PHYSIOLOGICAL EVALUATION OF AN AIR COOLED

SHIRT UTILIZING DYNAMIC INSULATION

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DESH DEEPAK KUMAR AURORA

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Approved by:

Stephan Konz

Major Professor

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INTRODUCTION

Man has been able to survive and work in hostile climates, whether hot or cold, not only because he had in his possession an excellent thermoregulatory system, but also due to his behavioural response and his ingenuity in controlling the microclimate surrounding his body. Unfortunately, these limits of maximum and minimum tolerable temperatures do not extend to all climates. There are many situations in industry and in the armed forces where human operators are expected to perform exacting tasks either in very hot environments, or when essential protective clothing contributes to a thermal stress on a man. Sometimes this thermal stress is so severe that man's performance is likely to suffer after a relatively short time. High humidity, improper ventilation, polluted atmosphere, low air speed, high rate of work, and lack of acclimatization to surrounding conditions can make the going still worse. Examples of such conditions are found in deep mines, maintenance work in hot steel furnaces, fire fighting, space capsule during reentry to earth's orbit, tanks in the sun, man in lunar environments, agricultural operations, construction, cotton industry, etc. Air conditioning seems to be the ideal solution, as it reduces air temperature and humidity and also provides pure cool air for breathing purposes. However, in some situations it is impractical, and often impossible to alter the whole environment to one of comfort. Therefore, interest is focussed on a system which provides complete or partial refuge to only the individual when surrounded by a hostile environment. Examples of complete protection are the suits worn by divers working deep in the ocean and astronauts outside of their spacecraft. Partial protection, at a reasonable cost, of the industrial worker in a hot, humid, earth environment, without greatly obstructing his mobility, is the objective of this thesis.

Various methods of providing a heat relief to a worker have been tried at Kansas State University. Duncan (1969) successfully tried a water cooled headdress. Sharma (1970) used an air cooled helmet and a vortex tube to reduce the heat stress. Gandhok (1970) got comparable results with a PVC jacket supplied with cold air from a vortex tube. Byrnes (1970) found a jacket to be more effective than a hood from physiological viewpoint.

Sharma's helmet had an advantage of providing cool and pure air for breathing in addition to cooling the man, whereas Gandhok's jacket protected a larger body area from heat stress. A cooling system was therefore developed which incorporated the advantages of both the above methods and was compatible with the work clothes of an industrial worker. A physiological evaluation of this system is presented.

LITERATURE REVIEW

Health problems created by heat in the occupational environment are frequently encountered by the industrial physician and others responsible for the health, safety, and productivity of the worker. Unlike most other environmental factors, heat does not affect just one or two specific tissues or functions of the exposed person but affects the whole physiological economy in sometimes subtle, yet always complex, fashions. Physiological acclimatization to heat improves the capacity of man to work in the heat, but this does not mean that the dangers or the disadvantages of a hot environment are abolished.

P. 78 Edholm (1967)

EFFECTS OF HEAT

Man tends to have a built in safety mechanism. As he gets hot and body temperature rises, he becomes uncomfortable and instinctively he will reduce his work level. The slow pace of work that is observed in hot countries is not due to laziness; it is due to physiological causes (Edholm, 1967). Skilled tasks and work requiring close attention and mental work are affected at even lower levels of heat stress than relatively unskilled physical work. Another related cause of loss of efficiency in heat is an increased incidence of illness, especially a variety of skin complaints.

A number of studies conducted all over the world have proved that a deterioration in human performance occurs much before the limits of tolerance are reached. Some studies are cited below:

Leithead and Lind (1964) cite the studies of Weston (1922), Wyatt et al. (1926), and Vernon et al. (1927, 1928, 1931) to show the effect of heat on human performance. Weston and Wyatt reported a decrement in the output in the cotton weaving industry when the effective temperature was raised above 70 to 73 F (21 to 23 C). Vernon et al. found that accident rates were higher in hot coal seams than in cooler seams.

Further, Leithead and Lind (1964) cite the studies of Wyndham, Strydom, Cooke and Mantz (1959) on acclimatized recruits engaged in filling mining cars with rocks at effective temperatures ranging from 81 to 96 F (27 to 36 C). Defining the rate of filling mining cars at 81 F (27 C) as 100%, the rate dropped to 50% when the effective temperature rose to 93 F (34 C). Increasing the wind velocity from 100 fpm to 800 fpm increased the output significantly only when the temperatures were above 90 F (32 C).

Bell et al. (1964) studied the effect on 8 male subjects of exposure to climatic conditions ranging in severity from 76 F (24.5 C) to 117 F (47 C) effective temperature on the performance of visual and auditory vigilance tasks in two series of experiments. Exposure time was decreased with increasing climatic severity. When the performance was examined in terms of signals missed to signals given, there was no evidence of a change in vigilance with different climatic conditions; but in both experimental series, a greater proportion of signals were missed as body (oral) temperature increased.

Wyndham and Strydom (1965) cite the studies made by Weiner and Hutchinson (1945), Mackworth (1950) and Pepler (1952-54) to give quantitative expressions to the effects of heat on man's performance of various tasks. These studies showed a significant deterioration in the performance of specific tasks when the effective temperature of the air was increased from 81 F (27 C) to 86 F (30 C). Mackworth showed that although men under high incentives had a higher general level of performance, the percentage fall off in performance due to heat was the same for the highly motivated as for men under normal conditions. Effect of incentives on the performance of workers has also been reported by Givoni and Rim (1962). They found that it is possible to maintain the maximal ability in hot environments for short periods, provided high incentives are offered. Even the physiological responses (body temperature) of a human being are affected by the incentives (Rohles, 1969).

Wing (1965) cites the studies of Blockley and Lyman (1950), Viteles and Smith (1946) and Wing and Touchstone (1965) to give lowest test temperatures yielding reliable decrements at each of several durations of exposure. Four studies were assessed for one hour exposures and the threshold was placed over 90 F (32 C) effective temperature. The tasks used in these cases were comparisons of symbols, number checking and mental addition, estimation of collision courses of airplane-silhouettes, and short term memory for lists of English words. The tasks used for two hour exposures were mental multiplication of numbers under seventeen and location of faults in an electrical circuit. The limit for two hour exposure was found to be 89 F (32 C) effective temperature. Similarly for three and four hour exposures the thresholds were at 87.5 F (31 C) and 87 F (30.6 C). When the threshold temperatures were plotted against the exposure time an exponential relationship was found, the limiting temperatures decreasing at an exponential rate as exposure time was increased.

It has been found that a moderate increase in body temperature does not necessarily decrease the efficiency of muscular work. Parker and Riley (1968) studied the effect of heat stress on 16 basic dimensions of perceptual-motor performance under stress conditions of 86 F (30 C) effective temperature for periods of six hours. Six tests showed facilitation and two degradation of performance. There was no statistical difference in the remaining. The mean oral temperature of the subjects was 101.2 F (38.4 C) and pulse rate 111 beats/min.

Duncan (1969) had 9 subjects do addition problems in a heat stress environment of 112 F (44 C) and 58% RH. Task productivity was measured by the total number of columns added per minute. A decline of 13% in the productivity was observed in heat stress when compared to the productivity in the neutral environment of 85 to 90 F (29.4 to 32.2 C) dry bulb.

Before going into the problem of providing heat relief to workers, the conditions which result in the increase in the heat content of the body and the reactions of the body to counteract the effect should be discussed.

HEAT REGULATION

Heat may be produced in, received by, or lost from the body, but the total must be kept close to zero if the body is to function efficiently.

Metabolism. The processes which constitute life in an animal cell are, in net, exothermic in nature. With the liberation of heat, the relatively complex molecules of protein, fat and carbohydrates are broken down, usually by oxidation, into simpler waste products, such as carbon dioxide, water and urea. The amount of heat liberated varies with the state of the individual. The rate of heat liberation for an average man can be 400 Btu/hr (100 kcal) while supine or 3000 Btu/hr (750 kcal) and more for very hard work (Leithead and Lind, 1964).

Exchange With Environment. There are four main methods by which the human body can exchange heat with the environment; namely, conduction, convection, radiation and evaporation.

The conduction component of heat transfer is brought about by contact between the skin and a solid or liquid body at a different temperature. The rate of heat transfer depends upon the temperature difference, contact area and conductivity of the skin.

The convective component is the heat carried away from the skin by a mass of moving gas, usually air, surrounding the body. The convective currents formed set the fluid in motion. Some heat is also lost by the same phenomena occurring with the inspired air. The convective component of heat exchange depends on the velocity of air, available heat transfer area and temperature difference.

Heat loss due to radiation is dependent on the geometric arrangement of the man's body and the radiating surfaces. Heat exchange due to radiation depends on the temperature difference between skin and the heat sources.

The evaporative component of heat transfer is due to the evaporation of liquid (usually water). The body may lose water from the skin or the lungs. The evaporative heat loss depends on the wetted body area and the vapor pressure difference between skin and environment. Of course, air velocity and environment temperature also play an important role in the heat transfer by evaporation.

Control. In human beings, the channels of heat loss and gain are modified and, to some extent controlled, by his physiological mechanisms. The human organism will not survive a body temperature outside the limits of 75 to 113 F (24 to 45 C); in normal life the interior of the body is maintained at 98.4 F (37 C). The essential organ of temperature regulation is the skin. The temperature of skin, and hence the heat loss or gain by the body, is regulated by the rate of flow of blood through it. The working of the system is explained by Edholm (1967) as follows:

> "The size of the cutaneous vessels can be altered by relaxation or contraction of the muscles lining these vessels. The control is exercised by the central nervous system by means of nerves which supply these vascular muscles. These vasomotor nerves are, in general, constrictor, and by varying the number of impulses in the nerves the vessels can either be maximally constricted or, in the absence of impulses, fully dilated. In some regions there are vasodilator nerves, and impulses down these nerve cause the muscles to relax and the vessels to open. The degree of activity of the vasomotor nerve is controlled by the temperature regulating centre in the brain, which in its turn is sensitive to the temperature of the blood supplying it as well as impulses from the skin itself. The temperature centre acts as a form of thermostat set at approximately 37 C. As well as controlling skin temperature by regulating blood flow through it, the sweat glands in the skin are also under its control. The sudomotor nerves supply these glands and their activity is regulated by the number of nerve impulses reaching the glands. When stimulated, sweat is formed consisting of water with some salt dissolved in it."

Heat Balance. The heat balance for the body is given as (Drake et al., 1969):

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

where

$Q_{metabolic}$ = Heat generated by the oxidation of food

Q_{work} = Useful work output

$Q_{sensible}$ = Heat transfer by radiation, convection and conduction

Q_{latent} = Evaporative heat loss

Q_{stored} = Energy stored in the body in the form of heat

The limit to heat storage appears to have been reached when the total accumulation of heat in the body has reached 150 kcal (600 Btu) (Webb, 1969). If heat storage of the body is still increased, heat stroke, heat exhaustion, heat cramps, dehydration or susceptibility of the body to disease can result.

HEAT RELIEF

Haines and Hatch (1952) attribute the interchange of heat between man and his environment to the following factors:

1. Air temperature
2. Air velocity
3. Moisture content of air
4. Mean radiant temperature of the solid surroundings.

A number of methods have been tried in industries to reduce heat stress on the workmen.

Air conditioning seems to be the ideal solution, since it reduces air temperature and humidity at the same time. However, its cost is prohibitive when the places of work are of large volume, and where massive heat sources are concerned. Also, in the cotton industry, warm and moist atmospheres are maintained as these conditions are most suitable for cotton weaving, so air conditioning of the industry will only harm the process.

When air conditioning is not practical the heat load can be reduced by insulation, static or dynamic, of either the heat source or of certain work stations.

Static insulation is obtained by the use of materials which are poor conductors of heat. The efficacy of this solution is limited by the necessary thickness of the insulation and the increased exchange surface by convection and radiation from the heat insulating covering.

Dynamic insulation is obtained by putting a moving barrier of air between the heat and the object to be protected.

At industrial work stations, massive fans are installed to move large volumes of air at high velocities. The heat exchange then takes place by evaporation of sweat. However, if the air temperature is more than 95 F (35 C), an increase in air speed results in heat gain by the body due to convection.

The other method adopted is to give the workers heat relief by frequent rest periods to cool down. This procedure is useful up to a certain point, but if environmental conditions are such that rest time becomes substantial, it becomes apparent that this is inadequate as a means of heat relief.

Still another useful method is acclimatizing the workers to the hot environment. Generally speaking, however, the limits of human tolerance of heat stress are fairly fixed, and beyond these limits, means must be found of reducing the heat load, rather than seeking to adapt man to it.

INDIVIDUAL COOLING

Temperature control of only the air space that is adjacent to the skin surface is a theoretically sound means of providing heat relief for the man at work. The concept requires cooling only the comparatively minute air envelope, or microenvironment, that serves as a medium of nonradiant heat exchange about the clothed body. For the individual, it combines the two basic industrial hygiene practices of environmental control and personal protection.

Extensive research, in the past few years, has been done to develop extravehicular space suits which can take good care of the high thermal hazards present in the outer space.

These sophisticated suits, though highly efficient and capable of isolating the wearer completely from the outside environment, are not suitable for industrial applications for several reasons: the cost of such suits is very high, heat loads in industry are not great so such sophisticated suits are not necessary, mobility of the wearer is seriously hindered if heavy cooling garments are worn, etc. Keeping the above features in mind, these sophisticated suits should be carefully scrutinized to form a basis for the evolution of a simple cooling suit. All the four modes of heat exchange, that is, conduction, convection, evaporation of sweat and radiation have been tried in these suits.

Liquid cooled garments use conductive cooling methods. A tight fitting garment, with thin tubes attached, is worn by the wearer. Cold water flows through the tubes and heat transfer from the skin to the water takes place by conduction. This method is very effective in conditions of high temperature and humidity, when natural evaporation of sweat is not appreciable. Another method of conduction cooling is the evaporation of recycled water from wicks in contact with the skin. The 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. This method has the advantage of control simplicity, flexibility in handling the varying heat loads, etc. (NASA, 1965).

Gas ventilated garments use convective and evaporative mode of heat exchange. Gas or air, cooled by the external source, comes in contact with the body of the wearer and heat removal from the body takes place by the evaporation of sweat. If the temperature of the air ventilating the garment is less than the skin temperature, heat loss also takes place by forced convection. However, heat loads more than 1200 Btu/hr (300 kcal) cannot be removed by this method (NASA, 1965).

Radiation cooling involves a tight fitting suit worn by the men. Heat is first transferred from the skin to the suit by conduction from which the heat exchange with the environment takes place by radiation. Another method involves an air gap between the skin and the inner surface of the suit. For low air velocities the exchange of heat between the skin and suit takes place by radiation, from the inner layer to the outer layer of the suit by conduction and from the outer layer to the environment again by radiation. The maximum theoretical heat removal rates by these two methods are 1100 and 880 Btu/hr (275 and 220 kcals) respectively (NASA, 1965).

Superiority of liquid cooling over gas ventilated cooling has already been proven by a number of experiments (Veghte, 1965), but there are many disadvantages associated with liquid cooling. Inflexibility of this cooling method to cushion varying heat loads is the major drawback. In addition the moisture content of the environment cannot be removed, a individual suit has to be designed for each wearer to have the same contact area and they let the wearer breathe hot and polluted air of the surroundings. The advantages of air cooling are, the air needed for cooling is available in all factories so it needs no extra investment of a compressor, it can be safely passed over the man's skin so a given heat transfer rate can be maintained with very small temperature gradients and, for ground systems, weight and power are not critical factors.

It has been shown by Konz and Duncan (1969) that in normal situations, in an industry, heat load is much more due to metabolism than due to the environment. Unless a high temperature radiant source is present, heat loads of the order of 1000 Btu/hr (250 kcal) are not exceeded. From this discussion it follows that air cooling can be successfully employed for many industrial situations.

Work on air ventilated garments is not new. Fetcher et al. (1949) said that in 1904 a patent was granted on a "Body Ventilating Apparatus" and a number of others have been issued since. They cited the work of Houghten et al. (1941) (who reported increased comfort and efficiency of workers in a hot environment when a simple ventilating coverall was worn), of the Armored Medical Research Laboratory (1943-45) (where ventilated garments for use in tanks were tried), and of the Aero Medical Laboratory (1945) where tests were conducted to select a suit, airflow and temperature, for men doing moderate work for limited period at 165 F (74 C) in the Climatic Hanger of the Air Proving Ground Command.

Greider and Santa Maria (1957) conducted a study to determine subjective comfort in a full pressure suit at various ambient temperatures using different ventilating air temperatures at 5 cfm (.14 m^3). The experiments were conducted at an altitude of 18,000 feet (5,500 m.). Fifty two-hour runs were made. Ventilating air temperatures were 60, 75 and 90 F (15.5, 24 and 32.2 C) and ambient temperatures (t_a), maintained constant during each run, ranged from 40 to 120 F (4.4 to 49 C) in increments of 10 F (5.5 C). No significant difference was found in the establishment of the comfortably warm (t_a=92 to 107 F (33.3 to 42 C)), comfortable (t_a=65 to 92 F (18.3 to 33.3 C)), and comfortably cool (t_a=52 to 65 F (9.9 to 18.3 C)) zones with various air temperatures. Changing the ventilating air temperatures from 60 to 90 F (15.5 to 32.2 C) had no significant effect on total water loss and evaporative water loss, provided the subjects were maintained in the same degree of comfort. The comfortably warm state caused a significant increase in both the evaporative water loss and total water loss over that found in a comfortable state.

Crockford et al. (1963) tested a ventilated suit assembly for use in hot environments. The suit assembly was made of two special garments: (a) an undergarment, made of a double layer of plastic film, separated by a loose plastic filler; (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 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 the legs by preventing the garment from ballooning onto the skin, where air was supplied to the assembly. The design of the assemblies was such that only a portion of the ventilating air was delivered to the space between the two layers of the undergarment. The remainder of the air was carried through a separate tube to a spray system inside the helmet.

The volume of the ventilating air varied from 10-25 cfm (.28 - .71 m^3), its temperature was controlled to ± .9 F (.5 C), between 86 - 100 F (30 - 37.8 C). Fifteen men, wearing the air ventilated clothing assembly were exposed to an environment of 178 F (81 C) for one hour. During the first 55 minutes the subjects stood in the hot room and in the last 5 minutes marked time at an energy cost of 475 - 600 Btu/hr. (120 - 150 kcal). The temperatures of air tested were 86 F (30 C), 90 F (32.2 C), 95 F (35 C) and 100 F (37.8 C) and volumes 10, 15, 20 and 25 cfm (.28, .42, .57 and .71 m^3). At ventilating volumes of 15 cfm (.42 m^3) and over, the subjects were able to establish bodily thermal equilibrium in an hour, irrespective of the temperature of air, as judged by their oral temperatures and pulse rates. Thermal equilibrium was never reached when only 10 cfm (.28 m^3) was supplied. They recommended a minimum of 25 cfm (.71 m^3) air flow rate at temperatures not more than 86 F (30 C) for such suits.

The above study was extended by Crockford and Hellon (1964). They conducted a few experiments to determine the most suitable form of insulation for a hot entry suit for use primarily in furnace wrecking where mean radiant temperatures of 392 F (200 C) are met and where heat reflecting garments are unsuitable due to rapid deterioration of the reflecting surface. Four methods of insulation were tested: (1) a uniform layer of high thermal resistance; (2) a heat reflecting outer layer; (3) an internal layer of material to reflect radiant heat, that is, a radiant heat barrier; and (4) dynamic insulation. In conventional ventilated garments, the air flows parallel to the body hence it is not utilized for the transfer of heat in the most efficient manner. In dynamic insulation the air flows out radially through a permeable suit. Dynamic insulation was found to be a highly efficient method for insulation.

Three types of material were tested for thermal conductance: (1) a foamed plastic, covered on both sides with neoprene coated terylene; (2) a radiant heat barrier constructed from string vest material, covered on both sides by a layer of aluminum which in turn was covered on both sides by thin cotton fabric; and (3) three different materials suitable for dynamic cooling. The radiant heat barrier had only a slightly lower thermal conductance than the foam plastic. When the conductance of unventilated foam plastic was compared with the conductance at an air flow rate of 2.32 cfm/ft^2 (.35 $m^3/min/m^2$), there was more than a fivefold decrease.

Four types of suits were tested: (1) a permeable suit made from .4 in. (1 cm) thick polyurethane foamed plastic bounded on each side by a layer of cotton fabric; (2) An impermeable suit made from the above material but bounded by impermeable neoprene-proofed terylene; (3) a radiant heat barrier suit made from two layers of aluminized fabric and kept about .4 in. (1 cm) apart by a spacer and (4) a suit similar to number 3 but constructed without the reflecting layers. No. 3 and 4 were discarded after two runs as they were found to be very heavy and cumbersome. All suits were tested with a standard air supply of 45 cfm (1.3 m^3) at inlet temperatures of 71.6 to 73.4 F (22 to 23 C). The radiant heat chamber had a mean radiant temperature of 374 F (190 C) and air temperature of 162 F (72 C). Five subjects performed a stepping task with a metabolic rate of 1000 Btu/hr (270 kcal).

With the air flow used in these experiments, dynamic insulation had a thermal conductance one fifth that of conventional static insulation, and sweat loss and oral temperature rises were reduced by one third and one half respectively.

Linehard et al. (1964) developed a new method for the relief of heat stress as encountered in some hot industrial processes. The equipment worn by the subject consisted of: 1) an enclosed vortex cooling unit attached by a belt to man's waist, 2) a simple air harness of perforated, flexible, noncollapsible plastic tubing worn over the upper trunk and under ordinary work clothing, and 3) an insulated, air supplied fabric hood and vest. The air escaped through the cloth and from beneath the fabric hood. One acclimatized workmen was exposed to an environment of 130 to 136 F (54.4 to 57.7 C) dry bulb and 20% RH. The task consisted of raising and lowering a 50 lb (22.7 kg.) weight every 5 seconds. The ventilating air temperature was between 65 to 80 F (18 to 27 C) with a flow rate of 20 cfm (.56 m^3). The subject was exposed to heat stress with and without the vortex tube for 60 minutes.

Without the vortex tube, the subject had to stop the work after 22.3 minutes due to nausea. With the vortex tube, the cumulative heart beats in 22.3 minutes of work were 2579, as compared to 3430 without. Without the vortex tube, the peak heart rate was recorded at 185 beats/min., only 20 minutes after the start of work. With the vortex tube cooling the peak heart rate did not exceed 160 beats/min. during the complete 40 minute work period. During the initial 35.3 minutes of exposure (work and rest) that were completed in each instance, the rectal temperature rose by 3.7 F (2 C) without the vortex tube, but only 1.6 F (.9 C) with the vortex tube. Use of the cooling device reduced the rate of accumulation of heatin the body by 50% and sweat loss threefold.

Veghte (1965) tested three different air distributing systems and one water cooling system under the Air Force operational full pressure suit (A/P 22S-2), with the suit unpressurized, and pressurized at 7.5 in. (192 mm) of Hg. 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 the central exit; and (3) the separate USAF MA-1 ventilating garment. Five subjects participated in experiments conducted at atmospheric pressure and a temperature of 109 F (43 C).

Temperature, humidity and flow rate of ventilating air were regulated by an elaborate commercial air conditioner to 69.8 F (21 C) and 5 cfm (.14 m^3). Water flow rate, in the water cooled garments, of 2.2 lbs/min (1 kg) was maintained at a temperature of 69.8 F (21 C).

Mean skin temperatures varied from control values of 93-95 F (34 to 35 C) up to 97 to 98.5 F (36-37 C) by the end of the air ventilating exposures. The average skin temperatures after 60 minutes were within .4 F (.2 C) of the original value. Skin temperature during the water cooled experiments remained in the comfort range and varied between 91.4 to 93 F (33 and 34 C). Tolerance times varied in the control, non-ventilated exposures from 60 to 95 minutes with little difference between pressurized and unpressurized conditions. Rectal temperature increase with the pressurized suit was 2.1, .5 and -.5 F (1.2, .3 and -.3 C) under control, ventilated and water cooled systems respectively; in the unpressurized suit the values were 2.5, .2 and -1.1 F (1.4, .1 and -.6 C) respectively. Air ventilating suits prevented serious heat storage but only with sweat losses of significant magnitude. The water cooled system proved superior to all of the air ventilating systems.

Van Pattern and Gaudio (1968) used a vortex tube for ventilating the air cooled garment for USAF aircrews. Three men were exposed to an environment of 130 F (54.5 C) and 44% RH with and without vortex tubes. During the control session, subjects wore thermal underwear only. In the experimental session they wore thermal underwear, the MA-3 cooling garment and a standard summer flying suit. The vortex tube supplied 10 cfm (.28 m^3) of air at 60 psi pressure, dry bulb temperature 63 F (17.5 C) and 42% RH.

In the control session, subjects were exposed for durations determined by subjective tolerance (30-50 minutes). In the experimental session, the upper limit of exposure was arbitrarily set at a time duration 100% greater (60-100 min.) than tolerance time without air cooling. The vortex tube cooling system prolonged the duration of heat exposure 100% over that resulting from exposure without cooling. At the termination of heat exposure, the subjects felt relatively well and, by physiological parameters, had not approached the limit of their thermal tolerance. This air cooling device significantly minimized the heart rate and rectal temperature changes that characteristically occurred as a result of thermal stress.

Croley (1969) has reported the use of a vortex tube to cool air for individual workers at Savannah River who are frequently required to work in atmospheres containing gases or dusts that are radioactive or chemical poisons. At Savannah River, personnel were supplied with air by: (1) large air distribution systems with centrally located compressors and chillers, (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 back packs. All these equipments were heavy, cumbersome, expensive and difficult to decontaminate. A simple, lightweight and inexpensive vortex tube was therefore tried. The vortex tube supplied air at 16 to 18 cfm (.45 to .51 m^3) at temperatures that were 50 to 60 F (10 to 15.6 C) colder than the inlet air temperature to a two piece plastic suit made of 6 mil PVC. Croley reported that this system is working satisfactorily at the Savannah River under various environments.

Three experiments have been conducted at Kansas State University using the method of air cooling.

Sharma (1970) supplied cold air at the rate of 6.5 cfm (0.18 m^3) and 70 F (21 C) from a vortex tube to a hard hat helmet. The effectiveness of this cooling system was tested on eight subjects exposed to a heat stress of 112 F (44 C) and 60% RH with and without the helmet. Subjects walked at a pace of 2 to 2.5 mph for 45 minutes in the heat stress environment. 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. He concluded that, if the helmet was to be used at such thermal and metabolic loads, it should be provided with higher flow rates, or the torso also should be enclosed with some air ventilated garment.

Gandhok (1970) used various air flow rates from a vortex tube with a .005 inch thick PVC jacket in an environment of 112 F (44.5 C) and 60% RH. Two subjects walked at 2 mph for 45 minutes under the stress conditions. Vortex tube outputs tried were 6.8 cfm (.19 m^3) at 68 F (20 C), 5.1 cfm (.14 m^3) at 64 F (17.7 C) and 4.4 cfm (.12 m^3) at 62 F (16.6 C).

The jacket kept mean skin temperature under the jacket, head temperature and rectal temperatures significantly lower than under the no jacket condition. The overall performance of the jacket was found to be better at 6.8 cfm (.19 m^3) at 68 F (20 C) and 5.1 cfm (.14 m^3) at 64 F (17.7 C). However both volumes were found to be inadequate and higher volumes, of the order of 25 cfm (.71 m^3), were recommended.

Byrnes (1970) compared the performance of the helmet and the jacket with six subjects in a heat stress environment of 110 F (43 C) and 60% RH. The ventilating air was supplied at the rate of 35 cfm (.99 in^3) and temperature of 70 F (21 C). The task consisted of alternately walking at 2 mph for 5 minutes on a treadmill sloped at 5%, and resting for 5 minutes during the 40 minute exposure to the heat stress. The jacket kept the sweat rate, heart rate, and the heat storage lower than the helmet. However, the subjects preferred the helmet due to the refreshing feel of the cooler air and easier breathing.

PROBLEM

For maintenance of thermal comfort in a hot environment a man must remain substantially in a steady state of heat balance. This implies that there will be a requirement to remove an amount of heat given by the sum of the heat flow from the environment, through the clothing layer and the exposed skin, and the sensible component of the man's metabolic rate. Usually, in the conditions which necessitate the use of cooling systems, the environment component of heat is less than the metabolic component. Hence the problem, essentially, is one of providing a comparatively minute envelope of cool air around the workmen. For the individual, it provides respiratory protection in addition to heat relief.

As mentioned before, a number of different suits have been tried successfully. But they all suffer from some serious drawbacks that prohibit their widespread application in industry. Essentially, to be acceptable, a cooling system should be:

1. cheap
2. trouble free and easy to maintain
3. light in weight
4. compatible with ordinary work clothes
5. should not restrict the mobility of the person while working
6. provide good protection from heat.

As all these characteristics are difficult to be incorporated in a single design; a compromise has to be made. To include as many of the above features as possible, we designed a system to cool only a portion of the human body.

Several experiments conducted at K.S.U. used cooling headwear. An air cooled helmet with a vortex tube (Sharma, 1970), though only a partial success from physiological viewpoint, provided clean cool air for breathing. It had the disadvantage of restricting the range of vision and was inconvenient to the wearer, besides protecting only 15% of body area from direct radiation. The air cooled jacket (Gandhok, 1970), though covering a larger body area, had improper air circulation inside the sleeves, partially restricted the mobility due to ballooning of the jacket, and did not provide any relief to the wearer from breathing hot air from the environment. The vortex tube used in the above experiments provided unmuffled cold air. The hot air exhausting from the rear end of the vortex tube formed a hot spot directly at the back of the subject. Byrnes (1970) found that people tend to like the cooling system which provides cool fresh air for breathing, even though it may not be the best from physiological viewpoint.

The proposed cooling system has an ordinary cotton shirt, fitted with plastic tubing for better circulation of cold air around the torso and upper arms, and an acetate cylinder to guide the cold air from the shirt onto the face. This design seems to include most of the features listed above. The other advantage of the system is that it incorporates the proven idea of dynamic insulation. A portion of the cooled air inside the shirt escapes out through the pores of the material and forms a cold layer outside. This acts as an additional layer to keep the heat away. As the sleeves of the shirt extend only to the elbow, the mobility of the man is unhindered.

The purpose of the experiment was to evaluate the effectiveness of the above described cooling system from the physiological point of view and compare its performance under various heat environments.

It was decided to supply 25 cfm (.70 m^3) of cooled air at 68 F (20 C) and 22% RH to the cooling system. Crockford, et al. (1963) recommended a minimum of 25 cfm of dry air at temperatures less than 86 F (30 C) for overall suits. In this experiment only 45% of the body area was to be covered. Assuming 50% of the air to leak out of the shirt due to its porous nature, 25 cfm of air at 68 F (20 C) was thought to be sufficient. Crockford and Lee (1967) recommended relatively dry air for ventilating a heat protective jacket, for cooling rates of less than 960 Btu/hr (240 kcal). Since in the proposed experiment, lower heat removal rates were expected, air with relative humidity of the order of 22% was used. Specifically, the effectiveness of an air cooled jacket, with an air flow rate of 25 cfm (.70 m^3), temperature 68 F (20 C) and relative humidity of 22%, was tested in the following 3 environments:

Environment 1. 104 F, 90% RH and air velocity less than 50 fpm

Environment 2. 112 F, 65% RH and air velocity less than 50 fpm

Environment 3. 130 F, 35% RH and air velocity less than 50 fpm

The effective temperatures in all the above environments were 100 F (38 C). The criteria were:

1. Heart Rate
    a. Increase in heart rate due to exposure (beats/min.)
    b. Extra cumulative heart beats during 30 min. exposure (beats)
    c. Reduction in the heart rate variability during the exposure (standard deviation of the interbeat intervals, seconds)
2. Increase in the mean skin temperature due to exposure (F)

3. Increase in the head temperature due to exposure (F)
4. Increase in rectal temperature due to exposure (F)
5. Sweat loss (gms/hr/m^2 of body area)
6. Change in the concentrations of creatinine, sodium, potassium, and amylase in saliva at the end of exposure and recovery (meq/liter)
7. Subjective evaluation of the cooling system.

METHOD

Task

The subjects were required to move a 5 lb. weight, back and forth through a distance of 5 feet. See Fig. 6. Two 28 in. high stools were arranged, one on either side of a 34 in. high table. The centers of the stools were 5 feet from the center of the table. Two 5 lb. bricks were placed on the table. The subjects lifted one brick with one hand, walked to the other stool, and placed it on the stool in 10 secs. Then they brought the brick back to the table again, in 10 seconds. Their pace was timed by an electronic timer, which clicked every 10 secs. The subject with the air ventilated shirt moved the brick from the table to the stool on the left, whereas the subject without the shirt moved it to the stool on the right.

Subjects

Four male undergraduates served as subjects. Table 1 gives their general physical characteristics. They wore only cotton shorts and socks during the test. The socks were provided to them, but they had to bring their shorts. They were paid $5.00 for each day of participation.

Table 1

General Characteristics of the Subjects

Subject	Age (years)	Weight (lbs)	Height (in.)	Body Area (m^2)	Build
1	18	137	69	1.70	Slender
2	21	172	71	1.98	Athletic
3	20	198	69	2.06	Stocky
4	22	148	67	1.81	Average
Mean	20.3	163.7	69	1.89	

APPARATUS

Test Chamber. The experiment was conducted in the KSU-ASHRAE environmental test chamber, located in the Institute for Environmental Research at Kansas State University. The chamber has been completely described by Nevins, Rohles, Springer and Feyerherm (1966). The air temperature, wall temperature, humidity and air flow in the 12 x 24 room were accurately controlled. The pretest room, adjoining the test room, housed the monitoring equipment and the air conditioner. Fig. 1 shows the layout of the pretest room. The objective of maintaining an environment of 80 F in the pretest room was not achieved due to the hot exhaust from the air conditioner. The environment temperature in the pretest room was 85 - 90 F (29.5 - 32.2 C).

Cooling System:

Shirt. A cotton shirt, "Big Mac", Sanforized VDR 7064, collar size 18", was acquired from J. C. Penneys. A portion of the sleeves was cut off, so that they extended to the elbows only. The collar and the shirt tail were cut off, and the ends were folded to run strings through them. Five, 2" long loops were sewed on the lower part of the shirt for passing a belt. The buttons in front were removed and replaced by a 1/2 inch wide velcro lining.

Two 3 inch long pieces of 5/8 inch ID copper tubes were inserted in a 1 3/4 inches diameter hard plastic tube connector at angles of 75 degrees as shown in Fig. 2. The one inch portion of the tubes inside the connector was cut off half way through the diameter. A 1/8 inch thick plastic disc with a 3/4 inch diameter hole was taped at the top of the hose connector.

EXPLANATION OF PLATE I

Fig. 1. View of the pretest room, housing the monitoring equipment and the air conditioner. Subjects 1 and 2 are sitting in the adjoining room, while their heart rate and temperatures are being monitored. The closed circuit TV system was used to monitor their activity. The dew point meter is on the air conditioner.

PLATE I

Fig. 1

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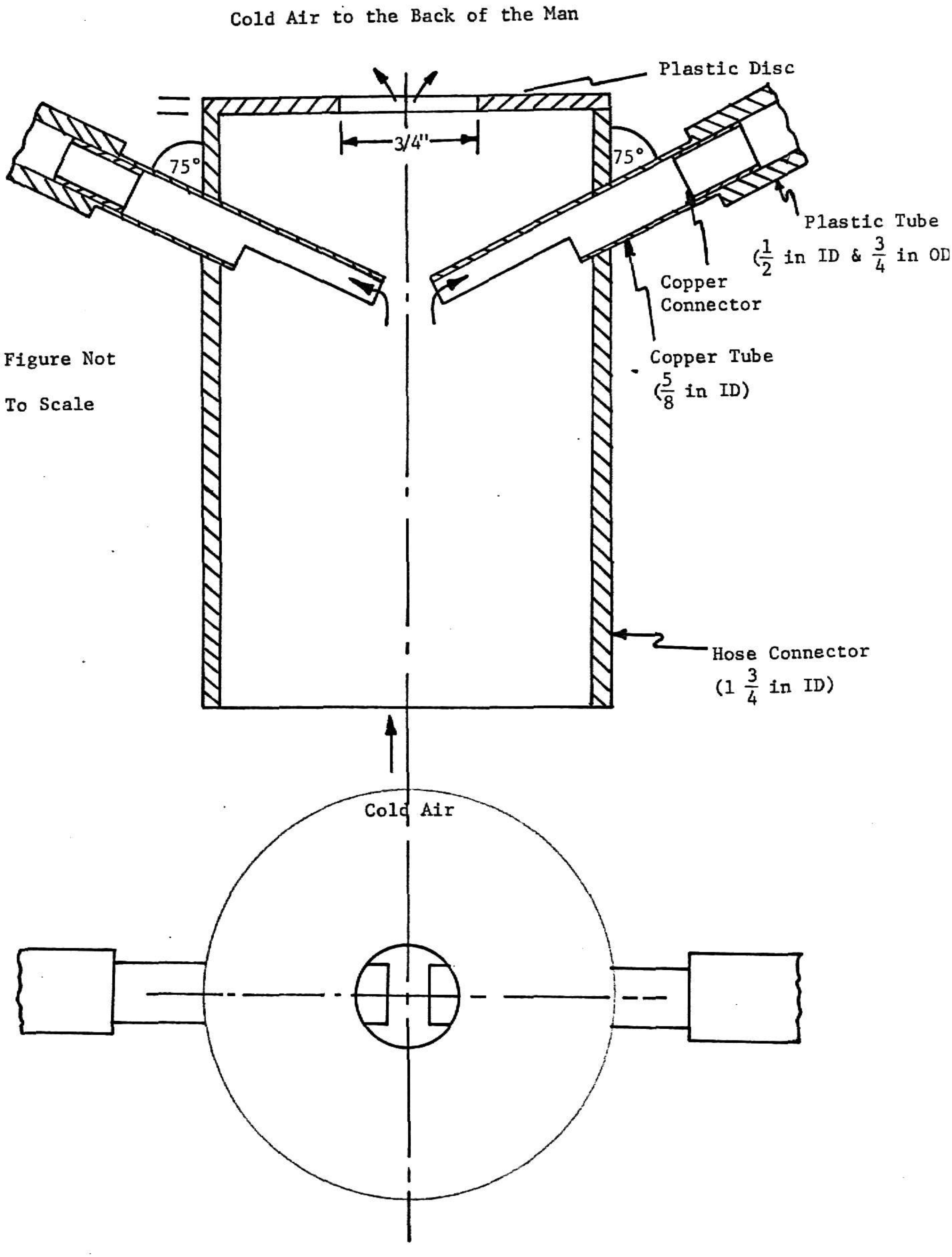

Fig. 2. Hose Inlet Assembly

A circular hole was cut off at the back of the shirt and this assembly was inserted in it. The other ends of the copper tubes were connected to a 1/2 inch ID and 3/4 inch OD and 9 feet long flexible plastic tubing, by a small copper connector. The tube was sewn to the shirt and taped with the heavy duty duct tape as shown in Fig. 3. The two U bends occurring in the plastic tube were replaced by two copper tube (8" long and 1/2 inch diameter) U bends. Sixteen slots, each 1/8 inch wide and 1/2 inch long, were cut in the section of the tube passing over the front portion of the body. Two of the slots directed the air into the sleeves. To maintain an air gap between the body and the shirt, a 1/16 in. diameter flexible wire was bent in the form of a ring and taped to the inside of the shirt.

A 10 inch high truncated cone, 10 inches in diameter at the top and 8 inches at the bottom, and made of .010 inch thick acetate sheet, served as a hood. A 5 inch wide and 50 inches long piece of nomex was sewn in the form of a skirt, and was taped to the lower end of the hood. This, when taped to the shirt, prevented the air from escaping to the environment from the bottom of the hood.

A 6 foot long flexible hose, insulated by a 1/8 inch thick 2 inch wide self adhering tape (made by Armstrong Cork Co., Lancaster, Pennsylvania), led air to the shirt.

Cooling Device. A modified Fedders, 23,000 Btu/hr. (5750 kcal) window type airconditioner was used to supply cold air to the system. The flow rate, temperature and the humidity of the cold air from the air conditioner were adjustable. Three blowers of 1/30 H.P. each were connected in series with

EXPLANATION OF PLATE II

Fig. 3 Inside view of the cooling shirt. The inlet hose assembly is at the bottom of the shirt and the two U bends, made from flexible copper tube, can be seen at the upper portion of the left and right side of the shirt.

PLATE II

Fig. 3

the air conditioner to increase the static pressure of the cold air. All the above connections were made by a 4 inch diameter flexible hose, which was insulated by glass wool. The whole of the above assembly was located in the pretest room.

An asbestos tube, 4 inches in diameter and 18 inches in length, fitted with a 90 degrees bend, which in turn was connected to the third blower, led the air into the test room. The other end of the asbestos tube was connected to the 2 inch diameter insulated flexible hose by a reducer made from foam rubber. The hose led the air to the jacket.

Instrumentation

Velocity Meter. An Alnor velometer, type 3002, range 0 to 2500 fpm and fitted with Jet no. 2220, was used to measure the air velocity. The pitot tube was inserted in the asbestos tube. The effect of the static pressure on the readings of air velocity was balanced by also inserting the balance tube of the velometer into the asbestos tube.

The instrument is calibrated to give the air velocity in fpm.

Dew Point Meter. The dew point of the air leaving the air conditioner was measured by a Cambridge System Dew Point Hygrometer, Model 990.

The sample of the cold air, for measuring the dew point, was taken at the outlet of the air conditioner.

Heart Rate Recorder. A Beckman Dynograph (Type RS) was used to record the heart beats of the subjects. Three E and M Instrument Co. surface electrodes were pasted and taped to the left side of the chest, near the heart.

The leads of these electrodes were connected to a junction box, worn around the waist by a belt. Electrical impulses received by these electrodes were transmitted to a DC amplifier. The output appeared as a series of peaks on a continuous roll of graduated paper, moving at a speed of 25 mm/sec. See Fig. 4.

YSI Skin Temperature Thermistors. Yellow Springs Instrument (YSI) thermistors, model 409, were used to measure skin temperature. The temperature sensitive area of the thermistors was 3/8 inches (9.5 mm) in diameter and 1/16 inches (1.6 mm) thick. One side of it was coated with ceramic and the other had a shining surface. These were held at the desired skin location by a heavy duty tape, with the shining surface of the thermistor pressing against the skin.

Rectal Probe. The deep body temperature was measured by inserting a 3/32 inch (2.28 mm) dia., YSI model 401, flexible thermistor to a depth of six inches in the anal canal of the subjects.

Digital Thermometer. The temperatures of the various parts of the body were measured by a United Systems Corporation digital thermometer, model 500. The leads of the various thermistors were connected to a junction box, which in turn was connected to the two channel digital thermometer. It could measure and visually display the temperatures recorded by 20 thermistors to an accuracy of .1 F (.055 C). The temperature range for this instrument was 59 to 122 F (15 to 50 C). Four knobs, numbered 0-9, could be used for identification purposes. The selector switch selected

EXPLANATION OF PLATE III

Fig. 4. Subject 2 with the skin and heart sensors on. The leads of the skin sensors are plugged into a junction box, which in turn is connected to the digital thermometer. The leads of the heart sensors are plugged into another junction box, worn by the subject on his waist by a belt, which is connected to the Dynograph.

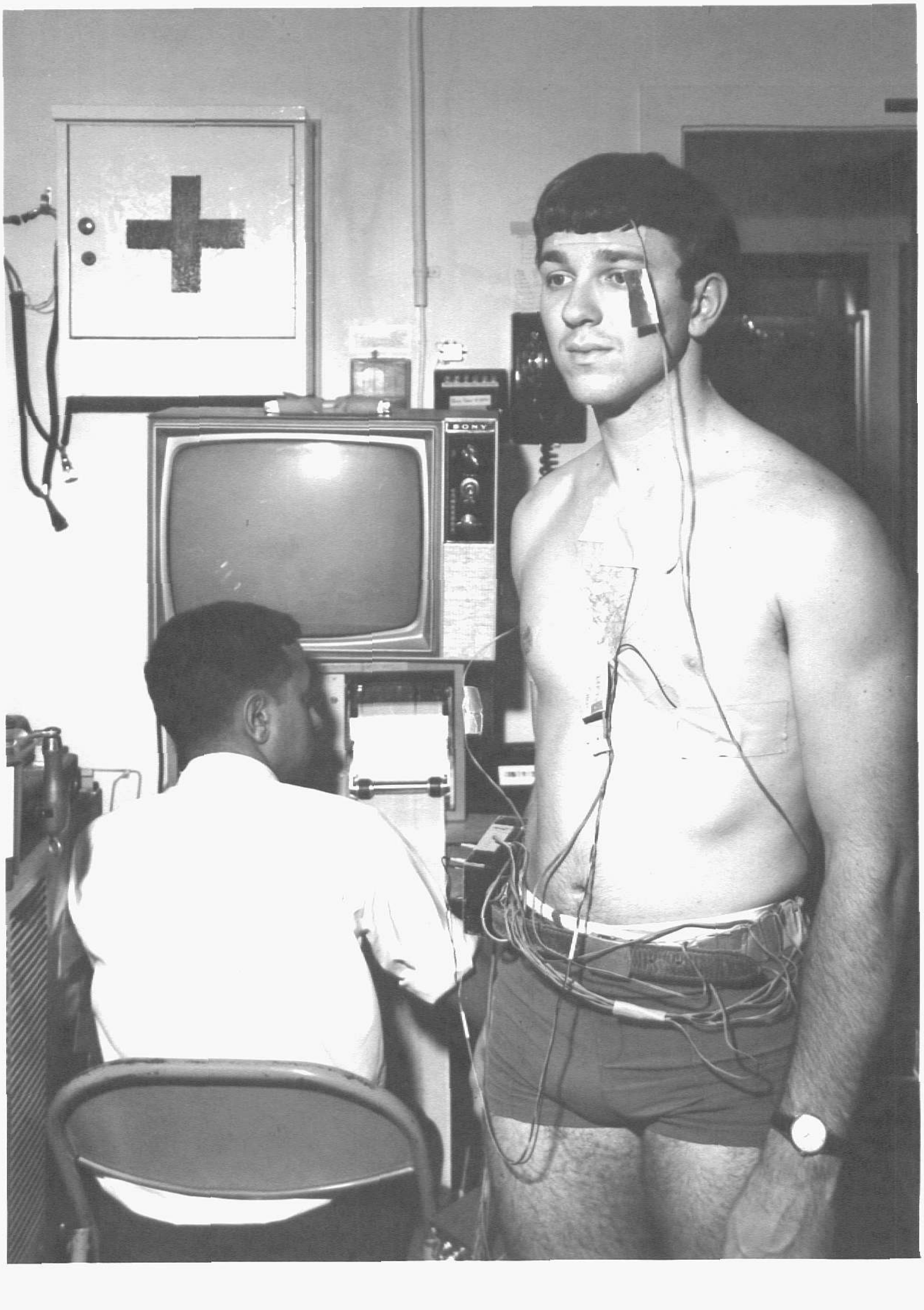

Fig. 4

the proper thermistor. The identification numbers and the corresponding temperatures could be printed on the paper tape by pressing the print button. The output was in 9 columns. The first four columns were the identification numbers and the last five, temperatures.

Beam Balance Platform Scale. A Fairbanks Morse & Co. Beam Balance Platform Scale was used to measure the weights of the subjects. The accuracy of this scale was .01 pounds.

Video Kit. A Sony Video Camera, model VCK-2100A, was connected to the Sony Video Recorder, model CV-2100, which in turn was connected to Sony TV Monitor, model CVM-1800. This camera, with a wide angle lens, was kept in the test chamber; the monitor with the recorder was kept in the pretest room. Thus the activities of the subjects while in the test chamber were watched continuously.

Electronic Timer. The movements of the subjects were paced by Grason-Stadler Company Electronic Timer, model E1100H. A light flash, which was followed by a beep, occurred after the adjusted interval of 10 seconds. In the present experiment, the instrument was switched to "Interval" and "Recycle".

Procedure:

Each day was divided into two, 2 hour sessions: session 1 started at 2:30 pm and session 2 at 4:30 pm. Subjects 1 and 2 were in session 1 and subjects 3 and 4 in session 2.

On the first day of the experiment the basal values of the various physiological parameters of the subjects were measured. The subjects were told repeatedly that they would not be exposed to the heat stress on that day. On the first day the subjects were weighed nude and their heights measured. Heart rate sensors and six skin temperature sensors were then placed on them. The skin sensors were located at left brow, left chest, left back, right upper arm, left thigh and left calf. Each subject inserted a rectal temperature probe to a depth of six inches. The subjects then sat on the chairs in the pretest room. At the end of 15 minutes of rest, the various temperature and heart rates were monitored every 5 minutes, for 30 minutes. The subjects then removed their sensors, dressed and left.

On the following six days, each subject was exposed to each of the three environments, once with the shirt and once without. Table 2 shows the testing schedule of the subjects with and without the shirt and in the three environments.

The test sessions were divided into three periods, as follows:

Period 1 (Duration 45 minutes): Subjects were weighed nude. The first saliva sample was taken. Heart rate, rectal and skin temperature sensors were put on. The location of the sensors was the same as on the first day. Fig. 4 shows subject 2 with the sensors. The subjects then sat on the chairs and their heart rates and temperatures were monitored every 5 minutes, for 10 minutes. In the last 5 minutes of this period, the second saliva sample was taken.

The subject who was scheduled to wear the shirt then donned the shirt and

Table 2

Testing Schedule

Date	Environment	Session	Subject 1	Subject 2	Subject 3	Subject 4
Oct. 31st	1	1	S	NS		
		2			NS	S
Nov. 3rd	3	3	NS	S		
		4			S	NS
Nov. 4th	2	5	S	NS		
		6			NS	S
Nov. 5th	2	7	NS	S		
		8			S	NS
Nov. 6th	3	9	S	NS		
		10			NS	S
Nov. 7th	1	11	NS	S		
		12			S	NS

NS Without Shirt

S With Shirt

Environment 1 104 F, 90% RH, air velocity < 50 fpm, 100 F Eff. Temperature

Environment 2 112 F, 65% RH, air velocity < 50 fpm, 100 F Eff. Temperature

Environment 3 130 F, 35% RH, air velocity < 50 fpm, 100 F Eff. Temperature strings at sleeves, waist and neck were tightened. The shirt was further tightened at the waist by a belt. The hood was then placed over him and was taped to the shirt. Fig. 5 shows subject 1 with the cooling outfit.

Period 2 (Duration 30 minutes): Subjects entered the test chamber. The hose carrying the cooled air was connected to the shirt. The string at the neck was then tightened or loosened, as required to have maximum air flow over the face.

The subjects moved a 5 lb. brick through a distance of 5 feet in 10 seconds. Their heart rate and various temperatures were monitored every 5 minutes. After 15 minutes in the test chamber, the third saliva sample was taken. The experimenter then measured the dry and wet bulb temperatures of the air leaving the shirt. A sling psychrometer was lowered into the hood and the bulbs of the two thermometers were held near the neck for about 5 minutes. The two temperatures were then read. The velocity of the air in the hose was measured by the velometer at the beginning, middle and end of the test. Fig. 6 shows subjects 1 and 2 inside the test chamber.

Period 3 (Duration 15 minutes): The subjects left the test room and immediately were draped with sheets. The shirt was taken off and the subjects were seated on the chairs. The fourth saliva sample was taken. Their heart rates and various temperatures were again monitored, every 5 minutes, for 10 minutes.

At end of this period, their sensors were removed, their body dried with towels and they were weighed nude. The subjects gave their fifth saliva sample before leaving.

EXPLANATION OF PLATE IV

Fig. 5 Subject 1 wearing the air ventilated shirt and the hood. The skin sensors are plugged into the junction box in subject's left hand.

Fig. 5

EXPLANATION OF PLATE V

Fig. 6 View of subjects 1 and 2 inside the test chamber.

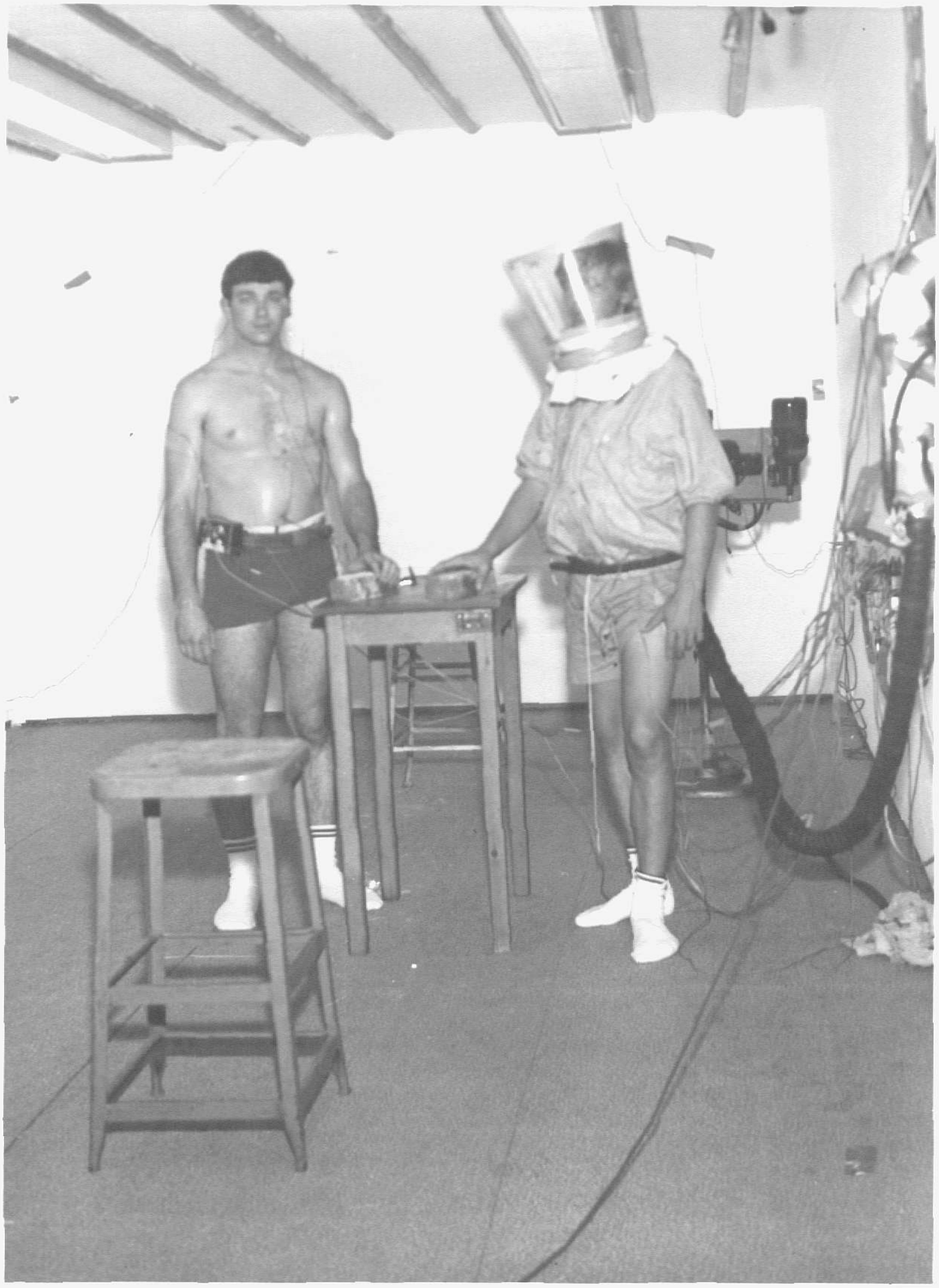

Fig. 6

Measurements:

Mean Skin Temperature. The skin temperature sensors were located on the right upper arm, left chest, left thigh and left calf. The mean skin temperature was calculated by Ramanathan's formula (Mitchell and Wyndham, 1969).

$$\text{Mean Skin Temperature} = 0.3\ (C + D) + .2(H + J)$$

where

C = Chest Temperature

D = Upperarm Temperature

H = Thigh Temperature

J = Calf Temperature

Head Temperature. The head temperature was measured at the forehead, above the left brow.

Rectal Temperature. The rectal temperature was measured by a rectal probe inserted to a depth of 6 inches in the anal canal.

Air Temperature.

Inside Shirt: The temperature of the air ventilating the shirt was measured by the skin temperature sensors, located at three locations. The first sensor measured the inlet air temperature in the hose carrying cold air, at the junction of the hose and the shirt. The second sensor was located on the inside of the shirt, matching with the position of the sensor on the right arm. The third sensor was located inside the shirt, matching with the position of the sensor at the chest.

Outside Shirt: The temperature of the air surrounding the shirt was measured by two skin sensors taped on the outside of the shirt. One sensor was located on the right sleeve, matching with the position of the skin sensor at the right arm and the other matched the position of the sensor at the chest. The mean of these two temperatures gave the average ambient air temperature surrounding the shirt.

Volume of Air. The volume of air delivered by the air conditioner to the shirt was calculated from the velocity of air in the 4 inch hose carrying cold air from the air conditioner. The volume of air delivered per minute was calculated from the following formula

$$Q = \frac{\Pi}{4} \times \frac{d^2}{144} \times V$$

where

Q = Flow rate, cfm

d = Diameter of the hose at the point where velocity is being measured, inches.

V = Velocity of air, fpm

The mean of the three readings of air velocity taken during the test gave the average air velocity in the hose.

RH of Air. The relative humidity of the incoming air was calculated from the dew point temperature and the dry bulb temperature of the air. Table 3 shows the volume, temperature and humidity of cold air on each day.

Table 3

Temperature and Flow Rates of Cooling Air

Environment	Subject	Air Flow Rate (cfm)	Air Flow Rate lbs/hr	Air Temperature (F)	Dew Point (F)	Relative Humidity (%)	Humidity Ratio lbs of water/ lb of dry air
1	1	26	117	70.4	30	22	.0035
(104 F, 90% RH)	2	24	108	70.4	20	13	.0021
	3	26	117	70.4	30	22	.0035
	4	26	119	60.6	23	23	.0024
Mean		25.5	115	67.9	26	20	.0029
2	1	24	109	64.5	24	20	.0026
(112 F, 65% RH)	2	26	117	69.0	24	17	.0026
	3	24	109	64.1	28	24	.0031
	4	26	117	71.0	22	17	.0024
Mean		25	113	67.1	25	19	.0027
3	1	26	116	72.8	21	13	.0022
(130 F, 35% RH)	2	26	117	70.0	32	24	.0038
	3	26	119	60.8	27	26	.0030
	4	26	115	69.2	28	20	.0031
Mean		26	117	68.2	27	21	.0030
Grand Mean		25.5	115	67.7	26	20	.0029

RH of Outgoing Air. Relative humidity of the air leaving the shirt was calculated from the dry and wet bulb temperatures. Table 4 shows the temperature and humidity of the air leaving the shirt.

Body Area. The body area of the subjects was calculated from the DuBois nomogram (Grollman, 1964). From the weight of the subject in pounds and the height in inches, the body area can be read in square meters.

Heart Rate. The heart rate of the subjects was monitored for about 20 seconds, every 5 minutes.

Sweat Loss. Sweat loss of the subjects was calculated from the nude weight of the subjects before the start of experiment and at the end of recovery and the weight of water consumed in this duration.

Sweat loss = Initial weight - weight at end of recovery
+ Weight of water consumed between two weighings.

Incidentally, in the present experiment the subjects did not consume water between the two weighings.

Saliva Samples. Five saliva samples of the subjects were taken each day. The first sample was taken when the subjects arrived for the test, the second one was just before they entered the heat stress chamber, the third was 15 minutes after their entry to the test chamber, the fourth, just after leaving the test chamber and the fifth, at the end of recovery. Each test tube was marked with the name of the subject, date and sample

Table 4

Temperature and Humidity of Air Leaving the Shirt

Environment	Subject	Dry Bulb Temperature (F)	Wet Bulb Temperature (F)	Relative Humidity %	Humidity Ratio lbs of water/lb of dry air
1	1	*	*	*	*
(104 F, 90% RH)	2	87	75	57	.0160
	3	*	*	*	*
	4	*	*	*	*
Mean		87	75	57	.0160
2	1	92	77	50	.0166
(112 F, 65% RH)	2	90	76	52	.0162
	3	93	77	47	.0164
	4	92	80	58	.0195
Mean		92	77.5	52	.0172
3	1	93	77	53	.0164
(130 F, 35% RH)	2	93	78	50	.0172
	3	93	80	56	.0192
	4	93	77	47	.0164
Mean		93	78	51	.0173
Grand Mean		92	77.5	52	.0171

*Data Not Available

number.

The saliva samples were sent on the following day to the Department of Infectious Diseases, Kansas State University, for analysis. The samples were analyzed for concentration of creatinine, amylase, sodium and potassium.

RESULTS

It was planned to expose a subject only once in a day to a heat stress environment. Due to a death in the family, subject 3 had to leave two days before the experiment was scheduled to end. Therefore the second exposure of the subjects 3 and 4 to Environments 1 and 3 was done during extra sessions conducted on days 4 and 5. These special sessions were held for environments 1 and 3 at 8:30 to 10:30 PM on day 4 and 9:30 to 11:30 AM on day 5, respectively.

Due to choking of the tube of the psychrometer with lime, the environment of the test chamber on the special session of day 5 was disturbed during the last 15 minutes of the test. The data for this period was therefore discarded. These values of the specific criterion were estimated by the following method:

For Subject Without Shirt: At a particular period, the mean of the values when the subject was wearing the shirt was calculated for Environments 1 and 2. The difference between this mean and the value for environment 3 was determined. This difference was added to the mean of the values for Environments 1 and 2 when the subject was without the shirt.

For Subject With Shirt: Similar to above, except that the difference was found from the values when the subject was without the shirt.

The significance of the effectiveness of the cooling system was determined with a three way analysis of variance. The performance of the shirt in the three environments was compared with a two way analysis of variance.

Heart Rate

The heart beats of the subjects were recorded on a roll of graduated paper on the strip chart recorder for about 20 seconds. The output appeared as a series of peaks. The heart rate was calculated from the distance (in mm) between the first and the sixteenth successive peak. This was divided by 15 to give average interbeat distance (in mm) between successive beats. Dividing the speed of paper (in mm/min.) by the average interbeat distance gave the heart rate in beats/min.

Figs. 7, 8, 9 and 10 show the heart rates of the subjects under the three environments and prestress, stress and recovery conditions. The basal value of the heart rate for a subject was the grand average of the three prestress readings taken on each of six days of exposure, plus the seven basal readings taken on the first day of the experiment. Table 5 gives the increase in heart rate of the subjects over their basals due to a half hour exposure. The average increase in heart rate of 30 beats/minute with the shirt was significantly ($\alpha < .01$) less than the average increase of 73 beats/minute without the shirt. The effect of subjects was also significant. Subject 3 benefitted the most from the shirt.

The cumulative extra heart beats due to 30 minutes of exposure to heat stress, with and without the shirt, for all the subjects are shown in Table 6. The average heart rate during a 5 minute period was the mean of the heart rate at the beginning and at the end of the period. These means of the six 5 minute periods during exposure were added and the sum (beats/5 minutes) was multiplied by 5 (minutes) to give total number of beats during exposure. From this the basal heart beats for 30 minutes were subtracted to give the cumulative extra beats due to exposure. The average extra cumulative heart beats of 609 beats with

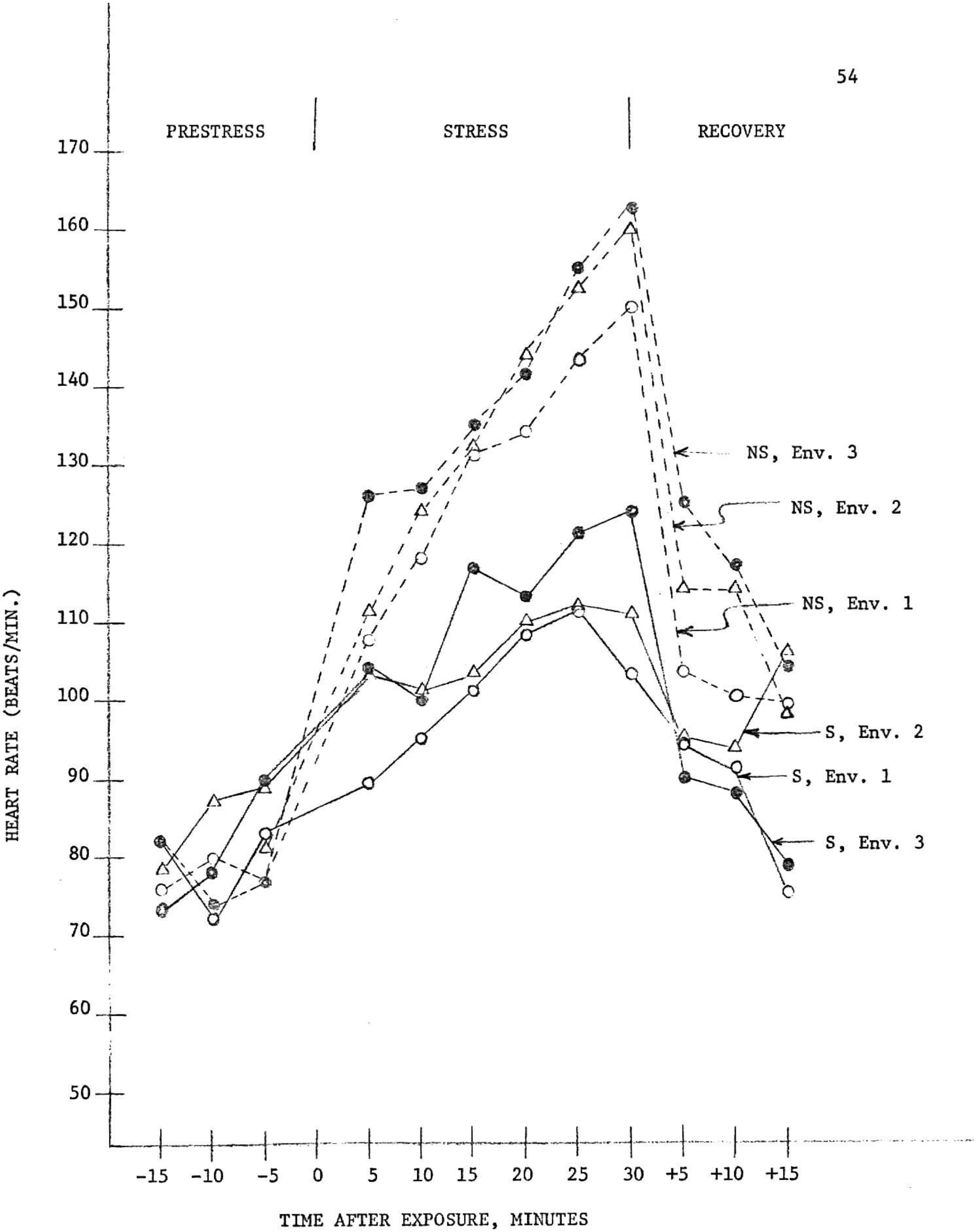

Fig. 7. Heart Rate for Subject 1

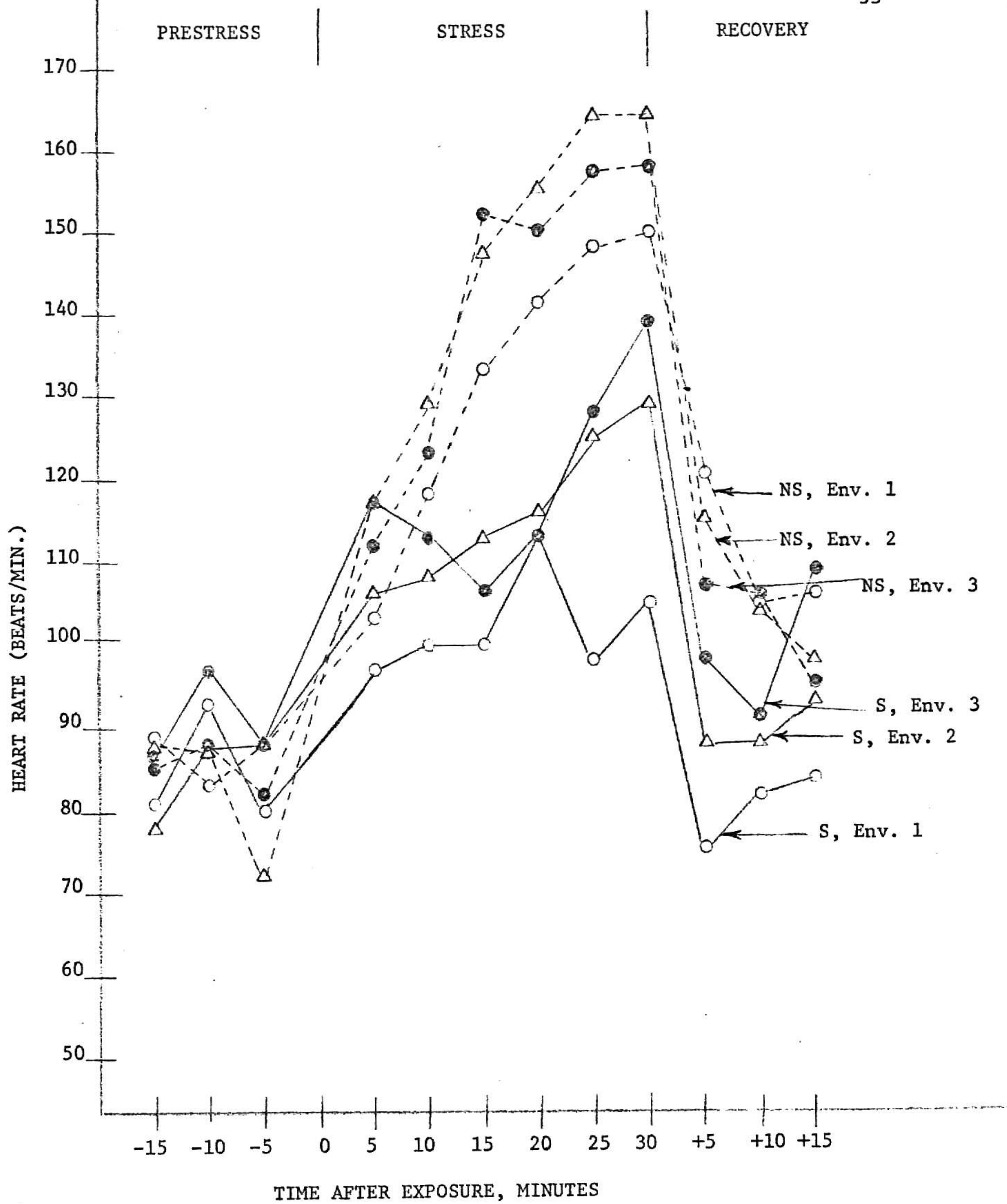

Fig. 8. Heart Rate for Subject 2

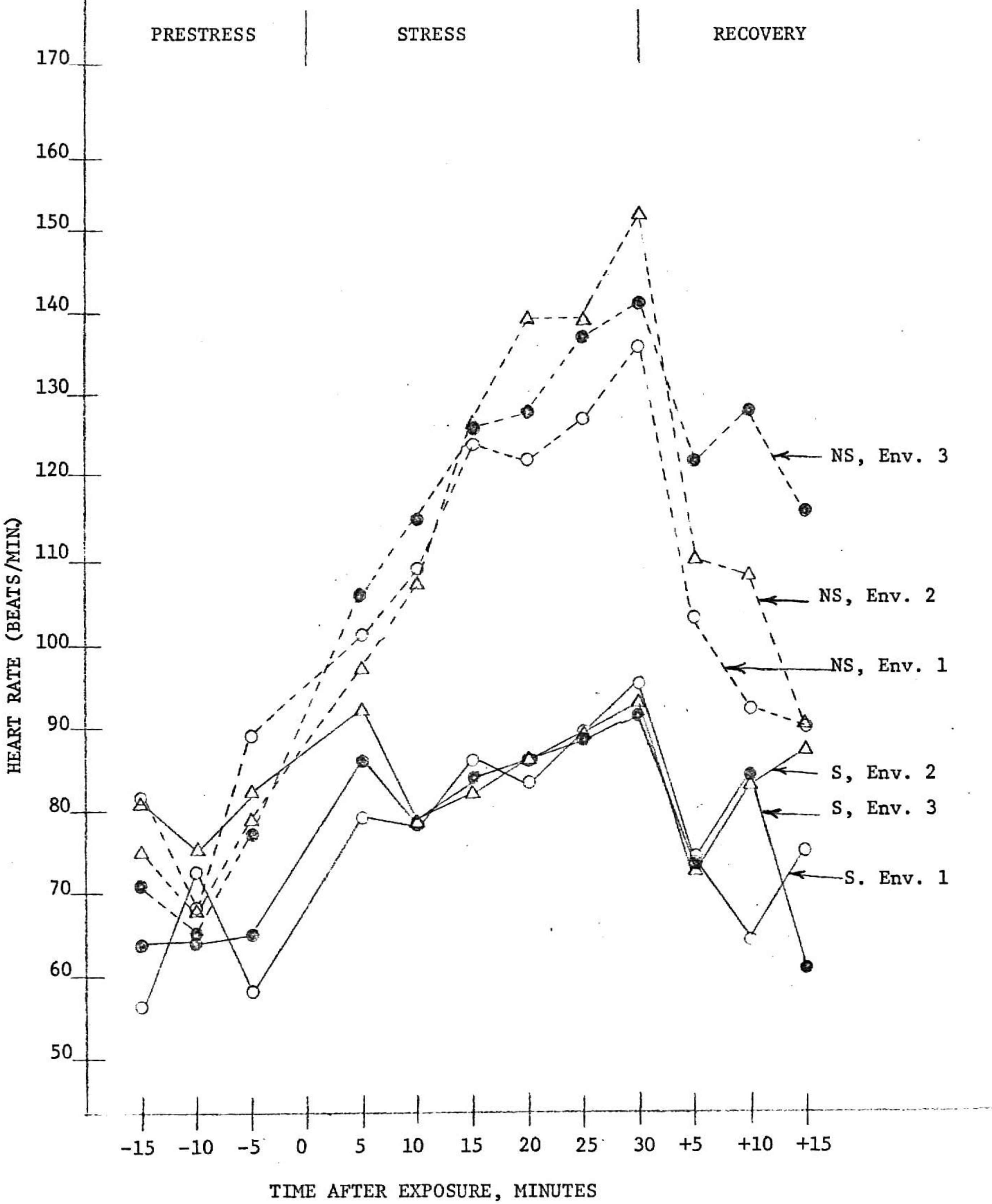

Fig. 9. Heart Rate for Subject 3

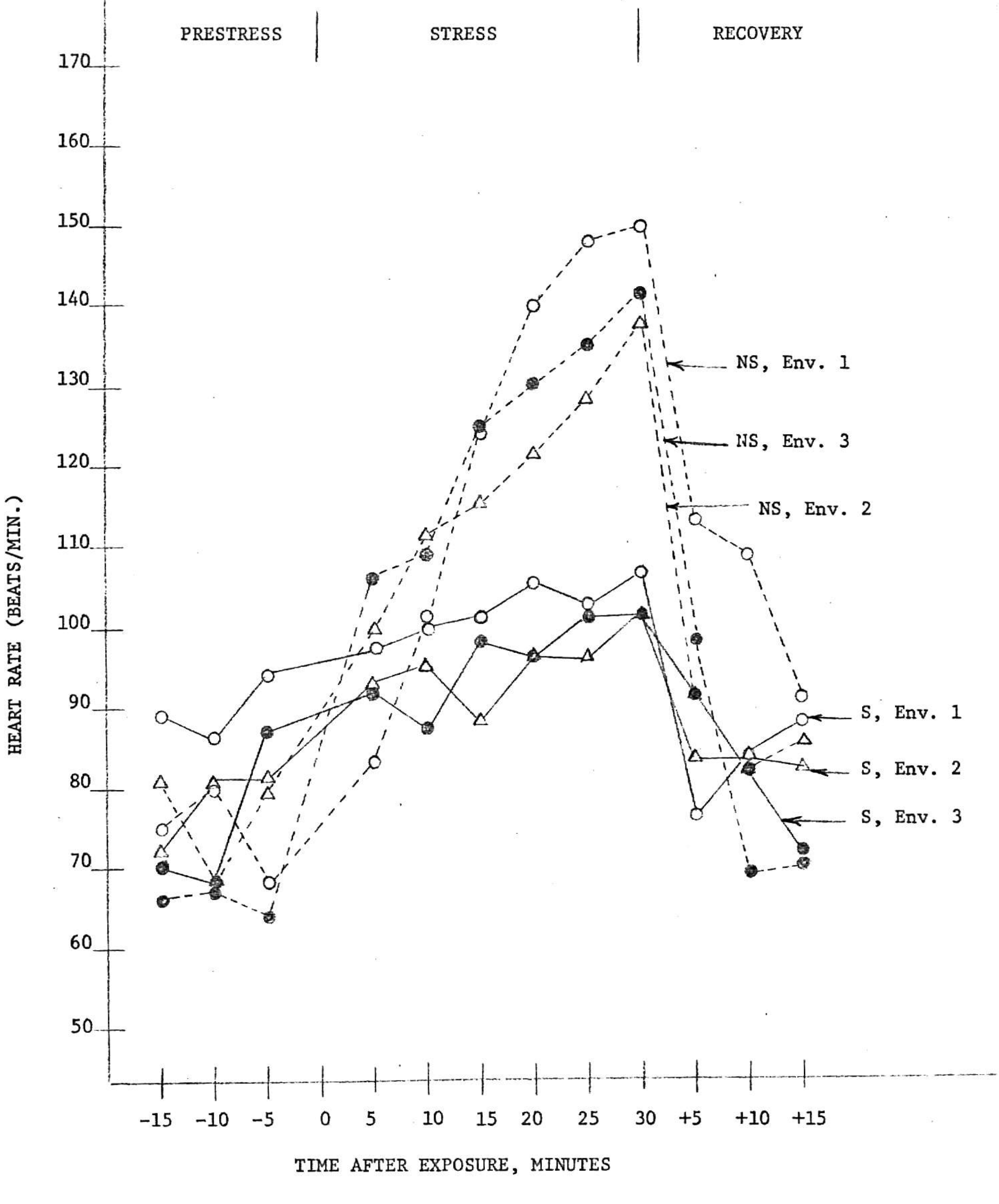

Fig. 10. Heart Rate for Subject 4

Table 5

Increase in Heart Rate (beats/min) Due to 1/2 hr Exposure to Heat Stress

	SHIRT				NO SHIRT			
	ENVIRONMENT				ENVIRONMENT			
Subject	1	2	3	Mean	1	2	3	Mean
1	23	31	44	33	70	80	83	78
2	20	44	54	39	75	79	73	76
3	24	22	20*	22	65	81	70	72
4	30	24	24	26	73	61	64*	66
Mean	24	30	35	30	71	75	72	73

*Estimated

Table 6

Cumulative Extra Heart Beats Due to 1/2 hr. Exposure to Heat Stress

	SHIRT ENVIRONMENT				NO SHIRT ENVIRONMENT			
Subject	1	2	3	Mean	1	2	3	Mean
1	590*	745	910	748	1340	1520	1625	1495
2	455	835	905	732	1310*	1600	1520	1477
3	330	450*	370*	383	1350	1495	1475	1440
4	705	485	530	573	1265*	1110*	1230*	1202
Mean	520	629	679	609	1316	1431	1462	1403

*Estimated

the shirt was significantly ($\alpha < .01$) lower than the 1403 beats without the shirt. The observations of the heart rate, which could not be recorded at times due to the malfunctioning of the equipment, were linearly interpolated from the preceeding and the following known observations.

Table 7 shows the decrease in the heart rate due to the shirt. To reduce the effect of days and subjects, the increase in heart rate while wearing the shirt was subtracted from the increase without the shirt. This data was analyzed with a two way analysis of variance. The mean differences in Environments 1, 2 and 3, though in descending order, were not significantly ($\alpha < .05$) different from each other. Hence there was no difference in the performance of the shirt in the three environments.

Heart Variability

Kalsbeek (Kalsbeek and Ettema, 1965 and Kalsbeek and Sykes, 1967) showed that the variability of the intervals between successive beats was less when the man was under greater mental load. The standard deviation of the interbeat intervals, therefore, is a measure of load on a man. Tables 8, 9 and 10 show the standard deviations of the interbeat intervals for the subjects in the three environments tested, with and without the shirt. The coefficient of variation have been tabulated in Appendix A for the three environments and both the conditions. Table 8, 9 and 10 show that the average standard deviation in Environment 1 dropped from .068 seconds in the neutral condition to .035 with the shirt and from .066 to .019 without the shirt. The same figures for Environment 2 were .058 to .034 and .068 to .020 and for Environment 3 were .063 to .035 and .066 to .019. A sign test showed that there was a significantly ($\alpha < .05$) smaller drop in the interbeat variability during

Table 7

Decrease in Heart Rate (beats/min.) Due to the Shirt

	ENVIRONMENT			
Subject	1	2	3	Mean
1	47	49	39	45
2	55	35	19	36
3	41	59	50	50
4	43	37	40	40
Mean	46	45	37	43

Table 8

Standard Deviation (Seconds) of the Heart Rate in Environment 1

Period	SHIRT Subject 1	2	3	4	Mean	NO SHIRT Subject 1	2	3	4	Mean
1	.041	.064	.066	.125	.074	.060	.052	.130	.054	.074
2	.037	.035	.130	.038	.060	.064	.018	.038	.071	.048
3	.063	.080	.084	.056	.071	.055	.043	.104	.108	.077
Mean	.047	.060	.093	.073	.068	.060	.038	.091	.078	.066
4	*	.025	.038	.098	.054	.020	*	.032	*	.026
5	*	.020	.099	.022	.047	.029	*	.023	.020	.024
6	*	.014	.035	.035	.028	.020	*	.016	.018	.018
7	.026	.023	.046	.043	.034	.024	.016	.023	.019	.020
8	.015	.020	.040	.023	.024	.020	.019	.010	.014	.016
9	.031	.023	.038	.034	.031	.018	.018	.014	.016	.016
Mean	.024	.021	.049	.042	.035	.022	.018	.020	.017	.019
10	.038	.060	.055	.035	.047	.042	.019	.018	.020	.025
11	.024	.032	.091	.062	.052	.038	.020	.020	.023	.025
12	.079	.073	.098	.047	.074	.040	.023	.031	.035	.032
Mean	.047	.055	.081	.048	.058	.040	.021	.023	.026	.027

*Data not Available

Table 9

Standard Deviation (Seconds) of the Heart Rate in Environment 2

Period	SHIRT Subject 1	2	3	4	Mean	NO SHIRT Subject 1	2	3	4	Mean
1	.063	.047	.082	.030	.055	.114	.070	.065	.115	.091
2	.087	.028	.062	.058	.059	.017	.028	.072	.053	.042
3	.069	.027	.090	.058	.061	.065	.100	.054	.060	.070
Mean	.073	.034	.078	.048	.058	.065	.066	.064	.076	.068
4	.020	.027	.025	.074	.036	.031	.020	.025	.048	.031
5	.022	.016	.063	.054	.039	.028	.024	.014	.020	.021
6	.074	.014	*	.060	.049	.020	.020	.015	.036	.023
7	.016	.010	*	.074	.033	.020	.020	.010	*	.017
8	.027	.026	.035	.034	.030	.018	.014	.020	.020	.018
9	.020	.024	.023	.018	.021	.020	.019	.016	.016	.018
Mean	.030	.019	.036	.052	.034	.023	.019	.017	.028	.021
10	.055	.020	.127	.055	.064	.024	.023	.014	.031	.023
11	.039	.032	.048	.077	.049	.025	.019	.018	.080	.035
12	.033	.027	.060	.112	.058	.020	.038	.042	.077	.044
Mean	.042	.026	.078	.081	.057	.023	.027	.024	.063	.034

*Data not Available

Table 10

Standard Deviation (Seconds) of the Heart Rate in Environment 3

Period	SHIRT Subject 1	2	3	4	Mean	NO SHIRT Subject 1	2	3	4	Mean
1	.065	.035	.065	.092	.064	.027	.062	.082	.086	.064
2	.105	.050	.092	.070	.079	.055	.031	.055	.076	.054
3	.030	.045	.075	.037	.047	.098	.028	.111	.084	.080
Mean	.067	.043	.077	.066	.063	.060	.040	.083	.082	.066
4	.020	.016	.041	.037	.028	.016	.020	.018	.022	.019
5	.036	.016	.102	.084	.059	.015	.020	.014	.028	.019
6	.014	.041	.038	.078	.043	.018	.020	.020	.018	.019
7	.038	.018	†	.040	.032	.020	.014	.028	†	.021
8	.020	.023	†	.014	.019	.019	.020	.010	†	.016
9	.014	.014	†	.026	.018	.022	.019	.019	†	.020
Mean	.024	.021	.060	.046	.035	.018	.019	.018	.023	.019
10	.047	.032	.043	.056	.044	.019	.026	.018	.020	.021
11	.063	.024	.070	.027	.046	.024	.019	.018	.105	.042
12	.045	.011	.161	.101	.079	.028	.032	.020	.020	.025
Mean	.052	.022	.091	.061	.057	.024	.026	.019	.049	.029

† Environment Disturbed

exposure when the subjects wore the shirt. The decrease in the coefficient of variation (Appendix A) from 7.7 % with the shirt to 4.9% without the shirt indicates that the decrease in variability is not just due to the increase in the mean. The above values show that the subjects were under less load with the shirt than without, as their hearts were beating less regularly with the shirt. Ten minutes after the subjects left the test chamber, the interbeat variability of the heart rate of the subjects with the shirt returned to normal. The heart of the subjects without the shirt was then beating more or less regularly. Figs. 11, 12, 13 and 14 show the standard deviation of the heart beat intervals, with and without the shirt, in the three environments. Fig. 15 shows the three point moving average of the mean standard deviation for all the four subjects in the three environments.

Sweat Loss

Table 11 gives the sweat of the subjects in gms/m^2 body area/hr with and without the shirt in the three environments.

The sweat loss of subject 3 in Environment 3 with the shirt and of subject 4 in environment 3 without the shirt had to be estimated due to disturbed environments. The estimation was done by the statistical method for finding missing observation (Fryer, 1966). A sign test showed that the average sweat loss of 375 gms/m^2 body area/hr with the shirt was significantly ($\alpha < .01$) less than the 930 without the shirt. With the shirt there was a wide variation in the sweat loss for different subjects in all the environments. However, the subjects sweated the most in Environment 3. Subject 3, who was a basketball player, sweated the most in all environments both with and without the shirt.

Table 12 shows the decrease in the sweat loss due to the shirt. These values were obtained by subtracting the sweat loss of a subject with the shirt, in a specific environment, from the coresponding value without

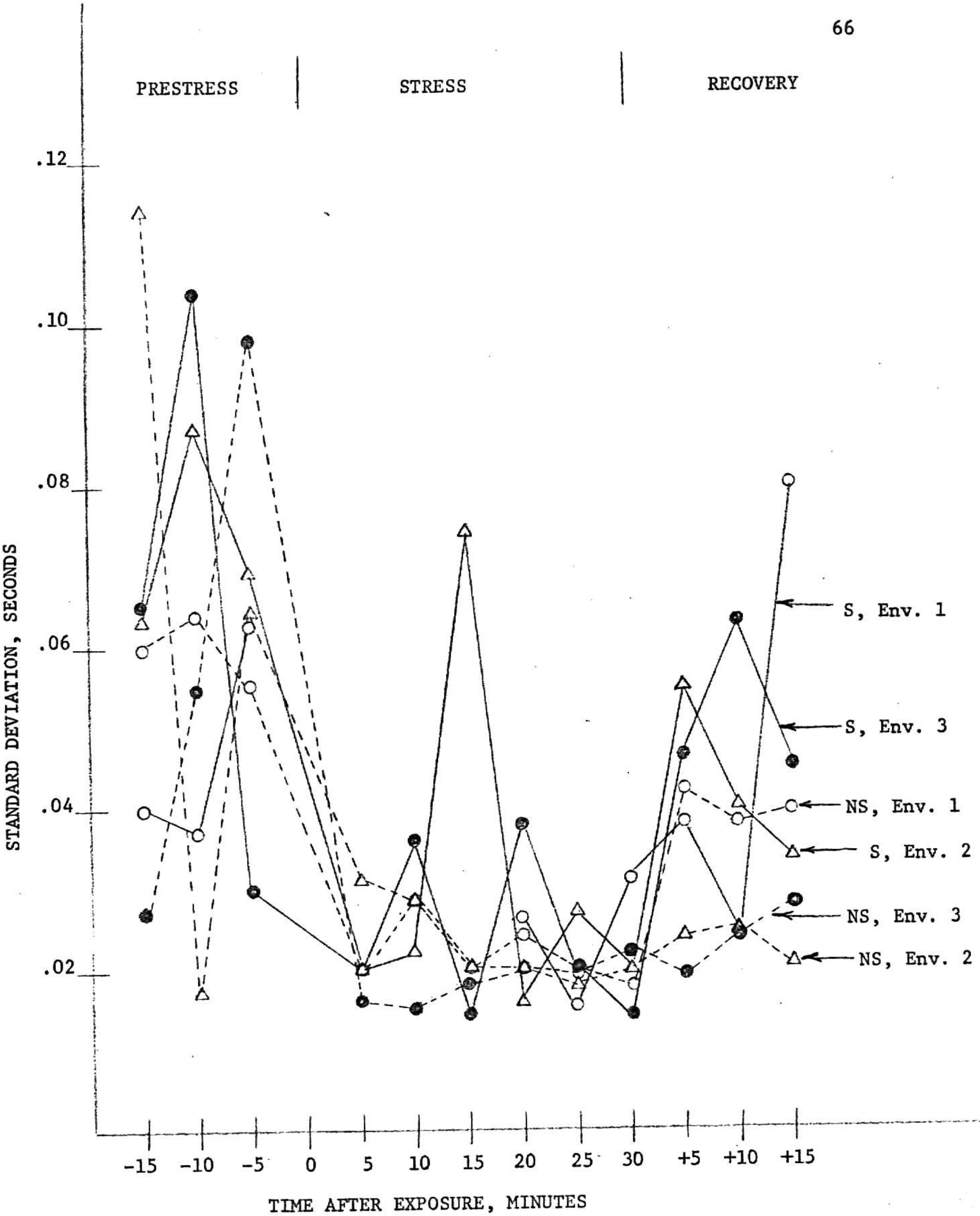

Fig. 11. Standard Deviation of Interbeat Intervals, Subject 1

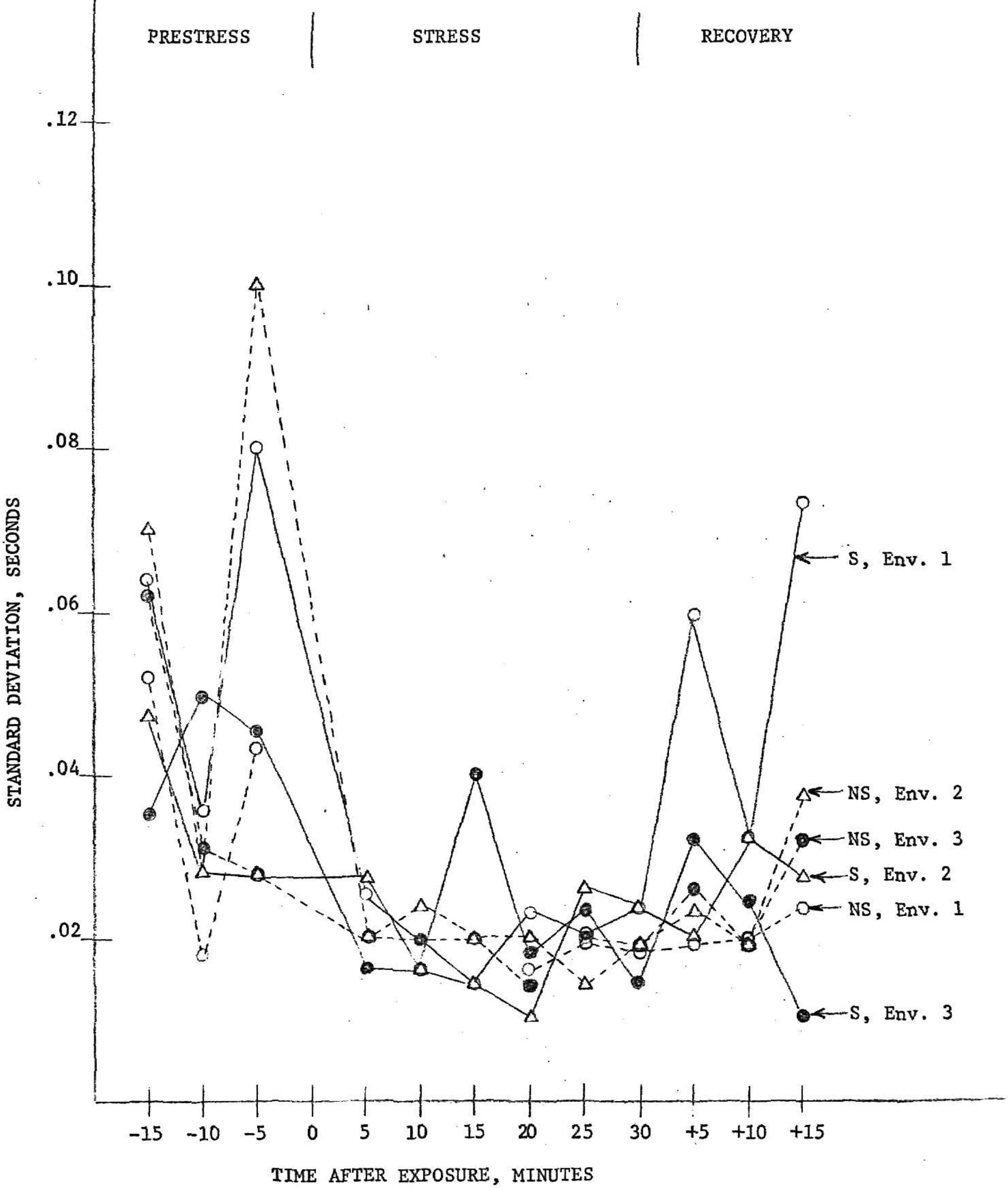

Fig. 12. Standard Deviation of Interbeat Intervals, Subject 2

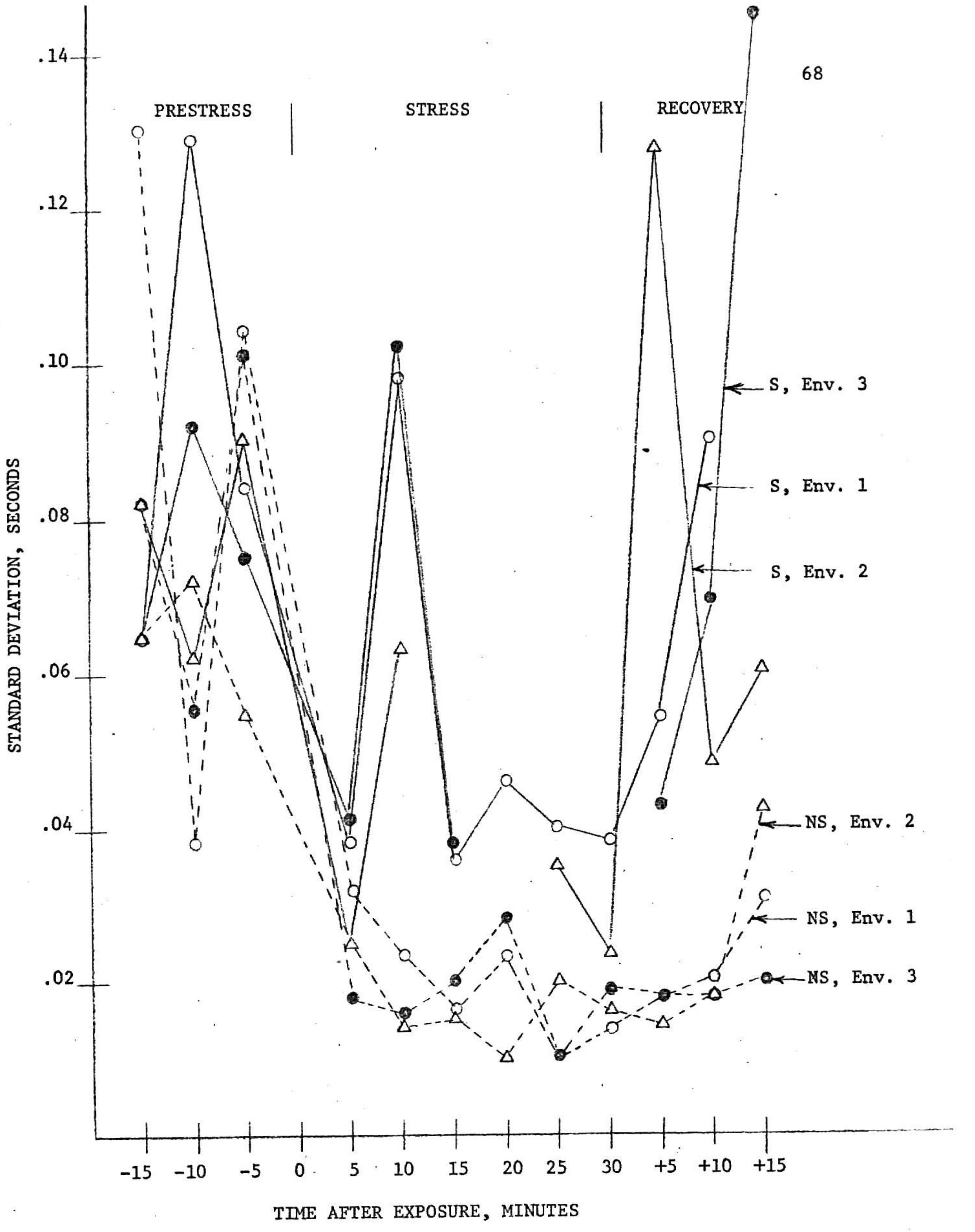

Fig. 13. Standard Deviation of Interbeat Intervals, Subject 3

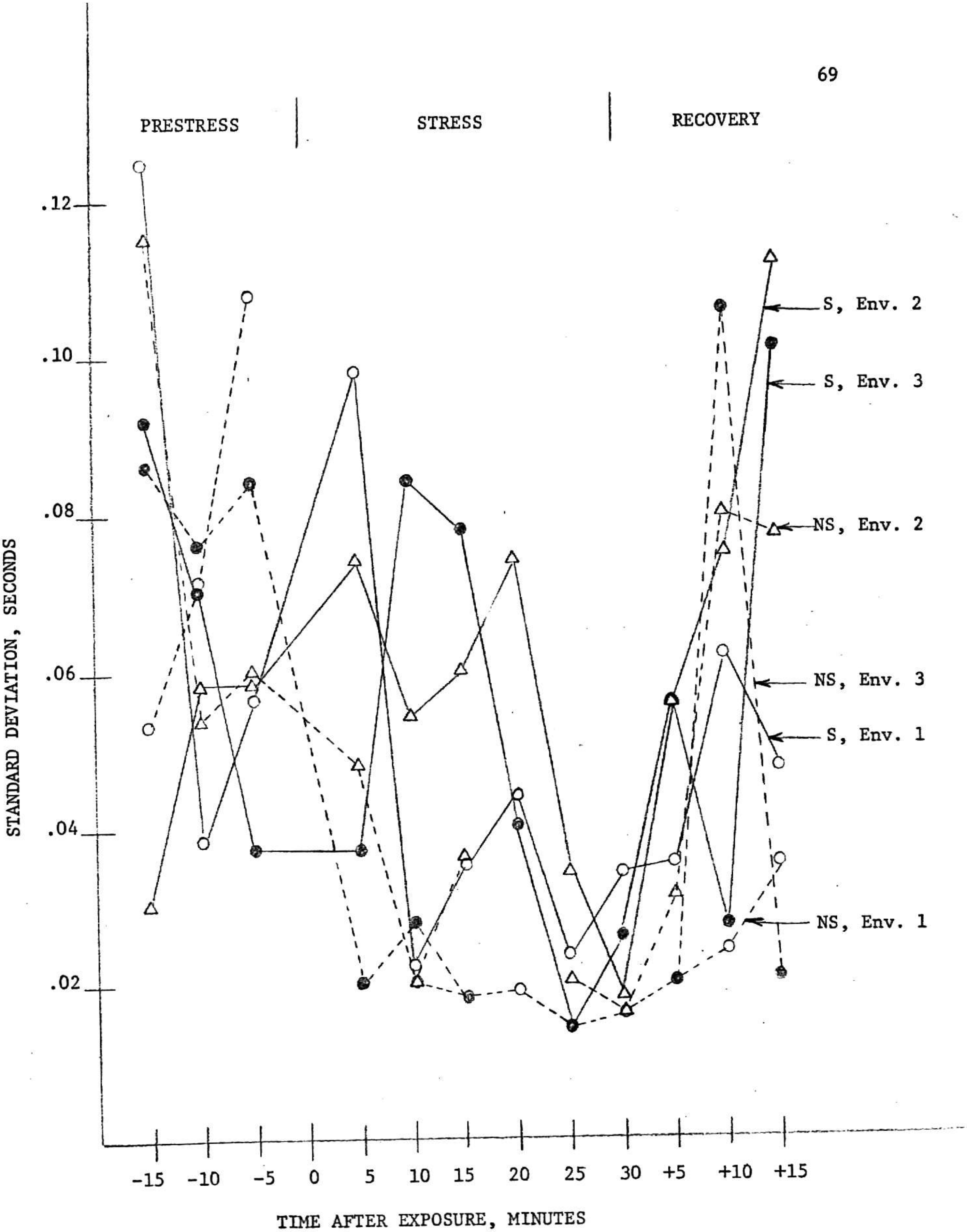

Fig. 14. Standard Deviation of Interbeat Intervals, Subject 4

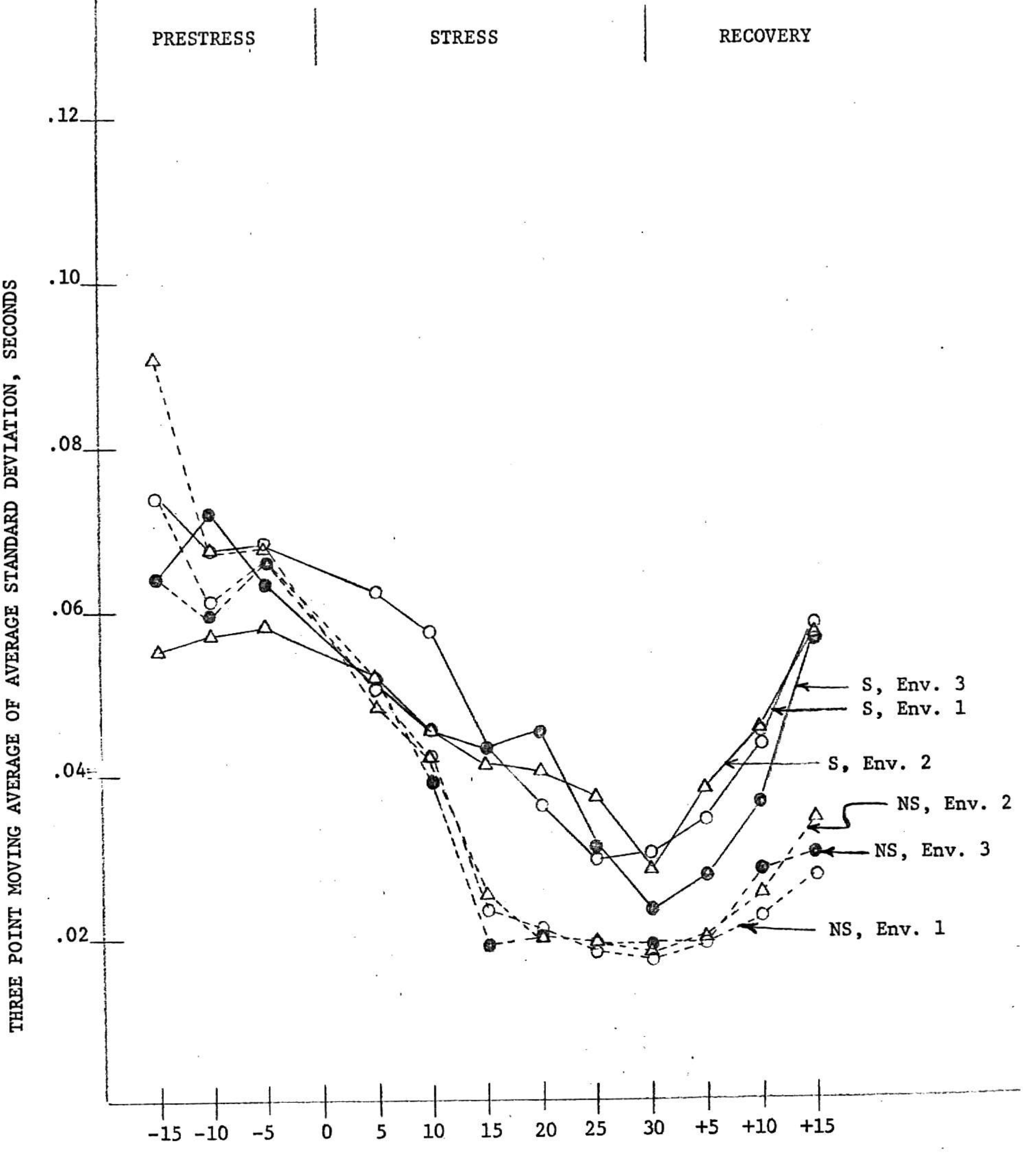

Fig. 15. Three Point Moving Average, of all 4 Subjects, of Heart Rate Variability

Table 11

Sweat Loss (grams/m^2 body area/hr.)

	SHIRT				NO SHIRT			
	ENVIRONMENT				ENVIRONMENT			
Subject	1	2	3	Mean	1	2	3	Mean
1	150	295	315	225	550	725	695	655
2	320	345	640	435	1020	1030	1060	1035
3	350	395	550*	445	955	1110	1200	1090
4	225	440	460	375	710	890	1195*	935
Mean	260	370	490	375	810	940	1035	930

*estimated

Table 12

Decrease in the Sweat Loss (gms/m^2 body area/hr) Due to the Shirt

	ENVIRONMENT			
Subject	1	2	3	Mean
1	400	430	380	430
2	700	685	420	600
3	605	715	650	655
4	485	450	735	560
Mean	550	570	540	555

the shirt. The average decrease in the sweat losses of 550 in Environment 1, 570 in Environment 2 and 540 in Environment 3 were not significantly ($\alpha < .05$) different from each other. This again showed that the performance of the shirt was same in all the environments.

Rectal Temperature

The basal value in each case was the rectal temperature observed just before the subjects entered the test chamber. Table 13 gives the increase during exposure in rectal temperature over the basal, with and without the shirt, in the three environments. The data for subjects 3 and 4, in Environment 3, with and without the shirt respectively, were estimated by the method described on page 52. A 3 way analysis of variance showed that the average increase in the rectal temperature of .5 F with the shirt was significantly ($\alpha < .05$) lower than the increase of 1.0 F (.6 C) without the shirt. No other effect was significant.

On Day 1, a decrease in the rectal temperature of all the subjects was observed, while they rested on chairs. During preexposure on Days 2-7, the rectal temperature decreased in 15, did not change in 4 and increased in 5 cases. These observations were in a near agreement with the findings of Duncan (1969), who reported a decrease in the rectal temperature during preexposure. The tendency of the rectal temperature to go down in the beginning of the exposure, as reported by Sharma (1970), was not observed in this experiment. Byrnes (1970) also did not observe a downward trend in his data. Without the shirt, the rectal temperature tended to increase for sometime after the end of exposure, before going down, even though the subjects had left the test chamber. This effect was not observed when the subjects wore the shirt. Figs. 16, 17, 18 and 19 show the rectal temperature of the four subjects, in all environments and conditions.

Table 13

Increase in Rectal Temperature (F) Due to 1/2 hr. Exposure to Heat Stress

	SHIRT				NO SHIRT			
	ENVIRONMENT				ENVIRONMENT			
Subject	1	2	3	Mean	1	2	3	Mean
1	.4	.6	.5	.5	1.0	1.0	.8	.9
2	.7	.2	.4	.4	1.1	.5	1.4	1.0
3	.5	.5	.5*	.5	1.0	1.6	1.3	1.3
4	.3	.5	.1	.3	1.1	.9	.7*	.9
Mean	.5	.5	.4	.5	1.	1.	1.	1.

*Estimated

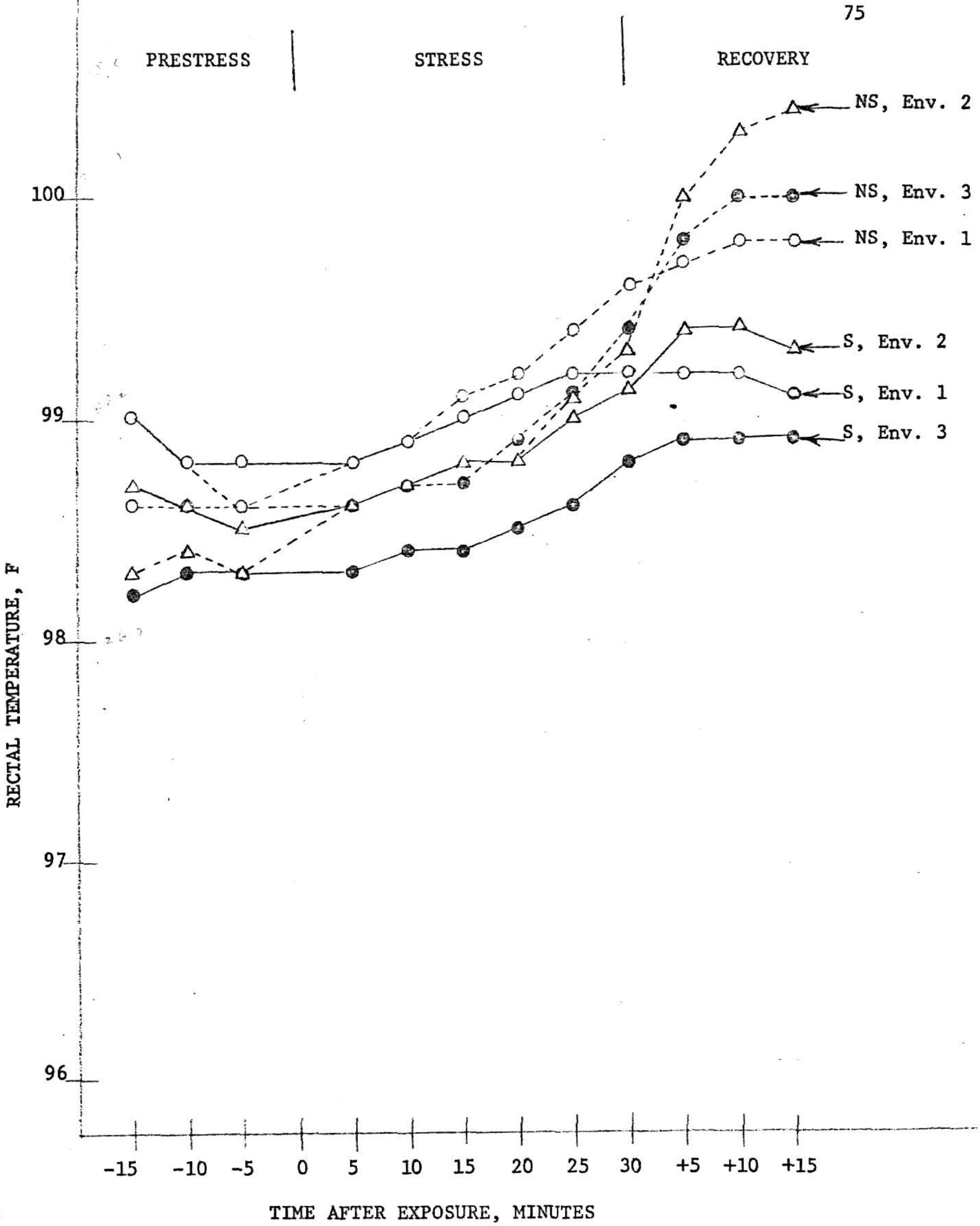

Fig. 16. Rectal Temperature for Subject 1

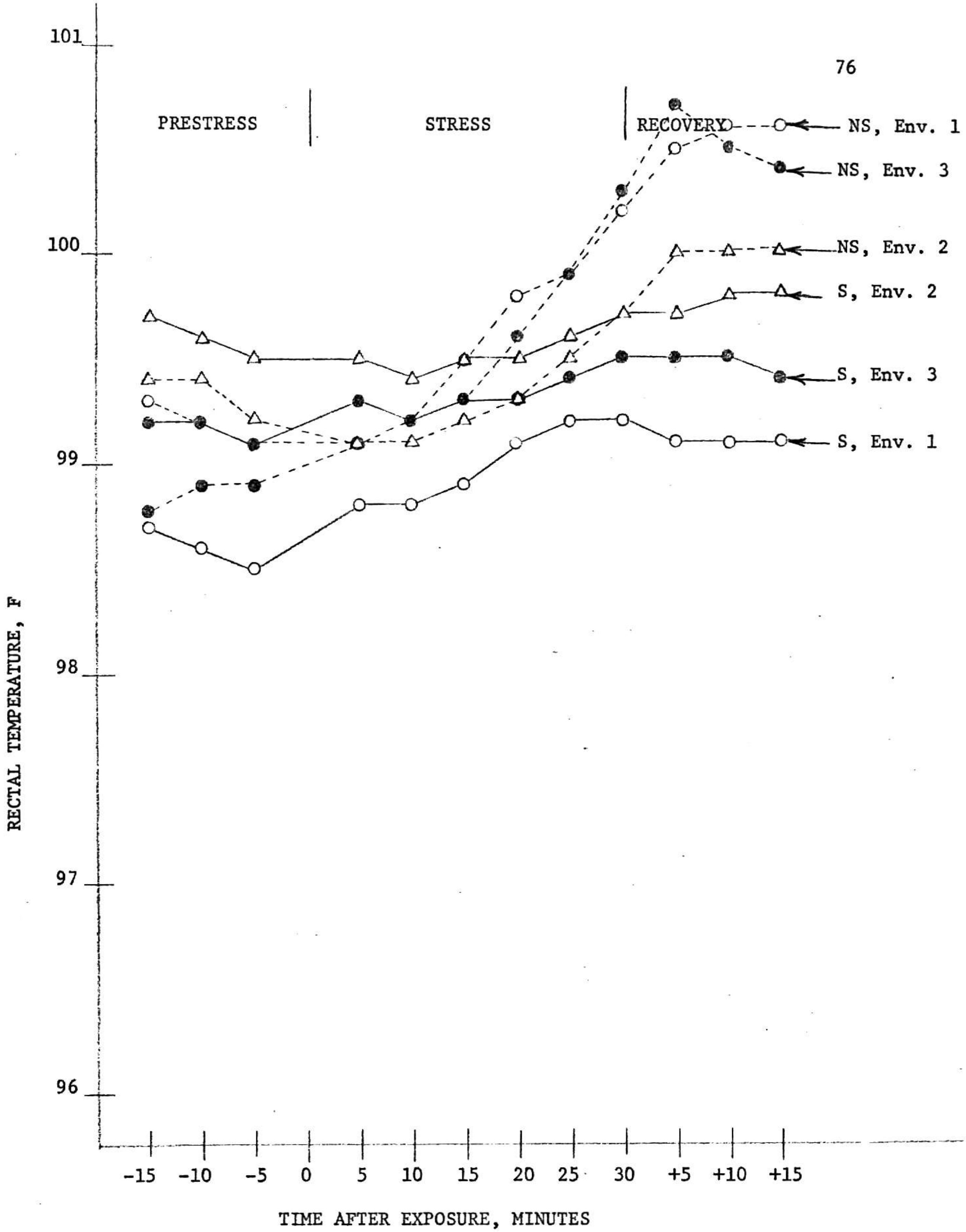

Fig. 17. Rectal Temperature for Subject 2

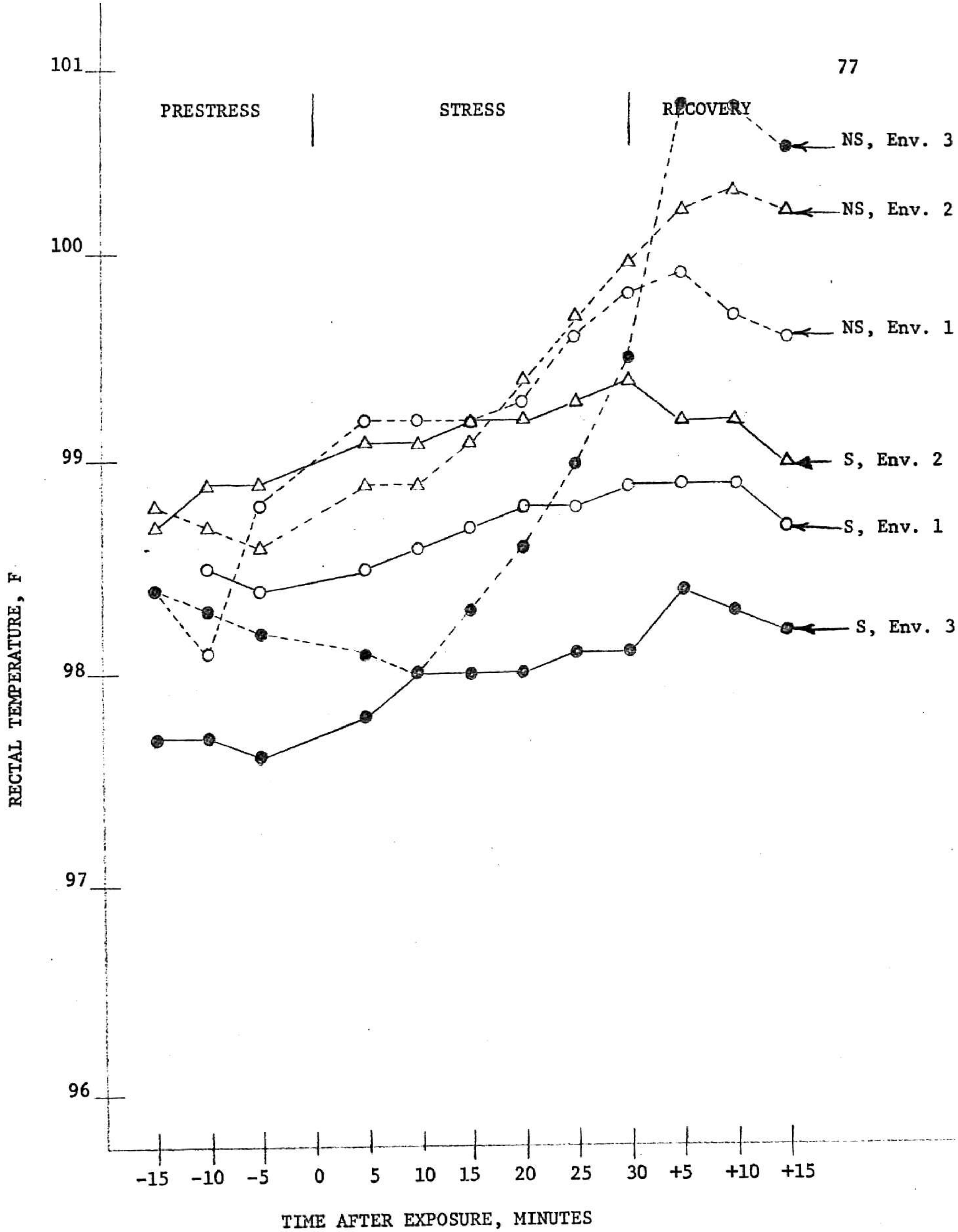

Fig. 18. Rectal Temperature for Subject 3

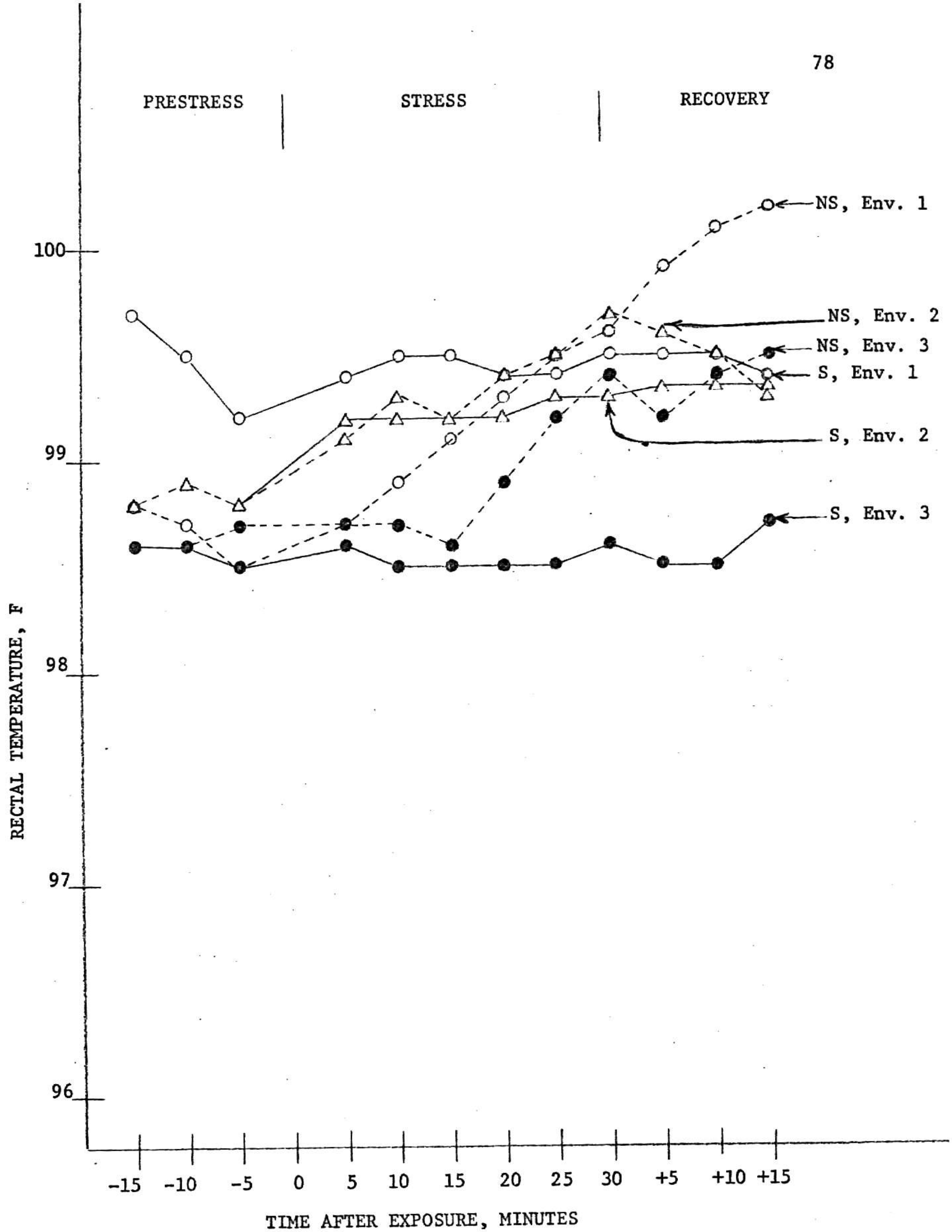

Fig. 19. Rectal Temperature for Subject 4

Table 14 shows the decrease in rectal temperature due to the shirt, calculated by the same method as heart rate and sweat loss. A two way analysis of variance showed that the average increases of .5, .6 and .5 F in Environments 1, 2 and 3 respectively, were not significantly ($\alpha < .05$) different from each other. Hence, with decrease in rectal temperature as the criterion, the performance of the shirt was same in all the three environments tested.

Head Skin Temperature

The head skin temperature of the subjects was estimated from the brow temperature. The basal value of the head skin temperature was the mean of the 18 prestress and 7 observations of brow temperature taken on the first day. Table 15 gives the increase in head skin temperature of the subjects, over the basal, due to the 30 min. exposure to heat stress. A three way analysis indicated that the 4.5 F (2.5 C) increase with the shirt was significantly ($\alpha < .01$) lower than the 6.6 F (3.7 C) increase without the shirt. The analysis also showed that the environment and the subject effects were also significant ($\alpha < .05$). Further analysis showed that the average increase in the head skin temperature in Environment 1 was significantly ($\alpha < .05$) less than the increase in Environments 2 and 3. There was no significant ($\alpha < .05$) difference between the increases in Environments 2 and 3.

Table 16 gives the decrease in the head skin temperature due to the shirt. A two way analysis of variance showed that the decrements of 2.3, 2.3, and 2.9 F (1.3, 1.3 and 1.6 C) in head skin temperature in Environments 1, 2, and 3 were not significantly ($\alpha < .05$) different from each other. The subjects effect also was not significant. It can

Table 14

Decrease in the Rectal Temperature (F) Due to the Shirt

	ENVIRONMENT			
Subject	1	2	3	Mean
1	.6	.4	.3	.4
2	.4	.3	1.0	.6
3	.5	1.1	.8	.8
4	.8	.4	.4	.5
Mean	.5	.6	.5	.5

Table 15

Increase in the Head Temperature (F) Due to 1/2 hr Exposure to Heat Stress

	SHIRT ENVIRONMENT				NO SHIRT ENVIRONMENT			
Subject	1	2	3	Mean	1	2	3	Mean
1	3.0	5.0	5.6	4.5	5.6	5.9	7.7	6.4
2	2.1	3.4	2.7	2.7	4.9	4.3	6.3	5.2
3	5.4	4.8	8.0*	6.1	7.4	8.6	10.9	9.0
4	4.4	5.2	5.2	4.9	5.5	6.0	6.2	5.9
Mean	3.7	4.6	5.4	4.5	5.8	6.2	7.8	6.6

Table 16

Decrease in the Head Temperature (F) Due to the Shirt

	ENVIRONMENT			
Subject	1	2	3	Mean
1	2.6	0.9	2.1	1.9
2	2.8	.9	3.6	2.4
3	2.0	3.8	2.9	2.9
4	2.0	3.8	2.9	2.9
Mean	2.3	2.3	2.9	2.5

be concluded from this that the performance of the shirt, with respect to head skin temperature, was statistically the same for all the three environments.

Figs. 20, 21, 22 and 23 show the head skin temperature of the subjects in the three environments. These figures show that the dry bulb temperature of the environments tends to affect the head skin temperature, though the wet bulb temperature is the same, although it could not be proved statistically.

Mean Skin Temperature

As mentioned before, the mean skin temperature was calculated using Ramanathan's formula. This was a weighted mean of arm, chest, calf and thigh temperatures. Table 17 gives the increase in mean skin temperature due to the half hour exposure to the heat stress. The average increase in temperature of 2.2 F (1.2 C) with the shirt was significantly ($\alpha < .01$) lower than the rise of 9.5 F (5.3 C) without the shirt. In addition, the environment, subject and subject x condition (S or NS) interaction were significant. Further analysis showed that the average increase in the mean skin temperature in Environment 1 was significantly ($\alpha < .05$) less than the increase under Environments 2 and 3. There was no significant ($\alpha < .05$) difference between the average increases under Environments 2 and 3. It can be concluded that with mean skin temperature as the criterion, subjects reacted differently to the shirt, and environment also played a part in the increase in mean skin temperature. Note that the results with the head skin temperature agree with the mean skin temperature.

Table 18 shows the decrease in the mean skin temperature due to the shirt. A two way analysis of variance showed that statistically ($\alpha < .05$)

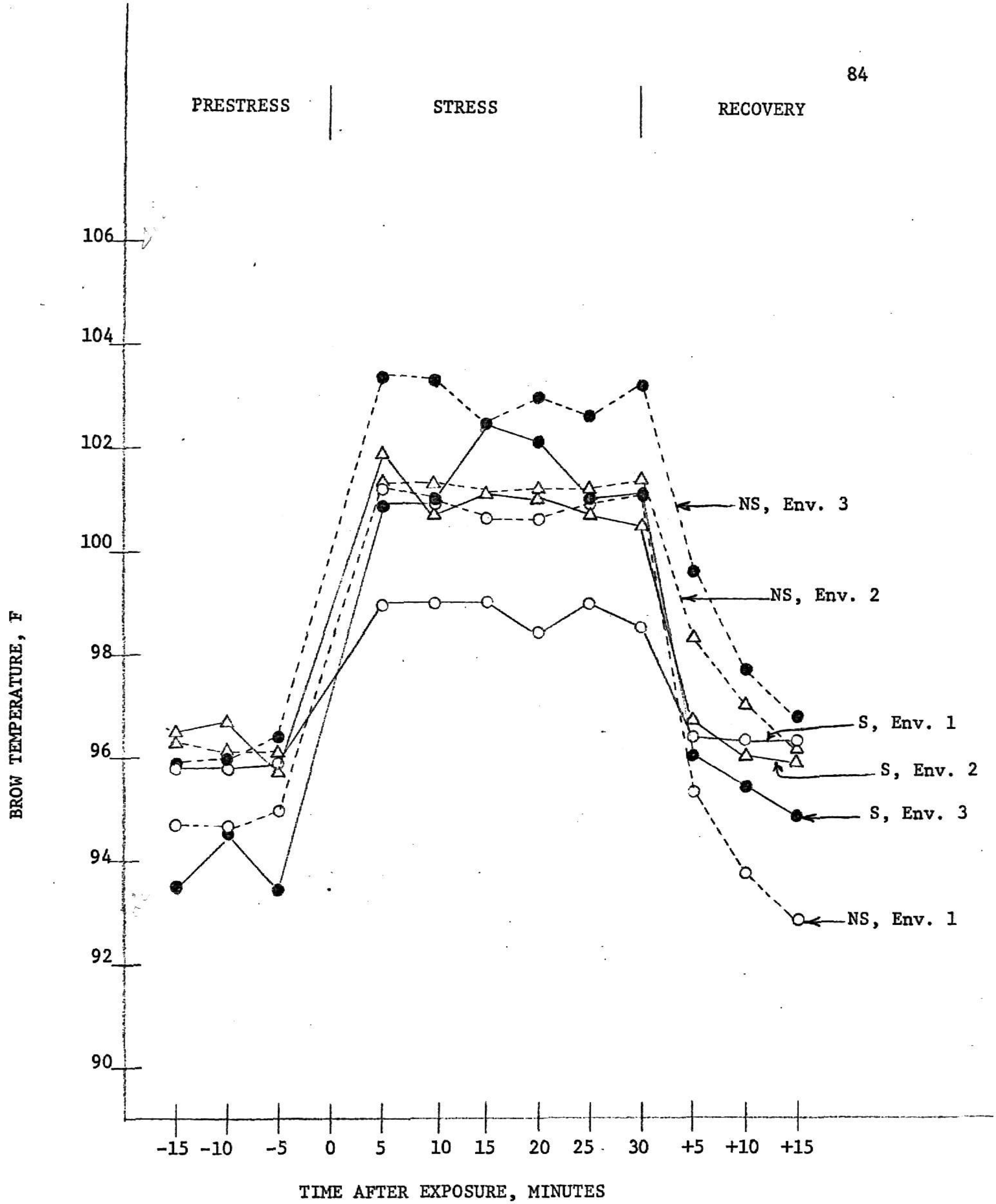

Fig. 20. Head Temperature for Subject 1

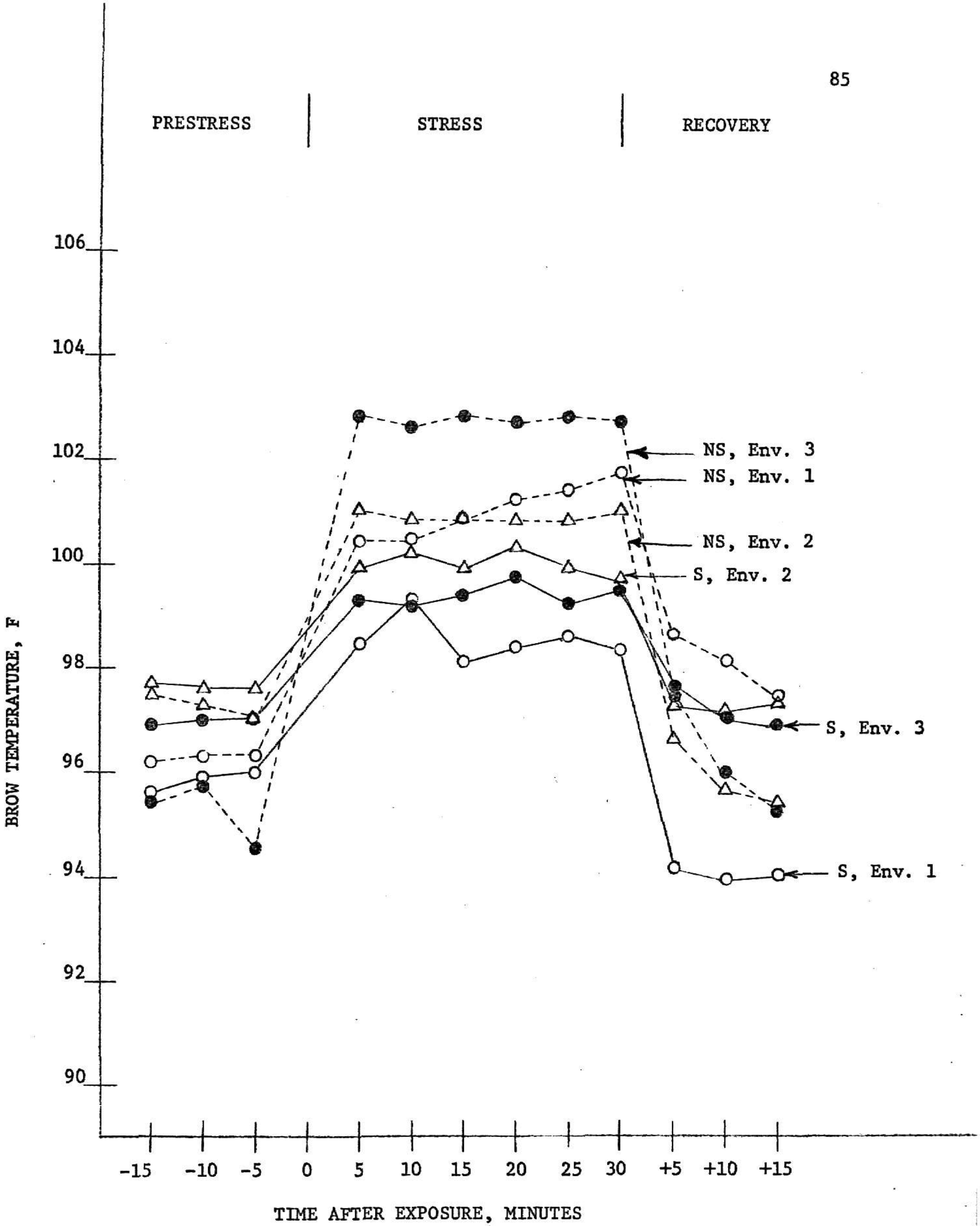

Fig. 21. Head Temperature for Subject 2

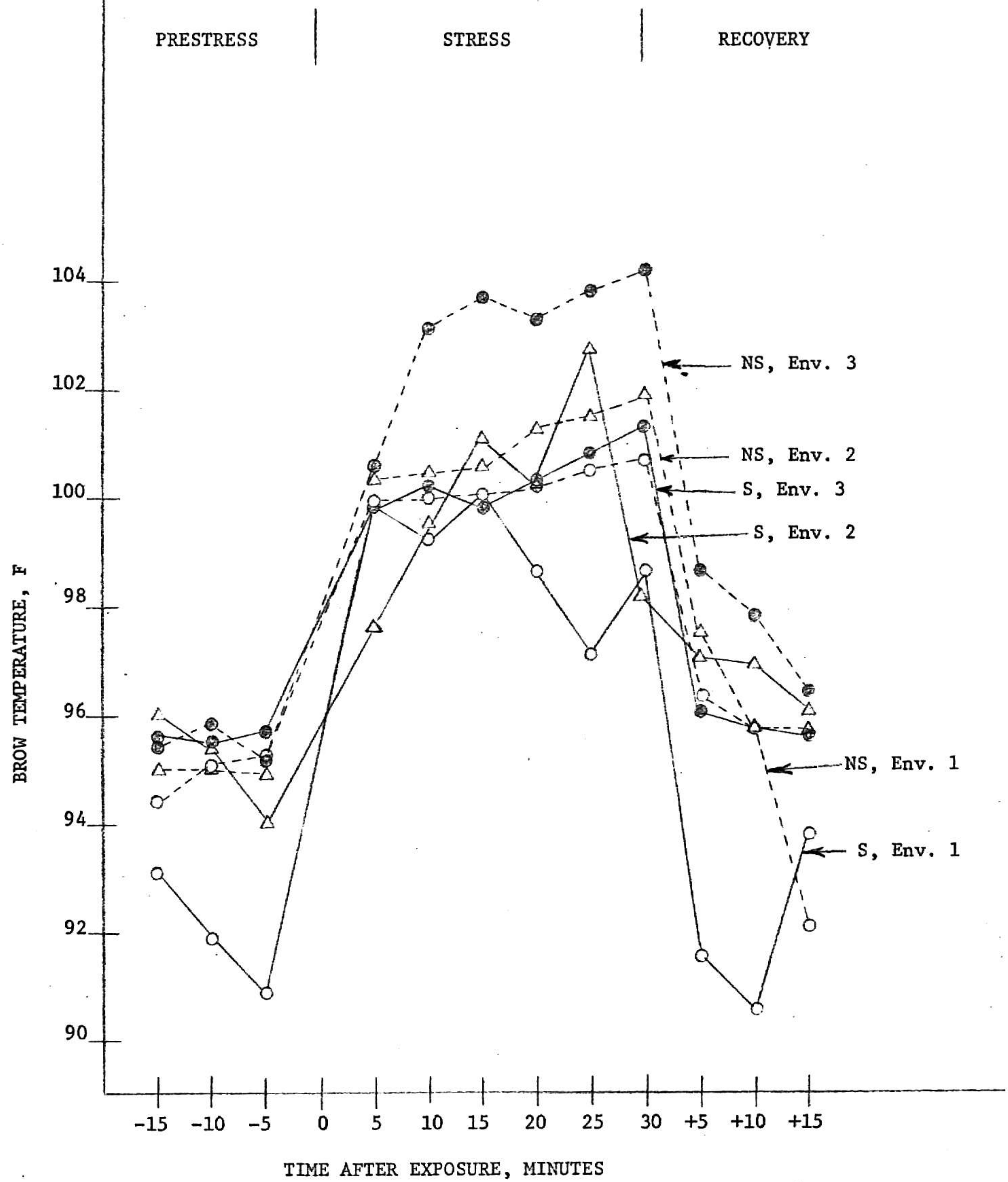

Fig. 22. Head Temperature for Subject 3

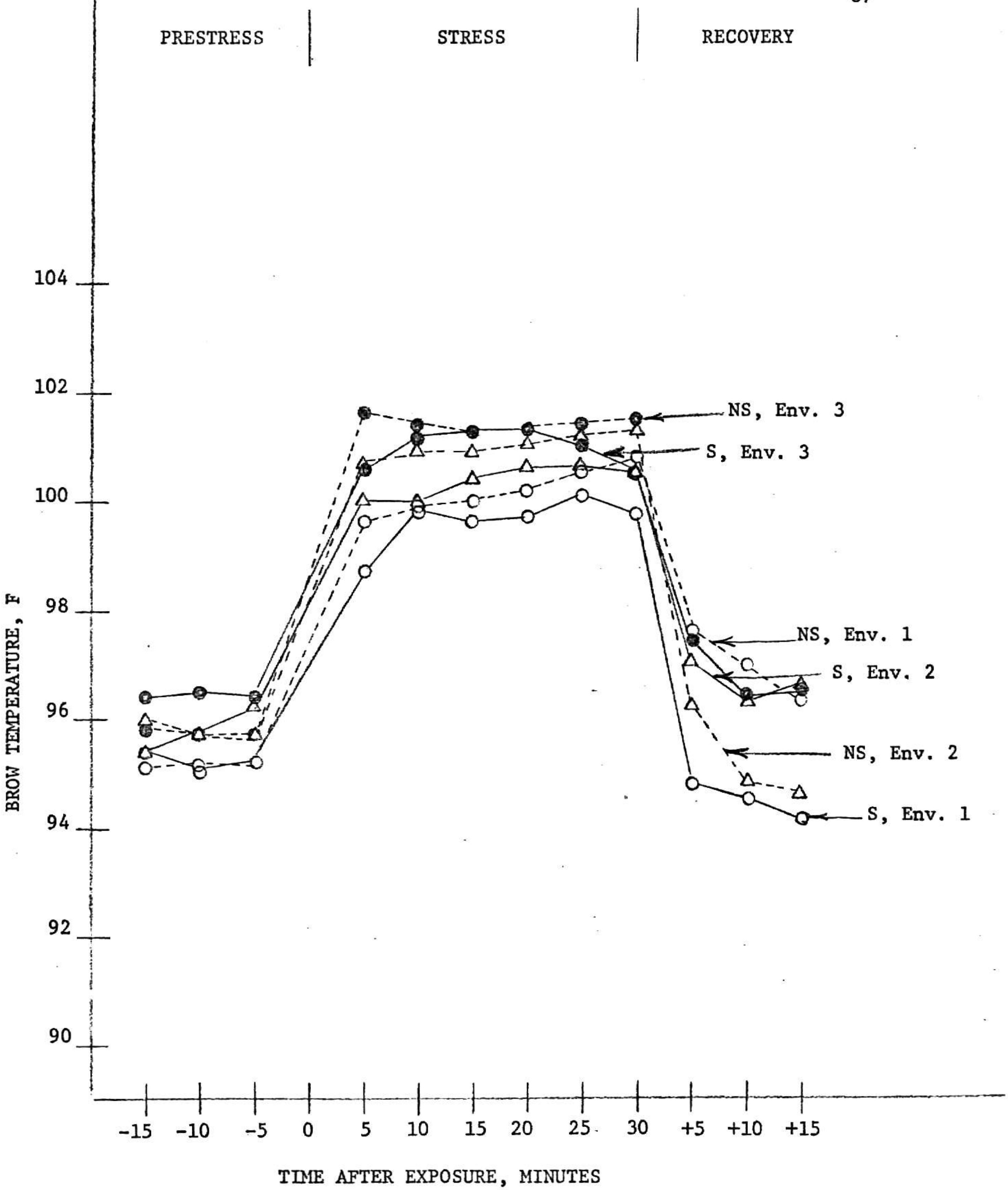

Fig. 23. Head Temperature for Subject 4

Table 17

Increase in the Mean Skin Temperature (F) Due to 1/2 hr Exposure to Heat Stress

	SHIRT				NO SHIRT			
	ENVIRONMENT				ENVIRONMENT			
Subject	1	2	3	Mean	1	2	3	Mean
1	2.0	4.4	5.6	4.0	8.3	9.2	10.8	9.4
2	3.2	4.6	6.5	3.6	9.2	8.6	11.1	9.6
3	- .2	-2.1	.4*	- .6	8.7	9.7	10.7	9.7
4	-1.5	3.4	3.5	1.8	8.3	8.8	11.1*	9.4
Mean	.9	2.6	4.0	2.2	8.6	9.1	10.9	9.5

*Estimated

Table 18

Decrease in the Mean Skin Temperature (F) Due to the Shirt

	ENVIRONMENT			
Subject	1	2	3	Mean
1	6.3	4.8	5.2	5.4
2	6.0	4.0	4.6	4.9
3	8.9	11.8	10.3	10.3
4	9.8	10.3	7.6	9.2
Mean	7.7	7.7	6.9	7.4

there was no difference in the performance of the shirt in the three environments. However, there was a tendency of a lower increase in the mean skin temperature when the dry bulb temperature of the ambient air was lower, although it could not be proved statistically.

Saliva

The change in the biochemical responses of the body were detected by analyzing the saliva secreted by the subjects. As mentioned before, five saliva samples were taken for each subject in each session. The first two samples were taken in the prestress condition, the third during the stress period and the last two after the stress period.

Creatinine: Table 19 shows the concentration of the creatinine in saliva in the three environments. No significant ($\alpha < .05$) change in the creatinine concentration was observed due to heat stress with or without the shirt in the three environments tested. However, the concentration tended to increase without the shirt and decrease with the shirt.

Sodium: Table 20 shows the concentration of sodium in the saliva. A sign test showed no significant ($\alpha < .05$) change in the concentration of sodium from prestress to recovery with the shirt but a significant increase without the shirt. With the shirt, a small decrease in concentration was observed in Environments 1 and 3 but an increase in Environment 2. Comparing the same values, in the No Shirt condition, the concentration of sodium increased more than twice from prestress to recovery.

Potassium: Table 21 shows the concentration of potassium in each condition. A sign test showed no significant ($\alpha < .05$) change in the concentration of potassium from prestress to recovery with the shirt, but a significant increase without the shirt. With the shirt, the average concentration decreased by a small amount in Environment 1 but increased

Table 19

Creatinine Concentration, (mg./100 ml.), in Saliva in the Three Environments

ENVIRONMENT	SUBJECT	SHIRT							NO SHIRT						
		BEFORE STRESS			STRESS	AFTER STRESS			BEFORE STRESS			STRESS	AFTER STRESS		
		SAMPLE NUMBER							SAMPLE NUMBER						
		1	2	Mean	3	4	5	Mean	1	2	Mean	3	4	5	Mean
1	1	*	.70	.70	†	†	†	†	.60	.46	.53	.84	1.14	1.14	1.14
	2	.68	.54	.61	.43	.40	.47	.43	†	†	†	†	†	†	†
	3	†	†	†	†	†	†	†	.25	.27	.26	.29	.27	.33	.30
	4	.50	.20	.35	.19	.17	.17	.17	†	†	†	†	†	†	†
	Mean	.59	.48	.55	.31	.28	.32	.30	.42	.36	.40	.56	.70	.73	.71
2	1	*	2.94	2.94	1.41	.72	.39	.55	1.48	.75	1.11	.57	.35	.80	.57
	2	.31	.24	.27	.19	.30	.40	.35	.87	.48	.67	.34	.40	.40	.40
	3	.40	.30	.35	.33	.32	.32	.32	.27	.33	.30	.24	.27	.38	.32
	4	.43	.38	.40	.23	.14	.24	.19	.17	.22	.19	.18	.27	†	.27
	Mean	.38	.96	.71	.54	.37	.34	.35	.70	.44	.57	.33	.32	.53	.41
3	1	.47	.50	.48	.53	.61	.43	.52	†	†	†	†	†	†	†
	2	†	†	†	†	†	†	†	.50	.34	.42	.29	.47	.45	.46
	3	.34	.21	.27	.18	.25	.17	.21	†	†	†	†	†	†	†
	4	†	†	†	†	†	†	†	.42	.13	.27	.20	.25	.17	.21
	Mean	.40	.35	.38	.35	.43	.30	.36	.46	.23	.35	.24	.36	.31	.33
Grand Mean		.45	.60	.59	.40	.36	.32	.34	.53	.34	.47	.38	.46	.52	.46

†Concentration less than .25 mg./100 ml. in diluted specimen

*Eliminated Outliers

Table 20

Sodium Concentration, (meq/liter), in Saliva in the Three Environments

ENVIRONMENT	SUBJECT	SHIRT							NO SHIRT						
		BEFORE STRESS			STRESS	AFTER STRESS			BEFORE STRESS			STRESS	AFTER STRESS		
		SAMPLE NUMBER							SAMPLE NUMBER						
		1	2	Mean	3	4	5	Mean	1	2	Mean	3	4	5	Mean
1	1	9.1	5.0	7.0	15.0	7.1	4.7	5.9	8.3	5.7	7.0	11.7	28.6	14.3	21.4
	2	11.3	8.0	9.6	9.5	7.5	7.3	7.4	12.0	4.3	8.2	13.3	40.0	15.4	27.7
	3	15.0	9.5	12.0	5.6	6.2	4.8	5.5	8.3	5.0	6.7	8.6	10.0	5.4	7.7
	4	6.0	5.0	5.5	3.7	6.3	4.2	5.2	6.3	3.6	4.9	5.9	12.5	7.7	10.1
Mean		10.3	6.9	8.6	8.5	6.8	5.3	6.0	8.7	4.7	6.7	9.9	22.8	10.7	16.7
2	1	12.3	4.4	8.3	5.6	5.5	6.7	6.1	5.5	8.0	6.8	6.8	27.5	20.0	23.7
	2	7.6	9.1	8.3	9.4	11.0	14.5	12.7	10.2	5.5	7.9	7.9	26.3	13.8	20.0
	3	5.5	7.2	6.4	4.0	4.2	5.0	4.6	5.0	5.4	5.2	16.7	11.4	12.5	11.9
	4	10.0	6.3	8.1	6.8	17.8	7.1	12.5	4.7	3.3	4.0	10.0	11.6	*	11.6
Mean		8.8	6.8	7.8	6.4	9.6	8.3	9.0	6.3	5.6	6.0	10.3	19.2	15.4	17.6
3	1	7.8	6.7	7.2	5.0	8.0	14.3	11.1	10.0	4.5	7.3	6.7	9.1	10.0	9.5
	2	12.0	10.8	11.4	5.5	8.0	16.0	12.0	7.4	7.9	7.6	12.5	18.8	17.5	18.1
	3	11.8	10.8	11.3	5.5	6.2	5.0	5.6	10.5	6.6	8.5	24.0	26.3	7.7	17.0
	4	10.7	3.8	7.2	6.1	7.4	4.7	6.1	4.2	3.7	3.9	5.0	11.2	3.3	7.3
Mean		10.6	8.0	9.3	5.5	7.4	10.0	8.7	8.0	5.7	6.8	12.0	16.3	9.6	13.0
Grand Mean		9.9	7.2	8.5	6.8	7.9	7.8	7.9	7.6	5.3	6.5	10.7	19.4	11.9	15.5

*Data Not Available

Table 21

Potassium Concentration, (meq/liter), in Saliva in the Three Environments

ENVIRONMENT	SUBJECT	SHIRT							NO SHIRT						
		BEFORE STRESS			STRESS	AFTER STRESS			BEFORE STRESS			STRESS	AFTER STRESS		
		SAMPLE NUMBER							SAMPLE NUMBER						
		1	2	Mean	3	4	5	Mean	1	2	Mean	3	4	5	Mean
1	1	22.7	18.7	20.7	12.5	14.3	11.9	13.1	23.8	22.5	23.1	16.7	25.0	41.5	33.2
	2	24.5	24.0	24.2	25.8	25.0	32.4	28.7	15.0	16.3	15.6	20.8	18.7	14.4	16.5
	3	10.0	11.9	10.9	11.1	12.5	11.9	12.2	13.7	14.8	14.2	14.8	17.7	24.6	21.1
	4	24.7	29.0	26.8	24.0	21.9	27.2	24.5	18.7	17.9	18.3	14.7	31.2	19.2	25.2
	Mean	20.5	20.9	20.7	18.3	18.4	20.8	19.6	17.8	17.9	17.8	16.7	23.1	24.9	24.0
2	1	18.3	19.1	18.7	23.4	22.6	22.4	22.5	17.4	21.1	19.2	15.2	22.0	34.5	28.2
	2	18.6	21.8	20.2	26.6	24.8	29.0	26.9	17.0	17.6	17.3	16.3	19.2	26.2	22.7
	3	18.5	18.5	18.5	18.0	19.5	22.0	19.7	19.7	20.2	19.9	17.6	24.1	28.1	26.1
	4	30.0	31.5	30.7	28.6	28.6	26.7	27.6	24.6	23.9	24.2	21.2	21.4	*	21.4
	Mean	21.3	22.7	22.0	24.1	23.9	25.0	24.4	19.7	20.7	20.2	17.6	21.7	29.6	25.1
3	1	14.4	19.3	16.8	20.0	22.7	31.4	27.0	15.0	13.5	14.2	16.6	22.7	25.0	23.8
	2	20.0	16.2	18.1	20.4	15.0	15.0	15.0	22.6	30.0	26.3	20.0	25.0	34.5	29.7
	3	18.1	14.3	16.2	17.3	18.8	21.4	20.1	19.7	12.5	16.1	10.0	15.8	23.0	19.4
	4	16.6	11.5	14.0	15.1	*	11.9	11.9	21.4	22.1	21.7	24.8	26.2	27.6	26.9
	Mean	17.3	15.3	16.3	18.2	18.8	19.9	19.5	19.7	19.5	19.6	17.8	22.4	27.5	25.0
	Grand Mean	19.7	19.6	19.7	20.2	20.3	21.9	21.2	19.0	19.3	19.2	17.3	22.4	27.3	24.7

*Data Not Available

in Environment 2 and 3, from prestress to recovery. Without the shirt, the maximum increase in the average concentration was observed in Environment 3.

Amylase: Amylase concentration in saliva is more prone to day to day changes than any other substance. This can be very well observed from Table 22. A sign test showed that there was no significant change in the average concentration of amylase in saliva from prestress to recovery with the shirt, but a significant increase without the shirt. With the shirt, the average concentration decreased in Environments 1 and 3, but increased in Environment 2. Without the shirt, the maximum increase in the average concentration was observed in Environment 2 and minimum in Environment 1.

Sodium to Potassium Ratio: Table 23 shows the sodium to potassium ratio in each Environment. The ratio was calculated for each subject, with and without the shirt for prestress and recovery periods. The average concentration of sodium in the prestress or recovery was divided by the corresponding concentration of potassium to give the required ratio. A sign test showed no significant ($\alpha < .05$) change in the ratio with the shirt, but a significant increase without the shirt. With the shirt the results were same as those reported by Byrnes (1970), who also did not find a significant change in the ratio with the cooling system on.

From the above we conclude that sodium, potassium, sodium to potassium ratio and amylase are affected by the heat stress and can be used as criteria for measuring heat stress. The shirt did check the increase in the concentration of the above substances in the saliva. Creatinine does not seem to be sensitive to the heat stress.

Table 22

Amylase Concentration, (Units/100 ml), in Saliva in the Three Environments

ENVIRON-MENT	SUB-JECT	SHIRT							NO SHIRT						
		BEFORE STRESS			STRESS	AFTER STRESS			BEFORE STRESS			STRESS	AFTER STRESS		
		SAMPLE NUMBER							SAMPLE NUMBER						
		1	2	Mean	3	4	5	Mean	1	2	Mean	3	4	5	Mean
1	1	8,000	1,950	4,975	160	1,930	419	1,175	10,095	8,545	9,320	4,267	9,143	12,572	10,857
	2	5,400	8,480	6,940	4,381	6,000	9,412	7,706	5,120	226	2,673	3,000	5,200	724	2,962
	3	120	95	107	111	125	267	196	2,667	27	1,347	*	1,247	3,175	2,211
	4	16,000	3,800	9,900	4,000	3,117	2,111	2,614	2,456	107	1,281	212	400	154	277
	Mean	7,380	3,580	5,480	2,160	2,790	3,050	2,922	5,080	2,230	3,655	2,490	4,000	4,160	4,077
2	1	6,720	3,290	5,005	2,200	1,714	2,000	1,857	8,000	2,364	5,182	1,214	14,800	26,000	20,400
	2	57	94	75	50	48	21	35	2,545	326	1,435	105	190	160	175
	3	74	912	493	5,440	158	198	178	1,600	2,261	1,930	400	12,364	12,500	12,432
	4	3,467	3,600	3,533	1,091	1,886	3,048	2,467	4,267	2,435	3,351	4,680	10,580	*	10,580
	Mean	2,580	1,970	2,277	2,200	950	1,320	1,134	4,100	1,850	2,975	1,600	9,480	12,890	10,942
3	1	1,750	2,667	2,208	2,667	4,909	5,429	5,169	1,940	1,745	1,842	348	3,941	3,860	3,900
	2	1,440	108	774	333	368	48	208	1,926	5,896	3,911	2,769	16,000	15,000	15,500
	3	1,984	1,550	1,767	2,182	3,471	2,987	3,229	21	13	17	32	12,632	12,308	12,470
	4	2,613	1,438	2,025	1,169	1,415	761	1,088	2,521	2,168	2,344	4,120	5,600	3,200	4,400
	Mean	1,950	1,440	1,694	1,590	2,540	2,310	2,423	1,600	2,455	2,028	1,820	9,543	8,590	9,068
Grand Mean		3,950	2,330	3,150	1,988	2,093	2,227	2,160	3,593	2,178	2,886	1,970	7,674	8,547	8,029

*Data Not Available

Table 23

Mean Sodium to Potassium Ratio in Saliva Before Heat Stress Versus After Heat Stress

		SHIRT		NO SHIRT	
ENVIRONMENT	SUBJECT	BEFORE STRESS	AFTER STRESS	BEFORE STRESS	AFTER STRESS
1	1	.34	.45	.30	.64
	2	.40	.26	.53	*
	3	1.11	.45	.47	.36
	4	.21	.21	.27	.40
	Mean	.52	.34	.39	.47
2	1	.44	.27	.35	.84
	2	.41	.46	.46	.88
	3	.35	.23	.26	.45
	4	.26	.45	.17	.54
	Mean	.36	.35	.41	.68
3	1	.43	.41	.51	.40
	2	.63	.80	.29	.61
	3	.70	.28	.53	.81
	4	.51	.51	.18	.27
	Mean	.57	.50	.38	.54
	Grand Mean	.48	.40	.39	.57

*Estimated as outlier

Heat Stored

Webb (1969) suggested the following emperical expression for the estimation of the heat stored in the body due to exposure:

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

where

Q = the amount of heat stored, kcal

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

m_b = weight of the body, kg

T_s = the change in mean skin temperature, C

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

Table 24 gives the rate of heat storage in the body, with and without the shirt, in the three environments. The values of the change in rectal and mean skin temperature in the three Environments were taken from Tables 13 and 17. The average heat storage rate of 220 Btu/hr (55 kcal) in the shirt condition was significantly ($\alpha < .01$) less than the heat storage rate of 760 Btu/hr (190 kcal) in the body in the No Shirt condition. Table 25 gives the decrease in the heat storage rate in the body due to the shirt and the ratio of this decrease to the heat stored in the No Shirt condition. The average decrease in the heat storage rate due to the shirt was 540 Btu/hr (135 kcal). The average ratio of heat removal to heat stored in the No Shirt condition was .69. For subject 3 in Environment 2 and subject 4 in Environment 3 the ratio was greater than 1. The probable reason for this may be that the relative weights of mean skin temperature and rectal temperature are not appropriate.

Heat Losses

Heat removal due to the cold air was estimated from the following formulas,

Table 24

Heat Storage kcal/hr (Btu) With & Without the Shirt in Three Environments

	SHIRT ENVIRONMENT				NO SHIRT ENVIRONMENT			
Subject	1	2	3	Mean	1	2	3	Mean
1	42 (168)	79 (316)	88 (352)	70 (280)	142 (568)	153 (612)	162 (648)	152 (608)
2	87 (348)	78 (312)	117 (468)	94 (376)	196 (784)	153 (612)	241 (764)	197 (788)
3	30 (120)	-2 (-8)	40 (160)	23 (92)	211 (844)	267 (1068)	264 (1056)	247 (988)
4	-3 (-12)	47 (188)	49 (196)	31 (124)	158 (632)	154 (616)	173 (692)	162 (648)
Mean	39 (156)	51 (204)	74 (296)	55 (220)	177 (707)	182 (727)	210 (840)	190 (760)

Table 25

Decrease in the Heat Storage Rate (kcal/hr (Btu)) due to the Shirt and Ratio of the Decrease to Heat Storage Rate in the No Shirt Condition.

	Heat Removal Rate kcal/hr (Btu)				Ratio			
	ENVIRONMENT				ENVIRONMENT			
Subject	1	2	3	Mean	1	2	3	Mean
1	100 (400)	74 (296)	74 (296)	83 (328)	.70	.48	.45	.54
2	109 (436)	75 (300)	124 (496)	103 (410)	.55	.49	.51	.52
3	181 (724)	269 (1076)	224* (896)	225 (896)	.86	1.00	.85	.90
4	161 (644)	107 (428)	124 (496)	131 (520)	1.02	.69	.71*	.81
Mean	138 (551)	131 (525)	137 (546)	135 (540)				

*estimated

$$C = 0.26\ V^{.6}\ (t_s - t_a)\ (P_A/760)^{.6}$$ (Mitchell et al. (1969))

$$E = 1.4\ V^{.37}\ (p_s - p_a)$$ (Nelson et al. (1947))

$$R = \sigma[1/\varepsilon_1 + (\frac{1}{\varepsilon_2} - 1)\ \frac{A_1}{A_2}]^{-1}\ (T_1^4 - T_2^4)$$ (Mitchell et al. (1969))

where

C = heat exchanged by convection in kcal/m^2 of body area/hr

R = heat exchanged by radiation in kcal/m^2 of body area/hr

E = heat exchanged by evaporation of sweat in kcal/m^2 of body area/hr

V = velocity of air in fpm

t_s = mean skin temperature in °C under the shirt

t_a = air temperature in °C(average of the temperature of the air entering and leaving the shirt)

p_s = vapor pressure of the skin in mm of mercury

p_a = vapor pressure of the air in mm of mercury

P_A = atmospheric pressure in mm of mercury = 760 mm (assumed)

σ = Stefan Boltzman constant = 4.88×10^{-8} kcal m^{-2} hr^{-1} K^{-4}

A_1 = surface area of the enclosed body in m^2 (body area)

A_2 = area of the surrounding surfaces in m^2 = area of the shirt = 1.21

ε_1 = emissivity of the skin = .94

ε_2 = emissivity of the shirt = .90

T_1 = mean surface temperature of the enclosed body in °K = skin temperature

T_2 = mean temperature of the surrounding surfaces in °K = shirt temperature

The velocity of air in the front portion of the shirt was measured by inserting both the ends of the Alnor Velometer inside the shirt. The air velocity at the back was estimated to be in the range of 400 to 600 fpm.

An average velocity of 500 fpm in the back of the shirt was assumed. The average air velocity inside the shirt used in the calculations was 362.5 fpm, the mean of the velocities at the back and front. The effective body area was the area of the upperarm, abdomen, chest and the back. The sum of the areas of the above portions are 35% of the total body area (Burton and Collier, 1964). The vapor pressure of the skin and the air were the saturation pressures at the mean skin and air temperatures from the psychrometric tables (ASHRAE Handbook, 1956). Temperature on the inside layer of the shirt, T_2, was estimated by averaging the temperature of the layer of the air at the inside and outside of the shirt. The emissivity of the skin was assumed to be .94 (NASA, 1965) and of the shirt .90 (Nelson et al., 1947).

Table 26 shows heat losses due to the shirt. It is to be noted that the calculations of the heat losses due to convection, evaporation and radiation were quite crude. However, it did give an idea of the heat losses from the body due to the cold air.

Subjective Evaluation

After the experiment, the subjects were given a questionnaire as shown in Figure 24. Three of the four subjects felt slightly cool or comfortable in all the environments. Subject 4 felt slightly warn in Environments 2 and 3. All the subjects called for refinement of the hood design. The general remark was that the air flow over the face was insufficient and the air which did reach the face warmed up quite a bit due to mixing with the ambient air. One of the subjects suggested sealing up of the top of the hood. Excepting for face cooling, they generally liked the experimental system.

Table 26

Heat Losses by Convection, Radiation and Evaporation of Sweat

SUBJECT	ENVIRONMENT	HEAT LOSS (kcal/m^2 body area/hr.) CONVECTION	RADIATION	EVAPORATION OF SWEAT	TOTAL	EFFECTIVE BODY AREA (m^2)	HEAT LOSS/hr. kcal/hr	MEAN
1	1(104F,90% RH)	59.5	9.1	58.6	127.2	.57	72.5	
2	"	66.9	19.0	67.9	153.8	.70	108.0	81.3
3	"	42.8	2.3	40.4	85.5	.74	63.4	
4	"	*	*	*	*	.62	*	
1	2(112F, 65% RH)	74.3	17.2	75.9	167.4	.57	95.5	
2	"	69.4	13.9	72.4	155.7	.70	109.0	76.6
3	"	25.6	- 1.2	22.7	47.1	.74	34.8	
4	"	49.7	6.5	51.8	108.0	.62	67.0	
1	3(130F,35% RH)	56.1	1.8	61.9	119.8	.57	68.2	
2	"	71.3	9.8	79.1	160.2	.70	112.5	72.8
3	"	49.2	- 2.3	44.9	91.8	.74	68.0	
4	"	42.3	-15.5	41.7	68.5	.62	42.5	

*Data not available

NAME

AGE HEIGHT WEIGHT

CLASSIFY YOUR OPINION ABOUT THE COOLING SYSTEM YOU HAVE USED ON THE FOLLOWING SCALE (MARK ONE) UNDER ENVIRONMENTS

	1	2	3
1. COLD			
2. COOL			
3. SLIGHTLY COOL			
4. COMFORTABLE			
5. SLIGHTLY COOL			
6. WARM			
7. HOT			

WHAT MODIFICATIONS DO YOU THINK SHOULD BE MADE IN THE COOLING SYSTEM?

GIVE YOUR COMMENTS ABOUT THIS METHOD OF COOLING.

Fig. 24. Questionnaire Given to Subjects for Comments

Air Circulation

Fig. 25 shows the temperatures at the skin, under the shirt, outside the shirt at two locations on the body and the environment. The graph for the right arm shows that the air temperature in the sleeves of the shirt was lower than the arm temperature. This is contrary to the results obtained by Gandhok (1970). Hence the air circulation in the sleeves was better than Gandhok's design. The temperature just outside the shirt was lower for the arms than the chest. The reason for this could be that adhesive tape used to keep the wire and the plastic tubing in place covered a large chunk of the front portion of the shirt, hence hindering the flow of air through the cloth.

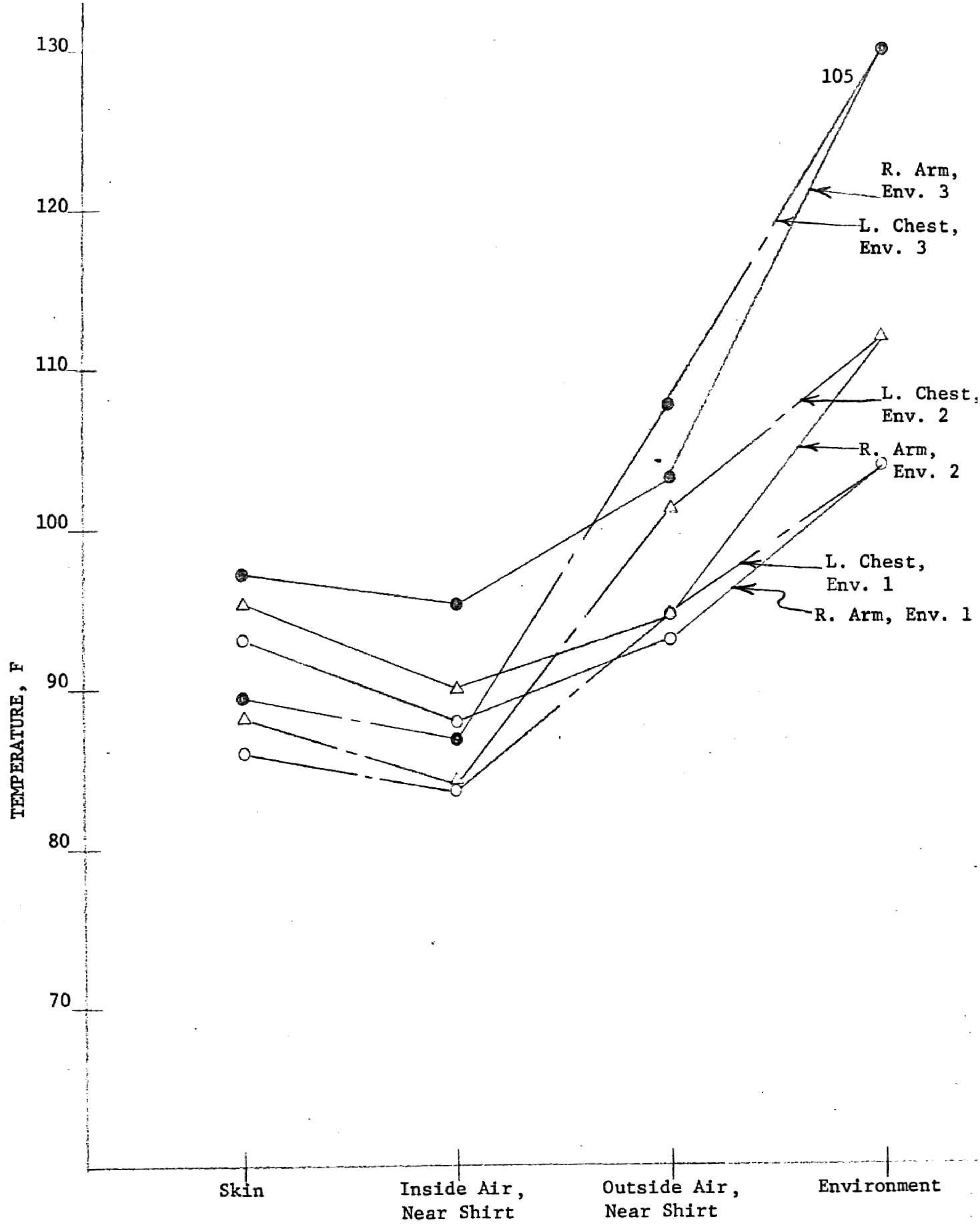

Fig. 25. Skin Temperature, Inside Air Temperature and Outside Air Temperature near the Shirt and Environment Temperature at the Right Arm and Left Chest.

DISCUSSION

The primary objective of this experiment was to investigate the effectiveness of an air cooled jacket, made from an ordinary work shirt (so that it was compatible with usual work clothes). The porous structure of the cloth provided dynamic insulation from the heat stress. Besides obstructing the inflow of heat toward the body, the cold air, escaping radially out of the shirt, tended to form a layer of cold air at temperatures 10 - 27 F (6 - 15 C) lower than the environment temperature, thus further protecting the wearer from heat stress. The psychological effects of breathing hot air were reduced by providing a hood made of a transparent material with the shape of a frustum of a cone. The cold air leaving the shirt at the neck, though at 93 F (33.5 C), was cooler than the environmental air. At an average air flow rate of 25.5 cfm (.71 m^3) at 68 F (20 C) and 22% RH, the cooling system, consisting of a shirt and a hood, was found to be quite efficient. The average heat storage rate with the shirt was 220 Btu/hr (55 kcal) as compared to 760 Btu/hr (190 kcal) without the shirt. Thus the average decrease in heat storage rate was 540 Btu/hr (135 kcal). This was more than 5 times the decrease in storage rate of 100 Btu/hr (25 kcal) obtained by Sharma (1970) and 7 times the decrease obtained by Gandhok (1970).

This rate of heat removal kept the average increase in heart rate to 30 beats/minute as compared to 73 beats/minute without the jacket. The significance of the effect of subjects indicated that different subjects reacted differently to the shirt. The performance of the shirt was better (although not statistically better) under conditions of low temperature and high humidity.

Mean skin temperature was the weighted mean of the arm, chest, thigh and calf temperatures. The increase in mean skin temperature in the shirt condition was one fourth of the increase when without the shirt. Although the heat stress in all the three environments was theoretically the same, dry bulb temperature seemed more important than humidity as far as skin temperature was concerned. It was observed that as soon as the subjects entered the test chamber in the 130 F and 35% RH condition all the skin temperatures shot up and then dropped down before increasing again. The reason for this could be that the thermal balance of the body was disturbed initially, due to a sudden thermal shock. With subjects 3 and 4 it was observed that the skin temperatures outside the shirt (at calf and thigh) were more when the subjects wore the shirt than without. The reason for this is unknown. The significance of the environment effects reinforced the supposition that the performance of the shirt was better in Environment 1.

The increase in head and rectal temperatures with the shirt were found to be significantly lower than without the shirt. There was no difference in the performance of the shirt in the three environments with these temperatures as the criteria.

The sweat loss of the subjects with the shirt was found to be only 40% of that without the shirt.

Concentration of sodium, potassium and amylase were good indicators of heat stress. The concentration of all these increased without the shirt. With the shirt, the change was not significant.

All the subjects, excepting one, found the cooling system satisfactory for the environments and task tested. However they wanted more air over the face.

CONCLUSIONS

The effectiveness of the proposed cooling system has been demonstrated. The system kept all the physiological parameters, that is, heart rate, head temperature, mean skin temperature, rectal temperature and sweat loss much below the No Shirt condition. The increase in the concentration of sodium, potassium and amylase was more with the shirt than without. Creatinine concentration was not found to be sensitive to heat stress.

A number of improvements in the shirt are still possible. The plastic tube used in shirt had a thickness of 1/8 inch; a thinner wall tube will reduce the weight of the system. The air distribution system inside the shirt could be improved by streamlining the path of the air, thus less resistance and consequently more static pressure of the air will be obtained. The outflow of the air directly to the environment from the hood resulted in the intermixing of the cold air and the hot air of the environment. Covering a large portion of the hood from the top will not only reduce the intermixing of the air, but will also help in guiding the air over the face only. Use of the above system under conditions of low temperatures (100 - 110 F) and high humidity is recommended.

REFERENCES

Armored Medical Research Laboratory Heat I: a) #9, Project 2-28, 1943. b) #16 Project T-2, 1945.

ASHRAE Handbook of Fundamentals, American Society of Heating, Refrigerating and Airconditioning Engineers, New York, 1967.

Bell, C. R., Provins, K. A., and Hirons, R. W. Visual and Auditory Vigilance During Exposure to Hot and Humid Conditions, Ergonomics, Vol. 7, July, 1964.

Blockley, W. V. and Lyman, J. H. Studies of Human Tolerance for Extreme Heat. III Mental Performance Under Heat Stress as Indicated by Addition and Number Checking Tests, AF Technical Report 6022, Wright Patterson Air Force Base, Ohio, 1950.

Burton, D. R. and Collier, L. The Development of Water Conditioned Suits, Royal Aircraft Establishment Technical Note No. M.E. 400, April, 1964.

Byrnes, D. Effect of Heat Stress on Saliva, M. S. Thesis, Kansas State University, 1970.

Crockford, G. W., and Lee, D. E. Heat Protective Ventilated Jackets: A Comparison of Humid and Dry Ventilated Air, British Journal of Industrial Medicine, Vol. 24, 1967.

Crockford, G. W., and Hellon, R. F. Design and Evaluation of a Ventilated Garment for Use in Temperatures up to 200°C. British Journal of Industrial Medicine, No. 21, 1964.

Crockford, G. W., Hellon, R. F., Humphreys, P. W., and Lind, A. R. An Air Ventilating Suit for Wear in Very Hot Environments. Ergonomics, Vol. 4, No. 1, January, 1963.

Croley, J. J., Jr. Cooling Individual Workers at a Large Atomic Installation. Proceedings of the Symposium on Individual Cooling, Kansas State University, Manhattan, Kansas, 1969.

Duncan, J. R. A Physiological Evaluation of Two Designs of a Conductive Cooling Hood, M. S. Thesis, Kansas State University, 1969.

Drake, R. M., Jr., Funk, J. E., and Moegling, J. B. Convective Heat Transfer in Gemini and Apollo Space Suits. Proceedings of the Symposium on Individual Cooling, Kansas State University, Manhattan, March, 1969.

Edholm, O. G. The Biology of Work, World University Library, McGraw Hill Book Company, New York, 1967.

Fryer, H. C. Concepts and Methods of Experimental Statistics, Allyn and Bacon, Inc., Boston, 1966.

Fetcher, E. S., Rapaport, S. I., Hall, J. F., and Shaub, H. G. Biophysical Requirements for the Ventilation of Clothing. Journal of Applied Physiology, Vol. 2, No. 2, August, 1949.

Gandhok, G. S. Physiological Evaluation of an Air Cooled Helmet System, M. S. Thesis, Kansas State University, 1970.

Givoni, B., and Rim, J. Effects of the Thermal Environments and Psychological Factors upon Subject's Responses and Performance of Mental Work, Ergonomics, 1962.

Greider, H. R., and Santa Maria, L. J. Subjective Thermal Comfort Zones of Ventilated Full Pressure Suit at Altitude, Aviation Medicine, June, 1957.

Grollman, S. The Human Body: Its Structure and Physiology. McMillan, New York, 1964.

Haines, G. F., and Hatch, T. Industrial Heat Exposure Evaluation and Control. Part I - Evaluation of Thermal Exchange, Reference Section - Heating Ventilating, November, 1952.

Houghten, F. C., Federber, M. B., and Gutherlet, C. Industrial Medicine, No. 10, 1941.

Kalsbeek, J. W. H., and Ettema, J. H. Sinus Arrhythmia and the Measurement of Mental Load. Communication of the London Conference of the British Psychological Society, December, 1965.

Kalsbeek, J. W. H., and Sykes, R. N. Objective Measurement of Mental Load. Laboratory of Ergonomic Psychology T.N.O., Jan Swammerdam Institute, Amsterdam, The Netherlands, 1967.

Konz, S., and Duncan, J. Cooling with a Water Cooled Hood. Proceedings of the Symposium on Individual Cooling, Kansas State University, Manhattan, March, 1969.

Lee, D. H. K. Heat and Cold Effects and Their Control. U. S. Department of Health, Education, and Welfare, Public Health Service Monograph No. 72, U. S. Govt. Printing Office, Washington, 1964.

Leinhard, W. F., Hughes, J. P., and Brassette, T. A. Man Cooling by a Vortex Tube Device. Archieves of Environmental Health, Vol. 9, September, 1964.

Leithead, C. S., and Lind, A. R. Heat Stress and Heat Disorders. Davis, Philadelphia, 1964.

Marbarger, J. P. Eng. Div. Memor. Rept. TSEAA-695-2FF, December, 1945.

Mackworth, N. H. Researches in the Measurement of Human Performance, Medical Research Council, Special Report Series No. 268, 1950.

Mitchell, D., Wyndham, C. H., Vermeulen, A. J., Hodgson, T., Atkins, A. R., and Hofmeyr, H. S. Radiant and Convective Heat Transfer of Nude Men in Dry Air, Journal of Applied Physiology, Vol. 26, No. 1, January, 1969.

Mitchell, D., and Wyndham, C. H. Comparison of Weighting Formulas for Calculating Mean Skin Temperature, Journal of Applied Physiology, Vol. 26, May, 1969.

NASA Contractor Report prepared by AiResearch Manufacturing Co. Study of the Thermal Processes for Man in Space. NASA CR-216, National Aeronautics and Space Administration, Washington, April, 1965.

Nelson, N. O., Eichna, L. W., Horvath, S. M., Shelley, W. B. and Hatch, T. F. Thermal Exchanges of Man at High Temperatures, American Journal of Physiology, 151, 1947.

Nevins, R. G., Rohles, F. H., Springer, W. E., and Feyerherm, A. A Temperature and Humidity Chart for Thermal Comfort of Seated Persons. ASHRAE Journal, Vol. 8, No. 4, April, 1966.

Pepler, R. D. Effects of Climatic Factors on Performance of Skilled Tasks by Young Men Living in Tropics, Medical Research Council (London) RNPRC 53/784, 654/797, 1952-1954.

Ramanathan, N. L. A New Weighting System for Mean Surface Temperature of the Human Body, Journal of Applied Physiology, Vol. 19, 1964.

Reilly, R. E., and Parker, J. F., Jr. Effect of Heat Stress and Prolonged Activity on Perceptual Motor Performance. NASA CR-1153, National Aeronautics and Space Administration, Washington, August, 1968.

Rohles, F. H. Psychological Aspects of Thermal Comfort, ASHRAE Convention, Denver, 1969.

Sharma, S. K. Physiological Evaluation of an Air Cooled System, M. S. Thesis. Kansas State University, 1970.

Van Pattern, R. E., and Gaudeo, R., Jr. Application of the Ranque Hilsch Vortex Tube to Aircrew Cooling Problems. AMRL-TR-67-124, Aerospace Medical Research Laboratories, Wright Patterson Air Force Base, Ohio, June, 1968.

Veghte, J. H. Efficacy of Pressure Suit Cooling Systems in Hot Environments. AMRL-TR-64-58, Aerospace Medical Research Laboratories, Wright Patterson Air Force Base, Ohio, October, 1965.

Vernon, H. M., Bedford, T., and Warner, C. F. The Relation of Atmospheric Conditions to the Working Capacity and the Accident Rate of Miners. Report of Industrial and Fatigue Research Board: No. 37, Her Majesty's Stationery Office, London, 1927.

Vernon, H. M., Bedford, T., and Warner, D. F. A Study of Absenteeism in a Group of Ten Collieries. Report of Industrial and Fatigue Research Board: No. 51, Her Majesty's Stationery Office, London, 1931.

Vernon, H. M., Bedford, T., and Warner, C. F., Two Studies of Absenteeism in Coal Mines. Report of Industrial and Fatigue Research Board: No. 62, Her Majesty's Stationery Office, London, 1931.

Webb, P. The Physiological Effects of Cooling. Proceedings of the Symposium on Individual Cooling, Kansas State University, Manhattan, 1969.

Weiner, J. S., and Hutchinson, J. C. D. Hot Humid Environments; It's Effect on Performance of Motor Co-ordination Tests, British Journal of Industrial Medicine, Vol. 2, No. 154, 1945.

Weston, H. C. A Study of Efficiency in Fine Linen Weaving. Report of Industrial and Fatigue Research Board: No. 20, Her Majesty's Stationery Office, London, 1922.

Wing, J. F. Upper Thermal Tolerance Limits for Unimpaired Mental Performance. AMRL-TR-65-71, Aerospace Medicine, Vol. 36, No. 10, October, 1965.

Wyatt, S., Fraser, J. A., and Stock, E. G. L. Fan Ventilation in a Humid Weaving Shed. Report of Industrial and Fatigue Research Board: No. 37, Her Majesty's Stationery Office, London, 1926.

Wyndham, C. H., Strydom, N. B., Cooke, H. M., and Maritz, J. S. Studies on the Effects of Heat on Performance of Work. Applied Physiology Lab Reports: 1-3/59, Transvaal and Orange Free State Chamber of Mines, Johannesburg, S. Africa, 1959.

Wyndham, C. H., and Strydom, N. B. The Effects of Environmental Heat on Comfort, Productivity and Health of Workmen, South African Mechanical Engineers, May, 1965.

Appendix A

Table 27

Coefficient of Variation of the Heart Rate in Environment 1

Period	SHIRT Subject 1	2	3	4	Mean	NO SHIRT Subject 1	2	3	4	Mean
1	.055	.088	.062	.166	.093	.076	.074	.162	.067	.095
2	.045	.058	.159	.057	.080	.085	.025	.051	.096	.064
3	.093	.107	.082	.080	.090	.072	.066	.116	.120	.093
Mean	.064	.084	.101	.101	.088	.078	.055	.110	.094	.084
4	*	.041	.052	.138	.077	.036	*	.055	*	.045
5	*	.034	.127	.037	.066	.056	*	.041	.036	.044
6	*	.022	.052	.059	.044	.043	*	.033	.037	.038
7	.047	.038	.062	.073	.055	.054	.039	.047	.044	.046
8	.028	.032	.060	.038	.039	.047	.049	.021	.033	.037
9	.052	.041	.059	.061	.053	.044	.048	.030	.039	.040
Mean	.042	.035	.069	.068	.055	.047	.045	.038	.038	.042
10	.062	.073	.068	.044	.062	.071	.037	.030	.036	.043
11	.036	.044	.103	.086	.067	.060	.034	.030	.040	.041
12	.098	.104	.125	.071	.100	.063	.041	.052	.054	.052
Mean	.065	.074	.099	.067	.076	.065	.037	.037	.043	.046

*Data Not Available

Table 28

Coefficient of Variation of the Heart Rate in Environment 2

Period	SHIRT Subject 1	2	3	4	Mean	NO SHIRT Subject 1	2	3	4	Mean
1	.079	.062	.112	.036	.072	.151	.103	.080	.160	.123
2	.127	.042	.069	.079	.079	.031	.040	.079	.066	.054
3	.101	.040	.132	.071	.086	.087	.118	.071	.074	.087
Mean	.102	.048	.104	.062	.079	.090	.087	.077	.100	.088
4	.034	.048	.038	.113	.058	.059	.040	.041	.078	.054
5	.037	.029	.085	.088	.060	.056	.051	.024	.037	.042
6	.125	.026	*	.088	.080	.052	.047	.030	.069	.049
7	.030	.020	*	.115	.055	.046	.036	.023	*	.035
8	.051	.054	.052	.056	.053	.045	.037	.047	.042	.043
9	.037	.053	.035	.029	.038	.052	.050	.041	.037	.045
Mean	.052	.038	.052	.081	.056	.052	.043	.034	.053	.045
10	.087	.030	.148	.077	.085	.045	.044	.025	.047	.040
11	.062	.048	.067	.106	.071	.047	.033	.031	.108	.055
12	.059	.042	.084	.160	.086	.034	.061	.063	.108	.066
Mean	.069	.040	.100	.114	.081	.042	.046	.040	.088	.054

*Data Not Available

Table 29

Coefficient of Variation of the Heart Rate in Environment 3

Period	SHIRT Subject 1	2	3	4	Mean	NO SHIRT Subject 1	2	3	4	Mean
1	.080	.050	.069	.104	.076	.039	.083	.100	.095	.079
2	.137	.081	.098	.080	.099	.080	.046	.060	.085	.068
3	.045	.066	.095	.052	.064	.130	.038	.138	.090	.099
Mean	.087	.066	.087	.079	.080	.083	.056	.099	.090	.082
4	.035	.031	.058	.057	.045	.033	.037	.034	.038	.035
5	.060	.031	.128	.119	.084	.030	.042	.026	.051	.037
6	.026	.071	.051	.122	.067	.040	.051	.044	.037	.043
7	.070	.035	†	.061	.055	.047	.033	.061	*	.047
8	.040	.048	†	.022	.037	.049	.051	.022	*	.041
9	.028	.031	†	.044	.034	.059	.050	.044	*	.051
Mean	.043	.041	.079	.071	.056	.043	.044	.038	.042	.042
10	.068	.051	.053	.084	.064	.042	.046	.036	.036	.039
11	.092	.037	.093	.038	.065	.048	.033	.037	.126	.061
12	.059	.019	.163	.120	.090	.052	.052	.040	.024	.042
Mean	.073	.036	.103	.081	.073	.047	.044	.037	.061	.047

*Data Not Available
†Data Discarded Due to Disturbed Environment

PHYSIOLOGICAL EVALUATION OF AN AIR COOLED SHIRT UTILIZING DYNAMIC INSULATION

by

DESH DEEPAK KUMAR AURORA

B. Sc. (Engg.) Mech., Ranchi University, India, 1965

AN ABSTRACT OF A MASTER'S THESIS

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ABSTRACT

An air cooling jacket, utilizing the dynamic insulation method, was developed at Kansas State University. The effectiveness of the jacket under three environments, 104 F (40 C) and 90% RH, 112 F (45.5 C) and 65% RH and 130 F (54.5 C) and 35% RH, was evaluated at an air flow rate of 25 cfm (.7 m^3), 68 F (20 C) temperature and 22% RH. With and without the jacket, four subjects moved a 5 lb. brick through a distance of 5 ft. in 10 seconds, in each of the three environments. The heart rate, head temperature, skin temperature, rectal temperature and sweat losses of the subjects were measured during 10 min. in a neutral environment, 30 min. in heat stress and 15 min. again in a neutral condition. Five saliva samples were taken: two in neutral, one in heat stress and two again in neutral.

The average heat removal rate of the jacket was 540 Btu/hr (135 Kcal). The shirt lowered the heart rate by 43 beats/min., increased heart variability from σ =.020 sec. to σ = .035 secs., lowered head temperature by 2.1 F (1.2 C), mean skin temperature by 7.3 F (4 C), rectal temperature by .5 F (.3 C) and sweat losses by 60% when compared to the no jacket condition. The increase in sodium, potassium and amylase concentration in the saliva was less with the jacket than without. The jacket seemed to work better in an environment of 104 F (40 C) and 90% RH, though the improvement was not statistically better.

Further refinements in the design of the cooling system can improve its efficiency.