AN EVALUATION OF AN AIR VENTILATED JACKET
IN A HEAT STRESS ENVIRONMENT

by 1264

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INTRODUCTION

Since the current model of human organism is the result of evolutionary processes over millions of years, it has developed substantial adaptability to the environmental variables within the world in which we live, including its atmosphere. There are however, certain natural environmental conditions that are outside the repertoire of the human being's range of adaptability. In addition to the environments to which a man is exposed in his everyday activities, science and technology are busy developing new kinds of environments for him, including capsules for the outer space, as well as for more mundane situations such as blast furnaces, cold storage warehouses, and underwater caissons for use in building bridges. Making the environment comfortable for working is of fundamental importance in human engineering.

Of the various atmospheric variables, the ubiquitous combination of temperature and humidity and associated factors related to human thermal equilibrium probably is of most universal concern.

Heat, associated with high humidity, is found in laundries, paper mills, textile mills, and canneries. Heat, associated with low humidity, is common in metal industries, such as steel mills, foundries, and reduction plants. Mining and chemical industries can present either of the above conditions according to the operations performed and climatic locations. Hot environments are also 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 hot, dry, desert climate to the hot, humid, jungle type of a climate, and where 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 may sometimes be similar, the threat to thermoregulation may depend on different principles in the two situations.

From an engineer's point of view, the human body may be likened to a heat engine. The body functions to convert 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. With the human body, the heat rejection occurs primarily from the body surface. Through blood circulation, heat is transferred to the skin and from skin it is transferred to the environment.

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 of approximately 81-86 F (27-30 C) (Threkeld 1962). On the warmer 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 greater 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 evaporative regulation. 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.

Often, it is not feasible nor economical to air condition the hot humid environment. In this environment, with no air conditioning, the human body tries to maintain the body equilibrium temperature by sweating and consequently evaporation of sweat. Since the sweat will not evaporate due to high humidity, the body temperature rises.

In air cooling, an air or gas ventilated garment is used. The air or gas, cooled by an external source, comes in contact with the body of the wearer. With this method, most of the heat removal takes place by the evaporation of sweat. Since heat is often associated with polluted or dirty air, air cooling has the additional advantage of furnishing clean breathing air.

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. However, heat removal also can be done by conductive cooling (Veghte 1965). In this method, the heat is removed from the body through conduction, and the subject can work comfortably without loss of body water through sweat. In the conductive method of 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. This method can be used with high temperature and high humidity and is a very effective method of cooling.

The purpose of this study was to evaluate an air ventilated jacket, and to find how effective it is in a heat stress environment of 112 F (44.4 C) and 60% R. H.

LITERATURE REVIEW

Most of the studies conducted in the area of individual cooling with air ventilated garments have been conducted by defense organizations in various countries. Crockford, Hellon, Humphreys, and Lind (1961) evaluated the performance of an air ventilated suit for wear in a very hot environment. The ventilated suit assembly was comprised of two special garments:

(1) An undergarment made of a double layer of plastic film, the two layers separated by a loose plastic "space filter", the purpose of which was to distribute the ventilating air over a large area of skin. The garment covered the trunk and the legs.

(2) An outer garment made of impermeable but pliable material, with an attached cylindrical helmet made of double layer of clear plastic with an intervening air space. The design was such that only a portion of ventilating air was delivered through the hose to the space between the two layers of plastic film comprising of the undergarment. The air then passed through numerous holes in the inner layer of the undergarment to ventilate the skin. The rest of the air escaped in the outer layer.

Fifteen men, wearing an air ventilated clothing assembly, were exposed to an ambient temperature of 178 F (81 C). The suit was ventilated with dry air at volumes between 10-25 cfm (0.29-0.72 m^3) at a temperature between 86 F (30 C) and 100 F (38 C). At ventilating volumes of 15 cfm (0.43 m^3) and over, the subjects were able to establish body thermal equilibrium within an hour, irrespective of the temperature of the air delivered to the suit.

Thermal equilibrium was never achieved when 10 cfm (0.29 m^3) of air was supplied.

The above study was extended by Crockford and Hellon (1964) who conducted a series of experiments in which they tested various types of materials for thermal conductance. The following materials were tested:

(1) A foamed plastic covered on both sides with neoprene-coated terylene with total thickness of 1/4" (6 mm).

(2) A radiant heat barrier constructed from string vest material 1/8" (3 mm) thick, covered on both sides by aluminum foil. The radiant heat barrier so formed was in turn covered on both sides by thin cotton fabric.

(3) Three materials that appeared suitable for dynamic insulation (a) a light felt like material, (b) 1/4" (6 mm) thick double cloth that is, an outer layer of worsted fabric woven with raised woolen pile inside, and (c) 0.39" (10 mm) thick open celled polyurethane foamed plastic.

It was concluded from the experiments that application of a form of dynamic insulation in a ventilated suit may be the most efficient method of protecting men from excessive heat loads under the working conditions met in the steel industry.

In the same study in further experiments the authors tested four types of ventilated suit assemblies:

(1) A permeable suit made from 0.39" (10 mm) thick polyurethane foamed plastic bounded on each side by a layer of cotton fabric.

(2) An impermeable suit made from .39" (10 mm) thick polyurethane foamed plastic bounded on each side by impermeable neoprene proofed terylene.

(3) A radiant heat barrier suit constructed from two layers of aluminized fabric, aluminum layers facing each other separated by a spacer of string vest material. The spacers held the two layers approximately 0.39" (10 mm) apart.

(4) A suit identical to No. 3 but constructed without reflecting layers.

All suits were tested with a standard air supply of 45 cfm (1.3 m^3) at a temperature measured at a point of entry to the suit of 71-73 F (22-23 C). The chamber was designed to simulate conditions found in the steel industry; that is to provide about 392 F (200 C) mean radiant temperature and 122 F (50 C) air temperature. Air velocity was 50 ft/min (15 m).

The suits were tried on five subjects. Suit three, incorporating a radiant heat barrier, was found to be very heavy compared with the other three suits, and on this account it was discarded after two runs.

In five pairs of experiments in which the permeable suit was worn on one occasion and the impermeable suit on another, the rise of oral temperature and the sweat rate was lowest in the permeable suit. In neither suit did the subject come into thermal equilibrium as judged by their oral temperature.

In the U.S.A. Veghte (1965) studied three different air cooling systems and one water cooled system and evaluated their efficacy in cooling a person with a full pressure suit. Five subjects participated in experiments at atmospheric pressure in a 109 F (43 C) environment. The pressure suit was worn unpressurized and pressurized.

Temperature, humidity and flow rate of ventilating air were regulated by an elaborate commercial air conditioner. The air temperature and the mass air flow delivered to each system remained constant at a temperature of

70 F (21 C). During the experiment, mean skin temperature varied from a control value of 93-95 F (34-35 C) up to 97-99 F (36-37 C). Heart rate was 100 beats/min.

In the same study, when using a water cooled suit with a water temperature of 70 F (21 C) and a flow rate of 132 lbs. per hour (60 kg), skin temperature remained in the comfort range and varied between 91-93 F (33-34 C). Heart rate decreased from the original control level to near basal values. The water cooled system proved superior to all of the air ventilated systems.

A few studies have been conducted to evaluate the utility of air ventilated suits for industrial purposes. Lienhard, Hughes, and Brassette (1964) used a vortex tube to cool an individual. The equipment consisted of

(1) An enclosed vortex cooling unit attached by a belt to a man's waist,

(2) A simple air harness of perforated, flexible, noncollapsible plastic tubing worn over the upper trunk and over ordinary work clothing, and

(3) An insulated, air supplied fabric hood and vest.

Through the use of a mixing valve an output of 20 cfm (.58 m^3) of air at a temperature varying between 65-80 F (18-25 C) could be obtained from the vortex tube. The cooling system was tried on one subject in a heat stress environment of 130-136 F (54-58 C) dry bulb; 15-20% R. H., and air velocity was 50 ft/min (15.2 m). The task consisted of raising and lowering 50 pounds every five seconds. For the subject when not being cooled, the heart rate rose to 185 beats/min after 20 minutes of work, whereas when he was cooled, the peak heart rate did not rise above 160 beats/min after 40 minutes of work. During the initial 35 minutes of exposure without the cooling, the rectal temperature rose 4 F (2 C); with cooling it rose 2 F (1 C). The sweat loss decreased almost to one third with cooling, as compared to not being cooled.

In another study, Croley (1969), at the Savannah River plant of DuPont, used an air ventilated jacket on workers working in a contaminated atmosphere. The air being supplied to the garment was cooled by a vortex tube. The vortex tube was found particularly useful, because it was carried by the user by means of a harness. When the inlet air was supplied at 24 cfm (0.69 m^3) and a pressure varying from 80-100 psig, the tube delivered 16-18 cfm (0.46-0.52 m^3) of air at 50-60 F (10-16 C) colder than the inlet temperature. The equipment was found to work satisfactorily and is still being used in the plant.

In an effort to find industrial applications of cooling by a vortex tube, Van Patten and Gaudio (1968) conducted studies with a garment ventilated by a vortex tube. Three subjects were exposed to a temperature of 130 F (54 C), both with and without aircooling. The vortex tube used compressed air at a pressure of 60 psi, and delivered 10 cfm of cold air at 63 F (17 C) dry bulb and 35% R. H.

In the control session subjects were exposed for a duration determined by subjective tolerance; that is, 30-50 minutes. In the experimental session, the upper limit of exposure was arbitrarily set at a time duration 100% greater; that is, 60-100 minutes. Rectal temperature, skin temperature, and heart rate were continuously monitored before, during, and after the exposure.

The 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 subjectively well, and the physiological parameters had not approached the limit of thermal tolerance. The cooling significantly reduced the heart rate and rectal temperature. The sweat loss during the cooling session was less than that lost during the control session, but was not statistically lower.

Drake, Funk, and Moegling (1968) evaluated the Gemini and Apollo pressure suits for sensible heat exchange in environmental facilities which permitted a wide range in ambient temperatures. In both pressure suits, if sensible heat exchange is considered, the flux distribution data showed that head, hands, and feet will be cooler than the rest of the body; while the arms, legs, and trunk will be in the warmer region. The overall and regional sensible heat exchange was better for the Apollo suit than for the Gemini suit.

Burton (1965) evaluated air ventilated suits mathematically and also performed some experiments. He concluded that the maintenance of heat balance by evaporation of sweat is a powerful human thermo-regulatory mechanism which can be exploited by providing a stream of dry air over a man's body. The main disadvantage is that, in hot environments or at high metabolic rates, a high continuous sweat rate must be maintained. Such a situation is at best uncomfortable to an unacclimatized wearer, and may approach the limits of tolerance and safety. There is also the high power requirement to keep this system working constantly.

Sharma (1970) used a helmet ventilated by a vortex tube which supplied 6.5 cfm (0.18 m^3) of air at 70 F (21 C). The helmet was tested on eight subjects in a heat stress environment of 112 F (44 C), 60% R. H., and an air velocity less than 50 ft/min (15 m). Each subject was exposed to the heat stress four times; twice with the helmet and twice without the helmet. The subjects walked in the heat stress environment at an estimated metabolic rate of 860 BTU/hr (215 K cal). The subjects remained in heat stress for 45 minutes.

The helmet lowered rectal temperature, head temperature, and the ear temperature significantly ($\alpha < .05$). The heart rate and the mean skin temperature were kept lower but not significantly. There was no significant difference in creatinine concentration in the saliva with and without the helmet.

The author concluded that, if the helmet was to be used at such thermal and metabolic rates, it should be provided with higher flow rates, or the torso should be provided with some air ventilating garment to prevent the environmental heat from flowing to the body by convection and radiation.

PROBLEM

As explained in the introduction, in a hot and a humid environment such as a mine, quarry, or a steel mill it is usually not economical to air condition the environment. Under these circumstances it is beneficial to cool the individual rather than cool the environment.

The problem then is where should an individual be cooled for most effective results? Konz and Morales (1968) cooled the head, with a water cooled hood, and gave as the reasons for cooling the head:

(1) The head, which contains the heat sensitive brain, has a large constant-volume blood flow (Burton 1966).

(2) It has the highest skin temperature (Winslow & Herrington 1949).

(3) The tissue insulation is relatively constant over a wide range of temperatures (Froese & Burton 1957).

(4) A majority of people are accustomed to having the head colder than the body through the use of clothing.

(5) Since the arms, legs and torso are not encased, mobility is good.

There are certain disadvantages in cooling the head with a stream of cold air:

(1) The noise of the air makes it difficult to communicate with wearer. It is possible to have an intercommunication system but this will increase the cost of equipment.

(2) Unmuffled noise of a vortex tube (Croley 1969), like that of the compressed air delivered by an open end tube, can cause headache, ear ringing, and nausea in less than two hours to a person using

this equipment (Fleming, D'Alonzo, and Zapp, 1954).

Keeping these difficulties in view it was decided to cool the torso and arms of the subject. The design of the jacket also cools a part of the neck and a little portion of the back of the head (see page 31). The jacket was supplied cold air from a vortex tube, details of which have been explained in the apparatus section.

The following seven criteria were used:

1. Mean skin temperatures under the jacket
2. Mean skin temperatures not under the jacket (the leg temperatures)
3. Head temperatures
4. Ear canal temperatures
5. Rectal temperatures
6. Heart rate
7. Sweat loss

The values for the increase were taken by comparison with the basal values which were taken in the neutral environment, prior to entry into the heat stress environment.

METHOD

APPARATUS:

Environmental test chamber:

The tests were carried out in the Kansas State University - American Society of Heating, Refrigeration and Air Conditioning Engineers Institute for Environmental Research test chamber.

As described by Jaax (1967) the chamber consists of two rooms, the test chamber and the pretest room. The test room is 12 x 24 ft (3.7 x 7.3 m) and its ceiling height is adjustable from 8 to 11 ft (2.4 to 3.4 m). All its interior surfaces are constructed of aluminum panels. The surface temperature of the panels is controlled by circulating chilled or heated water through copper tubes attached to the back of each panel. A system of mixing valves provides water at the required temperature which is then circulated in copper tubes at the back of the panels. Four independent circuits are available; two for the walls and one each for the ceiling and the floor. It is possible to obtain surface temperatures in the range of 40-150 F (4-65 C). The panel temperatures are monitored by thermocouples at each panel that sense the water temperature. A composite average temperature for each wall, ceiling and floor is displayed by an indicating potentiometer and a multipoint recorder.

Conditioned air, within a range of 40-150 F (4-65 C), enters the test room through perforated inlet strips located between the panels in the ceiling and leaves at the floor through a continuous slot around the perimeter of the room. Relative humidities from 10-95% can be maintained in the test room by another system consisting of a capillary washer, an absorption dehumidifier, separate fans, ducting and heating and cooling coils. Air velocity measured by room volume changes can be varied from 15-60 fpm (.08-.31 m).

The entire system is controlled automatically from a control room adjacent to the pretest room by a combination of electronic and pneumatic control equipment. In addition to measuring interior surface temperatures and dry bulb and wet bulb temperatures, the test room has globe thermometers hanging two feet from the ceiling and located such that each covers an equivalent area of the room.

Dry bulb and wet bulb air temperature in the test room are measured continuously by a stationary ventilated psychometer. Both temperatures are recorded independently in the control room by indicating potentiometers on circular charts.

The pretest room is 24 x 9 x 8 ft (7.3 x 2.7 x 2.4 m). It can be air conditioned to a desired temperature.

Rectal probe:

A 3/32" (2.38 mm) O.D. flexible precision thermistor was inserted in the subject's anal canal to a depth of six inches to measure the rectal temperature.

Ear probe:

A flexible 3/32" (2.38 mm) O.D. thermistor was slightly modified to measure the ear canal temperature. It was slightly bent at the ends for ease of insertion and for stability. It was inserted in the subject's ear up to a depth of 1/2" (12 mm). A foam block, along with ear muffs, was used to reduce the ambient air contact with the thermistor.

Skin thermistors:

The thermistors, which have sensitive areas at the ends which are 3/8" (9.5 mm) in diameter and 1/16" (1.6 mm) thick, were placed on the skin with the sensitive side in contact with the skin. Heavy duty duct tape was used to keep them in position. Care was taken to see that the thermistors did not become loose, as they might contact ambient air and begin giving false data.

Digital thermometer and temperature recording system:

A United Systems Corporation digital thermometer which has two input channels and a printer was connected to a junction box with 20 thermistors (7 on the subject without the jacket and 13 on the subject with the jacket). The unit is fitted with a selector switch by which each thermistor is selected. The output was a printed temperature with its associated sensor number. The time was put on the tape by hand.

Heart rate recording system:

The heart rate was measured by placing three surface electrodes around the heart. The electrodes were connected to a junction box worn around the waist of the subject. The junction box was connected to a switch on a Beckman Type RS Dynograph Strip Chart Recorder. The output was a series of peaks on a continuous roll of graduated paper.

Metabolic scale:

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

The jacket:

The jacket used for the study was made from .005" polyvinyl chloride, similar in most respects to the one used by Croley (1969).* The jacket is shown in Plate V. Snyder furnishes four sizes of jackets; namely, small, medium, large, and extra large. The neck, sleeve ends, and the bottom of the jacket which were fitted with elastic were modified and fitted with draw strings. This enabled the experimenter to partially control the flow of air through the jacket. The cold air entered from the back of the jacket, circulated through it and inflated it. It was estimated that 30% of the air escaped from the hips, 50% from the neck and 20% from the sleeves. The air from the neck cooled a portion of the head. A hood was provided with the jacket, which, when used, guided the cold air escaping from the neck to cool the neck, the ears, and the head.

The vortex tube:

Cold air to the jacket was supplied by a model 8603 vortex tube assembly, manufactured by Rite Hardware Mfg. Co., Glendale, California. The vortex tube (Plate I) was fixed on subject's back by a belt. The manufacturers explain the working of the vortex tube as follows:

> The vortex tube is a simple device which, when fed compressed air, emits a stream of cold air from one end and hot air from the other. There are no moving parts and air does everything by itself.
>
> The compressed air first enters holes that inject it at sonic speed circumferentially into the large tube near one end; thereby creating a small cyclone spinning as fast as a million revolutions per minute. The center of this cyclone is cold air that flows out to whatever is to be cooled. The rest of the air twists along the tube, grows hot and leaves through a valve at the far end. The valve imposes enough pressure on the vortex to drive the desired amount of air at the cold end.

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*The jackets were bought from Snyder Manufacturing Co., Inc., New Philadelphia, Ohio.

PLATE I

Fig. 1. A view of the model 8603 vortex tube. The cold air comes from the short end. The compressed air enters from the side. The knurled knob at the end controls the volume-temperature output.

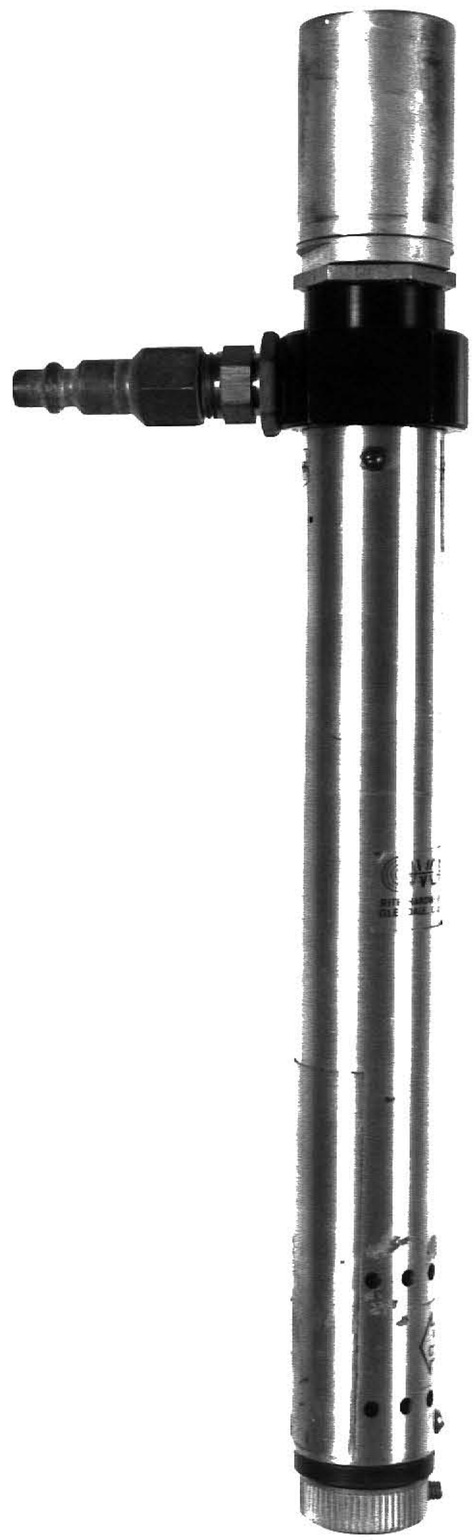

PLATE I

Four simultaneous effects are at work to produce the hot and the cold air. First the compressed air expands, cooling itself temporarily by transforming its thermal energy to mechanical energy.

Second, the air that spirals inward to the center of the cyclone tends to spin faster because of coriolis effect or conservation of angular moment. This acceleration can either be allowed or be restrained by a brake. If it is allowed, we have a runaway or free vortex that will do us no good because the air will emerge spinning with all this kinetic energy, immediately converting the kinetic energy back to heat through friction and no longer be cold. So it must be restrained and energy drained off. How this takes place is the third effect.

Third, the air in the tube is enormously turbulent and as viscous as molasses. Momentum is instantly transferred from one part to another by the myriad darting eddies of the air so that no part of the column can rotate faster than another. Therefore the high speed vortex that tries to form at the front forcibly turns the column, delivers power to it, and gets rid of its own energy. One-half horsepower is thus transferred at half a million RPM by a torque of one ounce-inch. The demonic agitation is generated by supersonic velocities, the barrage of torn boundry-layer eddies, and the repeated kicks, delivered by the nozzle jet to the revolving mass. This turns air into virtually a new state of matter during a few milliseconds of its residence within the tube. Any small object inserted in the vortex core is instantly cooled a hundred degrees Fahrenheit, revealing a heat transfer coefficient orders of magnitude higher than usually found in the flowing air, probably the greatest ever observed between air and solid.

Finally, the column of air that is being forcibly turned from the front rolls itself against the tube and heats up by friction. The hot air leaves the vortex tube with as much heat as the rest of the air leaves with cold--that is, there is an energy balance.

The vortex tube is shown in Plate I. It has a valve at the hot end which can control the split of the volume of air. The volume and temperature cannot be controlled independently.

Air measuring apparatus:

The differential pressure was measured by connecting the nozzle, shown in Fig. 3, to the vortex tube. The differential pressures, and the pressures upstream were measured by connecting the outlets to a water manometer. The procedure to calculate the volumes has been described in Appendix I.

PLATE II

Fig. 2. Rear view of subject 2 showing how the vortex tube was fitted to the subject. The hose carried the compressed air.

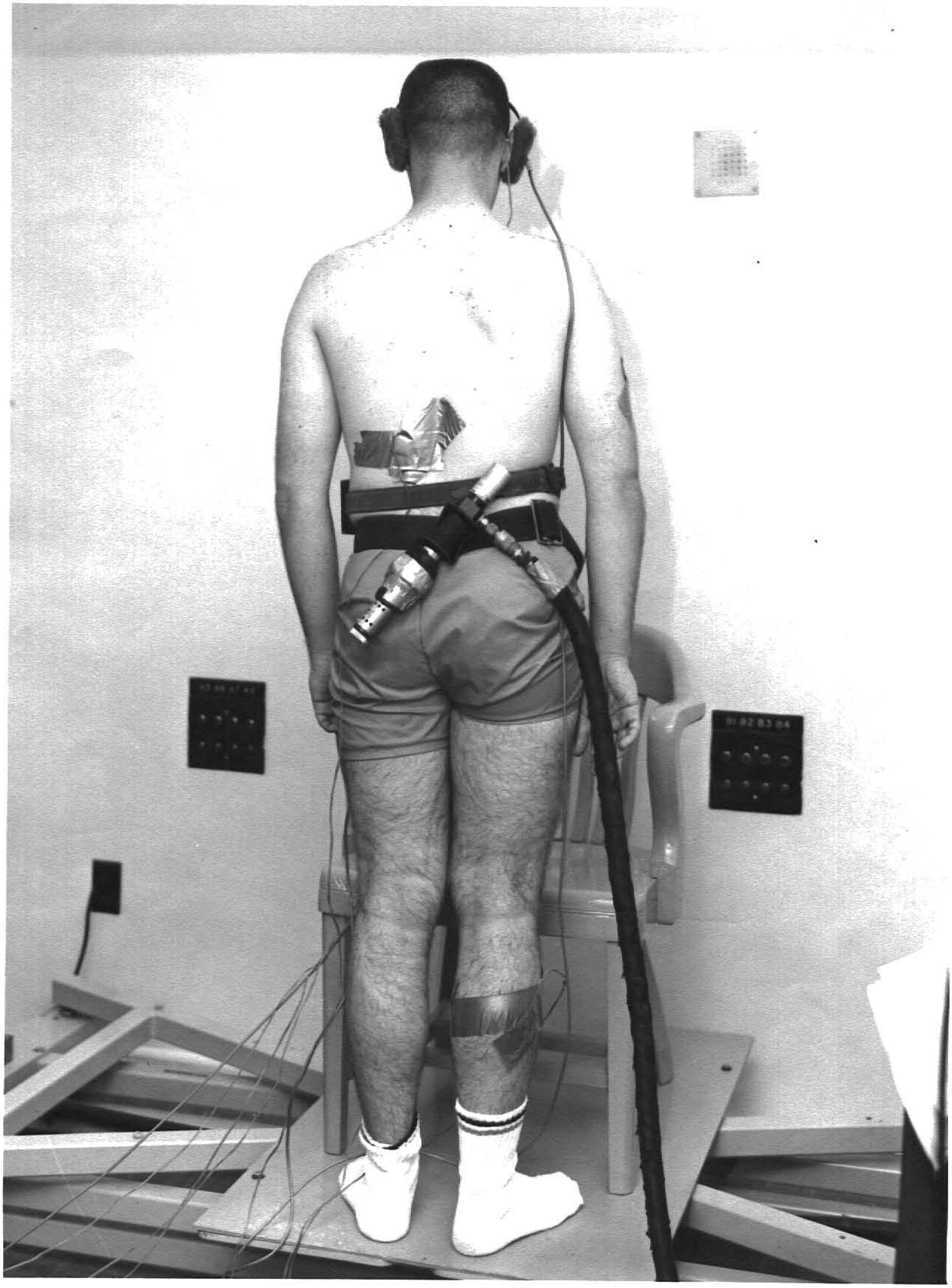

PLATE II

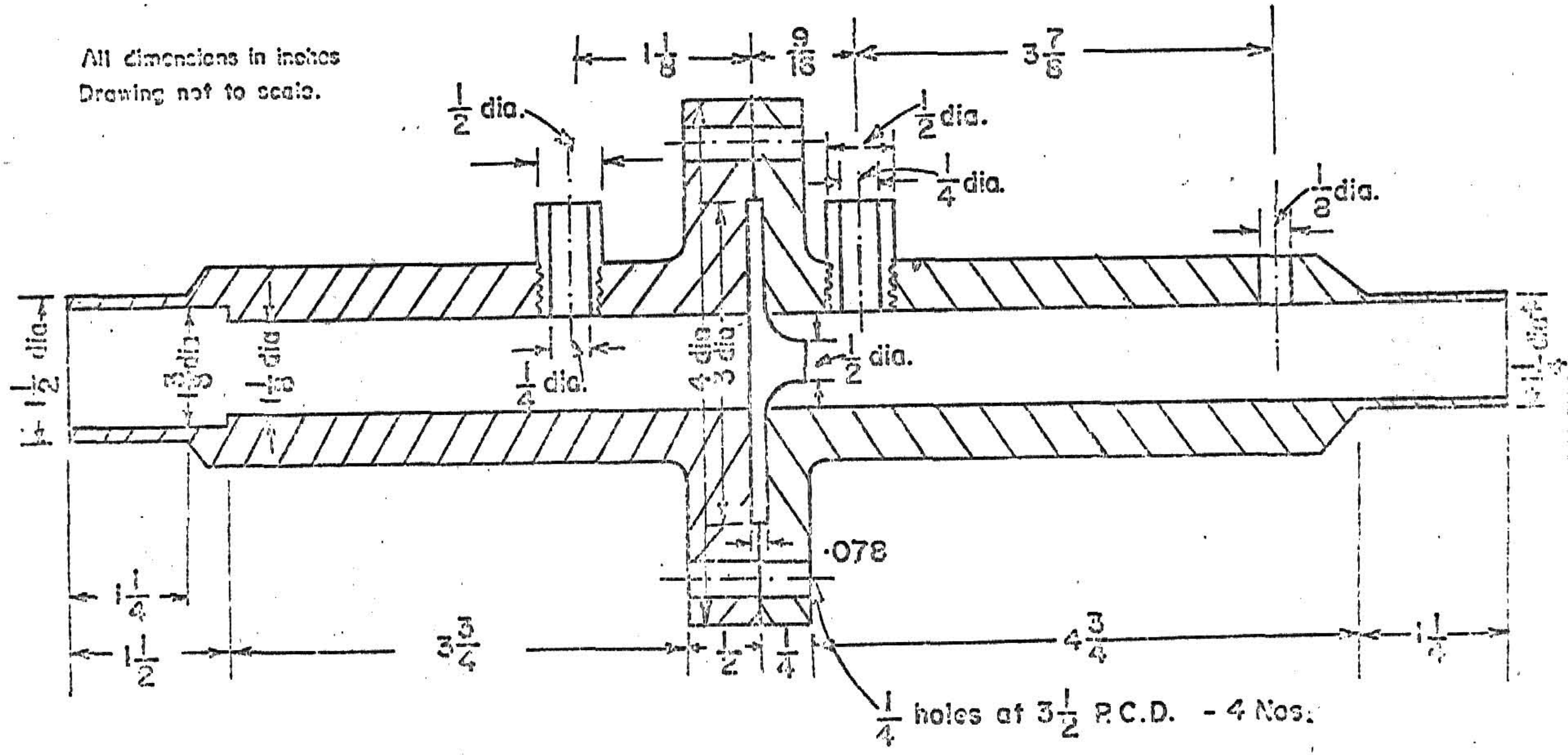

Fig. 3. Sketch of the nozzle.

Video tape equipment:

Video tape equipment consisting of a camera, video tape recorder, and a monitor were used to record and monitor the movements of the subjects when they were inside the test chamber. A wide angle lens was used in the camera to get the maximum possible view of the chamber and the subjects.

TASK:

The subjects remained in the heat stress environment for a period of 45 minutes; during this period they walked at a speed of 2 m.p.h. The floor was marked for a distance of 17 ft-6 inches, each marking being at 21" which was one step or stride. Both the subjects walked together until they reached the end of the marked area. Then they turned around and walked to the other end of the marked area. They repeated this procedure for 45 minutes. A metronome, set to give 100 beats/min., was used to pace the subjects. Walking at 2 m.p.h., according to Newburgh (1949), has a metabolic rate of 800 BTU/Hr (200 K cal) which is almost the same as the metabolic rate for moderate work at a machine or a bench. Every five minutes they stopped for approximately 30 seconds while their heart rate was recorded.

SUBJECTS:

Two male undergraduates at Kansas State University were paid to serve as subjects. Subject 1 was short and muscular and subject 2 was tall and muscular (Table 1). While in the test the subjects wore shorts and cotton socks. Both the subjects appeared to be highly motivated, and cooperated at every stage.

TABLE 1

Physical characteristics of the subjects

Subject No.	Age, Years	Height		Weight		DuBois Body Area, m^2
		Inches	Meters	Pounds	Kg	
1	20	63	1.60	115.8	52.6	1.52
2	21	70	1.78	153.8	69.9	1.90

MEASUREMENTS:

Skin temperatures:

The sensors were located as follows:

Subject without the jacket: One sensor was fixed on the left brow, left back, right arm, left thigh, and right calf. See Plate II and Plate IV. In addition, ear canal and rectal sensors were used.

Subject with the jacket: The subject with the jacket had the seven sensors mentioned above, but also had an additional sensor on the left side of the stomach. See Plate IV. There were five additional sensors to measure the temperature of the cold air ventilating the jacket and air surrounding the jacket. These sensors were fixed on the jacket and were located as follows:

(1) Two sensors, one on the inside, and one on the outside of the jacket matching with the position of the skin sensor on the back.

(2) Two sensors, one on the inside, and one on the outside of the jacket matching with the position of the skin sensor on the arm.

(3) One sensor on the inside of the jacket matching with the position of the skin sensor on the stomach.

PLATE IV

Fig. 4. Subject 2 with all the sensors when not wearing the jacket. The three heart electrodes are located around the left breast.

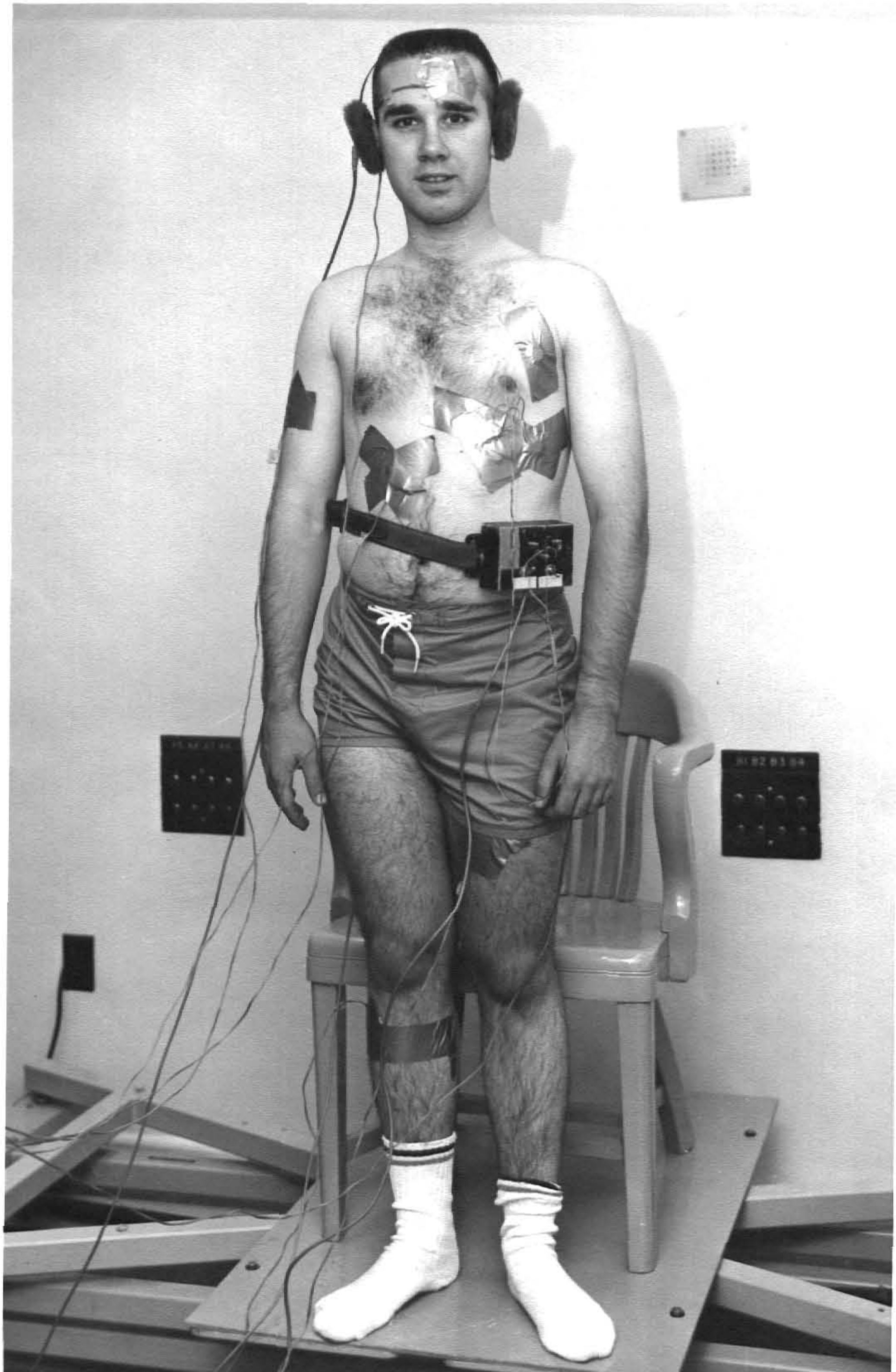

PLATE IV

Mean skin temperature was calculated for the subject without the jacket by taking an average of temperatures indicated by the sensors on the back and the arm. For the subject with the jacket, it was calculated by taking an average of the temperatures indicated by the sensors on the back, arm, and the stomach. With and without the jacket, the leg temperature was calculated by taking an average of the temperatures indicated by the sensor on the calf and the thigh.

The mean temperature of the ventilating air was calculated by taking an average of the three sensors which were located inside the jacket, one each near the stomach, near the back, and near the arm.

The mean temperature of the ambient air surrounding the jacket was calculated by taking an average of the temperatures indicated by the two sensors located on the outside of the jacket.

Temperatures were recorded every five minutes during pretest, stress, and recovery periods.

Volume of air being delivered by the vortex tube:

As explained in the apparatus section, the vortex tube has a valve which controls the volume-temperature of cold air. Some experiments were performed on the vortex tube prior to the study by observing the temperatures and the volumes at each setting of the valve and calculating the heat losses. It was predicted that optimal heat removal occurs when the valve is open 3/4 turn. Taking the observations as the basis it was decided to operate the valve at three positions, and this was referred to as high, medium, and low volume. Table 2 shows the valve positions and the volumes delivered at these positions. It should be emphasized that temperature and volume delivered from the vortex tube are not independently adjustable.

TABLE 2

Valve positions and the volumes delivered by the vortex tube

Valve Position	Quantity of Cold Air in Cfm	Temperature of Cold Air	
1/2 turn open	5-6 Cfm	80 F (26.6 C)	High Volume
3/4 turn open	4-5 Cfm	70 F (21.1 C)	Medium Volume
1 turn open	3-4 Cfm	62 F (16.6 C)	Low Volume

These target volumes and valve positions were set during the three different days when the subjects wore the jacket. The actual volumes determined each time have been shown in Results. The details of measuring the volume of air have been explained in Appendix I.

Relative humidity of the cold air coming out of the vortex tube:

By measuring the dry bulb and wet bulb temperatures of the cold air coming from the vortex tube, the R. H. of the air was determined.

Sweat loss:

The sweat loss was determined by weighing the subjects nude before they went into the test chamber and after the end of the recovery period. The difference in these two weights was added to the weight of the soft drinks taken by the subjects to give the sweat loss. The subjects were given cold drinks (7 Up or Coca Cola) whenever they wanted them.

Body area:

The height and weight of the subjects was taken, and the body area, using the DuBois formula, was determined in square meters.

Heart rate:

Three surface electrodes were fixed on the subject's chest. These were connected to a junction box tied around the waist with a belt. The junction box was connected to a strip chart recorder, which gave the heart beat in form of peaks on a continuous roll of graduated paper. The heart was monitored during the experiment every five minutes, and the time and the subject was written on the paper by the operator. Another junction box incorporating a switch was also provided to alternatively record the heart rate data for subject 1 and subject 2 (Fig. 5).

Urine and saliva samples:

The urine and saliva samples were collected three times each day; once during the pretest period, once when the subjects were about to come out of the test chamber, and once during the recovery period.

The subjects were asked to chew mints or lemon drops for one minute, then spit out the drop, and then discharge saliva for one minute into the test tube. The time was measured with a stop watch. The volume of saliva samples was not recorded due to an error in communication with the laboratory. The test tubes were marked with the name of the subject, the day, and the period during which the sample was collected (pretest, stress, or recovery).

For the urine samples, the subjects were asked to empty their bladder completely into a beaker. The total volume of the urine was measured in millilitres in a measuring jar, and a part of it was placed in a test tube. The test tube was marked with the name of the subject, the day, period during which the sample was collected, and the volume of the urine in millilitres. The samples were collected on all the six days of the experiment and were sent to Department of Infectious Diseases, Kansas State University, for

PLATE V

Fig. 5. Subject 2 wearing the jacket. He is holding the junction box for temperature sensors. Subject one without the jacket is holding the changover switch for the heart sensors. Subject one is wearing the junction box of the heart sensors on his waist.

PLATE V

analysis. The samples were analysed for quantity of creatinine, in mgs/ 100 mls.

EXPERIMENTAL PROCEDURE:

Each subject was tested in the heat stress environment for 45 minutes each day for six days. Table 3 shows the experimental design.

TABLE 3

Experimental design

Day	Date	Subject 1	Subject 2
Wednesday	7/23/69	NJ	J (Low Volume)
Thursday	7/24/69	J (High Volume)	NJ
Friday	7/25/69	NJ	J (Medium Volume)
Monday	7/28/69	J (Medium Volume)	NJ
Tuesday	7/29/69	NJ	J (High Volume)
Wednesday	7/30/69	J (Low Volume)	NJ

NJ - WITHOUT JACKET

J - WITH JACKET

The high, medium, and low volumes refer to the volume of the cold air delivered by the vortex tube to the subject wearing the jacket.

Before starting the actual experiment a pilot study of the project was carried out on 7/22/69, and all the instruments were found to work properly. The pilot study was a great help and it removed many problems which were difficult to foresee without the pilot study.

PLATE VI

Fig. 6. The basal temperatures and the heart beat are being recorded while in the pretest room.

PLATE VI

Each day the test period was divided into the following three sessions:

Session 1: 40 minutes in the pretest room. During this period the urine and saliva samples were taken. The subjects were weighed nude, and various temperature and heart rate sensors were attached. The temperatures and heart rate were monitored every 5 minutes for the last 15 minutes.

Session 2: 45 minutes in the test chamber. Both the subjects were taken into the test chamber. The subject who was to wear the jacket was fitted with it. Both the subjects walked at a steady pace of 2 MPH paced by the metronome. Their temperatures and heart rates were monitored every 5 minutes. Their urine and saliva samples were taken before they left the test chamber.

Session 3: 30 minutes in the pretest room. During this period their heart rates and temperatures were monitored every 5 minutes for the first 15 minutes. Then their sensors were removed and they were asked to dry their bodies. They were then weighed nude. Their urine and saliva samples were taken, and they dressed.

The same procedure was followed on each day. The subjects were given soft drinks when they wanted them.

Throughout the study the test chamber was maintained at 112 F (44.4 C) dry bulb and 60% R. H. The pretest room temperature was maintained at 80 F (26.5 C).

RESULTS

The data was analyzed with a two way unequal sub-class analysis of variance on an IBM 360/50 computer. The following criteria were analyzed:

1. Mean skin temperatures under the jacket
2. Mean skin temperatures not under the jacket (the leg temperatures)
3. Head temperatures
4. Ear canal temperatures
5. Rectal temperatures
6. Heart rate
7. Sweat loss

The temperatures were the rise above the basal temperatures in a period of 45 minutes, that is, during the exposure to the heat stress. The basal readings for each subject and for each day 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 sweat losses were calculated in gms/m^2 of body area/hour. The heart rate was measured in beats/min.

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

Mean skin temperature under the jacket:

The mean skin temperature for the subject with the jacket was calculated by taking an average of temperatures on the back, arm, and the stomach. For the subject without the jacket they were calculated by taking the average of temperatures on the back and the arm.

The data for subject 2 on days 1 and 3 had to be extrapolated. The sensor at the back was not insulated properly and started registering temperature of cold air instead of the body.

The rise in the mean skin temperature during exposure over the basal (Fig. 7 and 8, and Table 4) was smallest for subject 1 at medium volume, whereas for subject 2 it was at low volume.

The analysis (Table 5) showed a significant ($\alpha < .05$) effect for treatment. Further analysis by the Duncan's New Multiple Range Test (Table 4) showed that the means of temperature rise at low, medium, and high volume did not differ significantly ($\alpha < .05$). The means of all the three volumes differed significantly ($\alpha < .05$) from the means at the no jacket condition. It can be concluded that the mean skin temperature under the jacket was lowered by air cooling at low, medium, and high volumes.

Leg temperature:

The average of the temperatures on the calf and the thigh gave the leg temperature.

The rise in the leg temperature during exposure over the basal (Fig. 9 and 10, and Table 6) was the smallest for subject 1 at medium volume, and smallest for subject 2 at low and medium volumes.

The analysis did not show any significant ($\alpha < .05$) effect.

Although not statistically significant, high volume probably was the least effective in keeping leg temperature low.

Head temperatures:

A skin sensor on the left brow measured the head temperature.

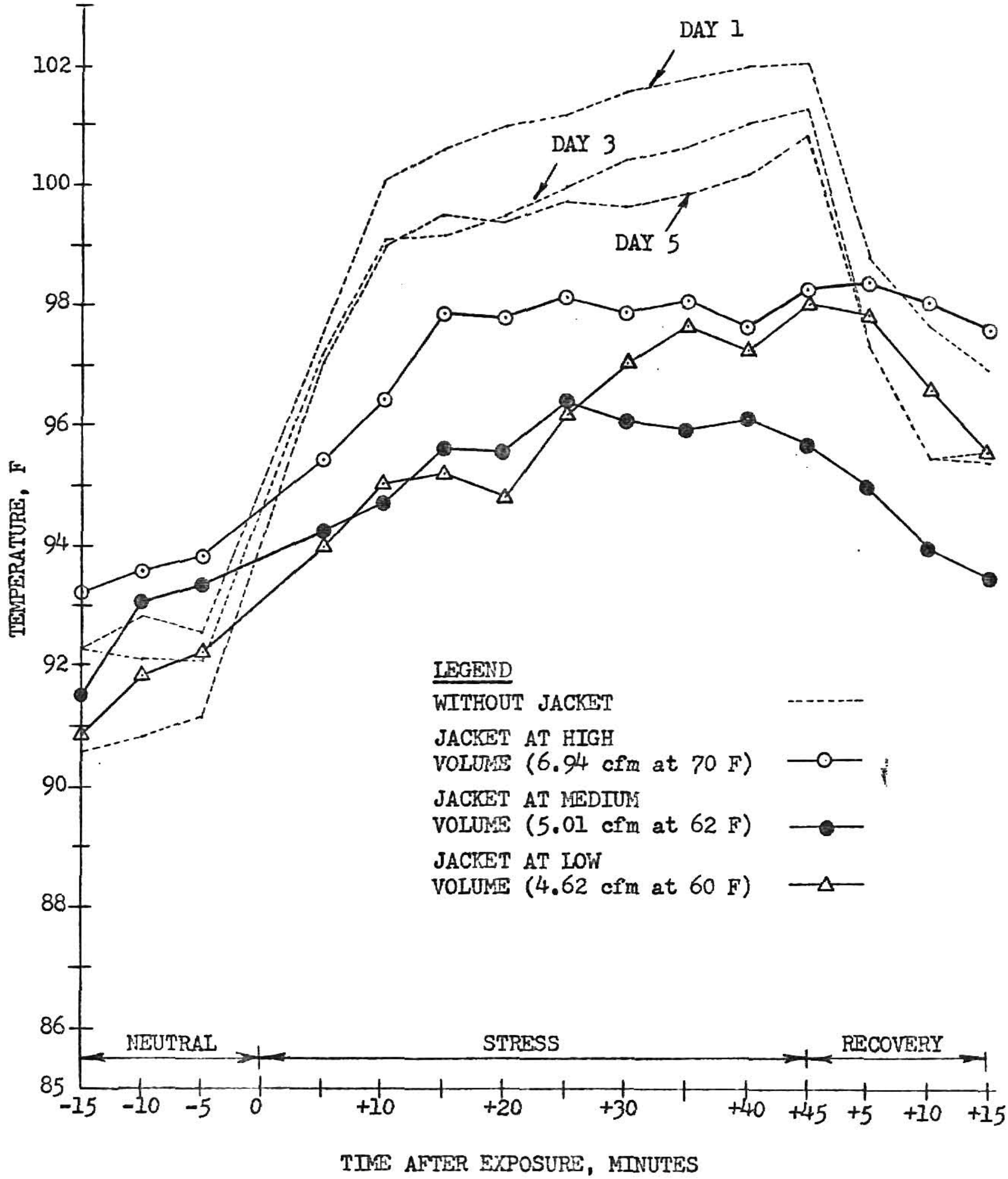

Fig 7. Mean skin temperatures under the jacket for subject 1.

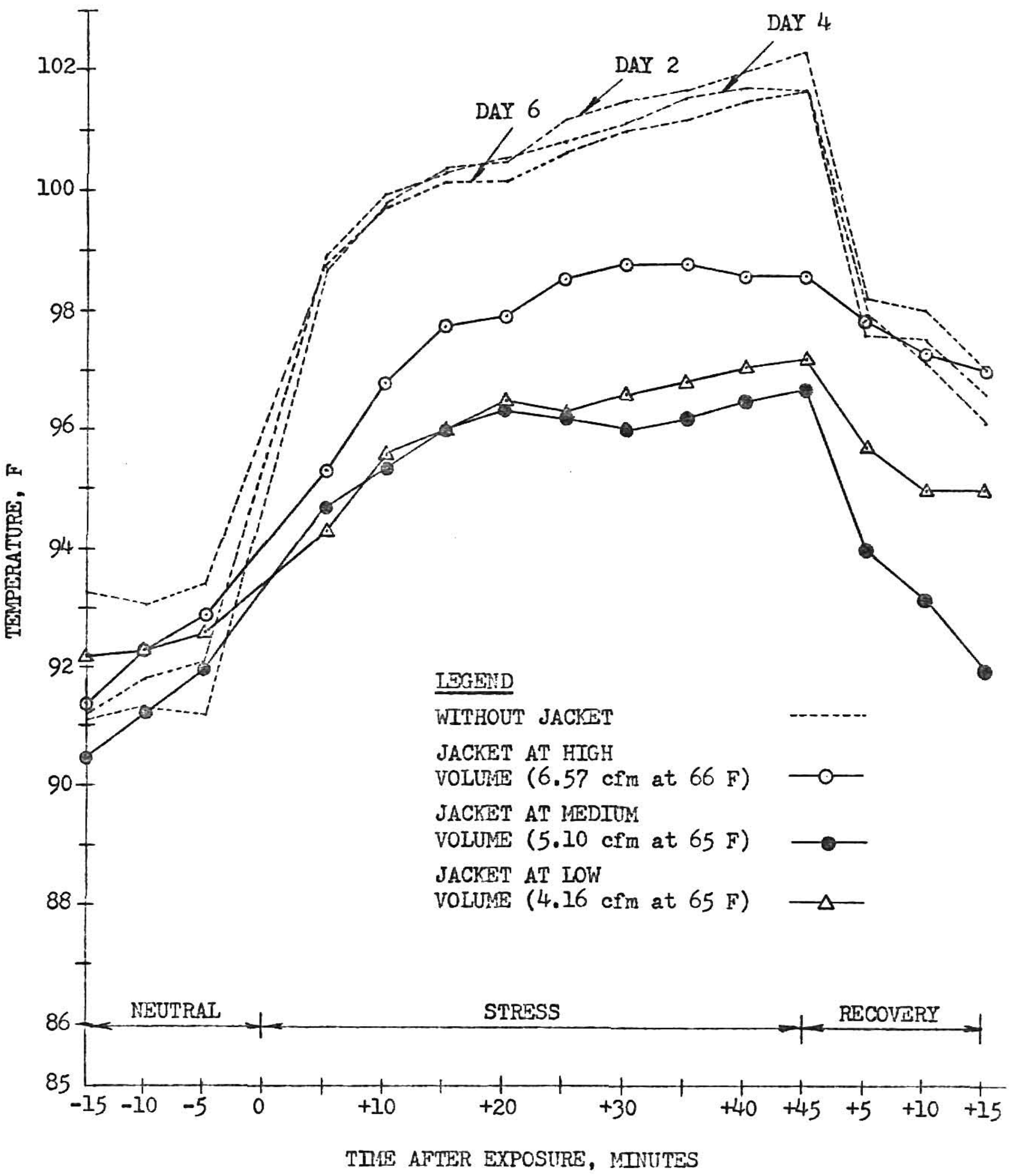

Fig. 8. Mean skin temperatures under the jacket for subject 2.

TABLE 4

Increase in the mean skin temperature (F) by condition

Subject	Medium Volume (5.1 Cfm at 64 F)	High Volume (6.8 Cfm at 68 F)	Low Volume (4.4 Cfm at 62 F)	Without Jacket
1	3.0	4.7	6.3	9.4, 9.0, 9.9
2	5.4	6.4	4.8	11.1, 10.1, 8.4
Means	4.20	5.55	5.55	9.65
	p = 2	p = 3	p = 4	
Standard error	0.862	0.862	0.862	
Least significant range	3.88 F	3.88 F	3.88 F	

The horizontal lines underline the means which are not significantly ($\alpha < .05$) different.

TABLE 5

ANOVA of mean skin temperatures under the jacket

SOURCE	D.F.	MEAN SQUARE	F-RATIO
Treatment	3	21.36	14.24*
Subject	1	1.35	0.90
Treatment x Subject	3	1.50	1.47
Residual	4	1.02	
TOTAL	11		

*Significant ($\alpha < .05$)

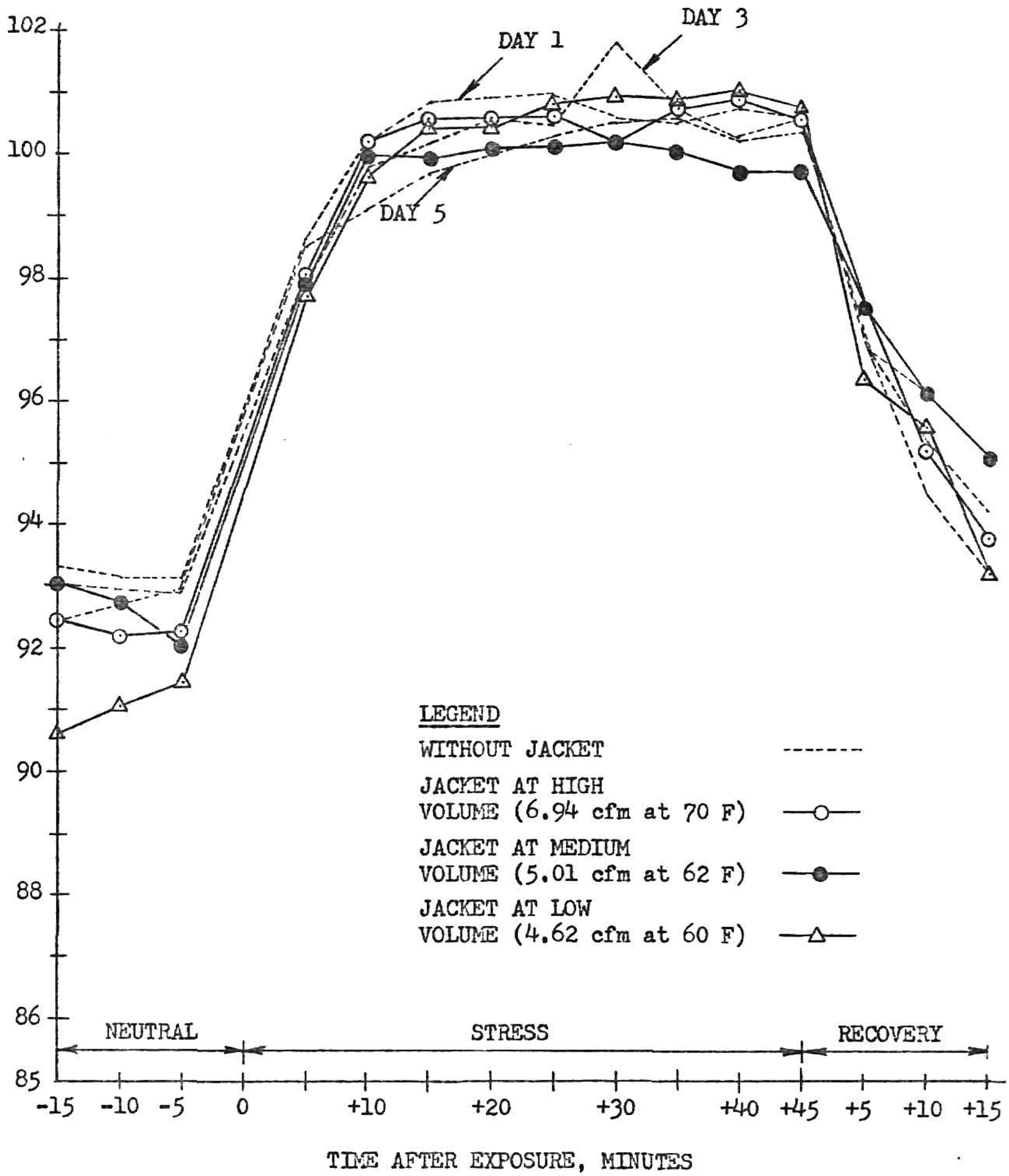

Fig. 9. Mean leg temperatures for subject 1.

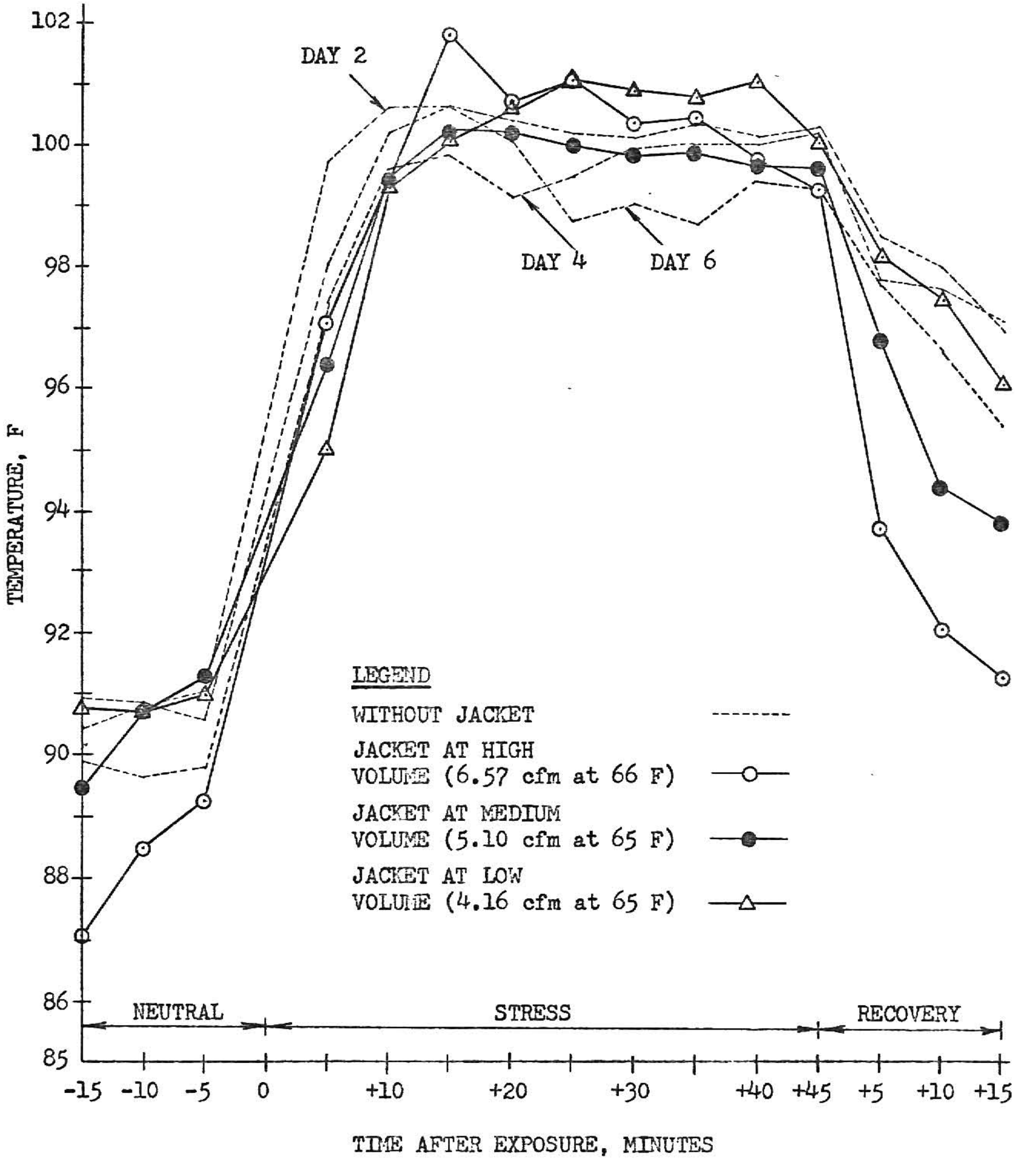

Fig. 10. Mean leg temperatures for subject 2.

TABLE 6

Increase in leg temperature (F) by condition

Subject	Medium Volume (5.1 Cfm at 64 F)	Without Jacket	Low Volume (4.4 Cfm at 62 F)	High Volume (6.8 Cfm at 68 F)
1	5.6	7.4, 7.2, 7.6	9.7	8.3
2	9.1	9.5, 10.3, 8.5	9.1	11.0
Means	7.35	8.41	9.40	9.65

TABLE 7

ANOVA of leg temperatures

SOURCE	D.F.	MEAN SQUARE	F-RATIO
Treatment	3	2.27	1.44
Subject	1	8.74	5.53
Treatment x Subject	3	1.58	3.76
Residual	4	0.42	
TOTAL	11		

The rise in the head temperature during exposure over the basal (Fig. 11 and 12, and Table 8) was smallest for subject 1 at high volume, and was smallest for subject 2 at medium volume. The means indicated that overall rise in head temperature was lowest at high volume.

The analysis did not indicate any significant ($\alpha < .05$) effect.

Ear temperatures:

The data for subject 2 on day 5 had to be extrapolated as the ear probe started registering temperature of ambient air due to inadequate sealing in the ear canal.

The rise in the ear temperature during exposure over the basal (Fig. 13 and 14, and Table 10) was smallest for subjects 1 and 2 at high volume.

The analysis (Table 11) did not indicate any significant ($\alpha < .05$) effect. Although not statistically significant, high volume probably was more effective and kept the ear canal temperature low.

Rectal temperature:

The rise in the rectal temperature during exposure over the basal (Fig. 15 and 16, and Table 12) was smallest for subject 1 at high volume, whereas for subject 2 the rise was smallest at medium volume. The means indicated that overall rise in the rectal temperature was lowest at high volume.

The analysis (Table 13) indicated a significant ($\alpha < .05$) effect for treatment x subject interaction. This can be attributed to the physiological differences among the individuals and the variation in the means of both the subjects. Although not statistically significant, medium and high volumes were probably more effective and kept the rectal temperature lower.

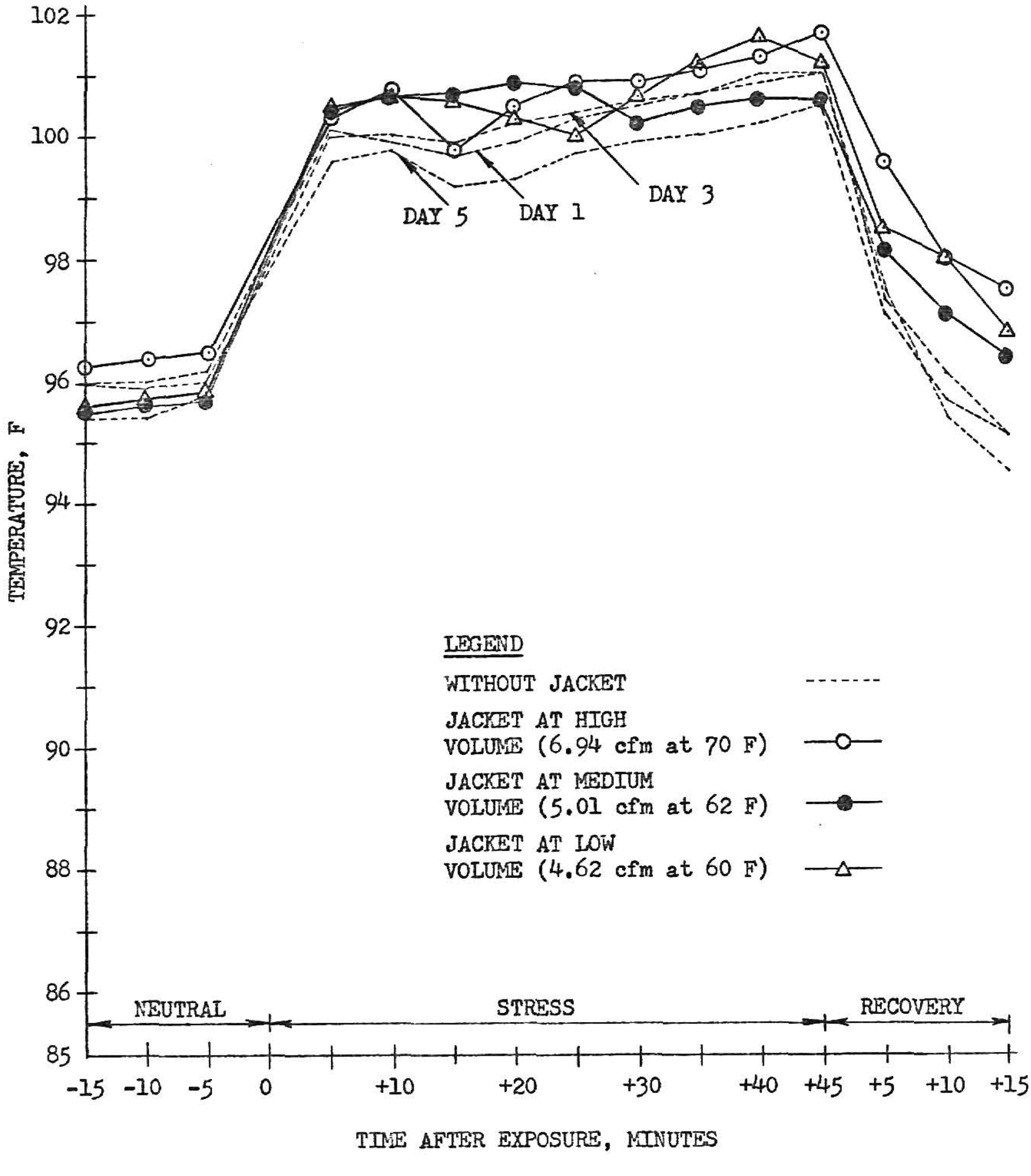

Fig. 11. Head temperatures for subject 1.

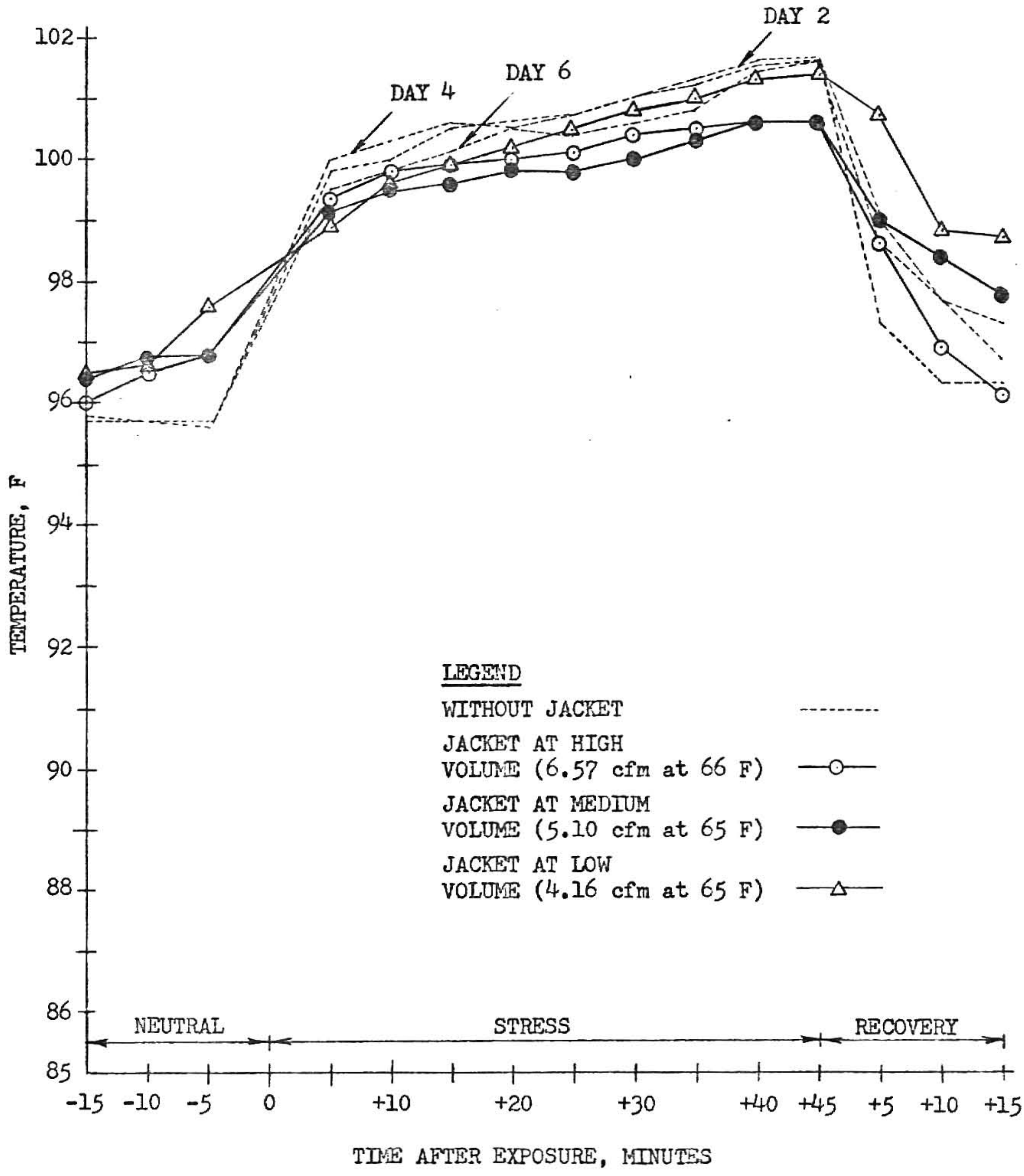

Fig. 12. Head temperatures for subject 2.

TABLE 8

Increase in head temperature (F) by condition

Subject	High Volume (6.8 Cfm at 68 F)	Medium Volume (5.1 Cfm at 64 F)	Low Volume (4.4 Cfm at 62 F)	Without Jacket
1	4.3	5.0	5.5	5.0, 4.5, 5.5
2	4.2	3.9	4.5	5.9, 5.9, 5.9
Means	4.25	4.45	5.00	5.45

TABLE 9

ANOVA of head temperatures

SOURCE	D.F.	MEAN SQUARE	F-RATIO
Treatment	3	0.98	1.27
Subject	1	0.25	0.32
Treatment x Subject	3	0.77	5.92
Residual	4	0.13	
TOTAL	11		

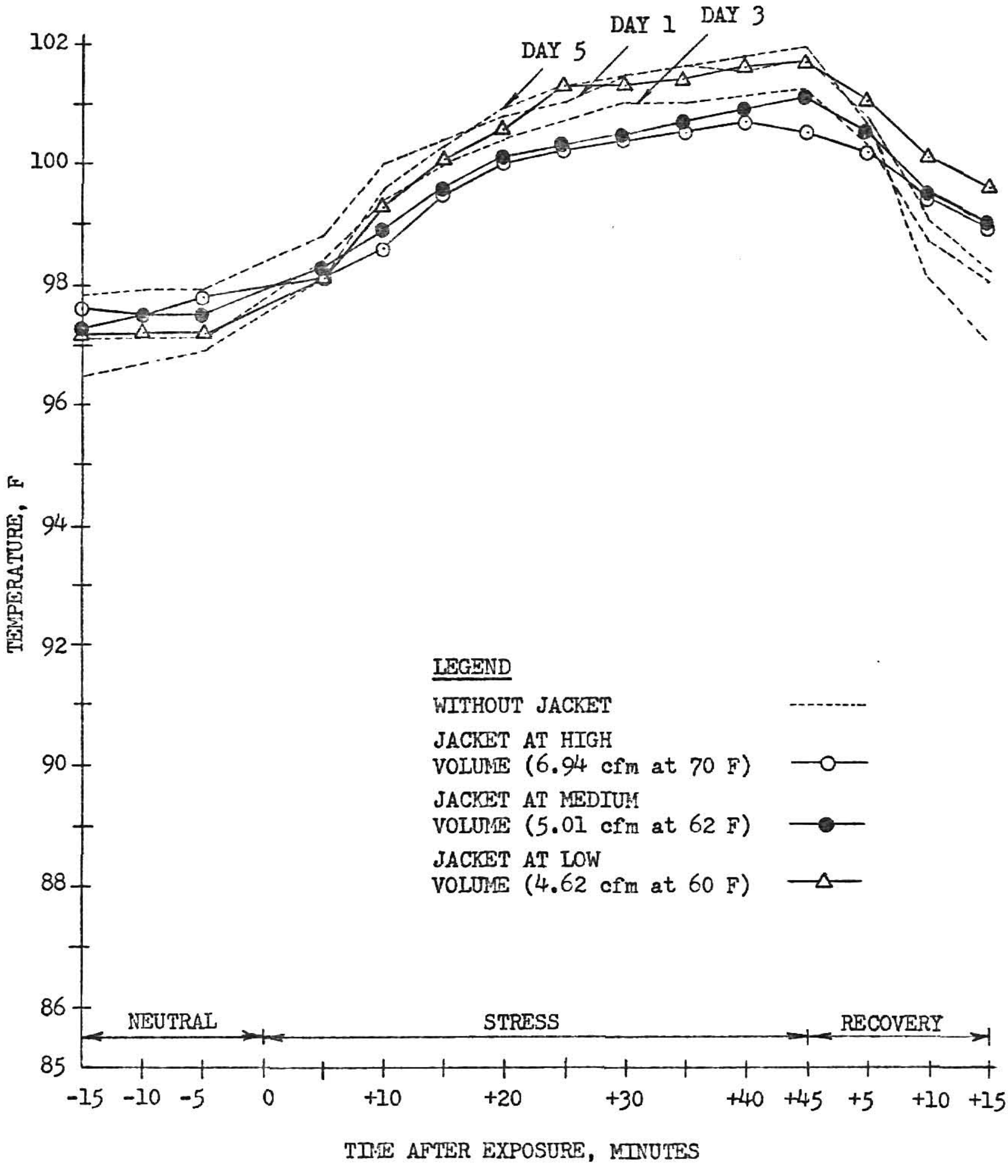

Fig. 13. Ear temperatures for subject 1.

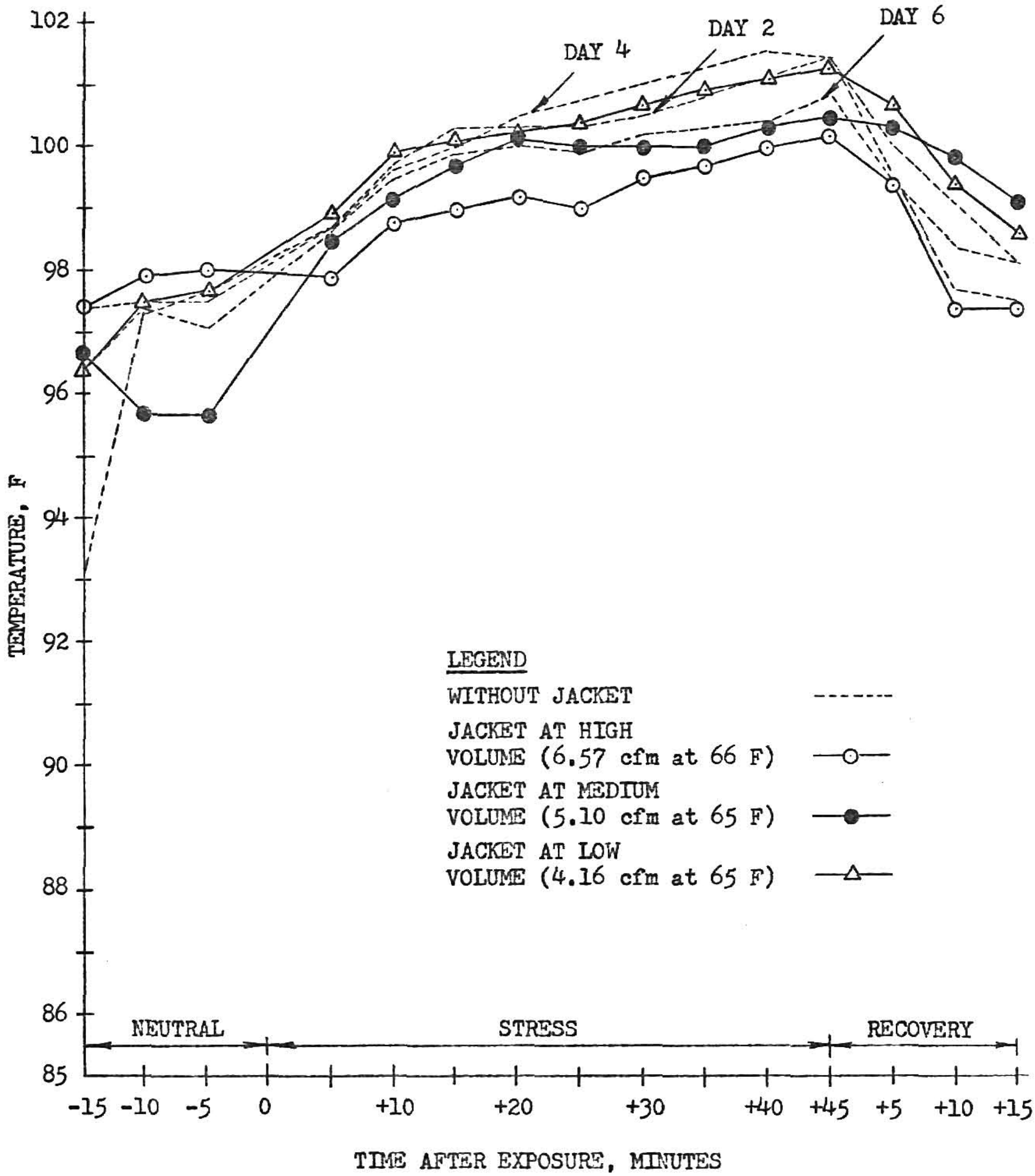

Fig. 14. Ear temperatures for subject 2.

TABLE 10

Increase in ear temperature (F) by condition

Subject	High Volume (6.8 Cfm at 68 F)	Medium Volume (5.1 Cfm at 64 F)	Low Volume (4.4 Cfm at 62 F)	Without Jacket
1	2.9	3.7	4.5	4.0, 4.1, 5.0
2	2.4	4.5	4.1	4.4, 5.5, 3.3
Means	2.65	4.10	4.30	4.40

TABLE 11

ANOVA of ear temperatures

SOURCE	D.F.	MEAN SQUARE	F-RATIO
Treatment	3	1.57	9.23
Subject	1	0.00	0
Treatment x Subject	3	0.17	0.22
Residual	4	0.75	
TOTAL	11		

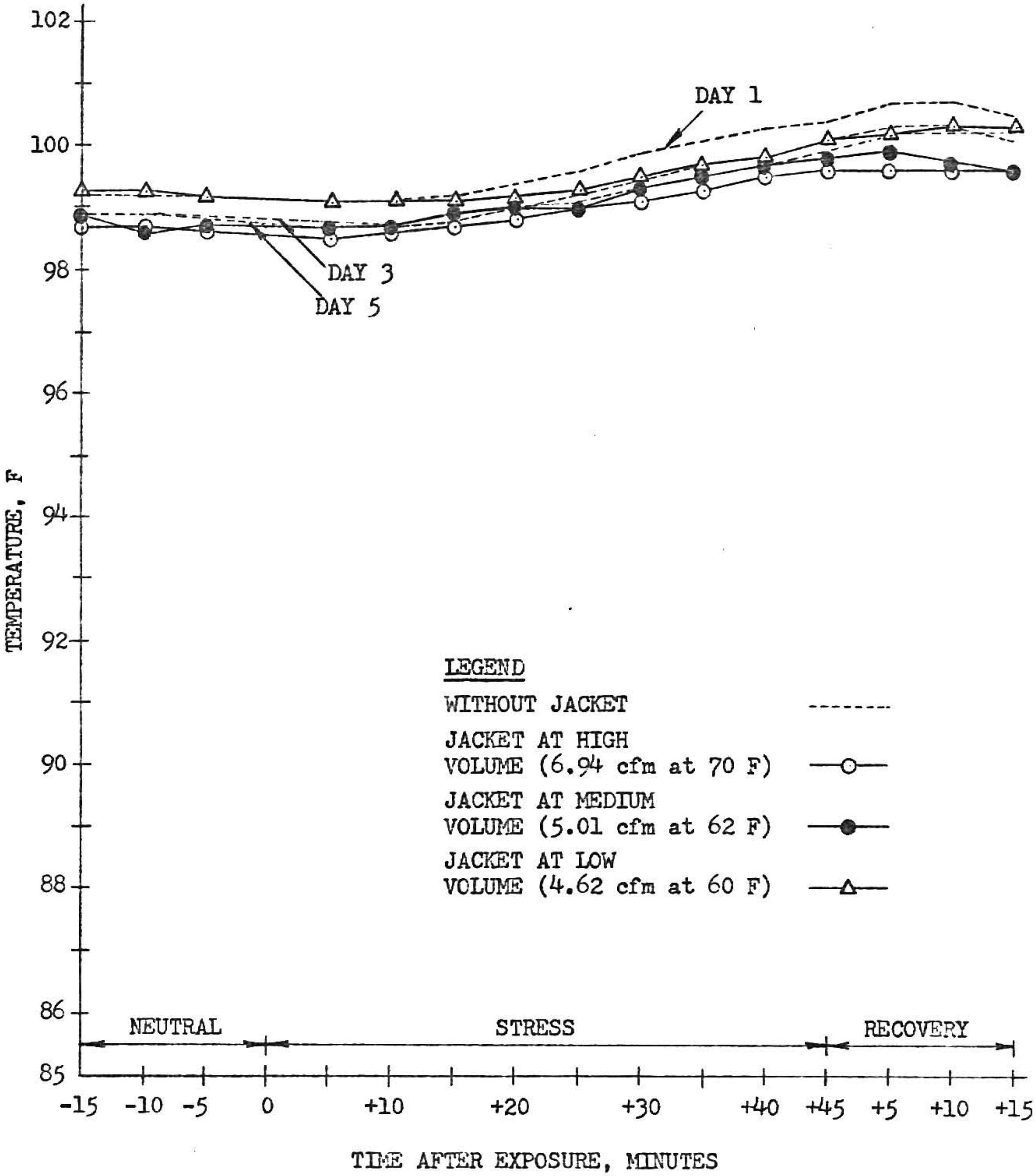

Fig. 15. Rectal temperatures for subject 1.

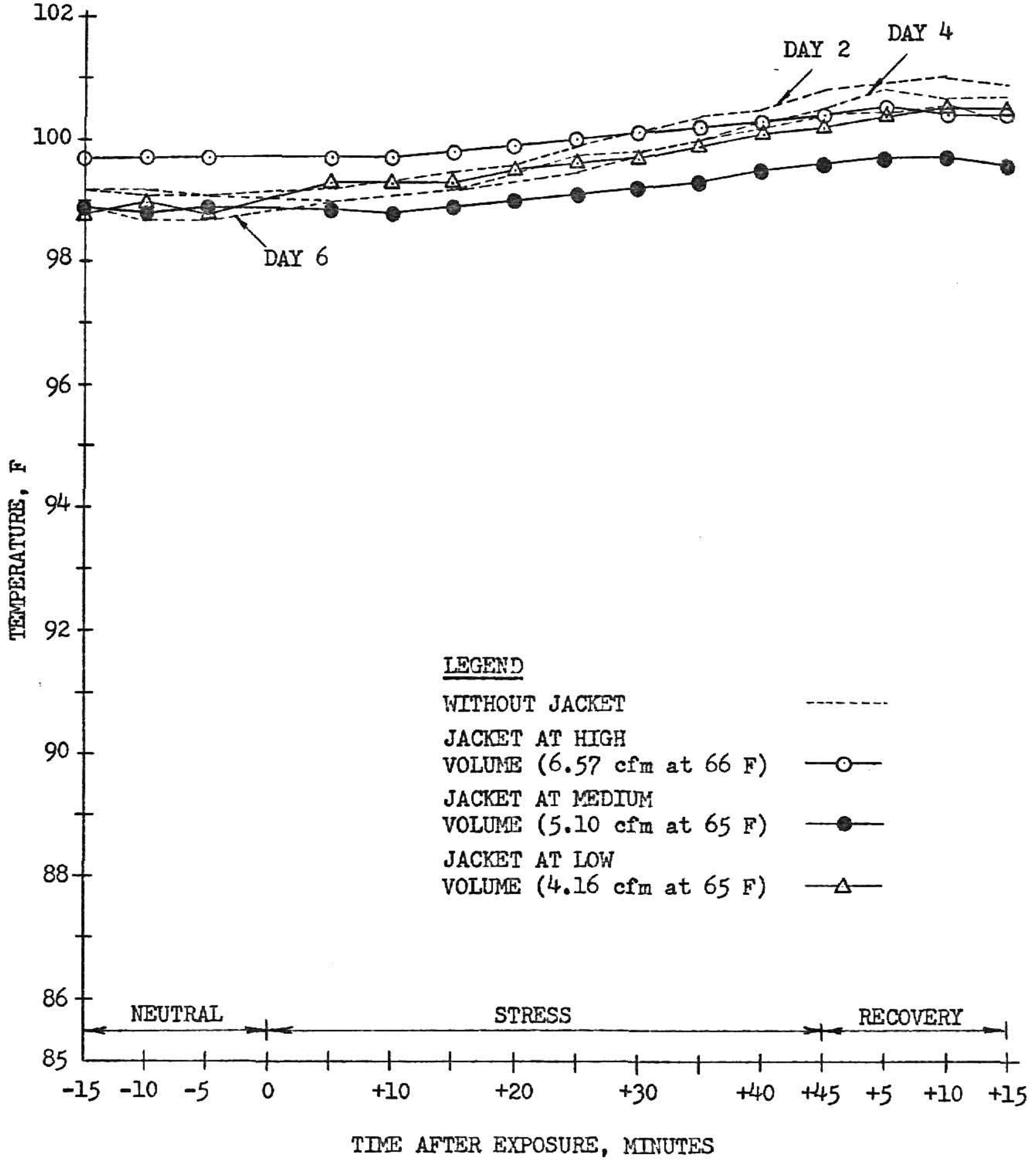

Fig. 16. Rectal temperatures for subject 2.

TABLE 12

Increase in rectal temperature (F) by condition

Subject	High Volume (6.8 Cfm at 68 F)	Medium Volume (5.1 Cfm at 64 F)	Low Volume (4.4 Cfm at 62 F)	Without Jacket
1	0.7	1.1	0.8	1.2, 1.0, 1.2
2	0.9	0.7	1.4	1.6, 1.4, 1.6
Means	0.80	0.90	1.10	1.33

TABLE 13

ANOVA of rectal temperatures

SOURCE	D.F.	MEAN SQUARE	F-RATIO
Treatment	3	0.19	1.46
Subject	1	0.02	0.15
Treatment x Subject	3	0.13	13.00*
Residual	4	0.01	
TOTAL	11		

*Significant ($\alpha < .05$)

Heart rate:

The rise in the heart rate during exposure over the basal (Fig. 17 and 18, and Table 14) was smallest for subjects 1 and 2 at high volume.

The analysis (Table 15) indicated a significant ($\alpha < .05$) effect for treatment. Further analysis by the Duncan's New Multiple Range Test (Table 14) indicated that the means at low and medium volume did not differ significantly ($\alpha < .05$). The mean at high volume differed significantly ($\alpha < .05$) from the means at low and medium volumes, and from the no jacket condition. Also the means at low and medium volumes differed significantly ($\alpha < .05$) from the no jacket condition.

It can be concluded that to keep the heart rate lower, high volume was more effective.

Sweat loss:

The sweat loss (Table 16) was lowest for subject 1 at low volume and was lowest for subject 2 at medium volume. The means indicated that the overall sweat loss was lower at high volume. Subject 1 had exceptionally high sweat loss at medium volume, and appeared to be an outlier in the data. By taking the ratios of sweat loss at various volumes between subject 1 and 2, the value for sweat loss at medium volume on day 4 probably should have been 550 gms/m^2 of body area/hr (0.11 lbs/sq. ft. of body area/hr).

However, using the observed data the analysis did not indicate any significant ($\alpha < .05$) effect.

The subjective feeling of the subjects showed that they felt more comfortable at medium and high volume.

Creatinine in the saliva:

When a man is in heat stress the salivary secretion is reduced because

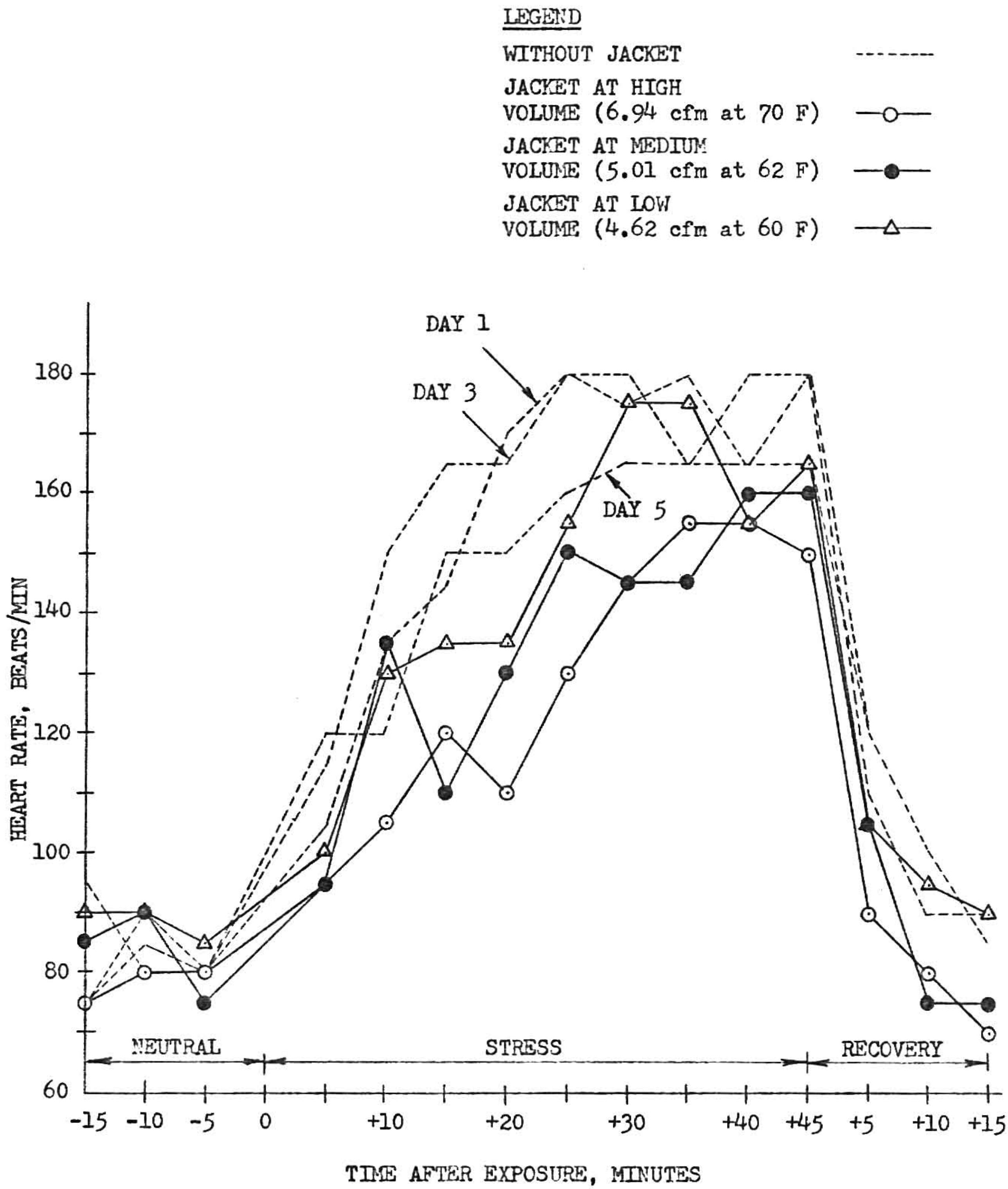

Fig. 17. Heart rate for subject 1.

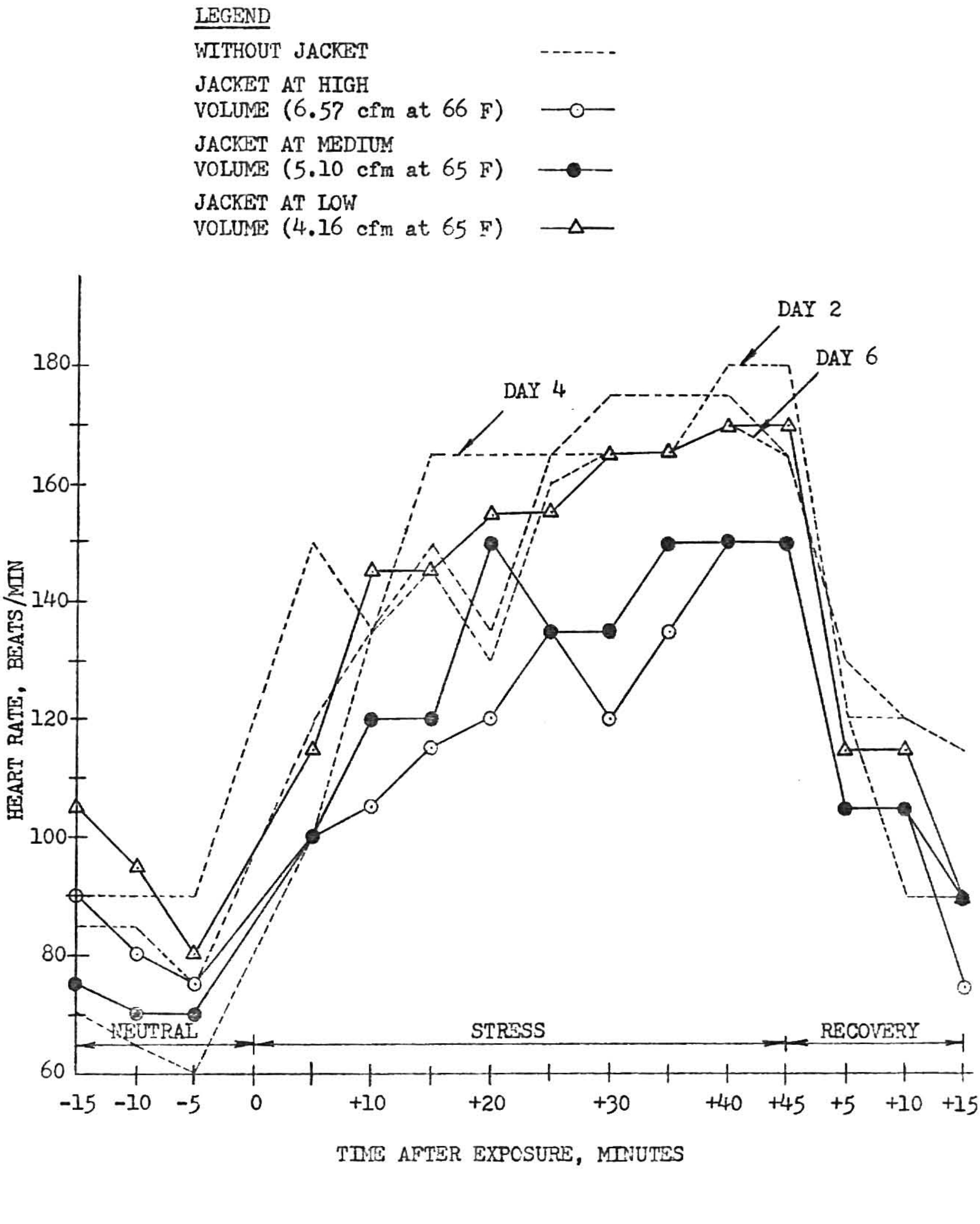

Fig. 18. Heart rate for subject 2.

TABLE 14

Increase in heart rate, beats/min, by condition

Subject	High Volume (6.8 Cfm at 68 F)	Low Volume (4.4 Cfm at 62 F)	Medium Volume (5.1 Cfm at 64 F)	Without Jacket
1	72	77	77	95, 83, 100
2	68	77	78	98, 75, 100
Means	70.0	77.0	77.5	92.0

Means 77.0 and 77.5 are underlined together.

	p = 2	p = 3	p = 4
Standard error	1.10	1.10	1.10
Least significant range	4.9 beats	4.9 beats	4.9 beats

The horizontal lines underline the means which are not significantly ($\alpha < .05$) different.

TABLE 15

ANOVA of heart rate

SOURCE	D.F.	MEAN SQUARE	F-RATIO
Treatment	3	312.44	128.04*
Subject	1	3.26	1.33
Treatment x Subject	3	2.44	0.02
Residual	4	134.68	
TOTAL	11		

*Significant ($\alpha < .05$)

TABLE 16

Sweat loss, gms/m^2 of body area/hr, by condition
*lbs/sq. ft. of body area/hr

Subject	High Volume (6.8 Cfm at 68 F)	Low Volume (4.4 Cfm at 62 F)	Medium Volume (5.1 Cfm at 64 F)	Without Jacket		
1	786 (0.157)	651 (0.130)	1191** (0.238)	1031, (0.206),	1264, (0.253),	872 (0.174)
2	504 (0.100)	772 (0.154)	418 (0.084)	865, (0.173),	925, (0.185),	774 (0.155)
Means	645 (0.128)	711 (0.142)	804 (0.161)	955 (0.191)		

*The sweat losses in lbs/sq. ft. of body area/hr are given in parenthesis.

**Probably an outlier.

TABLE 17

ANOVA of sweat loss

SOURCE	D.F.	MEAN SQUARE	F-RATIO
Treatment	3	62304.96	0.88
Subject	1	191196.06	2.72
Treatment x Subject	3	70201.43	3.10
Residual	4	22603.34	
TOTAL	11		

of the cellular dehydration (Bard, 1964). The composition of saliva sample may give an indication of the level of stress.

To eliminate the effect of days, the daily means of creatinine secretion in the control period were calculated by adding up the control values for all the subjects for each day irrespective of jacket or no jacket condition and dividing by the number of subjects.

The change in creatinine concentration from the daily means is shown in Table 18. With the jacket, the average difference from the daily means decreased from -0.003 mgs/100 mls. in the control to -0.040 mgs/100 mls. in stress; it decreased from -0.04 to -0.27 without the jacket. It was observed that the average creatinine concentration decreased by 0.31 mgs/100 mls. from control to stress. The Wilcoxon test was applied to the six pairs of the average values of creatinine concentration with and without the jacket. The decrease was not significant ($\alpha < .05$) for jacket vs no jacket. However when the control concentration vs stress concentration was tested, the difference between the ten pairs was significant ($\alpha < .05$).

In another experiment using the air cooled helmet (Sharma 1970), and using the same two subjects, the saliva samples were analyzed (Table 19). The averages were taken in the same way as explained above. With the helmet, the average difference from the daily means increased from -0.74 in control to -0.72 mgs/100 mls. in stress; it decreased from -0.54 to -0.97 mgs/100 mls. without the helmet. The average decrease in creatinine concentration was 0.20 mgs/100 mls. from control to stress. The Wilcoxon test was applied on the five pairs of the average values of creatinine concentration with and without the helmet. The decrease was not significant ($\alpha < .05$). When the control concentration vs stress concentration was tested, the

TABLE 18

Change from the daily means in creatinine concentration in saliva in mgs/100 mls. in this experiment

Subject		Jacket				Without Jacket			
		Low Vol.	Medium Vol.	High Vol.	Average	Exp 1	Exp 2	Exp 3	Average
	Control	*	0.35	-0.27	0.04	0.15	-0.07	-0.12	-0.01
1	Stress	*	-0.30	-0.32	-0.31	-0.75	-0.07	-0.17	-0.33
	Recovery	*	-0.30	-0.17	-0.23	-0.85	-0.23	-0.17	-0.26
	Control	-0.15	0.08	0.13	0.02	0.28	-0.35	*	-0.03
2	Stress	-0.75	-0.07	-0.27	-0.36	-0.12	-0.35	*	-0.23
	Recovery	-0.40	0.13	0.03	-0.08	0.08	-0.35	*	-0.13
	Control	-0.15	0.21	-0.07	-0.003	0.21	-0.21	-0.12	-0.04
Average	Stress	-0.75	-0.18	-0.29	-0.40	-0.43	-0.21	-0.17	-0.27
	Recovery	-0.40	-0.08	-0.07	-0.18	-0.38	-0.06	-0.17	-0.20

*Data not available.

TABLE 19

Change from the daily means in the creatinine concentration in saliva, mgs/100 mls. with air cooled helmet in Sharma's thesis (1970)

Subject		Helmet			No Helmet		
		Exp 1	Exp 2	Average	Exp 1	Exp 2	Average
	Control	-0.43	-0.25	-0.34	-0.47	-0.57	-0.52
1	Stress	-0.23	-0.35	-0.29	-1.42	-0.52	-0.97
	Recovery	0.27	-0.45	-0.09	-1.42	-0.57	-0.99
	Control	-0.88	-1.42	-1.15	*	-0.57	-0.57
2	Stress	-0.68	-1.62	-1.15	*	*	*
	Recovery	-0.68	-1.47	-1.07	*	-0.07	-0.07
	Control	-0.65	-0.83	-0.74	-0.47	-0.57	-0.54
Average	Stress	-0.45	-0.98	-0.72	-1.42	-0.52	-0.97
	Recovery	-0.21	-0.96	-0.58	-1.42	-0.32	-0.53

*Data not available.

difference between six pairs was not significant ($\alpha < .05$).

The creatinine in the urine samples was determined and the data showed that the results were not significant.

Volume and temperature of cold air:

As explained in Appendix I, the volume of cold air was calculated by measuring the pressure upstream, and the difference in pressure across the nozzle. Table 20 gives the volumes of air along with the temperatures and other data which was recorded during the experiment. The volume of air varied from 4.2 to 6.9 cfm (.1 to .2 m^3) at low, medium and high volumes. The dry bulb temperature varied from 62-70 F (16.6-21.1 C), and the humidity varied from 18-48%. A large variation in reported humidity was due to the crude method of measuring the variable. Throughout the experiment a supply pressure of 95 psig was maintained.

Body and air temperatures:

The skin temperature, inside air temperature, and outside air temperature (Table 21), indicated a lower value at the back. The gradient (Fig. 19) for the back is very steep. The gradient for the stomach is also steep, whereas the temperature for the arm rises upwards. This implies that the air circulation in the arms was not very effective. The design of the jacket requires improvement so that the air circulation is more uniform.

Heat extracted from the body by cold air:

Leithead and Lind (1964) give the Nelson formula for calculating the heat losses, which are as follows:

$$C = 0.5\sqrt{V}\,(t_s - t_a)$$

$$R = 5.7\,(t_g - t_a)$$

TABLE 20

Temperatures and volumes of cold air

Day	Volume	Pressure, Inches of Water: Difference in Pressure	Pressure, Inches of Water: Pressure Upstream	Atmospheric Pressure, Inches of Mercury	Weight of Air, lbs/hr	Density of Air, lbs/cu ft	Reynolds Number	Volume of Air, cfm	Average Volume, cfm	Temperature of Air, F: Dry Bulb	Temperature of Air, F: Wet Bulb	* Relative Humidity %
1	Low	0.4	0.2	29.90	18.85	.0755	26453	4.16	4.40	65	50	33
6	Low	0.5	0.3	29.90	21.17	.0763	29720	4.63		60	47	35
3	Medium	0.6	0.4	29.76	23.03	.0752	32330	5.10	5.05	65	54	48
4	Medium	0.6	0.45	29.90	23.16	.0760	32500	5.01		62	49	38
2	High	1.1	0.7	29.80	31.07	.0747	43613	6.94	6.75	70	58	48
5	High	1.0	0.7	29.92	29.80	.0755	41824	6.57		66	47	18

*The humidity of air is not consistant due to the crude method of measuring the variable.

TABLE 21

Mean body, cold air, and ambient air temperatures

Day	Volume	Body Temperatures Under the Jacket, F				Temperature of Air Inside the Jacket, F				Temperature of Ambient Air Outside the Jacket, F		
		T_2	T_3	T_6	Mean	T_7	T_9	T_{11}	Mean	T_8	T_{10}	Mean
1	Low	93.9	99.7	95.5	96.4	101.9	72.3	90.5	88.2	104.4	92.7	98.6
6	Low	93.7	98.6	94.6	95.6	101.3	74.7	98.0	91.4	104.0	86.0	95.0
3	Medium	95.6	98.0	96.0	96.5	101.3	72.0	93.3	88.8	104.9	92.0	98.5
4	Medium	95.7	95.5	95.9	95.7	99.0	84.3	86.4	89.9	103.5	94.6	99.0
2	High	93.5	98.2	96.7	96.1	102.3	70.6	93.0	88.6	107.3	89.9	98.6
5	High	96.8	99.0	96.0	97.3	101.4	85.6	90.4	92.5	104.9	94.0	99.5
Means		94.9	98.2	95.8	96.3	101.2	76.6	91.9	89.9	104.8	91.5	98.2

Key:

T_2 = mean skin temperature on the back

T_3 = mean skin temperature on the right arm

T_6 = mean skin temperature on the stomach

T_7 = mean air temperature inside the jacket above the right arm

T_8 = mean air temperature outside the jacket above the right arm

T_9 = mean air temperature inside the jacket above the back

T_{10} = mean air temperature outside the jacket above the back

T_{11} = mean air temperature inside the jacket above the stomach

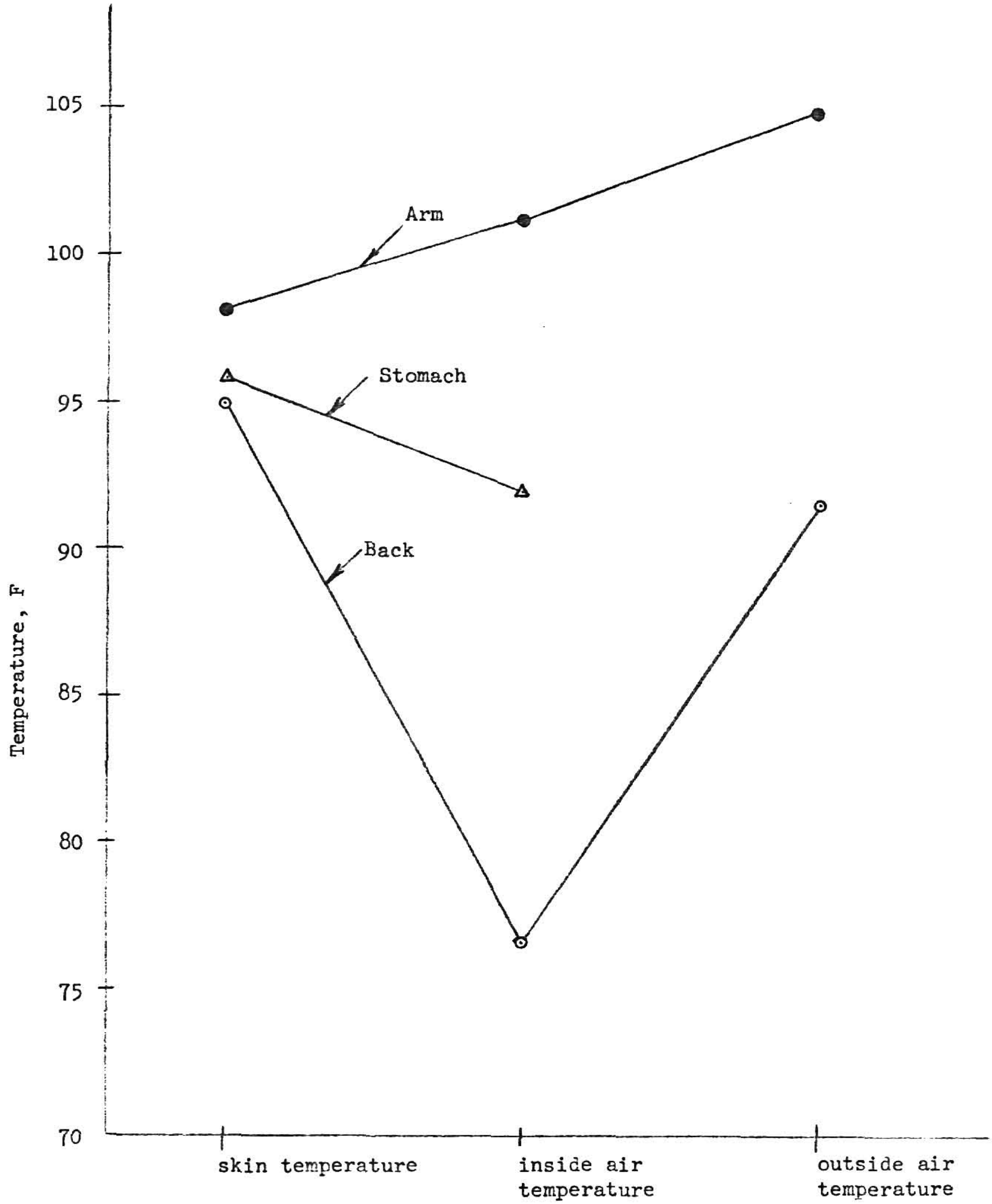

Fig. 19 Skin temperature, inside air temperature, and outside air temperature at the back, stomach and arm.

and $E = 1.4\ V^{0.37}\ (p_s - p_a)$

where

C = heat exchanged by convection in K Cal/m^2 of body area*/hr.

R = heat exchanged by radiation in K Cal/m^2 of body area/hr.

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

V = velocity of air in ft/min.

t_s = skin temperature in °C.

t_a = air temperature in °C.

t_g = globe temperature in °C.

p_s = vapor pressure of the skin in mm of mercury.

p_a = vapor pressure of the air in mm of mercury.

Velocity of the cold air could be calculated at the outlet of the vortex tube, since the diameter of the outlet was known. By previous experiments conducted by the author it was observed that average velocity of the air coming out at the neck was about 400 ft/min (121 m) and the velocity of air coming out of the sleeve was 200 ft/min (60 m). This was estimated by running the jacket at medium volume and measuring the velocities at the various outlets by ascertaining the rate at which smoke from a cigarette traveled. The average velocity of the air inside the jacket at medium volume was calculated by taking the mean of velocities at the outlets of the vortex tube, neck and sleeve. The average velocity of 420 ft/min (128 m) was approximately 2/3 of the vortex tube velocity. The average velocity at high and low volume was assumed to be 2/3 of their vortex tube velocities (Table 22).

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*The body area covering the torso and the arms was assumed to be one third of the total body area. (Burton and Collier, 1964)

TABLE 22

Potential heat losses by convection, radiation and evaporation of sweat

Day	Subject	Volume	Volume of Air, cfm	Air Temperature, F	Average Velocity in the Jacket, ft/min	Potential Heat Lost, BTU/Hr by						
						Convection	Mean	Radiation	Mean	Evaporation of Sweat	Mean	Total
1	2	Low	4.16	65	420	47	48	35	29	160	154	231
6	1	Low	4.63	60	420	48		23		149		
3	2	Medium	5.10	65	470	83	76	55	56	187	185	317
4	1	Medium	5.01	62	470	69		57		182		
2	1	High	6.94	70	650	96	90	63	59	142	146	295
5	2	High	6.57	66	650	85		55		151		

This approximation gave a rough idea of the average velocity of the air inside the jacket.

The heat extracted (Table 22) was calculated by the above formula. It was observed that the heat extracted by convection and radiation increases with the increase in volume. But in case of heat extracted by evaporation of sweat, it was maximum at medium volumes. This was because of having lower temperature and enough volume of air at the medium volume. A sample calculation of heat exchanged is given in Appendix II.

Actual heat storage and heat removal from the body:

Webb (1969) suggested an empirical formula for the heat stored in the body during a period as:

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

where

Q = the amount of heat stored, K Cal

0.83 = specific heat of the human body, K Cal/Kg C

m_b = the weight of the body, Kg

ΔT_s = change in the mean skin temperature, C

ΔT_{re} = change in rectal temperature, C

The rise in mean skin temperature was taken outside the jacket (Table 6), as it would be a better representative of the rise in the mean skin temperature. The rise in rectal temperature was taken from Table 12. The heat storage (Table 23), which was initially for 45 minutes, was converted to BTU/hr.

The most heat was removed with the jacket at medium volume (Table 23). There was no heat removed at low volumes, implying that the jacket did not benefit the wearer at the low volume.

The potential heat losses (Table 22) show maximum heat extraction

TABLE 23

Actual rate of heat storage and removal in the body; BTU/hr

Subject	Heat Stored				Heat Removed		
	High Volume	Medium Volume	Low Volume	No Jacket	High Volume	Medium Volume	Low Volume
1	281	254	326	298	17	44	-28
2	496	408	503	526	30	118	23
Means	388	331	414	412	23	81	- 2

potential at medium volume; a potential of 317 BTU/hr. We can conclude that at medium volume the jacket had an actual efficiency of 26%; at high volume an efficiency of 8% and was ineffective at low volume.

DISCUSSION

There was considerable variation in the data of the two subjects. Subject 1 was very short, and may not be a good representative of the American population.

Sharma (1970), who evaluated an air ventilated hood, used 6.5 cfm (0.18 m^3) at 70 F (21.1 C), which was approximately the same as the high volume in the present study. He observed that the hood reduced the heat load by 100 BTU/hr, and estimated that it removed 19% of the total heat storage of the body. In the present study at a volume of 6.8 cfm (0.18 m^3) at 68 F (20 C) the jacket removed 23 BTU/hr (Table 23) and the body had heat storage of 388 BTU/hr; this implies that the jacket removed 6% of the total heat load. These figures indicate that the hood was more efficient for heat removal and had better thermal efficiency. However the efficiency of the jacket at the medium volume was 26%, which is more than the efficiency of the hood.

Konz and Duncan (1969) cooled the individual by using two hoods with circulating water. Nine subjects were exposed for 75 minutes to a heat stress environment of 112 F (44.1 C) and 58% R. H. The water flow was 264 lbs/hr (120 Kg) and the temperature difference between inlet and outlet of the hoods was 2 F (1 C). Tap water at 60 F (15 C) was used for circulation in both the hoods. It was observed that the model C hood removed 245 BTU/hr and the model D removed 172 BTU/hr. The present design of the water cooled hood appears to be superior to the present design of the jacket which removed only 81 BTU/hr in the best condition; that is, at the medium volume.

In the present study the volume of air ventilating the jacket proved to be inadequate. At 5 cfm (.14 m^3) and at 63 F (17 C) the air had a heat removal potential of 185 BTU/hr by the evaporation of sweat. Assuming the heat removal potential in a new design of the jacket to be twice the present value, the new value for the potential heat loss by the evaporation of sweat will be 370 BTU/hr. The velocity and volume in the new design will be $(2)^{1/.37}$ times the present volume and velocity. This value is 670%.

In case of the potential heat removal by convection, the new design of the jacket would have $(6.7)^{1/2}$ times heat removal potential than the present design. This value is 260%. This implies that the new design of the jacket will have potential heat removal by convection as 76 x 2.6 BTU/hr or approximately 195 BTU/hr. Also assuming potential heat removal by radiation to be constant the total potential heat removal in the new design will be 370 + 95 + 56 = 621 BTU/hr. This value is approximately twice the total potential heat removed at the medium volume. Assuming the ratio between the potential and actual heat removed to remain the same, the actual heat removed in the new design will be approximately 160 BTU/hr. As stated earlier the new volume will be 5 x 6.7 = 33.5 cfm or approximately 35 cfm (1 m^3) at 63 F (17 C).

If air cooling is to be considered further the vortex tube ventilating the jacket must deliver 35 cfm (1 m^3) of air at 63 F (17 C). Another possibility is using a commercial air conditioner instead of a vortex tube. This type of arrangement will be cheaper to operate than the vortex tube. To make the system more effective, a tube should be provided in the jacket to give better circulation in the sleeves.

The urine and saliva samples were analyzed for creatinine. The analysis of the saliva samples was used in the results, but the analysis of urine samples was not used. This was because of not measuring the amount of discharge of urine, which was due to an error in communication with the laboratory.

SUMMARY

The present study was conducted using two male student subjects to evaluate an air ventilated jacket in a heat stress environment of 112 F (44.4 C) dry bulb; and 60% R. H. A vortex tube fixed to the subjects waist was used to ventilate the jacket. The subjects walked at 2 MPH in the heat stress for 45 minutes.

Each subject was exposed to the heat stress environment six times, three times with the jacket being ventilated by the three volumes (Table 24), and three times without the jacket.

TABLE 24

Change in physiological parameters on exposure to heat stress

Criterion	Air Volumes and Temperatures			
	6.8 Cfm at 68 F	5.1 Cfm at 64 F	4.4 Cfm at 62 F	Without Jacket
Increase in mean skin temperature, F	5.5	4.2	5.5	9.6
Increase in leg temperature, F	9.7	7.4	9.4	8.4
Increase in head temperature, F	4.3	4.5	5.0	5.5
Increase in ear temperature, F	2.7	4.1	4.3	4.4
Increase in rectal temperature, F	0.8	0.9	1.1	1.3
Increase in heart rate, beats/min	70	77	77	92
Sweat loss, gms/m^2 of body area/hr	645	804	711	955

The increase in the mean skin temperatures and heart rate showed a significant effect ($\alpha < .05$) for treatment. The overall performance of the jacket was best at 6.8 cfm at 68 F. These volumes were not found to be adequate and a volume of 35 cfm at 63 F (17 C) is recommended.

REFERENCES

ASHRAE Handbook, American Society of Heating, Refrigerating, and Air Conditioning Engineers, New York, 1956.

ASME Flow Measurement, Instruments and Apparatus, PTC 19.5; 4-1959, American Society of Mechanical Engineers, New York, 1959.

Bard, P., Medical Physiology, The C. V. Morby Company, St. Louis, 1964.

Burton, D. R., The Thermal Assessment of Personal Conditioning Garments, Ministry of Technology, Aeronautical Research Council Current Papers, C.P. No. 953, Her Majesty's Stationery Office, London, 1967.

Burton, D. R., and L. Collier, The Development of Water Conditioned Suits, Royal Aircraft Establishment, Technical Note No. Mech. Eng. 400, Ministry of Aviation, London, W. C. 2, April, 1964.

Crockford, G. W., R. F. Hellon, P. W. Humphreys, and A. R. Lind, An Air Ventilated Suit for Use in a Very Hot Environment, Ergonomics, Vol. 4, No. 1, January, 1961.

Crockford, G. W., and R. F. Hellon, Design and Evaluation of a Ventilated Garment for Use in Temperatures up to 200°C, British Journal of Industrial Medicine, Vol. 21, 1964.

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

Drake, R. M. Jr., J. E. Funk, and J. B. Moegling, Sensible Heat Transfer in the Gemini and Apollo Space Suits, Thermal Problems in Biotechnology, ASME, December, 1968.

Fetcher, E. S., S. I. Rapaport, J. F. Hall, and H. G. Shaub, Biophysical Requirements for Ventilation of Clothing, Applied Physiology, Vol. 2, August, 1949.

Fleming, A. J., C. A. D'Alonzo, and J. A. Zaap, Modern Occupational Medicine, Lea and Felujer, Philadelphia, 1954.

Froese, G., and A. Burton, Heat Losses from Human Head, Journal of Applied Physiology, Vol. 10;2, 1957.

Grollman, S., The Human Body: Its Structures and Physiology, Macmillan, New York, 1964.

Jaax, J. R., An Investigation of Thermal Comfort (Thermally Neutral) Conditions for Three Activity Levels. Masters Thesis, Department of Mechanical Engineering, Kansas State University, Manhattan, 1967.

Konz, S., and V. Morales, The Physiological Effects of a Water Cooled Hood in a Heat Stress Environment. ASHRAE Transactions, Vol. 74, Part II, December, 1968.

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

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

Liethead, C. S. and A. R. Lind, Heat Stress and Heat Disorders, F. A. Davis Co., Philadelphia, 1964.

Newburgh, L. H., Physiology of Heat Regulation and the Science of Clothing, Hafner Publishing Co., New York, 1949.

Sharma, S. K., Physiological Evaluation of an Air Cooled Helmet System, Master's Thesis, Kansas State University, Manhattan, Kansas, 1970.

Threkeld, J. L., Thermal Environmental Engineering, Prentice Hall, New Jersey, 1962.

Van Patten, R. E., R. Gaudio, Application of Ranque - Hilsch Vortex Tube to Air Crew Cooling Problem, Aeromedical Research Laboratory, Wright Patterson Air Force Base, Ohio, AMRL - TR - 67 - 124, June, 1968.

Veghte, J., Efficiency of Pressure Suit Cooling System in Hot Environment, Aeromedical Research Laboratory, Wright Patterson Air Force Base, Ohio, AMRL - TR - 65 - 68, 1965.

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

Winslow, C., and L. Herrington, Temperature and Human Life, Princeton University Press, New Jersey, 1949.

Wyndham, C. H., Role of Skin and Core Temperatures on Mans Temperature Regulation, Journal of Applied Physiology, Vol. 20, No. 1, January, 1965.

APPENDIX I

The volume of air was measured by inserting a nozzle in series with the vortex tube and measuring the pressures upstream and differential pressures at each end of the nozzle. The nozzle is sketched in Figure 3. It has a pipe diameter of 1.125" and the diameter of the nozzle is 0.5". The pressures upstream and the differential pressures were measured by a water manometer. The following formula as given in ASME Instrument and Apparatus Supplement (PTC 19.5; 4-1959) gives the mass of air:

$$W_h = 359\ C\ F\ d^2\ F_a\ Y_a \sqrt{\frac{h_w}{v_1}}$$

where W_h = mass of air in lbs/hr

C = coefficient of discharge (determined from the tables, PTC 19.5; 4-1959)

F = velocity of approach factor $= \dfrac{1}{\sqrt{1 - \beta^4}} = \dfrac{1}{\sqrt{1 - (0.44)^2}} = 1.03$

$\beta = \dfrac{\text{throat diameter of the nozzle in inches}}{\text{pipe diameter in inches}} = \dfrac{0.5''}{1.125''} = 0.44$

d = throat diameter of the nozzle in inches = 0.5"

F_a = thermal expansion factor = 1 (from PTC 19.5; 4-1959)

Y_a = expansion factor = .95 (from PTC 19.5; 4-1959)

h_w = differential pressure across the nozzle in inches of water (from Table 20)

v_1 = specific volume of air in cu ft/lb (determined from tables, PTC 19.5; 4-1959)

Having determined the mass and knowing the specific volume, the volumes of the air were determined in cfm. The value of the coefficient of discharge was determined by an iterative method assuming an initial value of 0.9.

APPENDIX II

Sample Calculation for potential heat losses for Subject 1, day 6, at low volume (Table 22).

Potential Heat exchanged by convection:

The formula for heat exchanged by convection as given by Liethead and Lind (1964) is

$$C = 0.5 \sqrt{V} (t_s - t_a)$$

where C = heat exchanged by convection in K Cal/m^2 of body area/hr

V = Velocity of air, ft/min

= 420 ft/min (Table 22)

t_s = skin temperature, C

= 95.6 F = 35.4 C (Table 21)

t_a = air temperature, C

= 91.4 F = 33.0 C (Table 21)

$C = 0.5 \times \sqrt{420} \times (35.4 - 33.0)$ K Cal/m^2 of body area/hr

assuming one third effective body area for the subject

body area of subject 1 is 1.52 m^2 (Table 1)

$C = 0.5 \times \sqrt{420} \times 2.4 \times 3.97$ BTU/K Cal $\times \frac{1.52}{3}$

= 48 BTU/hr

Potential Heat exchanged by radiation:

The formula for heat exchanged by radiation as given by Liethead and Lind (1964) is

$$R = 5.7 (t_g - t_a)$$

where R = heat exchanged by radiation in K Cal/m^2 of body area/hr

t_g = globe temperature, C

= 95.0 F = 35.0 C (Table 21)

t_a = air temperature, C

= 91.4 F = 33.0 C (Table 21)

$R = 5.7 \times 2.0 \times 3.97$ BTU/K Cal $\times \frac{1.52}{3}$

= 22.6 BTU/hr

Potential Heat exchanged by evaporation of sweat:

The formula for heat exchanged by evaporation of sweat as given by Liethead and Lind (1964) is

$$E = 1.4\ V^{0.37}\ (p_s - p_a)$$

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

p_s = Vapor pressure of the skin in mm of mercury

= 42.2 mm of mercury at 95.6 F (from psychometric tables, ASHRAE Handbook, 1956).

p_a = Vapor pressure of the air in mm of mercury

= 36.8 mm of mercury at 91.4 F (from psychometric tables, ASHRAE Handbook, 1956)

$E = 1.4 \times 420^{0.37} \times (42.2 - 36.8)$ K Cal/m^2 of body area/hr

$= 1.4 \times 420^{0.37} \times 5.4 \times 3.97$ BTU/K Cal $\times \frac{1.52}{3}$

= 149 BTU/hr

AN EVALUATION OF AN AIR VENTILATED JACKET
IN A HEAT STRESS ENVIRONMENT

by

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B. Sc. (Engg), Agra University, Agra (India) 1959

AN ABSTRACT OF A MASTER'S THESIS

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ABSTRACT

An air ventilated jacket was evaluated in a heat stress environment of 112 F (44.4 C) dry bulb and R. H. of 60% with two unacclimatized subjects. The subjects walked at 2 MPH for 45 minutes.

A vortex tube was used to supply cold air to the jacket. Each subject was exposed to the heat stress six times; three times with the jacket being ventilated by the following volumes, and three times without the jacket.

	Air volumes and temperatures			
Criterion	6.8 cfm at 68 F	5.1 cfm at 64 F	4.4 cfm at 62 F	No jacket
Increase in skin temperature under the jacket, F	5.5	4.2	5.5	9.6
Increase in leg temperature, F	9.7	7.4	9.4	8.4
Increase in head temperature, F	4.3	4.5	5.0	5.5
Increase in ear temperature, F	2.7	4.1	4.3	4.4
Increase in rectal temperature, F	0.8	0.9	1.1	1.3
Increase in heart rate, beats/min	70	77	77	92
Sweat loss, gms/m^2 of body area/hr	645	804	711	955

Mean skin temperature under the jacket and heart rate were found to be significantly affected. The overall performance of the jacket was found to be better at 6.8 cfm at 68 F (20 C). However, both volumes were found to be inadequate, and a volume of approximately 35 cfm is recommended for future designs.