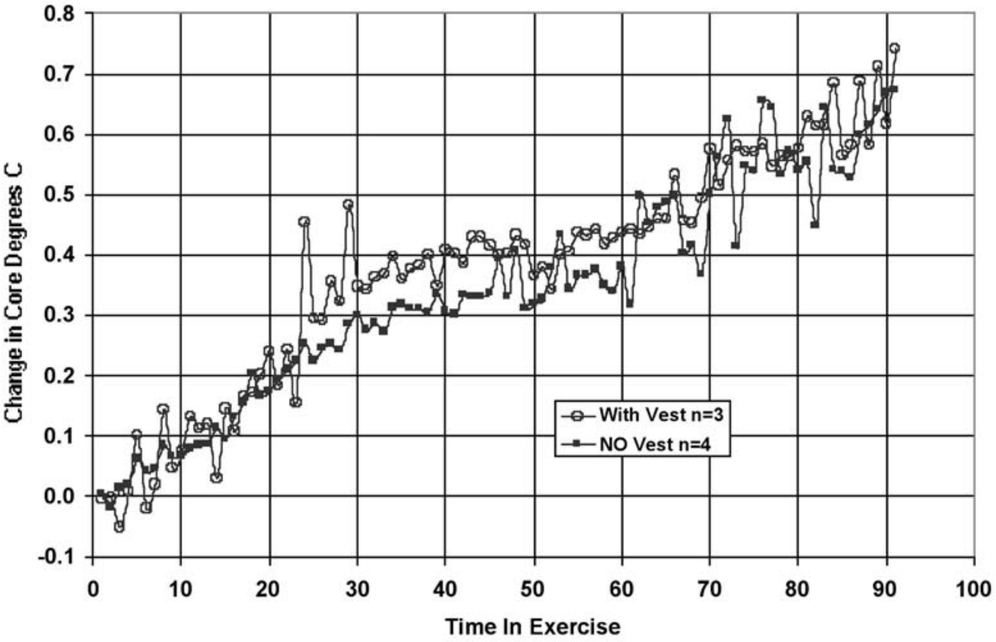

Figure 13.—Phase-change cooling vest evaluation

shows the rate of temperature gain in the two groups. The reduction in the rate of core temperature increase between the two groups was not statistically significant. This finding is in general agreement with other studies that have found no significant impact on core temperature changes or heart rate (Doerr, 1997; U.S. Air Force, 1997). The vests are generally accepted by the wearers because of the additional comfort they provide. They did not increase core temperature while the coolant remained below skin temperature. The studies have found that the vests do increase the length of time an operation can continue as defined by that point at which wearers voluntarily stop their exposure. This improvement in comfort must be used with caution to avoid overexpo-sures resulting from interference with the wearer's ability to perceive overheating.

CONCLUSIONS AND RECOMMENDATIONS

The combination of environmental conditions and work loads encountered during underground mine rescue exercises has resulted in unacceptable physical strain on rescuers before they reach the limits of the breathing apparatus. The condition of rescuers and not the remaining capacity of a breathing apparatus must be the limiting factor when planning emergency operations in thermally stressful environments. Guidelines provided by European rescue agencies provide a good framework for planning rescue operations with fit teams and adequate rest regimens.

The physical condition of team members should be monitored before and during emergency operations to identify and exclude those members with an abnormally high temperature and/or resting heart rate so that they do not become a risk to themselves and the team. Team members with high BMI's should be counseled and assisted in improving their fitness levels.

Team rest periods during emergency operations should be frequent and controlled by monitoring resting heart rates at not more than 20-minute intervals. Termination of rescue operations should be based on team status as measured by quantitative means and not self assessments.

The use of commercially available cooling devices should not be a substitute for monitoring and must be accompanied by training to reinforce the concept that comfort does not equate to safety.

Hydration of rescuers through supplying adequate water beforehand should become a standard practice prior to donning a breathing apparatus. Further research into the benefit of hydration-supplied apparatuses is needed to justify product development.

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