NASA CONTRACTOR REPORT

NASA CR-739
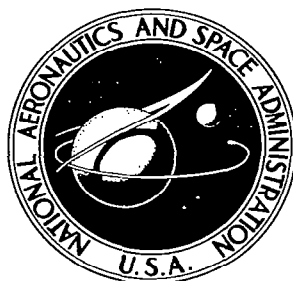
NASA CR-739

BIO-THERMAL RESPONSES TO VARIED WORK PROGRAMS IN MEN KEPT THERMALLY NEUTRAL BY WATER COOLED CLOTHING

by Paul Webb and James A. Annis

Prepared by
WEBB ASSOCIATES, INC.
Yellow Springs, Ohio
for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • APRIL 1967

BIO-THERMAL RESPONSES TO VARIED WORK PROGRAMS IN MEN

KEPT THERMALLY NEUTRAL BY WATER COOLED CLOTHING

By Paul Webb, M.D., and James A. Annis

ABSTRACT

During periods of heavy work, such as those expected in extra-vehicular activity, metabolic heat can be removed at nearly any reasonable rate with water cooled clothing. We have studied the cooling needed for various work levels up to 15 kcal/min (3600 Btu/hr), using five different programs of activity over 3 to 6-hour periods. With thermally isolated subjects, and using a fixed water flow rate of 1.5 lpm (3.3 lbs/min), we adjusted water inlet temperatures so that the men neither sweated nor became chilled. Experimental data show continuous curves for "Q" (quantity of heat removed), water inlet temperature, oxygen consumption, rectal temperature, and mean skin temperature. Mean body temperature is held nearly constant, and the subjects are "comfortable" throughout the experiments. From such data one can specify control of cooling for any reasonable level of work and for many patterns of work.

TABLE OF CONTENTS

LIST OF FIGURES

Bio-Thermal Responses to Varied Work Programs in Men

Kept Thermally Neutral by Water Cooled Clothing

SUMMARY

During periods of heavy work such as those expected in extra-vehicular activity, metabolic heat can be removed at nearly any reasonable rate with water cooled clothing. This is an experimental study of the cooling required for mild to strenuous work, using five different programs of activity, each lasting from three to six hours. Work rates were sustained at 5 kcal/min, 10 kcal/min, and 15 kcal/min (1200 Btu/hr, 2400 Btu/hr, and 3600 Btu/hr) for 2 hours, 1 hour, and 10 minutes respectively. Two other programs were tested in which work rates varied between 2 and 12 kcal/min, in periods lasting 10, 20, and 30 minutes.

Subjects were thermally isolated in insulated and impermeable clothing in an environmental chamber whose temperature was constantly kept very close to that measured beneath the impermeable clothing layer. Water cooled clothing was part of the assembly. Water inlet temperatures and flow rates were adjusted continuously so that the men neither sweated nor became chilled.

Thirty complete sets of experimental data show continuous curves for the following: "Q" (quantity of heat removed in the water cooled suit); water inlet temperature; oxygen consumption; rectal temperature; and mean skin temperature. Mean body temperatures computed from rectal and mean skin temperatures show that in most experiments the body heat content was held nearly constant.

The temporal relationships between changes in activity and oxygen consumption on the one hand and heat removal on the other are evident from the curves. These metabolic time constants have an important bearing on the design of a controller for operating a water cooled suit.

INTRODUCTION

Extravehicular activity (EVA) has a high metabolic cost, as evidenced by the sustained high heart rates of the Russian cosmonaut and the American astronauts who have tried it, and as suggested by the fatigue of these men when they returned to the vehicle. Heavy sweating was a serious complication in two of the EVA's in the Gemini program, causing early termination of the scheduled activities.

It is no surprise that metabolic cost is high in pressurized full pressure suits (Roth, 1966, and Streimer, 1964). The Gemini gas cooled pressure suit was designed for lower levels of heat production (Nelson, et al., 1964). Fortunately, a much more powerful means of heat removal in pressure suits is available for the Apollo program, the use of water conditioned undergarments.

Gas cooling loops in pressure suits, such as used in the Mercury and Gemini programs, were never intended to carry away metabolic heat at levels greater than 3 to 5 kcal/min (720 to 1200 Btu/hr) without a sizable sweat production and evaporative cooling. Cooling systems in the portable life support systems (PLSS) are easily overloaded by high sweating rates and heavy loads of moisture in the returning gas. In order to accomplish all of the required cooling convectively, extremely high flow rates would be needed, as much as 40-80 cfm, and the power required for circulating such high volumes of gas becomes prohibitive.

By contrast, liquid cooled clothing, first reported from the Royal Aircraft Establishment at Farnborough by Burton and Collier (1964) is extremely effective, and the cost of pumping the heat transfer fluid, usually water, is far less than the cost of pumping an adequate amount of air. Several studies have established the effectiveness of water cooled clothing: Burton (1966); Crocker, et al. (1964); SantaMaria, et al. (1966); Veghte (1965); Waligora and Michel (1966); and Wortz, et al. (1964). It has become evident that water cooled clothing is capable of removing metabolic heat at nearly any reasonable activity level, including those anticipated for space activities.

With such a powerful means for cooling an active man in a space suit, the matter of control of cooling becomes critical. One must know when the heat which is generated by activity will arrive on the body surface. If cooling is applied too early or too vigorously, overcooling results, with cutaneous vasoconstriction, sensations of chilling, and possible muscle cramps. If cooling is applied too little or too late, heat storage begins and sweating builds up rapidly. If sweating begins and then cooling is increased, there will be an overshoot resulting in a high sweat production before the heat removal system can catch up.

Our early experimental work with water cooled clothing (Crocker, et al., 1964) led to exactly these difficulties and led also to our proposing the present study as a means of defining the biothermal responses of men who are thermally isolated and cooled by a water cooled garment.

When a man begins to work, the following things increase: respiratory minute volume, oxygen uptake, carbon dioxide production, heat production in active muscles, and heart rate. (This list is not exhaustive.) All of these changes are fairly rapid and reach new plateau values within one to three minutes if the work level is constant. The extra heat which is being generated is held initially, or at least not totally distributed to the surface, and heat storage occurs. The core temperature, as measured by temperature probes in the rectum, esophagus, or external ear canal, reaches a higher plateau than at rest; the higher the work level the higher the plateau (Nielsen, 1938). (Also, see Figure 12 in this report.) In other words, heat loss from the body surface is dissociated in time from heat production.

As an active astronaut carries out varied duties on the surface of the moon or in EVA in orbital flight, his need for cooling will vary with the activity level. A controller must be part of the PLSS, a controller so made that it nicely matches his need for heat loss no matter what the activity. The controller should be able to avoid overcooling with sensations of chilling and surface vasoconstriction, and it should be able to avoid significant amounts of sweating because of undercooling. The question is, what signal input shall be used? One good answer is: oxygen consumption. Since we have a method for continuously monitoring oxygen consumption, we have proposed that the signal from this device be used to inform the controller what the activity level is at all times, when it changes, and by how much. If the time constants for oxygen consumption and for heat removal from the surface are known, then the controller can by suitable programming keep up with the astronaut's need for dissipation, avoiding the problems of overcooling and undercooling. The experimental data to establish the metabolic time constants needed did not exist. We set out to generate such a body of data, and the results are reported here.

With thermally isolated subjects (a condition which characterizes a man outside the vehicle in a full pressure suit) and a clothing assembly containing a water cooled suit controlled by the experimenters, we have put subjects through five different activities, each schedule lasting from three to six hours, maintaining as nearly as possible comfort and uniform body heat content throughout. Experimental data show continuous curves for the "Q" (quantity of heat removed), water inlet temperature, oxygen consumption, rectal temperature, mean skin temperature, and mean body temperature. The five activity schedules were accomplished by three subjects, making 15 experiments; then the 15 experiments were repeated, both to confirm the first set of data and to improve upon it. The whole group of 30 experiments constitutes the body of this report. From such data we show how a controller must perform for any reasonable level of work and for many patterns of work.

3.

METHODS

Clothing Assembly

The clothing assembly used in these experiments consisted of the following layers: water cooled garment, insulating suit with air distribution ducts, impermeable plastic coverall, outer insulation garment, impermeable gloves, and impermeable head covering. Figure 1 shows the layers diagrammatically.

The water cooled garment used is one of our own design, consisting of a network of small plastic tubes (Tygon vinyl plastic 1/8" OD by 1/16" ID). Parallel lines of tubing are joined approximately every two inches by small plastic loops so that when the garment is donned, diamond shaped openings measuring roughly two inches in length and one inch wide cover the body, and the tubing conforms closely to the contours of the arms, legs, and trunk. The fit of this garment is more or less universal, and the plastic tubes lie against the skin firmly despite changes in contours and angles when the subject is active. The garment is made in five segments, with one for each arm and leg, plus the adjoining quadrant of the trunk. An additional segment was made to cover the head and neck. Figure 2 is a diagram of this tubing design. All tubes in each segment originated in manifolds which were brought together to form a common inlet. All tubes in each segment ended in outlet manifolds, which were joined together in a common outlet. A proportioning of the total flow could be made by the subject by an adjustment of pinch clamps on each of the five inlet manifolds.

The hands, feet and face, representing about 12% of the body surface, were not cooled. We estimate that the contact area of the cooling tubes was just over 4000 cm^2, representing 22% of the surface of a man whose total surface area is 1.8 m^2.

The insulating suit of the next layer was a heavy nylon coverall with a flocced nylon insulating liner which gave a garment thickness of about 1/4 inch. On the innermost surface was an air distribution network consisting of 26 tubes covering the trunk, arms, and legs. Air was delivered to these tubes at a single fitting in the back, and it escaped from numerous small holes located along the inner face of each tube, and against the skin, which was covered only by the open diamond mesh of the water cooled undergarment.

The next layer was a coverall of 0.020 inch vinyl plastic covering the arms, legs, feet, and torso up to the neck. The coverall was donned through a gas tight zipper along the length of the back.

The hands were covered by plastic coated fabric gloves, and partially cooled by a loop of the inlet manifold tubing.

4.

Neoprene foam (.25" thick)

Facial area not cooled

Water cooling capillaries
showing diamond pattern

Insulating Layers
(enlarged view)

skin

Water cooling garment tube

Insulating suit
    nylon coverall
    flocced nylon
    air tubes

Vinyl coverall (.020" thick)

Outer insulating layer
    thermal knit underwear
    polyurethane foam (3/16")
    dacron cloth

Chamber air

Hand with cooling loop

Plastic coated
fabric gloves

Common outlet fitting

Common inlet fitting

Foot not cooled

Walking boot and stocking

Rubber boot
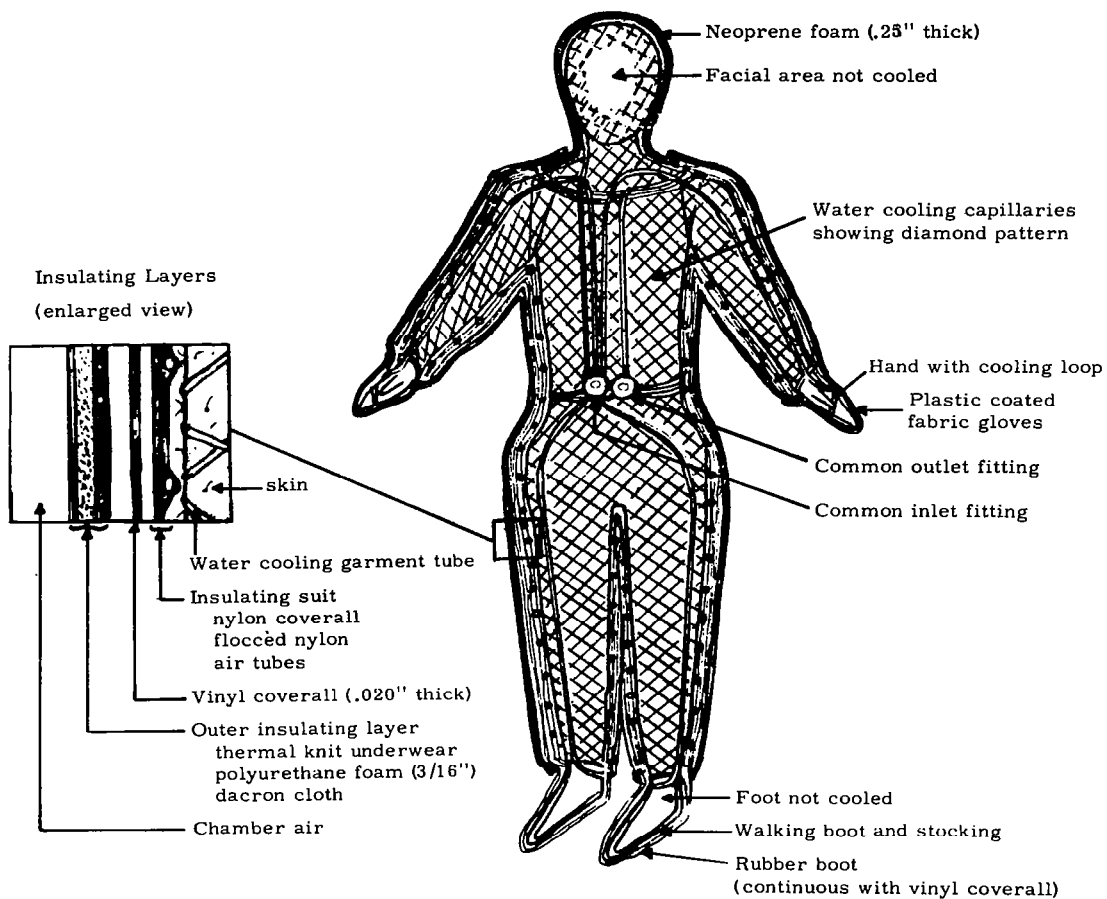(continuous with vinyl coverall)

Figure 1. Diagram of clothing layers in the clothing assembly.
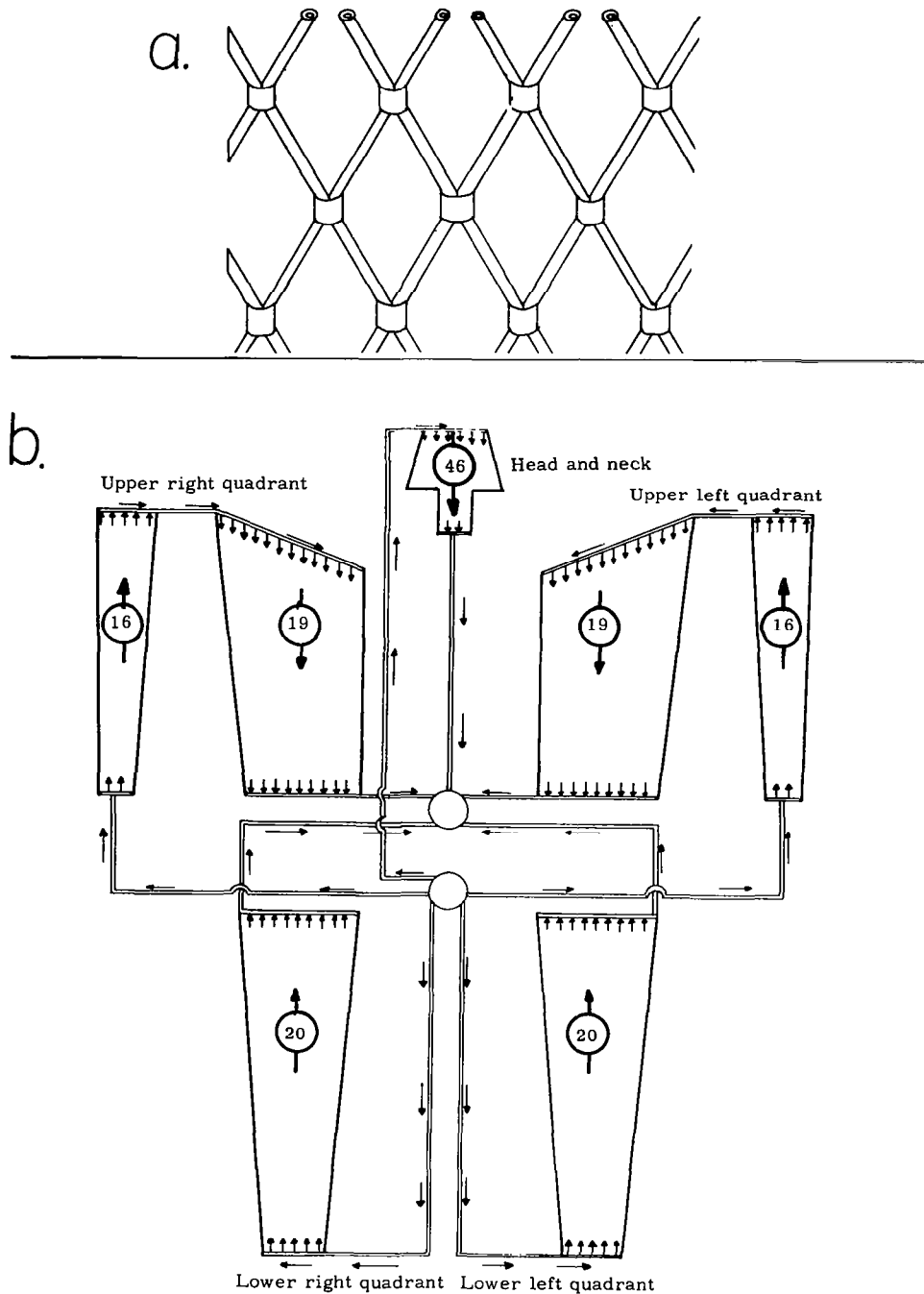
5.

Figure 2. a. Diamond pattern of parallel tubes
        b. Schema of water flow through the water cooling garment
            showing direction of flow and number of tubes in each area

The head was covered by a 1/4" neoprene foam skin-diver's helmet which left part of the face exposed.

The outer insulating layer was jacket and trousers of 3/16" polyurethane foam covered on the inside with thermal knit underwear cloth, and on the outside with Dacron cloth.

Cooling Control

Cooling was accomplished in this clothing assembly by adjusting the volume flow of water and the inlet temperature of the water, and by the small flow of warm dry air through the suit. Figure 3 shows the water and air flow circuits.

Control of water flow was accomplished in this clothing assembly by using an accurate metering pump (Model R230A, Milton Roy Company, 1300 East Mermaid Lane, Philadelphia, Pa.; range 100 to 2200 ml/min). Calibration curves for flow versus micrometer valve settings were made using accurately timed collection and weighing of pump output at various back pressures. Back pressures up to 25 psi had no effect on the calibration curve. In our water circuit back pressures were usually not higher than 5 psi, even during activity. Pump outputs were checked during the runs periodically by timed collections in a graduated cylinder, and were always accurate to better than 1% of value.

The control of inlet temperature of the water was accomplished by using tap water whose temperature was usually below the desired inlet temperature. If lower inlet temperatures were needed, the tap water was routed through a heat exchanger which was cooled by water from an insulated container which in turn was cooled by a 1-horsepower refrigeration unit. This pre-conditioned water was then reheated by two electric heaters in the line, one controlled by a hand set, variable autotransformer, the other controlled by an accurate proportional controller (Model 72, Yellow Springs Instrument Co., Yellow Springs, Ohio). Inlet temperatures over the range of 10°C to 33°C could be maintained to an accuracy of 0.1° C.

Dry air was distributed through the clothing assembly by means of the distribution network in the first insulating suit, the purpose being detection of sweating rather than removal of significant amounts of body heat. The flow was fixed at 2 cfm, a figure typical of the gas flow intended for water cooled space suits; inlet temperature was approximately equal to suit temperature (usually 28 to 30°C). The air was dried to a constant condition of -8°C dewpoint temperature by sending the flow through a large container of Drierite. The heat removed from the man-suit assembly was thus largely evaporative, and this is included in the corrected value for Q shown in the data curves.
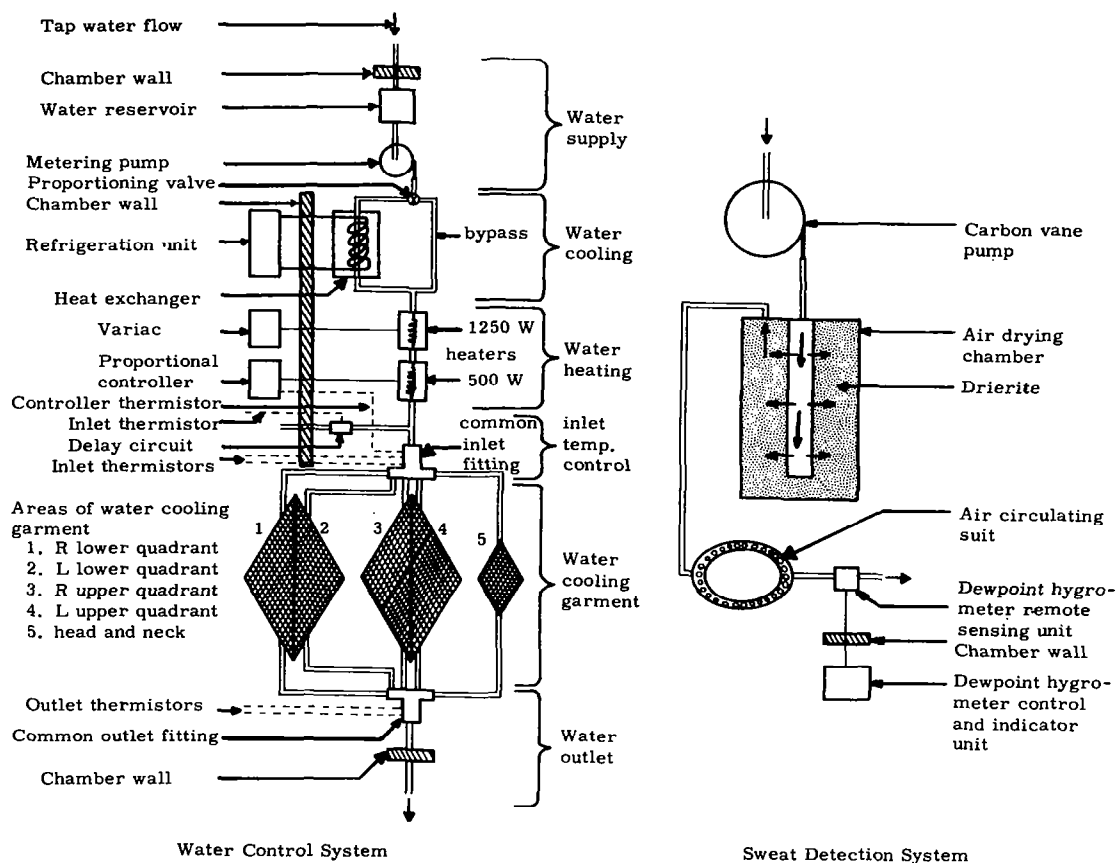
Water Control System

Tap water flow

Chamber wall

Water reservoir

} Water supply

Metering pump
Proportioning valve
Chamber wall

Refrigeration unit — bypass } Water cooling

Heat exchanger

Variac — 1250 W heaters } Water heating
Proportional controller — 500 W

Controller thermistor
Inlet thermistor
Delay circuit
Inlet thermistors

common inlet fitting } inlet temp. control

Areas of water cooling garment
1. R lower quadrant
2. L lower quadrant
3. R upper quadrant
4. L upper quadrant
5. head and neck

1 2 3 4 5 } Water cooling garment

Outlet thermistors
Common outlet fitting
Chamber wall

} Water outlet

Water Control System

Sweat Detection System

Carbon vane pump

Air drying chamber

Drierite

Air circulating suit

Dewpoint hygro-meter remote sensing unit
Chamber wall

Dewpoint hygro-meter control and indicator unit

Sweat Detection System

Figure 3. Diagrams of water control and sweat detection systems.

8.

Thermal Isolation

It was important to isolate the suited subject from the environment to prevent heat loss or gain from the environment, and to simulate the astronaut in space. If the isolation was complete, all of the heat removed appeared in the water stream. The astronaut is in a vacuum so that there is no convective or conductive heat loss or gain; heat loss by evaporation is very small because of the gas-tight pressure suit. Thermal radiation is effectively blocked by the insulation and the reflective outer layers of the protective garment over the pressure shell. The astronaut is in effect in a Dewar flask. We attempted to simulate this thermal isolation in our experimental setup.

The suit assembly as described is an effective insulation garment, and the impermeable layer prevents evaporative heat loss. (The evaporative loss from the expired air and the water contained in the small flow of air through the suit was measured and included in the computation of Q.) However, if the man-suit system were at a much different temperature from the air environment, some heat loss or gain would occur. To avoid this, we did the experiments in our environmental chamber, which is capable of rapid and accurate control of temperature in the range of suit temperatures encountered. Chamber temperature control was accurate to better than 0.5°C, and the response time of the chamber to a temperature disturbance is less than one minute. We measured a suit temperature under the impermeable suit and under the outer layer of insulation at all times during the experiments. The chamber temperature was then made to match that measured suit temperature, usually within ± 1°C. The resulting thermal gradient for heat gain or heat loss from the suited man was extremely small, and we feel that heat losses from the system were therefore small. We have not attempted to measure the heat losses or gains from the suit, relying instead upon the garment construction and the control procedure described.

Activity Schedules

Five different schedules of activity were used for each subject. The levels of activity were chosen to cover the range of metabolic rates expected in EVA. The patterns of activity were chosen to illuminate the problem of controlling metabolic heat loss during changing activity, and to simulate some of the features we felt would represent actual work in EVA. Figure 4 is an illustration of the nominal metabolic rates for each of the five activity schedules.

Schedule I is a simple step function or square wave at the moderately high work rate of 10 kcal/min, or 2400 Btu/hr, lasting for one hour. It is preceded and followed by a rest period of at least one hour (usually 1-1/2 to 2 hours), during which time physiological data is collected. Schedule II is another square wave exactly half as high and twice as long--5 kcal/min for 2 hours.
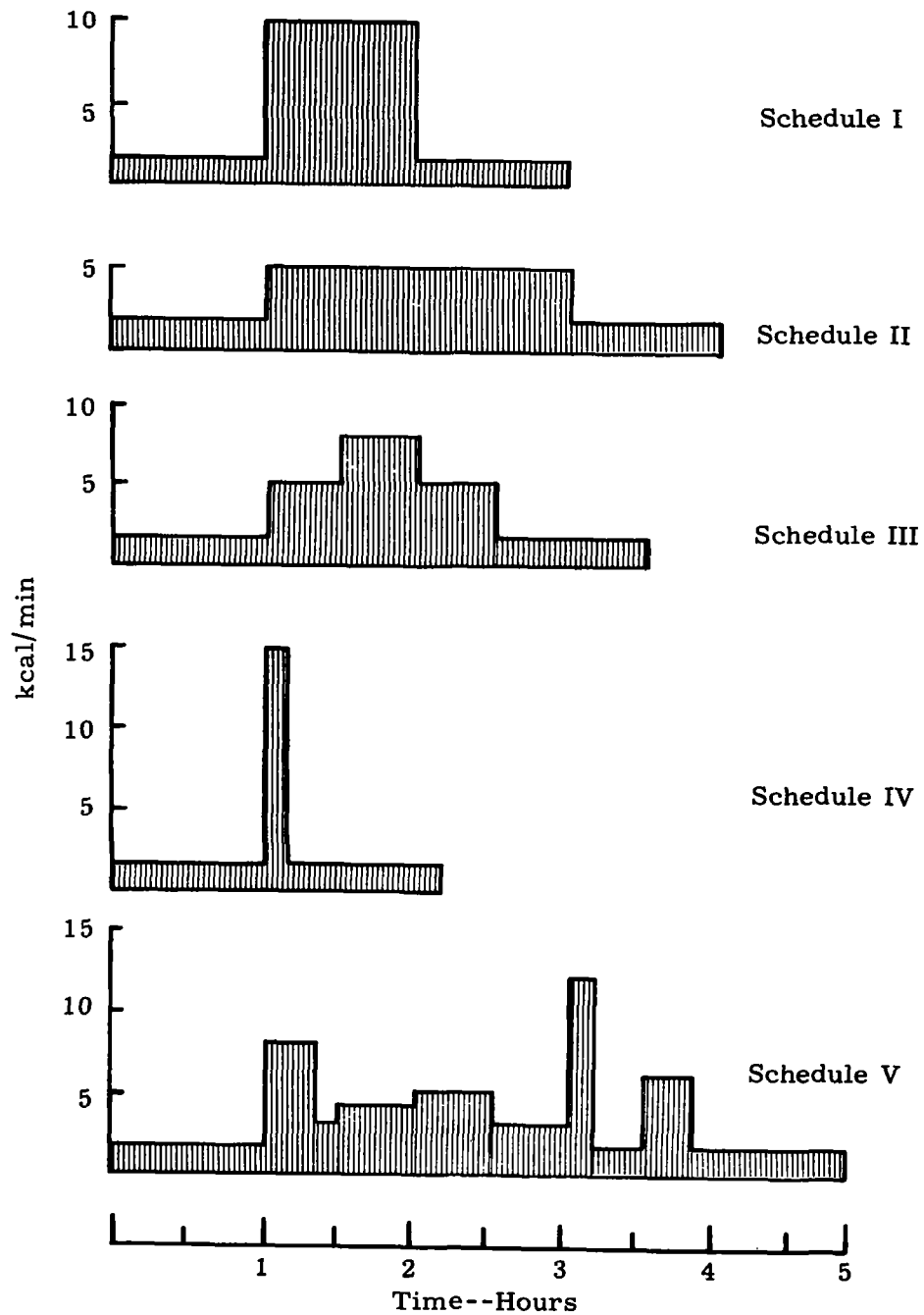
Figure 4. Levels of work and periods of work in the five activity schedules.

10.

Activity schedule III was designed to illustrate the effect of a preceding work period upon another level of work. The subject starts with 30 minutes at a 5 kcal/min level, immediately followed by 30 minutes at 8 kcal/min, and immediately followed again by a third half hour at the lower work level. Activity schedule IV is a short period of near maximal effort, chosen to represent what a non-athletic man can sustain for ten minutes. The nominal rate of 15 kcal/min is a high level of work largely in the aerobic range. Shorter periods at higher (largely anaerobic) rates are achievable by non-athletic men; however, our experience in observing time constants of rectal temperature change, oxygen uptake, heart rate change, and heat appearing on the body surface indicated that a 10-minute period was as short as would be meaningful. Again, the data was collected for long rest periods which preceded and followed the work.

Activity schedule V is a more or less random pattern of changing activity. We constructed this schedule on the basis of a highly imaginary activity pattern of an astronaut when leaving the LEM for his first trip on the lunar surface. The first 20-minute work period at 8 kcal/min represents a learning period in which he discovers the characteristics of the lunar surface and how to operate in the awkward space suit; he then does mild activity for ten minutes, and this is followed by two half-hour periods of gradually increasing work severity, during which he sets up equipment and makes observations. This is followed by a half-hour of mild activity, during which he is using equipment to make observations. The fifth short ten-minute period at high work level represents a short, vigorous activity like climbing down and up again from a crater, or digging a hole, or struggling with some unforeseen problem. This is followed by a 10-minute rest period, and that in turn by a period of moderate activity, during which he returns to the vehicle. The whole work schedule occupies nearly three hours. The varying levels of activity and the irregular times are a test of our ability to control the cooling. Eventually such a pattern of activity will be a test of an automatic controller.

In defense of such a variety of activity schedules, we would point out that natural human activity is not regular in either magnitude or duration. The square wave patterns of the first four schedules are not typical of the way people work. Intermittent work, in which the person chooses his own pace, is more typical of real life. There are many other ways to construct work schedules. We have chosen these five to test our ability to control, and to help define what an automatic controller must do.

The activity schedules were carried out by programmed walking on a motor driven treadmill. The treadmill speed and grade were adjusted to each subject in terms of his weight to produce as nearly as possible the nominal values for metabolic rate. As the data will show, we usually came within 10% of the nominal value for each subject.

Measurements

The quantity of heat removed, Q, was determined by measuring water flow and the change in water temperature across the man. Water flow was fixed accurately by the setting of the metering pump, and verified periodically by collection in a graduated cylinder. The change in water temperature, Δt_w, was measured with a selected pair of interchangeable thermistor probes (Yellow Springs Instrument Co. #401), which were calibrated against an accurate mercury in glass thermometer. The thermistor probe for measuring outlet temperature was located in the outlet fitting where all five outlet manifolds joined together. The inlet temperature probe was located near a special T fitting in the inlet line. A change in inlet temperature was detected by this thermistor roughly one minute after the change had been produced. The reason for the delay was that the network of tubing in the water cooled suit has a delay of roughly one minute for circulation time. We were interested in the Δt_w caused by heat added by the man, and not by a transient caused by a change of inlet temperature. The Q recordings (see next paragraph) were corrected on the final experiment records by adding the heat lost in insensible water loss and adding the energy which leaves the system as external work. External work was calculated from treadmill slope, when greater than zero, clothed weight, and distance travelled.

Q was continuously recorded from a special bridge circuit, shown in Figure 5. The Δt_w value was achieved by having the two primary thermistors located in adjacent arms of a Wheatstone bridge, wherein bridge unbalance equals Δt_w. Since Q is a multiple of Δt_w and water flow, bridge voltage was adjusted as a function of water flow rate, hence the bridge output signal was automatically Q in kcal/min (or in Btu/min, Btu/hr, or any other unit desired). The output signal of the Q circuit went to a wide chart potentiometric recorder, and a continuous record of Q was drawn on the chart paper.

Rectal temperature was measured by inserting to a depth of 10 cm a thermistor probe (Yellow Springs Instrument Co. #401). The temperature was read out on a Digitec model 501 digital thermometer (United Systems Corp., Dayton, Ohio) and the value logged every ten minutes or more frequently if the experimental conditions were changing rapidly.

Mean skin temperature was measured with copper-constantan thermocouples, which were connected directly to a Brown multipoint potentiometric recorder. In the first 12 experiments, ten skin locations were employed and an average was derived by reading each point every ten minutes, and sometimes every five, and an unweighted mean derived by calculation. In the last 18 experiments, 20 thermocouple locations were employed, and a special switch (Thermoelectric Corp., Saddlebrook, N.J.) was interposed between the thermocouples and the Brown recorder, which allowed either a print of all 20 points
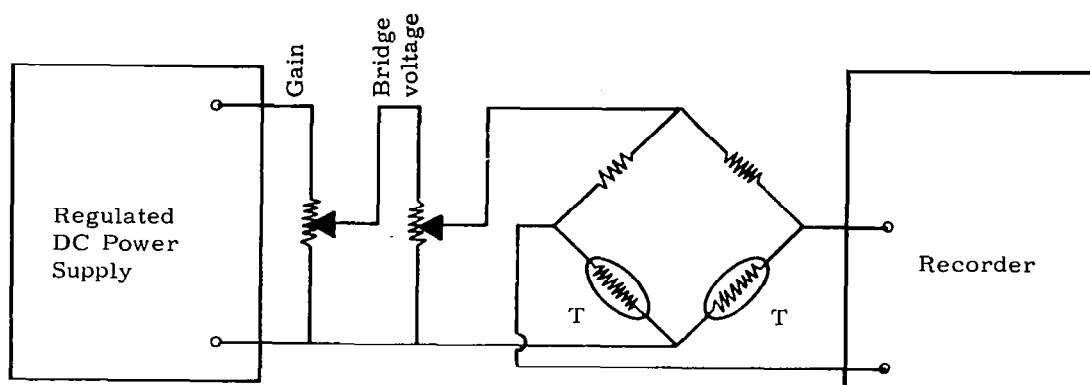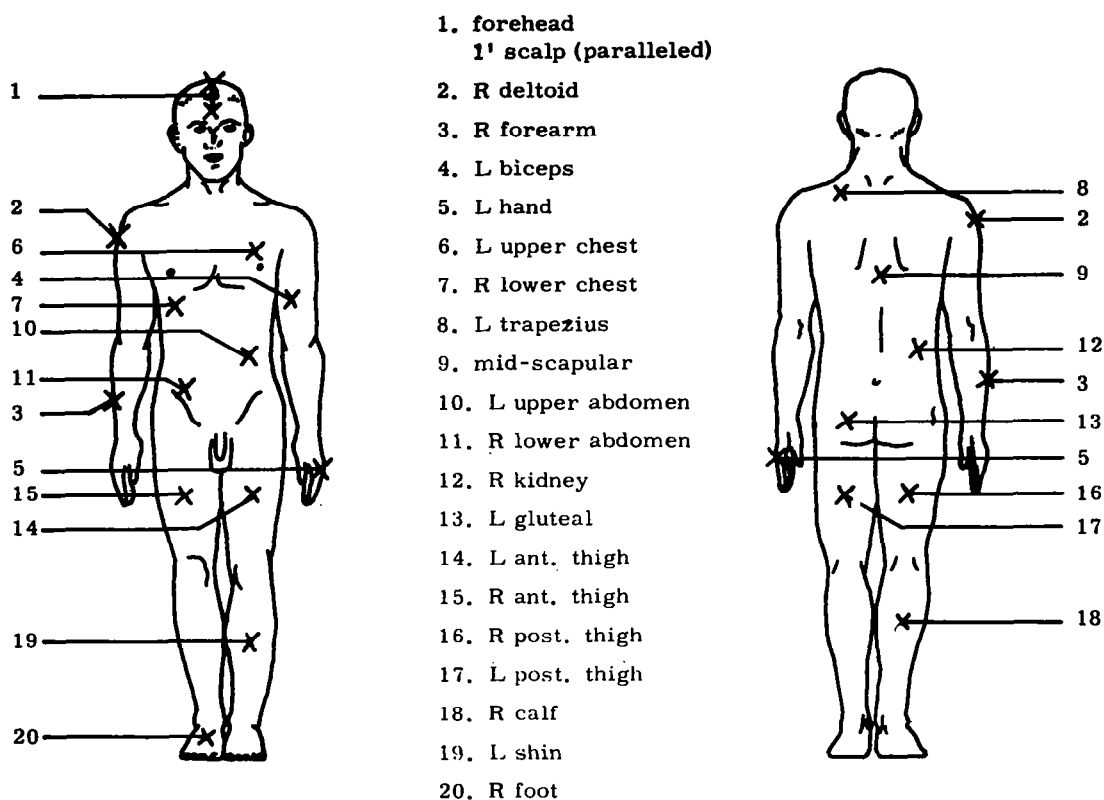
12.

Figure 5. Bridge circuit to give recording of Q. An adjustment of bridge voltage was made to match any change in water flow. Thus bridge output is a multiple of Δt_w and water flow rate.

individually, or it connected all thermocouples in parallel to produce an electrical average. This electrical average was checked periodically by taking a hand-calculated average of the 20 individual points. The electrical average never differed by more than $\pm 0.1°C$ from the calculated average. The ten thermocouple locations were all in skin areas cooled by the water cooled suit, and were located so as to be representative of the areas of the arms, legs, and trunk. The 20 thermocouple locations, shown in Figure 6, were also to represent the areas sampled in such number as to make an unweighted average appropriate. That is, the number of thermocouples for the trunk, for example, which is seven, is 34% of the thermocouples used, and the trunk area is 35% of the total. The 20 thermocouples included thermocouples on one hand and one foot, which were not cooled by the water cooled garment, and one of the two paralleled head thermocouples was on the forehead which was also not cooled. In the cooled skin regions the thermocouples were always fixed near the center of a diamond of the water tubing network, and lightly spring loaded to press against the skin.

Mean body temperature was calculated by multiplying the rectal temperature (t_r) by 0.7 and the mean skin temperature (t_{sm}) by 0.3 and adding the two together. The choice of weighting factors was arbitrary. Some people choose

Thermocouple Location Code

1. forehead
   1' scalp (paralleled)
2. R deltoid
3. R forearm
4. L biceps
5. L hand
6. L upper chest
7. R lower chest
8. L trapezius
9. mid-scapular
10. L upper abdomen
11. R lower abdomen
12. R kidney
13. L gluteal
14. L ant. thigh
15. R ant. thigh
16. R post. thigh
17. L post. thigh
18. R calf
19. L shin
20. R foot

Schema for surface area weighting of thermocouples

Body area represented	Thermocouples no.	fraction of total *	Fraction of body area represented (DuBois)
head-neck	1.5	.073	.070
arms-hands	4	.195	.190
trunk	7	.342	.350
thigh	5	.244	.190
leg-feet	3	.146	.200

*individual thermocouple fraction = .0488 for total of 20.5 thermocouples

Figure 6.   Thermocouple locations and schema for surface area weighting

$2/3 \times t_r + 1/3 \times t_{sm}$, especially if the experiment is done in a cold environment. Others prefer $0.8 \times t_r + 0.2 \times t_{sm}$ if the experimental conditions are warm. The choice of weighting constants seems to be related to the state of cutaneous vasodilation or vasoconstriction, and in our experiments we were trying to avoid either extreme. The mean body temperature, incidentally, is the only index we have of the heat content of the body. If our cooling control is correct, then the heat content of the body should not change significantly throughout the course of any of the activity schedules.

Change in body weight was measured on a Fairbanks platform balance with an accuracy of 0.01 lbs (approximately ±5 grams). Subjects were weighed nude before and after each experiment. In the last 15 of the 30 experiments the subjects were also weighed fully clothed while connected to instrumentation and cooling loops at the beginning of the first rest period and at the end of the final rest period. The clothing which was worn under the impermeable garment was also weighed before and after each experiment. From these measurements, we were able to calculate the evaporative heat loss for the entire schedule of activity. We separated water loss from the respiratory tract and water loss from the skin by calculating respiratory water loss from the respiratory volume measurements and subtracting this from the total. In this way values for "insensible weight loss" for the whole activity schedule, adjusted for each of the work periods in terms of respiratory loss, could be converted to insensible heat loss and used to correct the values for Q derived from the cooling water measurements.

Evaporative water loss from the air circuit (used only in the last 18 experiments) could be estimated from the readings of dewpoint temperature. Since the air circuit was used primarily as a detection device for the presence or absence of early sweating, the main purpose was not the calculation of insensible heat loss, which we thought to be more accurate from the changes in body weight. Such estimations as were done agreed with the weight changes.

Respiratory measurements were done with standard techniques for deriving respiratory minute volume, oxygen uptake, CO_2 production, and R.Q. At least twice during the course of each rest or work period in every activity schedule, 1 or 2 minute samples of expired air were collected by means of a mouthpiece, J-valve, and vinyl plastic Douglas bag. The volume was measured in a Collins 120-liter spirometer. Oxygen content was measured on a Beckman model C-2 paramagnetic analyzer; CO_2 content was measured with a Harvard Apparatus Company critical orifice meter; respiratory quotient was calculated from these values.

Continuous oxygen consumption measurements were attempted with our metabolic rate monitor (MRM). However, we experienced trouble with drift and linearity during these experiments, and we prefer to report the data from the standard measurements described in the preceding paragraph. The shapes of

the oxygen consumption curves as measured by the MRM are shown in the experiment graphs, but the levels are from the standard respiratory measurements.

Heart rate was obtained with EKG electrodes leading to a Gilson cardiotachometer, which gave us a continuous indication of heart rate. Active electrodes were located at the top of the sternum and the precordium, and the grounded or indifferent electrode was at the xiphoid process.

Subjects

Four subjects were employed in the 30 experiments. They are employees of the laboratory who are in good health and physically fit, although not athletic. From other experiments using the same people, we can say that their performance on the standard Harvard step test (20 inch step) is in excess of three minutes, and their maximum oxygen uptake is greater than three lpm. Their physical characteristics are presented in Table I. The skin fold measurements presented in the second part of the table were taken with a Lange caliper.

Table 1. Subject Characteristics

Subject	Age	Height		Weight		Surface Area
		cms	inches	kg	lbs	m^2
A	42	173	68	81.8	180	1.9
B	34	183	72	70.0	154	1.9
C	17	175	69	65.0	143	1.8
D	20	173	68	67.3	148	1.8

Skinfold Thickness

Subj.	right biceps mm	left abd. mm	r. sub. scap. mm	r. mid costal mm	left pectoral mm	r. iliac crest mm	right triceps mm	l. pat-ella mm	Aver. mm
A	5.5	33.0	28.0	22.5	9.0	22.0	10.0	11.0	17.6
B	3.7	7.2	10.0	6.5	5.1	4.4	6.6	4.8	6.0
C	2.8	13.0	17.0	9.0	5.0	11.5	6.0	7.0	8.9
D	2.8	7.0	7.0	5.5	4.5	8.0	4.5	6.0	5.6

Procedure

The subject reported to the laboratory about 8:30 a.m. and proceeded with attaching electrodes, inserting the rectal thermistor, and weighing. The dressing procedure occupied about an hour, and the initial rest period for the experiment usually began about 10:30 or 11 o'clock in the morning. In the longer experiments the subject was allowed to eat a light lunch during the rest period or during a period of mild work. Lunch and fluids taken during the course of an experiment were weighed and incorporated in the weight change for the run. The subject had an open intercom with the observers outside the chamber. He was allowed to read or listen to the radio as desired.

Certain changes in procedure were made during the course of the 30 experiments. In the first 11 experiments, while we were learning to control the amount of cooling required, we varied both water flow and water inlet temperature. Flows used ranged from 200 ml/min to 2000 ml/min. In the last 19 experiments, we had learned that the wide changes in flow were unnecessary and we fixed the flow rate at 1500 ml/min, since this had proved to be adequate for even the highest work rates. Control of temperature was easier at this flow rate, and it was not necessary to use low inlet temperatures.

In the first 12 experiments, only 10 skin thermocouples were used, and 20 were used in the last 18 experiments. It was possible to go to the higher number of thermocouples because of the acquisition of an averaging switch, which reduced the amount of hand calculation necessary.

In the first 7 experiments the outermost layer was the impermeable garment. In the last 23 the outer insulation garment was added to help insure complete thermal isolation.

In the first 11 experiments we did not use any air flow through the air distribution network. The subject was completely bottled up and any sweating which did occur was contained within the suit layers. The air flow measurement was added as a means of detecting the presence of light sweating.

Subject C completed the 5 activity schedules but was unavailable for the repeat runs. Subject D, about the same size and age, did the repeat runs; their biothermal responses were similar.

Control Criteria

During every experiment our intent was to have the subject perform the work called for and to cool him so that he did not sweat. At the same time we did not want to overcool him, or cool him too soon and cause discomfort and chilling. As the work proceeded we developed more sensitive criteria for undercooling and for overcooling.

Undercooling results in a subject who is not only too warm but who is sweating. In the early runs sweating was detected by the subject, whose face was exposed to the chamber environment and who therefore could sense the cooling effect. Any sweat formed elsewhere than on the face could not evaporate, since there was no air flow, and thus could not be sensed. We had an overall check on the amount of sweating by the weight changes recorded at the beginning and end of the runs. However, we wanted an objective method of detecting sweating during the course of the run. By adding a small air flow to the suit assembly and by measuring the dewpoint of the exit air, we were then able to detect early sweating as soon as the subject did, or sometimes sooner. Our basic criterion for success in cooling was that the sweat rate not exceed 100 grams/hr for the entire period of each activity schedule. The criterion was met in nearly every case. One of the 30 runs had a weight loss rate of 102 grams/hr, and two showed rates of 105 grams/hr. (This is total evaporative loss, including insensible loss.) Higher rates may have occurred for short periods, but this was hard to detect. The dewpoint measurement of the air leaving the suit allowed us to know when the sweating was below 8 grams/hr and when it exceeded 84 grams/hr, since the dewpoint meter went off-scale at the humidity corresponding to that rate of loss. The later runs were controlled so that the sweat rate was below 84 grams/hr.

Overcooling was signalled by subjective report. In some of the early experiments, where we were perhaps too determined to prevent sweating, we drove skin temperatures quite low, and one subject complained of leg soreness and imminent muscle cramps. In reviewing the first 10 experiments, we noticed something which promised to distinguish between those runs which were overcooled and those which were correctly cooled. In those experiments in which the subject had occasionally complained of early sweating, the Q figure was 80 to 90% of the heat production estimated from oxygen uptake. In those experiments where no sweating was reported at all, and the skin temperature was generally low during the course of work, we noticed that the Q was more like 50% of the work level estimated from oxygen consumption. This we took to be evidence of overcooling and vasoconstriction, with heat being stored in the body. The rectal temperature data do not entirely support this concept, but neither do they deny it. It may be that the single sampling point of internal temperature is not adequate to show this effect. Prolonged overcooling and continued high work rates might cause greater increases in rectal temperature if surface vasoconstriction prevented removal of heat. We do not know whether continuing such overcooling for longer periods would cause a high storage of body heat and heat collapse. This would be an interesting experiment to try.

Our control criteria, then, developed into a careful monitoring of several sources of information and adjustment of inlet temperature accordingly. For example, when the subject began to work following a rest period,

we observed that the Q curve began to change very quickly if the subject had been comfortable and had a mean skin temperature of 33°C or higher during the rest period. This increase in Q occurred without any induced change in water inlet temperature. As the Q began to increase, the technician operating the control of inlet temperature began to decrease inlet temperature in anticipation of the need for more cooling. Soon thereafter the subject would begin to ask for more cooling if he were not getting enough, or might say he felt as if he were going to sweat because of sensations like tingling on the skin. Subjective comments were helpful but occasionally misleading. With the air flow going, we would see a change in dewpoint temperature from an average of 12°C at suit outlet to 15 or 18°C. If cooling were not increased by dropping inlet temperature fast enough, the dewpoint indication would exceed 18°C and early sweating would be reported by the subject. We also learned as time went on what skin temperatures would be appropriate for each work level, and these were slightly different from subject to subject or from day to day. At the end of a work period, on return to rest, we often observed that the Q would start to decrease, usually within 15 or 20 seconds, again without any induced change in inlet temperature. Inlet temperature would not be changed until the subject reported that he wanted less cooling. We learned to raise the inlet temperature fairly rapidly so as to bring the skin temperatures back up to their pre-work level in a period of 30 to 40 minutes. We began to feel toward the end of the 30 runs that a well-controlled run kept the subject in a state of mild vaso-dilation without sweating. If this were true, then the changes in Q at the initiation or the termination of a work period were visible and appropriate. If we had overcooled, the vessels were constricted and we did not see this subject-induced Q change.

RESULTS

The results of the 30 experiments are shown on individual graphs in the Appendix, Figures A-1 through A-30. The graphs have been grouped by activity schedule, with the three initial trials of Schedule I and the three repeat trials of Schedule I being figures A-1 through A-6, all of Schedule II being A-7 through A-12, and so forth. On each graph, reading from top to bottom, are curves of rectal temperature, mean body temperature (in most cases), mean skin temperature, oxygen uptake, and Q. The time scale runs along the X axis. The temperature scale and the metabolic level scale are superimposed on the Y axis. The inlet temperature curves for the 19 experiments with fixed flow appear below, and are half scale, that is, 2° on the inlet temperature scale equals 1° on the skin, rectal, and mean body temperature scales.

Although all the changes in activity are step functions, and the oxygen consumption curves reach plateau values within the first one or two minutes, it is obvious that the Q curves follow a different time course. There is always a delay of from 1/2 minute to 3 or 4 minutes before any major change in Q is seen following a change in activity. Following the initial delay, the slope or time course of a Q change until a new equilibrium value is obtained is very different from the slope of the oxygen curve. In the best experiments (that is, best in terms of our final control criteria), the Q slopes are essentially exponential, with time constants related to the severity of the work. In general, the more severe the work the steeper the slope.

Activity schedules III and V are interesting since these are not single square wave changes in activity, but rather mixtures of work levels with or without rest periods interspersed. For example, the Q curves in schedule III show that the first half hour of work at 5 kcal/min influences the response of the Q curve to the second period of work immediately following, in that the rise time of Q after the initiation of the second work period is much quicker than we would expect if the second work period had been preceded by a rest period. Similarly, the third half hour work period of schedule III shows the effect of the preceding higher work level by a higher Q and in many cases a higher oxygen uptake, although the treadmill speed and grade were exactly the same as in the first work period. In schedule V, the effect of a preceding work period is particularly evident in periods 2, 3, and 4. The first period was a moderately high one, and the heat production in the second, third, and fourth periods of work is higher than expected. In other words, a preceding work period definitely influences the results of the period under observation.

Schedule IV is interesting in a different way. In nearly every case the rectal temperature begins to rise, and in all cases it definitely peaks after the work period is over. This is not true, of course, for oxygen consumption,

which rises to its maximum value within 2 or 3 minutes of the initiation of the near-maximal effort. The heat produced by the work continues to appear after the 10-minute work period is over, while the oxygen curve returns fairly rapidly when the work is finished. Schedule IV experiments are the clearest demonstrations of the dissociation in time between heat production (oxygen consumption) and heat dissipation or Q.

It would be tempting to try to integrate under the Q curves to see if all the heat which should have been produced in terms of the oxygen curve did actually appear sooner or later. We have not attempted this since many of the experiments were either slightly undercooled or slightly overcooled by our criteria. Also we are not able to say that we have a complete calorimetric measurement, although our experimental setup was designed to reduce extraneous heat loss or heat gain as much as possible. It was true that the mean body temperatures, which may have varied by 0.5 to 1.0°C during a work transient, were the same at beginning and end, and usually were constant when equilibrium rectal temperatures were reached.

To show the degree of similarity of the biothermal responses of our four subjects to the five activity schedules, we have grouped together the time histories of rectal temperature, mean skin temperature, and inlet temperatures (where the flow is fixed at 1500 ml/min) for each schedule, starting from the beginning of the first work period. These plots make up figures 7 through 11. The rectal temperature curves for each schedule group together fairly well. The skin temperature curves and the curves of water inlet temperature show more variability, including some variations between two similar runs by the same subject, especially in schedule V. However, the shapes of the curves and the magnitudes are characteristic for each activity schedule. It is the slopes of the curves which tell what an automatic controller must do to be as "successful" as we were in these technician-controlled runs.

Figure 12 plots the equilibrium rectal temperatures from activity schedules I and II against work rate. (A simple equilibrium is not seen in the other three schedules.) Also shown in the figure are similar data from a number of other sources--all similar to our data in that heat stress was not a factor.

Heart rates were typical for the work levels used and showed no evidence of heat stress. Average heart rates for various metabolic levels are given in the following table:

Rectal Temperature--°C

Mean Skin Temperature--°C

Inlet Temperature--°C

39
38
37

34
33
32
31
30
29
28
27

32
30
28
26
24
22
20
18
16

0   30   60   90   120   150

Legend

Subject A = O
Subject B = △
Subject C = ✗
Subject D = ☐

Time from start of work--min
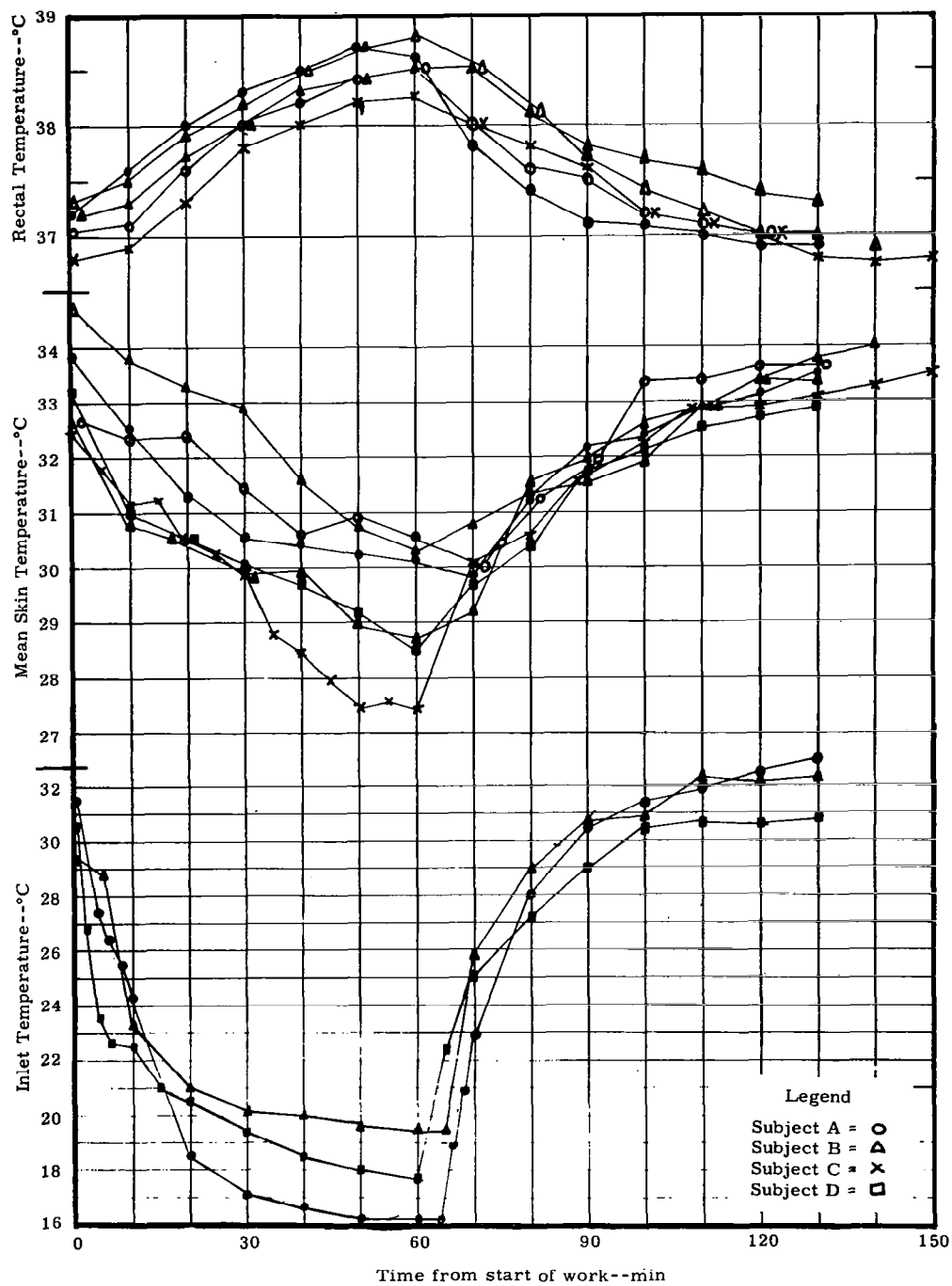
Figure 7. Biothermal responses, activity schedule I
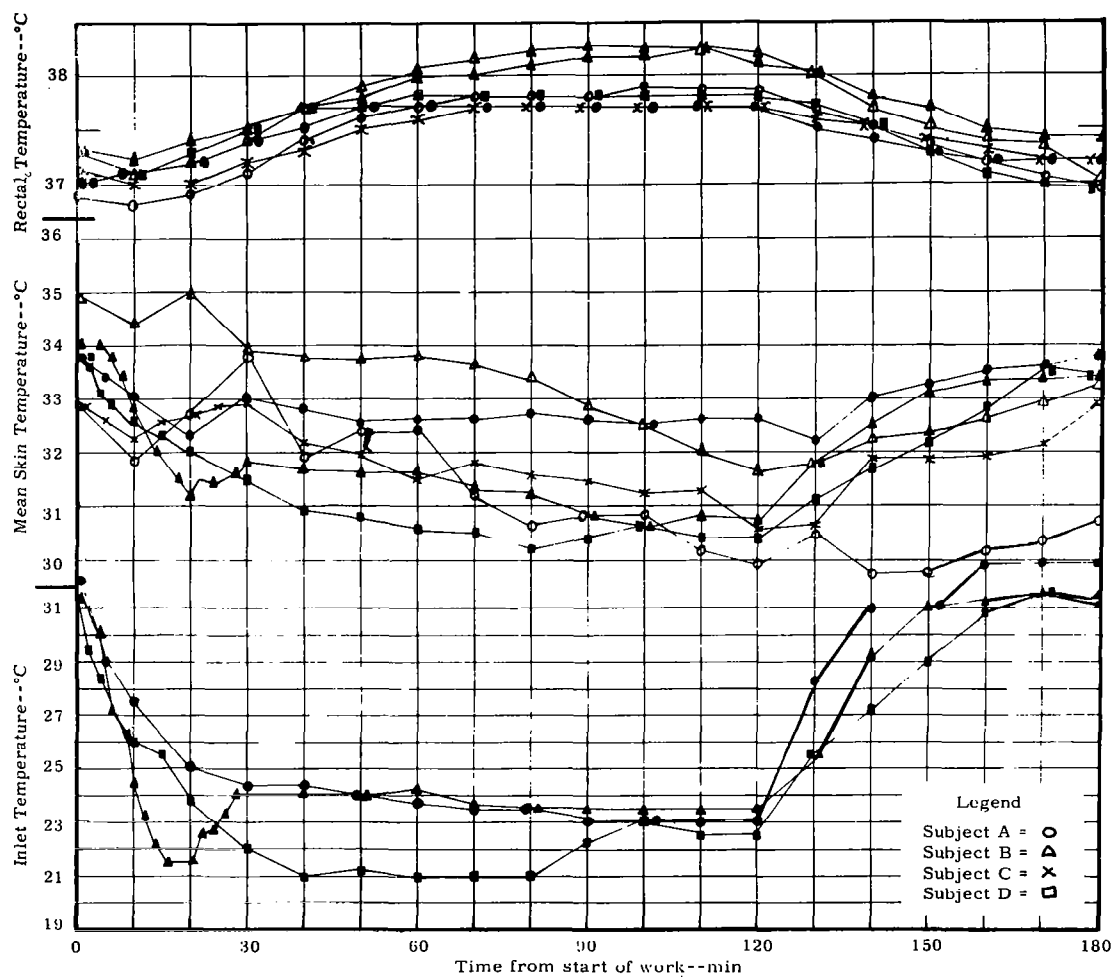
Figure 8. Biothermal responses, activity schedule II

23.
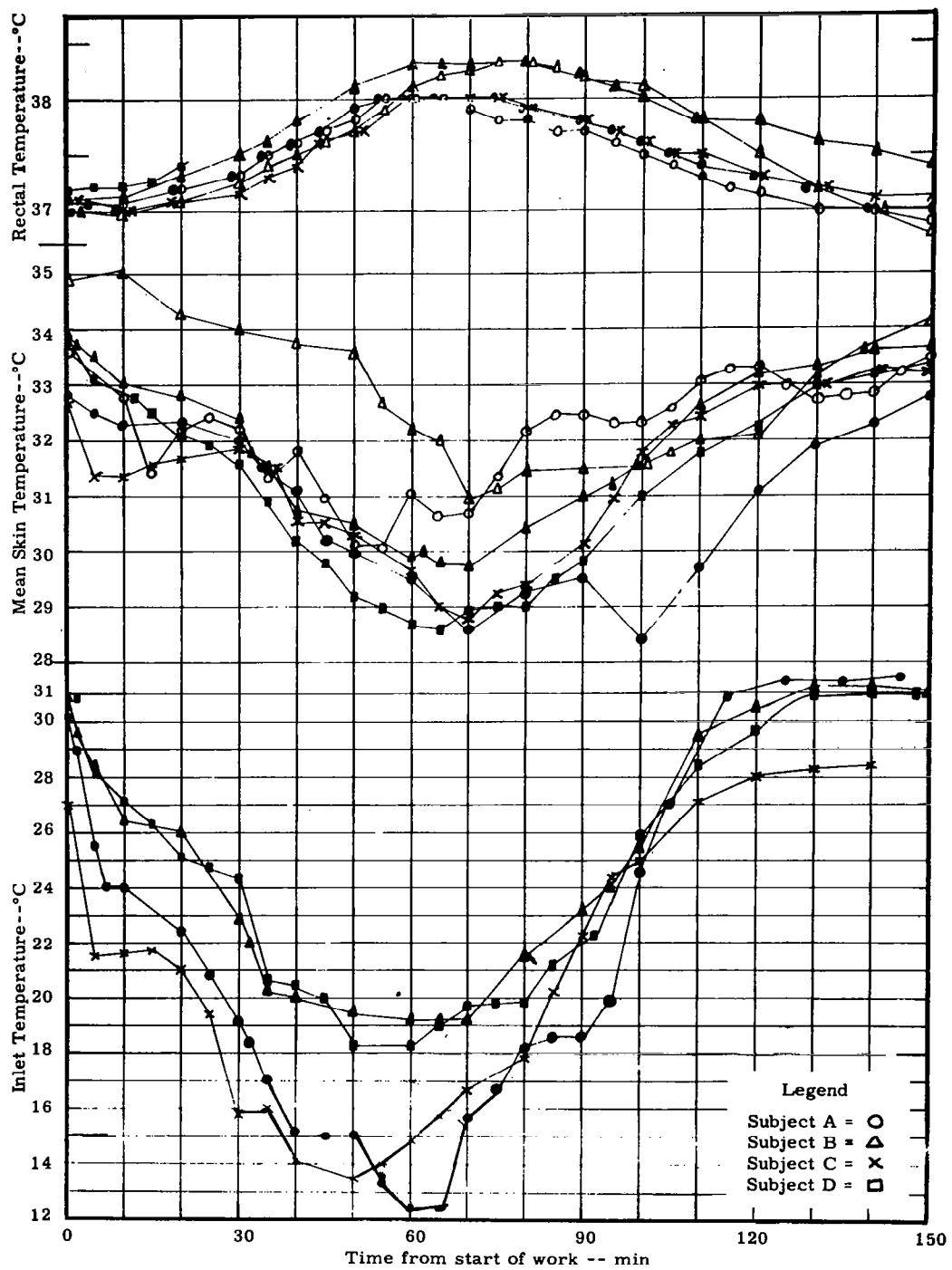
Figure 9. Biothermal responses, activity schedule III

24.
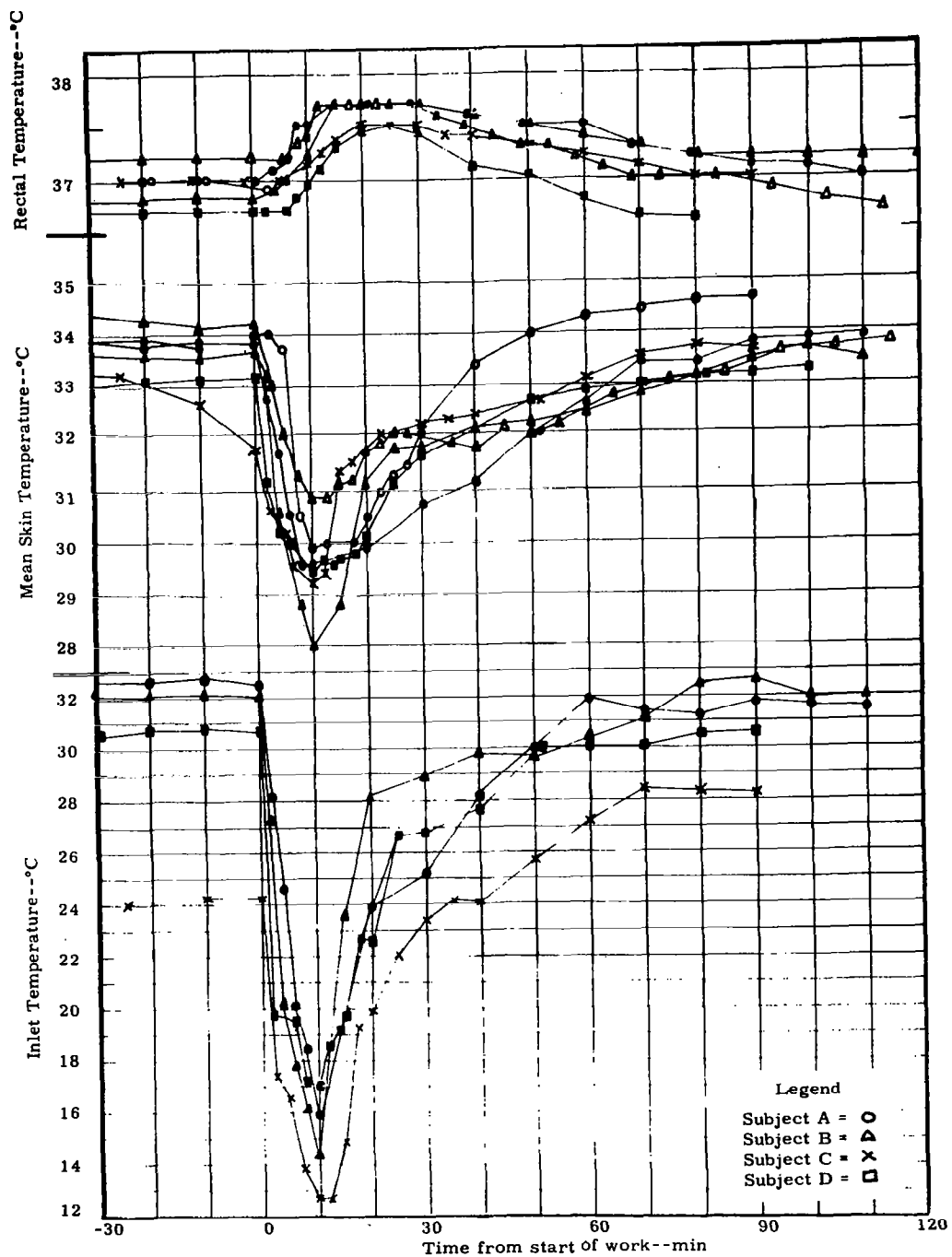
Figure 10. Biothermal responses, activity schedule IV
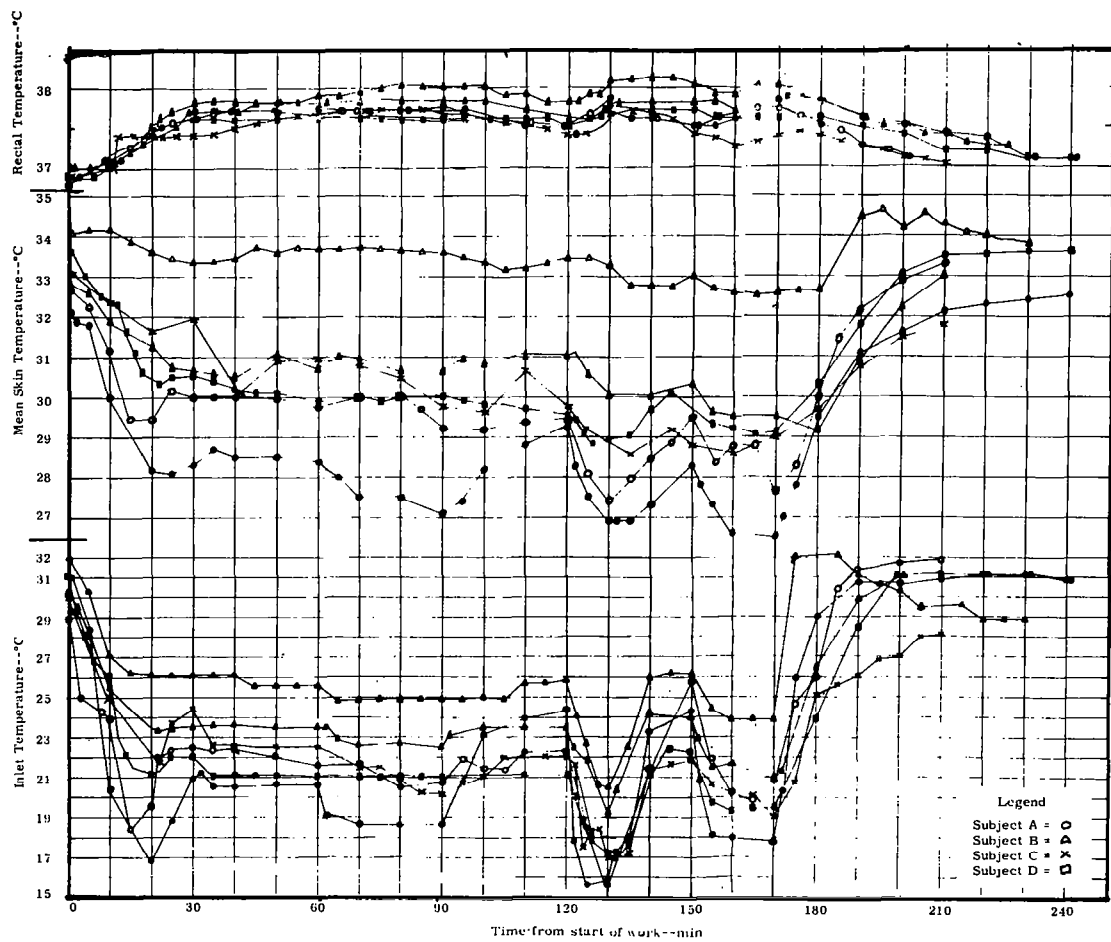
Figure 11. Biothermal responses, activity schedule V

26.
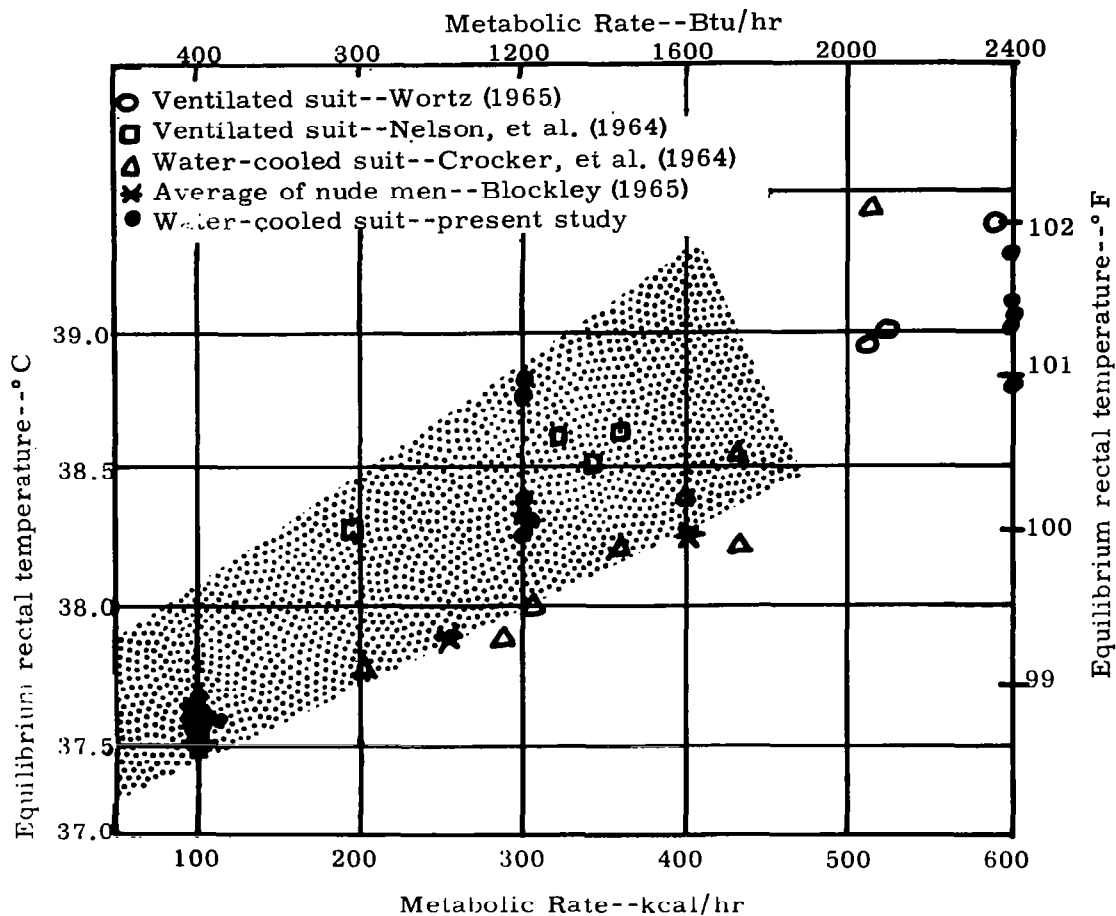
Figure 12. A plot of rectal temperatures at equilibrium (thermal balance) versus work level, incorporating data from many sources. The shaded area is an envelope of data from 5 sources from Webb (1964). The data from the present study are taken only from activity schedules I and II, since they lasted long enough at one metabolic rate to produce equilibrium states.

Table 2. Average heart rates for various metabolic levels

Metabolic Level kcal/min	Average Heart Rate beats/min	Approximate Variation beats/min
1.6 (rest)	75	± 5
3	95	± 5
4	100	± 5
5	105	± 5
6	115	± 5
8	125	± 5
10	150	± 10
15	165	± 5
18	175	± 5

Weight losses for each experiment are shown in Table A-1 of the Appendix. Most experiments had total weight losses below 100 grams/hr.

In order to show what temperature gradient was needed between skin temperature and cooling water for various rates of heat removal, we have shown in Figure 13 Q as a function of the surface Δt (difference between mean skin temperature (t_{sm}) and water inlet temperature (t_i)). Only fairly stable data from activity schedules I, II, and III are shown, and in only those later runs where flow was fixed. The straight line connecting the means of the data appears to be representative. This suggests that even at high rates of heat removal, associated with low mean skin temperatures, there was cutaneous circulation bringing heat to the surface for removal, and that vasoconstriction was not pronounced.

However, inspection of the individual experiments where the work level was high (activity schedules IV and V) shows that heat removal did not match heat production. At the lower work rates, Q sooner or later approached the estimated heat production; not so when the period was short or the metabolic rate was above 8 - 10 kcal/min. In Figure 14 we have plotted the highest values for Q, corrected for evaporative loss and external work, against metabolic rate for all the experiments. At high work rates Q does not equal heat production. This is perhaps largely due to the shorter times used for the higher work levels. But the effect may also be due to some upper limit of thermal conductance from core to surface. Other experimental work would be needed to establish what this limit is.
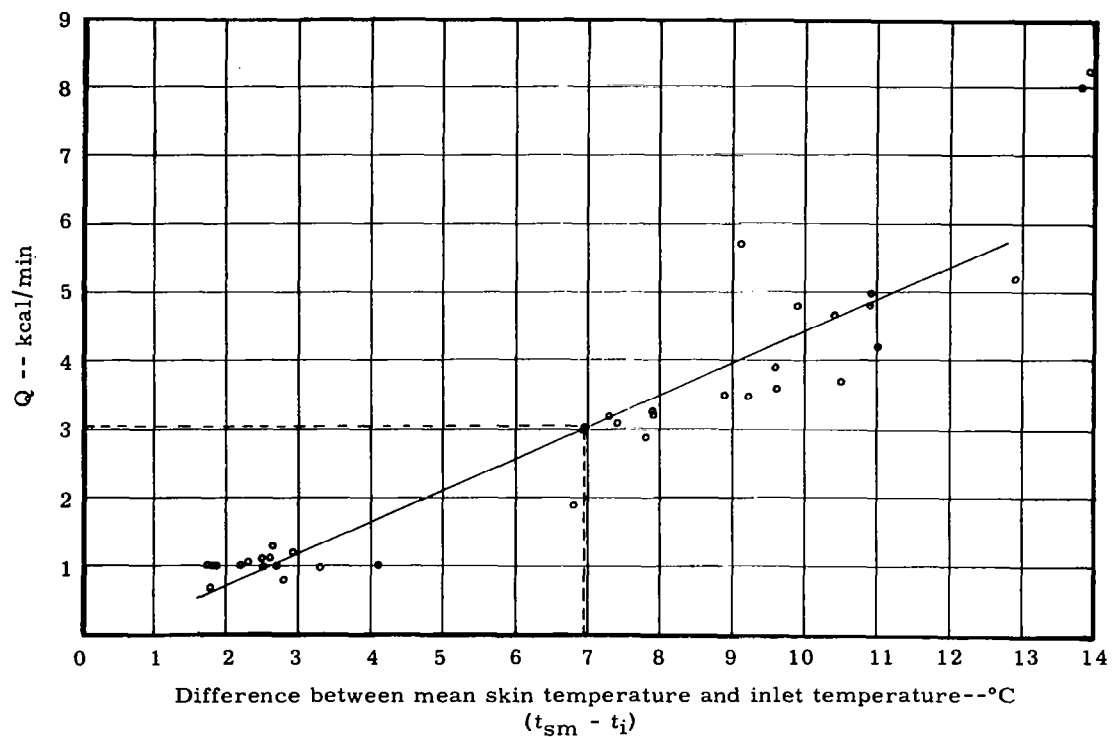
Figure 13. Q as a function of the difference between mean skin temperature (t_{sm}) and water inlet temperature (t_i).
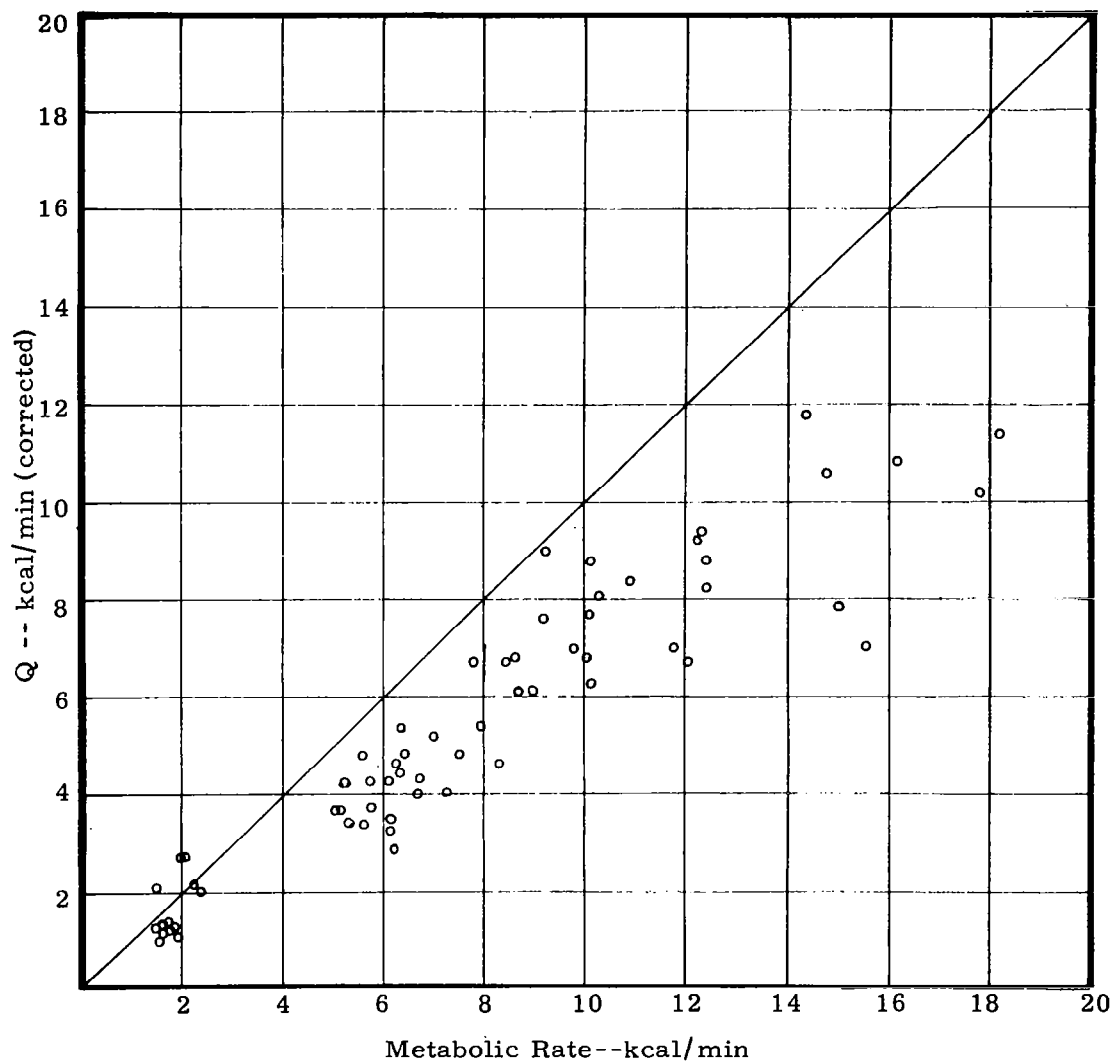
Figure 14. Highest values of Q versus metabolic rate.

DISCUSSION

The experiments reported here are significant in that they present for the first time fairly complete physiological data, or bio-thermal responses, of men at several work levels properly cooled in water cooled clothing. This information is essential for the design of a control system which would do automatically what we were doing by hand during these experiments. Water cooled clothing offers a powerful means of removing body heat, enough to be able to keep up with the heat dissipation required by a man doing nearly any sort of activity. It is so powerful, in fact, that one can not only drive the skin temperature to any desired level, one can cause overcooling and vasoconstriction during strenuous work. A controller must have some sort of information to work with, and at this point we are still holding the position that the most appropriate input signal to a controller would be oxygen uptake.

Further study of the data reported here may show how some other variables can be used for the input to a controller. For example, when a man is being properly cooled, we noticed an immediate change in Q when the work changed. This in itself might constitute at least the initial signal for a controller. The detection of sweating is another means of correcting or limiting the behavior of a controller, but it may be too slow and lead to large control oscillations. The measurement of skin temperature, even with only a few sampling points, might be yet another way to correct the behavior of a controller. Finally, pulse rate is an excellent indicator of metabolic level, and it is also an excellent indicator of other things like excitement, which may not have meaning in terms of metabolic heat production.

Analysis in depth of the present data will lead, we hope, to the design of an automatic controller which will be suitable for use in a PLSS and will allow an active astronaut doing extravehicular work to be properly cooled no matter what the work level nor what the period of work.

REFERENCES

1. BLOCKLEY, W. V. Human sweat response to activity and environment in the compensable zone of thermal stress: a systematic study. NASA CR-65260, National Aeronautics and Space Administration, Washington, D. C., 1965.

2. BURTON, D. R. Performance of water conditioned suits. Aerospace Med. 37: 500-504, 1966.

3. BURTON, D. R. and L. COLLIER. The development of water conditioned suits. Tech. Note ME-400, Royal Aircraft Establishment, Farnborough, England, 1964.

4. CROCKER, J. F., P. WEBB, and D. C. JENNINGS. Metabolic heat balances in men wearing liquid-cooled sealed clothing. AIAA-NASA Third Manned Spaceflight Meeting (AIAA publication CP-10), 111-117, 1964.

5. NELSON, W. G., L. BROWN, and L. R. KRUMLAND. Preliminary results of the Gemini extravehicular suit pressurization--ventilated test series. Report No. 55-3135, AiResearch Manufacturing Co., Los Angeles, 1964.

6. NIELSEN, M. Die regulation der Korpertemperatur bei muskelarbeit. Skand. Arch. Physiol. 79: 193-230, 1938.

7. ROTH, E. M. Bioenergetics of space suits for lunar exploration. NASA SP-84, National Aeronautics and Space Administration, Washington, D.C., 1966.

8. SANTAMARIA, L. J., M. B. BURGESS, and D. D. DERY. Physiological effects of water-cooling and oxygen ventilation in different space flight conditions. (Abstract) Aerospace Med. 37: 300, 1966.

9. STREIMER, I., D. P. W. TURNER, C. A. TARDIFF, and T. L. STEPHENS. An investigation of the effects of pressure suit wearing on work output characteristics. Aerospace Med. 35: 747-751, 1964.

10. VEGHTE, J. H. Efficacy of air cooling systems in pressure suits in hot environments. Preprints, 36th Annual Scientific Meeting, Aerospace Medical Association, Washington, D. C., 1965.

11. WALIGORA, J. M. and E. L. MICHEL. Application of conductive cooling for working men in a thermally isolated environment. (Abstract) Aerospace Med. 37: 306, 1966.

12. WEBB, P. (editor). Bioastronautics Data Book. NASA SP-3006, National Aeronautics and Space Administration, Washington, D. C., 1964.

13. WORTZ, E. C. Full pressure suit heat balance studies. Report No. LS-140, AiResearch Manufacturing Co., Los Angeles, 1965.

14. WORTZ, E. C., D. K. EDWARDS, and T. J. HARRINGTON. New techniques in pressure suit cooling. Aerospace Med. 35: 978-984, 1964.

APPENDIX

The complete experimental data are shown in Figures A-1 through A-30. Table A-1 shows a grouping of the 30 experiments by activity schedule with identifying information and other data.

Table A-1. Grouping of the 30 experiments by activity schedule
with identifying information and other data

Activity Schedule	Fig.	Subj.	Expt.#	Water Flow ml/min	Air Flow cfm	Outer Insulation	Weight Loss gm/hr
I	A-1	A	3	200-2000	0	-	100
	A-2	A	17	1500	2	+	105
	A-3	B	4	200-1500	0	-	74
	A-4	B	19	1500	2	+	86
	A-5	C	10	300-2000	0	+	44
	A-6	D	21	1500	2	+	91
II	A-7	A	1	200-750	0	-	97
	A-8	A	23	1500	2	+	102
	A-9	B	2	200-1000	0	-	59
	A-10	B	22	1500	2	+	66
	A-11	C	8	200-750	0	-	40
	A-12	D	24	1500	2	+	48
III	A-13	A	5	200-1500	0	-	43
	A-14	A	27	1500	2	+	70
	A-15	B	6	200-1250	0	-	41
	A-16	B	28	1500	2	+	84
	A-17	C	11	1500	0	+	37
	A-18	D	25	1500	2	+	61
IV	A-19	A	7	200-2000	0	-	52
	A-20	A	16	1500	2	+	105
	A-21	B	9	300-2000	0	-	29
	A-22	B	18	1500	2	+	86
	A-23	C	12	1500	0	+	27
	A-24	D	20	1500	2	+	48
V	A-25	A	13	1500	0	+	74
	A-26	A	30	1500	2	+	32
	A-27	B	14	1500	0	+	70
	A-28	B	29	1500	2	+	69
	A-29	C	15	1500	2	+	70
	A-30	D	26	1500	2	+	62
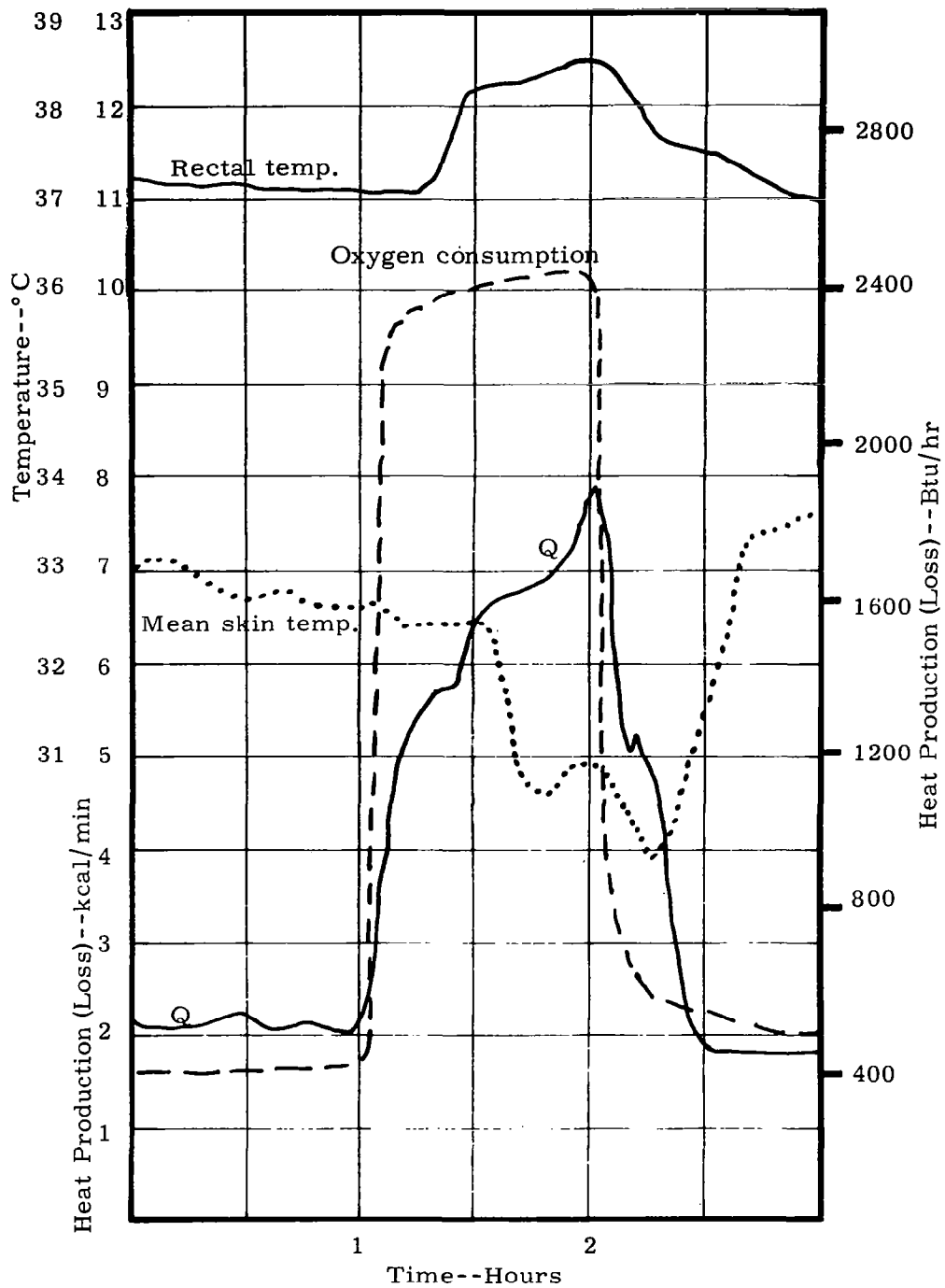
Figure A-1. Schedule I, Subject A

36.
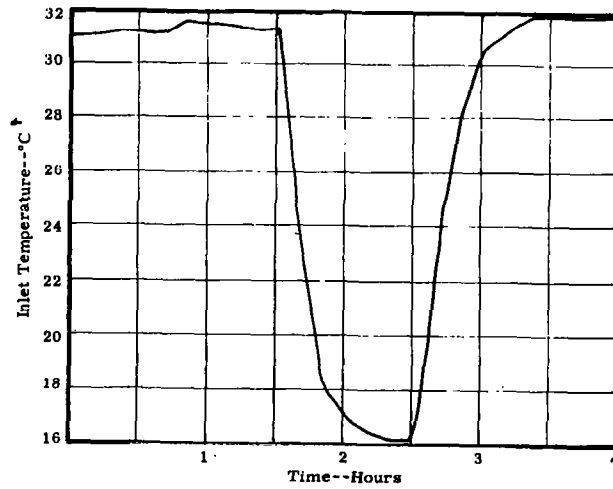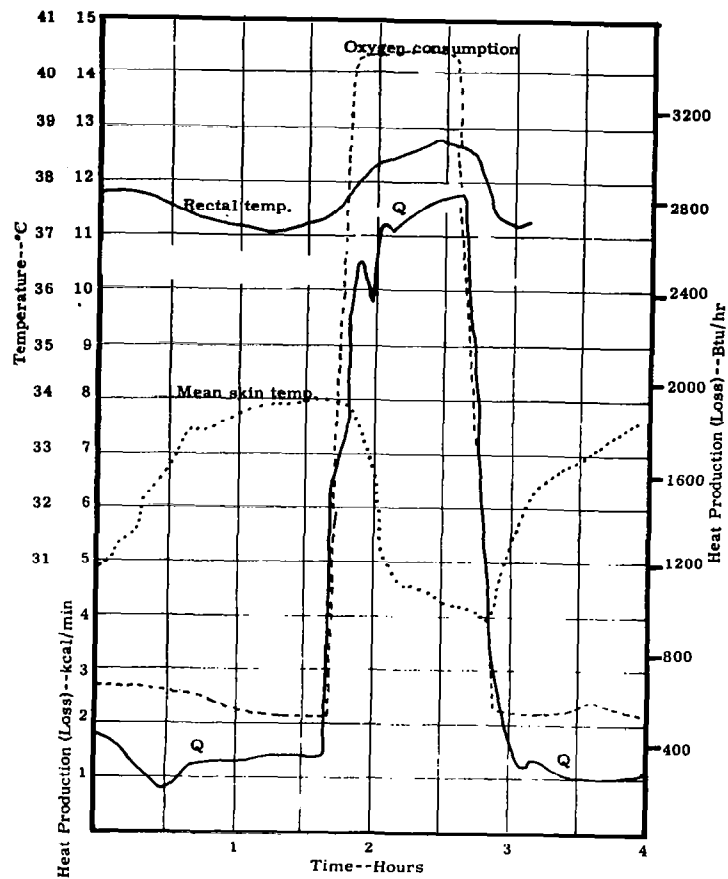
Figure A-2. Schedule I, Subject A
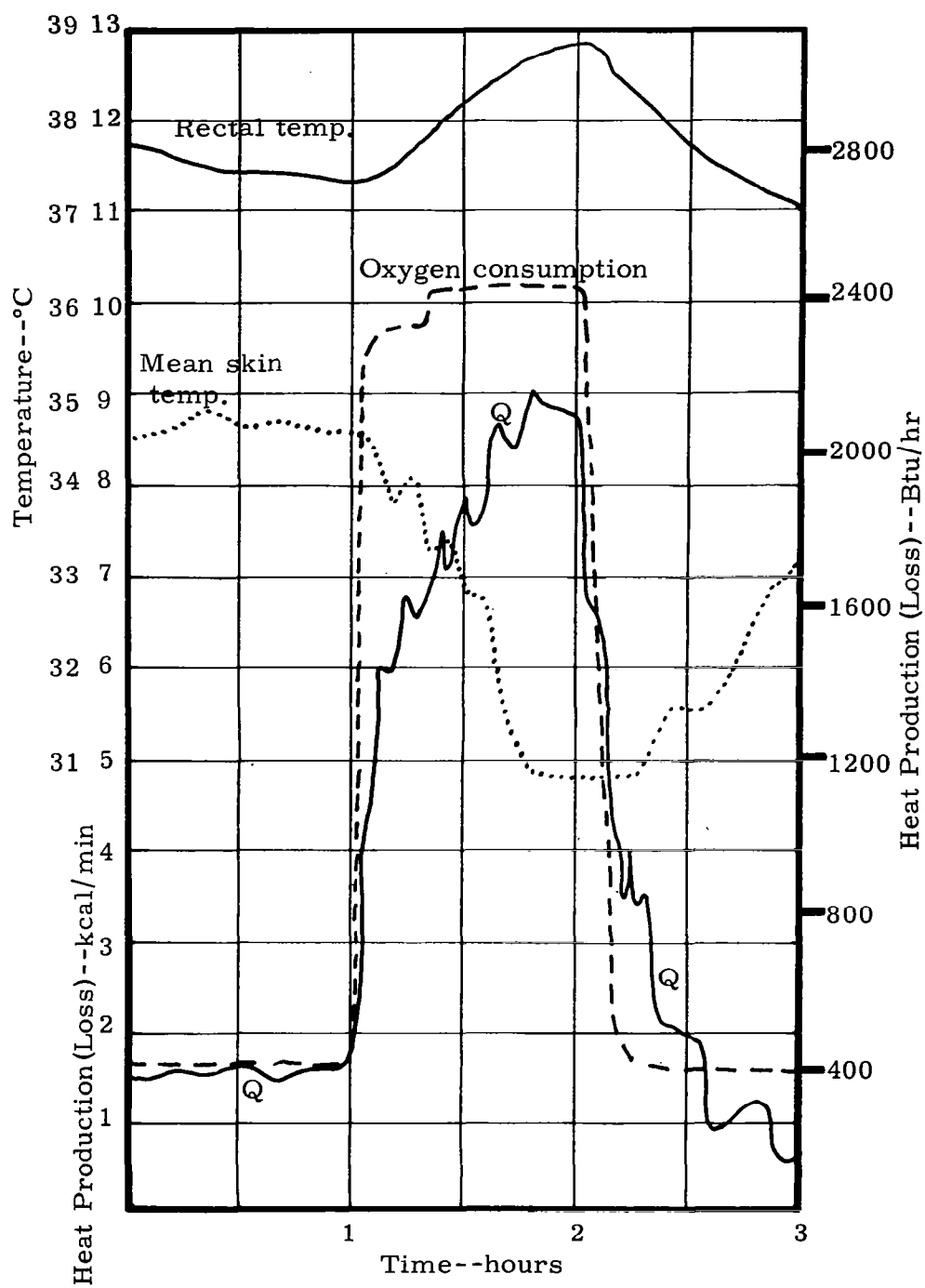
Figure A-3. Schedule I, Subject B
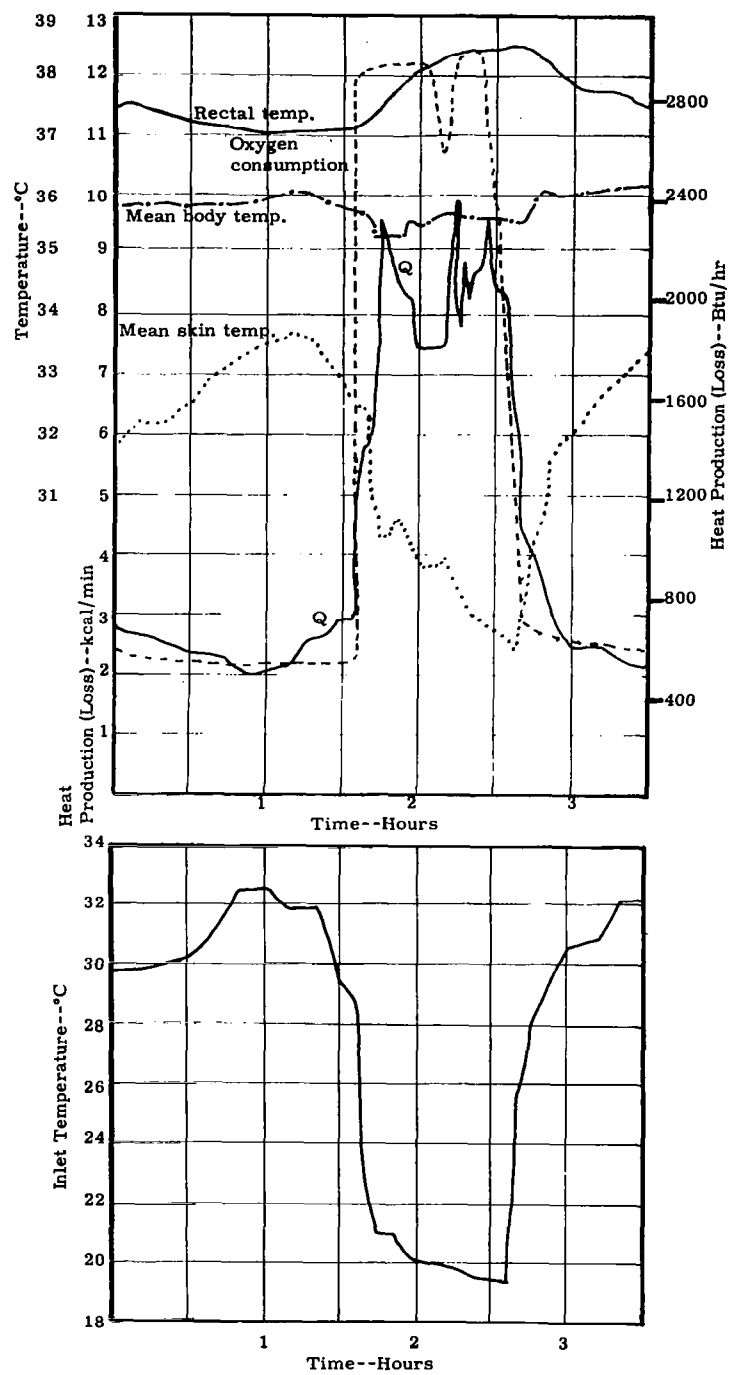
Figure A-4. Schedule I, Subject B
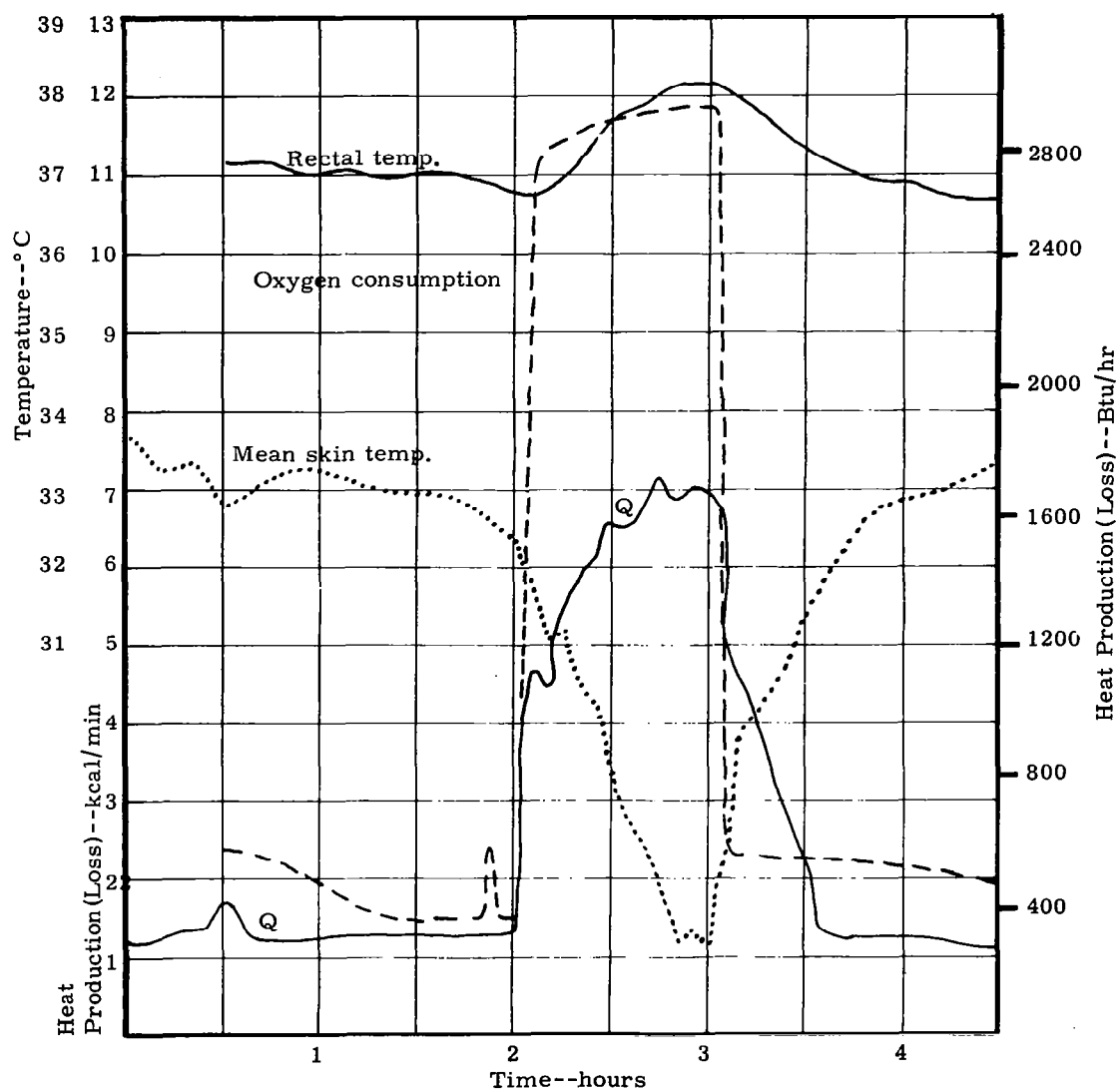
Figure A-5. Schedule I, Subject C
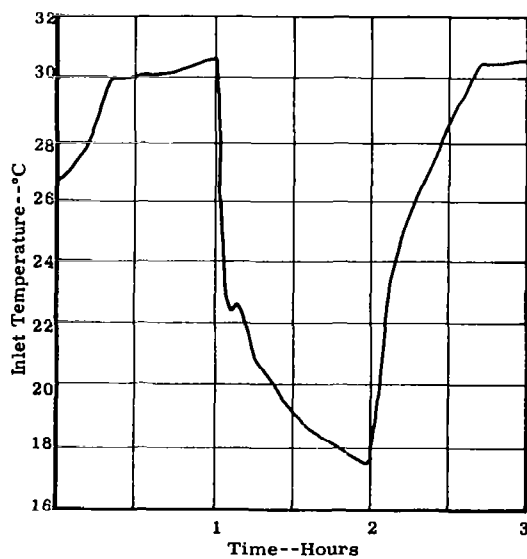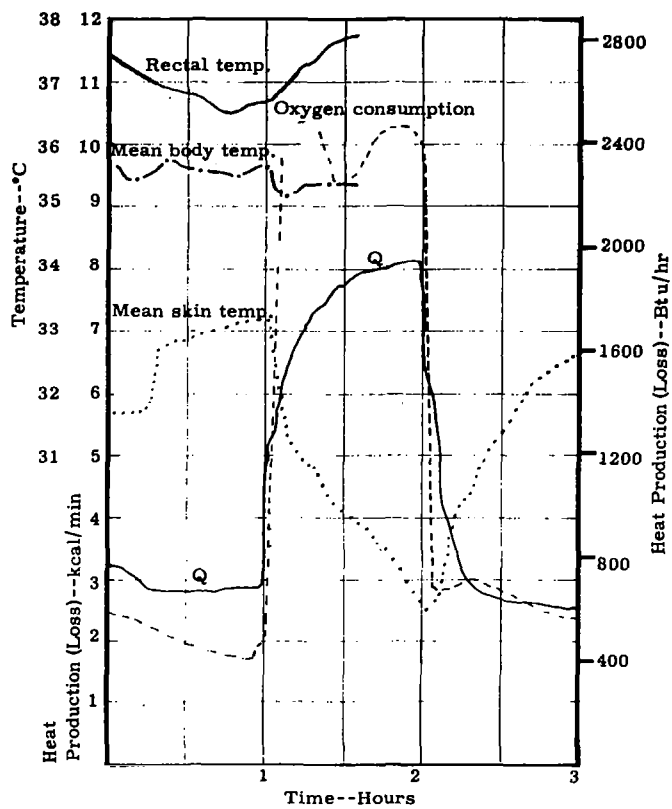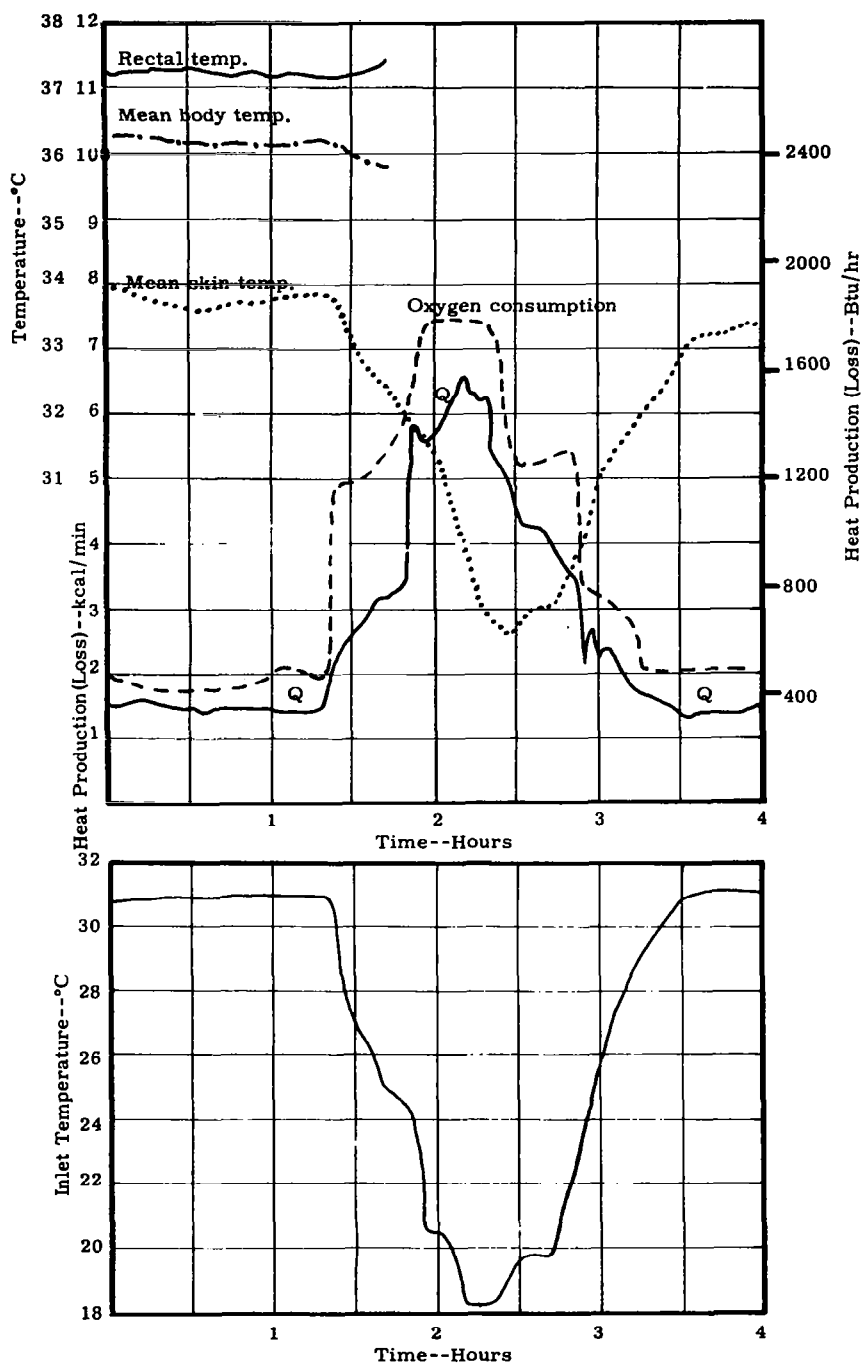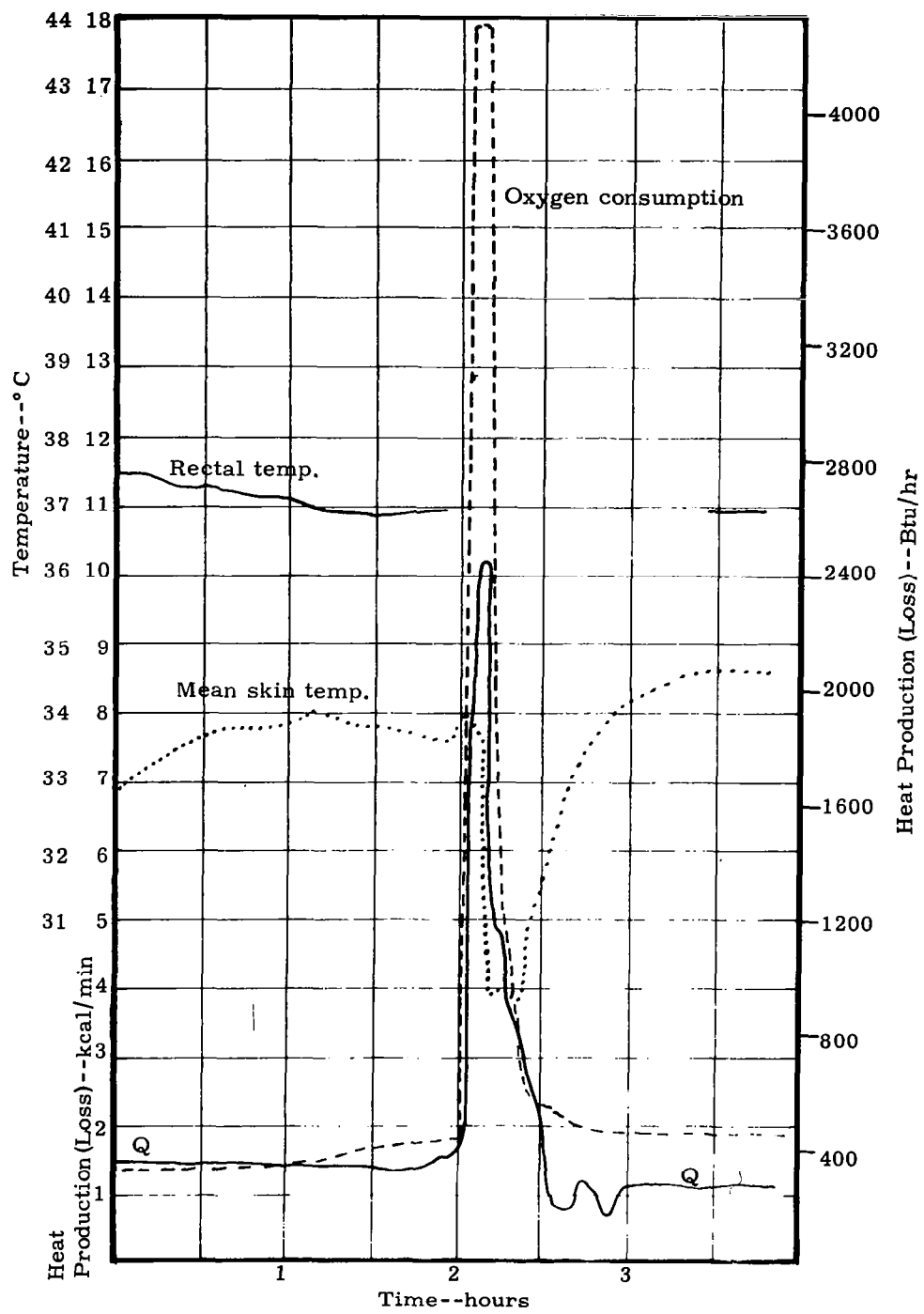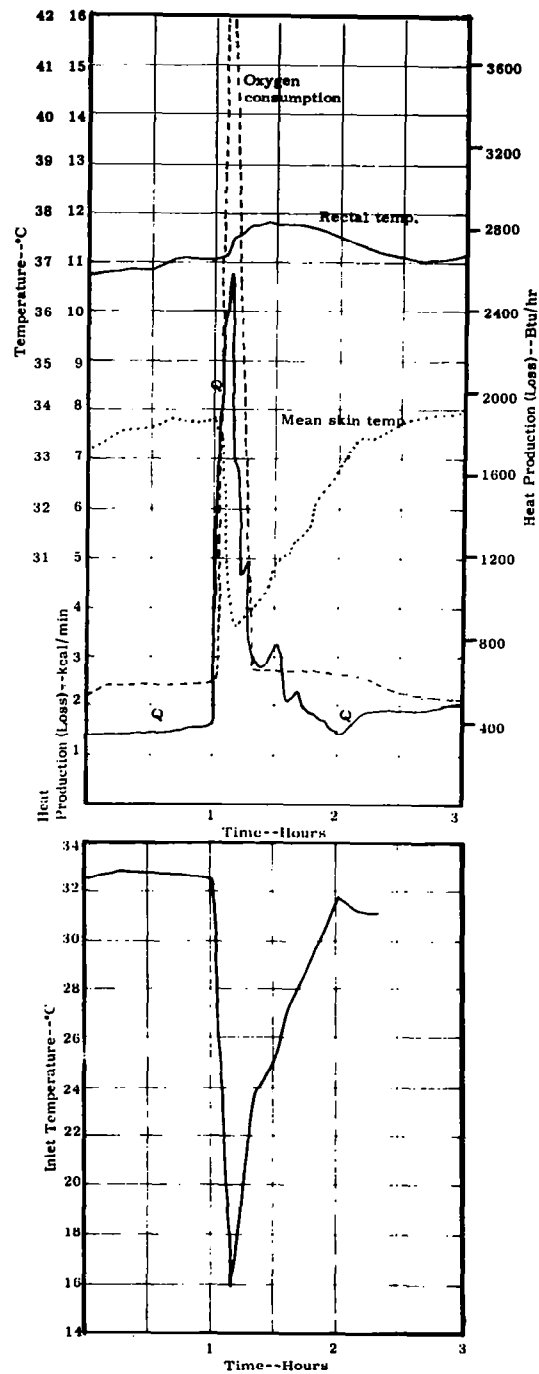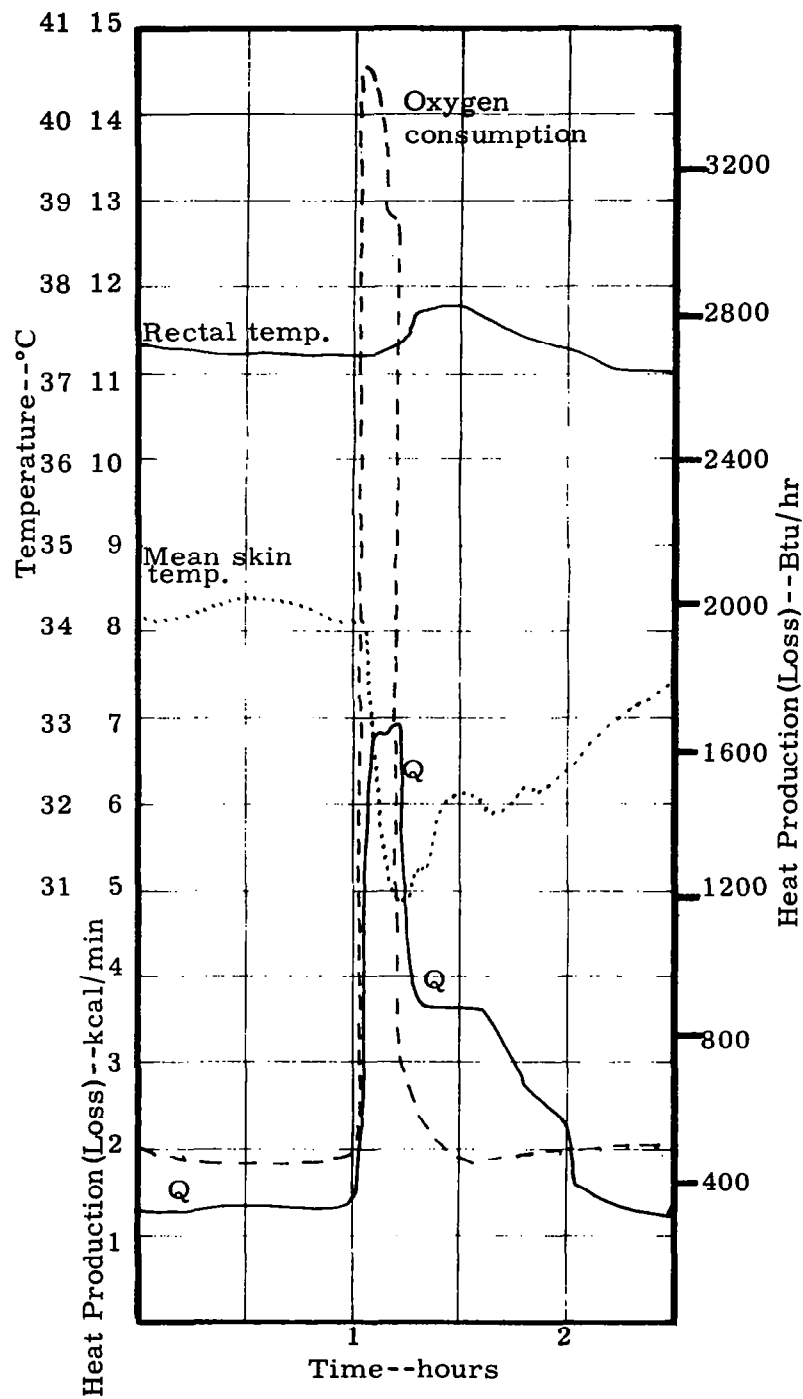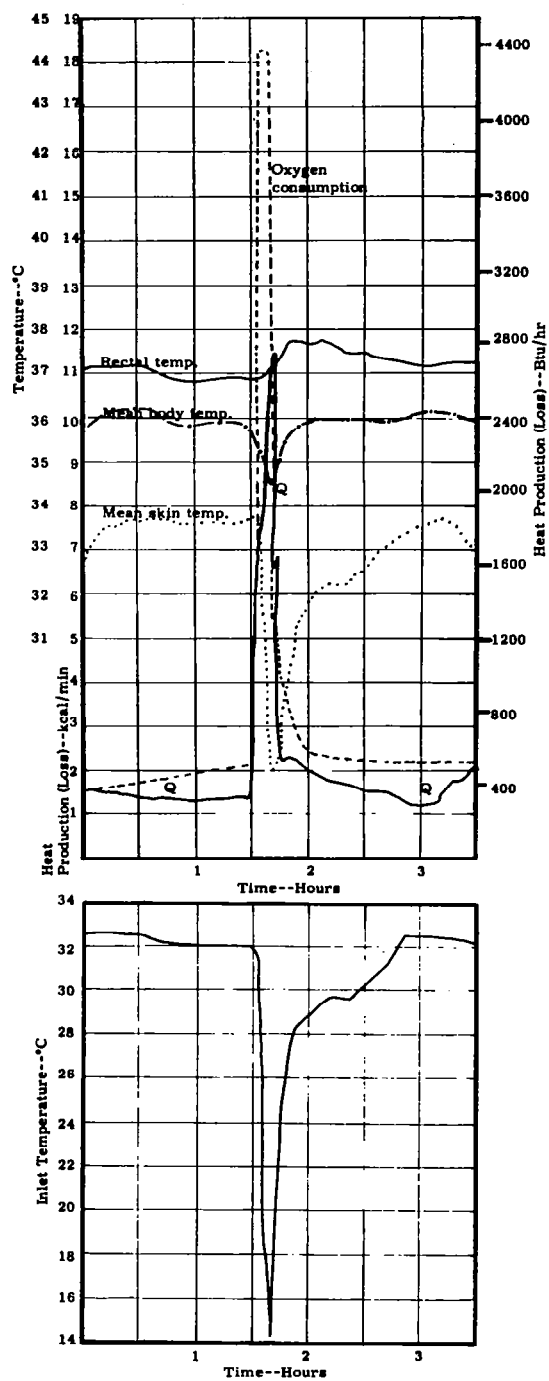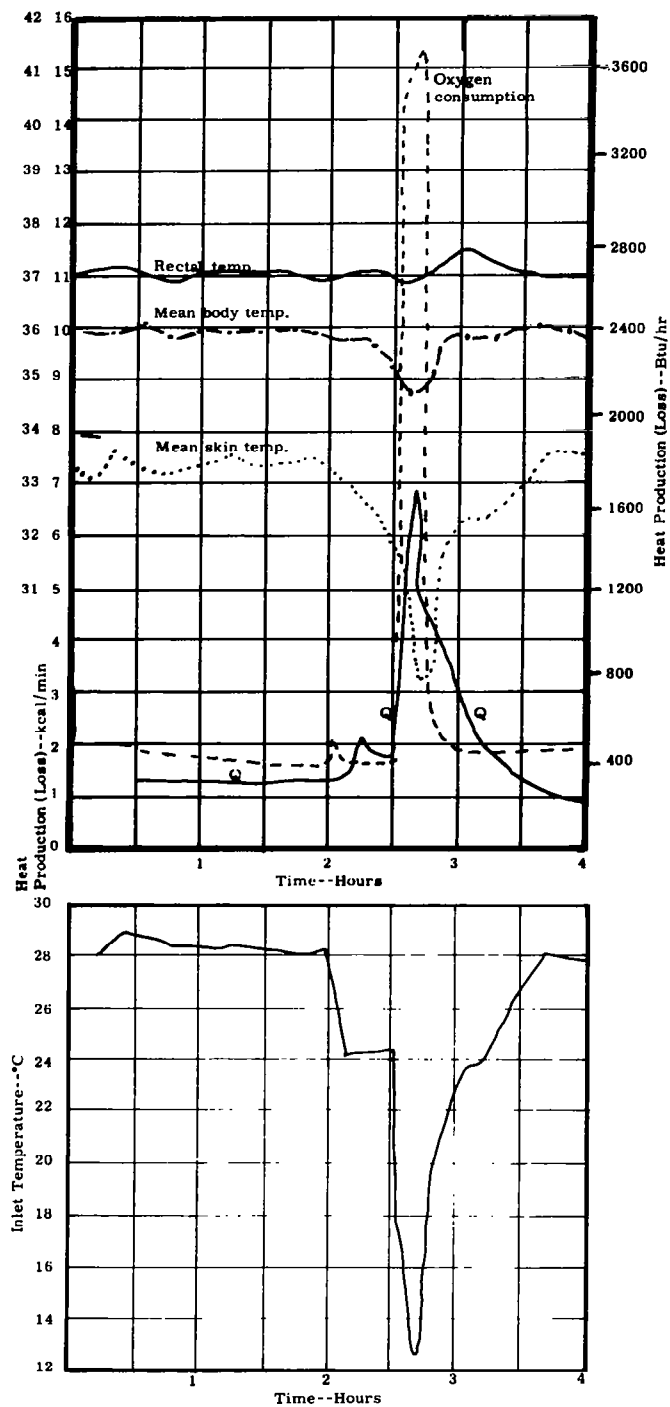
Figure A-6. Schedule I, Subject D
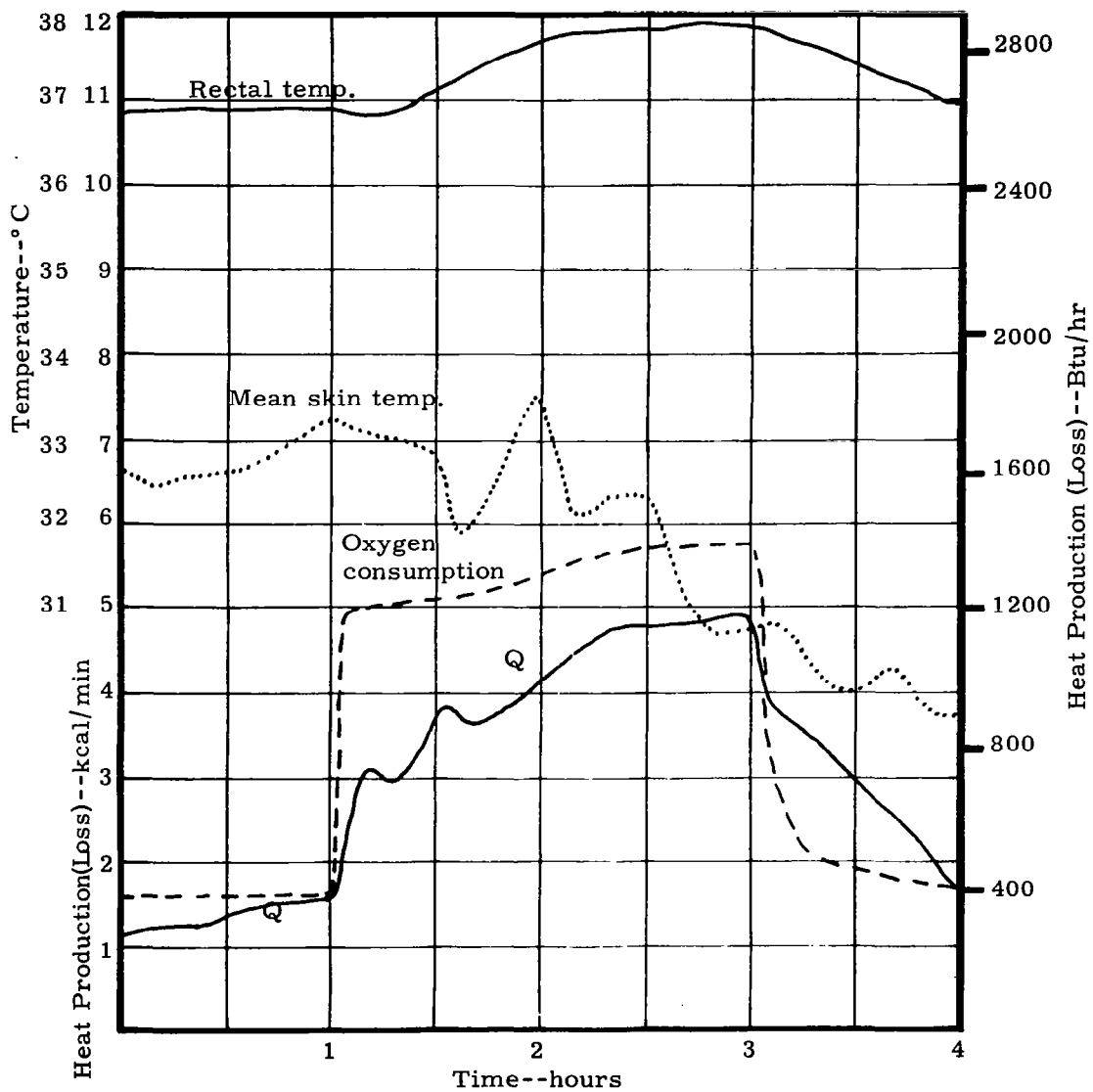
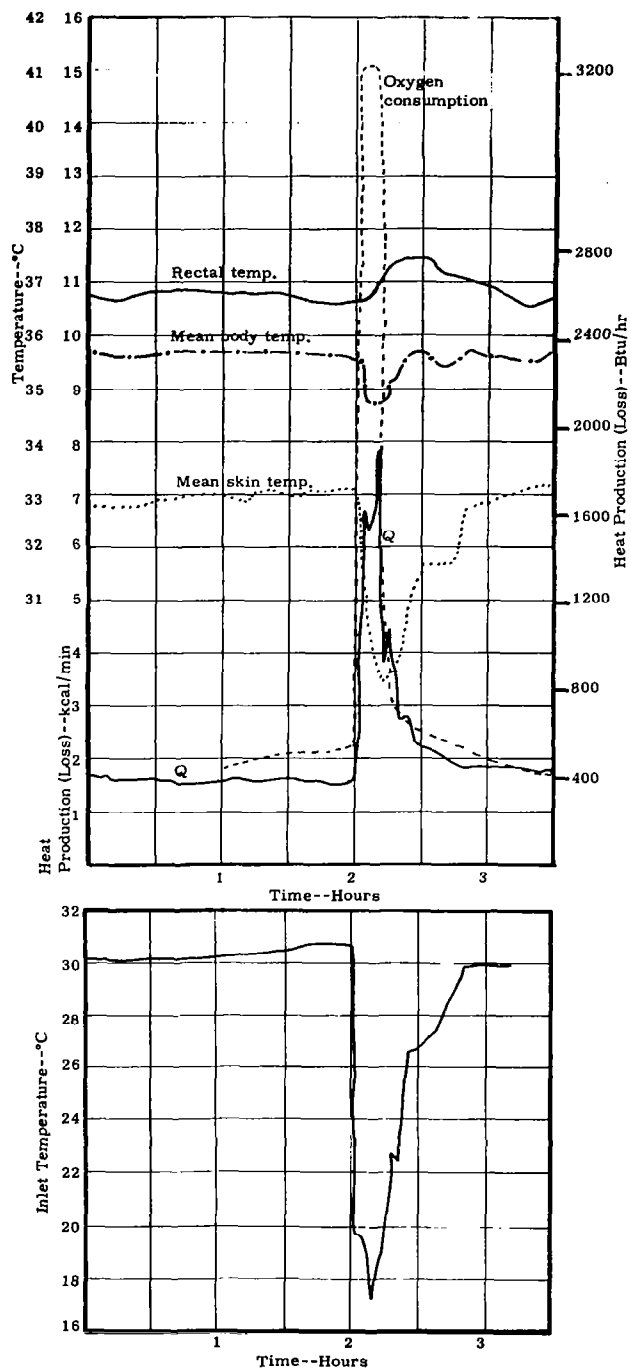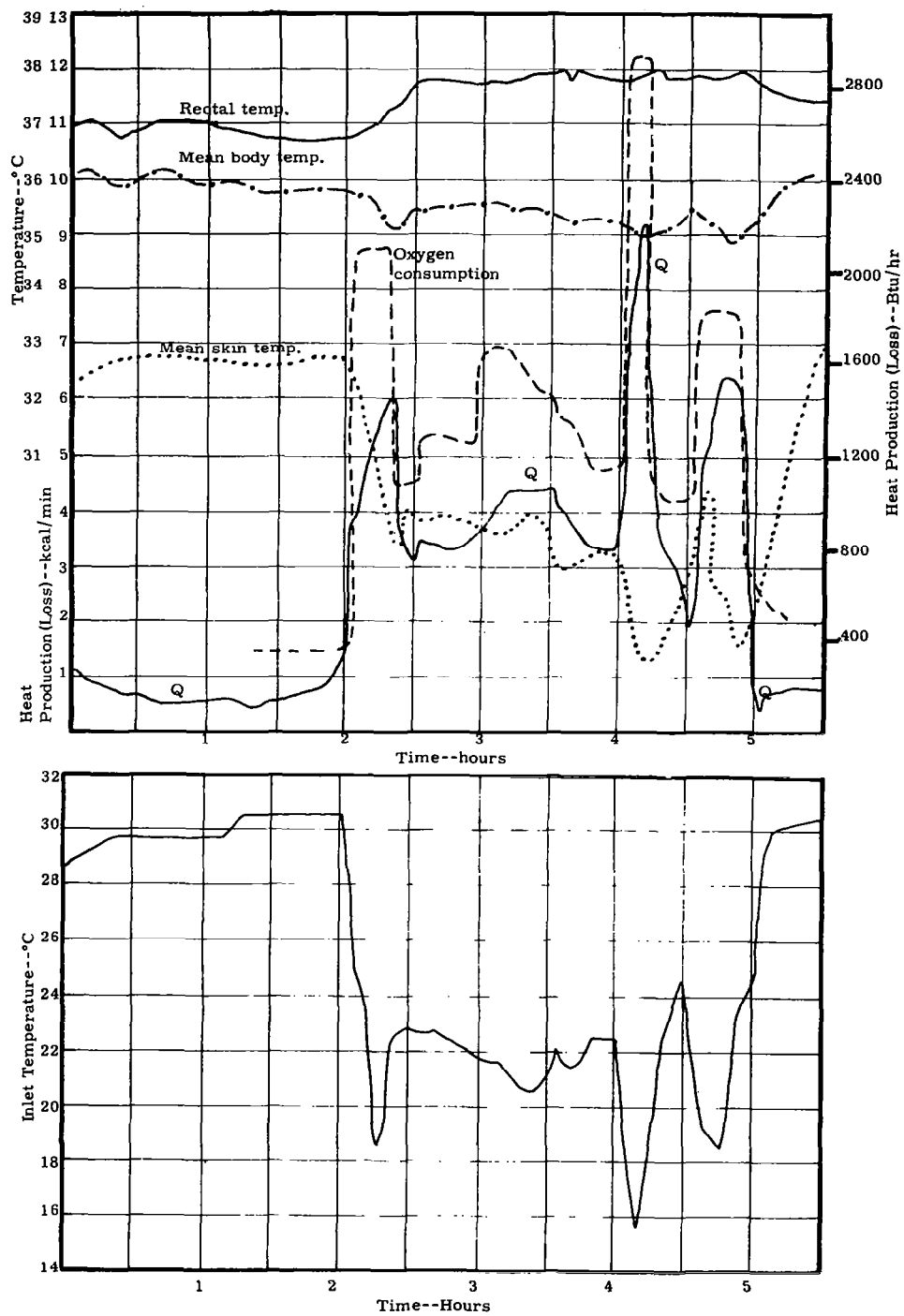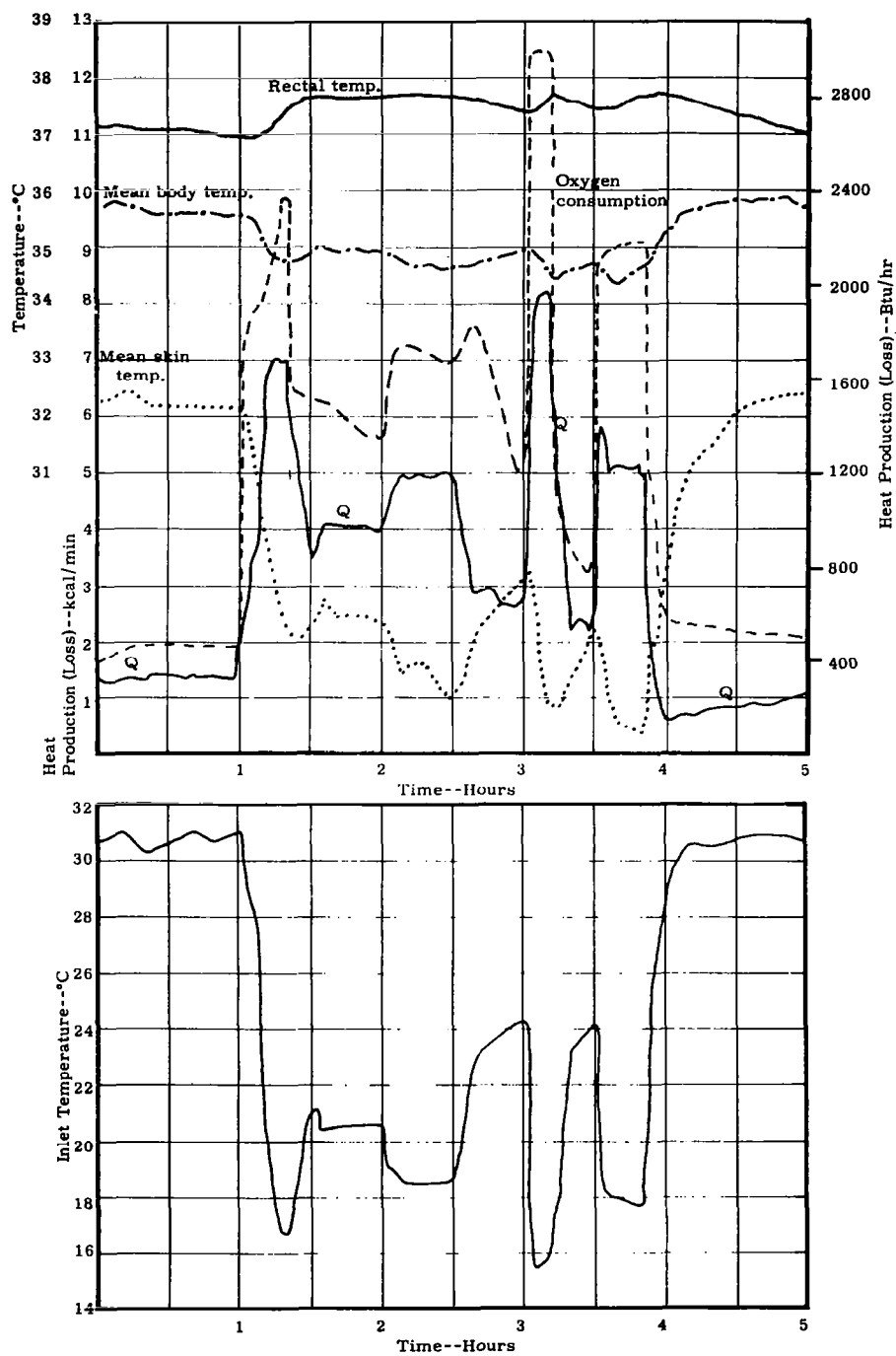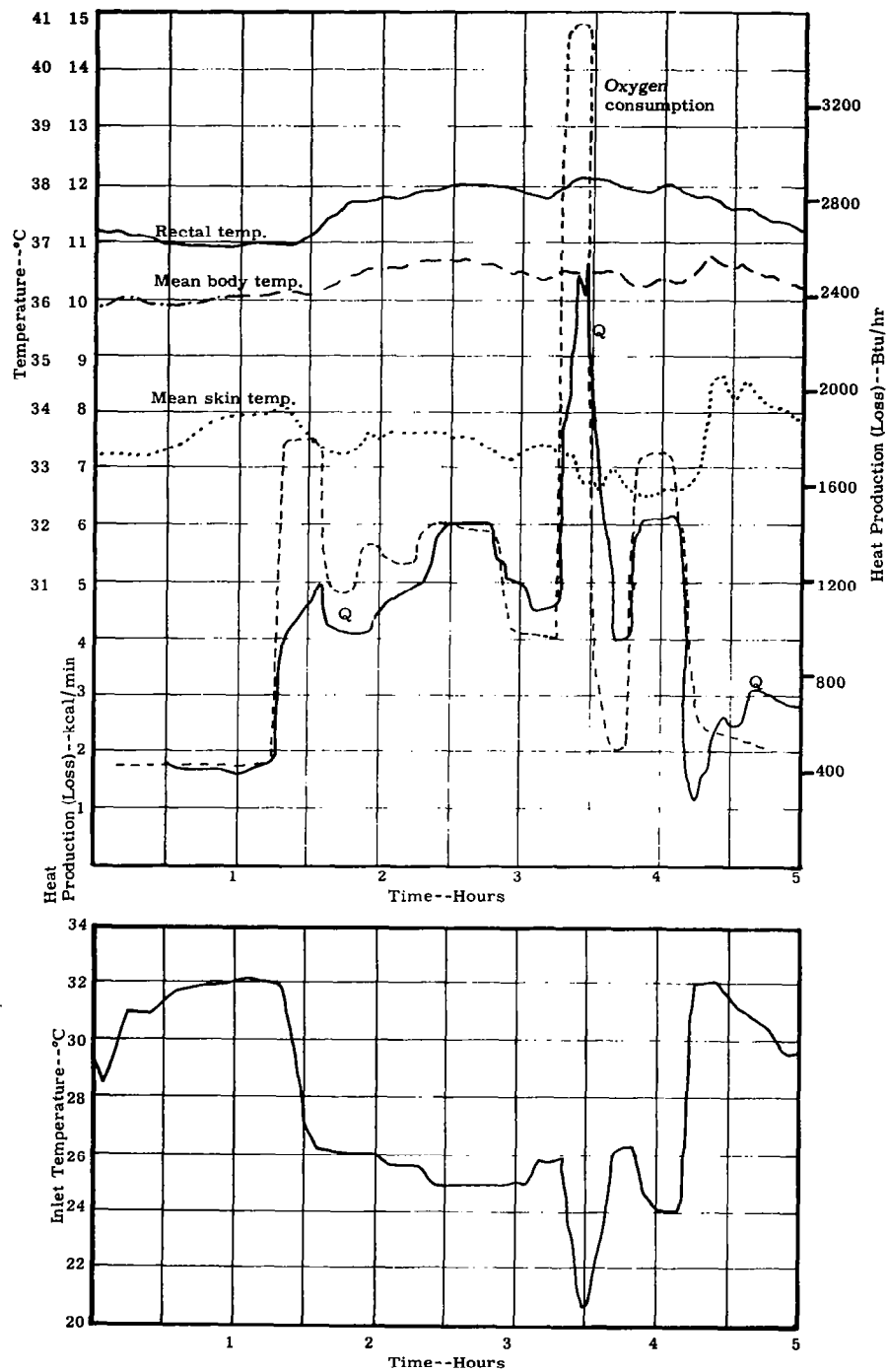Figure A-7.   Schedule II, Subject A
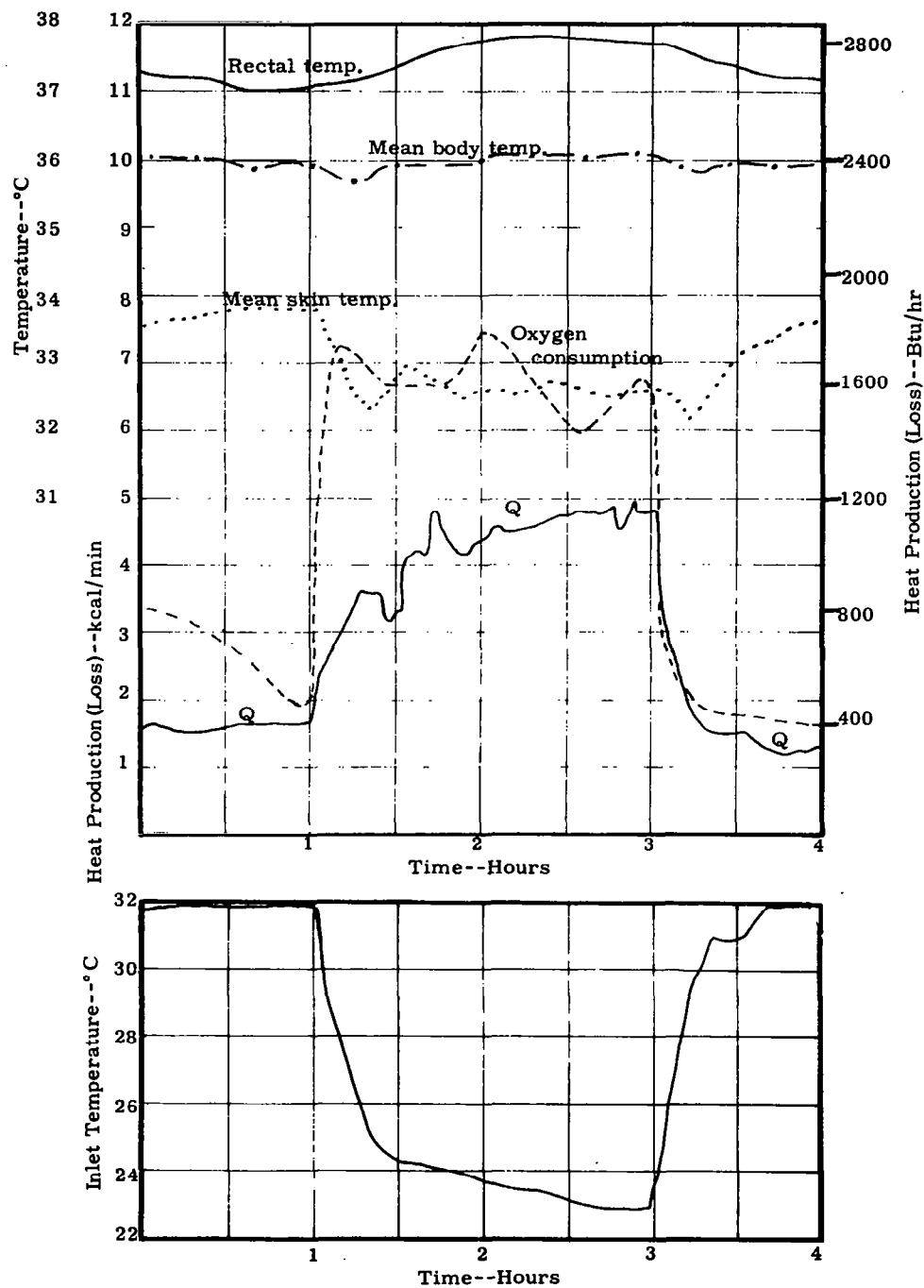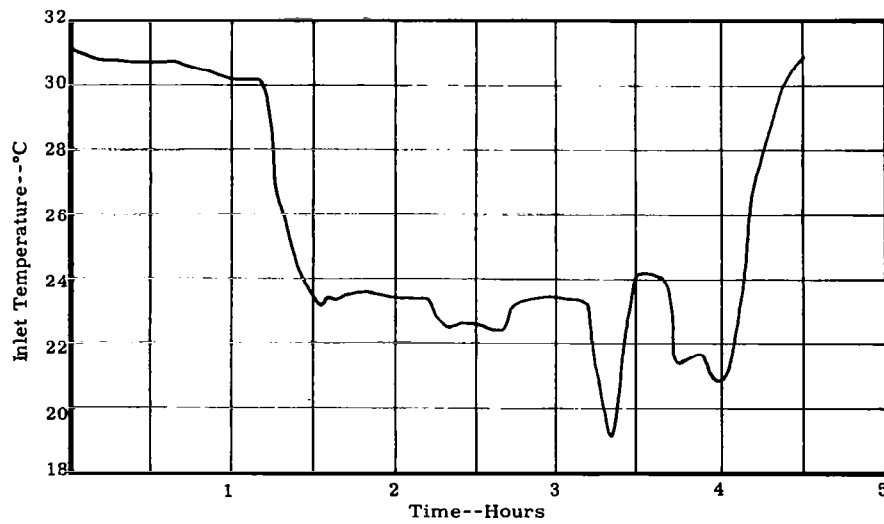
Figure A-8. Schedule II, Subject A
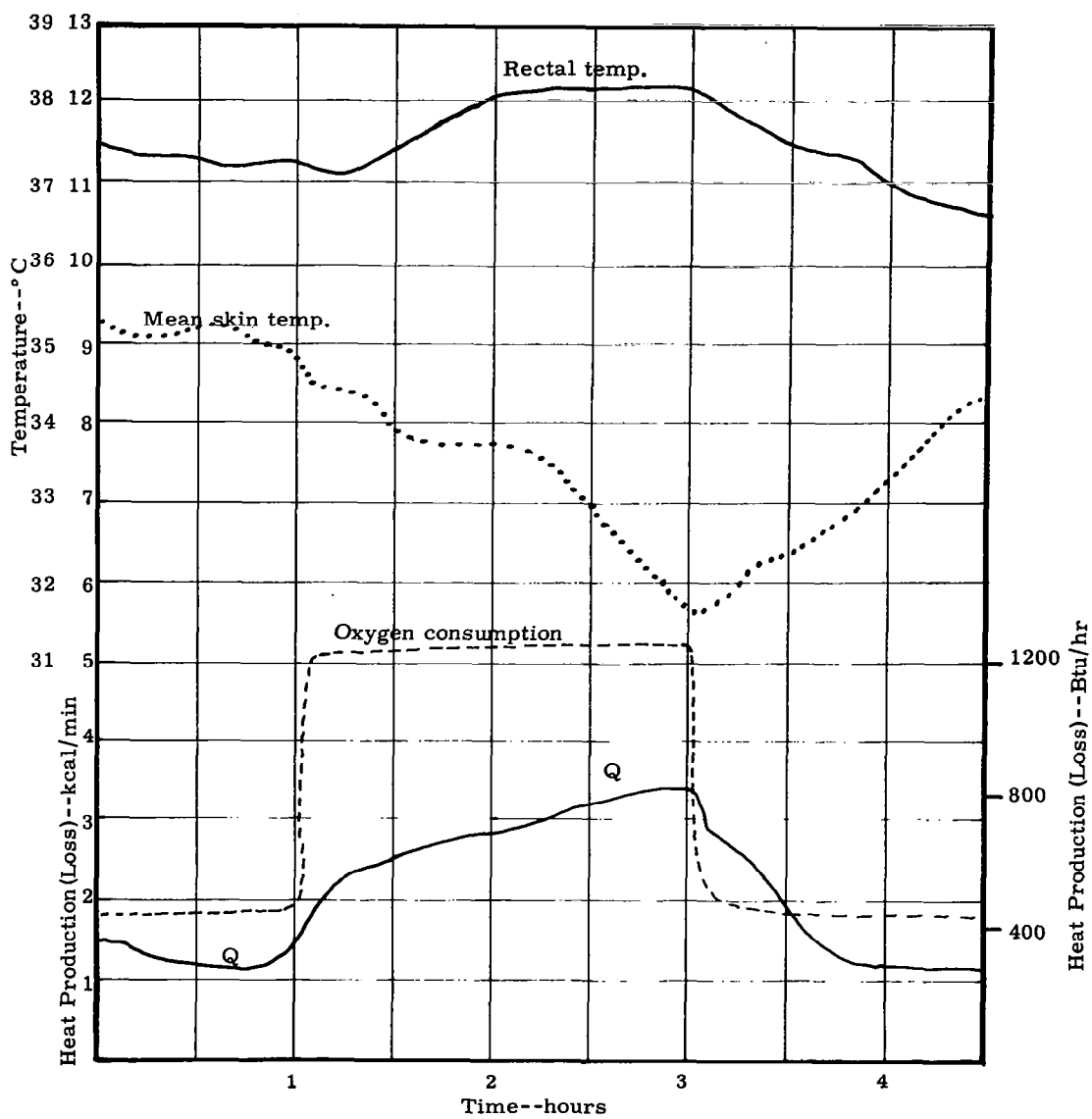
Figure A-9.   Schedule II, Subject B
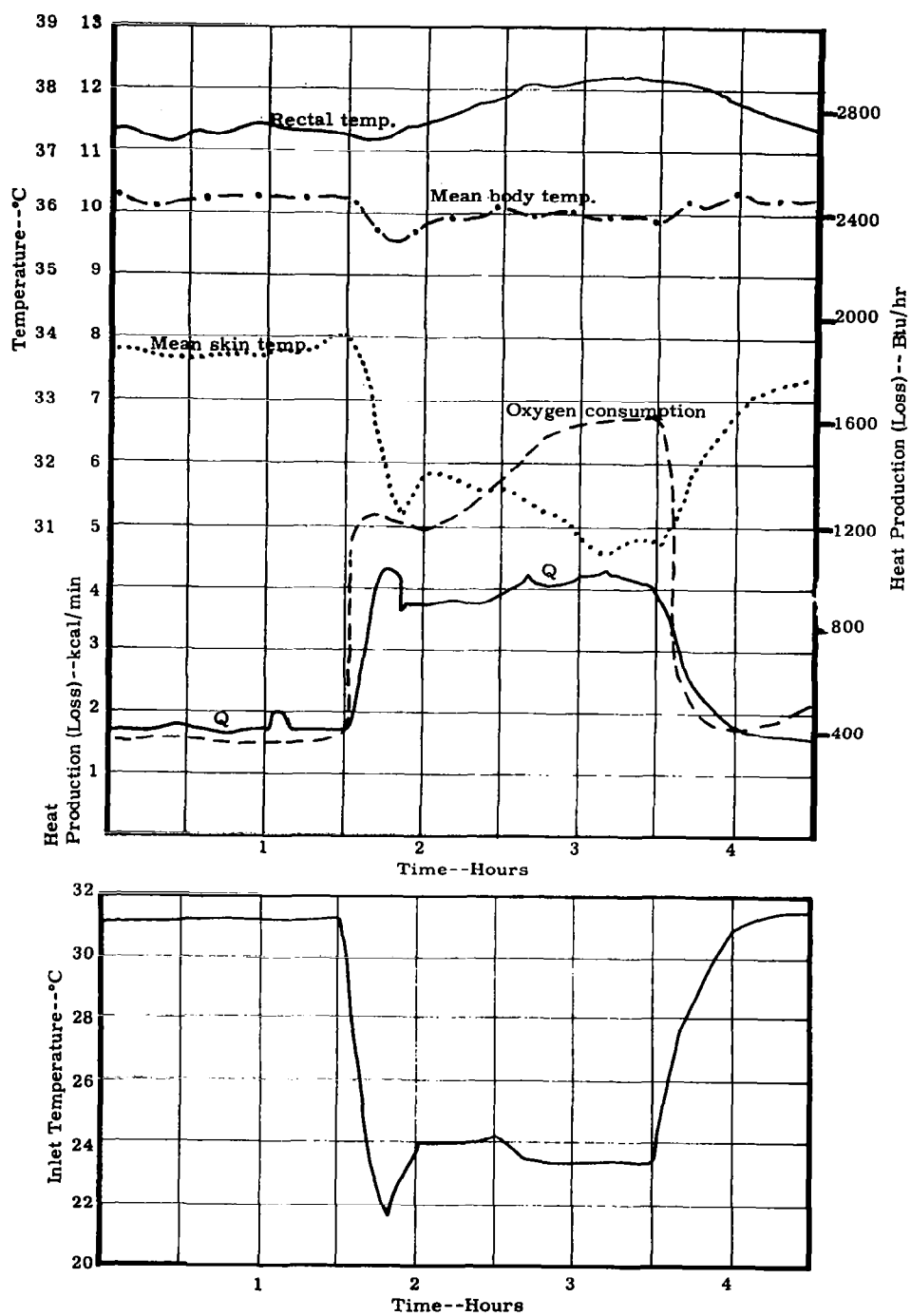
Figure A-10. Schedule II, Subject B
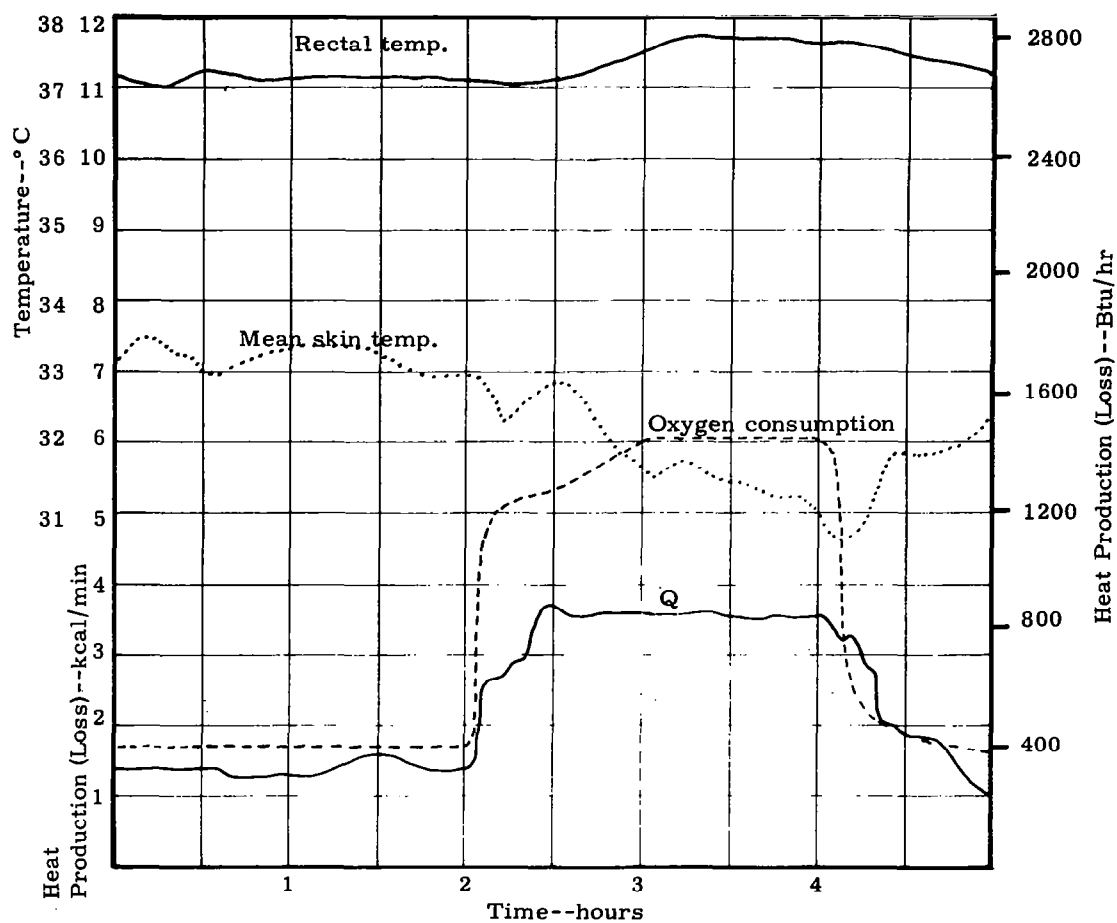
Figure A-11.   Schedule II, Subject C
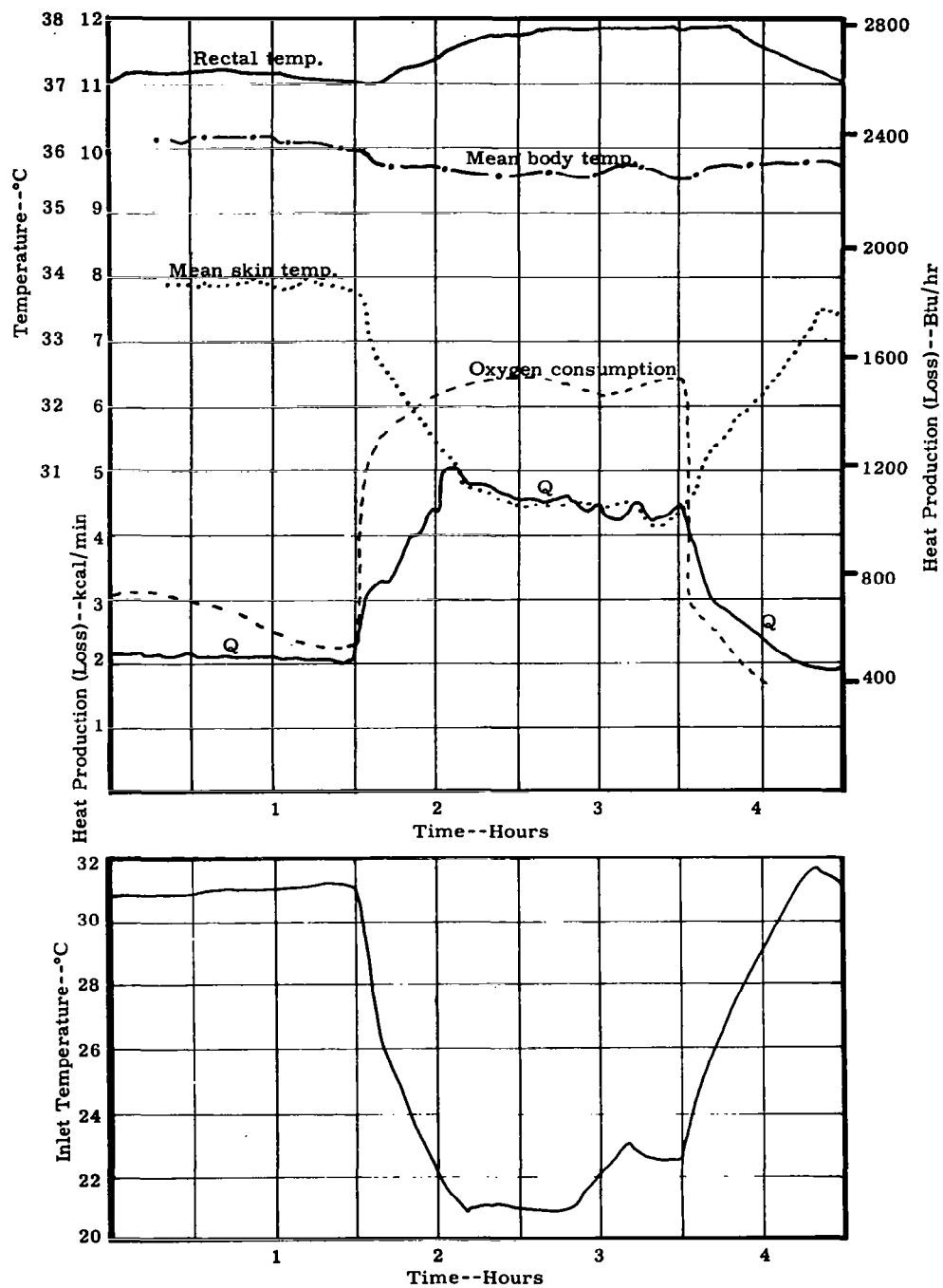
Figure A-12. Schedule II, Subject D
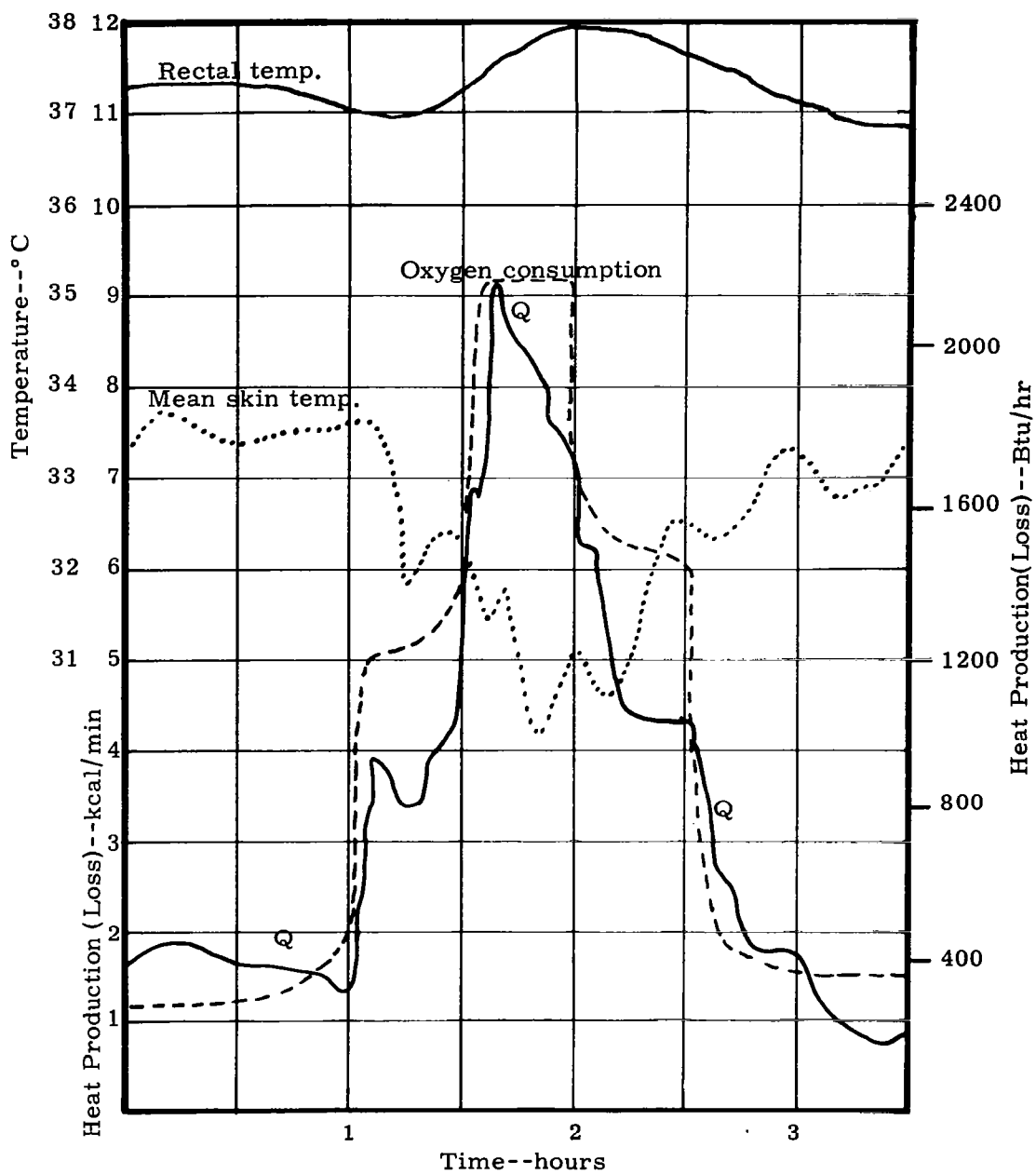
Figure A-13.   Schedule III, Subject A
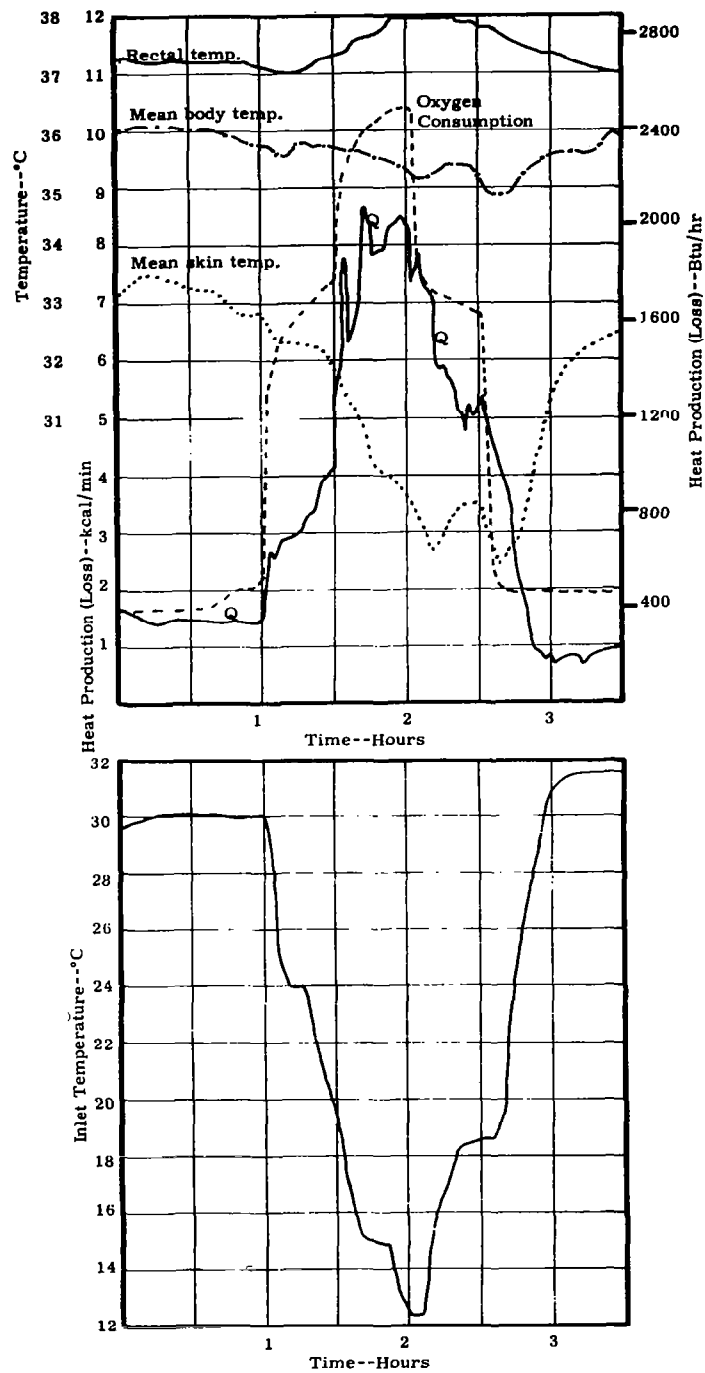
Figure A-14. Schedule III, Subject A.
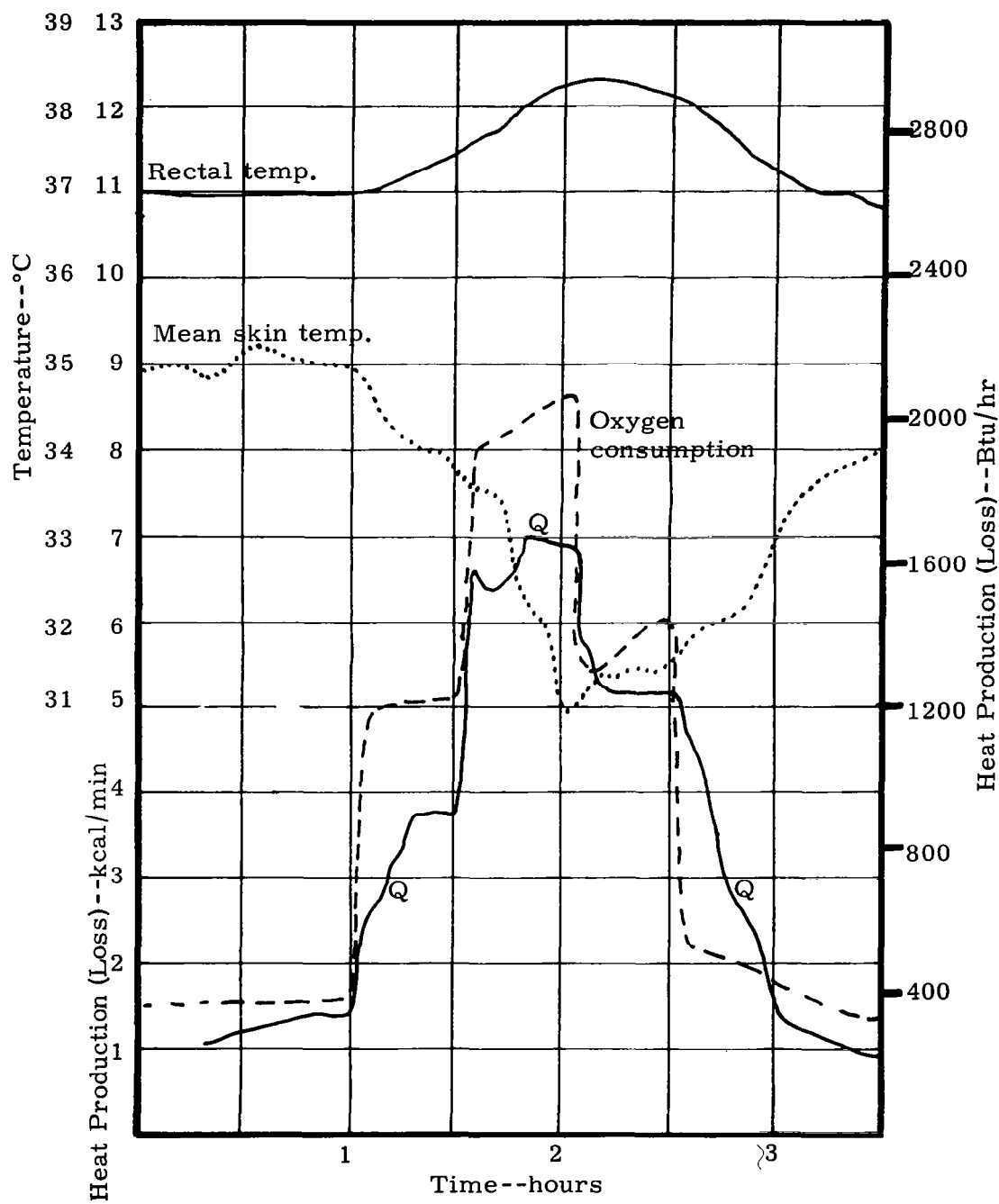
Figure A-15.   Schedule III, Subject B
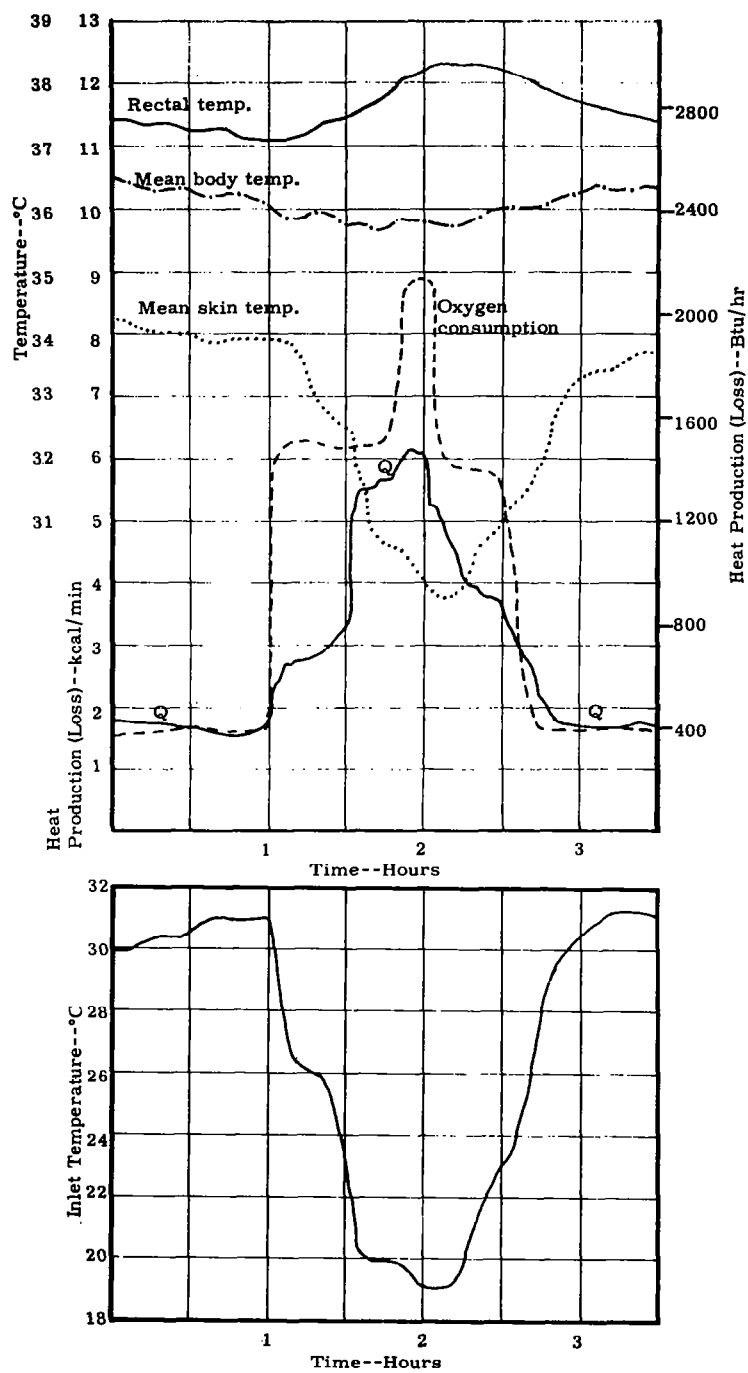
Figure A-16. Schedule III, Subject B

51.
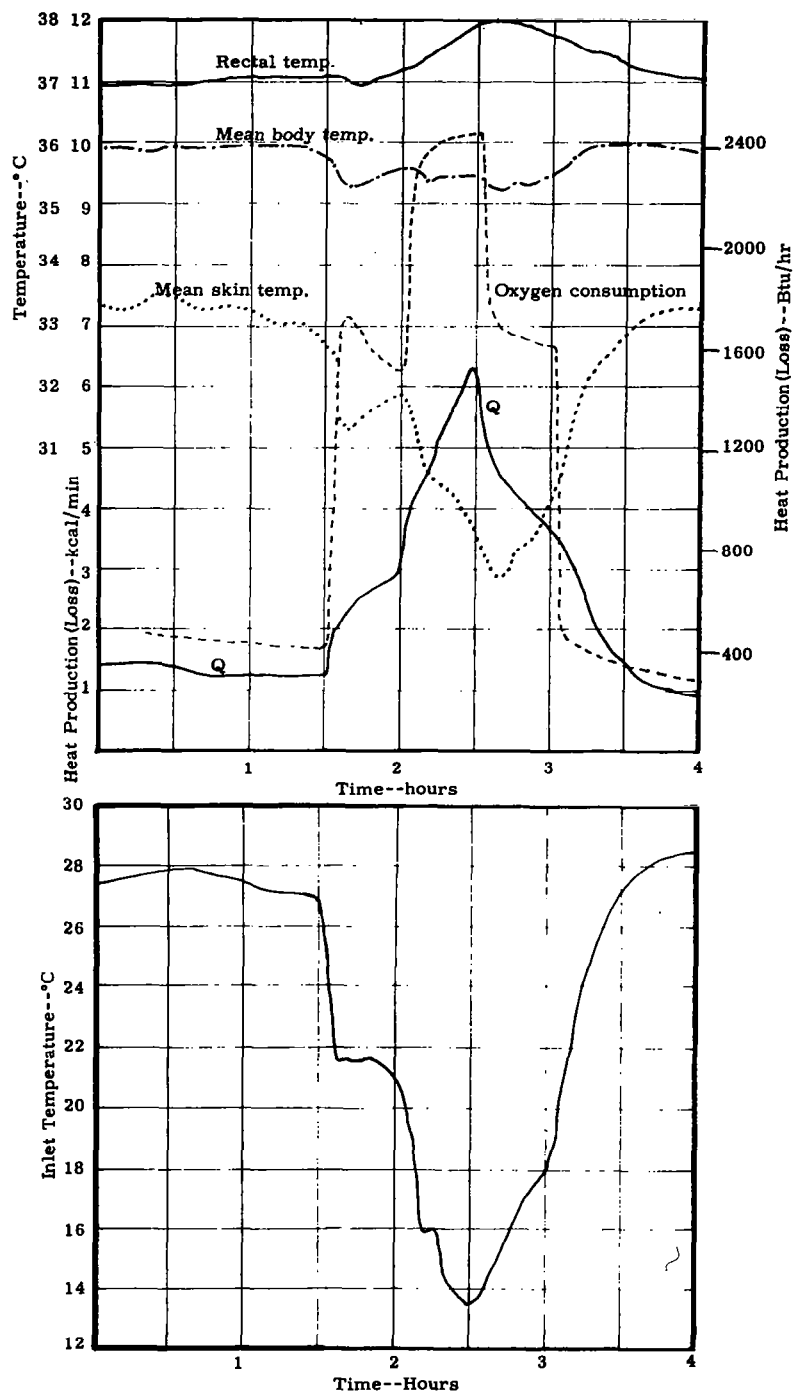
Figure A-17. Schedule III, Subject C

Figure A-18. Schedule III, Subject D

53.

Figure A-19. Schedule IV, Subject A

54.

Figure A-20. Schedule IV, Subject A

55.

Figure A-21. Schedule IV, Subject B

Figure A-22. Schedule IV, Subject B
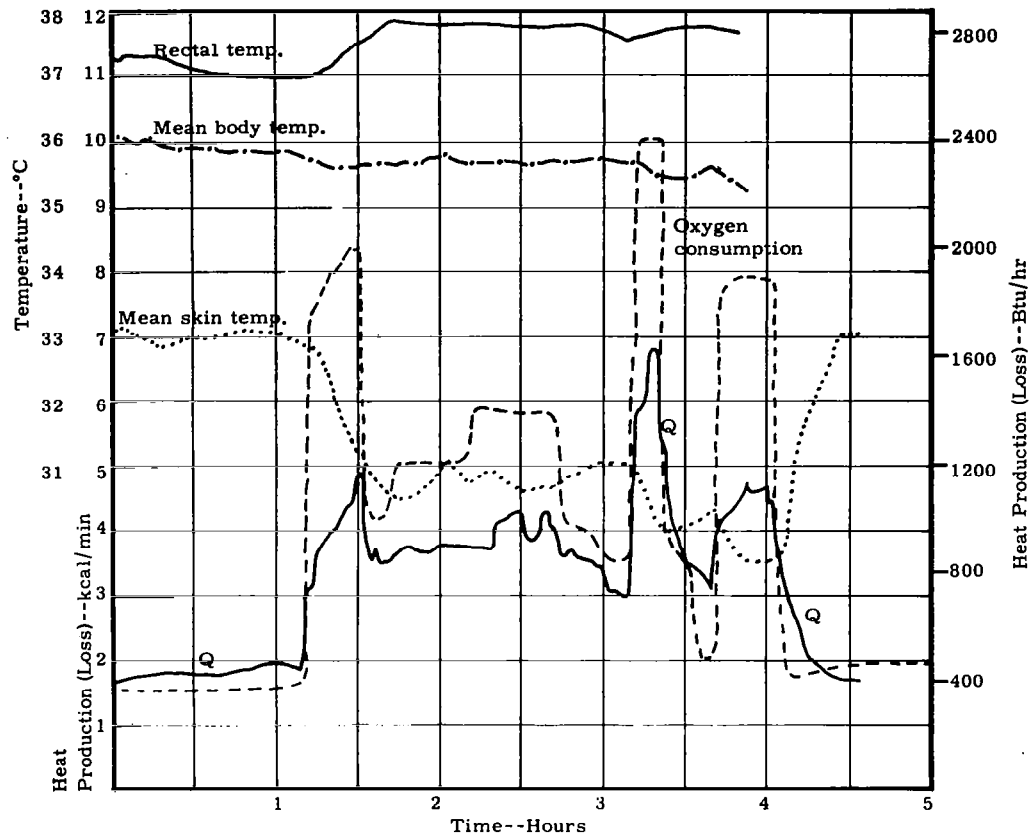
Figure A-23. Schedule IV, Subject C

58.

Figure A-24. Schedule IV, Subject D

59.

Figure A-25. Schedule V, Subject A

Figure A-26. Schedule V, Subject A

61.

Figure A - 27.   Schedule V, Subject B
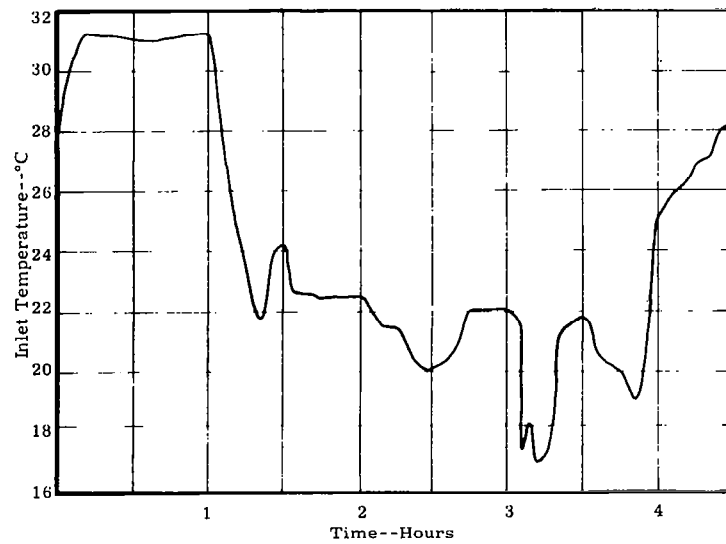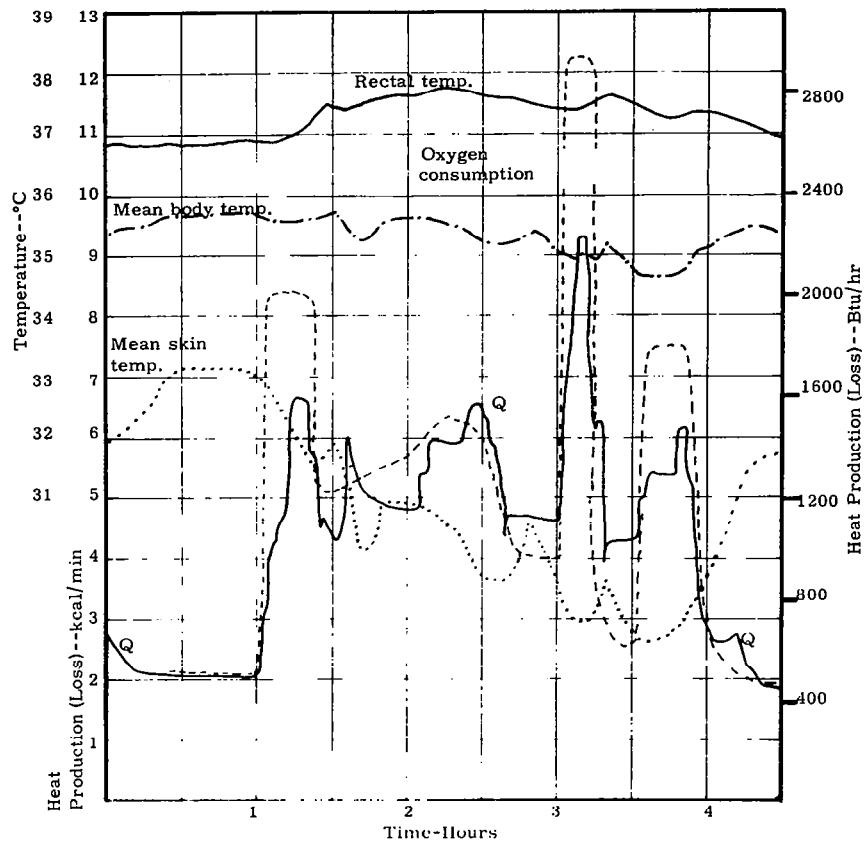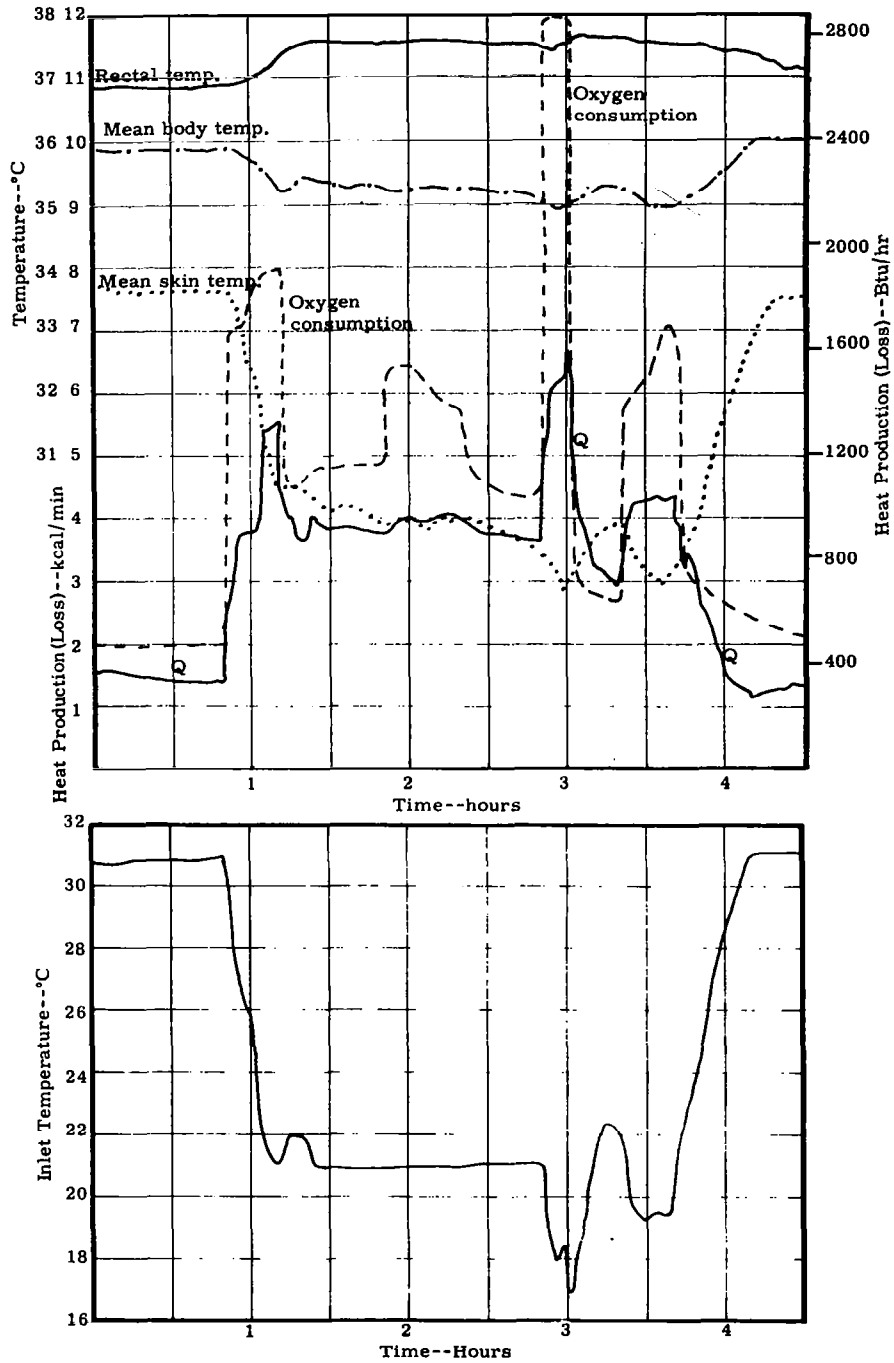
Figure A-28--Schedule V, Subject B

Figure A-29. Schedule V, Subject C

Figure A-30.   Schedule V, Subject D