PHYSIOLOGICAL EVALUATION OF AN AIR COOLED HELMET SYSTEM

by 1254

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INTRODUCTION

High ambient temperatures may be found in certain locations in industry due to the heat generated by machinery or by some industrial process. When high ambient temperatures are accompanied by high humidity, climates may become so severe that men can not be expected to work in them for more than a short duration of time without running the risk of a heat collapse. In addition, in many chemical, atomic, metal and other industries, the environment may be dusty, toxic or radioactive. Under such circumstances, the problem of protecting workers from the environment becomes two-fold. They should be protected against heat and should also be provided with pure breathing air.

An air cooled helmet system to provide a dual protection to industrial workers working in hot, dusty, and contaminated atmospheres is discussed in this thesis. Various kinds of ventilated suit assemblies have been extensively used in aircraft and space craft to provide men with a cool and comfortable environment. The suits have always encased the whole body of the wearer. If used in an industrial situation, such a suit would limit the mobility of the worker. Several experiments at Kansas State University with water cooled hoods (Konz and Duncan, 1969) have demonstrated that head cooling can provide effective partial protection against heat stress. The idea of head cooling incorporated with ventilated air garments resulted in the development of the air-cooled helmet system. The physiological evaluation of this system is presented.

LITERATURE REVIEW

General

Heat is a stress to which most people are exposed at one time or another. It may be in the form of naturally occurring hot climates, or artificial hot climates resulting from some industrial process. The heat stress presented by these conditions takes the form of large heat gains by convection and radiation, or is due to the restriction imposed by the environment to the evaporation of sweat. Leithead and Lind (1964) define the heat stress of any working situation as the combination of all those factors, both climatic and nonclimatic, which lead to convective and radiant heat gains by the body or which limit or prevent the heat dissipation from the body. This results in heat strain. The heat strain depends upon many variables such as air temperature, humidity, air speed, radiant heat of the surroundings, rate of work, amount and type of clothing worn, whether or not the individual is acclimatized, etc.

Heat Balance for Body

The processes that constitute life in an animal cell are, in net, exothermic. The food elements in the body, that is protein, fat, and carbohydrates, are broken down by oxidation into waste products such as carbon dioxide, water, and urea with the release of heat. At the same time there is a constant exchange of heat between the body and the environment by convection, radiation, conduction, and evaporation. The evaporation heat loss from the body comprises the heat lost by the evaporation of sweat from the surface of the skin, heat lost by water vapor diffusion through the skin and latent respiration heat loss. The heat balance for the body is given by (Drake et al., 1969):

$$Q_{metabolic} - Q_{work} - Q_{sensible} - Q_{latent} = Q_{stored}$$

where, $Q_{metabolic}$ is the heat generated by the oxidation of food elements, Q_{work} is the useful work output, $Q_{sensible}$ is the heat transfer by radiation, free and forced convection, and conduction, Q_{latent} is the evaporative heat loss, and Q_{stored} is the time rate of energy storage of body in the form of heat. Although heat storage of up to 600 Btu (150 kcal) (Webb, 1969) may be tolerated without a physical collapse, it should be essentially zero for normal steady state operating conditions.

In the normal environment, man may be exposed during the course of a day's activities to a wide range of ambient temperatures and, at the same time, may sustain considerable variation in metabolic rate, yet still maintain the heat balance of the body. The balance is achieved by the thermoregulatory system of the body, which maintains the internal temperature of the body at a certain level, called the 'set point', which is specific for an individual.

Thermoregulation

The proper balance between heat loss and heat gain is the responsibility of groups of nerve cells in the central nervous system termed 'the heat regulating centers' located in the basal portion of the forebrain, the hypothalmus. The hypothalmic centers receive their information about the thermal state of the body and its immediate environment through two channels, sensory nerves and the blood. Sensory nerves convey information mostly about the immediate thermal state of the skin; the blood, about the state of the body as a whole and particularly of deep structures (Lee, 1964).

Blood is the primary medium of heat transfer throughout the body. The skin abounds in arteriovenous anastomoses, which are formed where arteries and veins make direct connection with each other without the benefit of normal capillary connections (Grollman, 1964). The venous portion of each anastomosis is funnel shaped while the arterial portion is coiled into a ball like structure. The middle portion, which is the most contractile part of the entire structure, possesses a thick muscular wall (Grollman, 1964).

The hypothalmic control center consists of two parts. One part, the anti-rise center, is stimulated by an increase in temperature of the blood and transmits impulses to anastomoses, causing the muscular portion to dilate resulting in increased blood flow to the skin. In addition, impulses are sent to sweat glands, increasing perspiration, and to the respiratory center, causing panting. All these responses cause the rate of heat loss from the b[illegible] to increase. The antidrop center of the hypothalmus is stimulated when the blood temperature falls. Nerve impulses generated by this center cause the muscular portion of the anatomoses to constrict, thereby reducing the blood flow; at the same time surface hairs are stimulated to become erect, which acts to increase the insulating layer of the air surrounding the skin. Shivering is induced to increase heat production (Grollman, 1964).

The second mode of control by the hypothalmic centers is through the endoctrine system. Nerve fibres run from the hypothalmic centers to the adjacent anterior pituitary gland, which secretes a variety of hormones into the blood stream, and these in turn control the operation of other ductless glands such as the thyroid and adrenal cortex. Under cool conditions, some of the nerve impulses streaming from the hypothalmic anti-drop center go to the adrenal medulla and regulate its secretion of epinephrine, which participates in constriction of skin blood vessels. (Lee, 1964) As a result of negative water balance after exposure to heat, antidiuretic activity is detected in urine. (Hellman and Weiner, 1953) This is because of the increased release of antidiuretic hormone from the pituitary—probably due to increase in osmotic pressure in the plasma, or the decrease in circulating blood volume (Leithead & Lind, 1964). The effect of ADH is to reduce the output of urine by reabsorption of water in the renal tubules.

The body is under vasomotor regulation when the environmental temperature is in the range of 82.4 to 86 F (28 to 30 C) (Hardy and Soderstorm, 1938). In this range there is no sensible sweating. When the air temperature rises above 86 F (30 C), the body enters the zone of evaporative regulation and the cooling effect is obtained only by the evaporation of sweat. Two types of sweat glands populate the skin. Apocrine glands occur in the axilla, the mons pubis, the external auditory meatus, the eyelids, the circumanal area, the aureola and nipple of the breast and the labia minora of the female, and in the prepuce and scrotum of the male (Montagna, 1962). Their function is not thermoregulatory; Kuno (1956) considers that these glands serve some sexual function. The function of eccrine glands is primarily thermoregulatory and they are all over the surface of the body. Man has 2 to 5 million glands over the surface of the body with an average distribution ranging from 193 to 339 per square centimeter. Only the lips, the glans penis, the inner surface of prepuce, the clitoris, and the labia minora are free of eccrine glands (Montagna, 1962).

The sweat gland is developed from a narrow epidermal invagination which descends deeply into the dermis in the form of a tube. When it reaches a certain depth its downward growth ceases, and it lengthens by coiling upon itself. The duct is lined by one or two layers of cells, the coil by one layer. The duct is attached to epidermis at the tip of a rete peg and traverses the epidermis in a corkscrew fashion. The secretion of the eccrine sweat glands is clear aqueous solution, pH 4.0 to 6.0, in which the sodium, potassium, calcium, magnesium, and chloride ions are the major inorganic components (Percival, 1967).

The rate of sweating increases in proportion to increments in the environmental heat stress and with metabolic rate in work. Of all the substances to be found in the sweat, water and sodium chloride are the principle ones whose loss may affect homeostasis, particularly if they are not replaced before extensive depletion (Robinson & Robinson, 1954). Dehydration disturbs both tonicity and volumes of body fluid compartments, impairing circulation and thus impeding heat dissipation from the body (Pitts et al., 1944). Salt depletion results in reduced tonicy of body fluids with consequent reduction in extracellular fluid volume. Symptoms of nausea, fatigue, headache, and tachycardia may occur as a result of salt depletion (McCance, 1938; Keutman, et al., 1939; Taylor et al., 1943; Pitts et al., 1944).

Effects of Heat

Heat stress affects physiological and psychological efficiency of a man and, if too severe, poses hazards to health and even to life.

Psychological Effects

It is generally believed that heat causes a reduction in efficiency of an industrial worker. Evidence in support of this belief comes from the series of experiments conducted for the Industrial and Fatigue Research Board, London. Leithead and Lind (1964) have reported extensively the investigations carried out both in laboratories and in real industrial situations relating performance to warmth of atmospheres. They cite studies made by Wyndham, Strydom, Cooke, and Maritz (1959) on acclimatized mining recruits engaged in filling mining cars with rock in saturated environments ranging from 81 to 96 F (27.2 to 35.6 C). The rate of filling the cars dropped by 4% as the temperature rose from 81 F (27.2 C) to 84 F (28.9 C), but it declined 50% as the temperature was increased to 93 F (33.9 C). Increasing the air velocity from 100 to 800 fpm (0.5 to 4.0 m./sec.) did not increase the output at low temperatures but at temperatures above 90 F (32.2 C), there was a large increase in the work output, which presumably was caused by increased heat loss by evaporation.

Leithead & Lind (1964) also have reported the work of Weston (1922), Wyatt et al. (1926), and Vernon et al. (1927, 1928, 1931). Weston and Wyatt reported that the output declined in cotton weaving industry at wet bulb temperatures above 70 to 73 F (21.1 to 22.8 F). Vernon et al. reported that in a two year survey of ten British collieries, the accident rates in hot seams were substantially higher than in cooler seams.

Wing (1965) assessed fourteen experiments done in various laboratories and found that for men exposed to thermal stress, mental performance deteriorates well before physiological limits have been reached. These experiments established the threshold temperatures above which significant impairment of performance would occur for one, two, three, and four hour exposures. Four studies were evaluated on one-hour exposures. Tasks used in these experiments were estimation of collision courses of airplane-silhouettes, comparison of symbols, short-term memory for lists of English words, and number checking and mental addition. The one hour threshold was placed above an effective temperature of 90 F (32.2 C). In two, two-hour exposure studies, ability of the subjects to locate faults in electrical circuits, and their performance on mental multiplication of numbers under seventeen, were tested. The two-hour exposure limit was established as an effective temperature of 89 F (31.7 C). Three experiments on three-hour exposures using problem solving and reception of telegraphic messages were assessed and the threshold was placed at an effective temperature of 87.5 F (31 C). Only one study with a four-hour exposure was available. A number of tests such as mental multiplication were administered to the subjects and a statistically reliable drop in the number of completed multiplications was found at an effective temperature of 87 F (30.6 C). On reviewing the results of these studies, the lowest test temperatures yielding statistically reliable decrements in mental performance were found to decline exponentially as exposure durations were increased to four hours. See Fig. 1. This curve was compared with 'recommended' tolerance limit curve (determined by Lovelace and Gage, 1946 and reported by Connel, 1948) and with the curve representing 'marginal' conditions in which collapse is imminent (determined by Taylor, reported by Connel, 1948). The performance curve lay below both the tolerance curves at every point.

While there is, generally, a degradation in human performance under high thermal stress, there may be, due to arousal, a facilitation in performance of activities requiring minimal information processing and involving simple motor reactions. Slight to moderate amounts of environmental stress produce alertness which facilitates performance. On the other hand, benefits due to arousal may be completely lost if there is information overloading or distraction. Fox, Goldsmith, Hampton, and Wilkinson (1963) found that body temperatures of 102 F (38.8 C) would produce a state of arousal leading to improvement in performance of an auditory vigilance task. Poulton and Kerslake (1965) suggest that there are a series of changes in the arousal level as the man enters the heat stress. As the man enters the heat stress, there is an increase in the arousal level until his rectal temperature begins to rise, at which

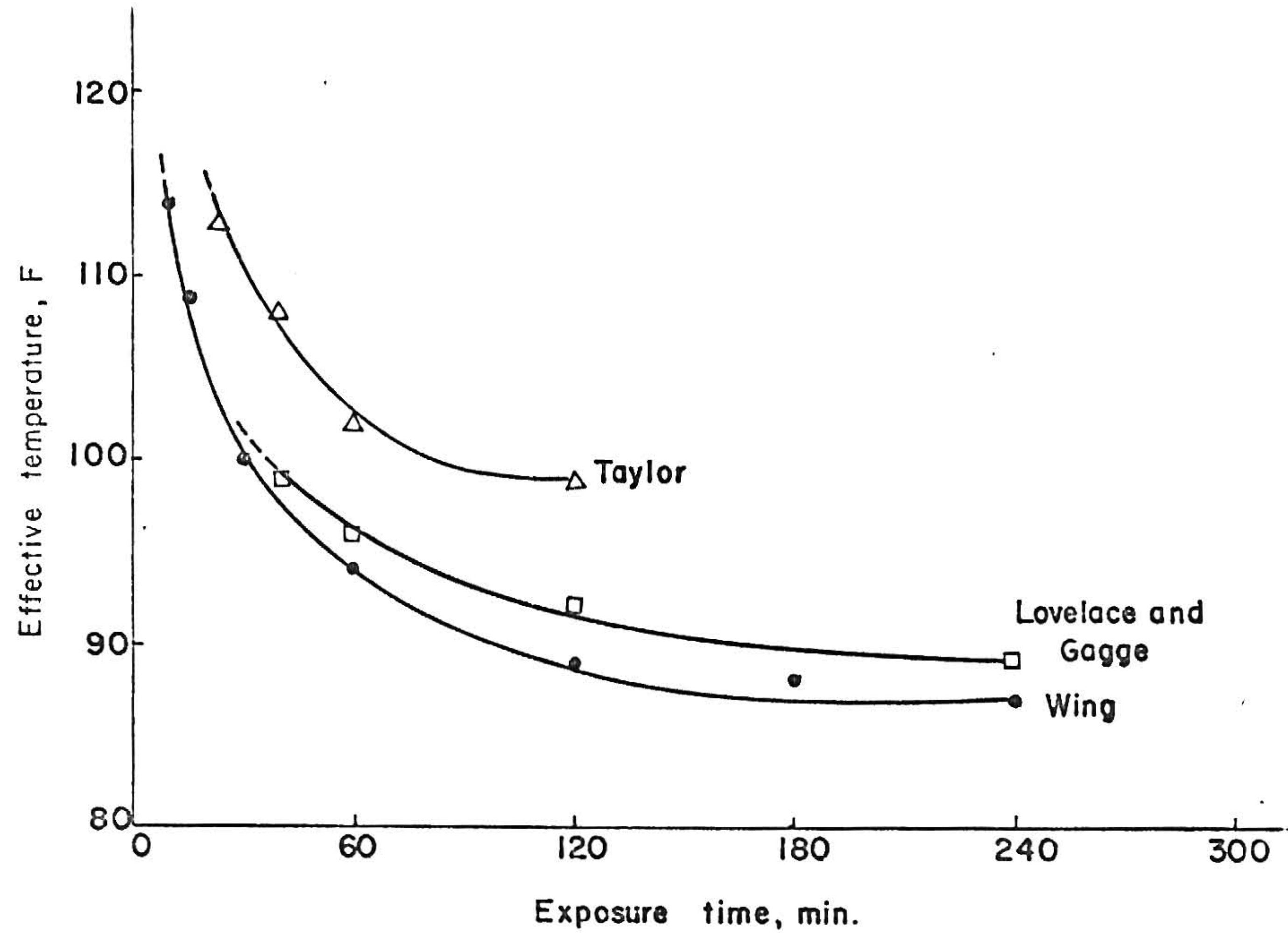

Fig.1. Comparison of the thermal tolerance limit for unimpaired mental performance proposed by Wing with the recommended physiological limit (Lovelace and Gogge) and the marginal physiological limit.

point the arousal level falls below normal. As the body temperature rises further, the arousal level rises back to normal again. Finally all performances deteriorate as the temperature increases further. The improvement and deterioration in the performance would, therefore, depend upon the state in which the person is in, with respect to arousal level.

Riley and Parker (1968) studied the affect of heat stress on 14 basic dimensions of perceptual-motor-performance such as arm-hand steadiness, wrist-finger speed, finger dexterity, manual dexterity, position estimation, control precision etc; 18 subjects were used in the study. The effective temperature was 86 F (30 C) and the exposure time was 6 hours. Only two of the tests showed degradation in performance and six showed facilitation. No statistical difference was observed in the remainder. The facilitation was explained in terms of alertness due to arousal. The mean oral temperature of their subjects during the stress was 101.2 F (38.4 C) and the pulse rate was 111 beats/min. which was interpreted as an above normal level of arousal. The degradation was observed on those tasks which were fairly complicated and involved some information acquisition.

Reducing Heat Stress

The typical approach towards reducing the heat stress in industrial situations has been to cool the environment in which a person is working. But there are many situations in which it is not feasible to cool the environment either due to economic reasons or due to process limitations. For example, in mines, at great depths where the high temperatures are accompanied with almost saturated air it is impossible to provide airconditioning; in the cotton industry, warm and moist atmospheres are maintained as these conditions are most suitable for cotton weaving; in heat treatment shops, rolling mills, boiler areas, people have to work under high radiant and convective heat loads. Numerous other examples may be found in steel, glass, rubber, or other industries where it is not possible to cool the working area.

Under such circumstances when the methods of altering the macro-environment fail, the man should be provided with a suitable artificial microenvironment around him which limits radiative and convective heat gains, providing at the same time some means of removing metabolic heat and that heat which enters the body through such an arrangement.

In the past few years, extensive research has been done to develop highly sophisticated extravehicular space activity suits due to the high thermal hazards present. These suits are highly efficient and are capable of isolating the wearer completely from the outside environment, but, for several reasons are not suitable for industrial applications. Firstly, an industrial situation usually does not present such a high thermal load; secondly, the cost of these suits is prohibitive; and thirdly, they seriously limit the mobility of the wearer. In spite of the fact that these suits are unsuitable for use in industry, they do provide an excellent base for the development of simpler and inexpensive suits or garments for industrial applications. Their principle and performance should therefore be looked into.

In terms of suit design for conditions of variable metabolic rate, one has the option to take advantage of cooling afforded by the evaporation of sweat or not to. In general, in water cooled garments essestially no sweating is obtained, while in air cooled garments, most of the cooling is obtained by evaporation of sweat. There are hybrid suits using both the liquid cooling and ventilation cooling feature; however, ventilation requirements are established primarily by the need to remove the water that diffuses through the skin from deep body tissues (Funk et al., 1966). In general, four principle suit concepts are used in the present day space programs (NASA, 1965). These are:

1. Ventilation cooling
2. Liquid loop cooling
3. Radiation cooling (conduction from body)
4. Radiation cooling (radiation from body).

The ventilation cooling approach is an extension of aircraft full pressure suit design and involves the use of a ventilating gas flow passed over the surface of the body; it utilizes the thermoregulatory mechanisms of the body for thermal control. Specifically, heat dissipation from the body is regulated by means of thermoregulatory control of the sweat mechanism. This method is satisfactory for relatively low metabolic rates and for total heat removal rates up to 1300 Btu/hr. (325 kcal) for ventilating gas flow rates up to 15 cfm at 3.7 psia (2.57 kg./cm^2.) (NASA, 1965). The Gemini suit used gas cooling where the system was expected to handle 600 to 1200 Btu/hr.

(150 to 300 kcal) (Nelson et al., 1964; Hedge, 1968). Also the gas cooling loops in Mercury projects were intended to carry away metabolic heat at levels of 720 to 1200 Btu/hr. (180 to 300 kcal) (Webb and Annis, 1967). With higher heat loads, the high rates of gas circulation required imply large pressure drops and, therefore, high blower power requirements (Hedge, 1968). Another disadvantage of ventilating garments at high metabolic rates is that for sizable heat removal a high continuous sweat rate must be maintained which is uncomfortable to the unacclimatized wearer and may approach the limits of tolerance and safety (Burton, 1969).

If the ventilating gas is supplied at a temperature lower than that of skin, in addition to evaporative heat loss, heat transfer between the gas and the man's skin will take place by forced convection also. The convective heat transfer is a function of air velocity (Fanger et al., 1968) and the evaporative heat loss is a function of water vapor partial pressure, the total pressure and the molecular weight of the ventilating gas (NASA, 1965).

With the liquid loop cooling method, the heat is removed from the body by conduction to tubes containing a heat transport fluid. The liquid cooled garments, in general, consist of a net fabric interwoven with small diameter (e.g. 1/8 in. (3.18 mm.) I.D.) plastic tubing. The tube is contiguous to the subject's skin so that heat is transferred primarily by conduction to the liquid flowing through the tubes. The heat removal is primarily a function of liquid temperature and tube length in contact with the skin. This type of thermal garment is capable of removing heat loads in excess of 2400 Btu/hr. (600 kcal) thus preventing active sweating of the skin (Richardson, 1969). Another method of conduction cooling is the evaporation of recycled water from wicks in contact with the skin. This scheme consists of a series of internal heat exchangers that condense water from the ventilating gas stream and return the condensate counter-current to the ventilating flow (by means of wicks) for evaporation. The reevaporative method may offer advantage over the conventional conduction cooling method with respect to control simplicity, flexibility in handling varying heat loads, and ability to provide emergency cooling (NASA, 1965).

Radiation cooling is possible in two ways. In the first case, cooling is done by conduction of heat from the body through the suit wall which is tightly in contact with the skin, to the outer surface, where it is rejected by radiation to the environment. An extravehicular suit designed for passive thermal control would have thermal properties tailored for the purpose. The second approach is to provide a gas space between the skin and the suit inner wall. For low gas velocities, the body would be cooled primarily by radiation to the inner wall of the suit, conduction through the wall, and radiation from the outer wall to the environment. Introduction of the air gap, however, reduces the heat loss from the extravehicular suit (NASA, 1965).

An air gap can also be introduced between the skin and the liquid cooled garment. The heat removal will then depend upon the radiation of heat from the skin to the coolant tube walls. This system, although less efficient, results in the reduction in size and weight of the portable environmental control system. For example, assuming an average design heat rejection rate of 1500 Btu/hr. (375 kcal), approximately 50 percent of the heat sink can be provided by radiation (in earth orbit), thereby effecting an evaporant saving of 0.72 lb/hr. (0.33 kg.) of operation and a fixed weight saving of 4 to 7 lbs. (1.81 to 3.18 kg.) (NASA, 1965).

Both liquid cooled and ventilated garments have advantages and disadvantages over each other. While ventilated garments prove inefficient for high thermal loads, the liquid cooled garments can not remove moisture, and temperature control can be considered to be a major problem area in the application of conduction cooling methods, as they provide constant heat removal and are not subject to thermoregulatory control.

For an industrial worker, the heat load is primarily from metabolism, convection, and radiation. The metabolic rate corresponding to moderate work (machinist) is 800 Btu/hr. (202 kcal) (Konz and Duncan, 1969). The convective heat is (Fanger, 1967):

$$C = A_{du} \cdot f_{cl} \cdot h_c \, (t_{cl} - t_a),$$

and the radiation heat is (Fanger, 1967):

$$R = A_{du} \cdot f_{eff} \cdot f_{cl} \cdot \varepsilon \cdot \sigma \cdot (T_{cl}^4 - T_{mrt}^4)$$

where,

C = the convective heat loss or gain, kcal/hr.

R = the radiation heat loss or gain, kcal/hr.

A_{du} = DuBois body area, m^2.

f_{cl} = the ratio of the surface area of the clothed body to the nude body

h_c = the convective heat transfer coefficient, kcal/m^2/hr./C

= $10.4\sqrt{v}$, where v = air velocity, m./sec.

t_{cl} = the clothing temperature, C

t_a = the air temperature, C

f_{eff} = the effective radiation area of the clothed body, m^2.

ε = the emissivity of the outer surface of the clothed body

σ = the Stephan Boltzman constant

T_{cl} = the clothing temperature, K

T_{mrt} = the mean radiant temperature, K.

Using the above equations, the convective and radiative heat loads for various ambient temperatures were calculated by Konz and Duncan (1969). Their results are presented in Table 1, which shows that, for most industrial situations, the convective and radiative heat loads are small. Konz and Duncan (1969) state that unless there is a high temperature radiation source, the heat load is primarily metabolic and is generally below 1000 Btu/hr. (250 kcal). If a local high temperature area source of radiation is present, Konz and Duncan state, radiation shields, fans, shorter exposure times, reflective clothing etc., also must be employed.

Since most of the industrial situations do not represent a very high thermal load, it appears that gas cooling technique can be satisfactorily applied in industry. A major advantage of using gas cooling methods is that compressed air, which may be used for cooling purposes,

Table 1

Convective and Radiant Heat Loads under Different Ambient Temperatures

Ambient/Mean Radiant Temperature, F*	Heat Gained (Btu/hr.) by Convection	Radiation
76	-1150	-406
90	- 420	-164
100	50	19
110	490	212
150	2400	1095

*Mean radiant temperature assumed equal to ambient temperature is readily available in almost any type of industry and therefore little initial investment will be needed. Air cooling can be particularly advantageous where one has to work in dusty, contaminated, or toxic atmospheres which may cause several respiratory diseases like pneumonoconiosis, emphysema, and chronic bronchitis.

Air of proper temperature blown under clothing near the skin can protect an individual against high, low or changing temperatures. The ambient atmosphere is thus replaced by an individual environment. Some research has been done on the applications of air cooling in industry and in armed forces. Fetcher et al., (1949) have cited the work of Houghten et al. (1941) (who reported increased comfort and efficiency of workers when a simple ventilating coverall was worn), of the Armored Medical Research Laboratory (1943, 1945) (where ventilating garments were designed for use in tanks), and of Marbarger (1945) (who reported an extensive series of tests of several ventilating garments at the Aero-Medical Laboratory; these tests were made to select a suit, air flow and temperature for men doing moderate work for limited periods at 165 F (74 C) in the Climatic Hangar of the Air Proving Ground Command).

Crockford et al. (1963) tested an air ventilated suit for use in very hot environments. The suit assembly comprised of two special garments: (a) an undergarment, made of a double layer of plastic film, the two layers separated by a loose plastic 'space filler'. The purpose of this garment was to distribute the ventilating air over a large area of skin, and the garment covered the trunk and the legs; (b) an outer garment made of impermeable but pliable plastic material with an attached cylindrical helmet made of a double layer of clear plastic with an intervening air space. A quilted layer of foam-plastic 0.204 inches (5 mm.) thick, to act as an insulating barrier to heat, was contained in the outer garment. Long string pants were worn beneath the ventilating undergarment to ensure a proper distribution of air over legs.

The volume of the supplied air was varied between 10 to 25 cfm (0.28 to 0.71 m^3/sec.) and the temperature of the air was controlled, to ± 0.9 F (0.5 C), between 86 and 100 F (30 and 37.8 C) as it entered the assembly. The hot chamber temperature was between 173 to 180 F (78 to 82 C). The humidity in the chamber was kept low. Air at different combinations of temperature and volume was supplied to 15 subjects during the one hour exposure. All the subjects reached thermal equilibrium, as judged by their oral temperatures and pulse rates, at the ventilating volume of 15 cfm, irrespective of the air temperature. When 25 cfm (0.71 m^3/sec.) of air was supplied to the suit at 86 F (30 C), one subject satisfactorily maintained thermal equilibrium for two hours.

The physiological effectiveness of a vortex tube cooling system was studied by Lienhard et al. (1964). The equipment worn by the subject under study consisted of a vortex tube, an air harness of perforated, flexible, and non-collapsible plastic tubing worn over the upper trunk and under the ordinary work clothing, and an insulated air supplied fabric hood and vest. The air was supplied by the vortex tube at temperatures between 65 to 80 F (18.3 to 26.6 C) and at a flow rate of 20 cfm

(0.56 $m.^3$/sec.). The test subject, a well acclimatized workman, raised and lowered a 50 lb. (22.7 kg.) weight every five seconds in an environment of 130 to 136 F (54.4 to 57.7 C) and 15 to 20% RH. The subject was exposed with and without vortex tube cooling.

During 22.3 min. of work without cooling, a total of 3430 heart beats were recorded. While performing the same work but with cooling, only 2579 heart beats were recorded. The saving in the heart beat cost amounted to 851 beats or 25% when the vortex tube cooling was used. When not cooled, the heart rate rose rapidly to 185 beats/min. after only 20 min. of work and the test was discontinued due to nausea after 22.3 min. of work. When cooled, the subject completed 40 min. of work without any symptoms of heat illness, and the peak heart rate did not exceed 160 beats/min.

The rate of increase of the body temperature was significantly less when the vortex tube cooling was used. During the 35.3 min. of exposure (22.3 min. of work and 13 min. of rest), the rectal temperature rose 3.7 F (2 C) without cooling, but only 1.6 F (0.9 C) with cooling. The volume of sweat lost was reduced threefold when the vortex tube cooling was used.

Crockford and Hellon (1964) have reported some experiments to determine a suitable form of insulation for a hot entry suit for use in furnace wrecking where mean radiant temperatures as high as 392 F (200 C) are found and where heat reflecting garments are unsuitable due to rapid deterioration of the reflecting surface. Three methods of insulating the suit were used: (1) a uniform layer of high thermal resistance (2) an internal layer of material to reflect radiant heat, that is, a radiant heat barrier, and (3) dynamic insulation. Dynamic insulation results as air flows out through a permeable suit (radial ventilation) rather than parallel to the body surface (axial ventilation), as in a conventional ventilation suit. These forms of insulation were tested in a heat flow model to assess their suitability for use in a ventilated garment. It was concluded, from these model experiments, that the application of a form of dynamic insulation in a ventilated suit may be the most efficient method of insulation. A radiant heat barrier had only a slightly lower thermal conductance than the foam plastic insulation. Conductance of foam plastic decreased five-fold when it was ventilated with 2.3 cfm/ft^2. (0.7 m.^{3}/min./m.^{2}) of air. Different insulating systems were then made up as suits and were evaluated physiologically under laboratory conditions.

The suit incorporating a radiant heat barrier was to be found very heavy, and on this count it was discarded as a possibility for use in a real world situation. The two suits which were tested were: (1) a permeable suit made from 0.408 in. (1 cm.) thick polyurethane foamed plastic bounded on each side by a layer of cotton fabric; (2) an impermeable suit made from 0.408 in. (1 cm.) thick polyurethane foamed plastic bounded on each side by impermeable neoprene-proofed terylene. The suits were supplied with 45 cfm (1.27 m.^{3}/sec.) of air at a temperature of 7.16 to 73.4 F (22 to 23 C). The radiant heat chamber had a mean radiant temperature of 374 F (190 C) and an air temperature of 122 F (50 C). Five subjects were used in the test who performed a step task and their energy expenditure was estimated to be 1080 Btu/hr. (270 kcal).

The rise in oral temperature and sweat rate were lowest in the permeable suit. On average, the rate of rise in oral temperature was halved by wearing a permeable suit and sweat rate in this suit was only two-thirds of that in the impermeable garment. However, thermal equilibrium was not achieved in either of the suits.

Veghte (1965) tested three different air ventilating systems and one water cooling system when used under a full pressure suit. It was felt that various cooling systems may perform well under antiexposure suits and other loose fitting garments but may not be suitable when worn under partial or full pressure suits because of constriction by the outer garment. The three air ventilating systems were: (1) a separate tubular system ducting air to various body areas through small plastic tubes; (2) the integral air distributing system of the full pressure suit which simply dumped the air at each extremity to flow back to central exit; and (3) the separate USAF MA-1 ventilating garment (USAF-1). In addition, a modification of USAF-1 was used in which air was forced to travel further under the garment to the central exit by closing the exit holes. Tests were made with the outer pressure suit pressurized at 7.5 in. (192 mm.) of Hg., and unpressurized. Ventilating air at 69.8 F (21 C) was supplied from a commercial air conditioner at 5 cfm (0.14 $m.^3$/sec.). Water at 69.8 F (21 C) was supplied to the water cooled suit at a flow rate of 2.2 lbs./min. (1 kg.).

Five sitting, resting subjects were exposed to an environment of 109.4 F (43 C) with each of these suits with the pressure suit pressurized and unpressurized. In the control tests, the pressure suit was worn without any ventilation. The experimental duration was two hours, or when rectal temperature crossed 102.2 F (39 C) or pulse rate 140 beats/min., in the control experiments.

Tolerance times in the control, non-ventilated exposures varied from 60 to 95 minutes with little difference between the pressurized and unpressurized conditions. Heart rates were under 100 beats/min. in the uninflated air ventilated experiments and below 110 beats/min. in the pressurized air ventilated experiments. Heart rates in the water cooled experiments remained near basal conditions and varied from 110 to 140 beats/min. in the control experiments. Among all the ventilated suits, the rectal temperatures and skin temperatures were lowest in the tubular suit. During the two hour exposure with the tubular suit, the rectal and skin temperatures rose 0.18 F (0.1 C) and 3.6 F (2.0 C) respectively, with the outer suit unpressurized, as against 2.5 F (1.4 C) and 8.1 F (4.5 C) in the control. Sweat loss during the two hour exposure with the tubular suit (unpressurized) was 1.06 lbs. (483 gms.) as against 1.25 lbs. (606 gms.) in the control. With the outer garment pressurized, these values were a little higher. The separate tubular air ventilating garment was superior in evaporative cooling efficiency to the other air ventilating systems. The water cooled system was, however, superior to all air evaporative systems. There was a marked reduction in the evaporative effectiveness of these distribution systems with pressurization.

In a recent study, Van Pattern and Gaudeo (1968) made use of a vortex tube to supply cold air to the cooling garment. Three subjects were exposed to 130 F (54.5 C), 44% RH environment with and without vortex tube cooling. The cooling garment used was a standard MA-3 USAF cooling garment, which was supplied with 10 cfm (0.28 $m.^3$/sec.) of air at 63 F (17.5 C) dry bulb and 37% RH. A compressor supplied air to the vortex tube at 60 $lbs./in.^2$ (42 $kg./m.^2$). In the control session (no cooling), subjects were exposed for durations determined by subjective tolerance (30 to 50 min.). In the experimental session (air cooling), the upper limit of exposure was arbitrarily set at a time duration 100% greater (60 to 100 min.) than tolerance time without air cooling. The vortex tube cooling system significantly reduced the heart rate and rectal temperature changes. The sweat lost during the cooling session was less than that lost during the control session; although the loss was not statistically significant, the duration of heat exposure during the cooling session was twice as long as that of the control session. In addition, air cooling in the MA-3 garment provided an evaporative surface equal to approximately 50% of the body surface area. The vortex tube cooling prolonged the duration of heat exposure 100% over that resulting from exposure without cooling. Also at the termination of heat exposure, the subjects felt subjectively well and, by physiological parameters, had not approached the limit of their thermal tolerance.

Croley (1969) has reported the use of vortex tube to provide cool breathing air to individual workers at Savannah River who work in atmospheres containing gases or dusts that are radioactive or chemical poisons. Prior to the use of vortex tube cooling, personnel were supplied breathing air by: (1) large air distribution systems with centrally located compressors and chillers, chillers being used to remove the heat of compression; (2) compressed air from portable compressors or large high pressure cylinders; (3) small cylinders of breathing air worn by personnel; and (4) containers of liquid air in a back pack. The first three methods provide air at ambient temperature. Croley reports that a portable refrigerator was built at Savannah River to cool the breathing air but it was expensive, cumbersome, and difficult to decontaminate. Also the rapid pick up of heat through hoses to the users virtually nullified the cooling. Liquid air packs can effectively supply cool breathing air but they are expensive and liquid air is hazardous to handle.

A vortex tube cooling system was therefore developed at Savannah River and is being extensively used there now. Inlet air is supplied to the vortex tube at 25 cfm (0.71 $m.^3$/sec.) and at 80 to 100 psig (57 to 70 $kg./cm.^2$ gauge). The vortex tube, in turn, delivers 16 to 18 cfm (0.45 to 0.51 $m.^3$/sec.) of air at 15 psig (10.5 $kg./cm.^2$ gauge) and at temperatures 50 to 60 F (10 to 15.6 C) lower than the inlet temperature to a protective suit worn by an individual worker. Croley reports that this system has performed satisfactorily at Savannah River under a variety of environmental conditions.

Operation of the Vortex Tube

A vortex tube is a small device which converts compressed air into streams of hot and cold air. There are no moving parts. The air first enters the tangential nozzles provided in the annular plenum between the body and the vortex generator. The nozzles accelerate the air and inject it circumferentially into the annular vortex chamber at sonic speed and create a forced vortex spinning at a million revolutions per minute (Van Pattern et. al., 1968, and Fulton Cryogenics Bulletin, 1966). The center of this vortex is cold air that flows out through a diffuser which lowers the pressure on the vortex core to permit the coldest possible air to be produced for the given operating conditions. The rest of the air churns down the other end of the tube at a much elevated temperature.

Several theories have been proposed to explain the working mechanisms of the vortex tube since its invention by Ranque in 1931. According to Ranque (1934), the principle involves the separation of hot and cold fluids from a current of compressible fluid under pressure by causing the fluid to flow with a gyratory helical motion along a surface of revolution, and dividing the said fluid into two coaxial sheets moving along each other. This movement results in the compression of the outer sheet by the inner. A rise in temperature of the outer sheet and a fall in temperature of the inner sheet are thus caused.

According to Rudkin (1946) since the gas near the wall is compressed more than that in the center, molecules of gas having less than average kinetic energy would be unable to penetrate the zone of highly compressed air and would be forced towards the center of the tube. They will be at a lower temperature due to their lower kinetic energy.

Roebuck (1946) observes that as the air enters the tube tangentially, a spiral of layers of rapidly rotating air are built up. If there were no frictional losses in the spiral band, the air would keep its initial linear kinetic energy at every point as it worked inward, toward the center. For a disk of fluid to have no slip between strands for such a spiral motion, the fluid should move as a solid disk--that is, have the same angular velocity at every point in the disk. Hence each layer of actual spiral will exert a force across its outer boundary on the next outer layer, doing work on it and speeding it up at the expense of its own kinetic energy, while at the same time receiving kinetic energy across its inner boundary from the next inner layer. There will thus be a flow of kinetic energy away from the center on all radii.

Under these conditions, the gas moves to the center only along a radially falling pressure, and the work done by the gas in expanding speeds up the angular velocity. This supplies another quantity of energy which is disposed off radially outward in part, and in part degraded to heat by viscous friction.

With the transfer of energy from the center radially outward, there is a material fall in temperature of the air at the center. By throttling the valve at the long end of the tube, an absolute pressure is produced at the center which is high enough to force a desired fraction of low energy gas in the center towards the other end of the tube.

PROBLEM

Temperature control of only the air space adjacent to the skin surface is a theoretically sound means of providing heat relief for the men at work. This concept requires cooling only the comparatively minute air envelope, or the microenvironment. For the individual, it provides respiratory protection in addition to heat relief.

The delivery of cool, clean air to the man at work in a hot environment poses some practical engineering problems. Past efforts have usually required large compressor type refrigeration units, expensive to install and maintain, and lacking in mobility. Also the transport of cool air from the cooling units to the workman results in reheating of air. Insulation of the hose helps but adds to the weight and bulk of the hose.

In most of the cooling systems discussed earlier, airconditioning of man has required the use of special clothing or protective suits into which air is delivered from an outside source. But none of these garments have been widely used in industry because they are too complex and costly for routine day to day use on most jobs. The man on the hot job tends to seek light weight work clothing and there is little hope for truly widescale adoption in industry of any system of man cooling unless it is economical, trouble free, and compatible with ordinary work clothing.

The personal airconditioner proposed for use in hot industrial situations is a helmet supplied with cold air from a vortex tube worn around the waist. This system seems to satisfy the above criteria and eliminates the problem of reheating of air in the supply hose as the cold air is available at the man himself. Moreover, both the vortex tube and helmet are simple, inexpensive, lightweight, and convenient for routine day to day use.

The purpose of the experiment was to know whether air cooling of the head would reduce the physiological cost of work in heat stress. Head cooling has several advantages. A large portion of the total body heat can be removed from the head as it has a large constant volume blood flow (Bazzet, 1968); it has the highest skin temperatures (Winslow and Herrington, 1949) and hence the highest temperature differential with the cooling fluid. This would suggest that head would dissipate large amounts of heat by convection and radiation. Also, since the forehead and neck produce more sweat than other parts of the body (Day, 1968), considerable amount of heat may be withdrawn from these areas by the evaporation of sweat. The tissue insulation of the head is relatively constant over a wide range of temperatures (Froese and Burton, 1957) and it takes little part in vasomotor response to cold (Hertzman and Roth, 1942). Moreover, the mobility of a man is not restricted if his head is encased. This, in itself, is an advantage of head cooling in industrial situations.

It was decided to supply 6 to 7 cfm (0.17 to 0.20 $m.^3/sec.$) of cold air to the helmet. This is 3 to 4 times in excess of the amount needed for breathing (Moore, 1968) and was thought sufficient for comfort cooling. The excess air is also sufficient to prevent pollutants, if any, present in the atmosphere (where this type of cooling system may be used) from infiltrating into the helmet. In all the experiments using air ventilated suits (encasing the whole body) that the author has come across, the amount of air supplied was between 10 to 25 cfm (0.28 to 0.71 $m.^3$/sec.). It was therefore felt that if only head was to be cooled, 6 - 7 cfm (0.17 to 0.20 $m.^3$/sec.) of air should be sufficient. Moreover, in an experiment conducted by Crockford et al. the air supplied to the helmet of the cooling suit, under the optimal air supply conditions, was 7.1 cfm (0.2 $m.^3$/sec.).

A vortex tube was used to cool the air supplied to the helmet. At the above volumes, the temperature of the air delivered was between 68 to 72 F (20 to 22.2 C), which, it was felt, was satisfactory. Since most of the cooling in such a system is done by the evaporation of the sweat, it is the volume of the air supplied which is more important, rather than the temperature. This was confirmed by the experiment of Crockford et al., who reported that the oral temperatures and pulse rates of the subjects were not affected by the temperature of the ventilating air.

Specifically, the air helmet, with an air flow rate of 6.5 cfm (0.18 $m.^3$/sec.) and at a temperature of 70 F (21.1 C) was investigated to find if it reduced the physiological cost in a heat stress environment of 112 F (44.4 C) and 60% R.H.

The criteria for evaluation of the performance of the cooling helmet was:

1. Heart rate
   a. The average number of extra heart beats during the exposure (beats/min.)

b. The average reduction in the heart rate interbeat variability during the exposure (standard deviation of the interbeat intervals).

2. Sweat loss (gms./hr./m.^{2}).

3. Change in the rectal temperature during the exposure (F).

4. Change in the ear canal temperature during the exposure (F).

5. Change in the head temperature during the exposure (F).

6. Change in the mean skin temperature during the exposure (F).

7. Change in the concentration of creatinine bodies in saliva at the end of exposure and recovery (mgs./100 mls.).

METHOD

Task

Walking at 3 miles/hr. (4.8 km.) was the task required of the subjects. A 15 ft. (4.54 m.) strip was marked on the floor of the test room. This strip was further marked by 6 equidistant lines, each line representing a stride as the subject walked. The subjects were asked to walk on the strip at the rate of 1.75 strides per second (0.57 seconds/stride) and thus their speed was 4.4 ft./sec. (1.33 m.). At the end of the marked strip, the subjects turned around and then walked back. Their walk was paced by a metronome which clicked every 0.57 seconds.

The task of walking at 3 miles per hour has an expected metabolic rate of 1050 Btu/hr. (264 kcal.) for an average man weighing 161 lbs.

(72 kgs.) (Leithead and Lind, 1964). This is similar to metabolic rate required of moderate work at a machine or bench (ASHRAE, 1967).

During the experiment the subjects could not keep up with the required pace. They actually walked at an estimated speed of 2 to 2.5 miles/hr. (3.2 to 4.0 km.) and their metabolic rate was estimated to be 860 Btu/hr. (215 kcal).

Subjects

Eight male students of Kansas State University served as subjects for $5 for each day of participation. Table 2 gives their general physical characteristics. The subjects wore cotton shorts and socks during the experiment.

Subjects 5 and 8 were replaced after the first day. They have been designated as subjects 9 and 10 in Table 2. Subject 9 was replaced as he was too flabby and was not representative of the general population. Subject 10 collapsed after 33 minutes of exposure on the first day and was advised by the doctor not to participate further in the experiment.

Apparatus

Test Chamber: The study was conducted in the KSU - ASHRAE environmental test chamber located in the Institute of Environmental Research at Kansas State University. The chamber is completely described by Nevins, Rohles, Springer, and Feyerherm (1966). The test chamber had an environment of 112 F (44.5 C), 60% RH, and an air velocity of less than 50 fpm (0.25 m./sec.). The pretest room, adjoining the test room, housed the monitoring equipment (see Fig. 2), and had a neutral environment of 82 to 84 F (27.8 to 28.9 C).

Table 2

General Characteristics of the Subjects

Subject	Age (years)	Weight (pounds)	Height (inches)	Body Area (sq. meters)
1	24	145	73	1.88
2	21	176	69	1.96
3	20	114	63	1.52
4	22	147	68	1.79
5	21	179	73	2.05
6	22	164	70	1.92
7	18	163	73	1.98
8	21	160	70	1.90
9*	18	280	72	2.46
10*	18	120	70	1.69
Mean	21	156	70	1.87

*Subjects replaced after day 1. Not included in the mean.

EXPLANATION OF PLATE I

Fig. 2. View of the pretest room providing the neutral environment and housing the monitoring equipment. Subjects three and four are seen sitting while their heart rate and body temperatures are monitored.

PLATE I

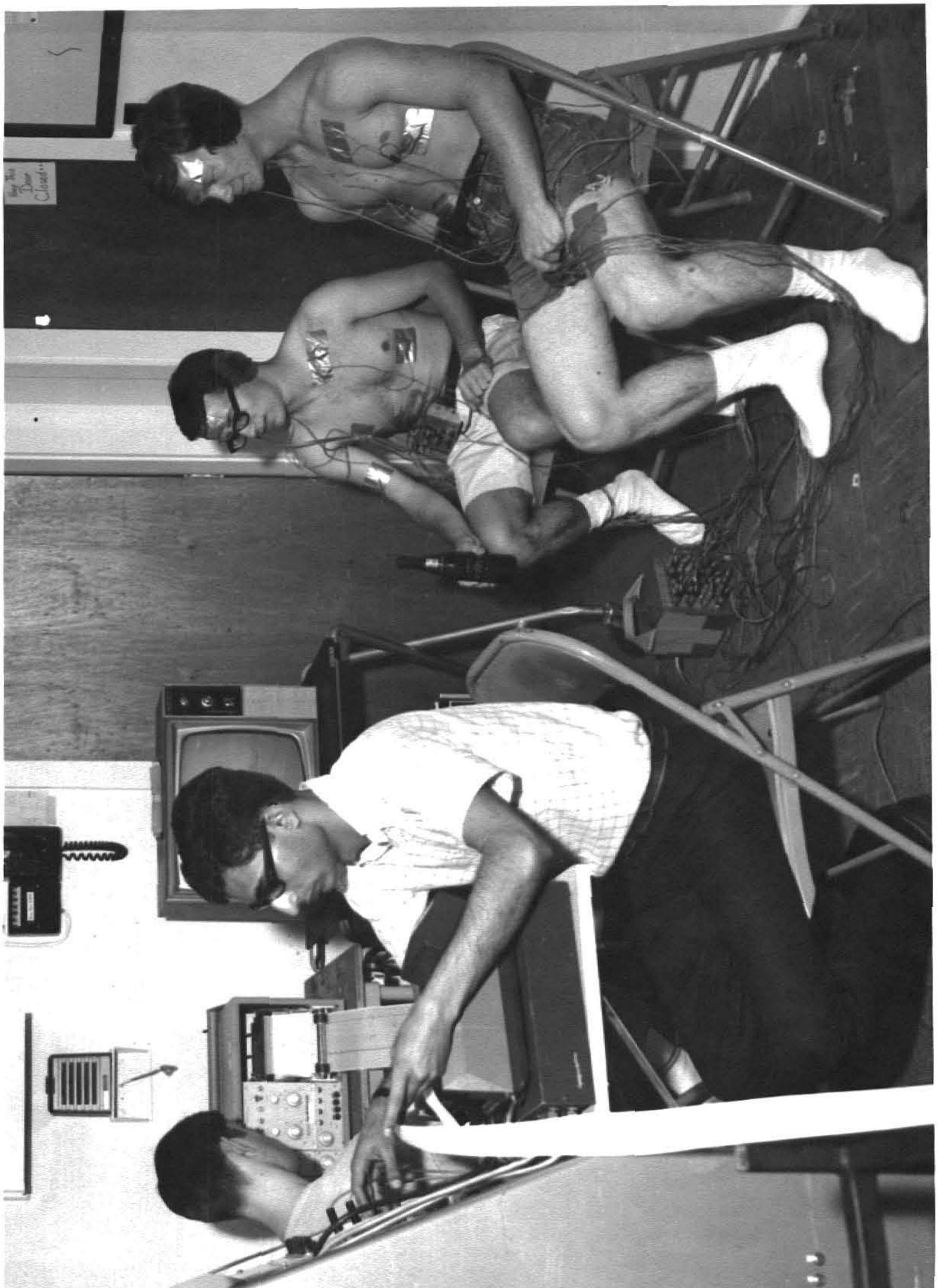

Fig. 2

Helmet: The helmet for use in the experiment was acquired from the Rite Hardware Manufacturing Company, Glendale, California. Fig. 3 shows one of the subjects wearing the hood. It is a hard hat helmet made with an inner and outer shell, both shells molded from light weight fiberglass reinforced resin. Air entered a chamber between the outer and inner helmet shells from the rear and was distributed over the head and neck area through a series of holes and slots in the inner shell. An adjustable, head hugging suspension assembly maintained a space between the helmet and the wearer's head. (This absorbs the shock of impact on the helmet and prevents head injuries). Two pressure pads were hinged on the sides of the helmet. An adjustable acetate face shield was attached to the pressure pads. The face shield could be easily raised or lowered. The helmet was provided with a white vinyl shroud which covered and lapped over the neck. A drawstring provided snugging up of the shroud. The air left the helmet under the shroud (the flow of the air under the shroud prevents any outside air from entering the helmet).

An internally insulated 1 1/4" (31.8 mm.) O.D., 2.5 ft. (761 mm.) long flexible hose connected the helmet with the vortex tube.

Vortex Tube: A Rite Manufacturing Co. Vortex tube, model 6803, was used to supply cold air to the helmet. Fig. 4 shows the vortex tube. It was 12" (305 mm.) long and weighed 0.71 lbs. (324 gms.) and was provided with a harness so that the vortex tube could be tied around the waist.

The total weight of the cooling system (vortex tube, harness, helmet, and the connecting hose) was 4.8 lbs. (2.2 kg.).

EXPLANATION OF PLATE II

Fig. 3. Front view of subject three wearing the helmet and holding the junction box in his hand.

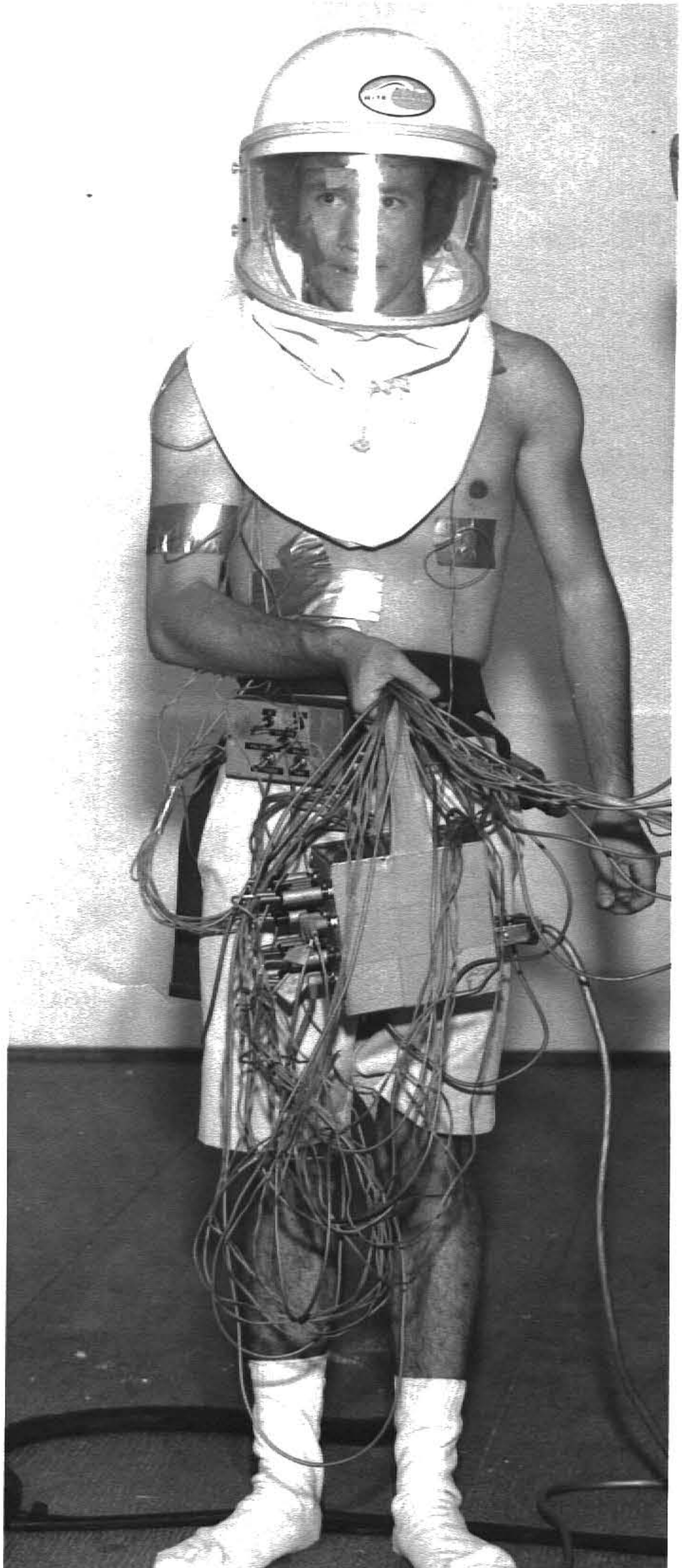

Fig. 3

EXPLANATION OF PLATE III

Fig. 4. The vortex tube used for supplying cold air to the helmet.

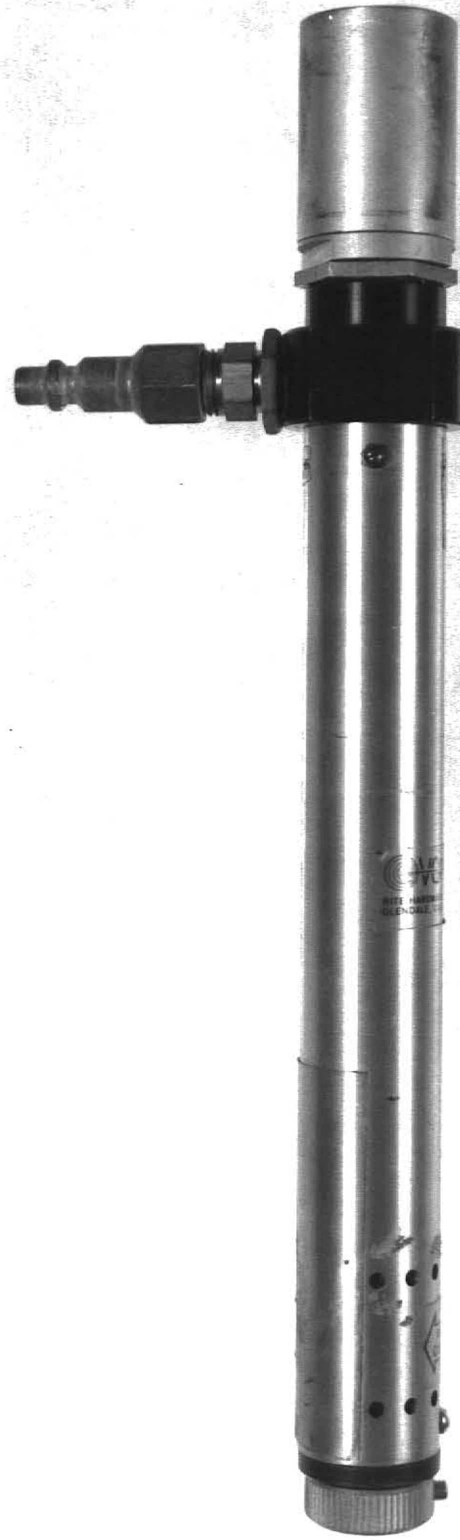

Fig. 4

Compressor: The Institute for Environmental Research houses a Quincy compressor, size 4 X 3, model 240, and an air tank with an automatic pressure regulation between 90 to 120 psig (63 to 84 kg./cm.^{2} gauge). It is driven by a 5 h.p. motor. This compressor is used to operate the pneumatically controlled equipment in the Institute. The same compressor was used to supply air to the vortex tube.

Pressure Hose: A 3/8 in. (9.5 mm.) I.D. pressure hose was used to tap the supply line of the above compressor and carried the compressed air to the test chamber. The hose was insulated on the outside with Virginia Foam Insulating Tape. A quick fit socket at the end of the hose mated with the plug on the vortex tube.

Air Flow Meter: An air flow measuring device was designed and built according to the specifications of the American Society of Mechanical Engineers (ASME Supplement, 1959). See Fig. 5. A thermometer was installed at a distance of 3 7/8 in. (98.4 mm.) from the center of the nozzle wall on the downstream side to measure the air temperature. A U-tube water manometer was used to measure the pressure differential across the nozzle and the pressure on the upstream side. The air flow rate was calculated by the Bernoulli equation.

Heart Rate Recorder: A Beckman Dynograph (Type-RS) was used to record the heart rate. Three surface electrodes were pasted on the subjects chest with double sided adhesive washers and duct tape. Electrical impulses received by these electrodes were transmitted to a d.c. amplifier and then to the dynograph. While recording the output, the paper moved at a speed of 25 mm./sec. (1.97 in./sec.) and each recording was [illegible] for about 15 seconds.

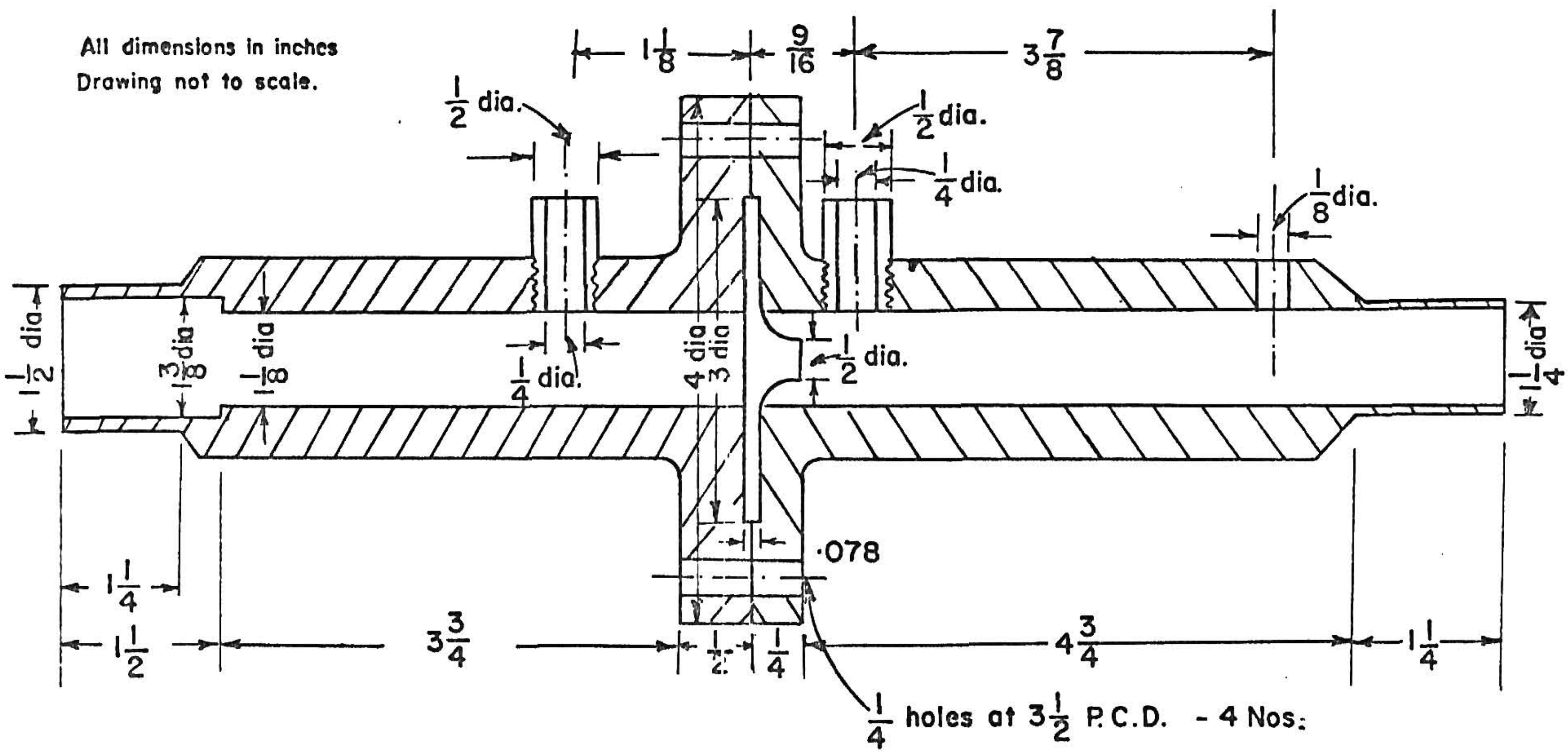

Fig.5. Sectional view of the air flow meter.

YSI Thermistors: The body temperatures were recorded by the Yellow Springs Instrument (YSI) thermistors. YSI, model 409, thermistors were used to measure the skin temperatures. A thermistor was first taped with Curad medical bandage. This bandage had an absorbent telfa pad centered on a thin, perforated plastic tape. Over this was taped a heavy duct tape. The use of the medical bandage proved very helpful because the telfa pad absorbed the sweat accumulated around the thermistor, helping the tape to stick better. There were very few occasions when a thermistor was dislocated due to the tape coming off.

A YSI, model 401, thermistor inserted to a depth of about 6 in. (150 mm.) was used to measure the rectal temperature.

The ear canal temperature was measured by a YSI, model 423, thermistor inserted to a depth of 1/2 in. (12 mm.) into the ear canal. Ear muffs were made to support the thermistor. The ear muffs were held on both the ears by the springing action of a thin metallic strip on which they were hinged. The ear muff insulated the ear canal from the ambient environment. Additional insulation was provided by conical foam rubber placed in the ear through which the ear probe entered the ear canal.

Digital Thermometer: All the thermistors were connected to a United Systems Corporation Digital Thermometer, model 500. The digital thermometer, which could measure temperatures from 59 to 122 F (15 to 50 C) to the nearest 0.1 F (0.055 C), was connected to a printer, and was also provided with an identification unit. Each experimental day, subject number and sensor number was identified by numbers from 1 to 20. The identification numbers and the corresponding temperatures were printed by pushing a print button.

Beam Balance Platform Scale: A Fairbanks and Morse Co. Beam Balance Platform Scale was used to weigh the subjects. It measured weight in pounds to the nearest .01 lb.

Video Kit: A Sony Video Camera, model VCK-2100A, placed in the test room, was connected to the Sony Videocorder, model CV-2100, which in turn was connected to the Sony TV Monitor, model CVM-180 U. The videocorder and the monitor were placed in the pretest room. With this system, the subjects were continuously watched on the monitor and their activities were recorded.

Procedure

Each subject underwent the stress conditions twice with and twice without the helmet. The experiment was, therefore, a factorial of two conditions (helmet and no-helmet) x eight subjects x two exposures. See Table 3.

Each subject was exposed to heat only once a day and two subjects were exposed at a time, one with the helmet and one without the helmet. This required four days of evaluation.

Each test day was divided into four, 2-hr. sessions. Two subjects participated in each session.

A test session was divided into three periods as follows:

Period 1 (duration 60 min.): During this period, urine and saliva samples were taken. The subjects were weighed nude. Heart rate, rectal temperature, ear temperature and skin temperature sensors were put on the subjects. Sensors for measuring the mean skin temperature were located

Table 3

The Helmet - No Helmet Sequence

Time	Subjects	Day 1	Day 2	Day 3	Day 4
1:00 - 3:00	1	H	NH	NH	H
	2	NH	H	H	NH
3:00 - 5:00	3	H	NH	NH	H
	4	NH	H	H	NH
6:00 - 8:00	5	H	NH	NH	H
	6	NH	H	H	NH
8:00 - 10:00	7	H	NH	NH	H
	8	NH	H	H	NH

on the stomach, lower back, right upper arm, and left upper leg. These temperatures were averaged to give the mean skin temperature. Three additional sensors, one each on the right cheek, right side of the neck, and above the left eye-brow were averaged to give the head temperature.

Fig. 6 shows subject three with the sensors on his body.

After the sensors were put on, the subjects were seated on chairs and their heart rates and the temperatures were monitored every 5 minutes for 15 minutes.

At the end of this period, temperature of the air delivered by the vortex tube, pressure differential across the nozzle, pressure upstream, and the supply pressure of the compressor were recorded.

Period 2 (Duration 30 min.): In this period, the subjects entered the test room. The vortex tube was strapped around the waist of the subject who was scheduled to wear the helmet. The helmet was put on his head and the shroud was snugged up with the draw string. The vortex tube was connected with the helmet by the flexible hose. The vortex tube was then connected with the air supply line. The other subject did not wear the helmet. Fig. 7 shows the subjects in the test room.

The subjects walked at an estimated speed of 2 to 2.5 miles per hour (3.2 to 4.0 km.) and their temperatures and heart rates were monitored every 5 minutes. At the end of the period, urine and saliva samples of the subjects were taken.

Period 3 (Duration 15 minutes) The subjects were taken out to the

EXPLANATION OF PLATE IV

Fig. 6. Front view of subject three with heart rate and body temperature sensors on his body. The leads of the heart rate electrodes are seen plugged to a small junction box worn by the subject around his waist. It was, in turn, connected to the Dyanograph. The leads from body temperature thermistors were plugged into the junction box lying on the floor, which was connected to the Digital Thermometer.

Fig. 6

EXPLANATION OF PLATE V

Fig. 7. Rear view of subjects three and four in the test room. Subject three is wearing the helmet. The helmet is seen connected to the vortex tube by a small flexible, insulated hose.

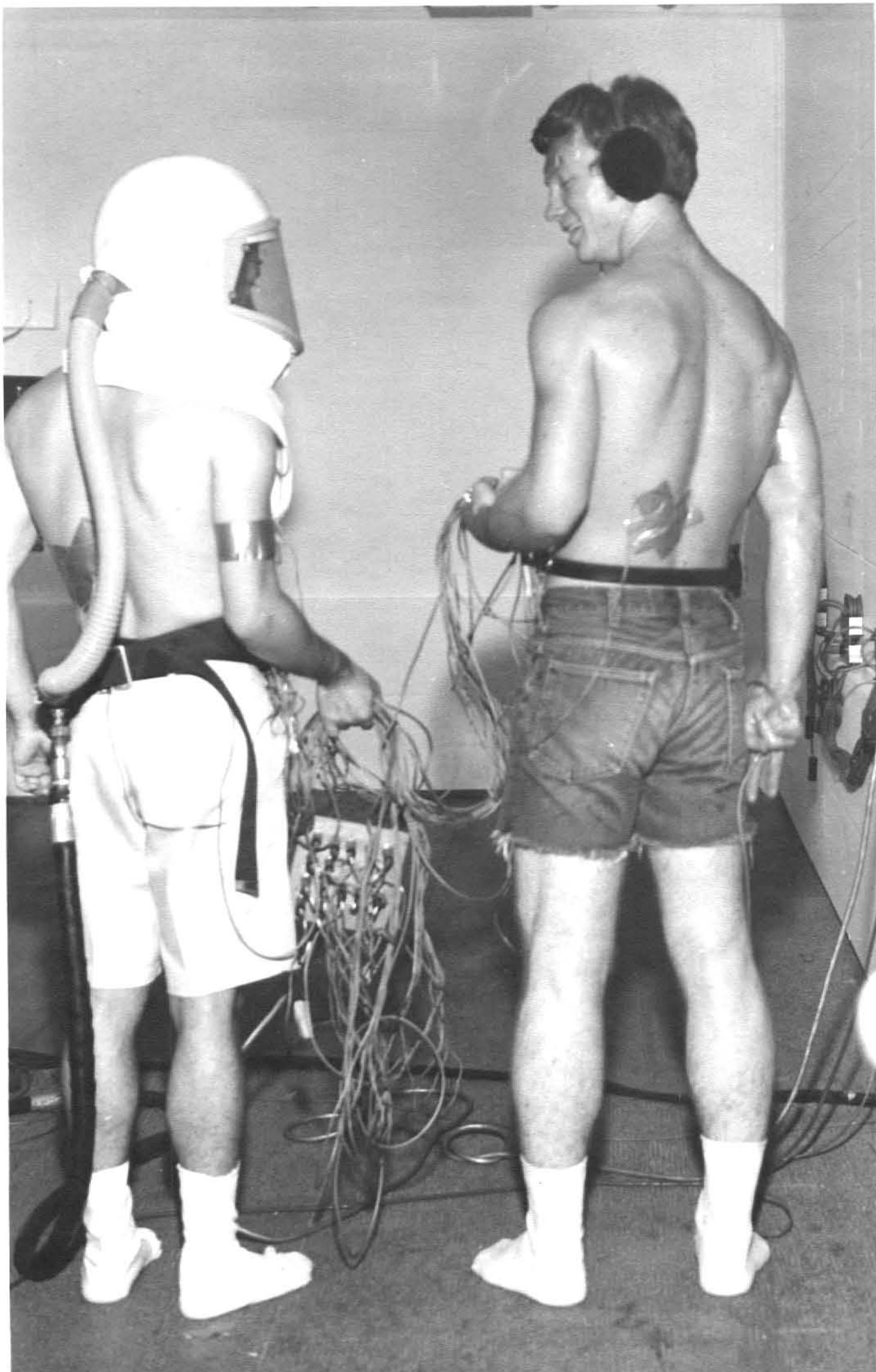

Fig. 7

pretest room, given sheets to drape around their body, and were seated on chairs. Their heart rates and temperatures were monitored every 5 minutes.

At the end of this period, their sensors were removed and their bodies were dried with towels and they were weighed nude.

Urine and saliva samples of the subjects were taken before they dressed and left.

The subjects were given Coke or Pepsi to drink whenever they requested.

Measurements

The heart rate and various body temperatures of a subject were recorded every five minutes during all the three periods in a session. The air flow data was recorded at the end of Period 1 in each session, just before the subjects were ready to move to the test chamber.

Sweat loss was calculated by adding the weight of the Pepsi or Coke consumed by a subject to the difference in the nude body weights at the beginning and the end of the test session.

Height and average weight of the subject were used to calculate his body area by the DuBois formula (Grollman, 1964).

The air flow rate was calculated by the following formula (See Appendix A):

$$Q = (5.96) \cdot D_2^2 \cdot C \cdot Y \cdot \sqrt{h_w/\rho_1(1-\beta^4)} \quad \text{cfm}$$

The air temperatures and flow rates to the helmet on each day and each test session are given in Table 4.

Table 4

Temperatures and Flow Rates of Cooling Air

Day	Session	Temperature (F)	Flow Rate cfm	Flow Rate lbs/hr.
1	1	70	6.57	29.80
	2	72	7.50	33.93
	3	68	6.63	29.51
	4	66	6.62	29.56
2	1	71	6.29	27.99
	2	69	6.28	28.05
	3	70	6.29	28.03
	4	69	6.28	28.05
3	1	68	6.92	31.13
	2	70	6.61	29.60
	3	69	6.28	28.06
	4	70	6.62	29.56
4	1	71	6.26	28.13
	2	71	6.26	28.13
	3	70	6.59	29.70
	4	70	6.59	29.69
Mean		70	6.53	29.30

RESULTS

As described earlier, two subjects participated in the experiment only on the first day and were replaced on the subsequent days; one of them was advised by the doctor not to participate in the tests and the other was not thought to be a good representative of the population being sampled. In addition, two subjects could not complete their scheduled exposure time with the helmet and four subjects could not complete without the helmet. The average time for which a subject remained in the heat stress was 44.0 min. with the helmet, and 42.5 min. without the helmet.

The heart-rate recorder did not work very well on the first two days of the experiment and therefore very little heart rate data is available for the first two days of the experiments.

Except for the above, the experiment went smoothly throughout.

Heart Rate

The heart beats of a subject were recorded on a continuous roll of graduated paper on the strip chart recorder (Dynograph). The output appeared as a series of peaks, and was recorded for about 15 seconds for each observation. The heart rate was calculated from the distances between the successive peaks. The interbeat distances in mm. were multiplied by the corresponding frequency of occurrence. The summation of this product was divided by the total frequency to give the average interbeat distance in mm. for one observation. The heart rate (in beats/min.) was then obtained by dividing the speed of the paper (in mm./min.) by the average interbeat distance (in mm.).

The standard deviation of the interbeat interval for each observation was calculated by the standard formula (Burr, 1953, p. 49). The coefficient of variation was obtained by dividing the standard deviation of the heart beats by the mean interbeat time. A computer program was used to compute the mean heart rate, its standard deviation, and the coefficient of variation for each observation. The computer program also grouped the data in periods of 5 min. For example, all data between 0 and 5 minutes are grouped as Period 1, all data from 6 to 10 minutes in Period 2, etc. Periods 1, 2, and 3 represent the pre-stress period; periods 4 through 12 represent the stress conditions, and 13 through 16 represent recovery from stress.

Since, due to the malfunctioning of the equipment, not much heart rate data could be recovered from the first two days of the experiment, only the last two days' data was analyzed.

The average rate of extra heart beats during exposure was calculated for a subject by summing all the observations of heart rates different from the basal rate (which was defined as the first observation in the prestress period) and dividing by the total number of observations during the exposure.

Table 5 gives the average rate of extra heart beats during exposure. The average rate of extra heart beats was 53 when the subjects wore the hood; this was not significantly lower than 59 when they did not wear the helmet. It will be noticed from Table 3 that the helmet did not seem to help subject 3 whose average increase in heart rate during the

Table 5

Average Increase in Heart Rate During Exposure, Beats/Min.

Subject	Helmet	No Helmet
1	35	47
2	36	44
3	90	80
4	51	75
5	52	59
6	42	45
7	53	65
8	66	58
Mean	53	59

exposure was 90 with the helmet and 80 without the helmet. This is due to the fact that subjects 3 and 4 walked faster than the rest of the subjects and almost kept pace with the metronome, while the other subjects did not. Also subject 3 was the shortest and the lightest of all the subjects and his heart presumably worked faster under the heavy stress. The cooling rate was insufficient for such a high thermal and metabolic load.

It has been suggested earlier (Kalsbeek and Ettema, 1965, and Kalsbeek and Sykes, 1967) that variability of the intervals between heart beats is a function of mental stress. The interbeat interval is reported to become more regular under mental load. It was proposed to investigate the effect of heat stress on the interbeat variability and to find whether the helmet provided any relief from the stress as measured by the interbeat variability. Table 6 presents the standard deviation of the interbeat intervals when the subjects wore the helmet and Table 7 gives the same under no-helmet conditions. Figure 8 gives a plot of the average standard deviation with respect to time. The coefficient of variation has been tabulated in Appendix B for both the conditions.

Tables 6 and 7 reveal that the heat stress does affect the heart rate variability. The standard deviation of the interbeat intervals dropped considerably as a subject was exposed to heat stress indicating that his heart was beating more uniformly under stress conditions. It is therefore evident that the heart rate variability can give an indication of the level of the stress inflicted upon the subject. The lower

Table 6

Standard Deviation of the Heart Rate (Subjects with the Helmet), Seconds

	Subject								
Period	1	2	3	4	5	6	7	8	Average
1	.084	*	.098	.016	.053	*	.047	*	.059
2	*	.039	.081	.037	.177	.039	*	*	.074
3	.040	*	*	.062	*	.028	.083	.056	.053
Average	.062	.039	.089	.038	.115	.033	.065	.056	.062
4	.019	.021	.043	.028	.038	.019	.063	*	.033
5	.024	.019	.018	*	.022	.019	.054	.043	.028
6	.019	.024	.020	.048	.013	*	*	*	.024
7	.019	*	.019	.032	.024	.020	.024	.019	.022
8	.030	.056	.017	.000	*	.009	.019	.017	.021
9	.016	.029	.019	.036	.026	.013	.009	.019	.020
10	.016	.009	.009	.000	*	.009	*	.018	.010
11	.023	.017	.016	*	.016	*	.016	.019	.017
12	.016	.020	.000	.056	*	.013	.016	.019	.020
Average	.020	.024	.017	.028	.023	.014	.028	.022	.021
13	.049	.038	.019	*	.024	.019	.028	.042	.031
14	.035	.077	.023	.049	.149	.020	.040	.014	.050
15	.033	.068	.053	.036	.177	*	.050	.022	.062
Average	.039	.061	.031	.042	.116	.019	.039	.026	.047

*Data not available

Table 7

Standard Deviation of the Heart Rate (Subjects Without the Helmet), Seconds.

	Subject								
Period	1	2	3	4	5	6	7	8	Average
1	.023	.144	.074	.097	*	.028	*	.035	.066
2	.036	*	.048	.095	.140	.028	*	.043	.065
3	*	.167	.068	*	.137	*	.072	.091	.107
Average	.029	.155	.063	.096	.138	.028	.072	.056	.079
4	.018	.044	.048	.034	.085	.024	.023	.083	.044
5	.013	.042	*	.019	.017	*	.018	.030	.023
6	.019	.019	.017	.020	*	.019	*	.000	.015
7	.019	.019	.016	.019	.038	.018	.019	.013	.020
8	.000	.023	.000	.009	.018	*	.019	.016	.012
9	*	.017	.038	.013	.019	.019	.019	.009	.019
10	*	.000	.009	**	.022	.012	.019	.019	.013
11	.020	.018	*	**	*	*	.026	*	.021
12	.019	.019	.016	**	.000	.019	.013	.024	.015
Average	.018	.022	.020	.019	.028	.018	.019	.024	.020
13	.027	.041	.019	.019	.018	.019	.026	.014	.022
14	.037	.016	.038	.014	.146	.013	.019	.017	.037
15	.032	.043	.034	.029	*	.020	.026	*	.030
Average	.032	.033	.030	.020	.082	.017	.023	.015	.029

*Data not available

**Subject could not complete the cycle

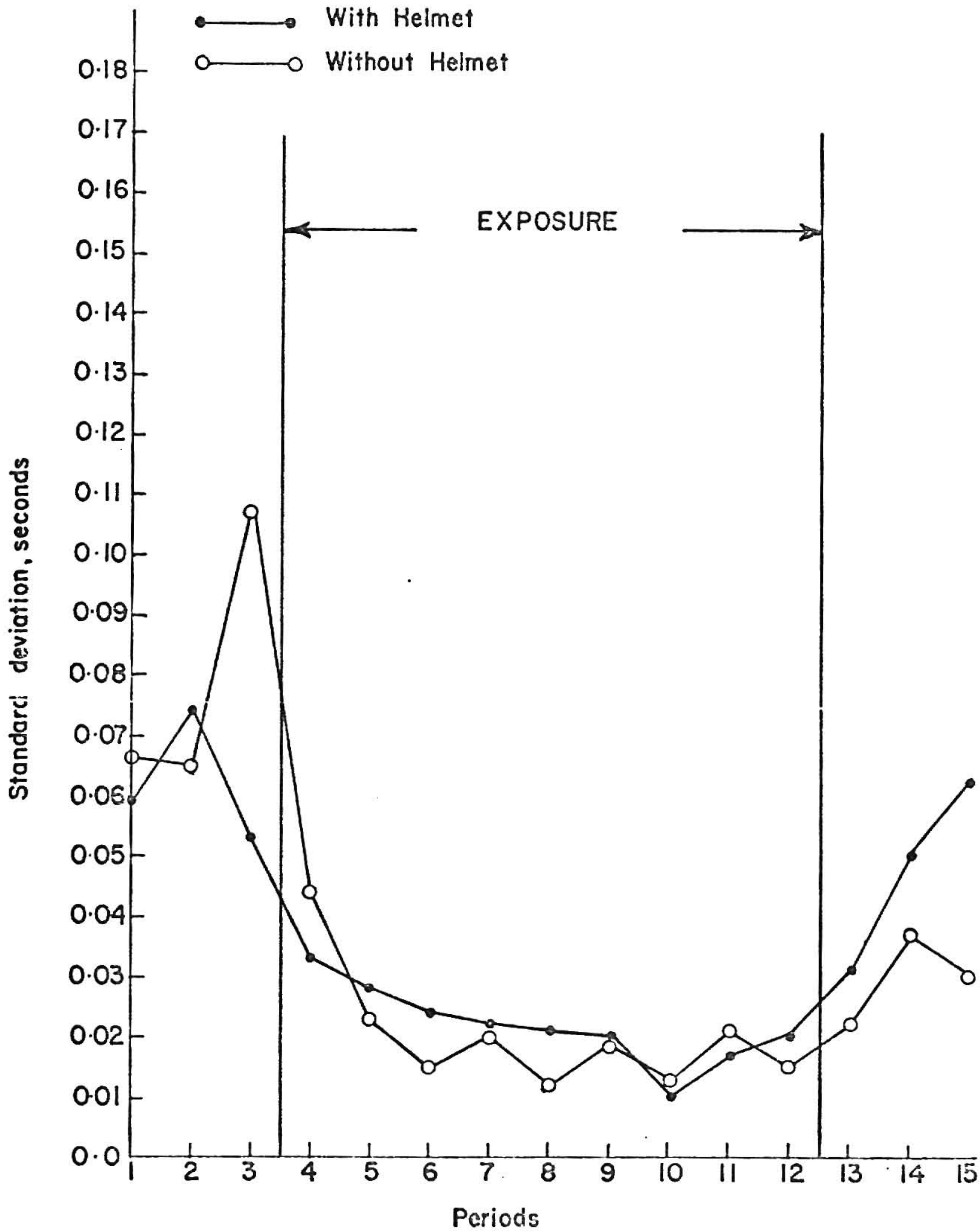

Fig.8. Average heart rate variabilty before, during, and after exposure to heat stress.

the drop in variability upon exposure to stress, the lower is the level of the stress inflicted.

The average standard deviation of the interval between beats dropped from .079 seconds in the neutral condition to .020 in the heat stress without the helmet; it dropped from .062 to .021 with the helmet. A sign test indicated that there was significantly ($p < .05$) less drop in the interbeat variability during exposure when the subjects wore the helmet. Note in Fig. 8 that the heart rate variability was back to normal within 15 min. (1 period = 5 min.) after exposure with helmet.

Sweat Loss

Table 8 gives the rate of sweat loss with and without the cooling helmet during the exposure. The data of subjects nine and ten on the first day has not been used because they were replaced on the subsequent days and their data was not representative. Subject nine sweated excessively even in the neutral environment; in the heat stress, he lost 838 gms./hr./$m.^2$ of water with the helmet. This is the highest sweat rate amongst all. Subject ten, on the other hand, lost very little sweat during exposure even without the helmet (485 gms./hr./$m.^2$). He collapsed after 33 min. of exposure, probably because he did not sweat enough to derive adequate cooling by evaporation. The sweat rate for subjects five and eight on the first day was estimated by averaging the same for all the subjects for the two exposures under the same condition (Helmet and No-Helmet). The difference in the averages for the two exposures was added (or subtracted) from the appropriate values for the second exposure to obtain an estimate of the sweat rate for the first exposure.

Table 8

Sweat Rate, gms./hr./m.^{2} of Body Area

	Helmet			No Helmet		
Subject	Exposure 1	Exposure 2	Mean	Exposure 1	Exposure 2	Mean
1	673	540	606	695	601	648
2	474	502	488	886	805	845
3	657	812	734	874	934	904
4	672	763	717	1125	1123	1124
5	718*	669	748	794	655	724
6	607	664	635	598	671	634
7	493	548	520	829	690	809
8	212	389	300	576*	544	560
Mean	563	624	593	797	765	781

*Estimated

The data in Table 8 was analyzed with a 3-way analysis of variance. Table 9 shows the variates in the ANOVA. The mean sweat rate during the exposure was 593 gms./hr./m.^{2} with the helmet which was significantly ($p < .05$) lower than the 781 without the helmet. As expected, the sweat rate of the various subjects was significantly ($p < .05$) different but there was no significant difference between the first and second exposures. The helmet x subject and helmet x exposure interactions were also significant ($p < .05$). The significance of the helmet x subject interaction indicated that the different subjects reacted differently to the helmet. The mean sweat rate with the helmet varied from 300 to 748 gms./hr./m.^{2} showing that there was a wide variation in the sweat rate of different subjects. The significance of the helmet x exposure interaction suggested that the subjects did not derive the same benefit from the helmet on both the exposures. In fact the mean sweat rate, with the helmet, increased from 563 gms./hr./m.^{2} on the first exposure to 624 on the second while the sweat rate without the helmet declined 32 on the second exposure.

Rectal Temperature

The rectal temperature declined in the prestress period (neutral environment). It was also noticed that the rectal temperature continued to decline for 5 to 10 minutes after the subjects entered the hot environment and continued to rise for 10 to 15 minutes after the subjects left the hot environment. Thus the heat exchange with the environment did not affect the rectal temperature immediately. The time lag was due to the time taken by the heat to flow from the environment to the deep body tissues and vice versa.

The change in the rectal temperature during exposure was calculated by subtracting the final rectal temperature value in the neutral environ-

Table 9

Analysis of Variance - Sweat Rate, gms./hr./$m.^2$

Source	DF	Mean Square	F	$F_{.05}$
H	1	280687	10.1*	5.59
S	7	84380	43.3*	3.79
X	1	1755	0.3	5.59
HS	7	27750	14.2*	3.79
SX	7	5204	2.6	3.79
HX	1	17344	8.9*	5.59
Error	7	1945		
Total	31			

H - Helmet - No Helmet (Fixed)

S - Subjects (Random)

X - Exposure (Fixed)

ment from the final rectal temperature value in the heat stress. The temperature at the end of the scheduled exposure was extrapolated for subjects three, four, seven, and eight for the days when they could not complete their exposure cycle by plotting their temperatures during the exposure against those of other subjects under the same helmet - no helmet condition. Table 10 summarizes the change in the rectal temperature during the exposure. The mean rise in the rectal temperature during the exposure was 1.23 F (0.68 C) with the helmet which was significantly ($p < .05$) lower than the 1.76 F (0.98 C) without the helmet. The subject effect and the helmet x exposure interaction were also significant ($p < .05$). As in the case of rectal temperature, the significance of the helmet x exposure interaction suggested that the effect of the helmet was not the same on both the exposures. The mean rectal temperature, with the helmet, rose by 1.12 F (0.6 C) on the first exposure and by 1.34 F (0.75 C) on the second while the rise declined without the helmet. The effect of the helmet thus declined on the second exposure.

Ear Canal Temperature

Table 11 gives the change in the ear canal temperature during exposure. The mean rise in the ear canal temperature was 1.9 F (1.09 C) with the helmet which was significantly ($p < .05$) lower than 5.28 F without the helmet. No other effects, including the interactions, were significant. It is, however, surprising that the change in temperature for different subjects was not significant. Note the large rise without the helmet; this indicates that the instrumentation was not perfect since tympanic temperature obviously did not rise 5.28 F.

Table 10

Change in the Rectal Temperature During Exposure, F.

	Helmet			No Helmet		
Subject	Exposure 1	Exposure 2	Mean	Exposure 1	Exposure 2	Mean
1	1.7	1.6	1.65	2.2	1.9	2.05
2	0.5	1.0	0.75	1.8	1.3	1.55
3	1.6†	2.0	1.80	1.8	1.6	1.70
4	1.4	1.9	1.65	3.1†	2.9†	3.00
5	0.4*	0.6	0.50	1.4	1.1	1.25
6	1.8	1.5	1.65	2.1	2.4	2.25
7	0.9	1.3	1.10	1.5†	1.4	1.45
8	0.7†	0.9	0.80	1.0	0.8	0.90
Mean	1.12	1.34	1.23	1.86	1.67	1.76

*Estimated

†Extrapolated

Table 11

Change in the Ear Canal Temperature During Exposure, F

	Helmet			No Helmet		
Subject	Exposure 1	Exposure 2	Mean	Exposure 1	Exposure 2	Mean
1	2.5	1.7	2.10	5.7	4.5	5.10
2	0.4	1.0	0.70	4.4	5.7	5.05
3	2.2†	2.4	2.30	5.7	4.9	5.30
4	2.7	2.9	2.80	4.9†	5.3†	5.10
5	2.8†	2.6	2.70	4.8	6.5	5.65
6	2.6	1.3	1.95	5.2	6.3	5.75
7	1.0	1.5	1.25	5.4†	5.4	5.40
8	2.3*	1.5	1.90	4.7*	5.1	4.90
Mean	2.06	1.86	1.90	5.10	5.46	5.28

*Estimated

†Extrapolated

Head Temperature

The head temperature was the average of the temperatures at three different locations on the head, that is, the forehead temperature measured above the left brow, the cheek temperature measured below the right cheek bone, and the neck temperature measured just below the right ear. The mean change in the head temperature during exposure was 2.66 F (1.44 C) with the helmet (Table 12) which was significantly ($p < .05$) lower than 6.35 F (3.5 C) without the helmet. The effect of the subjects was also significant ($p < .05$). No other effects, including the interactions, were found to be significant.

Mean Skin Temperature

The mean skin temperature (Table 13) was the average of only four different skin temperatures, that is, the stomach, the lower back, the right upper arm, and the left upper leg. The average rise in the mean skin temperature during exposure was 7.50 F (4.16 C) with the helmet which was lower than the 8.25 F (4.55 C) without the helmet. The difference, however, was not significant. No main effects or interactions were found to be significant.

Creatinine in the Saliva and the Urine

When a man is in the heat stress and is sweating profusely, the salivary secretion is reduced because of the cellular dehydration (Bard, 1961). Also changes in the concentration of organic matter are observed due to the variations in the blood flow (Langley, 1888). The above facts suggest that the changes in the composition of saliva should give an indication of the level of stress inflicted.

Table 12

Change in the Head Temperature During Exposure, F.

	Helmet			No Helmet		
Subject	Exposure 1	Exposure 2	Mean	Exposure 1	Exposure 2	Mean
1	3.0	2.1	2.55	5.9	5.8	5.85
2	1.8	1.8	1.80	6.4	6.7	6.55
3	2.9†	3.6	3.25	6.8	6.9	6.85
4	3.6	2.4	3.00	6.1†	7.8†	6.95
5	3.7*	3.6	3.65	6.4	7.1	6.75
6	2.9	3.5	3.20	6.2	6.1	6.15
7	1.8	2.1	1.95	6.5†	7.3	6.90
8	2.2	1.7	1.95	4.6*	5.1	4.85
Mean	2.73	2.60	2.66	6.11	6.60	6.35

*Estimated

†Extrapolated

Table 13

Change in the Mean Skin Temperature During Exposure, F.

	Helmet			No Helmet		
Subject	Exposure 1	Exposure 2	Mean	Exposure 1	Exposure 2	Mean
1	6.1	7.5	6.80	7.8	7.9	7.85
2	7.4	6.4	6.90	7.4	8.1	7.75
3	6.9†	8.0	7.45	8.2	7.2	7.70
4	8.1	7.3	7.70	9.6†	10.0†	9.80
5	7.8*	8.3	8.05	8.2	7.7	7.95
6	7.0	8.8	7.90	7.5	8.7	8.10
7	6.0	6.5	6.25	8.1†	9.0	8.55
8	8.8†	9.4	9.10	8.2*	8.5	8.35
Mean	7.26	7.75	7.50	8.12	8.38	8.25

*Estimated

†Extrapolated

At the initial level of investigation, it was decided to focus attention on the creatinine concentration in saliva. Saliva samples of the subjects were taken in the control (at the beginning of the prestress period), stress (at the end of the exposure), and recovery (15 min. after the exposure). It was observed the creatinine level (mgs./100 mls.) varied widely on each experimental day even in the control period. To eliminate the effect of the days, the mean creatinine secretion in the control period was calculated by summing up the control data for all the subjects for each day irrespective of the Helmet - No Helmet condition, and dividing by the number of subjects. The averages for day 1, 2, 3, and 4 were 1.23, 1.72, 0.87, and 0.70 mgs./100 mls. respectively. The change from the average for the control, stress, and recovery for each condition (Helmet - No Helmet) was calculated by subtracting the appropriate mean value from the observed creatinine level (Table 14).

It was observed that the creatinine level in saliva decreased as a result of exposure to heat stress. With the helmet, the average difference from the mean creatinine level decreased from 0.10 in the control to - 0.15 mgs./100 mls. in stress; it decreased from - 0.09 to - 0.35 without the helmet. The average level of creatinine, therefore, decreased by 0.25 mgs./100 mls. from the control to stress. This decrease was significant at 10% confidence level but was not significant at the 5% level. On comparing the Helmet and No-Helmet conditions, the average reduction of 0.25 mgs./100 mls. with the helmet was not significantly different from the 0.26 without the helmet.

Table 14

Change in the Creatinine Concentration in Saliva, mgs./100 ml.

Subject		Helmet			No Helmet		
		Exp. 1	Exp. 2	Average	Exp. 1	Exp. 2	Average
	Control	0.22	0.35	0.28	- 0.47	1.03	0.28
1	Stress	0.45	- 0.25	0.10	- 0.39	- 0.17	- 0.28
	Recovery	0.19	1.00	0.59	- 0.37	0.63	0.13
	Control	1.78	- 0.22	0.78	1.17	0.10	0.63
2	Stress	0.78	0.13	0.45	*	- 0.25	- 0.25
	Recovery	- 0.70	1.18	0.55	1.57	1.00	1.28
	Control	- 0.43	- 0.25	- 0.34	- 0.47	- 0.57	- 0.52
3	Stress	- 0.23	- 0.35	- 0.29	- 1.42	- 0.52	- 0.97
	Recovery	0.27	- 0.45	- 0.09	- 1.42	- 0.57	- 0.99
	Control	1.48	1.43	1.45	0.77	- 0.45	0.16
4	Stress	0.33	- 0.42	- 0.04	2.47	- 0.35	1.06
	Recovery	- 0.72	0.38	- 0.17	- 0.03	- 0.35	- 0.19
	Control	*	- 0.37	- 0.37	- 0.68	- 0.47	- 0.57
5	Stress	*	- 0.32	- 0.32	- 0.68	- 1.12	- 0.90
	Recovery	*	- 0.27	- 0.27	*	- 0.27	- 0.27
	Control	0.18	0.03	0.10	*	0.65	0.65
6	Stress	- 1.07	- 0.27	- 0.67	*	- 0.05	- 0.05
	Recovery	- 0.22	0.81	0.29	*	0.65	0.65
	Control	- 0.18	- 0.40	- 0.29	- 0.62	- 0.77	- 0.69
7	Stress	1.47	- 0.40	0.53	- 1.27	- 0.67	- 0.97
	Recovery	1.87	- 0.45	0.71	- 1.57	- 0.77	- 1.17
	Control	- 0.88	- 1.42	- 1.15	*	- 0.57	- 0.57
8	Stress	- 0.68	- 1.62	- 1.15	*	*	*
	Recovery	- 0.68	- 1.47	- 1.07	*	- 0.07	- 0.07
	Control	0.31	- 0.10	0.10	- 0.05	- 0.13	- 0.09
Average	Stress	0.13	- 0.44	- 0.15	- 0.26	- 0.45	- 0.35
	Recovery	0.00	0.09	0.04	- 0.36	0.03	- 0.16

*Data not available

In a similar experiment using an air ventilated jacket in which subject nos. 3 and 8 were employed, the reduction in the creatinine concentration in saliva upon exposure to heat stress was confirmed. The data was analyzed in a similar manner and is presented in Table 15. With the jacket, the average difference from the mean decreased from 0.03 mgs./100 mls. in the control to - 0.41 in the stress; it decreased from - 0.04 to - 0.27 without the jacket. The average creatinine concentration, therefore, decreased by 0.33 mgs./100 mls. from the control to stress. The decrease was significant ($p < .05$).

The volume of the urine excreted and the corresponding creatinine concentration (mgs./100 mls.) during the control, stress, and recovery are given in Table 16.

Heat Extraction

The potential heat removal rate of the helmet was 1013 Btu/hr. (253 kcal) (Appendix C).

Webb (1969) suggested the following empirical expression for the amount of heat stored in the body during a period of heat exposure:

$$Q = 0.83\, m_b\, (0.2\, \Delta T_s + 0.8\, \Delta T_{re})$$

where, Q = the amount of heat stored, kcal

0.83 = specific heat of the human body, kcal/kg. C

m_b = the weight of the body, kg.

ΔT_s = the change in the mean skin temperature, C

ΔT_{re} = the change in rectal temperature, C

An estimate of the heat extracted by the hood was made from the excess

Table 15

Change in the Creatinine Concentration in Saliva in the Experiment with a Cooling Jacket, mgs./100 mls.

Subject		Jacket				No Jacket			
		Low	Medium	High	Average	Exp. 1	Exp. 2	Exp. 3	Average
	C	*	0.35	- 0.27	0.04	0.15	- 0.07	- 0.12	- 0.01
3	S	*	- 0.30	- 0.32	- 0.31	- 0.75	- 0.07	- 0.17	- 0.33
	R	*	- 0.30	- 0.17	- 0.23	- 0.85	0.23	- 0.17	- 0.26
	C	- 0.15	0.08	0.13	0.02	0.28	- 0.35	*	- 0.03
8	S	- 0.75	- 0.07	- 0.27	- 0.36	- 0.12	- 0.35	*	- 0.23
	R	- 0.40	0.13	0.03	- 0.08	- 0.08	- 0.35	*	- 0.13
	C	- 0.15	0.21	- 0.07	0.03	0.21	- 0.21	- 0.12	- 0.04
Average	S	- 0.75	- 0.18	- 0.29	- 0.41	- 0.43	- 0.21	- 0.17	- 0.27
	R	- 0.40	- 0.08	- 0.07	- 0.18	- 0.38	- 0.06	- 0.17	- 0.20

C - Control
S - Stress
R - Recovery

*Data not available

Table 16

Volume of the Urine excreted (mls.) and the Corresponding Creatinine Concentration (mgs./100 mls.) during the Control, Stress, and Recovery

Subject		Helmet				No Helmet			
		Exp. 1		Exp. 2		Exp. 1		Exp. 2	
		Vol.	Conc.	Vol.	Conc.	Vol.	Conc.	Vol.	Conc.
	C	206	110	56	350	40	120	8	345
1	S	54	190	44	250	*	325	20	375
	R	14	230	8	300	8	290	10	410
	C	156	125	100	120	164	140	176	120
2	S	48	210	23	410	82	170	50	220
	R	8	345	9	450	8	325	9	290
	C	*	*	174	102	143	102	208	43
3	S	53	89	114	92	188	31	200	52
	R	134	110	52	131	*	48	82	94
	C	130	150	50	210	106	100	6	170
4	S	64	180	44	240	96	85	76	200
	R	12	470	10	360	*	*	11	420
	C	*	*	12	40	*	130	*	250
5	S	*	*	20	40	16	190	8	290
	R	*	*	*	*	10	245	10	325
	C	*	*	*	40	*	*	105	90
6	S	*	*	92	130	*	*	43	240
	R	34	400	13	395	*	*	29	325
	C	119	79	*	*	26	40	22	163
7	S	70	160	*	*	114	123	61	180
	R	*	400	50	420	*	450	7	550
	C	*	*	*	*	*	*	124	65
8	S	*	*	*	*	*	*	110	62
	R	48	39	215	28	*	*	*	*

C - Control
S - Stress
R - Recovery

*Data not available

heat stored in the body when the subject was exposed to the heat stress without the helmet. The mean weight of the subjects was 156 lbs. (70.7 kg.) (Table 2). The mean change in the rectal and skin temperatures for the two conditions was obtained from Tables 10 and 13 respectively.

Then

$$Q_H = 107.9 \text{ kcal/hr. } (431 \text{ Btu})$$

and, $$Q_{NH} = 132.9 \text{ kcal/hr. } (531 \text{ Btu})$$

where,

Q_H = the rate of heat storage in the body with the helmet

and, Q_{NH} = the rate of heat storage in the body without the helmet.

The heat benefit by the helmet was, therefore, 25 kcal/hr. (100 Btu). This is a combination of reduced radiation gain, increased convection and evaporation loss, and increased metabolic cost due to the weight of the cooling system.

The ratio of the actual heat benefit by the helmet and its potential heat removal rate gave the efficiency of the helmet, which was 10%.

DISCUSSION

The primary objective of the study was to investigate whether the helmet can provide effective cooling with moderate air flow rates. At an average air flow rate of 6.5 cfm (0.18 $m.^3$/sec.) and an average air temperature of 70 F (21.1 C), it was able to reduce the heat load by 100 Btu/hr. (25 kcal). Since the average rate of heat storage in the body without the helmet was 531 Btu/hr. (132.9 kcal), the amount of heat extracted by the helmet was 19% of the total heat storage.

With this rate of heat extraction, the rise in the rectal temperature was significantly suppressed. But the significant helmet x exposure interaction indicated that the effect of the helmet decreased with each exposure. The mean of the helmet x exposure interaction changed from 1.12 F (0.6 C) on the first exposure to 1.34 F (0.75 C) on the second exposure indicating that the average rise in temperature with the helmet increased with exposure.

The skin temperature was not influenced as much by the heat extraction from the body as the rectal temperature, because the skin was constantly exposed to the hot environment. The rise in skin temperature was lowered when the subjects wore the helmet but it must have been partly nullified by the decrease in the sweat rate and consequent reduction in the evaporative cooling of the skin. This is probably the reason why the rise in the mean skin temperature was not significantly less with the helmet than the rise without the helmet. But the skin temperature is an important factor in establishing a sensation of comfort, therefore, it must be appreciably lowered. This means a higher heat transfer rate must be provided.

The head was benefited most by the helmet because it was directly exposed to cold air and there was only a small rise in the head temperature (2.66 F (1.44 C)) in the 45 min. exposure to heat with the helmet; the corresponding increase without the helmet being 6.35 F (3.5 C). As expected, the rise in the ear canal temperature was less (1.96 F (1.09 C)) with the helmet than the 5.28 F (2.93 C) without the helmet. This is because the ear canal was insulated from the environment, and its temperature represented the temperature of the deeper body tissues. It may be noted that the 'subjects' effect in the analysis of variance was significant for the head temperature but not for the ear temperature. This means that different subjects had widely different changes in the head temperatures upon exposure, but the changes in their ear temperatures were not very different. If true, this would suggest that ear temperature is a very good index of heat stress evaluation when working with a large number of subjects.

For all the body temperatures, the helmet x subject effect was non-significant. This suggests that different subjects did not react differently to the helmet as far as their skin and deep body temperatures were concerned.

The rate of sweat production varied widely both with and without the helmet. Although the helmet was able to check the sweat production significantly, the sweat rate with the helmet varied from 212 to 812 gms./hr./m.^{2} The helmet x exposure interaction was also significant as in the case of rectal temperature, and the effect of the helmet was reduced with exposure. The sweat production (with the helmet) increased from 563 gms./hr./m.^{2} on the first exposure to 624 on the second.

The mean heart rate was, however, not significantly affected by the helmet. The use of the helmet reduced the average increase in the heart during 45 min. exposure by only 6 beats/min. Although this result is based on the data of only two experimental days, there is a clear indication that the cooling rate was not adequate for a metabolic load of 860 Btu/hr. (215 kcal). But the helmet was able to check the reduction in the heart rate variability. It was demonstrated by the experiment that the interbeat variability is definitely affected by the heat stress and there is a considerable reduction in the variability in the hot environment. The standard deviation of the interval between beats dropped by 75% upon exposure to heat without the helmet and by 66% with the helmet, the difference being statistically significant ($p < .05$).

The experiment gave an indication that the heat stress does affect the creatinine concentration in the saliva, although it could not be established statistically. Since the amount of saliva secreted is greatly affected by the amount of sweat produced, it seems that the volume of saliva secreted should be treated as another variable and the creatinine secretion per unit time rather than creatinine concentration should be looked into. Also other elements in saliva such as sodium, potassium, and magnesium should also be looked into.

CONCLUSION

From the above discussion it is evident that the helmet kept the subjects cooler and they had considerably lower sweat rates, head, ear, and rectal temperatures. It reduced the mean skin temperature and the cardiac cost but the amount of heat extracted from the body was not sufficient to keep the heart rate and mean skin temperature significantly lower. There was no significant difference in the creatinine concentration of saliva with and without the helmet. It was felt that the helmet should be tried with higher air flow rates, of the order of 15 cfm in order to extract more heat from the body. If the helmet is to be used with lower flow rates, the use of an air ventilated jacket on the torso is recommended to prevent the environmental heat from flowing into the body by convection and radiation.

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APPENDIX A

Calculation of the Air Flow Rate

The air flow rate was calculated by making use of the Bernoulli's theorm for mechanical energy balances to the flow between sections upstream and downstream from a nozzle placed perpendicular to the direciton of flow. The change in pressure which occurs when the air flows through the nozzle is indicated by the difference in water levels in the two legs of the manometer and may be directly related to the rate of flow in the pipe. The general equation for flow through air orifice or nozzle may be written in the form (Stearns et al., 1951):

$$\sqrt{U_2^2 - U_1^2} = C \sqrt{2g \, \Delta h} \tag{1}$$

where U_1 = average velocity in the pipe at the upstream pressure tap, ft./sec., at flow conditions

U_2 = average velocity through the orifice or nozzle, ft./sec., at flow conditions

g = the acceleration due to gravity, ft./sec.^{2}.

Δh = differential pressure across the orifice or nozzle, ft of flowing fluid at upstream temperature and pressure.

C = coefficient of discharge

If

A_1 = pipe area, in.^{2}

A_2 = throat area of the nozzle, in^2.

D_1 = pipe diameter, in.

D_2 = throat dia of the nozzle, in.

h_w = differential pressure across the nozzle, in. of water at 60 F

M = molecular weight of the air, 29.96

P_1 = absolute static pressure at the upstream tap, psi

Q = flow rate, cfm.

Re = Reynold's number referred to the diameter of the nozzle

T_1 = absolute temperature of air at upstream side, R

W = flow rate, lbs./hr.

Y = expansion factor, dimensionless

Z = absolute viscosity of air, centipoises, at flow temperature and pressure.

β = D_2/D.

ρ_1 = density of air at upstream pressure tap, lbs./cu. ft.

ρ_2 = density of air at downstream pressure tap, lbs./cu. ft.

μ = gas law deviation factor

10.73 = perfect law gas constant for these units

Since, $U_1 A_1 = U_2 A_2$

$$U_1 = U_2 (\beta)^2 \qquad (2)$$

From equations (1) and (2)

$$U_2 = \frac{C \sqrt{2g \Delta h}}{\sqrt{1 - \beta^4}}$$

$$= \frac{C}{\sqrt{1 - \beta^4}} \cdot \sqrt{64.34 \Delta h}$$

Also, $$W = 3600\ \rho_2\ U_2\ A_2 \tag{3}$$

$$A_2 = \frac{\Pi}{4}\ \frac{(D_2)^2}{144} \tag{4}$$

and, $$\Delta h = \frac{h_w}{12}\ \frac{62.37}{\rho_1} \tag{5}$$

$$\rho_2 = Y\ \ \rho_1 \tag{6}$$

From equations (2), (3), (4), (5) and (6)

$$W = 359.1\ (D_2)^2 \cdot C \cdot Y\ \sqrt{\rho_1\ h_w/(1-\beta^4)} \tag{7}$$

Density of air at upstream conditions ρ_1, was calculated from the following formula (Stearns et al., 1951, p. 11)

$$\rho_1 = \frac{MP_1}{10.73\ T_1 \mu_1}$$

The differential pressure across the nozzle was given by the difference in the levels of water in the two legs of the manometer. It was corrected for temperature by multiplying by 0.992, ratio of the densities of water at the room temperature (112 F) and that at 60 F (Stearns et. al., 1951, p. 287), to give h_w.

Y_1, the expansion factor was obtained from the graph of $\frac{h_w}{P_1}$ versus Y for $\beta = \frac{0.5}{1.125} = 0.44$ (ASME Supplement, 1959, p. 76).

The choice of the discharge coefficient C, depends upon the evaluation of Reynold's number, which in turn, depends upon the flow rate. It has, therefore, to be found out by trial and error. A value of 0.9 was initially assumed for C and the flow rate calculated. Reynold's number was then calculated by the following relationship (Stearns et al., 1951, p. 64)

$$Re = \frac{6.316\ W}{D_2 Z}$$

The value of Z was obtained at the upstream temperature from the graph between temperature and viscosity (ASHRAE, 1967, p. 85; conversion factor on p. 402).

Having calculated Reynold's number, value of C was found from curves (ASME Suppl. 1959, p. 16). This process was repeated until two successive values of C and W matched.

Having calculated W, the mass flow rate in lbs./hr., Q was calculated as follows:

$$Q = \frac{1}{60} \cdot \frac{W}{\rho_1} \text{ cfm.}$$

$$= 5.96\ D_2^2\ C.Y. \sqrt{h_w/\rho_1\ (1-\beta^4)}$$

APPENDIX B

Table 17

Coefficient of Variation of the Heart Rate, Seconds
(Subjects with the Helmet)

Period	1	2	3	4	5	6	7	8	Average
	Subjects								
1	.102	*	.117	.020	.044	*	.055	*	.067
2	*	.052	.098	.046	.16	.059	*	*	.084
3	.044	*	*	.078	*	.044	.105	.089	.072
Average	.073	.052	.107	.048	.106	.051	.080	.089	.074
4	.030	.035	.065	.040	.052	.034	.080	*	.048
5	.038	.033	.041	*	.033	.036	.094	.095	.052
6	.031	.040	.052	.093	.022	*	*	*	.047
7	.034	*	.056	.064	.044	.045	.052	.050	.049
8	.054	.100	.047	.000	*	.022	.043	.045	.044
9	.032	.066	.058	.084	.04	.030	.022	.058	.049
10	.031	.020	.031	.000	*	.024	*	.050	.026
11	.045	.037	.051	*	.033	*	.041	.057	.044
12	.032	.043	.000	.132	*	.033	.039	.058	.048
Average	.036	.046	.044	.059	.038	.032	.053	.058	.045
13	.079	.065	.047	.090	.036	.040	.049	.089	.061
14	.045	.106	.048	.059	.153	.036	.061	.024	.066
15	.045	.097	.087	.034	.156	*	.070	.045	.076
Average	.056	.089	.060	.061	.115	.038	.060	.052	.067

*Data not available

Table 18

Coefficient of Variation of the Heart Rate
(Subjects without the Helmet)

Period	Subjects 1	2	3	4	5	6	7	8	Average
1	.030	.147	.090	.131	*	.045	*	.068	.085
2	.052	*	.058	.120	.127	.038	*	.069	.077
3	*	.158	.084	*	.115	*	.091	.141	.118
Average	.041	.152	.079	.126	.121	.042	.091	.092	.093
4	.032	.058	.078	.060	.111	.044	.038	.141	.070
5	.024	.052	*	.047	.026	*	.035	.064	.042
6	.036	.031	.039	.052	*	.043	*	.000	.033
7	.043	.033	.037	.058	.071	.045	.044	.037	.046
8	.000	.041	.000	.027	.038	*	.047	.045	.028
9	*	.033	.107	.043	.042	.047	.051	.027	.050
10	*	.000	.031	**	.48	.029	.047	.050	.034
11	.047	.038	*	**	*	*	.071	*	.052
12	.048	.043	.048	**	.000	.051	.038	.072	.042
Average	.033	.037	.048	.048	.048	.043	.047	.054	.044
13	.051	.064	.046	.058	.032	.039	.054	.033	.047
14	.059	.026	.076	.045	.193	.028	.037	.037	.062
15	.045	.054	.048	.056	*	.036	.044	*	.047
Average	.051	.048	.056	.053	.112	.034	.045	.035	.052

*Data not available

**Subject could not complete the cycle

APPENDIX C

The Potential Heat Removal Rate of the Helmet

Maximum heat removal capacity of the helmet was calculated as follows:

Convection: The air velocity in the helmet was calculated by dividing the air flow rate by the area of the space between the head and the helmet, which was determined by projecting the periphery of the helmet and the wearer's head on a sheet of paper. The area bounded by these projections was measured by a planimeter. The air velocity was found to be 0.45 ft./sec. (0.14 m.)

Then, the heat loss by convection is (Fanger, 1967)

$$C = A_{du} \cdot f_{cl} \cdot h_c (t_{cl} - t_a)$$

where,

C = the convective heat transfer, kcal/hr.

A_{du} = the area of the head = 0.20 $m.^2$ (assumed)

f_{cl} = the clothing factor = 1

h_c = the convective heat transfer coefficient

= $10.4 \sqrt{V(\text{meters/sec.})}$

t_{cl} = the clothing temperature = the head temperature

= 35 C

t_a = the air temperature = 21.1 C

The convective heat loss was 11.4 kcal/hr. (45.6 Btu)

Radiation: The heat removed by radiation is

$$R = A_{du} \cdot \varepsilon \cdot \sigma \cdot (T_{cl}^4 - T_a^4)$$

where,

ε = the emissivity = 0.95

σ = the Stephan Boltzman constant =

= 4.96×10^{-8} kcal/m.^{2}/hr./K^4

T_{cl} = the head temperature = 308 K

T_a = the air temperature = 294.1 K

The radiation heat loss was 14.3 kcal/hr. (57.2 Btu)

Evaporation: The maximum heat removed by evaporation is given by the maximum amount of sweat that can be evaporated. Assuming the relative humidity of the incoming air to be 33% (determined by another experiment), the amount of water vapor picked up by the incoming air (at 70 F (21.1 C)) to be completely saturated at the head temperature (95 F (35 C)) is .031 lbs./lb. of air (Psychrometric chart in Leithead and Lind, 1964). The heat loss by evaporation is, then, given by

$$Q = .031 \times W \times L$$

where

W = mass flow rate of air = 29.3 lbs./hr. (Table 4).

L = Latent heat of vaporization of water

= 969 Btu/lb.

The evaporative heat loss was 895 Btu/hr. (223 kcal).

The potential heat removal of the helmet was the sum of the heat loss by convection, radiation and evaporation and was found to be 997 Btu/hr. (249 kcal).

PHYSIOLOGICAL EVALUATION OF AN AIR COOLED HELMET SYSTEM

by

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ABSTRACT

A ventilated hard hat helmet supplied with 6.5 cfm (0.18 $m.^3$/sec.) of air at 70 F (21.1 C) from a vortex tube was tested in a heat stress environment of 112 F (44.5 C), 60% RH and an air velocity of less than 50 fpm (0.25 m./sec.) on eight male subjects. Each subject was exposed to the heat stress twice with the helmet and twice without the helmet. The subjects walked in the heat environment at an estimated metabolic rate of 860 Btu/hr. (215 kcal). Heart rate, rectal temperature, head temperature, ear canal temperature, and mean skin temperature were recorded during 15 min. in a neutral environment, 45 min. in heat stress, and 15 min. in the neutral environment again. Urine and saliva samples were taken during prestress, stress, and recovery periods.

The helmet reduced heat storage in the body by 100 Btu/hr. (25 kcal), and the sweat rate by 24%. It lowered the rectal temperature, head temperature, and the ear canal temperature significantly ($p < .05$). The heart rate and the mean skin temperature were kept lower by the helmet but not significantly. There was no significant difference in the creatinine concentration in saliva with and without the helmet. It was concluded that, if the helmet was to be used at such thermal and metabolic rates, it should be provided with higher air flow rates, or the torso should also be provided with some air ventilated garment to prevent the environmental heat from flowing to the body by convection and radiation.