AN EVALUATION OF COMBINED AIR-COOLING AND WATER-COOLING FOR NON-PERMEABLE CLOTHING

by

I-CHUNG WANG

B. Sc. (Engg), Che. E., Tunghai University, Taiwan (ROC) 1977

A MASTER'S THESIS

submitted in partial fullfillment of the

requirement for the degree

MASTER OF SCIENCE

Department of Industrial Engineering

KANSAS STATE UNIVERSITY
Manhattan, Kansas
1980

Approved by:

Stephen K

Major Professor

ACKNOWLEDGEMENTS

The author would like to express his sincere gratitude to his advisor, Dr. Stephan A. Konz, who provided continual guidance and advice.

The author is grateful to Dr. N. Z. Azer and Prof. J. J. Smaltz for serving on his advisory committee.

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INTRODUCTION

Heat

Heat, associated with high humidity, is found in laundries, paper mills, texiles mills, canneries and power plants. Heat associated with low humidity is common in metal industries such as steel mills, foundries, and reduction plants. Mining and chemical indurtries can present either of the above conditions according to the operation performed and the climate. Hot environments also are encountered in agriculture, where people work outdoors in the blazing sun. As defined by Liethead and Lind (1964), heat is a stress to which most people are exposed at one time or another. A large proportion of the world's population lives and works in the tropical zones, where climatic conditions vary from a hot, dry, desert climate to the hot, humid, jungle type of a climate. The main factors which modify these conditions are the variability in the shape of the land masses, the altitude of the areas concerned and the direction of the wind that blows over them. The climatic heat stress presented by the desert condition takes the form of large heat gains by convection and particularly by radiation. In the hot, humid, jungle type of climate the stress is due rather to the restriction imposed by the environment on the evaporation of sweat. Thus, although the total heat stress in the two types of climate sometimes may be similar, the threat to thermoregulation may depend on different principles in the two situations.

Heat Load

For an industrial worker, the heat load is primarily from metabolism, convection, and radiation. The metabolic rate corresponding to moderate work (machinist) is 235 watts (Konz and Duncan, 1969). The convective heat is (Konz, 1979):

$$C = h_c \cdot A \cdot f_{clc} (t_{air} - t_{skin})$$

and the radiation heat is:

$$R = \sigma \cdot A \cdot f_{eff} \cdot f_{clr} \cdot F_{clr} \cdot e (T^4_{mrt} - T^4_{skin})$$

where,

C = convection gain (+) or loss (-), watts

h_c = convective heat transfer coefficient, watts/(m^2-C)

= 4.5 W/(m^2-C) for standing adults

= $8.3\ V^{.6}$ for seated adults

A = skin surface area, m^2

f_{clr} = multiplier to h_c for clothing

= $1/(1 + .155 (h_c) I_{clo})$

where h_c=2.9 W/(m^2-C) in still air (.15 m/s)

I_{clo} = insulation value of clothing, clo

V = air velocity, m/s

t_{air} = air temperature, ^{o}C

t_{skin} = skin temperature, ^{o}C

R = radiant gain (+) or loss (-), Watts

σ = Stefan-Boltzmann constant

= 5.67×10^{-8} Watts/(m^2-K^4)

f_{eff} = effective skin radiation area factor (.725 for standing, .696 for sitting)

f_{clr} = increase in radiant area due to clothing

= $1 + .155\ I_{clo}$

F_{clr} = multiplier to radiant heat transfer coefficient to adjust for clothing barrier

= $1/(1+.155(h_r)I_{clo})$ where h_r=5.2 W/(m^2-C), the reference radiant heat transfer coefficient

e = emissitivity (skin= .99; clothing in nonvisible radiation= .7)

T_{skin} = temperature in K of the skin, K= C + 273

T_{mrt} = mean radiant temperature in K of environment, K= C + 273

Using the above equations, the convective and radiative heat loads for various ambient temperatures were calculated by Konz and Duncan (1969). Table 1 shows that, for most industrial situations, the convective and radiative heat loads are small or negative. Konz and Duncan (1969) state that unless there is a high temperature radiation source, the heat load is primarily metabolic and is generally below 291 watts.

TABLE 1

Convective and radiant heat loads under different ambient temperatures

Ambient/Mean Radiant Temperature, °C*	Heat Gain Rate (watts) by Convection	Heat Gain Rate (watts) by Radiation
24.4	-334	-118
32.2	-122	- 47
37.8	14	6
43.3	142	62
65.6	698	318

*Mean radiant temperature assumed equal to ambient temperature

Heat Balance for Body

From an engineer's point of view, the human body may be likened to a heat engine. The body converts the chemical energy of its food into work and heat. As is true with an engine, the harder the body works, the greater the amount of heat produced. At the same time there is a constant exchange of heat between the body and the environment by convection, radiation, conduction, and evaporation. The evaporation heat loss from the body comprises the heat lost by the evaporstion of sweat from the surface of the skin, heat lost by water vapor diffusion through the skin and latent and sensible respiration heat loss. The heat balance for the body is given by (Konz, 1979):

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

where, $Q_{metabolic}$ is the heat generated by the oxidation of food elements, Q_{work} is the useful work output, $Q_{sensible}$ is the heat transfer by radiation, free and forced convection, and conductior Q_{latent} is the evaporative heat loss, and Q_{stored} is the rate of energy storage. Although heat storage of up to 174 watts (Webb, 1969) may be tolerated without a physical collapse, it should be essentially zero for normal steady state operating conditions. In the normal environment, man may be exposed during the course of a day's activities to a wide range of ambient temperatures and, at the same time, may sustain considerable variation in metabolic rate, yet still maintain the heat balance of the body. The balance is achieved by the thermoregulatory system of the body, which maintains the internal temperature of the body at a certain level, called the 'set point' (homeostasis), which is specific for an individual. The degree of activity and the amount of clothing worn by man affect the level of his zones of thermal neutrality. For a resting man, the neutral zone occurs within a range approximately 27 to 30°C dry bulb temperature (Threkeld, 1962). On the warm side of the neutral zone, there exists first a zone of vasomotor regulation. The surface blood vessels dilate and allow the blood to flow as close as possible to the outer surface. As the skin temperature increases, it provides a smaller temperature difference versus the environment, resulting in a loss of heat (or a reduction in the gain) by convection and radiation. For still warmer conditions, there is a zone of evaporation. The sweat glands become highly active, drenching the body surface with perspiration. If the air humidity and velocity permit sufficiently rapid evaporation, a further rise in body temperature may be prevented. This is the last line of defense; after this the body enters the zone of inevitable body heating.

Acclimatization

Acclimatization to high temperature is the result of processes by which the subject adapts himself to living and working in a climate which is hot and perhaps humid. It is manifested as a reduction in the heart rate and internal body temperature and increased sweating. An absence from work of one week may result in the worker losing between one-quarter and two-thirds of his acclimatization and a 3-week absence from exposure, whether in summer or winter, will mean virtually total loss of acclimatization (Lavenne, Brouwers, Bell and Crockford, 1971).

How to Beat the Heat (Konz, 1971)

To combat the effect of heat in a job environment there are two complementary strategies: reduce heat input to the body and increase heat loss from the body.

(1) Defense: reduce heat input

Metabolism. As you live, you burn food at a rate depending on how hard you work. Sitting at a desk uses about 115 w; walking at 3 mph, about 300 w. When a person is not losing heat fast enough, the most obvious thing to do is to slow the work pace from say 250 w to 150 w, generating less heat. Unfortunately, reducing the speed of work also reduces productivity.

Convection. To make more convective heat loss, the primary consideration is to keep air temperature less than 35°C. If the air temperature is greater than skin temperature, then you get a heat gain instead of a loss. Next, try to maximize the convective area. Clothing, such as trousers and a short-sleeved shirt, cover about 70 percent of the body, so shorts and no shirt aid convective loss. Unfortunately, this loss often is compensated for by radiation gain, so you are generally cooler if you keep your shirt on. Increasing air velocity helps since it improves evaporation, the body's primary method of heat loss.

Radiation. Keep temperatures of objects radiating to the body below the body surface temperature of 35°C. Clothing (a mobile shield), such as hats and long-sleeved shirt, is a first line of defense. A layer of clothing has a temperature approximately halfway between the skin and the environment, so it cuts radiation gain and losses approximately in half. Standing in the sun can add 170 w to a clothed person; it is considerably higher for those who take off shirt and hat. A second line of defense is a shield between the person and the radiation source. Shields are especially important for high-temperature sources, since the heat gain is proportional to the difference of the fourth power of the absolute temperatures of the two objects. Alumimum is a very good shield material because it has high reflectivity and doesn't corrode.

(2) Offense: increase heat loss

Convection and radiation. As suggested before, the simplest way to increase heat loss is to reduce the temperature of the surrounding air and walls below skin temperature. Then convection and radiation gain become losses. These losses balance metabolic heat for office work when the temperature is about 25.6°C. Using more muscles means more metabolic heat so, for physical work, the temperature should be in the low 20's.

Evaporation. What if it is not economical or practical to cool the environment? Then ladies perspire and men sweat. The key is the phase change when perspiration evaporates; it is evaporation, not sweating, that is beneficial. One choice is to decrease the pressure of the water vapor of the air, and thus increase the differential between it and the vapor pressure of the water on the skin. Usually, it is done by dehumidifying the air; but it also can be done by dropping the air temperature, since even saturated air lower temperatures has a lower vapor pressure. In general, dehumification is usually combined with air cooling and the result is air conditioning. A large portion of the benefit comes from the improved ability for sweat to evaporate. Increasing air velocity is another possibility. The point is to get the breeze to the worker. Increasing the evaporative area is another possibility. Large people have more surface area. Unfortunately, a large mass generates more heat, so the key ratio to maximize is surface area to mass. Surface area can be increased 10 to 15 percent by wearing clothing. Permeable, absorbent fabric, such as cotton and wool, act as a wick holding sweat so that it evaporates rather than dripping off and being wasted.

When ambient temperature is below skin temperature, any decrease in clothing increases dry heat loss and improves sweating. When ambient temperature is above skin temperature, there are three alternatives: (a) when clothing is dry, add clothing to prevent dry heat gain; (b) when clothing is wet, loosen or remove clothing to increase convection and evaporation; or (c) when clothing is wet in spots, loosen to allow increased convection.

Individual Cooling

Making the environment comfortable for working is of fundamental importance. At many hot workplaces it is neither practical nor economically possible to maintain a comfortable or even tolerable thermal environment by applying normal air conditioning principles. Especially in the coal, steel, and glass industries, many workers are exposed to unacceptably hot environments, caused either by considerable heat production from the industrial processes and/or by a high metabolic rate. A practical and economical way of improving these kinds of working conditions is use of individual cooling of the workers. For air cooling, there are two principal air cooling techniques: a) personal cooling devices (suit, jacket, helmet) worn by the worker where air is released <u>under</u> the clothing and b) spot cooling of the workplace by convection (air jet) where air is released <u>onto</u> the clothing. For water cooling, there are personal cooling devices (suit, jacket, helmet) which pass water through many small tubes positioned directly on the wearer's skin, thus effecting sensible heat transfer by conduction directly from the skin to the circulating coolant (Burton and Collier, 1964).

Non-permeable Clothing

Man is exposed to an increasing number of hostile environments as a side effect of the growth and development of industrial technology. Many of these environments are found in the nuclear, chemical, and metal-refining industries; from these, numerous chemicals and particulates are produced in solid, liquid, and gaseous forms that are sometimes fatal or hazardous to human health. This situation has led to the development of impermeable clothing that totally surrounds the worker in his own microenvironment and serves as a barrier to protect against invasion by the environment.

As mentioned before, human thermal homeostasis is maintained by a balance between the heat load to which the body is subjected at any given time and its capacity to dissipate heat. The heat load is the sum of environmental and metabolic heat. Heat dissipation depends on the cooling power of the atmosphere and physiological mechanisms responsible for the loss of heat, sweating and circulation. Whenever the total heat load exceeds heat dissipation capacity, body heat accumulates. If this situation is progressive, heatstroke will result. The case of the micro-climate under impermeable clothing is one of high ambient temperature, high humidity and low wind velocity. The low wind velocity keeps the air layer at the skin surface still, sweat evaporation is limited by high humidity and loss of ability to evaporate, and the high ambient temperature prevents heat dissipation by radiation or convection. So when heat stress conditions exist in the above environment, the normal human thermoregulation is impossible, and heat collapse occurs after a short exposure (Brown 1965).

Being impermeable, these kinds of clothing are very uncomfortable to wear for long periods. And in hot environments, they are quite unacceptable unless ventilated. Under such circumstances, the problem of protecting workers from the environment becomes two-fold. They should not only provide breathing air but also should protect the wearer against heat.

Air Cooled Garment & Water Cooled Garment

The method of creating an artificial microclimate by using clothing with a built-in cooling system consists of a cooling hood or helmet, vest or jacket and a suit which covers almost the entire body surface. The coolant can be air (cooled by a vortex tube or air at ambient temperature) or cooled water. In general, in water cooled garments essentially less sweating is obtained, while in air cooled garments, most of the cooling is obtained by evaporation of sweat. Air cooling can be particularly advantageous where one has to work in dusty, contaminated, or toxic atmospheres which may cause several respiratory disease such as pneumonoconiosis, emphysema, and chronic bronchitis. Though the evaporation of sweat is capable of easing the heat stress, at the same time the body loses water which makes it difficult for a person to work for a long time. Also, when the atmosphere is humid, evaporation normally is not very effective. In the above condition, for the conductive method of water cooling, a tight fitting garment is used in which cold water flows through a tube. The tube comes in contact with the body and the water removes the heat. So, the water cooling method can be used with high temperature and high humidity and is a very effective method of cooling.

In this study, an air-cooled hood (for breathing air) and a water-cooled jacket (for cooling the torso) were combined under non-permeable clothing for personal cooling. The heat stress environment was 35°C dry bulb temperature, 35°C mean radiant temperature, and 55% rh. The ambient air velocity was 0.15 m/s.

LITERATURE REVIEW

Protective clothing can be conveniently considered in three groups (Oxley, 1976): work clothing, treated fabric garments and proofed fabric garments. Considering protective clothing as a whole, the selection of fabrics should take account of their chemical resistance to the material handled, acceptability of the made-up garment (i.e. comfort in wear), snag and tear resistance, wear characteristics, flame resistance and antistatic properties.

For work clothing, the special consideration will be that the fabric should be shrink resistant; for reasons of comfort, cotton is normally the choice for underwear. For outer garments, the selection will depend upon the particular hazard presented by the material handled. A 70/30 terylene cotton mixture is very hard wearing and has the advantage of being almost completely shrink resistant. For treated fabric garments, the special consideration is ability to repel liquids. These fabrics are air permeable and so the garments are comfortable to wear and provide short-term protection against accidental liquid splashes. They are particularly useful for making laboratory coats, coveralls and aprons. A range of fabric materials, e.g. cotton, nylon, terylene, acrylic, can be treated with materials such as neoprene, PVC, and fluorocarbon polymer. An interesting recent development is the production of all-PVC fibre cloth. For proofed fabric garments, the fabric should be impermeable and non-absorbent. Being impermeable, proofed fabric garments are very uncomfortable to wear for long periods. In hot environments, proofed fabric coveralls and suits are quite unacceptable unless ventilated. In 1976, Thomas, Spencer, and Davies investigated the effects of wearing protective clothing in warm environments (24°C). The aim was to provide data from which recovery times could be assessed. Normal clothing (type O) and five protective assemblies (type C, H, N, P and V), four of which covered head and body, were tested on separate days for five cycles, each of 20 min work and 5 min rest. For all protective assemblies, increasing heat strain followed similar patterns when measured by heart rate, body temperature and subjective assessment. The results showed that when protective clothing was for the standing and stepping work in warm environments, heat strain always increased compared with normal clothing (type O). For each type of protective clothing the physiological and psychological reactions were greater than for normal clothing (type O). The assemblies can be separated into two groups: those with the greatest reaction - - type N (Non-powered respirator), P (powered respirator) and V (Visor); and those with intermediate reactions - - C (Compressed-air suit) and H (Heat and simple coverall combination). The physiological and psychological effects of working in the clothing assemblies during this study can be summarized in increasing order of magnitude as:

O H C P V N.

Rogan (1968) imposed heat stress by wearing a nonventilated suit and a whole-body ventilated suit during exposures from 32.2 to 36.6 °C dry bulb temperature at 90 to 95% rh. Six subjects lifted bricks for 30 minutes (about 3840 ft-lb of work) at a work rate of 349 watts. Ventilation of the suit was at 3.92 m^3/min (13 cfm) with input air temperatures ranging from 26.1 to 35.5°C. Mean skin temperature, mean heart rate and mean sweat loss were 34.0°C, 109 beats/min and 323 g/hr for subjects who performed in a ventilated suit, and 38.9°C, 150 beats/min and 916 g/hr for subjects who performed in a nonventilated suit.

Tanaka, Brisson and Volle (1978) studied the effect of workers' wearing impermeable clothing in a hot environment on body temperatures and heart rate. The subjects performed three different experiments in an artificial climate room on three different days. The experiments were as follows: sitting on a chair, wearing impermeable clothing and light underwear (experiment called "at rest"); walking on a level treadmill at the rate of 5 km per hour wearing the same clothes as "at rest" (experiment called "experimental walking"); and walking under the same conditions but wearing permeable clothing and light underwear (experiment called "control walking").

Each experimental time comprised 30 minutes. Ambient temperature was fixed at 33±1°C. Wind velocity was below 0.5 m/s. Relative humidity was 65±5 %. Even at rest, the T_{skin} increase was remarkable. At the 30th minute, T_{skin} reached 37.2±0.4°C. Experimental walking (wearing impermeable clothes) gave a significant ($p<0.001$) rise in T_{rectal}, T_{skin}, T_{body} and HR in comparison to control walking (wearing permeable clothes); for experimental walking, T_{rectal}, T_{skin}, and T_{body} at the 30th minute were 38.4, 38.1, 38.4°C respectively, and HR was 162 beats/min; for control walking they were 37.6, 35.9, 37.3°C and 96 beats/min.

To conteract the suppression of sweat evaporation occuring within the impermeable clothing, forced-air ventilation was used. A vortex tube was used to produce refrigeration within the impermeable suit, greater levels of thermal exposure were experienced, and the proposed increases in air-flow and cooling capacity allowed for increased levels of work.

It is sometimes necessary for men to enter the heat exchangers of nuclear reactors under shut-down conditions for the purposes of boiler inspection and routine maintenance (Rowlands 1970). With Calder Hall type reactors the usual temperatures encountered are about 30°C, this being achieved by allowing time for the heat exchangers to cool. It would be of considerable convenience and importance in cost saving, particularly with reactors designed for on-load refuelling, if men could carry out their inspection duties sooner after shut-down of the reactor, when the temperature of the working area is between 40 and 50°C. Radiological conditions require protective clothing and respiratory protection, and the resulting thermal situation could produce significant heat stress. One solution to this problem, which also may be present in other industrial operations, may be found in the use of ventilated clothing. It is shown that coating a standard PVC pressurized suit with radiant heat reflecting material and using a vortex tube to cool a dehumidified breathing air supply make moderate work feasible. At the lower end of the workplace temperature range considered, the thermal conditions for the suit wearer are comfortable. With increasing workplace temperature the thermal stress on the man increases through a zone of modest discomfort to a zone of marked discomfort which is barely tolerable. Up to about 46°C, exposures of a few hours appear acceptable, but between 46 and 50°C it would appear prudent to limit exposures to an hour or so. Above 50°C only brief exposures should be permitted. Likely values of the physiological responses, body temperature, heart rate and weight loss through sweating are given by the formula derived from earlier experiments (Rowlands, 1970) in which men worked in pressurized suits at normal temperatures are extrapolated to work place temperatures in the range 40-50°C.

In order to achieve thermal comfort while wearing protective clothing, heat from the body convection and by evaporation of sweat (by a ventilated suit assembly) must be controlled readily by the wearer's thermoregulatory system. This can be achieved only if air is flowing through the clothing micro-environment in "sufficient quantity" to remove sensible and insensible heat as required. The volume flow of air through the clothing assembly is therefore an important determination of thermal comfort. In Crockford, Hellon, Humphreys, and Lind's study (1963), when fifteen subjects, wearing a ventilated suit assembly, were exposed to an air temperature of 80°C, thirteen successfully completed one hour's exposure and one completed two hours' exposure without ill effects. The other subject was withdrawn from the chamber after 36 min when he was considered to be in a state of incipient heat collapse; the air supplied to his suit assembly was 283 L/min (10 cfm) at 37.8°C, i.e. the least beneficial of all the combinations of air temperature and volume of air supplied.

Variation of the temperature of the air supplied to the suit had no demonstrable effect on these experiments, but a critical total volume of air supplied appeared to be reached between .283 and .424 L/min (10-15 cfm), since only at the lowest volume of air supplied did the subjects fail to achieve, or nearly achieve, bodily thermal equilibrium. When.707 L/min (25 cfm) of air was supplied to the suit at 30°C, one subject satisfactorily maintained thermal equilibrium for two hours. If such a suit is used to protect men who have to work in high ambient temperatures, it is recommended that it should be ventilated with dry air (6-7 mm Hg vapor pressure) at a temperature not exceeding 30°C at the point where it enters the suit, and at a rate not less than .707 L/min (25 cfm), in order to provide an adequate safety factor.

Gandhok (1970) evaluated an air cooled jacket and Sharma (1970) an air cooled helmet. Both devices reduced the physiological strain imposed by heat stress. However, the vortex tube cool air source limited cooling air volume to approximately .170 L/min (6 cfm) which was only marginally effective. It was not sufficient cooling for breathing air for a high temperature and activity level. Furthermore the need for cooling in remote areas is not meet by an air cooling garment.

So, for cooling and offering breathing air in a remote area under high temperature and high activity level conditions, we need a better cooling garment to meet this requirement. Especially, in the nuclear, chemical and metal-refining industries, the cooling garment should have non-permeable clothing which can offer the workers both pure breathing air and the ability to protect them against heat. A combined air-cooled hood (for breathing air) and a water-cooled jacket (for cooling the torso) under non-permeable clothing could be a better solution for use in these conditions.

Can a water cooling system offer a equal or even better cooling function than air ventilation system under non-permeable clothing? Veghte (1965) tested three different air ventilating systems and one water cooling system when used under a full pressure suit. The three air ventilating systems were: (1) a separate tubular system ducting air to various body areas through small plastic tubes; (2) the integral air distributing system of the full pressure suit which simply dumped the air at each extremity to flow back to central exit; and (3) the separate USAF AM-1 ventilating garment (USAF-1). Tests were made with the outer pressure suit pressured at 192 mm of Hg and unpressurized. Ventilating air at 21°C was supplied from a commercial air conditioner at 0.14 m^3/s. Water at 21°C was supplied to the water-cooled suit at a rate of 1 kg/min.

Five sitting, resting subjects were exposed to an environment of 43°C. In the control tests, the pressure suit was worn without any ventilation. The experimental duration was two hours, or when rectal temperature crossed 39°C or pulse rate 140 beats/min in the control experiments. Tolerance time in the control, non-ventilated exposures varied from 60 to 95 minutes with little difference between the pressurized and unpressurized conditions. Heart rates were under 100 beats/min in the uninflated air ventilated experiments and below 110 beats/min in the pressurized air ventilated experiments. Heart rate in the water-cooled experiments remained near basal conditions and varied from 110 to 140 beats/min in the control experiments. Among all the ventilated suits, the rectal temperatures and skin temperatures were lowest in the tubular suit. During the two hour exposure with the tubular suit, the rectal and skin temperatures rose 0.1°C and 2.0°C respectively, with the outer suit unpressurized, as against 1.4°C and 4.5°C in the control. Sweat loss during the two exposures with the tubular suit (unpressurized) was 483 g as against 606 g in the control. With the outer garment pressurized, these values were a little higher. The separate tubular air ventilating garment was superior in evaporative cooling efficiency to the other air ventilating systems. The water cooled system was, however, superior to all air evaporative systems.

The torso has the largest ratio of body surface which is exposed to the heat. Is it the highest priority area of the body to be cooled? Webbon, William and Kirk (1977) studied four different system configurations (1. no cooling, 2. head cooling, 3. thorax cooling and 4. head & thorax cooling) under simulated mine rescue team operational conditions of 32.5°C wet bulb globe temperature (WBGT) and 1395 w metabolic rate. The system, which consists of a liquid circulation garment and belt-worn heat sink unit, was found to be capable of reducing the physiological strain by nearly 50 percent under these conditions. The final heart rate for the subjects in these four conditions were 142, 130, 122, and 112 beats/min. Their sweat loss, which provided effective cooling, were 0.50, 0.39, 0.31, and 0.32 kg in these conditions. From the results, the head/vest garment provides sufficient cooling to almost completely eliminate the thermal strain as shown by a neglible change in the rectal temperature over the course of the test. The torso garment was slightly superior to the head garment. In many papers the head is recommended as the best part of the body for local cooling (Fonseca, 1976) (Williams & Shitzer, 1974) (Shvartz, 1972) (Nunneley, Troutman and Webb, 1971) (Kissen, Hall & Klemm, 1971). But the torso is the body part which often is cooled locally. It is chosen not only because of its relatively large area (Shvartz, 1972) but also because it is easy to wear a cooling garment such as a shirt (Konz & Aurora, 1972), vest (Kaufman & Pittman, 1966) or jacket (Crockford & Hellon, 1964) (Strydom, Mitchell, Van Rensburg & Van Graan, 1974) (Wyndham, 1974) (Konz, Hwang, Perkins & Borell, 1974) (Konz & Duncan, 1976) (Duncan & Konz, 1978).

The superiority of water-cooled garments over air-cooled garments is evident (Chambers, 1970) (Burton, 1972) (Waligora & Michel, 1968). Besides its practically unlimited cooling capacity, the pumping power necessary to distribute the water is approximately 3000 times less than for air-cooled suits (Burton, 1972).

PROBLEM

In the nuclear, chemical and metal-refining industries, man is exposed to an increasing number of hostile environment as not only numerous chemicals and particulates are produced in solid, liquid, and gaseous forms, but also a heat stress exists. The problem of protecting workers from the environment becomes two-fold. The solution to this problem should be a non-permeable garment which can offer the workers both pure breathing air and the ability to protect them against heat.

The use of impermeable clothing with a built-in vortex tube cooling system might be a solution. But none of the vortex tube cooling garments are practical for use under service conditions in remote areas nor do they meet a requirement that the protective clothing should be self-contained. So, in this study, we combined air cooling hoods and a water cooling garment to offer the workers a better protection.

The two combinations of using these cooling garments in this study are:

(1) 3M Brand Whitecap Helmet (Model 5005AA) + Water Cooling Jacket (ILC Cool Vest 30019-82231): See Figure 1.
The 3M backpack can filter the ambient temperature air for pure breathing air. The cool vest is a completely portable water cooling garment for cooling the wearer's trunk. This combination is self-contained and is very

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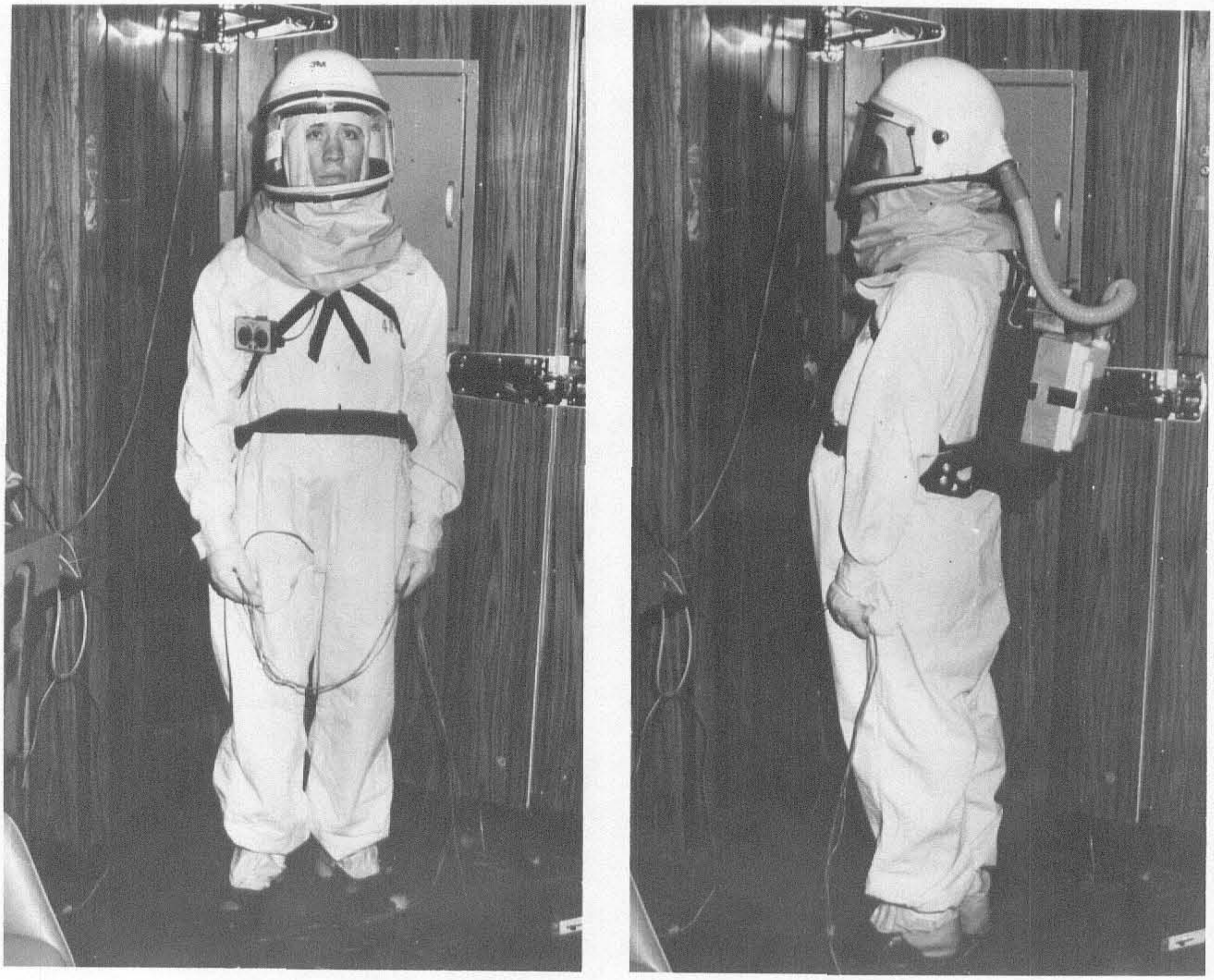

Figure 1. A view of subject 4 in the "Water-cooling + 3M Backpack system" condition.

practicable for using in a remote area.

(2) Compressed Air Line (Non-vortex) + Water Cooling Jacket (ILC Cool Vest #0019-82231): See Figure 2.

The compressed air line offers the wears not only sufficient breathing air but also cooler and drier air than the environment's. The water cooling jacket does the job of cooling.

The following four criteria were used:

1. Mean skin temperatures
2. Rectal temperature
3. Heart rate
4. Weight loss

The values for the increase were taken by comparison with the control condition (no cooling garment during the heat stress).

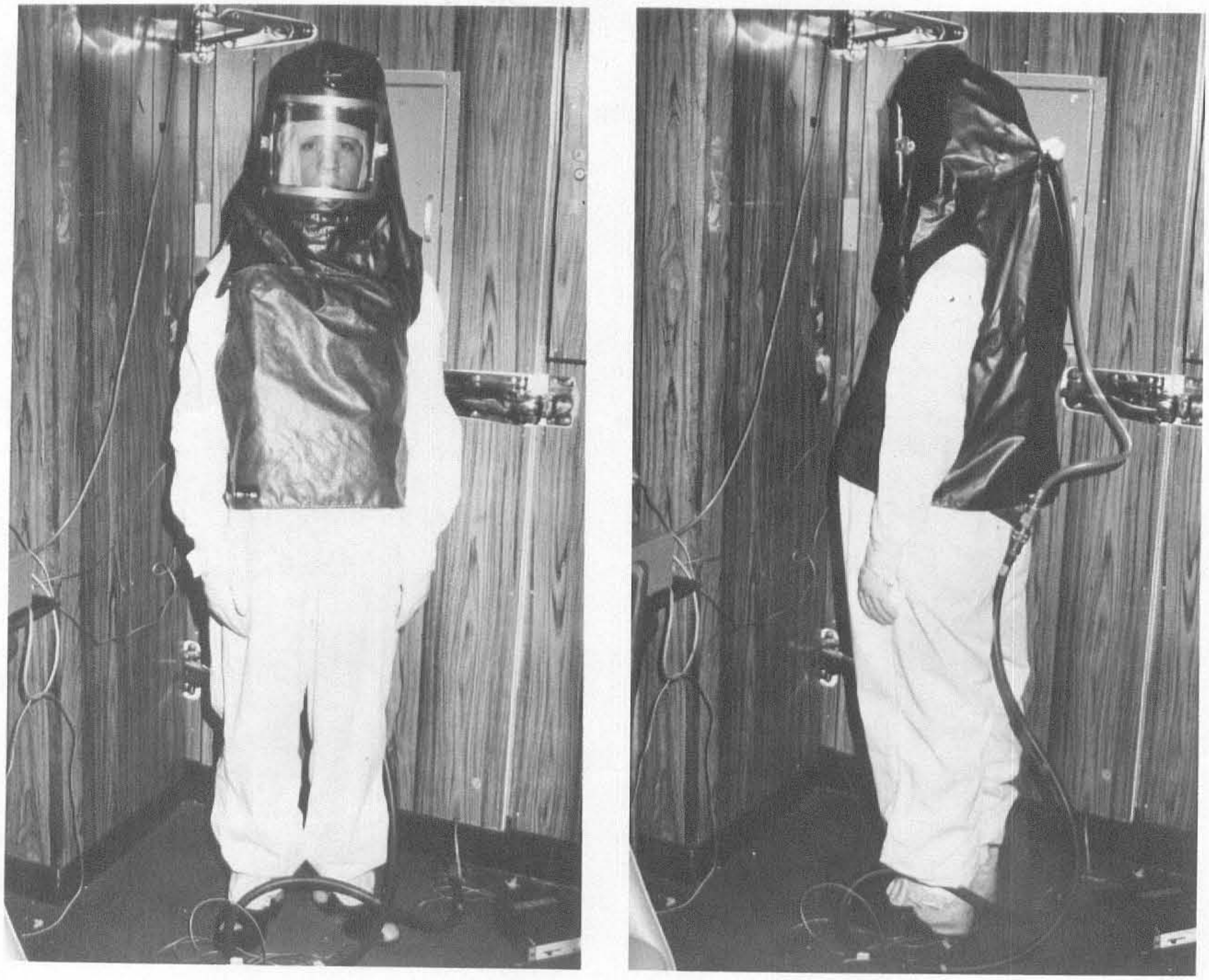

Figure 2. A view of subject 4 in the "Water-cooling + Compressed air line" condition.

METHOD

Task

One subject at a time remained in the heat stress environment for a period of 60 minutes; during this period he walked at a speed of 3.2 km/h. The floor was marked for a distance of 2.67 m, each marking being 0.533 m which was one step or stride. Then he turned around and walked to the other end of the marked area. He repeated this procedure for 60 minutes. A metronome, set to give 100 beats/min, was used to pace the subject. Walking at 3.2 km/h (Van der Walt and Wyndham, 1973) has a metabolic rate of 231 w, which is almost the same as the metabolic rate for moderate work at a machine or a bench (Konz and Duncan, 1969).

Subjects

Six male students of KSU acted as subjects (see Table 2). They completed a physical fitness exam (see Table 3) and a medical test in the KSU student health center. The subjects were paid $40.00 for the experiment.

Procedure

Each subject was tested in the heat stress environment (35°C dry bulb temperature, 55% rh, and air velocity of .15 m/s still air) for 60 minutes each day for three days.

According to the experimental design in Table 4, each day the test period was divided into the following periods:

Period 1: 30 minutes before entering the test chamber.

During this period the subject was weighed nude,

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TABLE 2

Physical characteristics of the subjects

Subject No.	Age yr.	Height cm.	Weight kg.	DuBois Body Area, m^2
1	21	180.3	81.8	2.020
2	19	185.4	79.1	2.030
3	22	198.1	106.8	2.420
4	29	172.7	68.2	1.810
5	18	186.7	82.7	2.080
6	18	182.9	75.0	1.965

TABLE 3

Results of subjects' physical fitness examination

	Rating			
Subject	Cardiovasocular (ml/kg-min)	Body fat (%)	Blood Pressure	Hand grip Strength
1	P (34.8)	G (13.5)	E (114/76)	E (88 kg)
2	G (46.8)	VG (10.0)	G (120/70)	E (110 kg)
3	A (41.2)	F (16.5)	G (120/72)	E (70 kg)
4	A (41.6)	E (7.5)	F (130/88)	E (79 kg)
5	VG (48.4)	VG (12.0)	F (126/80)	E (70 kg)
6	A (40.0)	E (7.0)	P (136/90)	E (88 kg)

Note: E: Excellent
VG: Very Good
G: Good
A: Average
F: Fair
P: Poor

TABLE 4

Experimental design

Subject	Water-cooling + 3M Backpack system	No Cooling	Water-cooling + Compressed air line
1	Mon @8	Wed @8	Fri @8
2	Fri @1	Mon @1	Wed @1
3	Wed @3	Fri @3	Mon @3
4	Tue @8	Sat @8	Thu @8
5	Sat @1	Thu @1	Tue @1
6	Thu @3	Tue @3	Sat @3

and the subject's skin temperature, rectal temperature and heart rate sensors were attached. His skin temperature, rectal temperature and heart rate were recorded every 5 minutes for the last 15 minutes.

Period 2: 60 minutes in the test chamber. The subject was taken into the test chamber. The subject walked at a steady pace of 3.2 km/h paced by the metronome. His temperatures and heart rate were recorded every 5 minutes.

Period 3: 30 minutes after leaving the test chamber. During this period, responses were recorded for the first 20 minutes. Then the sensors were removed and he was weighed during the last 10 minutes.

The same procedure was followed on each day. The test subject was allowed to drink no water during the test in order to restrict body cooling by this means. He was required to drink 250 ml of water during the pre-test to reduce potential dehydration. Criteria for removal were:

a) if nurse decided to remove subject

b) if subject wanted to be removed

c) if rectal temperature rise exceeded 1.1°C

d) if heart rate exceeded 180 beats/min

or e) if 60 minutes was reached.

Instrumentation

Test chamber: All testing was conducted in the first chamber on the north corrider in the Institute for Environment Research at Kansas State University.

The compressed air line (non-vortex):

The jacket with compressed air line without vortex tube was made by CESCO, 801-NA Neoprene-Nylon Canopy, one of the 801 series without a vortex cooling unit.

The water cooling garment: see Figure 3.

The ILC Cool Vest (#0019-82231), which was made by ILC DOVER Co., is a completely portable liquid cooling garment worn to aid in maintaining worker comfort and safety in extremely warm environments for one hour. Through the use of a centrifugal pump, chilled water is circulated throughout a series of passages within the vest.

The 3M Brand Whitecap Helmet:

This helmet is made by the 3M company. The Whitecap helmet (model 5005AA) is designed to provide maximum comfort when in the area of contaminated air. The helmet is constructed of reinforced fiberglass and is recommended for use with the 3M Brand Compressed Air Components (Vortex Air Cooler, Vortem Air Heater, Air Regulating Valve or the 3M Brand Powered Air Purifiers).

The non-permeable clothing: see Figure 4.

It is a type of nuclear power station garment

Figure 3. The water-cooling jacket, ILC Cool Vest (#0019-82231), was made by ILC DOVER Co. The jacket is reversed here to balance the weight of the 3M backpack, which is about to be donned.

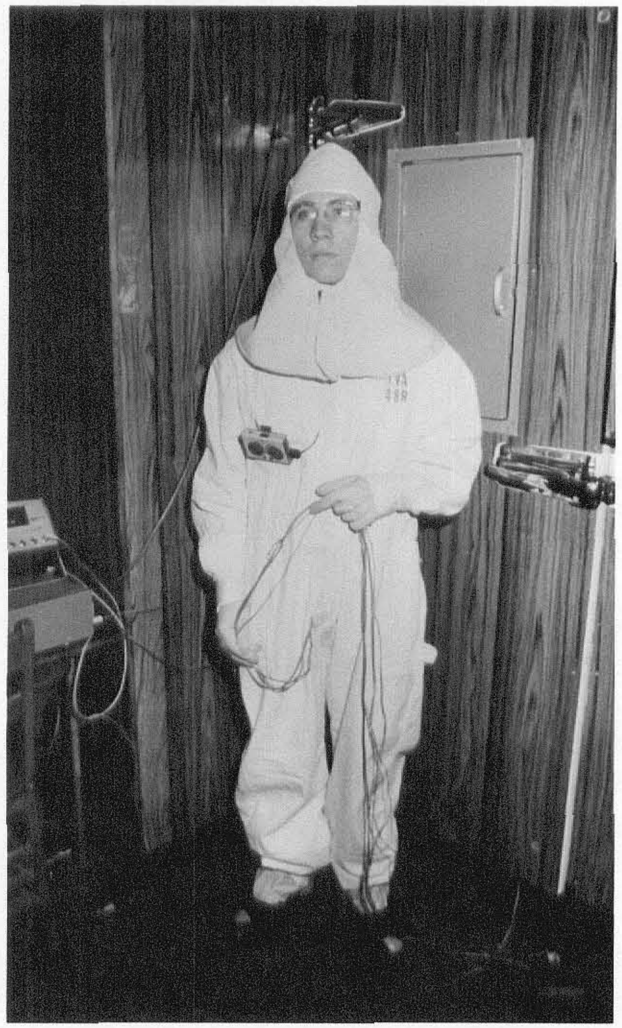

Figure 4. The non-permeable clothing, TVA 44, which was made by NPO.

which is made by NPO, TVA 44R C. It covers the whole body of the wearer.

Heart rate recording system:

EXERSENTRY is a personal heart rate monitor designed to be worn by a subject during walking, jogging, running, cycling and many other activities. When the subject wears the belt properly, the electrodes are automatically positioned.

Rectal probe: A 2.38 mm O.D. flexible precision thermistor was inserted in the subject's anal canal to a depth of 12 cm to measure the rectal temperature.

Skin thermistor:

The thermistors, which have sensitive areas at the ends which are 9.5 mm in diameter and 1.6 mm thick, were placed on the skin (left chest, left calf, and left arm). Tape was used to keep them in position. The skin temperature is determined by the following formula (Mitchell, Duncan and Wynham, 1965):

$$T_{skin}=0.5\ (T_{chest})+0.36\ (T_{calf})+0.14\ (T_{arm})$$

Metabolic scale:

The subjects were weighed on a Brookline Instrument Co. metabolic scale. It can weigh a subject to twenty grams.

RESULTS

The data was analyzed with a three way (condition, subject and time) analysis of variance for HR, T_{rectal} and T_{skin} and with a two way (condition and subject) analysis of variance for weight loss. The temperatures were the rise above the basal temperature during a period of 60 minutes, that is, during the exposure to the heat stress. The basal readings for each subject and for each condition were calculated by taking an average of the three readings taken on that day in the neutral environment, prior to the entry into the test chamber. The weight losses were calculated in $g/(m^2\text{-}h)$. The heart rate was measured in beats/min.

The variables that showed significant ($\alpha < .05$) effect for condition were analyzed further by Duncan's multiple range test to see which of the means differed significantly ($\alpha < .05$) from each other.

Heart rate:

The rise in the heart rate during exposure over the basal (Appendixes 1 to 9) was smallest in the "Water-cooling + Compressed air line" condition. Figure 5 is the mean heart rate for all subjects vs time.

The analysis (Table 5) indicated a significant ($\alpha < .05$) effect for condition, subject, time, condition x subject interaction, condition x time interaction and subject x time interaction. Further analysis by the Duncan's multiple range test (Table 6) indicated that the mean increase (27.4) for the

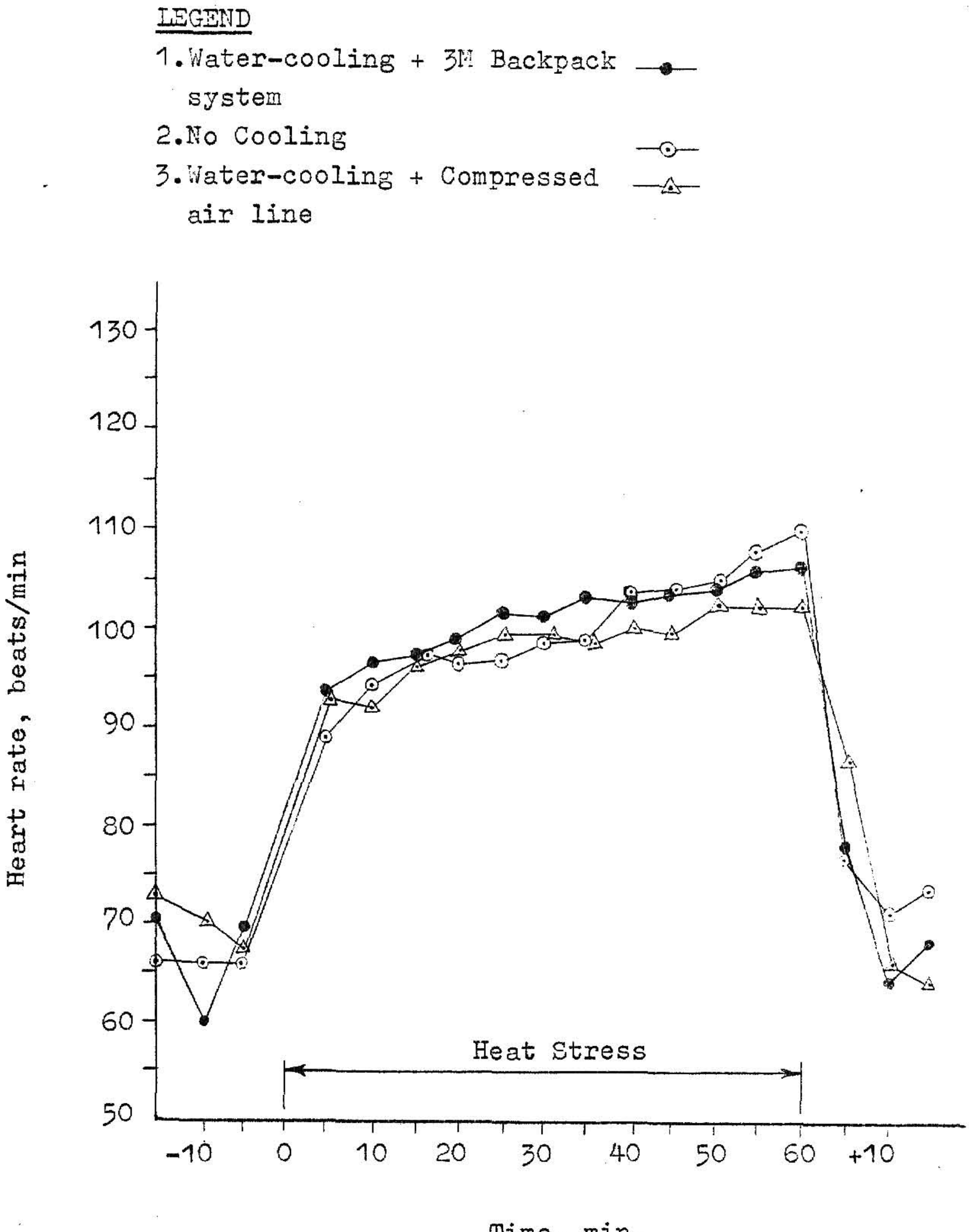

Figure 5. Mean heart rate for all subjects.

TABLE 5

ANOVA of heart rate

SOURCE	D.F.	MEAN SQUARE	F-RATIO
Condition	2	718.44	62.52*
Subject	5	852.72	74.21*
Time	11	307.36	26.75*
Condition x Subject	10	355.20	30.91*
Condition x Time	22	19.70	1.71*
Subject x Time	55	19.38	1.69*
Error	110	11.49	
TOTAL	215		

*Significant ($\alpha < .05$)

TABLE 6

Duncan's multiple range test for variable HR by condition. Means with the same letter are not significantly different. (Alpha level= 0.05, D.F.= 110 and Mean square= 11.49)

GROUPING	MEAN	N	CONDITION
A	33.3	72	2
A			
A	32.3	72	1
B	27.4	72	3

Note: Condition 1 means "Water-cooling + 3M Backpack system".

Condition 2 means "No Cooling".

Condition 3 means "Water-cooling + Compressed air line".

"water-cooling + compressed air line" condition differed significantly ($\alpha < .05$) from the means of the other two conditions, "water-cooling + 3M backpack system" (32.3) and "no cooling" (33.3). There was no significant difference between the means of the "water-cooling + 3M backpack system" condition (32.3) and the "no cooling" condition (33.3).

To keep heart rate lower, the "water-cooling + compressed air line" condition was most effective, giving an average saving of 5.9 beats/min vs the "no cooling" condition.

Rectal temperature:

The rise in the rectal temperature during exposure over the basal (Appendixes 10 to 18) was smallest in the "water-cooling + compressed air line" condition. Figure 6 is the mean rectal temperature for all subjects vs time. The analysis (Table 7) indicated a significant ($\alpha < .05$) effect for condition, subject, time, condition x subject interaction and subject x time interaction. From Table 8, the mean increase of .21°F for the "water-cooling + compressed air line" condition was significantly ($\alpha < .05$) lower than the means of the other two conditions. There was no significant difference between the means of the "water-cooling + 3M backpack system" and "no cooling" conditions (.26 and .27°F). The "water-cooling + compressed air line" condition was most effective to keep the rectal temperature lower, but the difference was only .06°F greater than the "no cooling" condition.

Mean skin temperature:

The mean skin temperature for a subject was calculated by

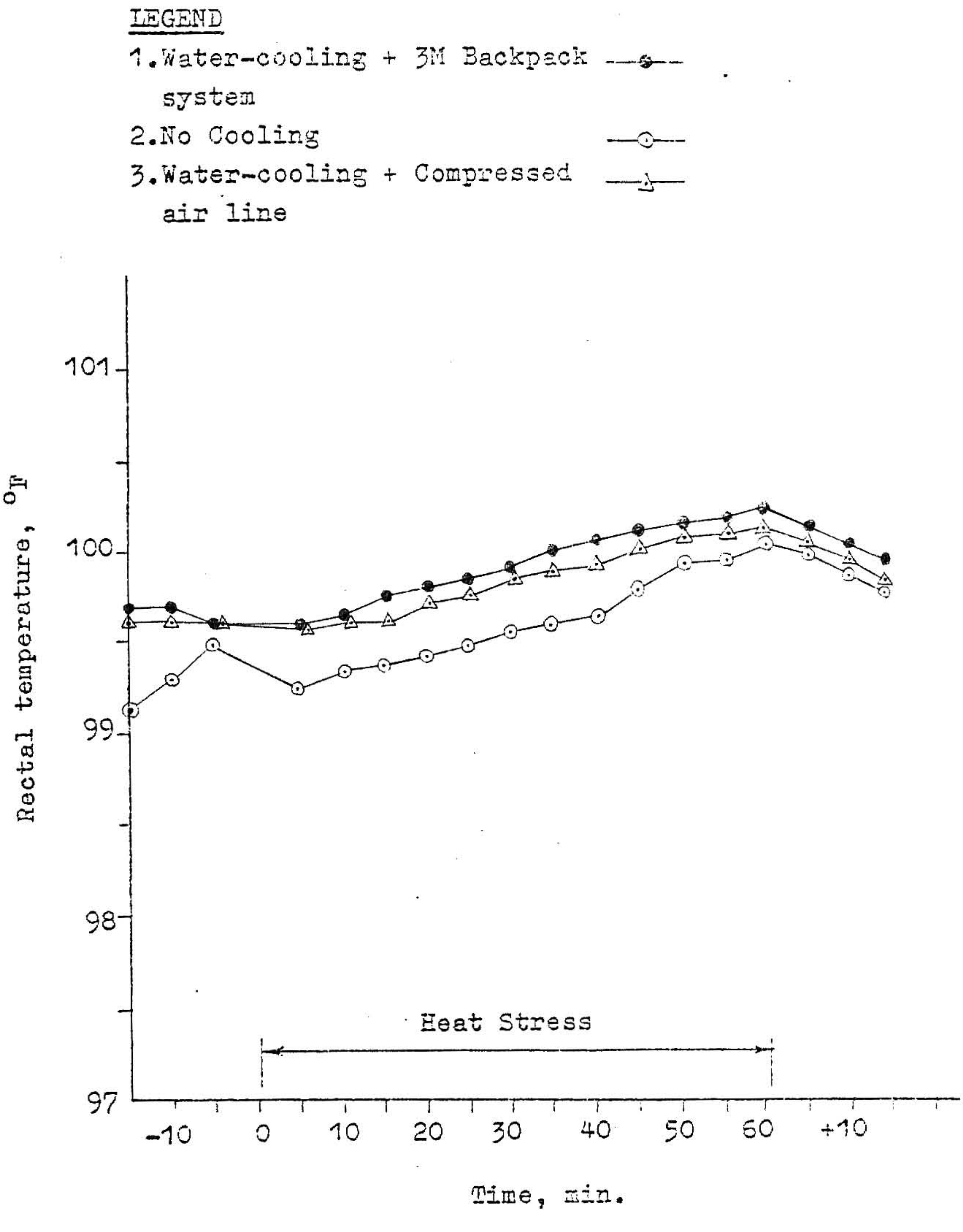

Figure 6. Mean rectal temperature for all subjects.

TABLE 7

ANOVA of rectal temperature

SOURCE	D.F.	MEAN SQUARE	F-RATIO
Condition	2	0.07	9.95*
Subject	5	2.48	325.63*
Time	11	0.75	98.45*
Condition x Subject	10	0.33	43.09*
Condition x Time	22	0.01	1.12
Subject x Time	55	0.04	5.73*
Error	110	0.008	
TOTAL	215		

*Significant ($\alpha < .05$)

TABLE 8

Duncan's multiple range test for variable T_{rectal} by condition. Means with the same letter are not significantly different. (Alpha level= 0.05, D.F.= 110 and Mean square= 0.007)

GROUPING	MEAN (°F)	N	CONDITION
A	0.27	72	2
A			
A	0.26	72	1
B	0.21	72	3

Note: Condition 1 means "Water-cooling + 3M Backpack system".

Condition 2 means "No Cooling".

Condition 3 means "Water-cooling + Compressed air line".

taking the weighed average of temperature on the subject's left chest, left calf and left arm.

The rise in the mean skin temperature during exposure over the basal (Appendixes 19 to 36) was smallest for subjects 1 and 6 in the "water-cooling + compressed air line" condition, whereas for subjects 2, 3, 4 and 5 the rise was smallest in the "water-cooling + 3M backpack system" condition. Figure 7 is the average value of mean skin temperature for all subjects vs time. The analysis (Table 9) indicated a significant ($\alpha<.05$) effect for condition, subject, time, condition x subject interaction and condition x time interaction. From Table 10, the means of all the three conditions differed significantly ($\alpha<.05$) from each other. The overall rise in the mean skin temperature (-9.23°F) was lowest in "water-cooling + 3M backpack system". The water-cooling with compressed air line lowered skin temperature -5.44°F while the control temperature rise was 6.44°F. The "water-cooling + 3M backpack system" condition was most effective in keeping the mean skin temperature lower. Appendixes 28 to 36 show the drop was due to a drop in chest temperature as arm and calf temperature were relatively equal in the three conditions.

Weight loss:

The weight loss (Table 11) was the same for subject 3 for the three conditions; this probably indicates poor experimental measurements. Using the observed data, the analysis (Table 12) didn't indicate any significant ($\alpha<.05$) effect for condition. But it indicated a significant ($\alpha<.05$) effect for subject. This can be attributed to the physiological differences between the

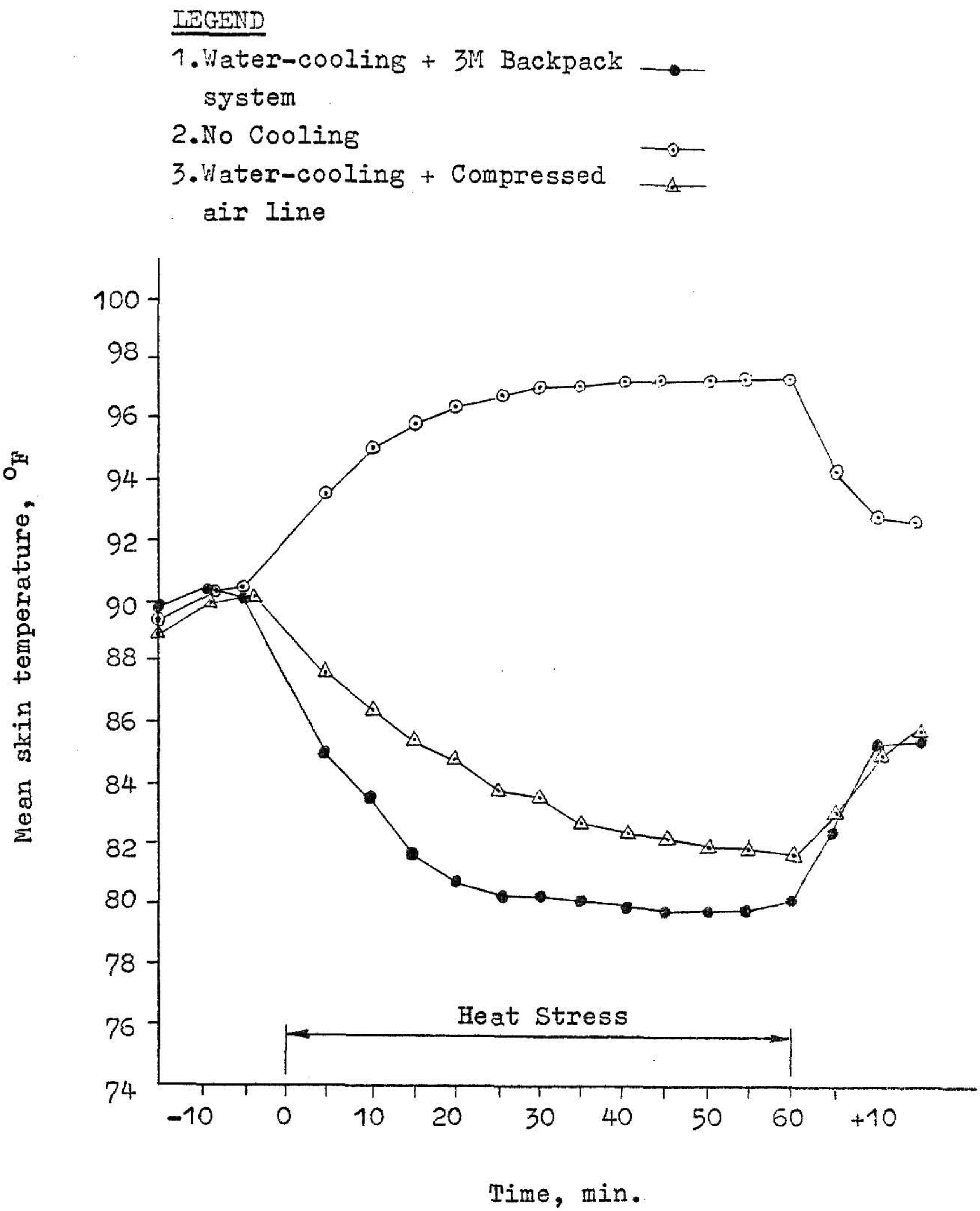

Figure 7. Average value of mean skin temperatures for all subjects. See Appendixes 19 to 36 for more detail.

TABLE 9

ANOVA of mean skin temperature

SOURCE	D.F.	MEAN SQUARE	F-RATIO
Condition	2	4568.36	1236.50*
Subject	5	36.68	9.93*
Time	11	11.09	3.00*
Condition x Subject	10	103.98	28.15*
Condition x Time	22	11.15	3.02*
Subject x Time	55	1.23	0.33
Error	110	3.69	
TOTAL	215		

*Significant ($\alpha < .05$)

TABLE 10

Duncan's multiple range test for variable T_{skin} by condition. Means with the same letter are not significantly different. (Aipha level= 0.05, D.F.= 110 and Mean square= 3.69)

GROUPING	MEAN (°F)	N	CONDITION
A	6.44	72	2
B	-5.44	72	3
C	-9.23	72	1

Note: Condition 1 means "Water-cooling + 3M Backpack system".
Condition 2 means "No Cooling".
Condition 3 means "Water-cooling + Compressed air line".

TABLE 11

Weight loss, $g/(h\text{-}m^2)$, by condition

Subject	Water-cooling + 3M Backpack system	No Cooling	Water-cooling + Compressed air line
	Condition		
1	326.2	458.6	329.3
2	239.8	242.1	199.4
3	206.4	206.4	206.4
4	172.0	173.6	220.9
5	111.6	280.7	151.9
6	426.2	508.5	249.4
Mean	247.0	311.6	226.2

Note: Weight loss by condition= The difference between "Subject's nude weight before 60 min. heat stress period" and "Subject's nude weight after 60 min. heat stress period" divided by the subject's surface area.

TABLE 12

ANOVA of weight loss

SOURCE	D.F.	MEAN SQUARE	F-RATIO
Condition	2	11907.5	2.91
Subject	5	27437.2	6.70*
Error	10	4095.9	
TOTAL	17		

*Significant ($\alpha < .05$)

individuals.

Subjects' comment:

All subjects felt most comfortable in the "water-cooling + compressed air line" condition. They all liked the water-cooling jacket, ILC Vest (30019-82231), because it worked well. Only two subjects felt a little bit cold in the first 10 minutes after they wore the water-cooling jacket and they get used to it very quickly.

All subjects felt the most uncomfortable condition was the "water-cooling + 3M backpack system" condition. This is because they had to carry 6.4 kg more load than they did in the "water-cooling + compressed air line" condition, and 12.5 kg more load than they did in the "no cooling" condition.

Volume and temperature of air and amount of ice supplied:

The supplied air flow velocity was measured with a Air Meter, Model W131, made by Weather Measure Corporation. See Appendix 37. Appendixes 38 to 40 give the volume of supplied air along with the temperatures, amount of ice initially inserted into the water-cooling jacket and other data which were recorded during the experiment. The temperatures of supplied air from the compressed air line were measured by a Anemotherm Air Meter, Model 60.

DISCUSSION

Gandhok (1970) evaluated an air cooled jacket and Sharma (1970) an air cooled helmet. Both devices reduced the physiological strain imposed by heat stress. However, the vortex tube cool air source limited cooling air volume to approximately 0.170 m^3/min (6 cfm) which was only marginally effective. From the pilot done for this study, the compressed-air line (without vortex tube) which can offer higher air flow (0.385 m^3/min) and the temperature of supplied air (31.4 ± 0.9^oC) was colder than the environment's (40^oC). From the results of the pilot study, the increase for HR, T_{rectal}, T_{skin} without cooling vs with compressed-air line were 42.1 beats/min to 34.8 beats/min, 0.83^oF to 0.60^oF and 6.58^oF to 4.01^oF. So, the cooling function of compressed-air line was significant in this pilot study.

The use of impermeable clothing with a built-in vortex tube cooling system might be a solution for the workers in a hot environment in the nuclear, chemical and metal-refining industries. But none of vortex tube cooling garments is self-contained for use under service conditions in remote areas. Also, the problem of protecting workers from the above environments becomes two-fold (offer pure breathing air and cooling simultaneously).

So, in this study, the primary objective was to evaluate combined water-cooling with compressed-air line (which can offer larger volume of breathing air and use less power than a vortex tube cooling garment) or with 3M Brand Whitecap Helmet (which can be used in a remote area).

The subjective feeling of the subjects showed that they felt most comfortable in the "water-cooling + compressed air line" condition. The rise in the heart rate and rectal temperature during exposure over the basal was smallest for all subjects in the "water-cooling + compressed air line" condition. That is because they got not only water cooling on their torso but also some cooling function from the cooler breathing air supplied from the compressed air line.

From the results of analysis (Table 10), the rise in the mean skin temperature during exposure over the basal was smallest for "water-cooling + 3M backpack system". This is because the 7.7 kg weight of the 3M backpack system made its belt tightly pressure the water cooling jacket onto the wearer's torso. This load, which is 6.4 kg more than the compressed air line helmet, is also one of the main reasons that made the subjects felt uncomfortable.

In this study, subject 3 is from the South and was accustomed to this hot environment (35^{o}C and 55% rh). He had the same weight loss for all conditions and felt more comfortable in the "no cooling" condition because there was no additional load on him. But after 60 min exposure, the rise in HR, T_{rectal} and T_{skin} over the basal were largest for the "no cooling" condition. That means that the combined water-cooling with compressed air line or with 3M backpack system condition maintained better or at least the same physiological conditions in comparison to "no cooling" condition for him.

Although there was no significant difference in the increase of HR, T_{rectal} and weight loss (expect T_{skin}) (see Table 6, 8 and 12) between the "water-cooling + 3M backpack system" condition and "no cooling" condition, it certainly is far better for a worker to be under the "water-cooling + 3M backpack system" condition than under the "no cooling" condition in the hot environment (35°C and 55% rh) of the nuclear power plant or chemical industries - - not only for its supplying safe breathing air and cooling, but also for its being completely self-contained for remote area service.

Every subject in this study felt that he had very sufficient cooling on his torso. Two subjects felt that the water-cooling jacket was a little bit too cold in the first 10 min. when they just put it on, but they both got used to it and liked it quickly during the heat stress period. This water-cooling jacket is loaded with 4 lbs (1.82 kg) of ice and 1500 ml water for a 60 minutes cooling duration. In order to make sure that the ice can last at least 60 minutes, larger pieces (36 cm length x 20 cm width x 12 cm height) of ice are better, because larger size ice has less surface area per unit weight and melts slower. The small size ice (24 cm length x 14 cm width x 10 cm height) melts faster and was overcooling at first.

Subject 4's computer simulation (Konz, 1979) didn't predict his data well. The predicted heart rate of subject 4 (Figure 8) is about 21 beats/min higher than his actual heart rate at the end of the 60 minutes heat stress period. However, it predicted

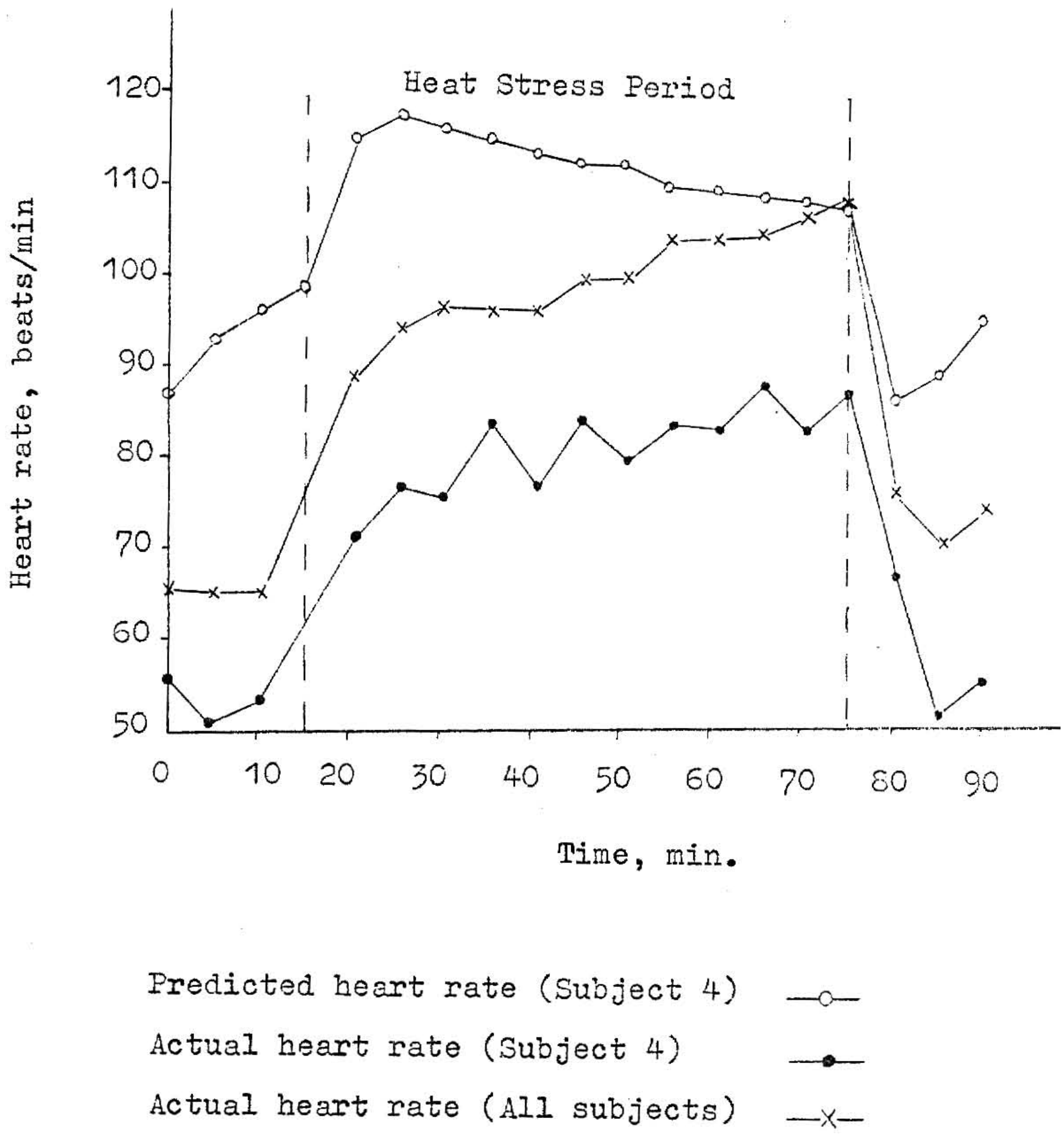

Figure 8. Computer simulation for predicting subject 4's heart rate in this experiment vs his actual heart rate for the no-cooling condition and mean subjects' response.

the mean subjects' heart rate much better, being within 2 beats/min at the end of the 60 minute heat stress period. The predicted rectal temperature (Figure 9) has a initial deep dip and does not reach the actual temperatures for subject 4.

In this study, the rectal temperature did not rise very much for the "no cooling" condition for all subjects. This is because there is still some permeability in the TVA clothing (it did pass some water as the TVA garment was wet on the outside at the end of the experiment). In the "no cooling" condition, the subject's face was not covered (see Figure 4). This allowed the subject to evaporate some sweat from the face and this made him feel more comfortable. For subject 4, his body heat storage is (Konz, 1979):

$$S = 1.15\ m \cdot C_p\ (MBT_f - MBT_i)/t$$

where S = body heat storage, gain (+) or loss (-), watts

m = weight of body, kg = 68.2 kg

C_p = specific heat of body = .83 (watt·hr)/(kg·°C)

MBT = mean body temperature, °C

= .67 (rectal temperature) + .33 (skin temperature)

MBT_i = initial mean body temperature, °C

$= .67\ (37.5) + .33\ (32.4) = 35.82°C$

MBT_f = final mean body temperature, °C

$= .67\ (37.8) + .33\ (36.3) = 37.27°C$

t = time, hours = 1 hour

so, $S = 1.15\ (68.2)\ (.83)\ (37.27 - 35.82)/1 = 94.4$ watts

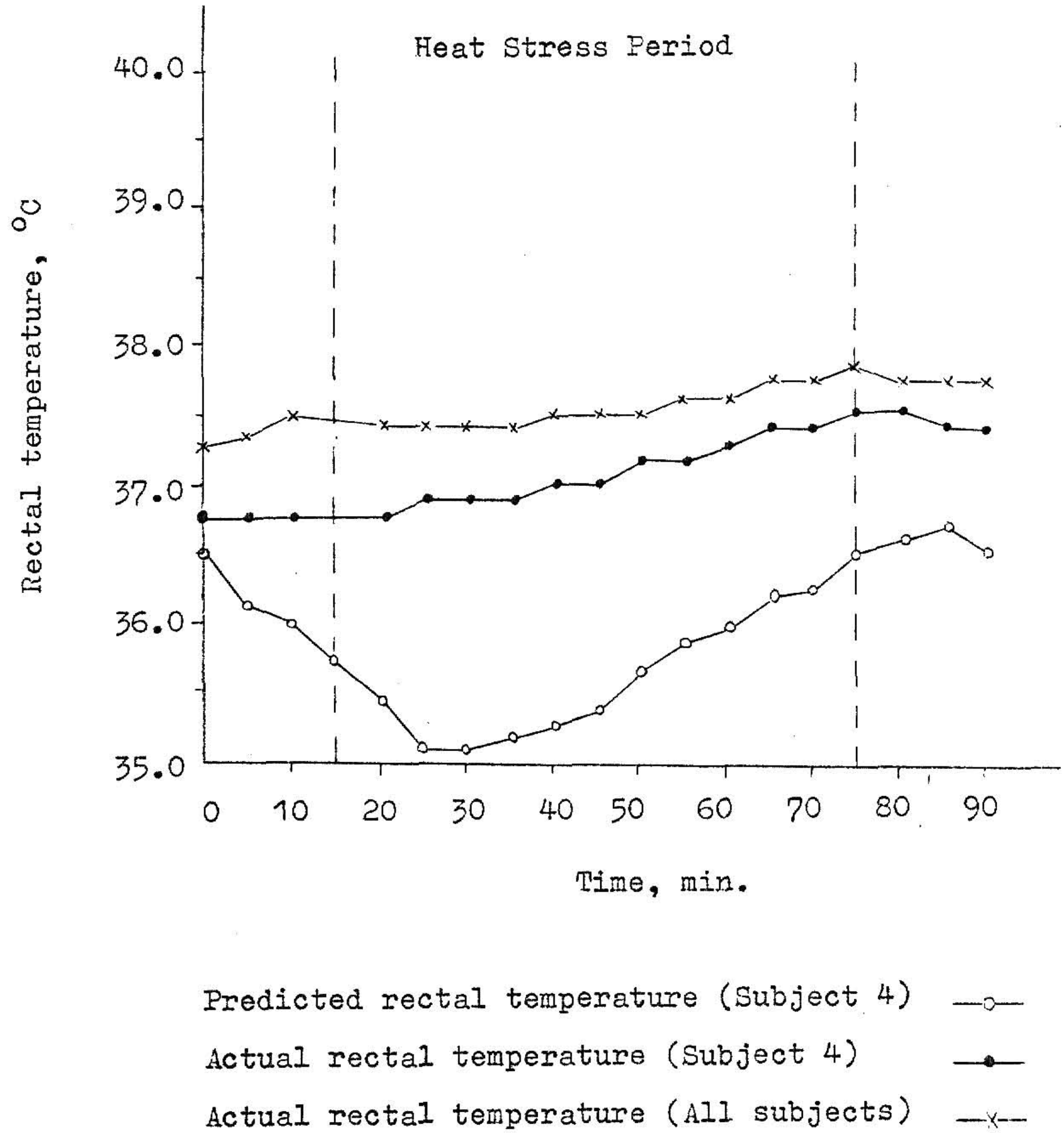

Figure 9. Computer simulation for predicting subject 4's rectal temperature in this experiment vs his actual rectal temperature for the no-cooling condition and mean subjects' response.

The heat balance for subject 4 is (Konz, 1979):

$$S = M - (\pm W) + (\pm R) + (\pm C) + (\pm E) + (\pm K)$$

where S = heat storage rate, watts

M = metabolic rate, watts = 231 watts

W = mechanical work accomplished rate, watts = 0 watt

R = radiation rate, watts = 0 watt (assumed closed to zero since skin temperature close to air temperature)

C = convection rate, watts = 0 watt (assumed closed to zero since skin temperature close to air temperature)

E = evaporation rate, watts = ? watts

K = conduction rate, watts = 0 watt

so, S = 94.4 watts = 231 watts + ($\pm$E)

E = 231 watts - 94.4 watts = 136.6 watts

From the above results, we know that if the TVA clothing was completely impermeable, then subject 4 should have a body heat storage about 231 watts. But because his sweat evaporated from his face or through the TVA garment when it was wet, this released 136.6 watts of heat and his body temperature rate of increase.

SUMMARY

The present study was conducted using six male student subjects to evaluate a combined water-cooling jacket and compressed air line (without vortex-tube) or 3M backpack system in a heat stress environment of 35°C dry bulb and 55% rh. A water-cooling jacket was worn on the subject's torso area and beneath his outer impermeable clothing. Either a compressed air line helmet or a 3M Brand Whitecap Helmet covered the subject's head and offered him pure breathing air.

The subjects walked at 3.2 km/h in the heat stress for 60 minutes. Each subject was exposed to the heat stress environment three times, twice with the water-cooling jacket and compressed air line (or 3M Backpack system), and one time without the cooling jacket and just wearing the TVA impermeable clothing.

The increase in the heart rate, rectal temperature and mean skin temperature showed a significant effect ($\alpha < .05$) for condition. The overall performance of these three conditions was best with "water-cooling + compressed air line". The increase in mean skin temperature was the lowest for the "water-cooling + 3M backpack system" condition. There was no significant difference in the increase of heart rate and rectal temperature between the "water-cooling + 3M backpack system" condition and the "no cooling" condition.

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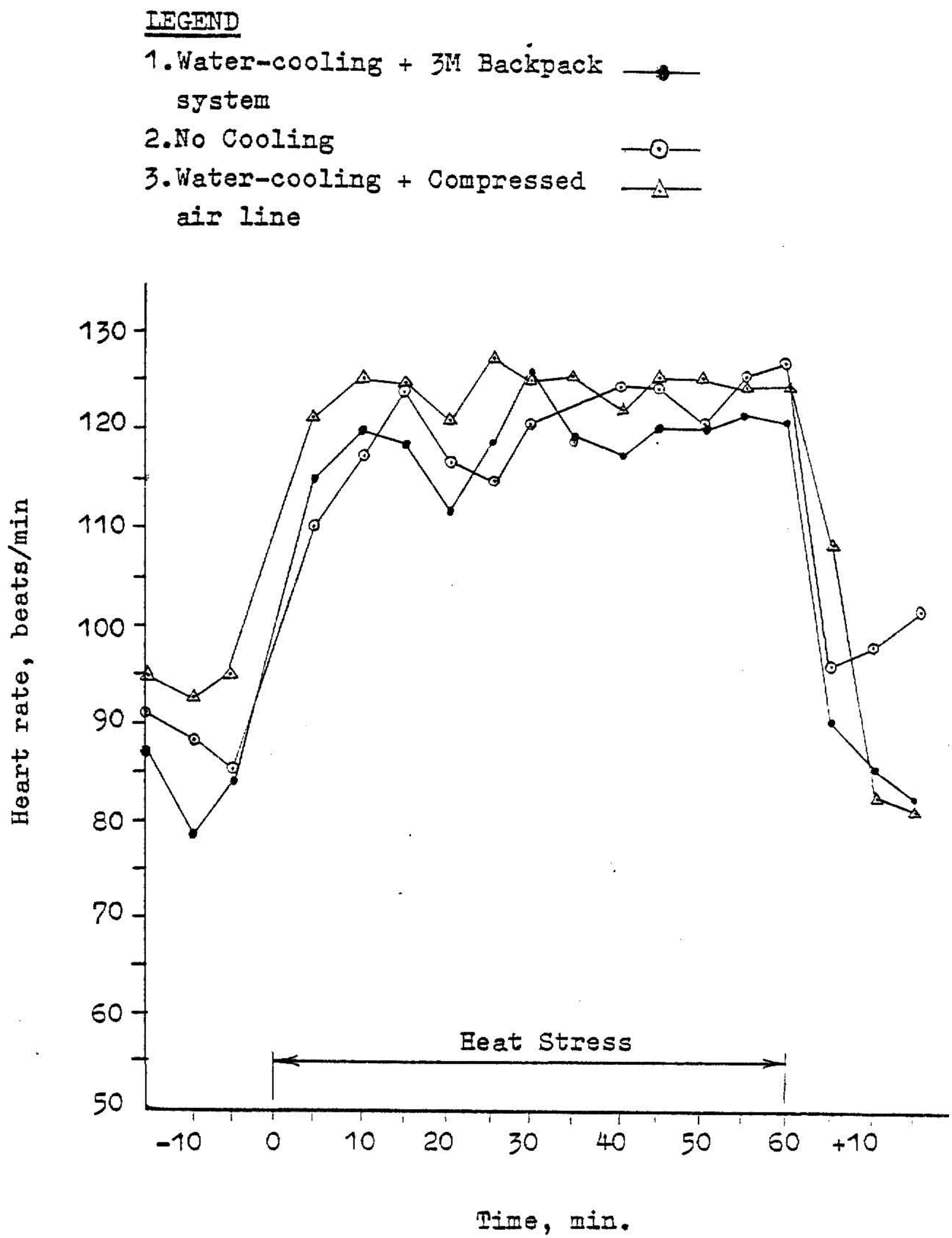
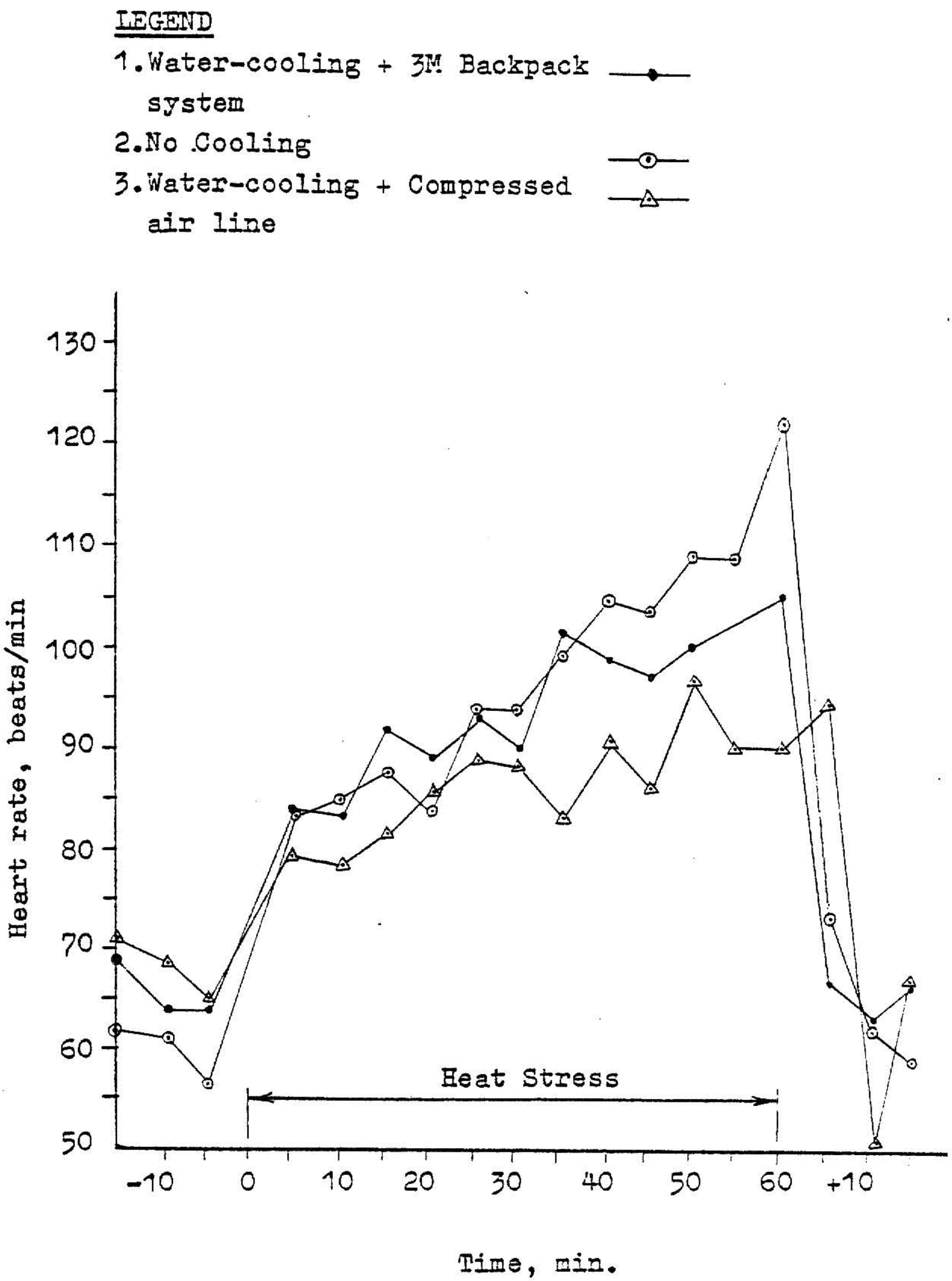
APPENDIX 1

Heart rate for subject 1



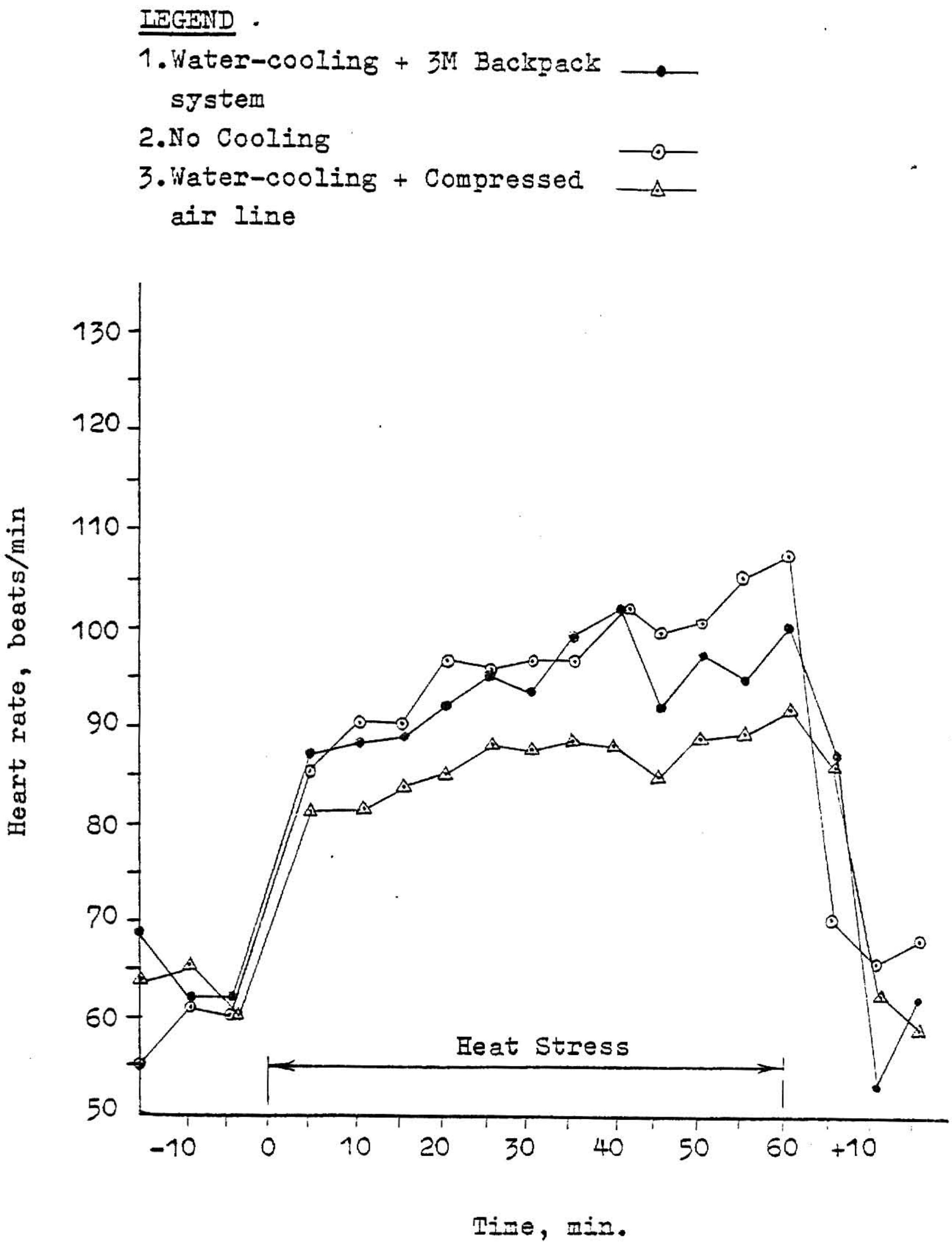
APPENDIX 2

Heart rate for subject 2



APPENDIX 3

Heart rate for subject 3

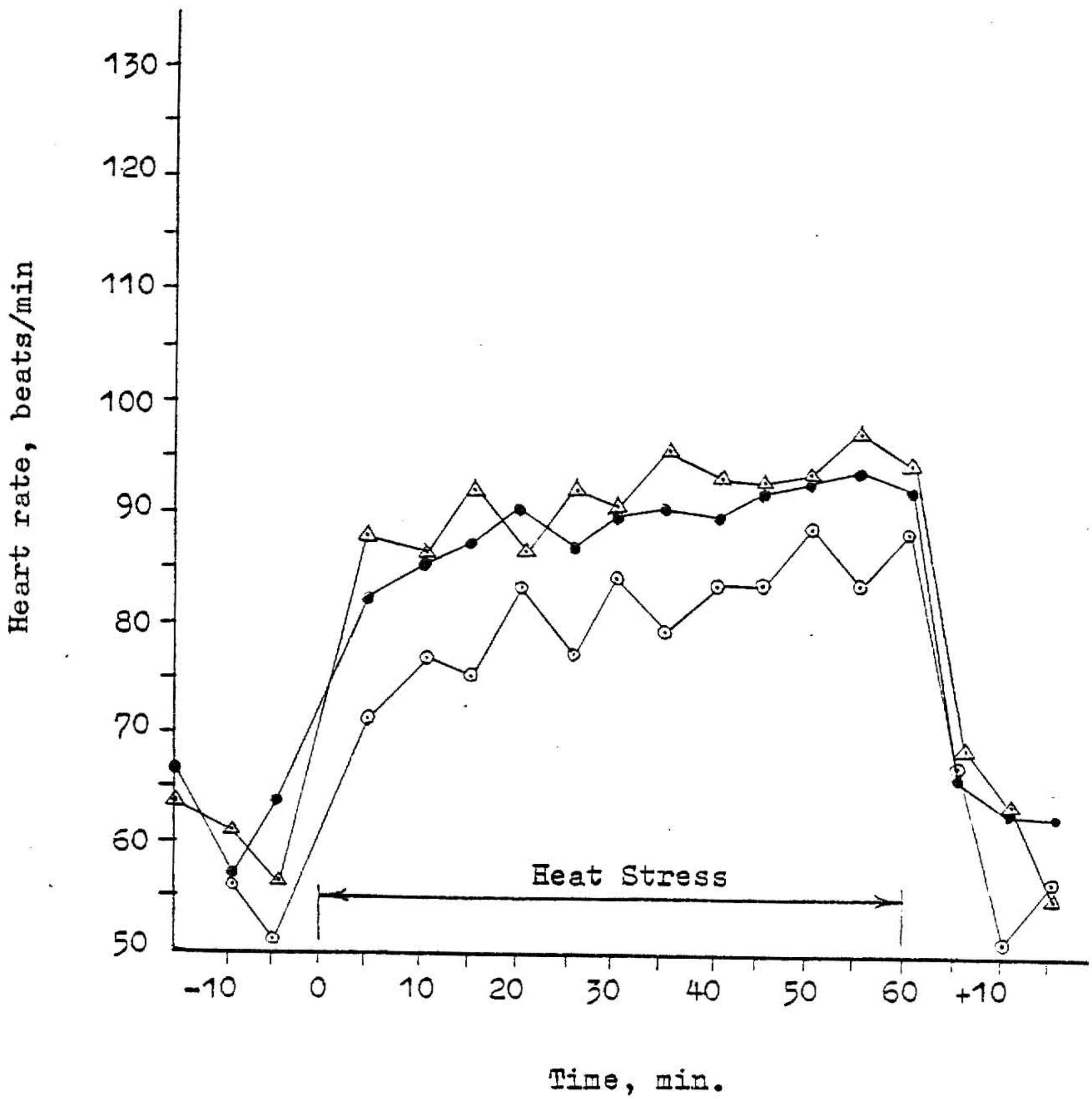


APPENDIX 4

Heart rate for subject 4

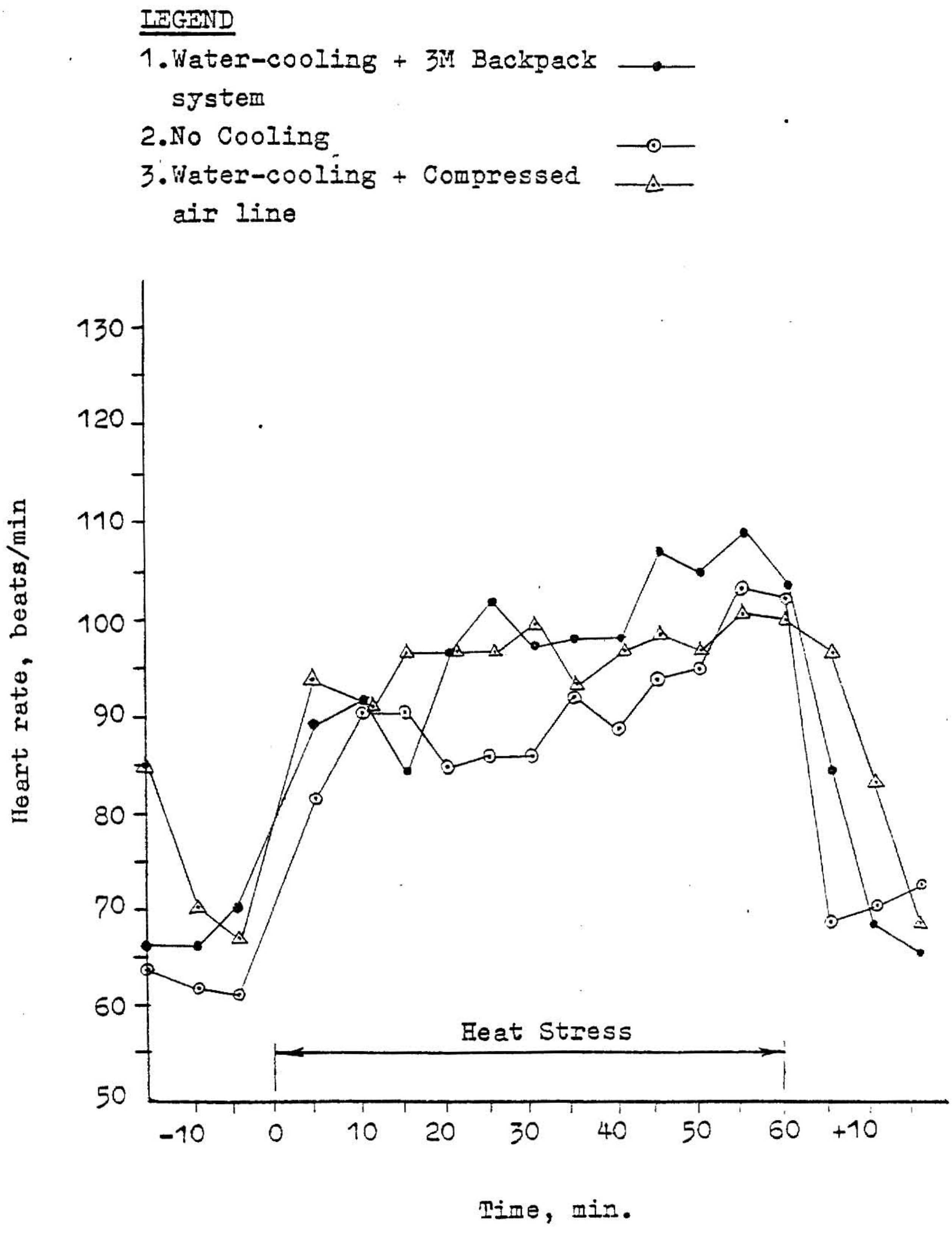
LEGEND

1. Water-cooling + 3M Backpack system
2. No Cooling
3. Water-cooling + Compressed air line



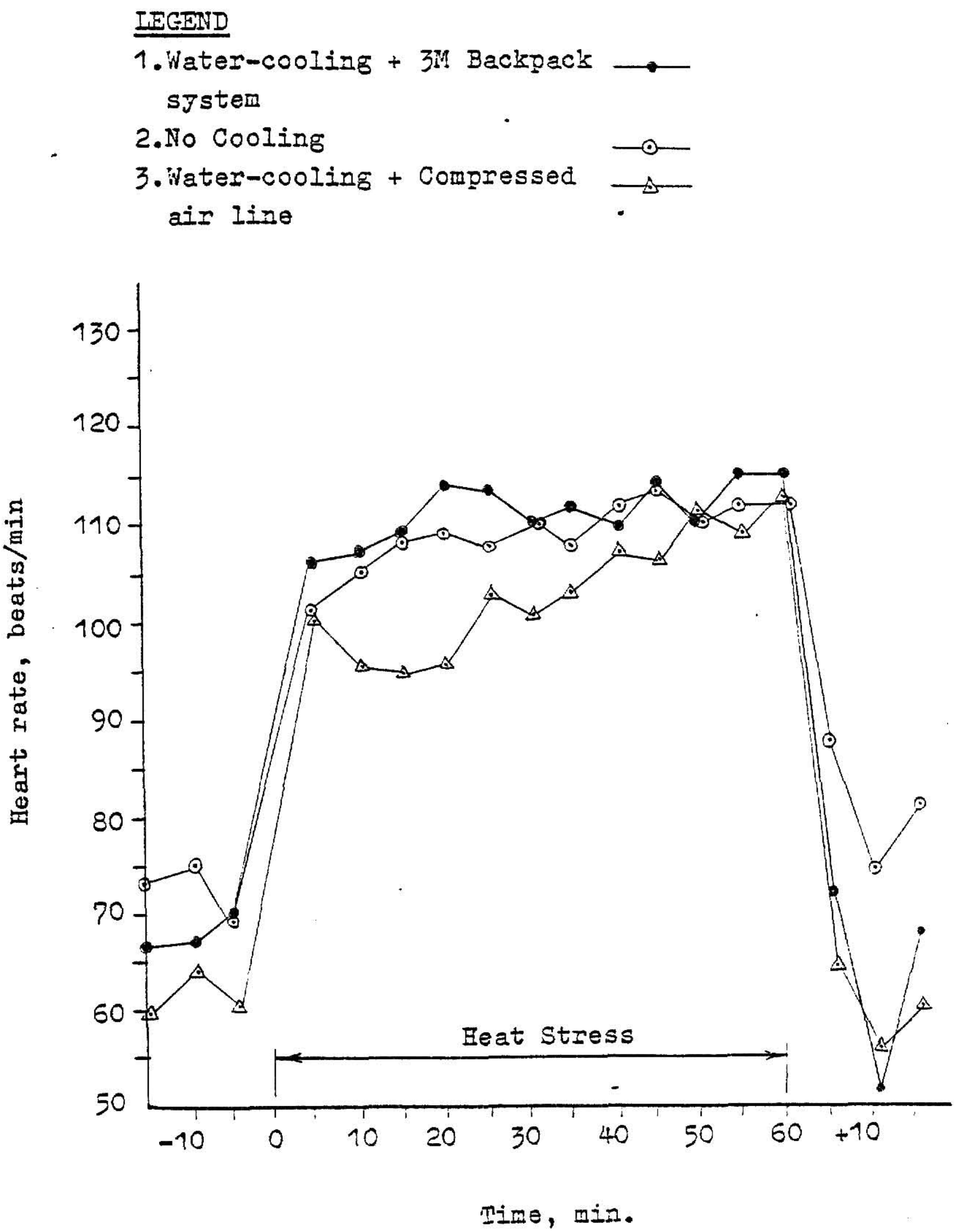
APPENDIX 5

Heart rate for subject 5



APPENDIX 6

Heart rate for subject 6



APPENDIX 7

Increase in heart rate, beats/min., by condition for subject 1 & 2

Condition

Time	Water-cooling + 3M Backpack system		No Cooling		Water-cooling + Compressed air line	
	Subj.1	Subj.2	Subj.1	Subj.2	Subj.1	Subj.2
5	31.7	18.3	22.0	24.3	26.7	10.7
10	36.7	17.3	29.0	25.3	30.7	9.7
15	34.7	26.3	36.0	27.3	29.7	12.7
20	27.7	23.3	28.0	23.3	26.7	16.7
25	35.7	27.3	26.0	34.3	32.7	20.7
30	42.7	24.3	32.0	34.3	30.7	19.7
35	35.7	36.3	30.0	39.3	29.7	13.7
40	33.7	33.3	36.0	45.3	26.7	21.7
45	36.7	31.3	36.0	43.3	30.7	16.7
50	36.7	34.3	32.0	49.3	30.7	27.7
55	37.7	33.3	37.0	49.3	29.7	20.7
60	36.7	39.3	38.0	61.3	29.7	20.7

Note: Increase in heart rate= (The heart rates from the data during the 60 min. heat stress period) - (Average of the first three heart rates from the data before the 60 min. heat stress period)

APPENDIX 8

Increase in heart rate, beats/min., by condition for subject 3 & 4

Condition

Time	Water-cooling + 3M Backpack system		No Cooling		Water-cooling + Compressed air line	
	Subj.3	Subj.4	Subj.3	Subj.4	Subj.3	Subj.4
5	22.7	19.3	26.3	17.5	18.0	17.7
10	23.7	22.3	31.3	23.5	18.0	25.7
15	24.7	24.3	31.3	21.5	21.0	31.7
20	27.7	27.3	37.3	29.5	22.0	25.7
25	30.7	23.3	36.3	23.5	25.0	31.7
30	28.7	26.3	37.3	30.5	24.0	29.7
35	34.7	27.3	37.3	25.5	25.0	35.7
40	37.7	26.3	43.3	29.5	24.0	32.7
45	26.7	28.3	40.3	29.5	21.0	32.7
50	32.7	29.3	41.3	34.5	25.0	32.7
55	29.7	30.3	46.3	29.5	26.0	36.7
60	35.7	29.3	48.3	33.5	28.0	33.7

Note: Increase in heart rate= (The heart rates from the data during the 60 min. heat stress period) - (Average of the first three heart rates from the data before the 60 min. heat stress period)

APPENDIX 9

Increase in heart rate, beats/min., by condition for subject 5 & 6

Condition

Time	Water-cooling + 3M Backpack system Subj.1	Water-cooling + 3M Backpack system Subj.2	No Cooling Subj.1	No Cooling Subj.2	Water-cooling + Compressed air line Subj.1	Water-cooling + Compressed air line Subj.2
5	21.7	37.7	18.7	28.7	20.0	38.7
10	23.7	38.7	27.7	32.7	15.0	33.7
15	16.7	40.7	27.7	35.7	22.0	32.7
20	28.7	45.7	21.7	36.7	22.0	38.7
25	34.7	44.7	22.7	34.7	22.0	41.7
30	29.7	41.7	22.7	37.7	25.0	38.7
35	30.7	42.7	29.7	34.7	19.0	40.7
40	30.7	40.7	25.7	38.7	22.0	44.7
45	39.7	45.7	30.7	40.7	24.0	43.7
50	36.7	40.7	31.7	36.7	22.0	48.7
55	41.7	46.7	40.7	38.7	26.0	45.7
60	35.7	46.7	38.7	38.7	25.0	49.7

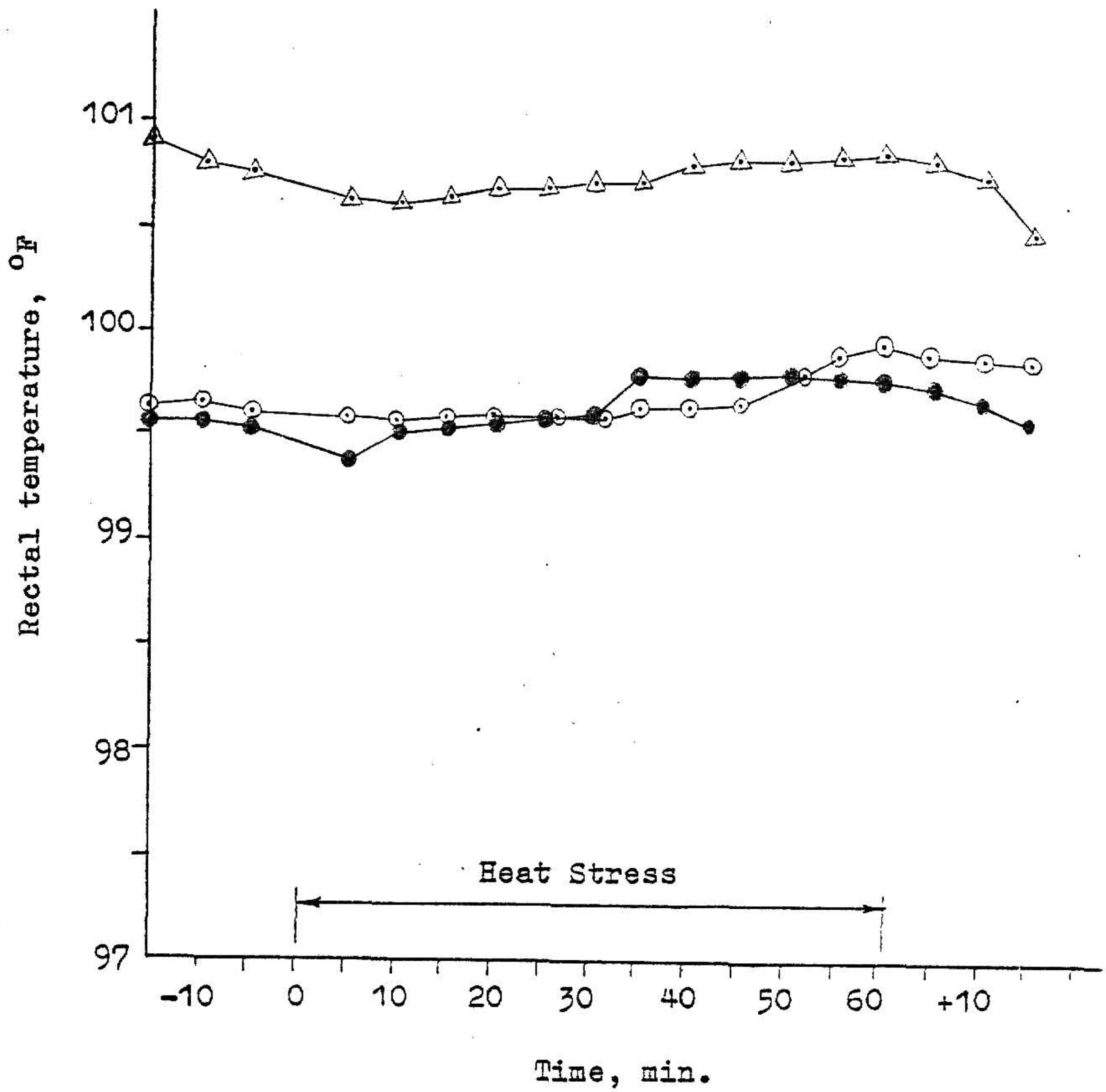
Note: Increase in heart rate= (The heart rates from the data during the 60 min. heat stress period) - (Average of the first three heart rates from the data before the 60 min. heat stress period)

APPENDIX 10

Rectal temperature for subject 1

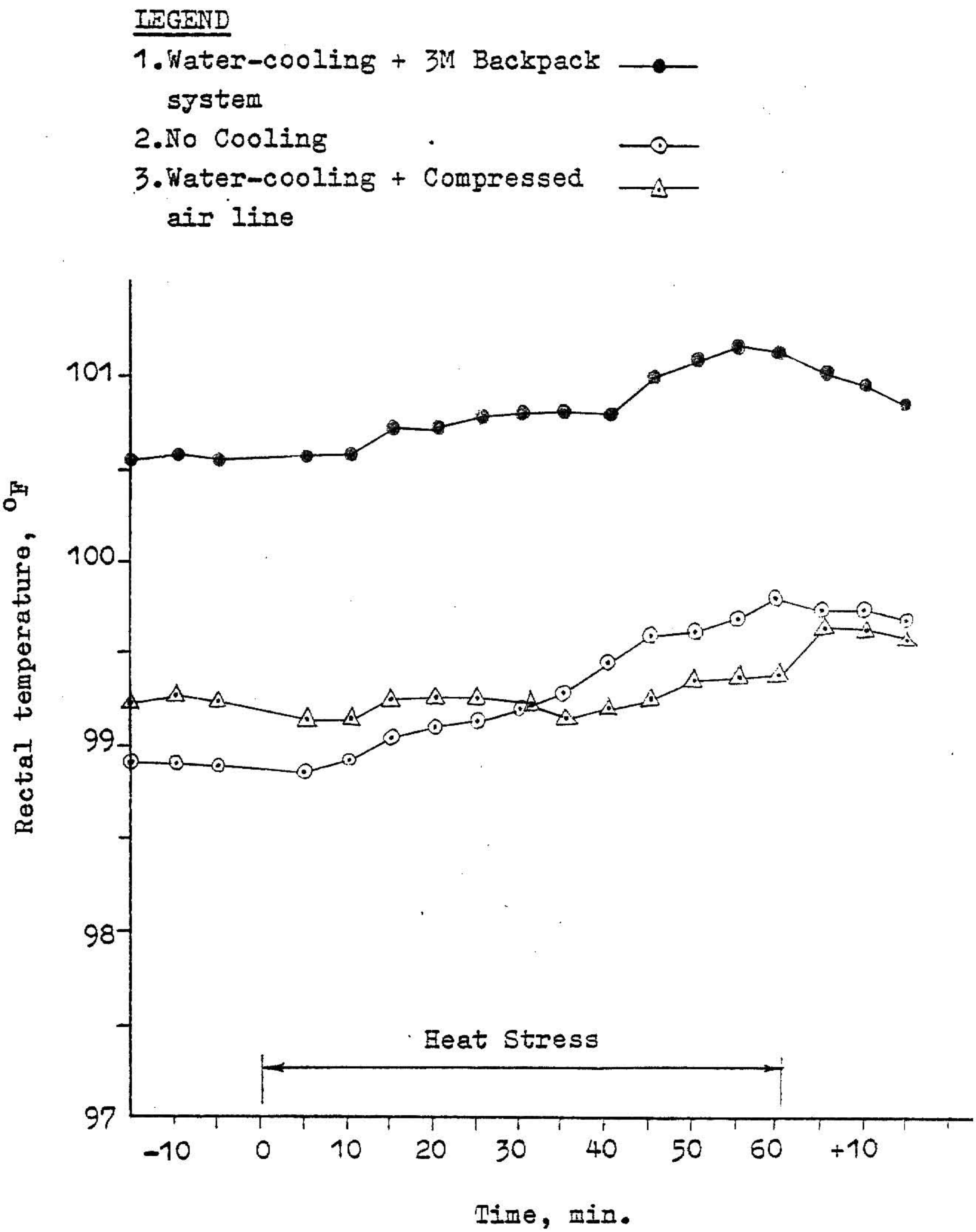
LEGEND

1. Water-cooling + 3M Backpack system
2. No Cooling
3. Water-cooling + Compressed air line



APPENDIX 11

Rectal temperature for subject 2



APPENDIX 12

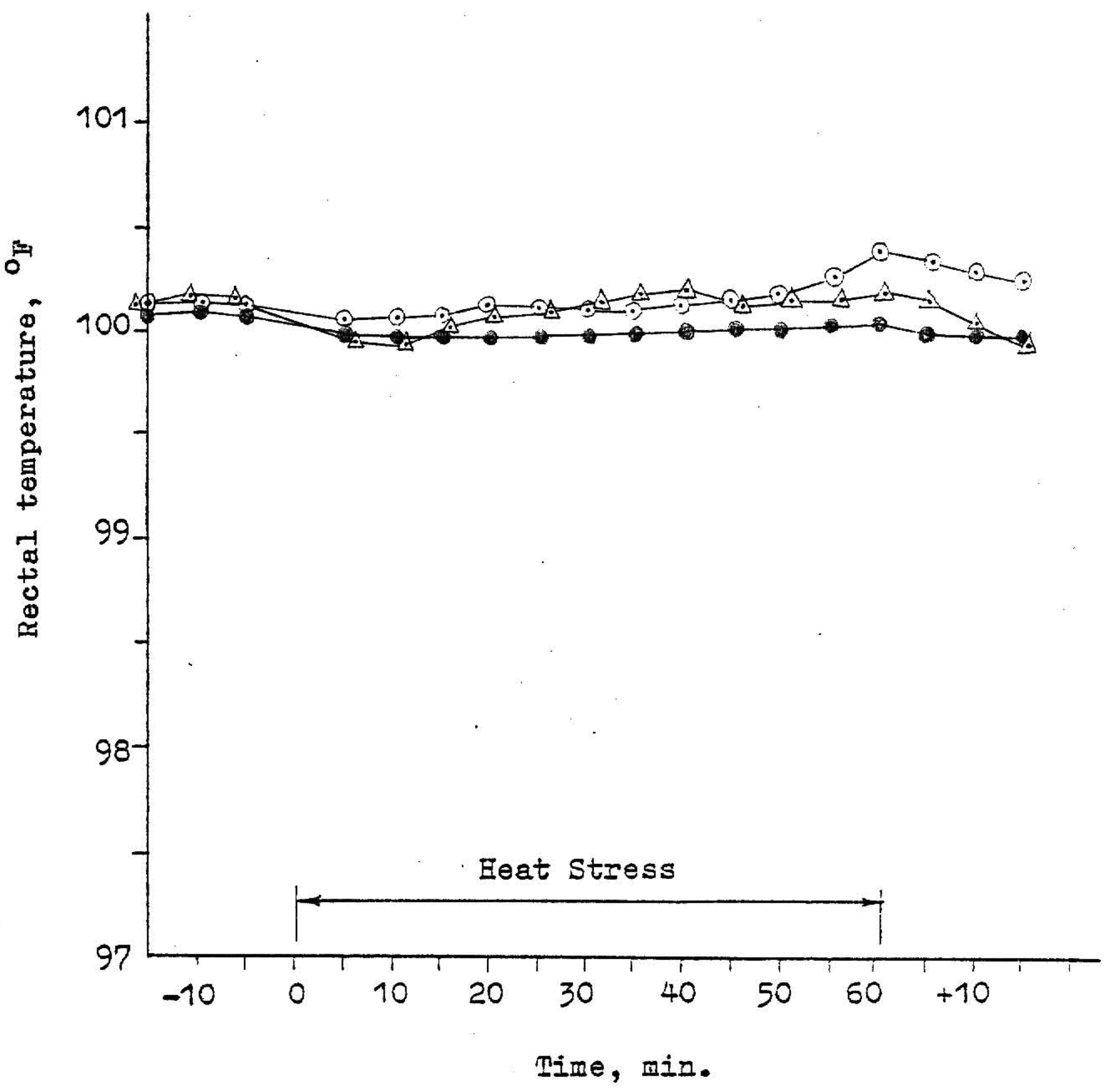
Rectal temperature for subject 3

LEGEND

1.Water-cooling + 3M Backpack system

2.No Cooling

3.Water-cooling + Compressed air line

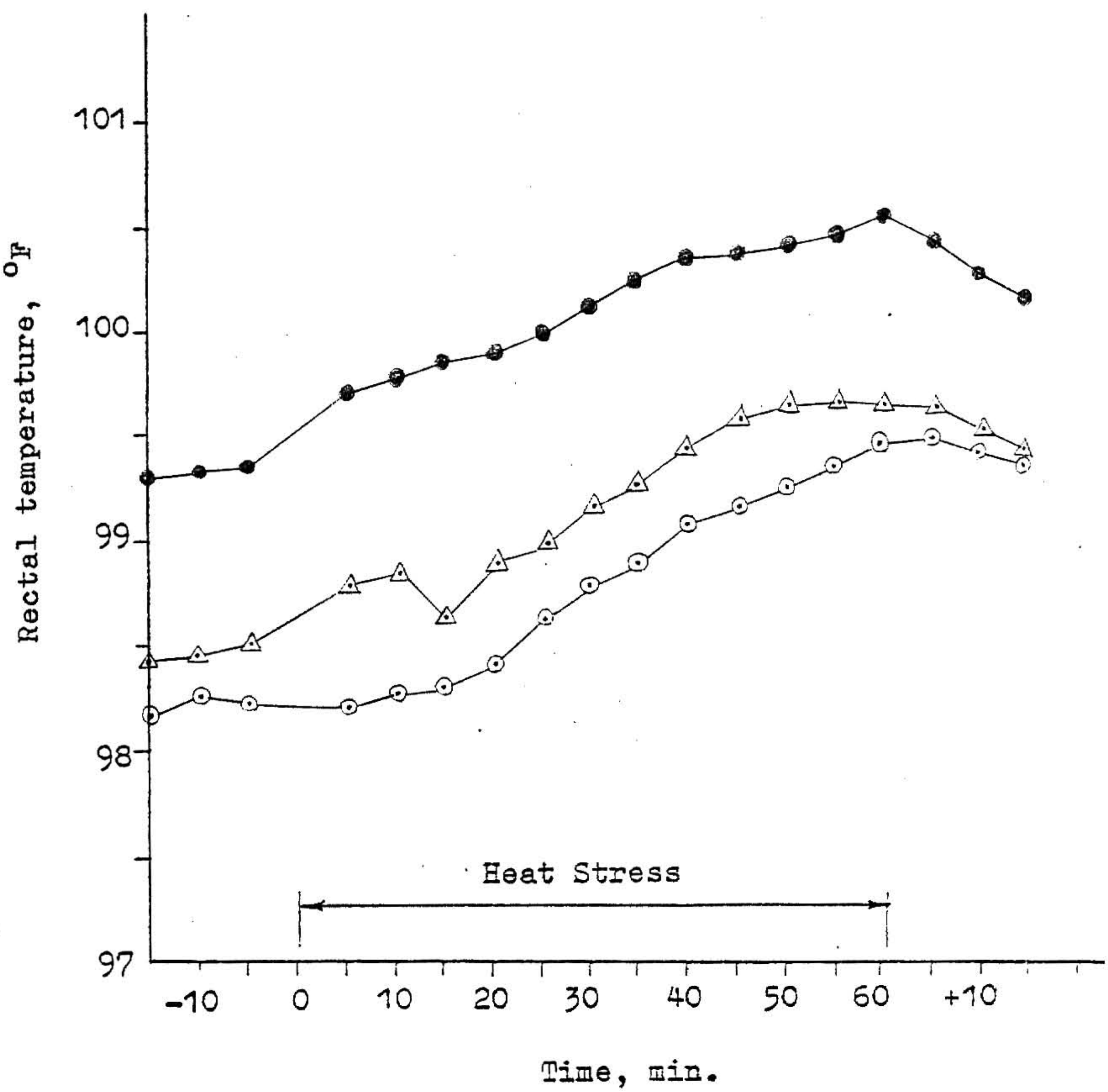


APPENDIX 13

Rectal temperature for subject 4

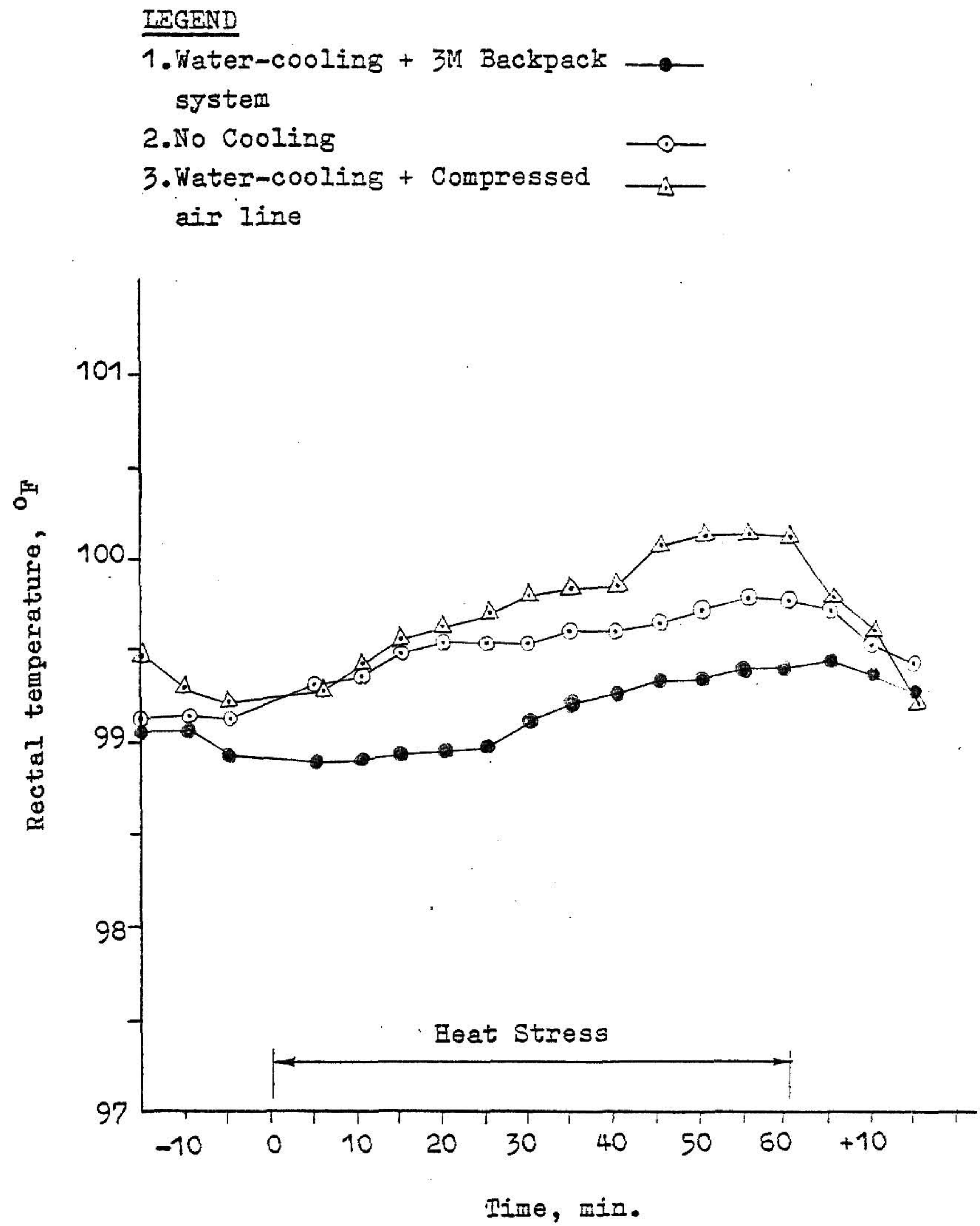
LEGEND

1. Water-cooling + 3M Backpack system
2. No Cooling
3. Water-cooling + Compressed air line



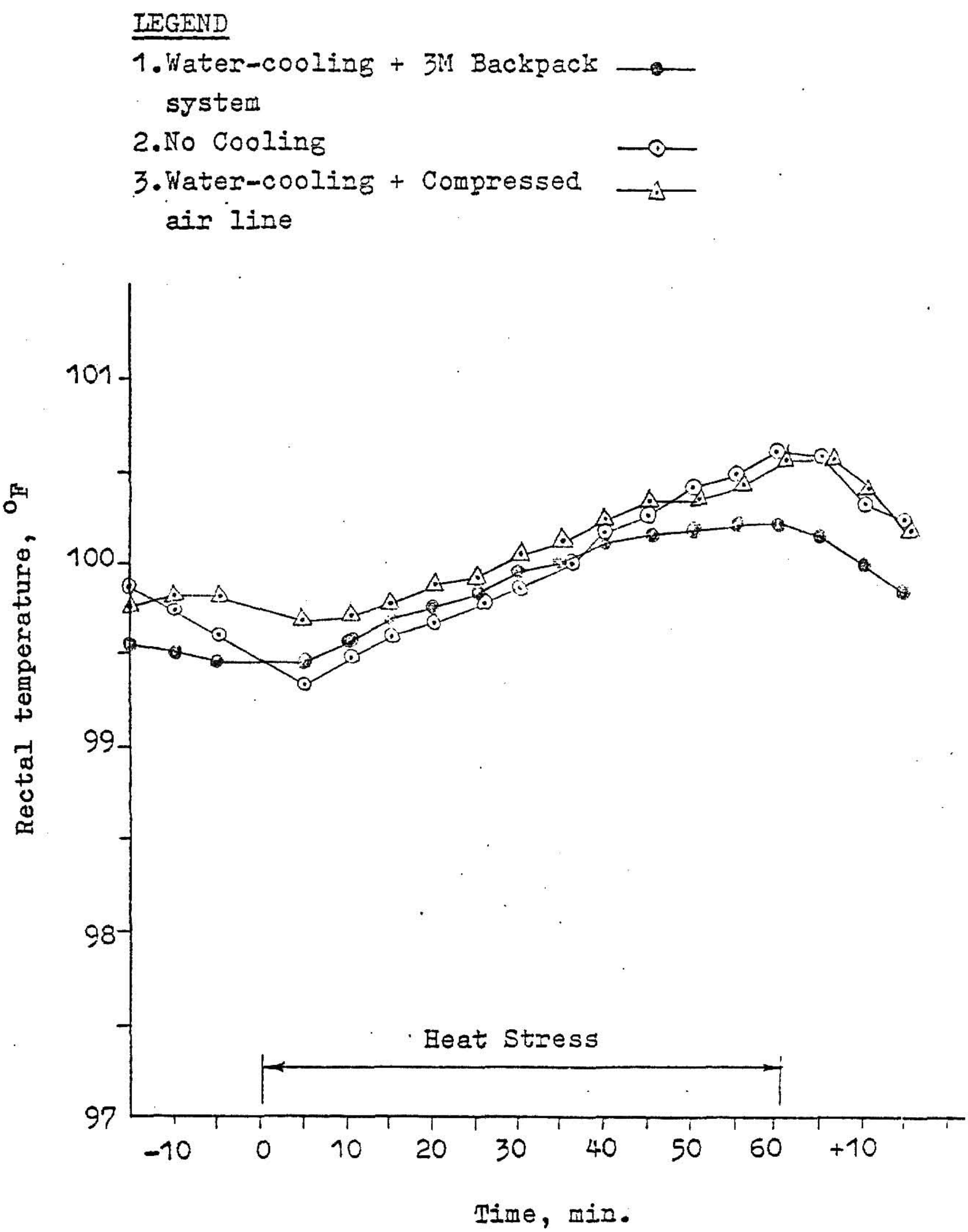
APPENDIX 14

Rectal temperature for subject 5



APPENDIX 15

Rectal temperature for subject 6



APPENDIX 16

Increase in rectal temperature, ^{o}F, by condition for subject 1 & 2

Condition

Time	Water-cooling + 3M Backpack system Subj.1	Subj.2	No Cooling Subj.1	Subj.2	Water-cooling + Compressed air line Subj.1	Subj.2
5	-0.17	0.02	-0.05	-0.09	-0.20	-0.16
10	-0.05	0.04	-0.08	0.02	-0.21	-0.16
15	0.00	0.20	-0.05	0.11	-0.20	0.00
20	0.05	0.20	-0.06	0.17	-0.16	0.00
25	0.08	0.24	-0.05	0.23	-0.15	0.00
30	0.12	0.26	-0.05	0.29	-0.10	-0.10
35	0.28	0.28	-0.03	0.33	-0.06	-0.20
40	0.26	0.26	-0.03	0.52	-0.03	-0.14
45	0.28	0.44	0.04	0.61	-0.06	-0.08
50	0.29	0.52	0.15	0.63	-0.06	0.05
55	0.28	0.58	0.20	0.71	-0.04	0.09
60	0.24	0.56	0.28	0.80	-0.03	0.12

Note: Increase in rectal temperature= (The rectal temperatures from the data during the 60 min. heat stress period) - (Average of the first three rectal temperatures from the data before the 60 min. heat stress period)

APPENDIX 17

Increase in rectal temperature, ^{o}F, by condition for subject 3 & 4

Condition

	Water-cooling + 3M Backpack system		No Cooling		Water-cooling + Compressed air line	
Time	Subj.3	Subj.4	Subj.3	Subj.4	Subj.3	Subj.4
5	-0.19	0.35	-0.06	-0.01	-0.12	0.26
10	-0.24	0.41	-0.04	0.07	-0.14	0.32
15	-0.25	0.49	-0.01	0.11	-0.07	0.14
20	-0.25	0.55	0.01	0.20	-0.01	0.36
25	-0.25	0.64	0.00	0.35	0.00	0.50
30	-0.24	0.78	-0.01	0.50	0.03	0.68
35	-0.23	0.92	-0.01	0.62	0.10	0.81
40	-0.20	1.02	0.00	0.77	0.12	0.09
45	-0.18	1.05	0.06	0.88	0.05	1.04
50	-0.17	1.09	0.10	0.99	0.07	1.11
55	-0.15	1.14	0.16	1.08	0.07	1.13
60	-0.13	1.21	0.26	1.17	0.08	1.10

Note: Increase in rectal temperature= (The rectal temperatures from the data during the 60 min. heat stress period) - (Average of the first three rectal temperatures from the data before the 60 min. heat stress period)

APPENDIX 18

Increase in rectal temperature, ^{o}F, by condition for subject 5 & 6

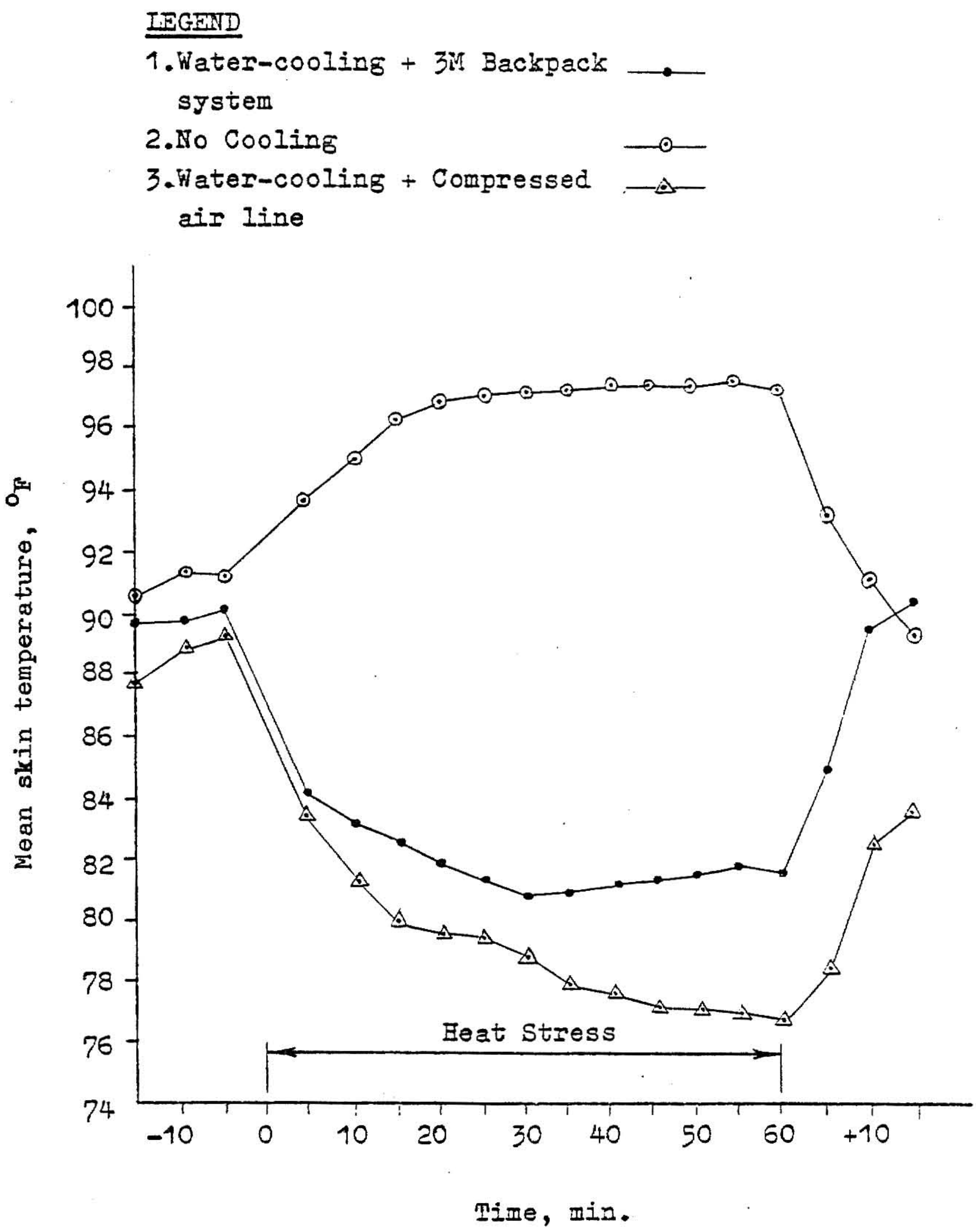
Condition

Time	Water-cooling + 3M Backpack system		No Cooling		Water-cooling + Compressed air line	
	Subj.5	Subj.6	Subj.5	Subj.6	Subj.5	Subj.6
5	-0.22	-0.05	0.19	-0.40	-0.08	-0.11
10	-0.19	0.09	0.24	-0.26	0.03	-0.08
15	-0.12	0.23	0.35	-0.17	0.19	-0.04
20	-0.10	0.29	0.37	-0.12	0.29	0.05
25	0.04	0.35	0.37	0.00	0.35	0.10
30	0.08	0.41	0.37	0.13	0.42	0.22
35	0.15	0.49	0.43	0.25	0.48	0.30
40	0.23	0.57	0.43	0.37	0.50	0.40
45	0.31	0.61	0.48	0.50	0.72	0.49
50	0.34	0.64	0.56	0.69	0.76	0.53
55	0.36	0.70	0.62	0.73	0.76	0.60
60	0.37	0.72	0.62	0.83	0.76	0.75

Note: Increase in rectal temperature= (The rectal temperatures from the data during the 60 min. heat stress period) - (Average of the first three rectal temperatures from the data before the 60 min. heat stress period)

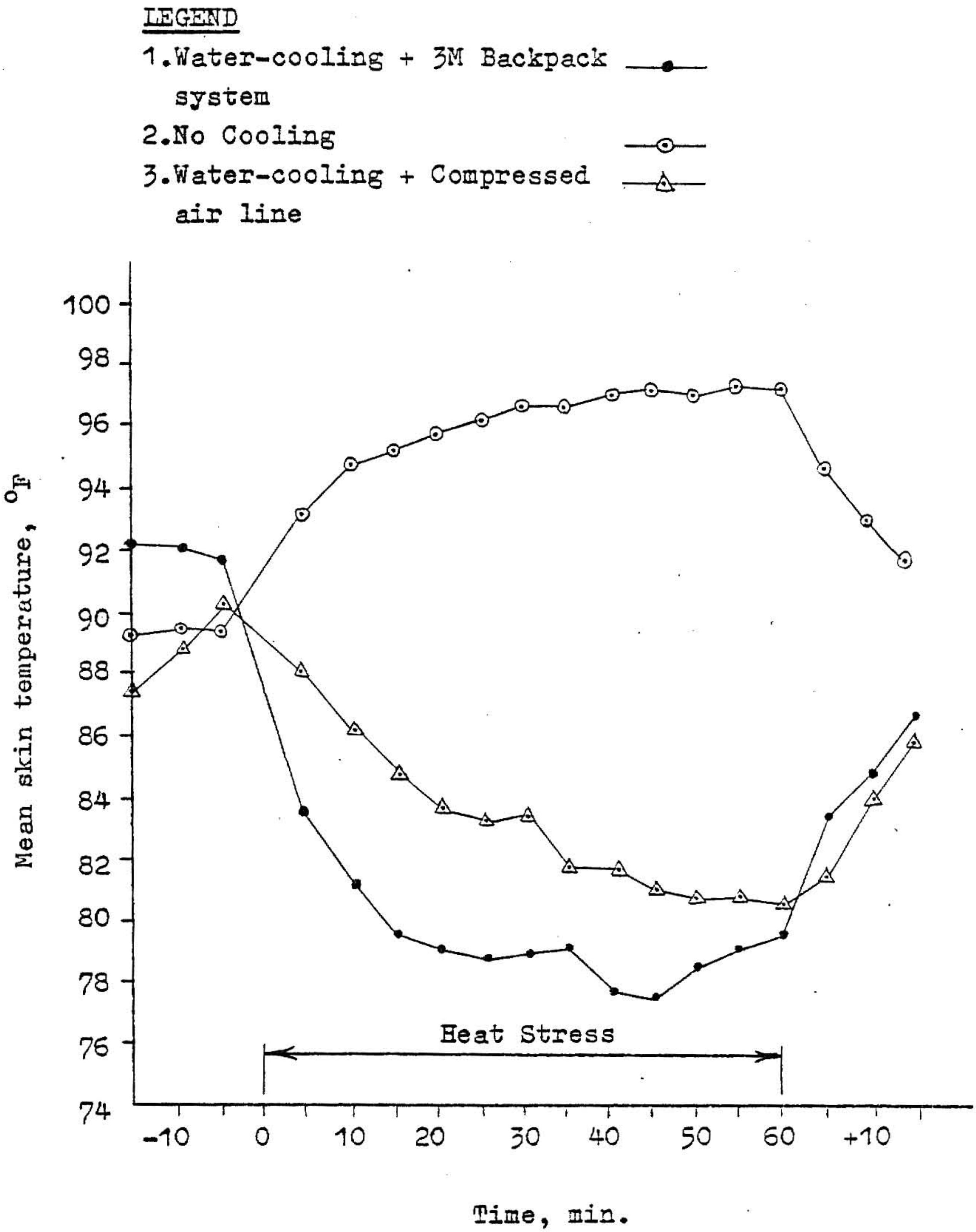
APPENDIX 19

Mean skin temperature for subject 1



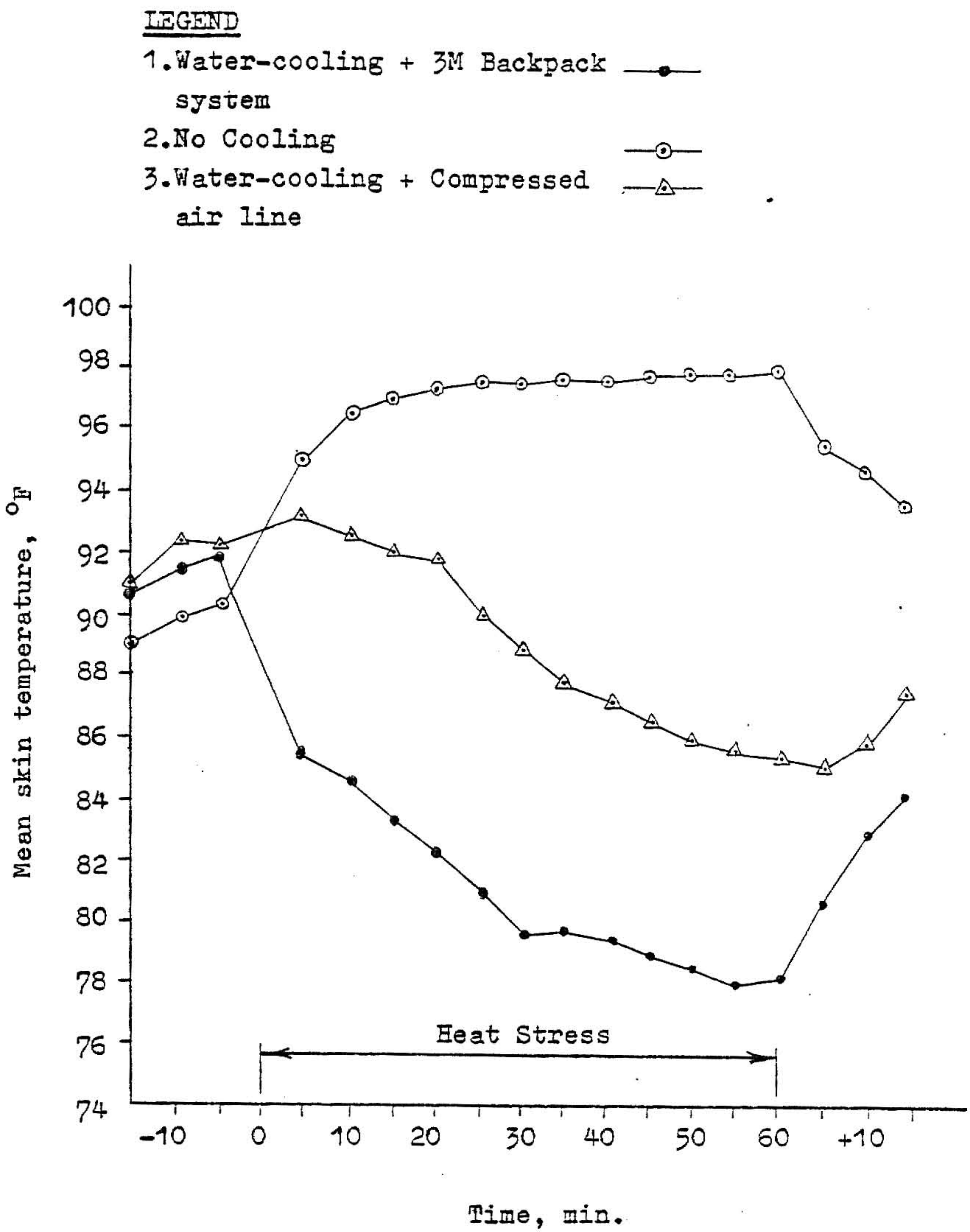
APPENDIX 20

Mean skin temperature for subject 2



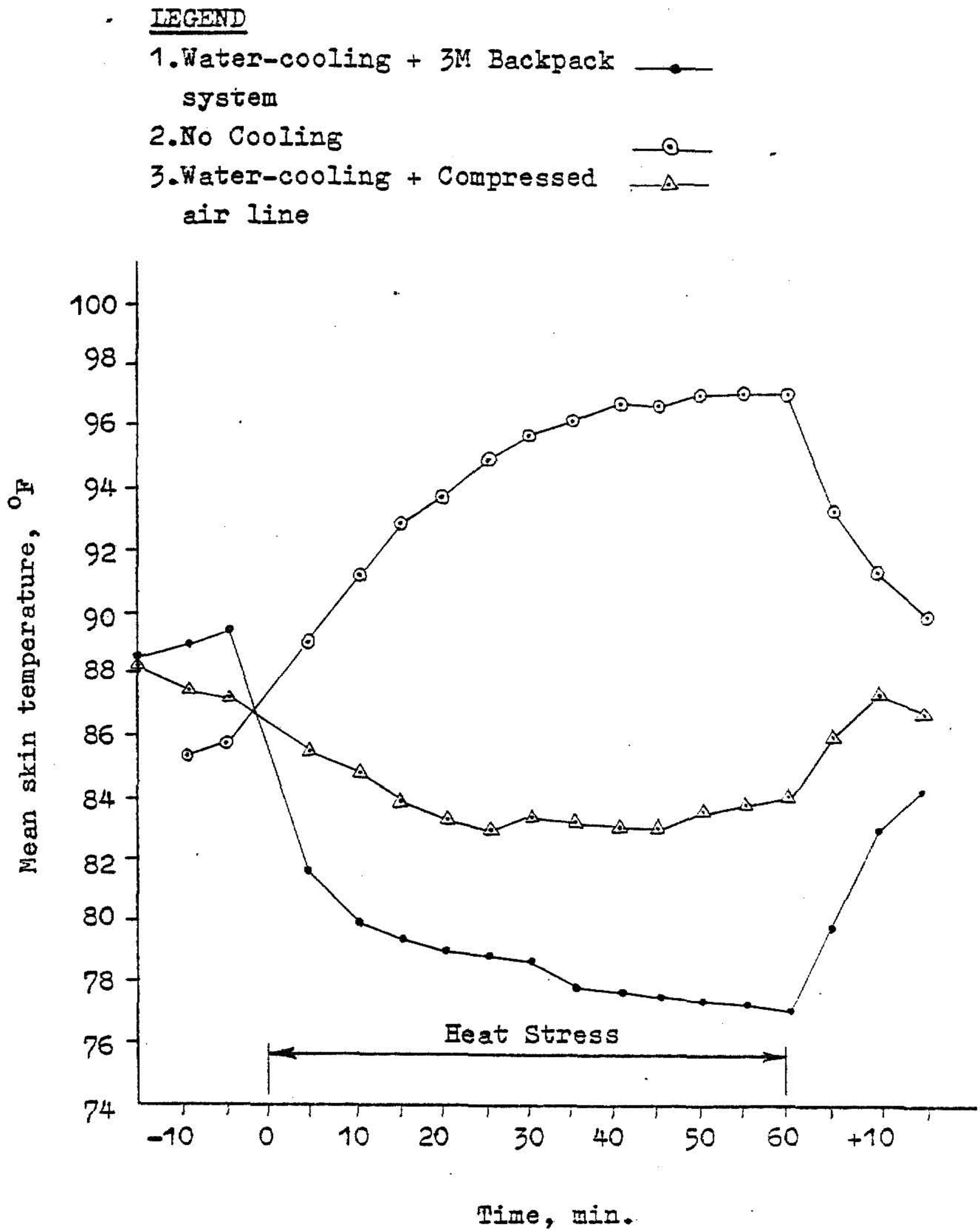
APPENDIX 21

Mean skin temperature for subject 3



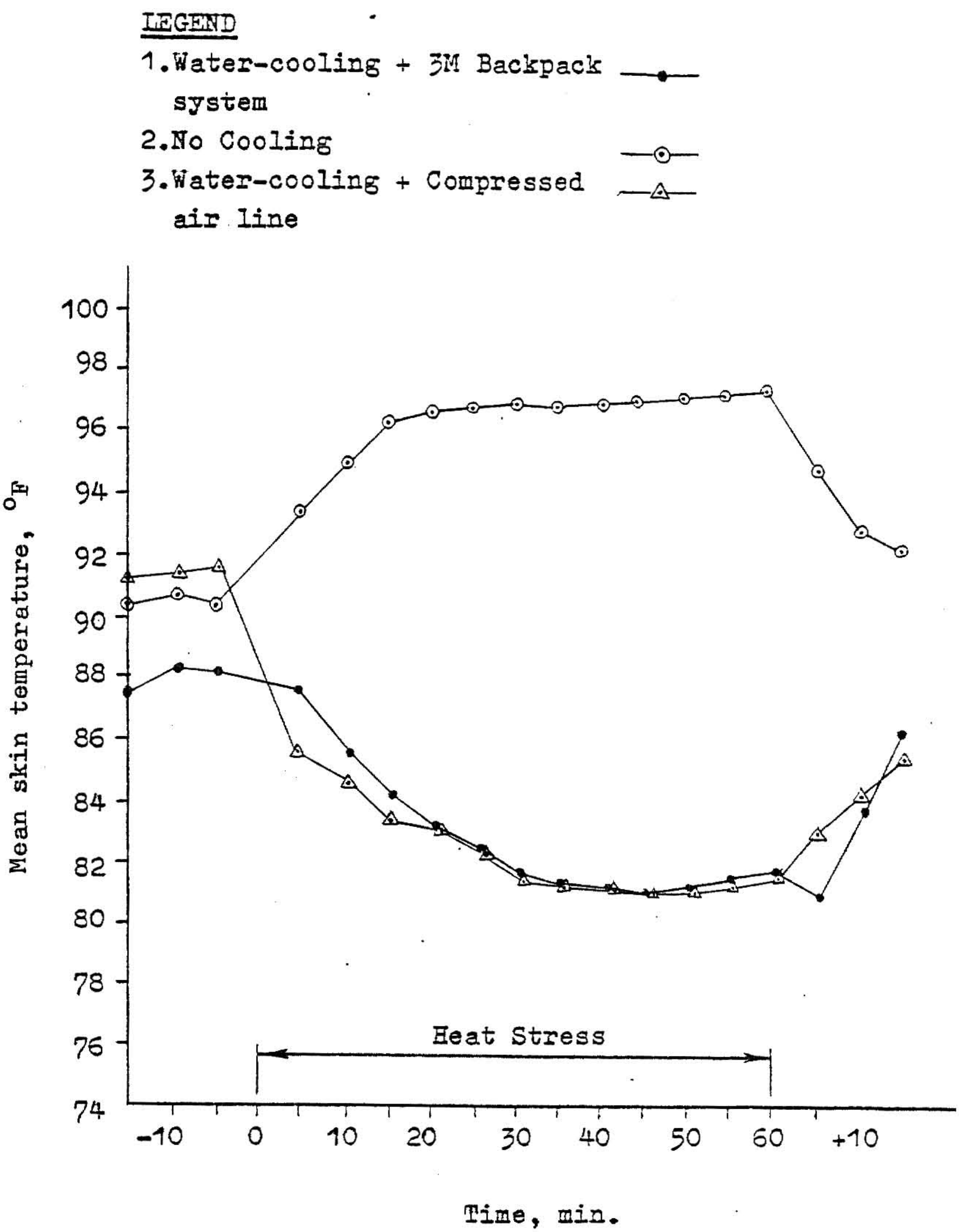
APPENDIX 22

Mean skin temperature for subject 4



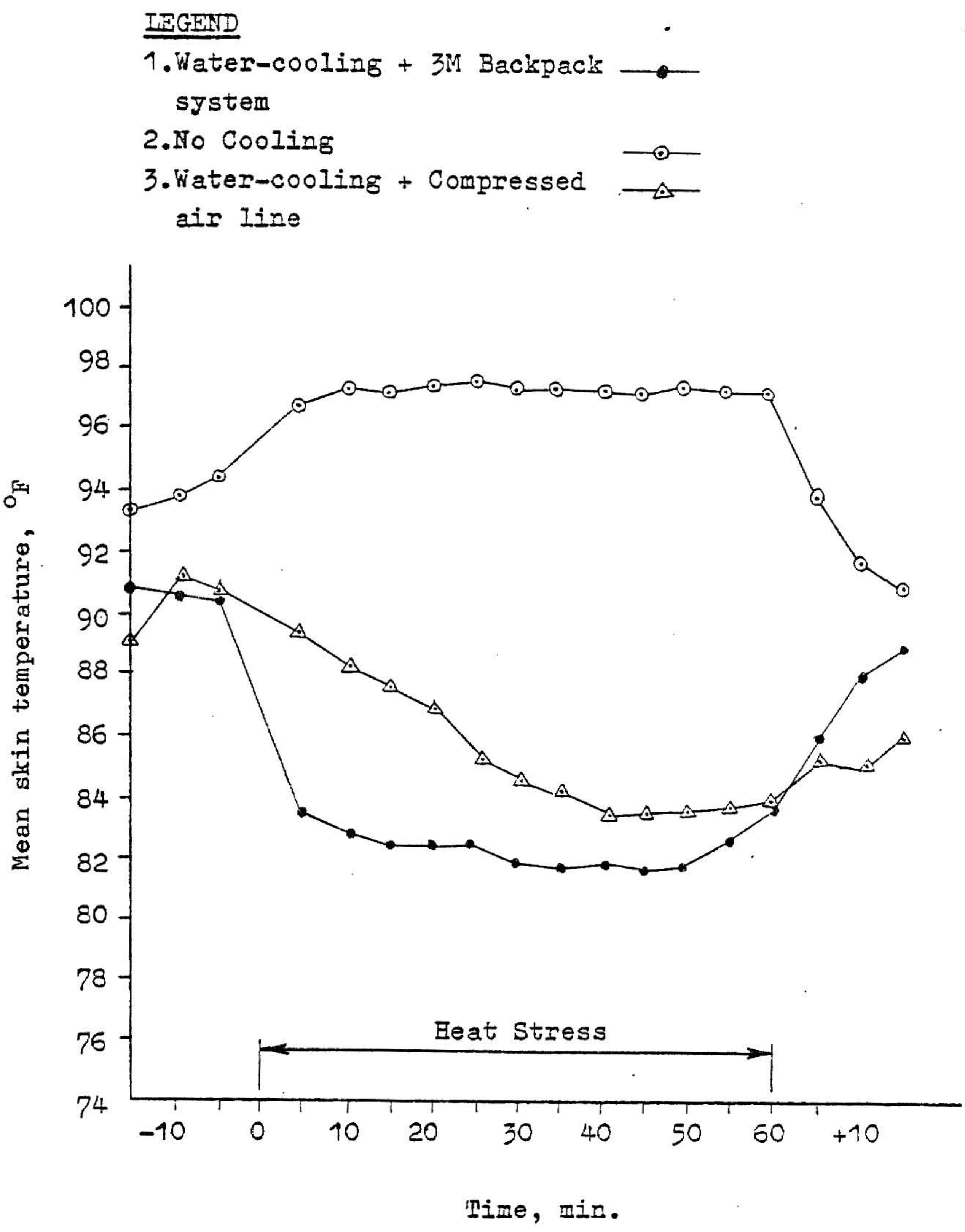
APPENDIX 23

Mean skin temperature for subject 5



APPENDIX 24

Mean skin temperature for subject 6



APPENDIX 25

Increase in mean skin temperature, °F, by condition for subject 1 & 2

Condition

Time	Water-cooling + 3M Backpack system		No Cooling		Water-cooling + Compressed air line	
	Subj.1	Subj.2	Subj.1	Subj.2	Subj.1	Subj.2
5	- 5.93	- 8.13	+ 2.86	+ 3.66	- 5.10	- 0.94
10	- 6.88	-10.90	+ 4.14	+ 5.10	- 7.54	- 2.85
15	- 7.47	-12.23	+ 5.11	+ 5.81	- 8.65	- 4.22
20	- 8.02	-12.91	+ 5.38	+ 6.11	- 9.12	- 5.05
25	- 8.69	-13.34	+ 5.74	+ 6.58	- 9.44	- 5.84
30	- 9.09	-13.33	+ 5.76	+ 6.78	-10.06	- 5.45
35	- 9.08	-13.46	+ 5.90	+ 6.72	-10.64	- 7.00
40	- 8.43	-14.11	+ 5.99	+ 6.95	-11.13	- 7.40
45	- 8.78	-14.47	+ 5.91	+ 7.09	-11.56	- 7.96
50	- 8.60	-13.84	+ 5.91	+ 6.87	-11.63	- 8.12
55	- 8.29	-13.00	+ 6.02	+ 7.03	-11.90	- 8.08
60	- 8.70	-12.62	+ 5.87	+ 6.94	-11.93	- 8.43

Note: Increase in mean skin temperature= (The mean skin temperatures from the data during the 60 min. heat stress period) - (Average of the first three mean skin temperatures from the data before the 60 min. heat stress period)

APPENDIX 26

Increase in mean skin temperature, °F, by condition for subject 3 & 4

Condition

Time	Water-cooling + 3M Backpack system Subj.3	Subj.4	No Cooling Subj.3	Subj.4	Water-cooling + Compressed air line Subj.3	Subj.4
5	- 5.69	- 7.27	+ 5.32	+ 3.23	+ 1.49	- 2.10
10	- 6.90	- 9.05	+ 6.38	+ 5.54	+ 0.41	- 2.90
15	- 7.99	- 9.85	+ 7.02	+ 7.06	+ 0.20	- 3.72
20	- 9.16	-10.17	+ 7.30	+ 8.18	+ 0.03	- 4.30
25	-10.52	-10.29	+ 7.51	+ 9.11	- 1.91	- 4.60
30	-11.52	-10.70	+ 7.36	+ 9.88	- 3.23	- 4.14
35	-11.50	-11.02	+ 7.43	+10.40	- 4.32	- 4.24
40	-11.82	-11.18	+ 7.42	+10.82	- 5.06	- 4.48
45	-12.43	-11.37	+ 7.45	+10.80	- 5.65	- 4.63
50	-13.10	-11.66	+ 7.47	+10.92	- 5.86	- 4.18
55	-13.56	-11.86	+ 7.46	+11.09	- 6.20	- 3.79
60	-13.29	-11.94	+ 7.47	+11.06	- 6.59	- 3.76

Note: Increase in mean skin temperature= (The mean skin temperatures from the data during the 60 min. heat stress period) - (Average of the first three mean skin temperatures from the data before the 60 min. heat stress period)

APPENDIX 27

Increase in mean skin temperature, °F, by condition
for subject 5 & 6

Condition

	Water-cooling + 3M Backpack system		No Cooling		Water-cooling + Compressed air line	
Time	Subj.5	Subj.6	Subj.5	Subj.6	Subj.5	Subj.6
5	- 0.21	- 6.95	+ 3.23	+ 2.70	- 5.48	- 1.26
10	- 2.21	- 7.77	+ 4.77	+ 3.26	- 6.91	- 2.41
15	- 3.77	- 8.26	+ 5.83	+ 3.23	- 7.64	- 2.68
20	- 4.71	- 8.26	+ 6.12	+ 3.37	- 8.31	- 3.71
25	- 5.67	- 8.23	+ 6.30	+ 3.55	- 9.11	- 5.34
30	- 6.04	- 8.65	+ 6.40	+ 3.32	- 9.51	- 5.91
35	- 6.29	- 8.79	+ 6.30	+ 3.23	- 9.75	- 6.35
40	- 6.57	- 8.74	+ 6.38	+ 3.17	- 9.95	- 6.83
45	- 6.71	- 8.88	+ 6.49	+ 3.03	- 9.99	- 6.77
50	- 6.59	- 8.78	+ 6.54	+ 3.06	-10.25	- 6.80
55	- 6.41	- 8.06	+ 6.58	+ 2.56	-10.24	- 6.77
60	- 6.16	- 7.02	+ 6.66	+ 2.48	- 9.92	- 6.75

Note: Increase in mean skin temperature= (The mean skin temperatures from the data during the 60 min. heat stress period) - (Average of the first three mean skin temperatures from the data before the 60 min. heat stress period)

APPENDIX 28

Chest temperature, °F, for condition 1

	Subject						
Time	1	2	3	4	5	6	Mean
-15	87.65	91.40	90.36	88.66	86.16	91.60	89.30
-10	87.74	91.38	91.23	89.10	86.83	91.24	89.59
- 5	87.69	91.06	91.35	89.64	86.76	91.10	89.60
0	***	***	***	***	***	***	***
5	74.03	72.10	76.25	71.44	84.20	74.32	75.39
10	70.72	65.02	72.96	66.46	79.00	70.80	70.82
15	68.58	65.21	69.87	63.95	74.32	68.70	68.60
20	67.02	60.54	67.10	62.00	71.52	68.18	66.06
25	65.86	59.54	64.36	61.59	69.09	68.34	64.80
30	65.37	59.36	62.24	60.46	67.82	67.60	63.81
35	65.39	59.03	62.24	59.80	67.09	67.29	63.47
40	65.57	57.94	61.60	59.33	66.37	67.60	63.07
45	65.82	58.59	60.56	58.96	66.06	67.47	62.91
50	66.18	59.40	59.34	58.55	66.25	67.64	62.89
55	66.82	60.85	58.37	58.24	66.67	69.32	63.38
60	66.07	61.57	58.82	58.00	67.09	71.58	63.86
+ 5	76.58	73.14	66.68	67.96	68.60	79.50	72.08
+10	85.06	79.13	72.28	74.52	76.98	85.24	78.87
+15	87.80	82.76	75.10	77.75	82.10	89.31	82.47

APPENDIX 29

Chest temperature, °F, for condition 2

	Subject						
Time	1	2	3	4	5	6	Mean
-15	88.70	88.20	87.41	86.60	90.85	93.98	89.29
-10	87.98	88.62	89.18	86.98	91.34	93.76	89.64
- 5	87.76	88.28	89.60	85.62	90.39	93.68	89.22
0	***	***	***	***	***	***	***
5	91.77	91.86	95.14	90.60	94.20	96.73	93.38
10	92.99	93.56	96.52	93.10	95.87	97.16	94.87
15	94.38	94.44	97.37	94.55	96.88	97.12	95.79
20	94.77	94.88	97.75	95.50	97.18	97.42	96.25
25	95.57	95.58	97.94	96.32	97.38	97.80	96.76
30	95.70	95.85	97.78	96.84	97.42	97.77	96.89
35	96.07	95.87	97.75	97.14	97.46	97.76	97.01
40	96.25	96.21	97.69	97.56	97.50	97.84	97.18
45	96.23	96.36	97.67	97.31	97.56	97.76	97.15
50	96.14	96.31	97.62	97.34	97.63	97.62	97.11
55	96.32	96.38	97.60	97.50	97.60	96.65	97.01
60	96.10	96.30	97.60	97.50	97.63	96.55	96.95
+ 5	91.83	95.05	96.65	94.83	95.66	94.74	94.79
+10	89.30	92.88	94.90	92.34	94.30	92.62	92.72
+15	87.30	91.74	93.96	90.74	93.03	92.06	91.47

APPENDIX 30

Chest temperature, °F, for condition 3

Time	Subject 1	2	3	4	5	6	Mean
-15	85.98	85.32	91.36	88.44	90.82	88.85	88.46
-10	86.70	86.84	93.10	87.56	90.82	89.60	89.10
- 5	86.96	88.10	93.55	87.10	91.60	89.74	89.51
0	***	***	***	***	***	***	***
5	72.10	81.60	92.70	79.90	77.90	85.10	81.55
10	65.90	76.72	89.49	76.10	74.22	81.38	77.30
15	63.08	73.60	88.37	73.84	72.07	79.81	75.13
20	62.06	71.64	87.76	71.60	70.10	77.82	73.50
25	61.00	70.12	84.04	70.50	68.35	74.73	71.46
30	59.90	71.05	81.20	71.02	67.40	73.34	70.65
35	58.90	68.33	79.06	71.10	66.83	72.43	69.44
40	57.88	67.10	77.65	70.30	66.52	71.66	68.52
45	57.20	66.30	76.56	69.74	66.32	71.60	67.95
50	56.86	65.78	76.08	70.71	66.49	71.36	67.88
55	56.57	65.60	75.39	71.14	65.75	71.52	67.66
60	56.55	65.12	74.62	71.75	66.48	71.56	67.68
+ 5	63.62	69.78	75.66	78.40	71.24	77.67	72.73
+10	72.60	73.88	79.26	81.76	75.16	79.34	77.00
+15	75.75	77.21	81.97	81.98	78.10	82.42	79.57

APPENDIX 31

Calf temperature, °F, for condition 1

Time	Subject 1	2	3	4	5	6	Mean
-15	92.35	92.77	90.06	88.06	88.39	89.10	90.12
-10	92.97	92.61	91.18	88.74	89.05	89.10	90.61
- 5	93.35	92.68	92.16	88.69	89.26	89.29	90.90
0	***	***	***	***	***	***	***
5	93.02	94.70	93.79	90.75	89.86	91.76	92.31
10	94.58	96.62	94.83	92.23	91.40	94.10	93.96
15	96.00	96.94	96.00	93.49	92.92	95.65	95.17
20	96.68	97.38	96.70	94.53	94.11	96.28	95.95
25	96.84	97.61	96.85	95.61	94.76	96.14	96.30
30	96.87	97.88	97.14	96.15	95.49	96.32	96.64
35	96.98	98.00	97.27	96.34	95.88	96.34	96.80
40	97.08	97.82	97.35	96.52	96.13	96.06	96.83
45	97.14	96.34	97.22	96.60	96.22	95.90	96.57
50	97.20	96.93	97.17	96.61	96.30	96.10	96.72
55	97.22	97.16	97.25	96.63	96.32	95.74	96.72
60	97.12	97.23	97.32	96.80	96.38	95.56	96.74
+ 5	94.90	94.23	94.64	92.76	93.80	92.83	93.86
+10	95.98	90.84	93.22	92.82	90.94	90.05	92.31
+15	94.90	89.44	92.87	91.95	90.18	87.70	91.17

APPENDIX 32

Calf temperature, °F, for condition 2

Time	Subject 1	2	3	4	5	6	Mean
-15	92.64	90.85	90.10	83.48	89.45	92.61	89.86
-10	95.44	91.20	90.30	84.00	89.80	94.63	90.90
- 5	95.29	91.24	91.06	84.00	90.32	95.50	91.24
0	***	***	***	***	***	***	***
5	95.34	93.88	94.34	85.83	92.14	96.02	92.92
10	97.14	95.10	95.07	87.90	93.58	96.83	94.27
15	98.00	95.62	95.60	89.62	94.87	96.92	95.10
20	98.24	95.87	95.85	91.07	95.24	96.92	95.53
25	98.30	96.06	96.09	92.38	95.40	96.84	95.84
30	98.34	96.18	95.98	93.80	95.61	96.34	96.04
35	98.32	96.06	96.13	94.82	95.43	96.32	96.18
40	98.36	96.13	96.18	95.49	95.59	96.24	96.33
45	98.27	96.28	96.24	95.89	95.77	96.13	96.43
50	98.36	95.75	96.32	96.28	95.80	96.31	96.47
55	98.39	96.05	96.29	96.59	95.92	96.20	96.57
60	98.30	95.96	96.22	96.61	96.07	96.14	96.55
+ 5	95.95	93.62	93.31	92.30	93.30	93.40	93.65
+10	94.60	92.77	92.64	91.06	91.15	91.56	92.30
+15	93.14	92.34	92.56	89.53	91.60	90.00	91.53

APPENDIX 33

Calf temperature, °F, for condition 3

Time	Subject 1	2	3	4	5	6	Mean
-15	90.14	89.70	89.83	87.00	91.30	89.34	89.55
-10	91.19	90.77	91.08	86.78	91.42	94.63	90.98
- 5	91.80	92.58	90.36	87.07	91.36	92.60	90.96
0	***	***	***	***	***	***	***
5	93.95	93.59	92.89	90.10	92.80	92.35	92.61
10	95.66	94.70	93.89	92.40	93.73	93.83	94.04
15	96.62	95.31	94.76	92.98	94.52	95.25	94.91
20	96.88	95.63	95.19	94.45	95.24	95.57	95.49
25	97.57	95.59	95.27	95.30	95.55	95.34	95.77
30	97.59	95.58	95.33	96.08	95.65	95.64	95.98
35	97.73	94.94	95.30	96.12	95.82	95.84	95.96
40	97.90	95.38	95.25	96.60	95.82	95.84	96.13
45	97.93	95.13	95.23	96.89	95.97	96.10	96.21
50	98.10	95.33	95.30	97.07	95.07	96.30	96.20
55	98.07	95.76	95.33	97.24	96.10	96.35	96.48
60	98.06	95.60	95.33	96.90	96.10	96.36	96.39
+ 5	95.14	93.69	92.95	94.00	95.97	92.58	94.06
+10	95.02	93.93	91.58	93.20	92.76	90.86	98.89
+15	94.09	93.27	91.66	92.70	92.76	89.45	92.32

APPENDIX 34

Arm temperature, ^{o}F, for condition 1

Time	Subject 1	2	3	4	5	6	Mean
-15	90.79	92.76	92.80	89.36	90.36	91.83	91.32
-10	90.24	92.70	92.90	89.86	90.22	91.83	91.29
- 5	90.35	92.34	92.75	89.80	89.84	91.60	91.11
0	***	***	***	***	***	***	***
5	96.54	97.81	97.97	95.14	94.63	96.10	96.36
10	97.58	98.44	98.36	96.43	95.00	96.84	97.11
15	97.38	98.10	98.60	96.42	96.60	96.82	97.32
20	97.22	98.09	98.33	96.26	96.87	97.10	97.31
25	96.20	98.02	98.06	96.25	96.99	97.05	97.10
30	94.99	98.00	97.72	95.96	97.05	96.24	96.66
35	94.71	97.98	97.53	95.58	96.83	96.30	96.49
40	94.87	97.66	97.30	95.60	96.80	96.24	96.41
45	94.90	96.60	97.00	95.36	96.62	96.13	96.10
50	94.76	96.70	96.69	94.76	96.60	95.75	95.88
55	94.68	96.92	96.70	94.38	96.34	95.78	95.80
60	94.63	96.86	96.83	94.23	96.48	95.60	95.77
+ 5	89.60	91.76	93.72	88.30	92.04	90.24	90.94
+10	88.35	90.71	93.12	86.84	90.60	87.76	89.56
+15	86.70	90.88	92.80	86.34	90.05	87.30	89.01

APPENDIX 35

Arm temperature, ^{o}F, for condition 2

Time	Subject 1	2	3	4	5	6	Mean
-15	92.62	88.56	91.74	86.58	89.85	93.18	90.42
-10	92.20	88.24	91.84	86.08	89.36	92.80	90.09
- 5	91.88	88.24	91.36	86.08	89.30	92.71	89.93
0	***	***	***	***	***	***	***
5	97.42	94.86	96.82	90.35	94.76	97.22	95.24
10	97.60	95.94	97.60	92.64	96.10	97.60	96.25
15	97.39	96.56	97.80	93.89	96.73	97.25	96.60
20	97.26	96.48	97.77	94.76	96.83	97.18	96.71
25	96.86	96.86	97.96	95.10	96.99	97.37	96.86
30	96.38	97.00	97.76	95.10	96.99	97.06	96.72
35	96.14	96.93	97.96	95.07	96.58	96.50	96.53
40	96.03	97.03	98.02	94.86	96.62	96.01	96.43
45	95.76	97.14	98.11	94.57	96.76	95.56	96.32
50	95.83	97.10	98.28	94.32	96.75	95.83	96.35
55	95.94	97.25	98.36	94.23	96.86	96.03	96.44
60	95.86	97.10	98.55	93.92	96.90	95.98	96.39
+ 5	89.32	92.32	94.61	88.54	93.46	91.22	91.58
+10	86.22	91.07	93.46	86.28	91.40	88.88	89.55
+15	85.46	90.70	93.23	86.10	90.30	87.74	88.92

APPENDIX 36

Arm temperature, ^{o}F, for condition 3

Time	Subject 1	2	3	4	5	6	Mean
-15	89.34	90.10	91.85	89.46	92.10	89.69	90.42
-10	89.98	90.70	92.26	88.74	92.23	89.53	90.57
- 5	90.16	91.62	91.86	88.58	92.21	89.70	90.69
0	***	***	***	***	***	***	***
5	97.50	95.90	96.22	93.69	96.37	95.50	95.86
10	97.83	96.86	97.37	95.60	96.94	96.76	96.89
15	97.50	96.63	97.68	96.32	97.37	96.83	97.06
20	97.07	96.85	97.49	96.44	97.74	95.72	96.89
25	96.80	96.74	96.73	96.00	97.48	95.76	96.59
30	96.30	96.30	97.33	95.44	97.78	95.85	96.50
35	95.36	96.58	97.23	94.36	97.62	95.48	96.10
40	95.04	96.98	97.08	94.23	97.35	94.77	95.91
45	94.32	96.46	96.85	94.42	97.37	94.72	95.69
50	94.60	96.62	96.86	93.71	97.21	94.84	95.64
55	93.80	96.60	96.83	94.50	97.29	94.38	95.57
60	93.64	96.10	96.77	93.46	96.94	94.34	95.21
+ 5	87.52	93.01	94.24	89.74	93.82	90.12	91.41
+10	85.49	93.22	93.10	87.48	93.33	88.31	90.16
+15	83.97	92.92	92.89	87.05	93.66	87.20	89.62

APPENDIX 37

The volume of supplied air was measured by setting an air meter near the neck cross sectional area of the helmet part of the compressed air line jacket, 801-NA Neoppene-Nylon Canopy (without vortex-tube) or 3M Backpack system. Since we can tighten the rope and let the supplied air come out only through the air meter, the volume of supplied air passing through the limited neck cross sectional area is calculated by the following formula:

$$Q = A \cdot V$$

where,

Q = the volume of cooled air supplied from a compressed air line system or supplied air from 3M Backpack system

A = area of that the supplied air flows through
= area of the air meter (model W131)
$= \pi r^2 = 3.1415\ (0.105\ m/2)^2 = 0.00866\ m^2$

V = air velocity recorded from the air meter

APPENDIX 38

Volume and temperature of air and amount of ice supplied during the heat stress period for subject 1 & 2

	Condition		
	Water-cooling + 3M Backpack system	No Cooling	Water-cooling + Compressed air line
	Subject 1 (Subject 2)	Subject 1 (Subject 2)	Subject 1 (Subject 2)
1. Temp. of heat stress period	34.9±0.9°C (34.8±0.8°C)	36.0±1.0°C (35.5±0.5°C)	35.8±0.7°C (35.6±0.6°C)
2. Humidity of heat stress period	50-57% rh (58-63% rh)	50-58% rh (53-58% rh)	50-56% rh (47-54% rh)
3. Volume of air supplied	0.309 m^3/min (0.333 m^3/min)	none (none)	0.333 m^3/min (0.333 m^3/min)
4. Temp. of air supplied	34.9°C (34.8°C)	none (none)	28.9°C (32.8°C)
5. Humidity of air supplied	50-57% rh (58-63% rh)	none (none)	46% rh (46% rh)
6. Amount of ice initial inserted	1.82 kg (1.82 kg)	none (none)	1.82 kg (1.82 kg)
7. Additional load carried by subj.	12.5 kg (12.5 kg)	none (none)	6.1 kg (6.1 kg)

APPENDIX 39

Volume and temperature of air and amount of ice supplied during the heat stress period for subject 3 & 4

	Condition		
	Water-cooling + 3M Backpack system	No Cooling	Water-cooling + Compressed air line
	Subject 3 (Subject 4)	Subject 3 (Subject 4)	Subject 3 (Subject 4)
1. Temp. of heat stress period	$36.2 \pm 0.5^{\circ}C$ ($35.9 \pm 0.9^{\circ}C$)	$35.0 \pm 1.0^{\circ}C$ ($34.5 \pm 0.5^{\circ}C$)	$35.6 \pm 1.1^{\circ}C$ ($34.8 \pm 0.8^{\circ}C$)
2. Humidity of heat stress period	50-54% rh (52-59% rh)	50-58% rh (46-53% rh)	50-56% rh (54-60% rh)
3. Volume of air supplied	$0.346\ m^3/min$ ($0.346\ m^3/min$)	none (none)	$0.309\ m^3/min$ ($0.361\ m^3/min$)
4. Temp. of air supplied	$36.2^{\circ}C$ ($35.9^{\circ}C$)	none (none)	$29.4^{\circ}C$ ($29.4^{\circ}C$)
5. Humidity of air supplied	50-54% rh (52-59% rh)	none (none)	47% rh (49% rh)
6. Amount of ice initial inserted	1.82 kg (1.82 kg)	none (none)	1.82 kg (1.82 kg)
7. Additional load carried by subj.	12.5 kg (12.5 kg)	none (none)	6.1 kg (6.1 kg)

APPENDIX 40

Volume and temperature of air and amount of ice supplied during the heat stress period for subject 5 & 6

	Condition		
	Water-cooling + 3M Backpack system	No Cooling	Water-cooling + Compressed air line
	Subject 5 (Subject 6)	Subject 5 (Subject 6)	Subject 5 (Subject 6)
1. Temp. of heat stress period	35.3±0.9°C (35.5±0.5°C)	35.8±0.2°C (34.8±0.8°C)	34.8±0.8°C (35.6±0.5°C)
2. Humidity of heat stress	48-52% rh (53-60% rh)	55-59% rh (56-63% rh)	55-59% rh (49-55% rh)
3. Volume of air supplied	0.394 m^3/min (0.361 m^3/min)	none (none)	0.346 m^3/min (0.333 m^3/min)
4. Temp. of air supplied	35.3°C (35.5°C)	none (none)	31.1°C (31.1°C)
5. Humidity of air supplied	48-52% rh (53-60% rh)	none (none)	50% rh (47% rh)
6. Amount of ice initial inserted	1.82 kg (1.82 kg)	none (none)	1.82 kg (1.82 kg)
7. Additional load carried by subj.	12.5 kg (12.5 kg)	none (none)	6.1 kg (6.1 kg)

AN EVALUATION OF COMBINED AIR-COOLING AND WATER-COOLING FOR NON-PERMEABLE CLOTHING

by

I-CHUNG WANG

B. Sc. (Engg), Che. E., Tunghai University, Taiwan (ROC) 1977

AN ABSTRACT OF A MASTER'S THESIS

submitted in partial fulfillment of the

requirements for the degree

MASTER OF SCIENCE

Department of Industrial Engineering

KANSAS STATE UNIVERSITY
Manhattan, Kansas

1980

ABSTRACT

This investigation attempts to assess the effects of wearing protective clothing in a hot environment (35°C dry bulb and 55% rh). The aim was to provide better protection for workers in the nuclear, chemical and metal-refining industries where man is exposed to an increasing number of hostile environments such as chemical, particulates or radiation as well as heat stress.

In this study, the primary objective was to evaluate combined water-cooling with compressed-air line or a 3M Brand Whitecap Helmet (which can be used in a remote area) vs no external cooling.