A PHYSIOLOGICAL EVALUATION OF TWO DESIGNS OF A CONDUCTIVE COOLING HOOD

by 5009

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INTRODUCTION

In many industrial situations a man is required to perform a task in a heat environment that severely limits his available time to work at the task and his effectiveness. Examples of such situations are: maintenance work in boiler rooms or hot furnaces, manual work in deep mines, and operations in hot, humid environments of steel plants, founderies, farms and building construction.

It is impractical, and often impossible, to alter the entire environment to one of comfort where the human body functions normally. Therefore interest is focused on systems which provide complete or partial refuge to the individual when surrounded by a hostile environment. Complete protection is demonstrated in the suits worn by divers working deep in the ocean and astronauts outside of their spacecraft. Partial protection of industrial workers in a hot, humid, earth environment is the objective of the cooling-hood system discussed in this thesis.

The cooling-hood system is characterized by local cooling of the head by circulating cold water through tubes in close contact with the head. This system has been developed over the past three years at Kansas State University and has proven to be effective in significantly reducing the physiological demands of increased heart rate, skin temperature, body temperature, sweat loss, and oxygen consumption of a man active in a moderate heat stress environment (Morales and Konz, 1968).

LITERATURE REVIEW

Much current research has been done in developing personal conditioning systems. Most of the published work on conductive individual cooling systems from the United States and Great Britain are reviewed and summarized in this section.

The Development of Conductive Individual Cooling

Garrett Corp.

Research conducted by the Garrett Corporation in October, 1962 investigated methods of reducing the latent heat load of personnel wearing pressure suits (Wortz, Edwards and Harrington, 1964). Previous research had indicated that at moderate work rates subjects sweated excessively, even at high ventilating gas flow rates through the suit. A system was developed to reduce the sweat rate of the suit wearer significantly and to provide adequate cooling even at high metabolic rates. This system incorporated several liquid-to-gas heat exchangers of various configurations in the gas stream inside the pressure suit. Cooling was accomplished by repeatedly cooling the gas (oxygen) as it flowed over the surface of the body. As the gas passed over the skin, it alternately cooled the skin and then was recooled itself by the heat exchangers. Gas was delivered to the suit at 2, 4, or 6 cubic feet per minute at temperatures varying from 46 to 60 F (7.8 to 15.6 C). The inlet temperature and flow rate of the glycol coolant in the closed-loop refrigeration system were controlled but not reported.

Four prototype heat exchanger configurations were evaluated. All four designs placed the coolant fluid lines in a G-suit pattern around the trunk and thighs. Configuration "A" was composed of windings of vinyl tubing; "B" was made of vinyl tubing attached to canvas garments; "C" was made of metallic finned piping; and "D" was made of shrouds of rubber life raft material with internal channels.

At a metabolic rate of 1000 Btu/hr. (252 kcal), configuration "A" removed 430 Btu/hr. (108 kcal); "B" removed 485 Btu/hr. (122 kcal), and "C" removed 750 Btu/hr. (189 kcal). No data was given for configuration "D". Without the aid of the internal heat exchangers the suit wearer would have had to remove the latent heat by sweating at the rate of 454 gm/hr. It was reported that of the two cooling effects present in this system, the periodic heating and cooling of the ventilating gas and continual evaporation-condensation cycle, the latter was the more important. It was suggested that the cooling effect of the evaporation-condensation cycle could be enhanced by providing a wicking material to carry the condensed moisture away from the heat exchangers so that it would be reevaporated. It was concluded that due to the physiological stress problems associated with ventilation cooling methods at high metabolic rates, future life support systems and space suits would utilize liquid cooling methods.

RAF.

The earliest totally conductive cooling garment was designed to be used by flight crews of the Royal Air Force and was termed a "water conditioned" suit (Burton and Collier, April, 1964). The first prototype suit consisted of a one-piece cotton undergarment to which socks and gloves were added, thus covering the entire body except for the head. To this suit was added forty parallel circuits of black pvc tubing--each one about four feet in length with a 1.5 mm. (.06 in.) I.D. The tubing was threaded in and out of the suit material--placing about seventy-five percent inside the suit next to the skin.

A detailed design study considering weight and the pumping power required to achieve a particular performance preceded the construction of the first prototype suit.

On November 14, 1962, approximately two months after the initial concept was formulated, the suit was evaluated in three experiments to determine if the subject's body heat could be extracted by a water cooled suit without causing discomfort to the subject. The suit was insulated from the ambient environment. In the first experiment mattresses were used as insulation and in the second and third experiments insulation was provided by granulated cork. Water inlet temperatures ranging from 55.4 F (13 C) to 84.2 F (29 C) and water outlet temperatures ranging from 73.4 F (23 C) to 89.6 F (32 C) were reported with mass flow rates ranging from 8 to 50 lb/hr. (3.6 to 22.7 kg).

These experiments indicated that a reasonable amount of heat could be extracted with less than one square foot of tube contact area, and a deep body to water temperature difference of only 18 to 36 F (10 to 20 C). There was no evidence of any consistent undercooling or over-cooling in any parts of the body, and at heat extraction rates equal to the metabolic rate there was no subjective impression of local cooling.

The information stimulated further interest in water conditioned suits. The Crew Systems Division at the Manned Spacecraft Center in Houston, Texas requested Burton and Collier to develop a suit for application in extra-terrestrial environments and to demonstrate its performance in Houston, Texas. A second prototype suit was constructed. Maintaining the basic form of the first prototype, the length of the forty tubes was increased from 4 to 6 feet, the tubing was sewn into the inside of the garment rather than threaded in and out, and the manifold design was improved reducing the total pressure drop through the suit by nearly one-half.

During the demonstration of the second prototype suit at the Manned Spacecraft Center, a subject wearing the water conditioned suit performed a step task with an estimated metabolic rate of 1300 Btu/hr. (328 kcal) in an ambient temperature of 98.6 F (37 C). The subject, after over an hour of work, complained of being cold, for at times the water inlet temperatures were nearly freezing and flow rates of 150 lb/hr. (68.1 kg) were maintained. The results indicated that sweating could be completely suppressed and that heat extraction rates up to 3400 Btu/hr. (857 kcal) could be obtained. With the water conditioned suit charged with water but not circulating, and with the unpressurized pressure suit worn over the water conditioned suit ventilated with dry oxygen at 15 cf/m the subject's sweat rate exceeded 454 grams per hour and the test was stopped after 45 minutes.

The first two prototype suits had proved their effectiveness and, therefore, attention was focused on building a practical garment. A new suit was built to stretch elastically to provide a good fit, the tubes were sewn into the garment, the tubes were transparent for inspection purposes, and the manifolding was improved to reduce the suit pressure drop, reduce corrosion, and increase the strength of the joints to prevent leaks. The problems associated with these improvements were solved and the first demonstration suit was completed in December, 1963.

Using the demonstration suit, a series of experiments with two experienced subjects was performed in which the subject controlled the suit's heat extraction rate (Burton and Collier, Jan. 1965). A light-weight flight suit, boots, and helmet were worn over the water conditioned suit. The insulation value of the clothing was estimated to be 0.8 clo units. The subject varied the suit heat extraction rate by controlling the suit inlet water temperature; the temperature value was unknown to the subject. The environmental globe temperature was used as an independent variable over the range 91.4 to 169.8 F (33 to 76 C). Air movement was low and constant. The water flow rate through the suit was used as an independent variable and varied from 30 to 150 lb/hr. (14 to 68 kg) for constant globe temperatures. Occassional recording of the subjects' oral temperatures, pulse rates, and weight loss were made and found to be normal.

Another experiment with 20 inexperienced subjects seated in an ejection seat in an environment with a 113.0 F (45 C) globe temperature permitted the subjects to select and adjust desired inlet water temperature. The water flow rate was kept constant at 60 lb/hr. (27.2 kg) for the 40 minutes of exposure. No physiological measurements were recorded. The range of the final inlet water temperature was between 41.9 and 88.2 F (5.5 and 31.2 C). The mean cooling rate chosen by the 20 subjects was 550 Btu/hr. (139 kcal) with a standard deviation of 162 Btu/hr. (41 kcal). The subjective comments indicated that the suit provided too much cooling on the forearms, upper arms, and shoulders;

and, although no direct cooling was applied to the head, hands or feet, some of the subjects stated that they probsbly would be happier with head cooling.

Further improvements on the demonstration suit were made to ease the difficulties of manufacturing a practical garment, and to improve the comfort of the suit on the skin. The improved suit was designated a development suit (Burton and Collier, July 1965). This suit used the same basic garment and tubing as in the demonstration suit; but rather than sewing the tubes into the garment, they were located in thin cloth tunnels sewn onto the suit. This design reduced the tendency of the tubes to form loops and kinks and permitted the tubes to slide freely. The suit was more comfortable due to the more uniform surface presented to the skin.

The development suit was tested on two subjects exposed to a 114.8 F (46 C) globe temperature and one subject exposed to 149.0 F (65 C). The subjects, wearing a lightweight flight suit, were seated and were asked to control the suit heat extraction rate to what they considered to be a comfortable level by adjusting their suit inlet water temperature. The results indicated that the development suit was not as effective as the earlier demonstration suit.

The highest heat extraction rate, with 41.0 F (5 C) water flowing at 100 lb/hr. (48.4 kg) through the suit, was 1300 Btu/hr. (328 kcal) for the latest suit and 1550 Btu/hr. (390 kcal) for the previous model suit. The latest suit was subjectively more comfortable than the previous suit as the cooling distribution was more uniform. The upper arms and shoulders were no longer overcooled, changes in body posture no longer dragged large areas of suit over the skin, and the tubes showed no signs of kinking. Notwithstanding the 250 Btu/hr (63 kcal) lower heat removal capability, the development suit was considered to be a substantial improvement over its predecessors--bringing the concept close to a practical, production item. Further work was proposed to increase the conductivity of the tube material and to improve the contact of the tubes with the skin.

Burton (Nov., 1965) presented a detailed report of the theoretical characteristics of personal conditioning systems. Using experimental data gathered from research with water conditioned garments, evaporative cooling garments, and convective cooling garments he attempted to derive a method of making valid comparisons between the thermal performances of the various personal cooling systems. The purpose of the study was to develop an experimental program to enable cooling system designers to choose the best type of cooling for a particular application, and to offer a method of comparing one personal cooling system versus other personal cooling systems.

Allan (1966) also contributed to the development of conductive individual cooling.

Wright-Patterson AFB

The United States Air Force, concerned about the problems of keeping men in thermal equilibrium for a period of many hours or days while wearing full pressure suits in space vehicles, also searched for the most effective individual cooling method of a person exposed to moderate thermal stress (Veghte, Oct., 1965). Three different air ventilating systems and one of the Royal Air Force's water conditioned suits were evaluated under a full pressure suit. Five subjects, sitting at rest, participated in a total of 60 experiments at atmospheric pressure in a 109.4 F (43 C) environment. Each subject wore each of the cooling systems with the pressure suit unpressurized and then pressurized. Control experiments were also conducted in which the pressure suit was worn without ventilation. The duration of the experiment was two hours or whenever the subject's rectal temperature exceeded 102.2 F (39 C), heart rate exceeded 140 beats/minute, or whenever the subject requested to be removed from the test chamber. In addition to rectal temperature and heart rate, 17 skin temperatures on each subject were recorded and averaged and total sweat loss was measured by weighing the subject before and after the exposure. In the air ventilating systems, the inlet air temperature was 69.8 F (21 C) at a mass flow rate of 23 lb/hr. (10.4 kg). In the water conditioned suit the inlet water temperature was 69.8 F (21 C) at a mass flow rate of 132 lb/hr. (60 kg). The duration of the experiment for the control condition varied between 60 and 95 minutes.

The average change in the mean skin temperature was +9.4 F (5.2 C) for the control, +2.5 F (1.4 C) for the air ventilating system, and -0.9 F (0.5 C) for the water conditioned suit. The average change in rectal temperature was +2.5 F (1.4 C) for the control, +0.2 F (0.1 C) for the air ventilating system, and -1.1 F (0.6 C) for the water conditioned suit. The average change in body heat storage was +233.0 Btu/m^2/hr. (58.7 kcal/m^2/hr.) for the control, +32.2 Btu/m^2/hr. (8.1 kcal/m^2/hr.) for the air ventilating system, and -36.6 Btu/m^2/hr. (9.2 kcal/m^2/hr.) for the water conditioned suit. The average total sweat loss was 606 grams for the control, 483 grams for the air ventilating system, and 123 grams for the water conditioned suit. Total body heat storage varied from -139 Btu

(35 kcal) with the water conditioned suit to +198 Btu (50 kcal) with the air ventilated suit and +596 Btu (150 kcal) during the control condition. Heart rates remained below 110 beats/minute while subjects wore the ventilating systems, but decreased from initial levels to near basal conditions when subjects were wearing the water conditioned suit. In the control condition, terminal heart rates varied from 110 to 140 beats/minute.

It was concluded that the water conditioned suit was superior to all air ventilating systems and kept subjects comfortable throughout the heat exposure. The air ventilating suits prevented serious body heat storage but only by permitting large sweat losses of over 400 grams during the two hour exposure.

In an attempt to test the human temperature regulation theory of integration of various inputs by the hypothalamus, Byrne (May, 1968) performed an experiment to measure some of the responses to regional surface cooling in human subjects exposed to moderate heat stress and increased humidity. He stated that if the integration theory was correct, stimulation of cold receptors with simultaneous diminished activity of warm receptors would change responses such as sweating, heart rate, and perhaps rectal and total body temperature in the presence of a constant thermal stimulus. In this experiment, water cooled heat exchangers placed on small, selected areas of the body surface provided the constant thermal stimulus. The hypothesis tested was that peripheral input was of significant importance in the control of sweating.

Eight male subjects ranging in age from 22 to 46 years with a mean body surface area of 1.86 m^2 participated in a total of 38 experiments.

The data recorded during the first 90 seconds and last 90 seconds of each experimental trial were used for the statistical analysis. During the cooling trials, the water-cooled pads were worn over the underwear. The subjects also wore a summer flying suit, cotton socks, and high-topped work shoes.

The water cooled pads consisted of two 5.9 by 11.8 in. (15 by 30 cm.) rectangles which could be used as a combined unit with a 139.5 in^2 (900 cm^2) cooling surface. The pada were constructed of plastic tubing connected between brass manifolds at the top and bottom of each pad. The external surface of each pad was covered with an inch-thick layer of loose-textured gauze to minimize heat losses to the ambient environment. Inlet water temperature was 69.8 $\pm$ .9 F (21 $\pm$ 0.5 C) with the flow rate of 132.0 $\pm$ 6.6 lb/hr. (60.0 $\pm$ 3.0 kg).

Two series of control experiments with the subject not being cooled were performed; one during the spring, and one during the fall. The effect of the cooling pad was evaluated during the summer at three body locations: the abdomen, the scapula, and the thighs.

After being seated outside the test chamber for a 5 to 10 minute baseline period, the subject entered the 115.7 F (46.5 C), 19% R.H. test chamber environment and remained seated for a 120 minute exposure.

Local surface cooling caused significantly less sweat loss than recorded for either control group. The average sweat rate was 370 grams/hour for the spring control, 365 for thigh cooling, 325 for the fall control, 300 for abdominal cooling, and 275 for scapular cooling. The 275 and 300 were significantly ($p < .05$) lower than the 365 and 370.

The average increase in heart rate was 12 beats/min. for the spring control, 11 for the fall control, 11 for scapular cooling, 9 for thigh cooling, and 9 for abdominal cooling. The change in heart rate was less, though not significantly, than the control conditions for all cooling locations.

The totsl body temperature was less with sll cooling locations than in the controls, and the change in rectal temperature was not significantly different for any of the conditions.

The report concluded that the results substantiated the theory of integration of peripheral sensory inputs as the major contributing factors in the human temperature regulating mechanism. It was, also, shown that during moderate heat stress, sweat production was reduced by stimulating peripheral cold receptors, and was probably further reduced by the decreased activity of warm receptors in the areas locally cooled.

Bowen (1963) and Kaufman (1966) also contributed to the development of conductive individual cooling. A comprehensive survey of thermal control techniques for extra-vehicular space suits, including conductive cooling, was presented by Hedge (1968).

Hamilton-Standard

The Hamilton-Standard Division of the United Aircraft Corporation did research on a personal conductive cooling system to be used during Apollo spaceflight missions (Jennings, 1966). Earlier studies had indicated that conductive cooling using liquids offered less system weight for higher cooling loads and longer periods of activity than did gas ventilation systems.

The first of a series of Hamilton-Stsndard cooling garments was designed using the information available from Burton and and Collier (1964, 1965). The garment design used transparent pvc tubing (0.063" I.D., 0.031" wall) sewn to an open mesh cotton net fabric. Body cooling by evaporation of sweat was permitted by gas circulation through the mesh. The tubes were in direct contact with the wearer's skin. Local tube length distribution was made proportional to body mass distribution, on the assumption that body heat generation was directly proportional to the local mass of muscle tissue. In the first cooling garment, ten cooling tubes, each 74 inches long, started at each wrist and ankle. Of the 247 feet of tubing, 232 made contact with the skin. The hands, feet, and head were not cooled. Garments made of an elastic material rather than the cotton net were also evaluated.

In addition to the cooling garment, an oversized neoprene foam garment, a quilted insulating garment, woolen socks, foam gloves, canvas shoes with rubber cleats, and helmet with goggles were worn. The test subject walked for three or four hours on a treadmill.

Inlet water temperatures of 45, 60, and 75 F (7.2, 15.6, 23.9 C) with flow of about 240 lb/hr. (108 kg) were evaluated. The design criterion was a sweat rate of 100 gms/hr.

The cooling garments provided adequate cooling at high metabolic rates with comfort and control of sweating. The rectal temperature stayed below the safety limit, 102 F (38.9 C). The cooling garments were capable of suppressing the sweat rate below the design objective of 100 gms/hr. Rectal temperature was a function of the garment's heat extraction rate for all equilibrium conditions and was independent of the average water temperature. This was noted as evidence of the capability of the body's temperature control system to govern the rate of cooling over wide ranges of conditions. Thus, it was stated, because an automatic feedback control system already operates in the body, there is little need for an automatic control system for the garment which would decrease reliability of the system.

Additional research by Hamilton-Standard ia reported by Howard (1968) and Kincaid (1965). The development and final design of the Apollo spaceflight portable life-support system and cooling garment developed by the Hamilton-Standard Diviaion of the United Aircraft Corporation was reported in Aviation and Space Technology (June, 1968).

A. D. Little

To perform an analysis of the heat tranafer between a man and a liquid cooled garment, Richardson (1967) made assumptions based on data extracted from the literature. He selected a water cooled garment of the type reported by Burton and Collier (1964), acknowledging that clothing worn under the garment decreased the garment efficiency, and that the garment could remove heat at the rate of 2000 to 3000 Btu/hr. (504 to 756 kcal).

He stated that most tested and projected liquid cooled garments circulated 200 to 300 lbs/hr. (191 to 136 kg) of water through 30 to 50 passages of 4 to 8 foot lengths. He assumed that the subject wearing the garment was in an adiabatic enclosure. He assumed, also, that the average deep body temperature was 98.6 F (37 C), the lowest skin temperature to prevent sensible sweating was 93 F (33.9 C). The suit was assumed to cover 15 ft^2 ($1.4m^2$) of body area with tubea spaced 1 inch apart.

It was stated that heat energy generated by the body flows from various depths of the skin to the surface area at the tube vicinity where it encounters an additional thermal resistance in the tube wall. From a mathematical model of the heat transfer problem it was concluded that the thermal resistance of the tube wall was the limiting factor in the entire heat transfer process. Inlet temperature was a very critical variable, whereas at large flow rates (above 200 lb/hr.) (90.8 kg) heat extraction rate was relatively insensitive to changes in flow rate.

Webb Associates

After two American astronauts experienced heavy sweating which caused early termination of the scheduled extravehicular activities during their Gemini spaceflights, the gas cooled pressure suit system was abandoned and new interest focused on water conditioned suits.

In research conducted for the National Aeronautics and Space Administration, Webb Associates, Inc. studied the cooling required of a water-cooled garment to keep men thermally neutral while working at various metabolic rates (Webb and Annis, 1967). This study, acknowledging the effectiveness of water cooled garments, was concerned with controlling the timing of the cooling. An earlier experiment had shown the importance of correct timing of cooling (Crocker, et al, 1964). Cooling applied too early or too strongly resulted in overcooling with associated cutaneous vaso-constriction, sensations of chilling, and the possibility of muscle cramps. Cooling applied too late or too little resulted in heat storage and rapid formation of sweat. If, after the sweating had begun, the cooling was increased, there was an overshoot which resulted in a high sweat production before the heat removal system could catch up. These findings of earlier research led to the study to define biothermal responses of men who were thermally isolated and cooled with a water cooled garment. Because the cooling requirement varies directly with the activity level, this research attempted to establish metabolic time constants for an automatic controller which would be able to prevent overcooling with sensations of chilling and vasoconstriction, and prevent excessive sweating due to undercooling. The input signal chosen for the controller was oxygen consumption. The criterion was that the weight loss not exceed 100 gms/hr. for the entire period of each activity schedule; this included respiratory water loss, which could be as much as 50 grams/hr. plus diffusion of water through the skin, which was estimated to be 15 grams/hour, plus an additional 35 grams/hour considered to be caused by physiological and psychogenic responses. Undercooling was detected when the dew point of the air flow through the suit indicated a sweat rate exceeding 84 gms/hr. Overcooling was determined by subjective report.

Four thermally-isolated subjects wearing a clothing assembly containing the water cooled suit manually controlled by the experimenters were tested at five different activity levels. The subjects ranged in age from 17 to 42 years and in body area from 1.8 to 1.9 m^2. Each test lasted from three to six hours with the intent being to have the subject perform the designated activity while being cooled so that he neither sweated nor became chilled. A total of 30 experiments provided the data necessary to show how a controller must perform for different levels and patterns of work.

The clothing assembly consisted of the following layers: water cooled garment, insulating suit with air distribution ducts, impermeable gloves and impermeable head covering. The hands, feet and face, representing about 12% of the body surface, were not cooled. The water cooled garment's network of small vinyl plastic Tygon tubes (1/16" I.D., 1/32" wall) were spaced approximately every two inches by small plastic loops so that, when the garment was donned, diamond shaped openings measuring about two inches long and one inch wide covered the body. The contact area of the cooling tubes was estimated to be just over 4.3 ft^2 (0.4m^2). The total length of tubing in the garment was not given.

Cooling was controlled by varying the inlet water temperature and flow rate of the water cooled garment, and by maintaining a small flow of warm dry air through the suit. The dry air was distributed through the suit at an inlet temperature approximately equal to suit temperature 82.4 to 86.0 F (28 to 30 C) and at 2 cfm. The purpose of the air flow was to facilitate detection of sweating rather than removal of significant amounts of body heat. The inlet water temperature was varied from 50.0 to 91.4 F (10 to 33 C) and the flow rate from 12 to 288 lb/hr. (6 to 132 kg). The wide changes in flow rate did not significantly change the heat extraction rate and it was therefore fixed at 198 lb/hr. (90 kg) for the last 19 experiments.

Thermal isolation was achieved by the effective insulation of the clothing assembly and by maintaining the ambient environment at the same temperature as that of the suit under the outer layer of insulation.

Five different schedules of treadmill activity, representing the range of metabolic rates expected in extravehicular activities, were used. In schedule I each subject worked at a rate of 2380 Btu/hr. (600 kcal) for one hour. A rest period of one hour preceded and followed the work period for each activity schedule. In schedule II the work level was 1190 Btu/hr. (300 kcal) for 2 hours. Schedule III investigated the effect of a preceding activity upon another activity level. Each subject started at a 1190 Btu/hr (300 kcal) level for 30 minutes, then worked at 1910 Btu/hr. (480 kcal) for 30 minutes, and finished with another 30 minutes at 1190 Btu/hr. (300 kcal). Schedule IV was defined as a 3570 Btu/hr. (900 kcal) activity for 10 minutes. Schedule V was constructed by arranging several hypothetical activity levels of working on the lunar surface for nearly three hours, and was designed to eventually test the performance of an automatic controller.

In all of the step function activities, the oxygen consumption reached plateau values within the first one or two minutes. A change in heat extraction rate lagged 1/2 to 4 minutes behind a change in activity level. Following the initial delay in response to a change in activity, the slope or time course of a change until a new equilibrium value was recorded for heat extraction was much different than for oxygen consumption. Heat extraction rate slopes were reported to be essentially exponential (positive, concave), with time constants related to the severity of the activity. Generally, if the activity level was higher, the slope was steeper.

In schedule III and IV, with mixtures of activity levels with and without rest periods intersperced, it was noticed that a preceding work period definitely influenced the results of a period being observed. The influence was such that the rise time of the heat extraction rate in a period following work was much quicker than if the latter period had been preceded with rest.

In schedule IV the rectal temperature rose and peaked after the work period was over; whereas, the oxygen consumption rose to its maximum value within 2 or 3 minutes of the initistion of the near-maximal effort. During this activity schedule, the difference in time between heat production (oxygen consumption) and heat extraction was shown clearly.

The average heart rate was 70 to 80 during the resting metabolic level of 384 Btu/hr. (96 kcal). During the highest activity level of 429 Btu/hr. (108 kcal) the average heart rate was 170 to 180. The heart rates were typical for the activity levels and showed no signs of heat stress.

The report concluded that the water cooled garment was a powerful means of removing body heat generated during nearly any activity. Not only could the mean skin temperature be driven to any desired level, but even overcooling and vasoconstriction could be achieved during strenuous work. A summary of this research was presented in Webb and Annis, 1968.

Using the data gathered from the 30 experiments conducted in 1966, Webb Associates developed a reasonably accurate biothermal model of working man in a water cooled garment, and continued research in developing an automatic heat extraction rate controller for their water cooled garment (Webb, Annis, and Troutman, June, 1968). A new water cooled garment was used which had different charscteristics from those of the

1966 suit, and this required a change in the gain of the heat extraction rate controller.

Initial experiments explored the effects of various controller gains and time constants, and then automatic control was evaluated with two subjects doing four different patterns of work on a treadmill. The input to the controller was a continuous oxygen consumption signal.

Water circulated at 198 lb/hr. (90 kg) through the garment.

The water cooled garment incorporated the cooling tubes and skin temperature sensors into a single garment. The insulation and water impermeability properties were improved by using a 0.25 inch thick unicellular foam neoprene "wet suit" and helmet of the type worn by SCUBA divers and by filling the spaces between the cooling tubes with 1/8 inch thick nylon fabric lined foam neoprene. The 150 feet of neoprene rubber cooling tubes (5/32" I.D. and 1/32" wall) were cemented onto the inner surface of the suit. The tubing extended 3/32 inch above the insulation to make contact with the skin. The 2.0 clo garment had a thickness of about 3/8 inch. The water cooled garment covered approximately 86% of the total body surface area. The hands, feet, and face were not cooled but were insulated from the ambient environment. The hands were covered by rubber surgeon's gloves, the feet by two pairs of wool socks and walking boots, and the face by a face mask which was part of the device that continuously monitored the oxygen consumption.

The two subjects were 29 and 35 years old with body surface areas of 2.0 and 1.9 m^2.

The four work schedules were:

a. 2150 Btu/hr. (540 kcal) constant work level for 1 hour.

b. 1190 Btu/hr. (1300 kcal) for 30 minutes, then
1910 Btu/hr. (480 kcal) for 30 minutes, then
1190 Btu/hr. (300 kcal) for 30 minutes.

c. near maximal work for 10 minutes.

d. an intermittent work period with near maximal work for 1 minute, followed by 1 minute rest, cycled repeatedly for 20 minutes.

The results indicated that during rest the water inlet temperature needed to be 78.8 F (26 C). For long periods of rest, one decree C above or below 78.8 F (26 C) caused a significant change in physiological response. The required inlet water temperature at rest for the water cooled garment used in 1966 had been 87.8 F (31 C). Not only was the resting value of inlet water temperature lower for the new suit, but the final temperatures at work were also lower. These differences indicated that the new suit was less efficient in extracting heat than the 1966 suit. The new suit had larger tubing which provided for wider contact as well with moving parts as did the diamond pattern of the 1966 suit.

This project reinforced the finding of the 1966 experiments that the skin temperature should not be allowed to rise, but must fall during work.

The results proved that the correct settings for the automatic controller had been established for their water cooled garment. During the work schedule of 1190 Btu/hr. (300 kcal) for 30 minutes, followed by

1910 Btu/hr. (480 kcal) for 30 minutes, ending with 1190 Btu/hr. (300 kcal) for 30 minutes, one subject was reported to have been subjectively comfortable with a weight loss of only 45 gms/hr.

A shortcoming of the experimental controller used was that it was designed only for the man while working. During long periods of rest, slight overcooling would eventually lead to low skin temperatures, loss of body heat and shivering, thus causing an increase in oxygen consumption and therefore a command for cooling. It was suggested that the controller should be improved by adding some feedback such as skin temperature to correct the controller during long periods of rest.

Other possible input signals of heart rate and skin temperature were suggested for the controller and a discussion of a final heat extraction rate controller evolving from the experimental controller was presented. This research proved that an open loop automatic controller worked, and that its performance was equal to and better than the best manual control of water cooled garments.

Webb (1969) presented a summary of his experience in the area of individual cooling at the Symposium on Individual Cooling at Kansas State University.

Manned Spacecraft Center.

Research at the Crew Systems Division of the Manned Spacecraft Center, Houston, Texas was conducted to show the effectiveness of liquid-cooled garments in extracting high levels of metabolic heat (Waligora and Michel, 1968). Six male subjects walked on a treadmill at metabolic rates between 795 to 1990 Btu/hr. (200 to 500 kcal) while wearing a liquid cooled garment under a pressure suit with an insulated cover or with an arctic clothing assembly. Two liquid-cooled garments were evaluated. The prototype garment, copied from the British, incorporated 240 ft. (73 meters) of tubing and the developmental garment incorporated 300 ft. (91 meters) of tubing. The pvc tubing (0.64 "I.D., .031" wall) (1.6 mm I.D., 0.8 mm wall) of both garments was sewn to the inside of cotton undergarments. The tubing did not cover the feet, hands, neck or head.

In the first two tests with the prototype liquid-cooled garment, the coolant flow rate was kept constant at 110 lb/hr. (50 kg) and inlet temperatures varied from 39.9 F (4.4 C) to 59.9 F (15.5 C).

The most subjectively comfortable coolant inlet temperature was found to be 50 F (10 C). Subjects definitely sweated at a coolant inlet temperature of 59.9 F (15.5 C) and were overly cool at a coolant inlet temperature of 44.1 F (6.7 C). In the third and fourth tests of the prototype garment, the coolant flow rate was varied between 61.5 and 170 lb/hr. (28 and 77 kg) and the coolant inlet temperature varied between 46.0 and 50.9 F (7.8 and 10.5 C). The data indicated that the flow rate could be varied widely and when the average tube temperature was constant the heat extraction rate and comfort would not be affected.

The fifth and sixth tests compared the liquid conductive cooling system to the gas ventilation cooling system with respect to comfort, steady state skin temperature, and sweat loss. The liquid-cooled garment was used with an inlet temperature of 50.0 F (10 C) and a flow rate of 110 lb/hr. (50 kg). The ventilation system used a gas flow rate of 425 liter/min. with a dry bulb temperature of 73.4 F (23 C), 34% R.H.

At a metabolic rate of 1180 Btu/hr. (315 kcal), the mean skin temperature was 84.0 F (28.9 C) with the liquid cooled garment, and 91.9 F (33.3 C) with the gas ventilated garment. The average sweat loss was 150 grams with the liquid cooled garment, and 750 grams with the gas ventilated garment.

Fourteen tests were conducted with a developmental liquid cooled garment. An arctic clothing garment was worn over the liquid cooled garment to minimize the heat loss to the environment. Only a small area of the face was exposed to the ambient environment. The subjects worked from 2 to 3 hours at metabolic rates between 397 and 2600 Btu/hr. (655 kcal) to determine the range of comfortable activity levels at inlet coolant temperatures of 44.1 F (6.7 C) and 59.9 F (15.5 C). These were the two lower temperatures proposed for a three-position manual control for the liquid-cooled garment. The coolant flow rate was maintained at 240 lb/hr. (109 kg).

The skin temperatures were directly related to the metabolic rate at each inlet coolant temperature. When the subject was comfortable, the average sweat rate was between 30 and 80 gms/hr. It was reported that all subjects complained of overcooling at the beginning of all tests, and shivering occurred during some portion of five of the tests. At a metabolic rate of 2600 Btu/hr. (655 kcal), the subject never established a steady state rectal temperature. This test was terminated in less than 1 hour when the subject's heart rate was recorded to be 180 beats/min. and his rectal temperature was 102.4 F (39.1 C). Thus, with an inlet temperature of 44.1 F (6.7 C), the liquid cooled garment was unable to maintain thermal balance at the high activity level. An activity level of 1990 Btu/hr. (500 kcal/hr.) approached the maximum work rate at which thermal balance could be provided with the liquid cooled garment.

These results provided a basis from which subsequent liquid cooled garments could be evaluated. It was reported that three later development garments: one of a stretch material; the same garment with a thin nylon liner; and one of stretch material, liner, and quarter-length sleeves were evaluated. It was concluded that the stretch material improved conductivity of the suit. Further research was being made with liquid cooled garments and an automatic control of inlet coolant temperature was being investigated.

Devos (1965) and Santamaria (1966) also contributed to the development of conductive individual cooling.

Welson and Co.

Kelly, of B. Welson and Co., Hartford, Connecticutt, described the characteristics of the two cooling garment models manufactured by his company, and stated that they were making full-length flight garments for the Apollo space mission (personal communication). The garment was made of an elastic fabric to which pvc tubing was sewn. Two models were being manufactured: a full length 3 pound suit of 300 feet of tubing, and a 2 pound vest of 150 feet of tubing. It was stated that the garment was to be worn under normal clothing with the tubing in contact with the skin. The full length garment was said to have a cooling capacity in excess of 2000 Btu/hr. (504 kcal) with inlet water temperatures ranging from 35 to 70 F (95 to 158 C) and flow rates ranging from 71 to 142 lb/hr. (32.2 to 64.4 kg). The vest was said to have a cooling capacity of 1000 Btu/hr. (252 kcal) with inlet water temperatures ranging from 35 to 70 F (1.7 to 21.1 C) and flow rates ranging from 38 to 71 lb/hr. (17.3 to 32.2 kg. The garments were evaluated in a 112 F (44.1 C) laboratory environment, and were used by pilots in advanced aircraft test flights and by drivers for aeveral hours during car races under 140 F (60 C) ambient temperatures.

Kansas State University

A water cooled hood system designed to cool individuals working at common industrial activity levels between 476 to 1190 Btu/hr. (120 to 300 kcal) was first evaluated in November, 1966 at Kansas State University (Morales and Konz, 1968).

The hood was constructed of medium weight canvas duck to which 23 feet of 3/16" I.D., 1/32" wall, polyethelene tubing was cemented. A detailed description of the cooling hood was presented by Morales (1967).

During the evaluation, water entered the hood at 50 F (10 C) at a flow rate of 145 lb/hr. (65.9 kg). Ice water from a reservoir was pumped through the hood and returned to the reservoir to be recooled. Two male subjects with an average body surface area of 1.97 m^2 were tested with and without the hood in two different environmental conditions. One was a neutral environment of 76 F (24.4 C), 50% R.H. still air; the other was a heat stress environment of 100 F (38.0 C), 70% R.H. atill air. The subjects wore cotton shorts and tennis shoes, and were in each environmental condition four hours. During 10 minutes of each hour of exposure they pedalled a bicycle ergometer at a metabolic rate between 715 and 1430 Btu/hr. (180 and 360 kcal). A 25 minute rest period preceded and followed the 10 minute work period.

During the neutral environment the physiological responses were nearly the same with or without the cooling hood. Generally, the average head skin temperature was lower than the average body skin temperature. Without the hood the head skin temperatures were about 3 F (1.7 C) higher. Rectal temperatures and skin temperatures were essentially constant with or without the hood.

In the stress environment the average change in head skin temperature with the hood during work was +4 F (2.2 C). The average change in head skin temperature during recovery was roughly -3 F (-1.7 C). The average change in head temperature without the hood during work was only about 1 F, (0.6 C), but was approximately 8 F (4.4 C) above the level when wearing the hood. The rate of change in rectal temperature was nearly the same with or without the hood for both subjects. The general effect of the cooling hood on heart rate was lower maximum values and lower minimum values. Without the hood, the maximum heart rate was 160 beats/minute; whereas with the hood, the maximum was 145. With the hood, the heart rate returned to basal between cycles; while without the hood, the heart rate never returned to basal.

The weight losses calculated for each of the last four days indicate the effect of the hood on sweat rate. In the neutral condition the average sweat rate without the hood was 146 gms./hr./m^2, and with the hood 58. In the heat stress environment the average sweat rate without the hood was 490 gms./hr./m^2, and with the hood 203. The hood was able to reduce the sweat rate 88 gms./hr./m^2 in the neutral condition and 287 in the heat stress environment. The subjects, when wearing the hood, sweated at approximately 40% of the rate without the hood for both environmental conditions.

Using the cooling hood constructed by Morales (1967) three more experiments were conducted to study the effect of localized cooling of the head in various environmental conditions (Konz and Nentwich, 1969). Two male subjects wearing only shorts participated in all three experiments and wore hood-A with 41 F (5 C) water circulating through it at 225 lb/hr. (102 kg).

In experiment one, the subjects did addition problems in a neutral environment and in four heat stress environments (99, 103, 107, and 112 F; 70% R.H.) (37.2, 39.7, 41.9, 44.5 C). The exposure time in the heat was one hour or when the subject's rectal temperature had risen 2 F (1.1 C) or when the subject wished to leave. The average rectal temperature was not influenced by the hood in the 99 and 103 F (37.2 and 39.7 C) environments. The difference in average sweat rate between "no-hood" and "hood" conditions was 21.3, 47.1, 136.8 and -25.2 gms./hr./m^2 for the 99, 103, 107, and 112 F environment respectively. The average change in columns added per minute in heat stress versus neutral environment was -1.9 with the hood and -2.2 without it in the 112 F environment. The percent error was less in the heat stress than in the neutral environment. In experiment-two, the two subjects did a number recall task in a neutral environment and an environment of 107 F (41.7 C), 70% R.H. There was no significant difference in the change of rectal temperature between "hood" and "no-hood" conditions for exposure times from 34 to 80 min. The average difference in sweat rate between "no-hood" and "hood" conditions was 76 gms./hr./m^2. In experiment-three, the two subjects walked on a level treadmill at a metabolic rate between 953 to 1190 Btu/hr. (240 to 300 kcal) in an environment of 100 F (37.8 C), 70% R.H. Each subject walked for 20 min. and then rested 20 min. throughout the 60 to 80 min. exposures. The average difference in sweat rate between "no-hood" and "hood" conditions was 126 gms./hr./m^2 more without the hood than with the hood. It was concluded that the cooling-hood reduced physiological cost, and no dangers of wearing the hood were observed.

The results with hood-A suggested that the cooling-hood could be improved by increasing the tube contact with the skin and by providing a closer fit. Therefore, hood-B was constructed with approximately 21 feet of flat oval rubber tubes of .024 inch wall thickness. The flatter, thinner tubes and closer fit of hood-B were expected to improve the heat extraction capability.

Gupta (1969), (Konz and Gupta, 1969), evaluated hood-B on eight male subjects in an environment of 100 F (37.8 C), 70% R.H. for two hours of exposure. The inlet water temperature to the hood was 40 F (4.4 C) and the flow rate was 130 lb/hr. (59 kg). The sedentary subjects performed a creative mental task of forming anagrams from sets of eight letters. Each subject participated in two experimental sessions; one with the hood, and one without the hood.

Productivity declined about 8% less with the hood. During the hour before entering the heat environment the average rectal temperature decreased .5 F (0.3 C). In the heat, the rate of change in rectal temperature with the hood was not significantly different from the rate of change without the hood.

In the hest, the average sweat loss was 148 $gms/hr./m^2$ without the hood and 98 with the hood. Therefore, hood-B significantly reduced the average sweat loss by 50 $gms/hr./m^2$. It was concluded that hood-B was less effective than hood-A in extracting hest from the man. It was suggested thst hood-B's poorer performance was due to its failure to cool the important areas of the throat and forehead, its openness to flow of hot ambient air, and its inability to wick perspiration away from the skin.

McDonnell Douglss

The Evaporative Cooling Garment System developed by the McDonnel Douglas Astronautics Co. was designed for high heat removal rates between 5000 to 7000 Btu/hr. (1260 to 1764 kcal)(Bitterly, 1969). This is a conductive cooling garment, in that the body heat is conducted through the garment membrane next to the skin surface into the garment interior where water supplied to a wicking material is exposed to a vacuum. The water changes from liquid to gas within the garment and the heat energy is removed in the form of cold steam. This garment offers high efficiency in removing heat and high system reliability.

E. I. DuPont

Individual workers required to work in toxic atmospheres were provided cool breathing air by a vortex tube cooling system (Croley, 1969). Because the workers were wesring heavy or nonporous protective clothing, the danger of heat exhaustion shortened their useful working periods. The vortex tube distributed 30 to 80 F (-1.1 to 26.7 C) air at flows from 12 to 21 cfm at 85 psig through a plastic suit worn over the protective clothing. Thus, the worker was provided a light, portsble, inexpensive cooling garment.

Summary

The conclusions from these reports indicate that conductive cooling garments provide individuals a system of low weight with high heat extraction capability for long periods of activity. Sweat loss may be reduced or completely suppressed. Physiological cost is lower, permitting longer exposure times and unimpaired performance due to heat stress.

Preliminary Considerations

The variables associated with research on man-environment interactions listed by Rohles (1967) and the variables of a current list, Table 1, (Rohles, personal communication) were considered the structure within which this research was performed. All of the physical variables were controlled by the research facility. Of the organismic variables only sex was controlled. Of the reciprocative variables, social, incentive, and activity were held constant, whereas, diet, exposure, and clothing were not. The variable of clothing; that is, the cooling-hood, wss the independent variable studied.

Table 2 presents the many variables associated with the cooling hood performance. Of these, the fluid, flow rate, inside diameter, and manifold pattern were controlled.

There are several advantages in selecting the head as the site for extrscting heat from the body. The head, which contains the heat sensitive brain, has the highest skin temperatures (Winslow and Herrington, 1949) snd, therefore, the largest temperature differential with the cooling tubes. There is a large constant-volume blood flow supplying the head (Bazett, 1968). The tissue insulation is relatively constant over a wide range of temperatures; that is, there is little vasoconstriction as a response to cold (Froese and Burton, 1957). The forehead and neck produce more sweat than other parts of the body (Day, 1968) and therefore offer the best location for reducing sweat loss. The head, because of

TABLE 1

Variables Associated with Research on Man-Environment Interactions

Physical Variables

- Sound
- Light
- Area-Volume
- Radiation
- Inspired Gas
- Atmospheric Pressure
- Force Field
- Air Movement
- Temperature - Relative Humidity

Organismic Variables

- Age - Sex
- Rhythmicity
- Psyche
- Drive
- Body Type
- Basal Metabolic Rate
- Genetics

Reciprocative Variables

- Diet
- Clothing
- Exposure
- Social
- Incentive
- Activity

TABLE 2

Variables Associated with Conductive Cooling-Hood Heat Extraction Rate

Conductive Fluid
Inlet Fluid Temperature
Fluid Flow Rate
Tube Inside Diameter
Tube Wall Thickness
Length of Tubing
Conductivity of Tube Material
Distance Between Tubes
Manifold Pattern
Size - Area of Contact
Insulation From Ambient Environment
Insulation From Skin

clothing customs, is accustomed to being colder than the rest of the body. Also, since arms, legs, and torso are not hindered, mobility is good and a small garment with few sizes can fit a large portion of the population. Because reducing the skin temperature suppresses sweating (Hardy, 1961), an attractive feature of conductive cooling is the avoidance of a performance decrement due to dehydration.

A comprehensive review of research into the effects of high temperatures on human performance was presented by Pepler (1963). He stated that the variables of degree of heat, length of work, amount of energy expended, characterteristics of individuals, and amount of incentive influence the occurrence of a performance decrement in heat. Wing (1965) presented a review of fourteen experiments on the effects of high ambient temperatures on human mental performance and concluded that performance deteriorates well before physiological limits have been reached. He noted the experiments of Blockley and Lyman (1950) where a significant performance decrement occurred on a mental task (addition) at effective temperatures between 100.5 and 114 F (38.1 and 45.6 C).

Herrington (1968) reported the range of physiological responses which oppose deviation of body temperature from an optimal level. He stated that the 24 hour average rectal temperature in the upper range of survival was 109.4 F (43 C) with the corresponding amount of heat stored equal to 1479 Btu (372 kcal).

The average heart rate for a resting man was reported to be 74 beats/min. An approximate upper limit of heart rate for seated, resting subjects in heat stress was 140 beats/min.

Resting unacclimatized subjects have been dehydrated by sweating at a rate of 1800 gm/hr. during 30 minutes exposure to a 122 F (50.1 C), 44% R.H.

environment. When the large amounts of sweat are evaporated the mechanism which produces sweat offers the greatest aid to the temperature regulating mechanism. The rate of sweat secretion, though, is not constant; it rises with body temperature until it reaches a maximum, and then, as the body temperature continues to rise, the sweat rate decreases due to sweat gland fatigue (Ladell, 1964). The significance of the failure of the sweat rate to remain at its maximum level is seen in its relationship with heat stroke. Heat stroke is characterized by a complete cessation of sweating and a possibly fatal rapid rise in body temperature.

PROBLEM

In the previous cooling-hood experiments the system had the following components: hood, cold water reservoir, condensing unit or ice supply, and pump. The water was cooled by the condensing unit or by adding ice, pumped through the hood, and then returned to the reservoir to be used again.

The system used for this experiment had only two components: hood, and cold water supply. The condensing unit and pump were eliminated by taking advantage of the cold water and pressure conveniently supplied by the city water lines.

The two hoods, designated hood-C and hood-D, were evaluated using city tap water at 60 F (15.6 C) at a flow rate of 264 lb/hr. (120 kg) in an environment of 112 F (44.1 C) and 58% R.H.

Hood C and Hood D were investigated to determine if they reduced physiological cost, improved performance, and if their differences in construction affected physiological cost and performance.

The physiological criteria were:

1. heart rate
    a. the average rate of extra heart beats during exposure (beats/min.),
    b. the average rate of extra heart beats during recovery (beats/min.),
    c. the range of heart rate for the individual (beats/min.),
    d. the rate of change in heart rate during exposure (beats/min./hr.).
2. sweat loss (gms./hr./m^2).
3. rectal temperature rate of increase (F/hr.).
4. ear canal temperature rate of increase (F/hr.).
5. skin temperature rate of increase (F/hr.).
    a. brow temperature
    b. neck temperature
    c. back temperature
    d. chest temperature

The performance criteria were:

1. number of completed columns per minute
2. ratio of columns incorrect over columns completed.

METHOD

Task

The subject performed a mental task--addition. Four six-digit, random numbers were combined to make an additional problem, and twenty such problems were placed on a sheet of paper. During the first 25 minutes of a 30 minute exposure to a neutral environment, each subject was given a new problem sheet every five minutes; the subjects rested during the last five minutes. During a scheduled 75 minute exposure to the heat stress environment, each subject was given a new problem sheet every five minutes until he had completed a maximum of 10 sheets. During the remainder of the exposure time the subjects rested sitting.

Apparatus

Test Chamber: The nine test sessions were conducted in the environmental test chamber located in the Institute for Environmental Research at Kansas State University. The test room is a 12' x 24' x 8' enclosure in which temperature, humidity, and air velocity may be controlled accurately. A detailed description of this facility is presented by Nevins, Rohles, Springer and Feyerherm (1966). The pre-test room, adjoining the test room, housed the monitoring equipment (see Figure 1), and provided a "neutral environment". The pre-test room air conditioning system was not functioning, thus permitting the temperature of the "neutral environment" to rise to 85 F (29.4 C) during the evening sessions and 90 F (32.2 C) during the afternoon sessions.

YSI Rectal Probe: A Yellow Springs Instrument Model 401 thermistor was inserted approximately 6 in. into the subjects anal canal to measure rectal temperature.

YSI Skin Temperature Thermistors: Yellow Springs Instrument Model 409 thermistors were used to measure skin temperatures. The temperature sensitive area was 3/8" in diameter, and was taped with heavy duct tape to the desired skin location. The tape insulated the thermistor from the ambient environment, and kept it flat against the skin surface.

Figure 1. View of Pre-Test Room with Monitoring Equipment.

YSI Ear Temperature Sensor Assembly: A Yellow Springs Instrument Model 423 thermistor was incorporated into the device used to measure the ear temperature. The sensor was constructed to prevent injury to the tympanic membrane and to insulate the thermistor from the ambient environment. The tip of the .083 in. dia. thermistor extended 1/2" beyond the plastic tubing (1/8" I.D., 5/16" O.D.) placed around the thermistor head. Duct tape wrapped around the plastic tubing held the thermistor in place and produced a 3/8" outside diameter. Starting 2 1/4" behind the tip of the thermistor, duct tape was wrapped to a 1/2" outside diameter. This assembly was held in the ear canal and insulated by the 1 3/4" foam rubber of the hood. In this manner, the ear temperature sensor was located a maximum distance of 1/2 inch from the inside of the hood.

Body Temperature Recording System: The thermistor leads of each subject were connected to a junction box which was connected to a United Systems Corporation Digital Thermometer, Model 500, with the ability to measure and visually display temperatures from 59 to 122 F to the nearest 0.1 F. The number of the experimental day, subject number, and temperature location number were recorded manually by a United Systems Corporation Manual Identification Unit Model 651. The Identification Unit provided four columns; one was used for the number of the experimental day, two and three for the subject number and four for the sensor number. Thus, the output of the system was composed of a paper tape printed with four columns of identification numbers, and four columns for each temperature measurement. The time of measurement was written on the paper tape by the operator.

Heart Rate Recording System: Heart rate was detected by three E & M Instrument Co. surfece electrodes pasted and taped to the chest. The electrode leads were connected to a junction box worn around the waist. The junction box was connected to a three way switch on a Beckman Type RS Dynograph strip-chart recorder. The operator recorded the time of measurement and the subject's initials near the measurement on the chart paper.

Beam Balance Platform Scale: The subjects were weighed on a Fairbanks Morse & Co. beam balance platform scale calibrated by the State of Kansas Bureau of Weights and Measurements. It measured weight in pounds to the nearest 0.01 lb.

Hood Water Temperature Recording System: (See Figure 2) Four, 9 foot lengths of copper-constantan (24 gauge) thermocouple wire with accuracy of ± 1.5 F were used to measure the temperatures of the inlet and outlet water of both hoods.

The junction of each thermocouple was made by spot welding the copper wire and the constantan wire. The junction was dipped in silver solder to insure a good junction contact with a low response time. Each wire was drawn through 8 1/2 feet of plastic tubing (1/8" I.D., 1/32" wall) which provided a shield against the ambient environment. The thermocouple junction extended 1 1/2 inches beyond the plastic tubing which was melted around the thermocouple wire. The melted tubing did not provide a water tight seal around the wire. Therefore, 1 1/2 inches from the point where the tubing was melted, the tubing, but not the wire, was severed. The opening left between the wire and tubing was then filled with hot, liquid

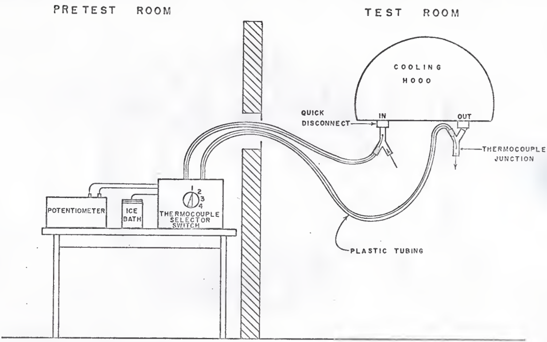

Figure 2. Cooling Hood Water Temperature Recording System.

beeswax. When the beeswax cooled and solidified, a water tight seal between the wire and tubing was obtained.

Each thermocouple junction was placed in one branch of a plastic Y-connector (3/16" I.D.) approximately one inch into the flow path. The pressure (interference) fit between the plastic tubing and the branch of the Y-connector was water tight, but the joint was well wrapped with duct tape to insure a tight seal. The outside surface of the Y-connector covering the thermocouple junction was well wrapped with duct tape to further insulate the thermocouple from the ambient temperature.

A Y-connector assembly was connected to a cooling hood by means of a plastic quick-disconnect. For an inlet assembly, the quick-disconnect was attached to the trunk of the Y-connector. For an outlet assembly, the quick-disconnect was attached to the branch of the Y-connector opposite the thermocouple junction.

The four thermocouples were soldered to a selector switch which was connected in series with a reference junction and in series with the switch board terminals. The terminals on the switch board were connected to a Leeds and Northrup potentiometer. A 32 F (0 C) reference junction was provided by an insulated jar containing ice floating in water. The potentiometer measured the difference in potential (milivolts) between the selected thermocouple junction and the reference junction.

The operator selected the desired thermocouple, recorded the difference in potential, and, later, converted the potential difference to a temperature (F) measurement.

Subject Monitoring System: A Sony Video Camera, Model VCK-2100 A, placed in the test room, was used to observe the subjects during the heat stress exposure. The camera was connected to a Sony Videocorder, Model CV-2100, which was connected to a Sony TV Monitor, Model CVM-180U, both placed in the pretest room. With this system, the status of the subjects could be continuously monitored and recorded simultaneously from the pretest room.

Water Delivery System: Water was tapped from a water line in the pretest room and directed through a Fischer and Porter Flowrator located in the pretest room. From the flowrator the water flowed through a rubber hose which passed through a window port into the test room where the flow was divided by a Y-connector into the two flows supplying the two hoods. Equal lengths of tubing were used to insure equal pressure drops to the hoods. From the hoods the water flowed through tubing to a drain in the test room.

Cooling-Hoods: Both Hood-C (Figure 3) and Hood-D (Figure 4) were constructed from the same pattern (size 7 hat block) with the same tube manifolding design, but with different materials. The manifolding design channeled the hood inlet water into two circuits. One circuit circulated water over the back of the head, left side and neck, and then to the outlet. The other circuit circulated water over the forehead, right side, and then to the outlet. The length of tubing was nearly the same in both circuits of each hood so as to maintain an equal pressure drop and flow rate through each circuit. However, due to a probable larger pressure drop from 5 more feet of tubing in Hood-C, the flow rate through Hood-C may have been slightly slower than the rate through Hood-D. This

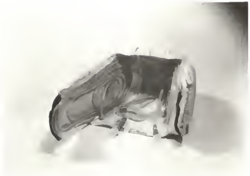

Figure 3. Views of Hood-C.

Figure 4. Views of Hood-D.

difference was considered negligible at a flow rate of 264 lb/hr. (120 kg) to the hoods.

Both hoods were insulated on both sides with 1 3/4 inches of foam rubber material to minimize heat transfer from the ambient air to the cooling fluid. A small hole was placed through the insulation of the left panel to hold the ear temperature sensor.

Hood-C was constructed with a total of 27 feet of Excelon tubing (3/16" I.D. and 1/32" wall) sewn to a Nomex cloth shell.

Hood-D was constructed with a total of 22 feet of Tygon tubing (3/16" I.D., 1/16" wall) sewn to a double-knit nylon shell. When the tubing was sewn to the double knit nylon material, Hood-D was stretched to a size slightly larger than Hood-C; Hood-D was roughly 2 in. wider across the forehood.

Hood-C was expected to be the more effective because it had 5 more feet of tubing, one-half the wall thickness, and a tighter fit than did Hood-D.

Plastic tubing was used because it was the easiest material with which to direct the water flow and to form into the shape desired. After trying different tube configurations, the spiral was found to maximize the length of tubing for a given area without disturbing the laminar flow through the tubes. The inlet and outlet manifolding was placed at the back of the hood to take advantage of the natural contour of the head and to prevent the water lines from hindering the wearer's hands and arms. As is shown in Table 3, which summarizes the physical characteristics of hood-C and hood-D, the tubing was concentrated on the forehead and neck.

TABLE 3

Summary of Characteristics of Hood-C and Hood-D

	Hood-C	Hood-D
Tubing Material	Excelon (Vinyl)	Tygon (pvc)
I.D. (in.)	3/16	3/16
Wall Thickness (in.)	1/32	1/16
Hood Material	Nomex	Nylon

Location	Tube length, ft.	
Right side	5.5	5.5
Forehead	8.0	5.0
Left side and neck	8.5	9.5
Back	5.0	2.0
Total	27.0	22.0

The tubing was held firmly in place by sewing into an open-weave cloth which could absorb the wearer's perspiration. Quick-disconnects were incorporated into the inlet and outlet manifolds to permit ease in donning and doffing the hood.

Subjects

Nine male Kansas State University students participated as subjects. Table 4 presents the general physical characteristics of each subject. During the experiment, they wore only cotton shorts, and for the required three sessions of participation, each received fifteen dollars.

Procedure

Each subject was weighed nude and his height measured. Heart rate sensors and four skin temperature sensors were then placed on the subject. One skin temperature sensor was located above the left eyebrow, one on the neck below the right ear, one on the upper chest below the right shoulder, and one on the lower back below the left shoulder. Each subject inserted a rectal temperature probe to a depth of 6 inches.

The dry weight of each subject's cotton shorts was recorded. Each subject donned his shorts and was then weighed with sensors and shorts.

The three subjects did addition problems for 25 minutes in the pre-test room while the physiological baseline data were recorded. After 30 minutes in the pre-test room, the subjects entered the test room, each donning the hood designated for him, and worked addition problems during the scheduled 75 minute heat stress exposure. Six days of evaluation were required to schedule nine subjects for all three hood conditions. Table 5 illustrates the schedule followed: Subjects 1, 4, and 7 followed

TABLE 4

Characteristics of the Subjects

Subject	Age (years)	Weight (pounds)	Height (inches)	Body Area (sq. meters)
1	23	134	66.0	1.69
2	20	179	69.3	1.98
3	21	190	70.3	2.04
4	22	149	68.0	1.81
5	21	168	68.3	1.90
6	18	143	67.3	1.76
7	24	170	69.0	1.93
8	19	157	69.3	1.87
9	19	141	69.3	1.79
Mean	21	159	68.5	1.86

TABLE 5

Schedule Followed in Evaluating Three Hood Conditions for Nine Subjects

Day	Time	Hood-C	Hood-D	No-Hood
		Subject		
Thursday		2	3	1
Friday	1-5 PM	1	2	3
Saturday		3	1	2
Thursday		5	6	4
Friday	6-10 PM	4	5	6
Saturday		6	4	5
Sunday		9	8	7
Monday	6-10 PM	7	9	8
Tuesday		8	7	9

NH, C, D; subjects 2, 5, and 9 followed C, D, NH; and subjects 3, 6, and 8 followed D, NH, C.

If a subject's rectal temperature rose 2 F above his baseline value, if he desired to leave the test room, or if he completed the scheduled exposure, he was removed, seated in a chair in the pre-test room and given a cotton sheet to drape around himself.

Recovery data was recorded for 30 minutes. At the end of the recovery period each subject was weighed with shorts and sensors and then permitted to remove the sensors.

Each subject removed his wet shorts which were weighed to give the value of sweat loss from the body but absorbed by the cotton shorts.

The subjects then showered, dressed, and departed.

Measurements

Heart rate data was recorded every three minutes for approximately fifteen seconds duration for each subject. Output was recorded on a continuous roll of strip chart recorder paper with the number of "r" waves being converted to beats per minute.

Sweat loss was approximated by subtracting body weight after exposure from body weight before exposure and then subtracting from that value the difference between the subject's wet and dry shorts. This value of sweat loss in pounds was then converted to grams per hour of exposure per square meter of body surface area.

All skin and body temperatures were measured every three minutes. However, the ear canal temperature was measured only while wearing the hoods.

The inlet and outlet water temperatures of the hoods were measured several times throughout the test. From the difference between hood inlet and outlet water temperature, the heat extraction rate of each hood was calculated.

RESULTS

After the first afternoon of testing, the data collecting proceeded very well. The subject being tested in the no-hood condition on the first afternoon initiated the experimenter to the reality of working with human subjects. The subject was removed from the test room after an exposure of only 39 minutes when his heart rate increased 45 beats per minute above his basal rate. The remaining days of testing caused little worry; although, as Table 6 indicates, five subjects were unable to remain in the test room for the scheduled 75 minutes when not wearing a cooling-hood.

The results were analyzed using the Wilcoxon Matched-Pairs Signed-Rank Test (Siegel, 1956).

To facilitate comparisons, the data presented in the following tables represent equal exposure and recovery periods for each subject for all three hood conditions and are in ascending order of exposure time.

TABLE 6

Elapsed Exposure Time (minutes) in Heat Stress Environment

Subject	Hood-C	Hood-D	No-Hood
1	75	69	39
2	69	75	69
3	69	69	60
4	75	69	75
5	75	75	69
6	69	75	75
7	75	75	75
8	75	75	75
9	75	75	54
Mean	73	73	66

Heart Rate

The average rate of extra heart beats was calculated for a subject by summing all observations of heart rates different from his basal rate during an exposure or recovery period and dividing by the number of observations in that period. An individual value for heart rate was determined by counting the "r" waves during, roughly, a 15 second interval and converting to beats per minute. The basal rate was defined as the average of the ten individual values of heart rate recorded in the neutral environment prior to entering the heat stress environment.

Table 7 presents the average rate of extra heart beats during exposure and recovery. Figure 5 shows the average change from the basal heart rate during exposure and recovery for subjects 4, 5, 6, 7 and 8. The average rate of extra beats was 15 beats/min. when subjects wore Hood-C; this was not significantly lower than the 17 when they wore Hood-D. Both were significantly ($p < .05$) lower than the 28 beats/min. in the no-hood condition.

Table 8 presents the range of individual values of heart rate recorded during each experimental session for each subject. There was no significant difference between any of the three hood conditions in the minimum values recorded, therefore, the lowest minimum value observed during the three sessions for each subject was used to eliminate from the comparisons the effect of increased heart rate due to anxiety. The average maximum value of 120 beats/min. for hood-C was significantly ($p < .05$) lower than the 125 for hood-D which was significantly ($p < .05$) lower than the 135 for no-hood. That is, C was 5 less than D which was 10 less than no-hood. The average range of 46 beats/min. for hood-C was

TABLE 7

Average Rate of Extra Heart Beats During Exposure and Recovery (beats/minute)

Subject	Exposure Time (min.)	Exposure C	Exposure D	Exposure NH	Recovery C	Recovery D	Recovery NH
1	39	13	20	26	7	10	5
9	54	10	14	23	10	5	1
3	60	14	22	39	4	12	26
2	69	18	18	26	7	6	15
4	69	16	18	25	-1	2	16
5	69	12	17	29	0	1	23
6	69	15	13	29	6	8	15
7	75	19	15	27	11	7	26
8	75	21	15	27	11	9	16
Mean		15	17	28	6	7	16

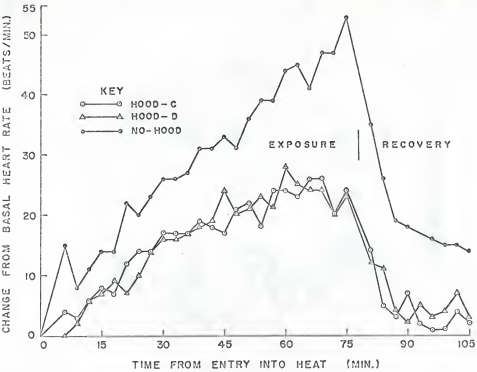

Figure 5. Average Change from Basal Heart Rate During Exposure and Recovery for Subjects 4, 5, 6, 7, and 8.

TABLE 8

Range of Individual Heart Rate Values (beats/min.)

Subject	Min.	Hood-C Max.	Hood-C Range	Hood-D Max.	Hood-D Range	No-Hood Max.	No-Hood Range
1	78	130	52	136	58	147	69
9	84	126	42	123	39	129	45
3	84	144	60	145	61	152	68
2	60	111	51	116	56	108	48
4	68	114	46	126	58	132	64
5	60	100	40	105	45	120	60
6	84	126	42	129	45	150	66
7	75	120	45	120	45	140	65
8	72	108	36	123	51	136	64
Mean	74	120	46	125	51	135	61

significantly ($p < .05$) lower than the 51 for hood-D. They were both significantly ($p < .05$) less than the 61 for no-hood. That is, C was 5 less than D which was 10 less than no-hood.

Table 9 presents the rate of change in heart rate during exposure for each subject and hood condition. The rate of change was calculated by subtracting the basal heart rate value from the final heart rate value in the heat stress environment and dividing by the hours of exposure time. The average rate of change in heart rate of 22 beats/min./hr. for hood-C was not significantly less than the 28 for hood-D. However, they both were significantly ($p < .05$) less than the 45 for no-hood. The average heart rate at the end of the heat exposure was 108 beats/min. for hood-C, 116 for hood-D, and 133 for no-hood.

Subject one's basal heart rate before wearing hood-C was 92 beats/min. and before hood-D was 84. His heart rate increased to 108 with hood-C and 123 with hood-D over a 39 min. exposure. Thus, the difference in basal rates magnified the difference between C and D. It was also observed that subject 1 had a lower rate of change in heart rate with no-hood than with hood-D. This occurred because his basal rate before the no-hood condition was 103 beats/min. and his heart rate after 39 min. of exposure increased to 140. The variation of his basal rate hindered the comparison between hood-D and no-hood.

Subject 3's basal heart rate was 96 beats/min. with both hood-C and hood-D, but his heart rate increased to 114 with C and 145 with D over a 60 min. exposure. For subject 3, the difference between C and D appears to be a true difference.

TABLE 9

Rate of Change in Heart Rate During Exposure (beats/min./hr.)

Subject	C	D	NH
1	25	60	57
9	19	20	41
3	18	49	54
2	22	19	34
4	19	25	45
5	20	17	44
6	25	27	43
7	24	16	50
8	23	19	39
Mean	22	28	45

Sweat Loss

Table 10 shows the sweat rate with and without cooling hoods during the heat stress exposure. The average sweat rate of 300 $gms./hr./m^2$ when the subjects wore hood-C was not significantly lower than the 319 when they wore hood-D. However, both were significantly ($p < .05$) lower than the 472 of the no-hood condition.

Rectal Temperature

The rate of change in rectal temperature was calculated by subtracting the final rectal temperature value of the preceding period from the final rectal temperature value of the period in question and dividing by the elapsed time between the two values. Table 11 summarizes the rate of change in rectal temperature during the pre-exposure, exposure, and recovery periods. Subject 3 when wearing hood-C used a broken rectal probe; therefore, his data was invalid. The 1.0 F/hr. (0.56 C) average rise when wearing hood-C was not significantly lower than the 1.1 F/hr. (0.61 C) average rise when wearing hood-D. Both however, were significantly ($p < .05$) lower than the average 1.7 F/hr. (0.94 C) for no-hood.

During the 30 minute pre-exposure period the average rate of change in rectal temperature was -0.6 F/hr. (-0.33 C) for all hood conditions. Of the twenty-six values recorded for the rate of change in rectal temperature during pre-exposure, all 26 were negative. This indicated ($p < .01$) that, regardless of the hood to be worn during the exposure, rectal temperatures decreased before the exposure. Thus the subjects either consciously or unconsciously lowered their body temperature before

TABLE 10

Sweat Rate (grams/hr./m^2) During Exposure

Subject	Hood-C	Hood-D	No-Hood
1	271.5	339.1	347.3
9	184.3	323.2	563.0
3	453.5	392.3	620.2
2	406.8	498.9	756.8
4	284.7	258.8	284.7
5	193.9	348.7	548.4
6	405.4	241.5	525.7
7	243.3	273.3	244.7
8	259.7	197.0	361.8
Mean	300.3	319.2	472.5

TABLE 11

Rate of Change in Rectal Temperature (F/hr.) During Pre-Exposure, Exposure, and Recovery.

Subject	Pre-Exposure C	Pre-Exposure D	Pre-Exposure NH	Exposure C	Exposure D	Exposure NH	Recovery C	Recovery D	Recovery NH
1	-0.6	-0.3	-0.9	0.6	0.9	0.8	0.0	0.8	1.2
9	-1.0	-0.6	-0.6	0.9	1.0	2.0	-0.4	0.2	-0.4
3	*	-0.6	-0.3	*	0.4	1.8	*	0.2	0.4
2	-0.3	-0.3	-0.6	1.0	1.7	2.2	0.3	-0.3	0.0
4	-0.6	-1.2	-0.2	0.9	1.2	1.5	0.6	0.2	-0.2
5	-0.6	-0.4	-0.4	0.6	1.1	1.9	0.4	-0.4	-0.2
6	-0.2	-0.2	-0.8	1.7	1.0	2.3	0.0	0.4	0.2
7	-0.2	-0.2	-0.8	1.2	1.4	0.9	0.2	-0.2	-0.2
8	-1.0	-1.6	-1.0	1.0	0.8	2.0	0.0	-0.2	-0.6
	-0.6	-0.6	-0.6	1.0	1.1	1.7	0.1	0.1	0.0

*Data not available

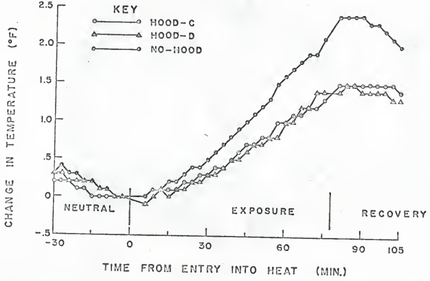

Figure 6. Average Change in Rectal Temperature During Pre-Exposure, Exposure, and Recovery for Subjects 4, 5, 6, 7, and 8.

entering the heat stress environment. Figure 6 shows the average change in rectal temperature during pre-exposure, exposure, and recovery for subjects 4, 5, 6, 7, snd 8. The average rectal temperature at the end of the heat exposure was 100.2 F (38.2 C) for hood-C and hood-D, and 100.7 F (39.1 C) for no-hood.

Ear Canal Temperature

Due to the individual differences in the subject's head sizes and ear locations, and the constant size of the cooling-hoods, the placement of the ear canal temperature sensor into the ear canal was inconsistent. The wide range of values shown in Table 12 gives evidence that the ear temperature sensor was not adequately insulated or placed far enough into the ear canal. These results do indicate, though, how tightly hood-C fit around the ears and how loose hood-D was. The -0.4 F/hr. (-0.22 C) rate of change in ear canal temperature for subjects wearing hood-C was significantly ($p < .05$) lower than the 2.5 F/hr. (1.39 C) rate of change when wearing hood-D and the 1.3 F/hr. (0.7 C) when wearing no-hood. Although Table 12 indicates a significant difference between the 2.5 F/hr. (1.39 C) for hood-D and the 1.3 F/hr. (0.7 C) for no-hood, it conceals the temperature values from which the change was computed. For hood-C, the sverage initial value was 95.5 F(35.3 C) and the average final value wss 95.3 F (35.2 C). For hood-D, the average initial and final values were 95.8 F and 98.3 F (6.9 C) respectively; and, for no-hood, 100.1 F (37.9 C) and 101.4 F (38.6 C).

Brow Temperature

The rate of change in brow temperature, shown in Table 13, gives

TABLE 12

Rate of Change in Ear Canal Temperature (F/hr.) During Exposure

Subject	C	D	NH
1	0.0	2.0	1.6
9	0.7	3.4	1.5
3	-2.0	1.2	0.7
2	1.3	2.6	1.2
4	-2.1	3.1	1.3
5	-1.2	3.1	2.3
6	-0.3	1.9	1.9
7	0.5	*	0.6
8	*	2.6	0.9
Mean	-0.4	2.5	1.3
Mean Initial Value	95.5	95.8	100.1
Mean Final Value	95.3	98.3	101.4

*Outliers

TABLE 13

Rate of Change in Brow Temperature (F/hr.) During Exposure and Recovery

Subject	Exposure C	Exposure D	Exposure NH	Recovery C	Recovery D	Recovery NH
1	-2.8	2.3	6.2	1.6	-5.2	-12.0
9	-3.1	2.7	4.2	8.0	-8.6	- 8.4
3	-3.8	0.5	4.5	9.4	-4.6	- 8.2
2	-1.2	*	3.6	*	*	-10.3
4	-4.7	2.4	5.0	9.8	-4.6	- 9.6
5	-5.1	-1.8	4.4	13.2	1.0	- 8.4
6	-3.0	-2.1	3.6	*	*	*
7	-6.3	0.4	5.0	15.4	-0.6	- 6.2
8	-3.9	1.3	3.6	7.4	-7.8	- 6.6
Mean	-3.8	0.7	4.5	9.3	-4.3	- 8.7

*Data not available

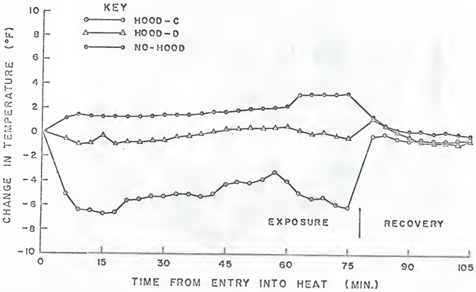

Figure 7. Average Change in Brow Temperature During Exposure and Recovery for Subjects 4, 5, 6, 7, and 8.

a good indication of the differences in hood construction. The -3.8 F/hr. (-2.1 C) average rate of change in brow temperature for hood-C was significantly ($p < .05$) lower than the 0.7 F/hr. (0.4 C) for hood-D which was significantly lower ($p < .05$) than the 4.5 F/hr. (2.5 C) for no-hood. On inspection of the hoods it is evident that hood-C, with a high concentration of tubing with a thinner wall on the forehead, would do better than hood-D which has less tubing with a thicker wall. Figure 7 shows the average change in brow temperature during exposure and recovery for subjects 4, 5, 6, 7 and 8 for all three hood conditions. The average brow temperature at the end of the heat exposure was 92.5 F (33.6 C) for hood-C, 97.2 F (35.7 C) for hood-D, and 100.6 F (38.2 C) for no-hood.

As will be seen in all of the tables expressing results of skin temperatures, the negative values of rate of change in temperature during recovery show the effect of rapid skin cooling due to evaporation of sweat.

Neck Temperature

The most difficult temperature location to record was that of the neck. After being in the heat stress environment for a short time, many of the neck temperature sensors became exposed to the ambient temperature as the sweat loosened the adhesive tape seal placed over the sensor; this often went unnoticed. Table 14 indicates the 1.6 F/hr. (0.89 C) rate of change in neck temperature between subjects wearing hood-C and the 1.3 F/hr. (0.72 C) rate of change of hood-D was not significantly different. The 4.6 F/hr. (2.6 C) change for the no-hood condition was significantly ($p < .05$) greater than for hood-C or hood-D.

TABLE 14

Rate of Change in Neck Temperature (F/hr.) During Exposure and Recovery

Subject	Exposure C	Exposure D	Exposure NH	Recovery C	Recovery D	Recovery NH
1	0.9	*	6.6	-5.2	*	-12.8
9	*	*	*	*	*	*
3	1.5	1.3	4.0	-5.2	-3.8	- 7.6
2	1.0	1.7	4.1	-4.0	-5.1	-10.0
4	0.4	1.7	3.7	-0.4	-3.6	- 7.0
5	*	0.8	5.7	*	-1.8	-13.2
6	1.7	*	3.8	-0.8	*	- 9.8
7	3.1	1.0	*	-4.6	-0.6	*
8	2.6	1.3	4.5	-4.4	*	- 4.2
Mean	1.6	1.3	4.6	-3.5	-3.0	- 9.2

*Data not available

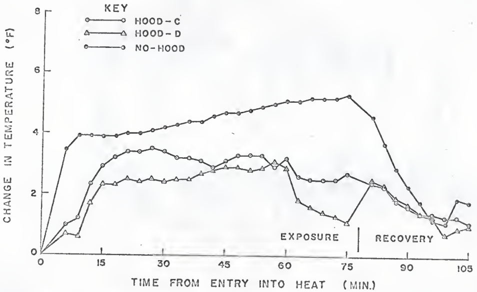

Figure 8. Average Change in Neck Temperature During Exposure and Recovery for Subjects 4, 5, 6, 7 and 8.

The 1.6 F/hr. rate of change in neck temperature with hood-C was greater than the 1.3 F/hr. for D. Although the difference was not significant, it could be expected as hood-D was constructed with a higher concentration of tubing in the neck strap. Figure 8 shows the average change in neck temperature during exposure and recovery for subjects 4, 5, 6, 7 and 8 for all three hood conditions. The average neck temperature at the end of the heat exposure was 97.2 F (35.7 C) for hood-C, 97.8 F (36.6 C) for hood-D, and 100.9 F (38.3 C) for no-hood.

Chest Temperature

The chest temperature was also difficult to record for some subjects. Those subjects with abundant hair over their chest were unable to prevent the temperature sensor from eventually loosening and then recording the ambient temperature. Table 15 gives the average rate of change in chest temperature during exposure and recovery for each subject and hood condition. Figure 9 shows the average change of chest temperature during exposure and recovery for subjects 4, 5, 6, 7 and 8 for all three hood conditions. The average chest temperature at the end of the heat exposure was 99.7 F (37.6 C) for hood-C, 99.9 F (37.7 C) for hood-D, and 101.1 F (38.5 C) for no-hood. There was no significant difference between any of the three hood conditions.

Back Temperature

Table 16 gives the average rate of change in back temperature during exposure and recovery for each subject and hood condition. Figure 10 shows the average change of back temperature during exposure and recovery for subjects 4, 5, 6, 7 and 8 for all three

TABLE 15

Rate of Change in Chest Temperature (F/hr.) During Exposure and Recovery

Subject	Exposure C	Exposure D	Exposure NH	Recovery C	Recovery D	Recovery NH
1	*	*	*	*	*	*
9	*	*	5.2	- 5.8	*	- 8.8
3	4.5	5.3	7.2	- 9.0	-14.5	-13.3
2	3.9	3.9	4.7	-10.6	- 6.0	-12.0
4	4.2	3.7	6.2	- 7.0	- 9.6	-10.4
5	4.3	4.4	4.2	- 5.2	-10.0	- 8.2
6	4.4	5.8	5.5	- 7.4	*	-11.2
7	*	4.9	4.1	*	-11.6	- 4.6
8	4.0	3.5	5.4	-10.2	*	- 6.0
Mean	4.2	4.5	5.3	- 7.9	-10.3	- 9.3

*Data not available

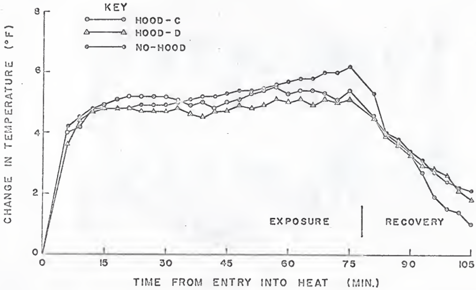

Figure 9. Average Change in Chest Temperature During Exposure and Recovery for Subjects 4, 5, 6, 7, and 8.

TABLE 16

Rate of Change in Back Temperature (F/hr.) During Exposure and Recovery

Subject	Exposure C	Exposure D	Exposure NH	Recovery C	Recovery D	Recovery NH
1	5.7	7.2	*	-14.8	-16.0	*
9	7.9	6.0	7.0	- 9.8	- 9.4	- 8.2
3	3.6	5.5	4.9	- 5.4	- 6.2	- 8.4
4	3.7	6.3	6.7	-14.6	- 7.4	- 6.0
5	5.3	5.2	5.7	- 9.4	- 9.4	-11.6
6	4.6	6.0	5.8	- 9.4	- 9.0	-18.0
7	4.3	6.7	*	- 8.4	-12.6	*
8	4.2	6.4	6.0	-11.2	- 9.0	- 8.0
Mean	5.0	6.0	5.8	-10.7	-10.7	-11.0

*Data not available

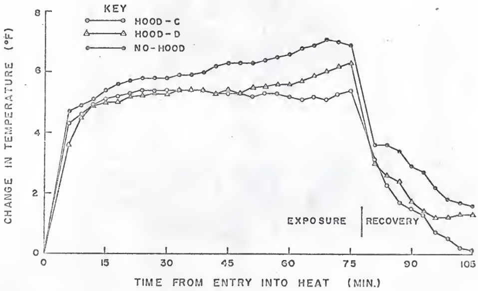

Figure 10: Average Change in Back Temperature During Exposure and Recovery for Subjects 4, 5, 6, 7, and 8.

hood conditions. The average back temperature at the end of the heat exposure was 99.9 F (37.7 C) for hood-C and hood-D, and 100.8 F (37.3 C) for no-hood. There was no significant difference between any of the three hood conditions.

Productivity

Task productivity was measured by the total number of columns completed per minute. Task percent error was measured by the ratio of columns incorrect over columns completed. The effect of learning was apparent. The average rate of addition in the neutral environment of the pre-test room was 13.5 columns/min. the first session, 16.1 the second, and 16.9 the third. Table 17 shows the average change in columns added per minute during exposure versus the neutral environment prior to that exposure. Output declined about 13% in the heat but the -1.6 columns for hood-C, the -1.9 for hood-D, and the -2.9 for no-hood were not significantly different. Table 18 shows the average change of percent error during exposure versus the neutral environment prior to that exposure. There was no significant difference between the 1.2% for hood-C, the 0.1% for hood-D, and the -0.4% for no-hood.

Heat Extraction

By recording the temperature difference between the hood's inlet and outlet water before, during, and after the subjects wore them, an estimate of the heat extracted from the environment and from the head was made. The average difference between inlet and outlet water temperature while hood-C was being worn was 2.02 F (1.12 C) and when not being worn was 1.09 F. (0.61 C). The average difference while hood-D was

TABLE 17

Average Change in Columns Added per Minute During Exposure Versus the Preceding Neutral Environment

Subject	Hood-C	Hood-D	No-Hood
1	-6.5	-4.7	-7.0
9	0.4	-0.6	-0.1
3	-3.5	-0.9	-2.8
2	-0.7	-5.7	-5.9
4	-0.4	-0.9	-4.3
5	0.3	-1.8	-3.5
6	-1.0	0.6	0.3
7	-0.6	-1.3	-1.1
8	-2.4	-2.0	-2.1
Mean	-1.6	-1.9	-2.9

TABLE 18

Average Change of Percent Error During Exposure Versus the Preceding Neutral Environment

Subject	Hood-C	Hood-D	No-Hood
1	2.4	-0.8	-1.4
9	-2.8	1.5	1.5
3	1.0	-0.5	0.8
2	1.9	-0.2	1.8
4	1.0	-0.6	-3.9
5	2.0	1.7	-2.8
6	0.1	-1.6	1.1
7	1.5	-0.2	-1.3
8	3.7	1.2	0.4
Mean	1.2	0.1	-0.4

TABLE 19

Average Heat Extraction Rate of Hood-C and Hood-D from the Head (Btu/hr.)

Subject	C	D	C/D
1	155.8	84.5	1.8
9	179.5	203.3	0.9
3	240.2	169.0	1.4
2	240.2	155.8	1.5
4	256.1	175.3	1.5
5	198.7	223.3	0.9
6	360.6	180.6	2.0
7	303.1	183.5	1.7
8	269.3	169.0	1.6
Mean	244.8	171.6	1.4

being worn was 1.65 F (0.94 C), and not being worn was 1.00 F (0.56 C). Thus, the total heat removed from the man and environment by hood-C was 533.3 Btu/hr (134.4 kcal) and by hood-D, 435.6 Btu/hr. (109.8 kcal). Hood-C extracted 54.0% of its total heat from the environment, while hood-D extracted 60.6% of its total heat from the environment. Table 19 shows the average values of rate of heat extraction from the head of each subject for hood-C and hood-D. The heat extraction rate of 244.8 Btu/hr. (61.7 kcal) for hood-C was significantly ($p < .05$) greater than the 171.6 Btu/hr. (43.3 kcal) for hood-D. The range of individual values of heat extraction rate was from 132.0 to 541.2 Btu/hr. (33.3 to 136.3 kcal) for hood-C, and from 97.7 to 301.0 Btu/hr. (24.6 to 75.8 kcal) for hood-D. This range indicates the importance of close fit of the hood to the individual.

The Man-Environment Heat Exchange

By modifying the expressions of the steady-state thermal comfort equation formulated by Fanger (1967) to represent the heat exchange between a nude sedentary subject and the heat stress environment, an estimate of the rate of heat storage in the average subject was made. Since the temperature of the man was changing throughout the exposure, the rate of heat storage was evaluated at six instants in time (t=0, 15, 30, 45, 60, 69 minutes) from entry into the heat stress environment.

The general form of the equation representing the heat exchange between man and environment is:

$$H \pm R_w \pm R_d \pm R \pm C_v \pm C_d - D - E = \pm S$$

where,

H = the internal heat production in the human body

R_w = the latent respiration heat

R_d = the dry respiration heat

R = the heat of radiation

C_v = the heat of convection

C_d = the heat of conduction

D = the heat of water vapor diffusion through the skin

E = the heat of evaporation of sweat from the skin surface

S = the heat stored by the body.

The internal heat production (H) is equal to the metabolic heat (M) less any mechanical work; since no mechanical work was done, all of the metabolic heat appeared as internal heat production. For the sedentary activity of this experiment, the metabolic heat (M) was estimated to be 60 kcal/hr./m^2 (238 Btu) (Fanger, 1967). For the average subject with 1.86 m^2 (20.0 ft^2) of body surface area, M was 111.6 kcal/hr. (444 Btu). Because of the environmental conditions of 112 F (44.1 C) dry bulb, 58% R.H., and still air (less than 50 ft/min.)(0.25 m/sec.), the subject was exposed to an environment in which he could lose heat only by restricted evaporation of aweat and by conduction to the cooling hood. Heat was gained by radiation from the walls and room surfaces (+R), and by convection from the ambient air ($+C_v$). It was assumed that D, R_w, and R_d were either zero or negligible. Thus, the subject could only have stored heat (+S), with the rate of storage dependent upon his physiological response.

Therefore, the heat exchange equation is reduced to:

$$M + R + C_v - E - C_d = + S.$$

Radiation

The rate of heat gained by radiation (R):

$$R = A_{eff} \cdot \varepsilon \cdot \sigma \cdot [(t_{mrt} + 273)^4 - (t_s + 273)^4] \text{ kcal/hr}$$

where,

A_{eff} = the effective radiation area of the nude body (m^2)

$$A_{eff} = f_{eff} \cdot A_{Du}$$

where,

f_{eff} = the ratio of the effective radiation area of the body to the total surface area of the body

A_{Du} = the Dubois area (surface area of the nude body)(m^2)

ε = the emissivity of the surface of the body

σ = the Stefan-Boltzmann Constant = 4.96×10^{-8} ($kcal/m^2hr.K^4$)

t_s = the mean skin temperature of the body (C)

t_{mrt} = the mean radiant temperature of the environment (C)

The value of f_{eff} depends upon the body position and for the seated position is given as 0.65 (Fanger, 1967). Therefore, A_{eff} was 1.21 m^2 for the average subject.

Emissivity (ε) of the skin surface was assumed to be 0.99 (Winslow and Herrington, 1949).

The values for the mean skin temperatures were calculated from the average back and chest temperatures of subjects 4, 5, 6, 7, and 8. The two skin temperature locations constitute a rough approximation of the true mean skin temperature.

Mean radiant temperature (t_{mrt}) was assumed to be 44.1 C (112 F); equal to the room air and wall temperature.

Thus, the rate of heat gained by radiation:

$$R = 5.95 \times 10^{-8} [101.11 \times 10^{8} - (t_s + 273)^4] \text{ kcal/hr.}$$

Convection

The rate of heat gained by convection (C_v):

$$C_v = A_{Du} \cdot h_c \cdot (t_a - t_s) \text{ kcal/hr}$$

where,

h_c = the convective heat transfer coefficient (kcal/m^2hr C)

t_a = the ambient air temperature (C)

The magnitude of the convective heat transfer coefficient (h_c) depends upon whether the heat transfer is by free convection or forced convection. Since the air velocity was less than 50 ft/min. (0.25 m/sec.), the heat transfer was by free convection so h_c was a function of the temperature difference ($t_a - t_s$):

$$h_c = 2.05 (t_a - t_s)^{0.25} \text{ kcal/m}^2\text{hr.C.}$$

Thus, the rate of heat gained by convection:

$$C_v = 3.81\ (44.1 - t_s)^{1.25}\ \text{kcal/hr.}$$

Evaporation

The true amount of the rate of heat transfer from the body by evaporation of sweat from the skin surface (E) is unknown.

The maximum capacity that the ambient air has for accepting water vapor from the subject's skin is designated as E_{max} (Hertig and Belding, 1963). Knowing that the environment could accept a limited, known quantity of water vapor, a judgement was made of the amount contributed by evaporation of sweat from the subject.

In this experiment, the subject's ability to lose heat was severely restricted. That is, the sweat rate was much greater than the rate of evaporation of sweat, as indicated by the pools of sweat left in the test room by each subject.

As stated by Hatch (1963), the rate of heat transfer by evaporation (E) is proportional to the area of the wetted surface, the air velocity over the surface, and the difference between the vapor pressure exerted by water at the surface temperature and the partial pressure of the ambient water vapor:

$$E = k_e \cdot V^n \cdot W \cdot A_{Du} \cdot (P_s - P_a).$$

When the fraction of wetted surface area (W) = 1.0, as was in this experiment:

$$E_{max} = K_e \cdot (P_s - P_a) \cdot (0.252 \text{ kcal/Btu}) \text{ kcal/hr.}$$

where,

E_{max} = the maximum rate of heat transfer from the body surface by evaporation of sweat that the ambient air can accept (kcal/hr.)

$K_e = k_e \cdot V^n \cdot A_{Du} = 4.0\ V^{0.6}$, an empirical expression of the evaporative heat transfer coefficient formulated by Hatch (1963) for a "standard man" of 154 lbs and 20.0 ft^2 of surface area with the air velocity (V) expressed in ft/min.

P_s = the vapor pressure of water at the skin surface (mm Hg)

P_a = the partial vapor pressure of the ambient air (mm Hg).

In the environment of 112 F dry bulb temperature, 98 F wet bulb temperature, the relative humidity (R.H.) of the air is 58% (Jennings, 1956).

The partial vapor pressure of the ambient air is the product of the relative humidity of the air and the saturation pressure of vapor at the dry bulb temperature of the ambient air. Therefore, since the saturation pressure of water vapor at 112 F is 1.5504 psi (Keenan and Keyes, 1936) or 23.5 mm Hg. the partial vapor pressure of the ambient air is 23.5/.58 = 40.5 mm Hg.

Thus, in the experimental environment with a maximum air velocity of 50 ft/min,

$$E_{max} = 4.0\ (50)^{0.6}\ (P_s - 40.5)(0.252) \text{ kcal/hr.}$$

or,

$$E_{max} = 10.5\ (P_s - 40.5) \text{ kcal/hr.}$$

E_{max} does not represent the true value of the rate of evaporative heat loss from the body, only the maximum value of the rate of evaporative heat which the ambient air can accept in the form of water vapor. In the environment with an ambient temperature greater than the body temperature some of the evaporation of sweat is done by heat transfer from the environment to the sweat. Thus, each gram of sweat evaporating from the body surface removes some heat from the body and some heat from the environment.

Because the test room was maintained at a constant 58% R.H., it was assumed that each subject had an individual E_{max}. That is, the maximum amount of water vapor which the environment could accept was not divided among the three subjects, the pools of sweat of each subject, and any other source of water vapor in the test room.

Therefore, 3/4 E_{max} was chosen to represent a rough estimate of the rate of evaporative heat loss from the body. Thus,

$$E_{est} = 3/4\ E_{max} = 7.87\ (P_s - 40.5)\ \text{kcal/hr.}$$

Conduction

The rate of heat extracted from the body by conduction (Cd):

$$Cd = \dot{m} \cdot c \cdot (t_o - t_i) \cdot (0.252\ \text{kcal/Btu})\ \text{kcal/hr.}$$

where

$\dot{m}$ = the mass flow rate of water through the hood = 264 lb/hr.

c = the specific heat of water = 1.0

t_o = the hood outlet water temperature (F)

t_i = the hood inlet water temperature (F)

Thus, the rate of heat extracted by conduction:

$$Cd = 66.53\ (t_o - t_i)\ \text{kcal/hr.}$$

The inlet and outlet water temperature values used were those representing the heat conducted only from the head. It was assumed that the water temperature differential due to the environment was constant (1.09 F for hood-C, 1.00 F for hood-D).

Substituting all of the derived terms into the general heat exchange equation gives:

$$111.60 + 5.95 \times 10^{-8}\ [101.11 \times 10^{8} - (t_s + 273)^4]$$
$$+ 3.81\ (44.1 - t_s)^{1.25} - 7.87\ (P_s - 40.5)$$
$$- 66.53\ (t_o - t_i) = S\ \text{kcal/hr.}$$

The values of the mean skin temperatures, water vapor pressures at the skin surface, and hood inlet and outlet water temperatures at the specified times for the three hood conditions were entered into the equation with the resulting values of rate of heat transfer between man and environment presented in Table 20.

Figures 11, 12, and 13 show the average effect of the individual components of the rate of heat storage with hood-C, hood-D, and no-hood respectively for subjects 4, 5, 6, 7 and 8. Figure 14 compares the average total rates of heat stored with hood-C, hood-D, and no-hood.

Neglecting the rate of heat transfer at t = 0, this analysis indicates

Table 20

Rate of Heat Transfer Between Man and Environment (kcal/hr)

		M	R	C_v	E	C_d	Total Rate (kcal/hr)	Accumulative Total Heat Stored (kcal)
	C	111.6	68.9	63.6	0	0	244.1	-
t=0	D	111.6	71.0	66.1	0	0	248.7	-
	NH	111.6	68.9	63.6	0	0	244.1	-
	C	111.6	49.3	41.1	-56.7	-62.4	82.9	20.7
t=15	D	111.6	48.6	40.3	-67.8	-40.1	92.6	23.2
	NH	111.6	47.8	39.6	-67.8	0	131.2	32.8
	C	111.6	47.1	38.8	-67.8	-61.3	68.4	37.8
t=30	D	111.6	47.8	39.6	-67.8	-38.8	92.4	46.3
	NH	111.6	47.1	38.8	-67.8	0	129.7	65.2
	C	111.6	47.8	39.6	-67.8	-66.1	65.1	54.1
t=45	D	111.6	45.0	36.5	-67.8	-44.8	80.5	66.4
	NH	111.6	42.1	33.6	-79.5	0	107.8	92.2
	C	111.6	47.8	39.6	-67.8	-81.2	50.0	66.6
t=60	D	111.6	45.0	36.5	-67.8	-55.4	69.9	83.9
	NH	111.6	41.4	32.8	-79.5	0	106.3	118.8
	C	111.6	47.1	38.8	-67.8	-81.2	48.5	73.9
t=69	D	111.6	42.1	33.6	-79.5	-56.8	51.0	91.6
	NH	111.6	40.7	32.1	-79.5	0	104.9	134.5

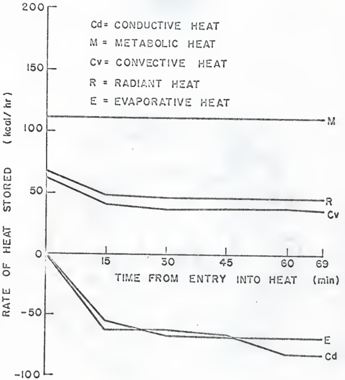

Figure 11. Average Effect of Individual Components of the Rate of Heat Storage With Hood-C.

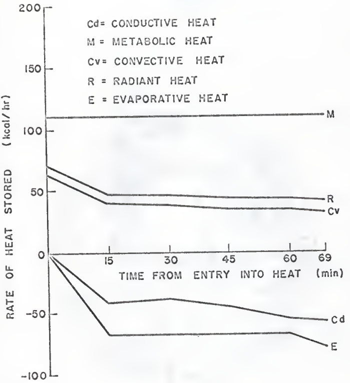

Figure 12. Average Effect of Individual Components of the Rate of Heat Storage With Hood-D.

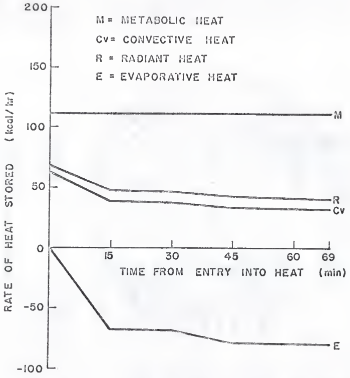

Figure 13: Average Effect of Individual Components of the Rate of Heat Storage With No-Hood.

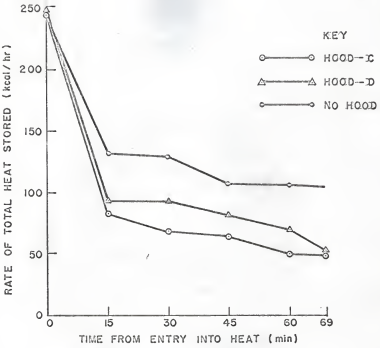

Figure 14. Average Total Rates of Heat Stored with Hood-C, Hood-D, and No-Hood.

that the average subject stored 73.9 kcal (293 Btu) with hood-C, 91.6 kcal (364 Btu) with hood-D, and 134.5 kcal (534 Btu) with no-hood.

So that some measure of the validity of these results could be made, the amount of heat stored by the subject was also estimated by the empirical expression for men in heat exposures presented by Webb (1969):

$$S = m \cdot c \cdot (0.8\Delta T_r + 0.2\Delta T_s)$$

where,

S = the stored heat (kcal)

m = the weight of the body (kg)

c = the specific heat of the human body = 0.83

ΔT_r = the change in rectal temperature (C)

ΔT_s = the change in mean skin surface temperature (C).

The average change in rectal temperature (ΔT_r) was 1.3 F (0.72 C) for hood-C, 1.4 F (0.78 C) for hood-D, and 2.1 F (1.17 C) for no-hood. The average change in mean skin temperature (ΔT_s) was 5.4 F (3.0 C) for hood-C, 5.7 F (3.17 C) for hood-D, and 6.6 F (3.67 C) for no-hood. For these values and the average weight of 159 lb (72 kg) of the five subjects, the estimate of the heat stored in the body was 70.6 kcal (280 Btu) for hood-C, 75.1 kcal (298 Btu) for hood-D, and 99.8 kcal (396 Btu) for no-hood.

From the comparison of the two estimates, it is seen that the more complicated method ($S = M+R+Cv-E-Cd$) yields a value 4% greater than the simpler method ($S = m \cdot c \cdot \Delta T$) for hood-C, 18% greater for hood-D, and 26%

greater for no-hood. Because the relationship between the two estimates is not constant for the three hood conditions the two methods of estimating the heat stored in the body do not seem to be compatible. The error may come from the many assumptions used or the crude technique in measuring the mean skin temperature or the empirical coefficients used for weighting the change in rectal temperature and mean skin temperature. Possibly the fraction of E_{max} that removes heat from the body changes for different hood conditions.

With the assumption that 3/4 E_{max} was evaporated from the subject, and that every evaporated gram of sweat removed 0.58 kcal (2.3 Btu), an index of the utilization of sweat was calculated. The utilization of sweat (U) expressed as a percentage indicates what benefit the subject received from the sweat he produced:

$$U = \frac{E_{est} = 3/4\ E_{max}\ (\text{gm/hr.})}{\text{Actual Sweat Loss (gm/hr)}} \times 100\ (\%)$$

The utilization (U) was 20% for hood-C and hood-D, and 15% for no-hood. Thus, with a cooling hood, for every 10 grams of sweat produced, 2 grams were evaporated from the skin surface. With no-hood, for every 10 grams of sweat produced, 1.5 grams were evaporated from the skin surface. Of the remainder, some sweat dripped off of the body and was left in the test room, and some remained on the body which was evaporated when the subject recovered in the pretest room environment.

DISCUSSION

The results of this research provide additional support to the feasibility of the cooling-hood system. Moreover, the designs of hood-C and hood-D appear to be significant improvements in the development of that system.

The fact that hood-C and hood-D were able to significantly reduce the rate of increase in rectal temperature indicates improvement over previous hood designs (see Table 21). Morales (1967) indicated that hood-A in an environment of 100 F (37.8 C) and 70% R.H. limited the average rate of change in rectal temperature for two subjects to 0.2 F/hr. (0.11 C). Without hood-A, the average rate of change was 0.7 F/hr. (0.39 C). Therefore, the rate of change was 0.5 F/hr (0.28 C) less with hood-A than without it. Konz and Nentwich (1969) indicated that in an environment of 107 F (41.7 C) and 70% R.H. (experiment two) there was no significant difference in rate of increase in rectal temperature between hood-A and the no-hood condition with two subjects tested at four different lengths of exposure time. The average rate of change with hood-A was 0.4 F/hr. (0.22 C); and without the hood, 0.5 F/hr (0.28 C) Therefore, the rate of change in rectal temperature was only 0.1 F/hr. (0.06 C) less with hood-A than without it in a thermal environment more stressful and with an activity level less strenuous than that of the initial evaluation. Gupta (1969) reported the inability of hood-B to significantly reduce the rate of increase in rectal temperature of eight sedentary subjects in an environment of 100 F (37.8 C) and 70% R.H.

TABLE 21

Summary Comparison of Hood-A, Hood-B, Hood-C, and Hood-D

	Average change in rectal temp. (°F/hr.)		Average sweat loss (gms./hr./m^2)	
	With Hood	Without Hood	With Hood	Without Hood
Hood-A 100 F/70% R.H. 2 subjects 3 to 5 kcal/min 4 hr.	0.2	0.7	204	486
Hood-A 107 F/70% R.H. 2 subjects sedentary 34 to 88 min.	0.4	0.5	155	231
Hood-B 100 F/70% R.H. 8 subjects sedentary 2 hr.	0.5	0.7	98	148
Hood-C 112 F/58% R.H. 9 subjects sedentary 75 min.	1.0	1.7	300	472
Hood-D 112 F/58% R.H. 9 subjects sedentary 75 min.	1.1	1.7	319	472

The average rate of increase in rectal temperature with hood-B was 0.5 F/hr. (0.28 C), and without it 0.7 F/hr. (0.39 C). Thus, hood-B decreased the average rate of change 0.2 F/hr. (0.11 C). The average rate of change in rectal temperature with hood-C was 1.0 F/hr. (0.56 C); and without it, 1.7 F/hr. (0.95 C). Thus, hood-C reduced the rate of increase 0.7 F/hr. (0.39 C). The rate of change in rectal temperature with hood-D was 1.1 F/hr. (0.61 C); and without it, 1.7 F/hr. (0.95 C). Therefore, hood-D reduced the rate of increase 0.6 F/hr. (0.33 C). Although the thermal environment was more stressful than any of the others, both hood-C and hood-D were able to produce greater differentials in the rate of change in rectal temperature between the hood and no-hood conditions.

Likewise, both hood-C and hood-D were more effective than previous hood designs in reducing sweat loss (see Table 21). For two sedentary subjects in a 107 F (41.7 C), 70% R.H. environment, hood-A decreased the average sweat loss 76 grams/hr./m^2 (Konz and Nentwich, 1969). When evaluated on two subjects at metabolic rates between 3 to 5 kcal./min. in an environment of 100 F, (37.8 C), 70% R.H., hood-A decreased the average sweat loss 282 gms./hr/m^2 from the sweat loss without the hood (Morales and Konz, 1968). The average sweat loss of eight sedentary subjects in a 100 F (37.8 C), 70% R.H. environment was reduced 50 gms./hr./m^2 with hood-B (Gupta, 1969). The difference in average sweat loss between hood-C and no-hood was 172 gms./hr./m^2; and between hood-D and no-hood, 153 gms./hr./m^2. Both hood-C and hood-D were more effective than the previous hoods when compared at the same activity level. Because the activity level may effect the amount of heat extracted by the cooling-hood, hood-C and hood-D should be evaluated at higher activity levels and less stressful thermal environments.

The ability of hood-C and hood-D to reduce the physiological demands of increased heart rate and skin temperature supports the conclusions of Morales and Konz (1968), Gupta (1969), Konz and Gupta (1969), and Konz and Nentwich (1969). The pre-exposure decrease in rectal temperature that was reported by Gupta (1969) was also observed in this research. It is believed that this decrease cannot be attributed to a physiological response to the environment because of the 85 to 90 F ambient temperature of the pre-test room; therefore the response probably is psychological. The decrement in task performance observed is in agreement with that reported by Konz and Nentwich (1969).

It was somewhat surprising to see little difference between hood-C and hood-D with respect to the results in the physiological criteria of heart rate, sweat rate, change in rectal temperature, and change in neck temperature. It was thought that hood-C which had more tubing of thinner wall thickness and closer skin contact, would provide evidence to conclude that its virtues were best. Such was not the case. Only for rate of change of brow temperature was it evident that hood-C's design of higher concentration of thinner-walled tubing and closer skin contact could be a better design than that of hood-D's. However, the measurement of heat extraction rate clearly shows the superiority of hood-C over hood-D.

These results are encouraging for they may be interpreted as meaning that the human body when in a hot, humid environment, is not particular of the mechanical design of a cooling system, but only asks that some cooling be provided.

Another encouraging finding of this research was that the cooling-hood system is effective even when using tap water. This eliminates, in most instances, the need for costly pumping and refrigeration equipment, and, therefore, provides an economical, versatile, and reliable individual cooling system available to any industry.

SUMMARY AND CONCLUSIONS

The effectiveness of hood-C and hood-D in reducing the physiological strain of nine male subjects while in a heat stress environment (112 F dry bulb, 98 F wet bulb, still air) was investigated.

The subjects were sedentary and did addition problems for 25 minutes in a pretest room environment (85 to 90 F, 50% R.H.) and for 50 of a 75 minute exposure in the heat stress environment. Each subject had three exposures to the heat environment; once while wearing hood-C, once with hood-D, and once with no-hood.

It was concluded that:

1. The extra heart beats were less with hood-C than D, but not significantly so. Both hoods produced significantly lower extra heart beats than no-hood.
2. The sweat rate was less with hood-C than D, but not significantly so. Both hoods produced significantly lower sweat rates than no-hood.
3. The rate of change in rectal temperature was less with hood-C than D, but not significantly so. Both hoods produced significantly lower rates of change in rectal temperature than no-hood.

4. No statistically valid information of the rate of change in ear canal temperature was obtained because the temperature measuring device was not adequately insulated from the environment or located consistently in the ear canal.
5. The rate of change in brow temperature for hood-C was significantly less than hood-D, and both were significantly less than no-hood.
6. The rate of change in neck temperature was less for hood-D than C but not significantly so. Both hoods produced significantly lower rates of change in neck temperature than no-hood.
7. There was no significant difference in the rate of change in chest temperature or back temperature between the three hood conditions.
8. There was no significant difference in task productivity between the three hood conditions.
9. The heat extraction rate for hood-C was significantly higher than for hood-D. C removed 40% more heat.
10. Less heat was stored by subjects when wearing hood-C or hood-D than with no-hood.

These conclusions indicate that hood-C and hood-D are of value in reducing the physiological strains associated with exposure to a heat stress environment.

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A PHYSIOLOGICAL EVALUATION OF TWO DESIGNS OF A CONDUCTIVE COOLING HOOD

by

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ABSTRACT

Two conductive cooling-hoods, model-C and model-D, developed at Kansas State University are described and the results of their evaluation presented.

The hoods, with tap water (60 F)(15.6 C) circulating through them at 264 lb/hr. (120 kg), were evaluated in a heat stress environment of 112 F (44.1 C) 58% R.H. Each of nine male college-age subjects, wearing cotton shorts, participated in three days of evaluation which required them to wear "C" one day, "D" another day, and "no-hood" the remaining day. Heart rate, skin temperatures, ear canal temperature, sweat loss and rectal temperature were recorded for each subject during 30 min. in a neutral environment and 75 min. in the heat stress environment. The subjects did addition problems while seated (estimated metabolic rate of 60 kcal./hr./m^2).

When compared at the same activity level, both hood-C and hood-D were improvements over previous cooling-hoods; hood-C was slightly superior to hood-D. The average change from basal heart rate was 15 beats/min. for "C", 17 for "D", and 28 for "no-hood". The average sweat loss was 300 gms./hr./m^2 for "C", 319 for "D", and 472 for "no-hood". The decrement in task performance was -1.6 columns per min. with "C", -1.9 with "D", and -2.9 with "no-hood". The change in errors was 1.2% with "C", 0.1 with "D", and -0.4 with "no-hood".

A cooling-hood system using tap water was demonstrated to be feasible.