B. Webbon
B. Williams
P. Kirk
NASA-Ames Research Center,
Moffet Field, Calif.

W. Elkins
Acurex Corporation,
Mt. View, Calif.

R. Stein
U. S. Bureau of Mines,
Pittsburgh, Pa.

A Portable Personal Cooling System for Mine Rescue Operations

The high temperatures, which are often encountered by mine rescue teams during emergency situations, may cause severe physiological strain. For example, at the Somerset coal mine, temperatures of 49°C (120°F) with 100 percent relative humidity caused the normal rescue team recovery mission to be shortened from 2 h to only 25 min. In order to increase the team's effectiveness and comfort under such conditions, the U. S. Bureau of Mines (USBM) initiated a program with the National Aeronautics and Space Administration (NASA) to develop and test a personal cooling system based on technology developed for the thermal control of space-suited astronauts. The resulting system, which has 88 watt-h (300 Btu) heat absorption capacity, weighs approximately 5 kg (11 lb) and is compatible with existing rescue team breathing apparatus. Several different system configurations were tested under simulated mine rescue team operational conditions of 32.5°C (90°F) wet bulb globe temperature (WBGT) and 1.0 l O_2/min (1200 Btu/h) metabolic rate. The system, which consists of a liquid circulation garment and belt-worn heat sink unit, was found to be capable of reducing the physiological strain by nearly 50 percent under these conditions. A simple analytical heat balance model was used to predict the effects of the thermal control system for other environments and metabolic rates. It was found that in the most severe environments, WBGT greater than about 35–37°C, that the maximum endurance time could be further increased by providing an insulating overgarment to reduce the heat gained from the hot environment.

Introduction

The high temperatures, which are often encountered by mine rescue and recovery teams during emergency situations, may cause such severe physiological strain that rescue operations are greatly hindered.

Following the disasters at the Belle Isle salt mine [1],[1] the Cane Creek potash mine [2], and more recently the fire at the Somerset coal mine [3], the teams were forced to drastically shorten their useful work time due to the exhaustion caused by the thermal stress. For example, at the Somerset mine the normal work period of 2 h had to be decreased to 25 min because of the 49°C (120°F) air temperature combined with nearly 100 percent relative humidity. A portable, personal cooling system could greatly increase the endurance time in such a harsh environment. A survey of cooling systems showed that there were none available that met the expected requirements. Therefore, the U. S. Bureau of Mines (USBM) initiated a collaborative program with the National Aeronautics and Space Administration (NASA) to develop a personal cooling system based on technology developed to provide thermal control for space-suited astronauts. The results of this program are described later.

System Requirements

The primary performance requirement for the system is to provide sufficient cooling to allow 1–2-h operation in a hot, wet, and dirty environment. The cooling system must be rugged and compact, since the team members are already burdened with more than 20 kg of equipment. The cooling system must also be compatible with the existing face mask and breathing apparatus, be simple for relatively untrained persons to don and use, and be intrinsically safe for use in an explosive atmosphere.

The environmental requirements are given in Table 1. These were somewhat arbitrarily defined by the USBM and NASA. The actual conditions following a disaster may vary widely and it was felt to be unreasonable to require the system to have the capacity to handle the worst environment that might ever be encountered. This would result in an unnecessarily large system that would seldom, if ever, be needed.

Current Federal government requirements for mine rescue breathing apparatus specify a range of metabolic rates from 0.31 l/O_2min (~360 Btu/h) to 3.32 l O_2/min (~3700 Btu/h) [4, 5]. An integrated average metabolic rate of 1.5 l O_2/min for a 2-h mission is re-

[1] Numbers in brackets designate References at end of paper.

Contributed by the Aerospace Division of THE AMERICAN SOCIETY OF MECHANICAL ENGINEERS and presented at the Seventh Intersociety Conference on Environmental Systems, San Francisco, Calif., July 11–14, 1977. Manuscript received at ASME Headquarters April 8, 1977. Paper No. 77-ENAS-53.

Table 1 Environmental and metabolic rate requirements

Environmental	
Globe Temperature	- 40°C (104°F)
Wet Bulb Temperature	- 29°C (84°F)
W.B.G.T. (0.7 wet bulb +0.3 dry bulb)	- 32.5°C (90°F)
Air Velocity	- 0
Metabolic	
Minimum Metabolic Rate	- 0.3 ℓO_2/min (360 Btu/hr)
Integrated Average Metabolic Rate	- 1.0 ℓO_2/min (1200 Btu/hr)
Peak Metabolic Rate	- 3.32 ℓO_2/min 3700 Btu/hr
System	
Average System Heat Transfer Rate	- 44 watts (150 Btu/hr)
Maximum System Heat Transfer Rate	- 88 watts (300 Btu/hr)
Garment Inlet Temperature Range	- 10-21°C (50-70°F)
Heat Sink Capacity	- 88 watt-hrs (300 Btu)
Mission Duration	- 2 hrs.

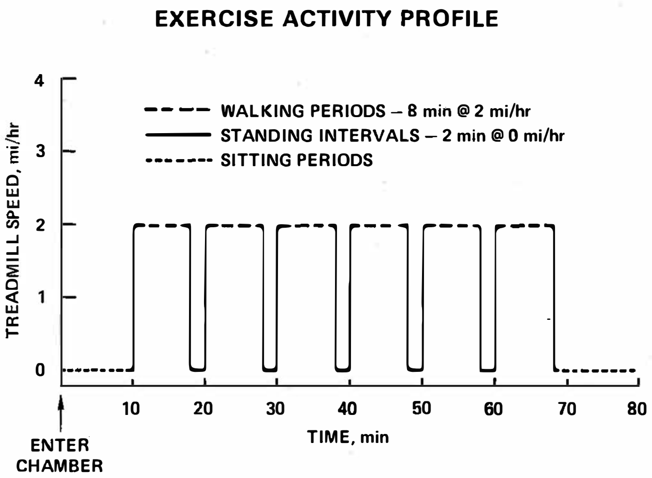

Fig. 1 Exercise activity profile

quired. In addition to reviewing current requirements, the participants in a mine rescue team contest were observed in order to subjectively gain an understanding of their actual work rates while performing a simulated rescue and recovery mission.

The activity profile shown in Fig. 1 was selected as representative of the expected exercise rates. The metabolic rate requirements, in particular the transient variations, for a cooling system are quite different from those for a breathing apparatus. The breathing apparatus must be more conservatively designed since it must have more than enough capacity to handle the immediate demand following any possible variations in gas flow requirements. However, the time constants that describe the body's thermoregulatory system are considerably greater than for the respiratory system. Thus, an external cooling system need not be required to have sufficient rate capacity to handle all metabolic rate transients. The real requirements are to have sufficient heat transfer rate capacity to handle the average heat load and to have a heat sink capacity greater than the total, integrated heat load that must be absorbed over the course of the mission.

The cooling system would consist of a heat sink unit and a liquid circulation garment worn by the miner. The cooling garment configuration chosen would determine the fraction of the total metabolic load which would be removed by the circulating water and this in part would determine the performance requirements for the heat sink unit. NASA experience with liquid cooling garments (LCG) [6] and the desire for a system that would integrate easily with the existing rescue equipment indicated that a partial coverage rather than a full body LCG would probably be adequate. Three configurations were selected for test: (1) head cooling only, (2) thoracic cooling only, and (3) head and thoracic cooling. Head cooling had previously been found to be very effective in reducing the thermal strain on sedentary subjects in hot environments and for subjects performing light exercise [7–9]. It was hypothesized that head and thoracic cooling would provide adequate cooling for the exercise rates and environments predicted for mine rescue operations.

Preliminary Tests

A brief initial test program using a bicycle ergometer and ambient laboratory conditions was performed using a modified, existing LCG to determine the heat load range as a function of exercise rate for the three garment configurations. With the inlet water temperature set at 13°C, it was found that the head cooler would remove approximately 44 W (150 Btu/h) regardless of the total metabolic rate. The head/thorax garment heat removal was found to vary approximately linearly from 59 W (200 Btu/h) at 0.67 l O_2/min to 146 W (500 Btu/h) at 1.68 l O_2/min. Thoracic cooling only was not tested at this time since it was felt that it would fall between the other two cases. The ratio of garment heat removal to total metabolic rate was essentially constant at ~25 percent for the combined head and thorax garment while for the head garment it decreased from about 40–50 percent for a sedentary subject to less than 10 percent at the higher rates.

These data were then used to determine the heat transfer rates for the system as shown in Table 1. They were also used in a simple analytical heat balance model to estimate the maximum rescue mission duration for each of the garment configurations for environments different from the selected test conditions. The maximum duration was defined to be the time required for a thermal storage of 189 kcal (1000 Btu) or a body weight loss of 5 percent to be reached. These results are summarized in Fig. 2.

System Design and Fabrication

The key element in the cooling garments and the heat sink unit is a flexible heat-sealed, coated fabric assembly with integrally formed liquid circulation channels which was developed during earlier NASA contract programs (6). The assembly incorporates inlet and outlet manifolds and multiple, closely spaced, parallel flow paths to form a simple, flexible, and high thermal effectiveness contact heat exchanger. This heat exchanger patch can be sewn into an overgarment

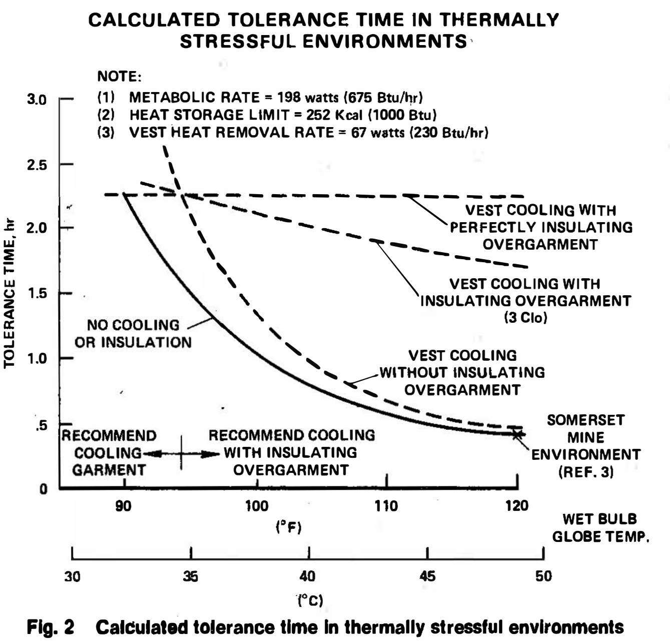

Fig. 2 Calculated tolerance time in thermally stressful environments

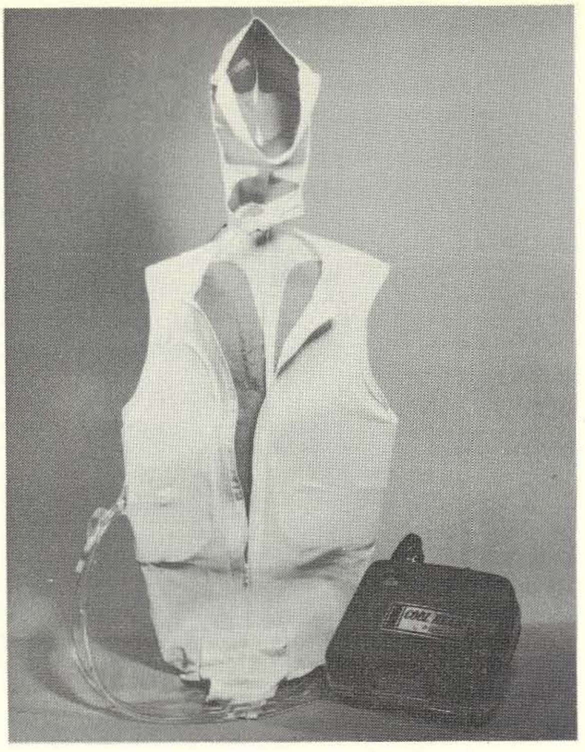

Fig. 3 Head/vest garment and cooling unit

which holds it in contact with the skin. Fig. 3 shows the complete garment assembly fabricated for the current program. The head cooler is removable to allow thorax or head only cooling.

It had previously been found that the head both requires and comfortably can tolerate lower contact temperatures than other areas of the body for a given heat removal rate [7–9]. Therefore, in all cases the cool inlet water first flows through the head assembly. This assembly consists of two patches with a total area of 554 cm^2 (86 $in.^2$). The patches are sewn inside an elastic cap which has been shaped so as not to interfere with the breathing mask assembly. The outlet flow from the head is then split and the water flows in parallel through the two torso patches and is then collected for return to the heat sink. The torso patches have a total area of 1884 cm^2 (292 $in.^2$). In this manner, the head acts as an intermediate heat exchanger to warm the water to a comfortable temperature before it is circulated around the thorax.

Since the cooling system is an addition to the existing rescue equipment ensemble for use only when needed, the heat sink unit could not be physically integrated with the existing equipment. A belt-worn unit that could be comfortably located anywhere on the existing equipment belt according to individual preference was chosen as the baseline design.

Other NASA funded studies of advanced heat sinks [10, 11] had shown that an ice heat sink was the most logical choice to meet the present requirements. A trade study of various types of circulation loop-heat sink interfaces was performed and a sealed heat sink cartridge surrounded by a contact heat exchanger was selected for the following reasons:

1 The heat sink cartridge is a common steel can that is inexpensive, reliable, and can be easily refrozen in an ordinary refrigerator.

2 The unit does not require any melt water to be drained or ice to be handled.

3 Once all the ice is melted, the heat sink cartridge can be easily replaced with a fresh cartridge without disturbing the sealed circulating loop.

The cartridge contains 1 l of a 4-percent alcohol in water solution. The alcohol was added to minimize the volume change associated with freezing. One l of solution provides a heat sink capacity of 79.7 kcal (316 Btu).

Following selection of the heat sink unit configuration, the required heat exchanger area and liquid flow rate were analytically determined. It was found that both the garments and the heat sink unit should function at the required heat transfer rates and temperatures with a cooling unit heat exchanger area of 465 cm^2 (72 $in.^2$) and flow rates anywhere in the range from 9 to 55 l/min (20–120 lb/h). Eighteen l/min (40 lb/h) was selected, since this flow rate provided a safe heat transfer margin with a reasonable pumping power requirement.

Since the thermal resistance inside the ice cartridge varies as the ice is melted away from the walls, consideration was given to internal finning of the cartridges. However, preliminary testing suggested that agitation of the unit, which was expected as the wearer walked, might provide sufficient internal circulation to increase the heat transfer rate to the required level without the addition of fins.

The heat exchanger patches require 10–15 psig to "inflate" the flow passage. This requires an accumulator to accommodate the volume difference between the operating and idle modes and a pressurization system to maintain the patch back pressure. A molded, elastic 180-cc (11-$in.^3$) reservoir with a downstream restrictor orifice to maintain pressure in the patches was selected after consideration of several alternatives.

An electrically driven pump provides sufficient pressure for the initial pressurization and then requires less than 6 W of power to maintain the required flowrate, since the actual pressure drop in the patches is quite low. Power is supplied from a sealed, rechargeable, 12-V, 1.5 amp-h battery located in a separate pouch attached to the belt.

A simple, linear proportioning valve was designed to control bypass of flow around the heat sink and thus provide an operator-controlled garment inlet temperature.

The garments are connected to the heat sink unit using self-sealing quick disconnects. Fig. 4 shows the complete heat sink assembly with an attached head cooler. The total system weight is 4.3 kg (9.4 lb) with the head cooler as shown in the figure and 5.0 kg (11.1 lb) with the head/vest garment.

Test Protocol

The human test phase of the program was performed in an environmental chamber at NASA-Ames Research Center using a treadmill and the exercise profile shown in Fig. 1. Four healthy male subjects were used. The basic experimental matrix consisted of the three different garment configurations plus the control (no garment) tests. Each subject was required to repeat each of the four test conditions two times in random order during the course of the study. Most human testing was done using a laboratory pumping/chilling apparatus as a heat sink. The portable heat sink unit, which was being developed in parallel with the garment tests, was tested separately to determine its performance. A later series of tests of the full system was performed. An additional test condition simulated a loss of cooling (system failure) on a subject wearing the garment.

PORTABLE PERSONAL COOLING SYSTEM

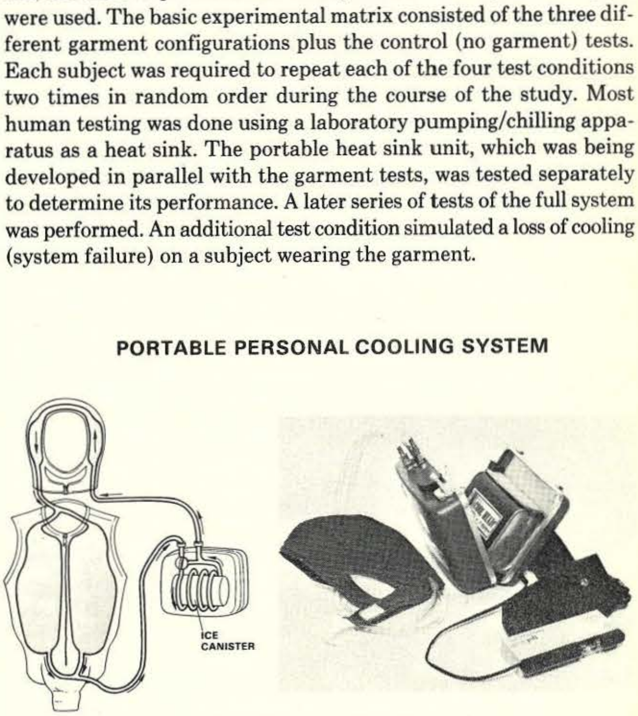

Fig. 4 Portable personal cooling system

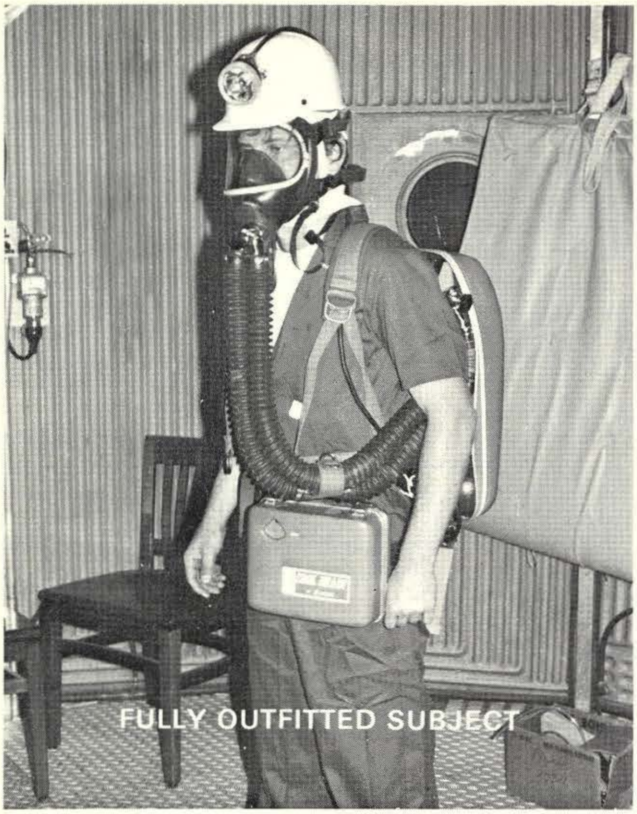

Fig. 5 Fully outfitted subject

The subjects were instrumented to determine core temperature skin temperatures of the left forearm, calf, thigh, and chest; ECG; and respiratory rate. Total metabolic rate was determined using an on-line mass spectrometer to measure O_2 consumption and CO_2 production. The garments were instrumented for water inlet temperature, delta temperature from inlet to outlet, and water flow rate in order to determine the garment heat load. All of these data were automatically recorded at one-minute intervals. The subjects own evaluation of their thermal state on a qualitative scale was also recorded periodically during the exercise period.

The chamber temperature controls and the laboratory pumping/chilling unit were set prior to arrival of the subjects to allow sufficient time for equilibration. Analysis of the portable cooling unit indicated that it should be capable of supplying 13°C water to the garment inlet. Therefore, all runs were made using a fixed garment inlet temperature of 13°C. The subjects inserted their individual rectal probes, an initial nude weight was taken, and the ECG electrodes and skin thermistors were fitted. They were then dressed in the cooling garment and a standard mine rescue team equipment ensemble. This included cotton coveralls, a Draeger Model BG 174-A breathing apparatus, equipment belt, hard hat, light, and battery. A simulated heat sink unit was attached to the belt for all cooling runs. The fully equipped subject was then weighed just prior to the start of the test. Fig. 5 shows a subject ready for test.

The subject entered the chamber and sat for 10 min while all systems were checked. Following the test the subject was again weighed while fully equipped. The subject then stripped and toweled off any excess sweat so that a second nude weight could be taken. A minimum recuperation period of two days was required before any subject was retested. It was found that only one subject per day could be run due to fatigue of the test personnel who were also in the hot environment.

Test Results

All data were analyzed in two ways. First, for each subject, mean values for each physiological parameter were calculated for each of the four test conditions in the test matrix. In this manner the subject served as his own control in the comparison. In addition, all data from all subjects for a given test condition were pooled for statistical analysis. The results of each method were consistent. Therefore, only the pooled data will be presented here.

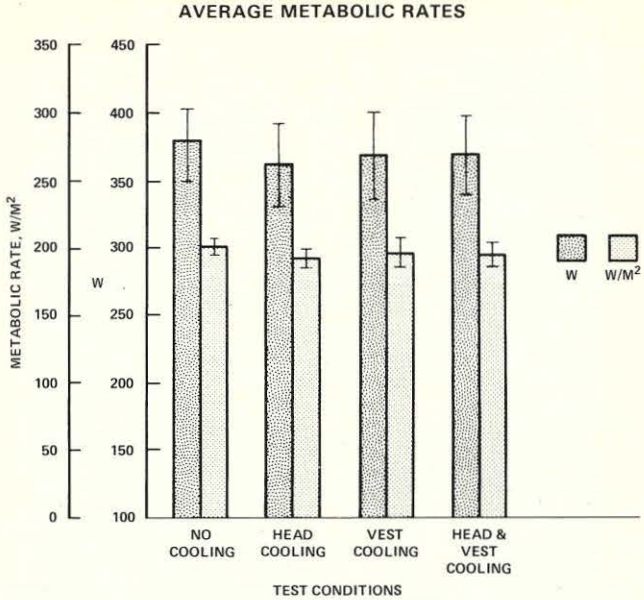

Fig. 6 Average metabolic rates

Fig. 6 shows the total metabolic rates as calculated from the oxygen consumption data for the last 20 min of each run. This figure shows that for all cooled conditions the total metabolic rate is slightly reduced when compared to the uncooled case even though the subjects were burdened with the additional weight of the cooling system. There is no significant difference in the metabolic rates for each of the cooled conditions.

The cooling garment heat load for each case is shown in Fig. 7. This figure shows the total heat addition to the circulating water as it passes through the garment. This total heat addition consists of the metabolic heat removed from the subject plus the heat gain from the environment. This represents the real heat load that must be absorbed by the heat sink and therefore no testing was performed during this study to distinguish between the two components of the heat load. Calculations showed that the heat load from the environment might

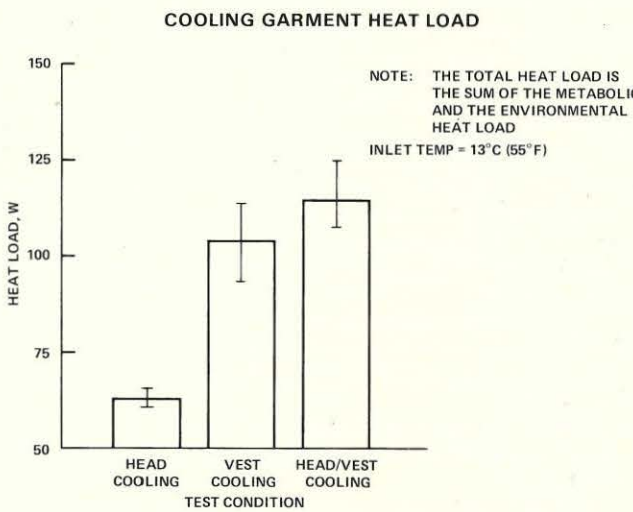

Fig. 7 Cooling garment heat load

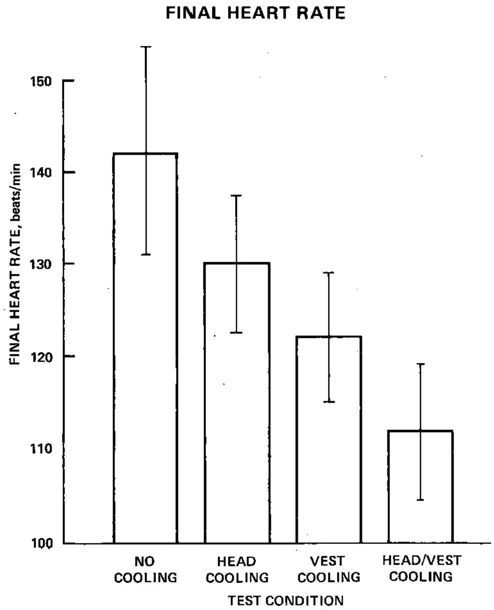

Fig. 8 Final heart rate

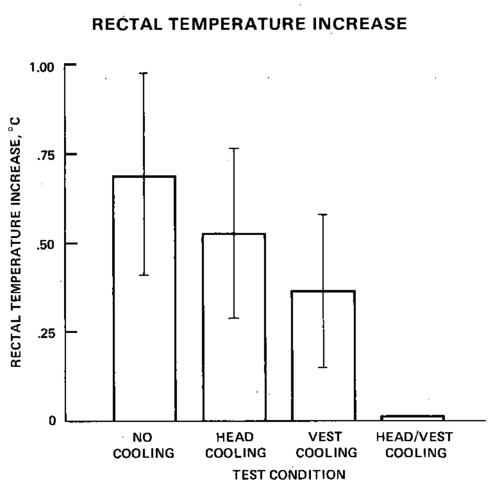

Fig. 9 Rectal temperature increase

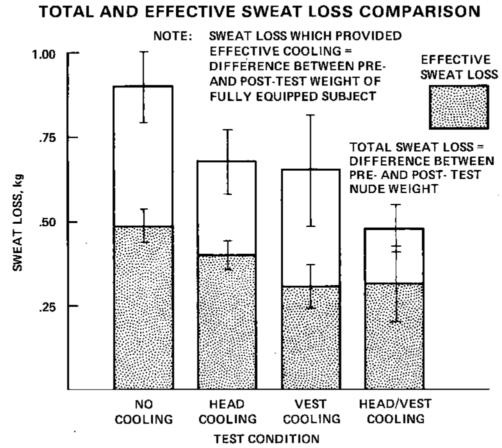

Fig. 10 Total and effective sweat loss comparison

Table 2 Thermal strain indices

Test Condition	Thermal Strain Index, I
no cooling	3.0 ± .5
head cooling	2.5 ± .4
thorax cooling	2.2 ± .5
head and thorax cooling	1.6

$$I = \frac{HR}{100} + \Delta T + \Delta W \qquad (12)$$

HR = final heart rate (beats/min)

ΔT = rate of increase of rectal temperature (°C/hr)

ΔW = rate of body weight loss (Kg/hr)

constitute as much as 30–40 percent of the total heat load for the tested conditions.

The heart rate and rectal temperature data shown in Figs. 8 and 9 clearly illustrate the benefits of cooling for the simulated mine rescue mission. The head/vest garment provides sufficient cooling to almost completely eliminate the thermal strain as shown by a negligible change in the rectal temperature over the course of the test.

The same trends are observed in the sweat loss data shown in Fig. 10. Here the total sweat loss is defined as the difference between the pre- and post-test nude weights. The effective sweat loss is defined as the difference between the two clothed weights. The total sweat loss rate determines the time to onset of exhaustion due to dehydration, while the effective sweat loss is the fraction which evaporated from the skin and provided cooling. As expected, in both cases the same trend of decreased thermal strain with increased heat removal is observed.

Table 2 presents the standard thermal strain indices as calculated from these data. The results of the cooling unit tests are given in Figs. 11 and 12. Water at a constant inlet temperature was supplied to the cooling unit and the heat transfer rate was calculated from the measured flow rate and temperature difference. Most runs were made while the unit was being shaken to simulate walking. This causes internal circulation inside the ice container and greatly increases the heat transfer rate as shown by the two representative heat transfer rate curves on Fig. 11. The increase in thermal conductance caused by the shaking is also clearly shown by the conductance curves on Fig. 11. The conductance values are the average calculated conductance for all of the heat transfer data and not just the two typical heat transfer rate curves presented.

The average heat transfer rate as a function of inlet temperature is shown in Fig. 12. The heat transfer rates measured for the various garments (Fig. 7) at the tested inlet temperature of 13°C are also shown. Note that the cooling unit outlet temperature, as shown on the lower ordinate scale, corresponds to the inlet temperature to the garment. For example, Fig. 12 shows that the cooling unit can supply the garment with water at 15°C (59°F) if the garment outlet temperature is about 17.7°C (63.9°F). Under these conditions the cooling unit's heat transfer rate is about 55 W (188 Btu/h). If at any time the heat load from the garment is greater than the capacity of the cooling unit, the temperatures in the flow loop will increase until the heat transfer rates in the garment and the cooling unit are equal. This occurs because the garment heat load, metabolic heat removal plus the environmental load, decreases as the liquid temperature gets nearer to the skin and the environmental temperature. At the same time the rate capacity of the cooling unit is increasing as shown on Fig. 12.

It was not possible to fully instrument the flow loop in order to measure the actual heat transfer rate while the subjects were exercising with the complete system. However, the subjects' comments were that they generally felt warmer and less comfortable when the portable cooling unit was used rather than the laboratory cooling unit.

The tests run with the subjects wearing the garments without water circulation in order to simulate a failed heat sink unit produced es-

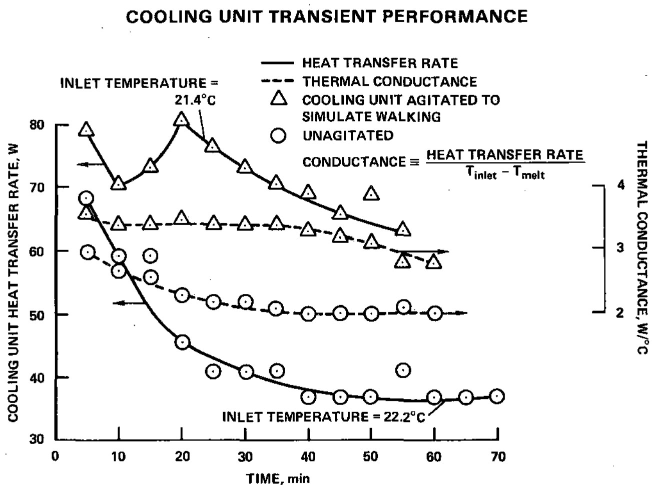

Fig. 11 Cooling unit transient performance

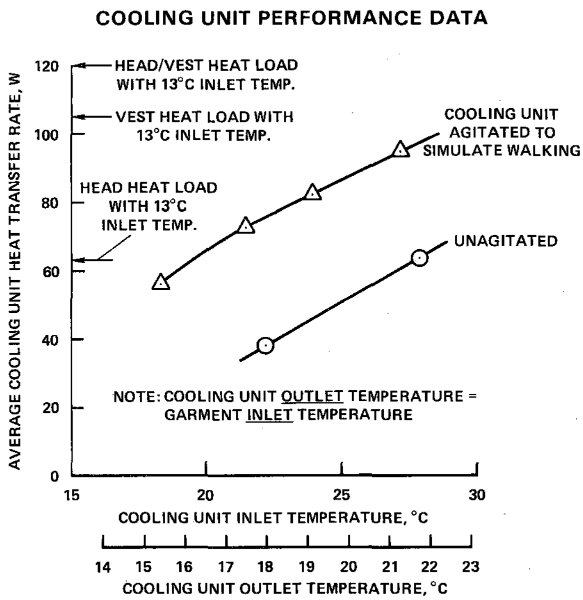

Fig. 12 Cooling unit performance data

sentially the same results as the uncooled, control runs. Therefore, there is no significant thermal penalty associated with wearing the garments should a heat sink unit fail.

Discussion

In all cases the subjects greatly preferred any of the cooling garment configurations over the uncooled condition, even with the extra weight penalty.

The head cooler provides nearly the same physiological benefits as the torso-only garment and its lesser heat load allows greater duration without changing ice canisters. However, use of the head cooler with a breathing mask requires great care to insure that a proper mask seal is made and that the cooling garment flow is not blocked when the mask harness is tightened. The subjects indicated that this garment was the least desirable of the three configurations tested.

The torso garment is slightly superior to the head garment when comparing physiological benefits. However, the increased heat load (Fig. 7) will cut the heat sink duration by approximately 40 percent. The decreased heat sink duration will require that the ice canister be changed more frequently, approximately once every hour. This drawback may be offset by the elimination of the mask interference problem.

The subjects preferred the combined head/torso garment over the other configurations. As the data show, this garment is able to almost completely relieve all symptoms of thermal strain for the tested conditions. However, this is done at the expense of further shortening the heat sink duration. This garment configuration also has the same mask compatibility problems as the head-only system.

As shown in Fig. 12, when the measured garment heat load is imposed the cooling unit is not presently capable of supplying the 13°C water that the subjects found comfortable. The subjects' comments indicate that the combined system's cooling capacity is not as effective in maintaining comfort as they would like. The solution to this deficiency is felt to be straightforward. Analysis indicates that adding insulation over the garment patches and connecting tubing can decrease the system heat load, under the test conditions, by as much as 30–40 percent. The cooling unit heat transfer rate can be further increased by internally finning the ice container. It is felt that one or both of these changes will increase the system capabilities to meet the rather severe test conditions.

The environmental heat load can be further reduced, in some cases, if a complete insulating overgarment is worn. As shown in Fig. 2, this should be considered whenever the dew point is such that no evaporative sweat cooling can occur, and the total environmental temperature is greater than the skin temperature, so that the body is gaining heat by natural convection and radiation.

Conclusions

Design improvements which appear desirable as a result of the test program include:

1 Insulation should be added over the patches and the inlet and outlet tubes to reduce the external heat load from the environment,

2 internal finning of the ice canister to improve the heat transfer rate,

3 slightly enlarging the heat sink case to allow the battery to be incorporated within the case,

4 redesign of some heat sink unit components to simplify fabrication and assembly,

5 an insulating overgarment should be considered for use in the most severe environments.

When both the physiological benefits and integration with the other equipment are considered, the results of the present manned test program do not definitively determine which of the garment configurations is optimum. Therefore, the Bureau of Mines plans to conduct its own test series using actual rescue team members as subjects to further refine the system.

The overall conclusion of this program is that a portable cooling system such as that described herein can successfully meet the stipulated requirements. The system, when it is fully developed, is expected to have many applications in addition to mine rescue.

Acknowledgment

The authors wish to acknowledge the financial support and guidance of the Pittsburgh Mining and Safety Research Center, USBM.

References

1 Brown, H., O'Connor, J. A., Dovidas, C. M., Capps, R., Final Report on Major Mine-Fire Disaster Belle Isle Salt Mine, Cargill, Inc., St. Mary Parrish, La., U. S. Department of the Interior, Bureau of Mines, Mar. 1968, 46 pp.; available for consultation of Bureau of Mines Mining and Safety Research Center, Pittsburgh, Pa.

2 Westfield, J., Knill, L. D., Moschett, A. C., Final Report of Major Mine Explosion Disaster Cane Creek Mine, Potash Div., Texas Gulf Sulfur Co., Grand County, Utah, U. S. Department of the Interior, Bureau of Mines, Aug. 1963, 30 pp.; available for consultation at Bureau of Mines Mining and Safety Research Center, Pittsburgh, Pa.

3 Rameym, R. W., Miller, L. R., Gunderson, T. O., Muncy, T. G., Phelps, J. H., Bulter, P. W., Sides, G. H., Johnson, R. T., and Scott, D. L., "Recovery" Somerset Mine; presented at the Sixty-Ninth Regular Meeting, Rocky Mountain Coal Mining Institute, Vail, Colo., June 1973, 17 pp.; available for consultation at Bureau of Mines Mining and Safety Research Center, Pittsburgh, Pa.

4 Kamon, E., Bernard, T. E., and Stein, R. L., "Steady State Respiratory Responses to Tasks Used in Federal Testing of Self-Contained Breathing Apparatus," *Journal of American Industrial Hygiene Association,* Vol. 36, 1975; pp. 886–896.

5 Department of the Interior, Bureau of Mines, "Respiratory Protective Devices: Test for Permissibility of Fees," *Federal Register,* Vol. 37, No. 59, Part 2, 1972 (30 CFR 11 H).

6 Williams, B. A., McEwen, G., Montgomery, L. D., and Webbon, B. W., "Effectiveness of a Modular Liquid-Cooling Garment and a Standard Apollo Liquid-Cooling Garment: A Comparison at Four Work Levels," Forty-Seventh Annual Scientific Meeting-Aerospace Medical Association, May 1976.

7 Nunneley, S. A., *Water Cooled Garments: A Review, Space Life Sciences,* 2:335–360, 1970.

8 Nunneley, S. A., Troutman, S. J., and Webb, P., "Head Cooling in Work and Heat Stress," *Aerospace Medicine,* 42, 1971, pp. 64–68.

9 Shvartz, E., "Effect of a Cooling Hood on Physiological Responses to Work in a Hot Environment," *Journal of Applied Physiology,* 29, 1970, pp. 36–39.

10 Williams, J. L., Webbon, B. W., and Copeland, R. J., "Advanced Extravehicular Protective Systems (AEPS) Study," NASA CR 114382, Mar. 1972.

11 Roebelen, G. J., and Kellner, J. D., "Ice Pack Heat Sink Subsystem—Phase II Final Report," NASA CR 137611, Jan. 1975.

12 Hall, J. F., and Potte, J. W., "Physiological Index of Strain and Body Heat Storage in Hyperthermia," *Journal of Applied Physiology,* 15, 1960, pp. 1027–1030.

transactions of the ASME

Published Quarterly by
The American Society of
Mechanical Engineers
Volume 100 • Number 1
February 1978

journal of engineering for industry

EDITORIAL STAFF
Editor, **J. J. JAKLITSCH, JR.**
Prod. Editor, **F. D. WOOTEN**
Editorial Prod. Asst., **K. DAHL**

POLICY BOARD, COMMUNICATIONS
Chairman and Vice-President
I. BERMAN

Members-at-Large
M. J. RABINS
W. J. WARREN
G. P. ESHENBRENNER
R. C. DEAN, JR.

Policy Board Representatives
Basic Engineering, **J. E. FOWLER**
General Engineering, **S. P. ROGACKI**
Industry, **J. E. ORTLOFF**
Power, **A. F. DUZY**
Research, **G. P. COOPER**
Codes and Stds., **P. M. BRISTER**
Ad Hoc Computer Technology Com., **I. BERMAN (Ex Officio)**
Nom. Com. Rep., **A. R. CATHERON**
Business Staff
345 E. 47th St.
New York, N. Y. 10017
212/644-7786
Mng. Dir., Publishing, **C. O. SANDERSON**

OFFICERS OF THE ASME
President, **S. P. KEZIOS**
Exec. Dir. & Sec'y., **ROGERS B. FINCH**
Treasurer, **ROBERT A. BENNETT**

EDITED AND PUBLISHED quarterly at the offices of The American Society of Mechanical Engineers, United Engineering Center, 345 E. 47th St., New York, N. Y. 10017. Cable Address, "Mechaneer," New York. Second Class postage paid at New York, N. Y., and at additional mailing offices.

CHANGES OF ADDRESS must be received at Society headquarters, seven weeks before they are to be effective. Please send old label and new address.

PRICES: To members, $25.00, annually; to nonmembers, $50.00. Single copies, $15.00 each. Add $1.50 for postage to countries outside the United States and Canada.

STATEMENT from By-Laws. The Society shall not be responsible for statements or opinions advances in papers or . . . printed in its publications (B-13, Par. 4).

COPYRIGHT © 1978 by The American Society of Mechanical Engineers. Reprints from this publication may be made on condition that full credit be given the TRANSACTIONS OF THE ASME, SERIES B—JOURNAL OF ENGINEERING FOR INDUSTRY, and the author, and date of publication be stated.

INDEXED by the Engineering Index, Inc.