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TOLERANCE FOR WORK-INDUCED HEAT STRESS  
IN MEN WEARING LIQUIDCOOLED GARMENTS

**CASE FILE  
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## TOLERANCE FOR WORK-INDUCED HEAT STRESS IN MEN WEARING LIQUID COOLED GARMENTS

This report describes the second phase of a continuing investigation of heat tolerance in men unable to dispose of metabolic heat as fast as it is produced within the body.

Phase I of this work, reported in NASA C. R. 108419 (ref. 1) was concerned with loss of the capability for transferring body heat to the environment, simultaneously with the start of physical work and continuing to the point of incipient collapse. In those experiments, the subjects were in effect totally insulated from their surroundings and were thus forced to store within their bodies all of the heat generated by walking on a treadmill at various speeds and grades, yielding standardized metabolic rates up to about 7 or 8 times resting values.

The present phase of the investigation examines two new facets of the problem, viz., (a) the effect of work rate (metabolic rate) on tolerance time when body heat storage rate is a fixed quantity, and (b) tolerance time as a function of metabolic rate when heat loss is terminated after a thermal quasi-equilibrium has been attained under comfortable conditions of heat transfer.

Apart from the empirical determination of practical limits for heat stress exposures of these types, the aim of the present study is to elucidate the nature of the physiological mechanisms involved, in the hope that predictive techniques can eventually be evolved for use in the management of emergencies involving cooling system failure. The man-in-space program depends for its extra-vehicular activities of astronauts on the ability to transfer body heat from the skin surface to a back-pack disposal system. Should any element of this personal micro-climate control system malfunction, recovery of the individuals and minimum compromise of their mission will require accurate estimates and predictions of what can be done and what the risks of collapse are. The present investigation should contribute significantly to the attainment of this capability.

### SUBJECTS

Our four experimental subjects are professional fire fighters, ranging in rank from Fire Apparatus Engineer to Fire Captain and in age from 27 to 38. All four men were drawn from the group of ten firemen who participated in the earlier Phase I

experiments. Table I shows their age, weight, height and fitness test score. Fitness scores from last year and relative heat stress tolerance ranking established in Phase I are also shown.

TABLE 1 - SUBJECT DATA

Subject	Age	Ht. (in.)	Wt. (lb.)	Fitness Test Max. Time (min.)		Heat Tol. Ranking 1969(a)
				1971	1969	
RB	35	72	179	(1)14	14	79
				(2)14	16	
				(3)16	14	
BD	36	74	174	(1)13(b)	12(b)	100
				(2)13	13	
				(3)15	13	
FD	38	73	180	(1)17	16	78.5
				(2)18	18	
				(3)18	17	
GH	27	70	168	(1)15	14	59
				(2)15	16	
				(3)15	16	

(b) This subject unused to cycling; had muscle fatigue problem not affecting treadmill walking or heat tolerance limit.

(a) Percentage of max. cumulative endurance time for best subject, in Phase I series.

In the study reported here, two different types of stress programs were employed, combining measured work (treadmill walking) and thermal stress. In the first, work was performed at three different metabolic levels (1500, 2000 and 2500 Btu/hr), while heat removal was regulated so as to induce heat storage within the body at a rate of 1000 Btu/hr. In the second, the same series of work rates were employed, but heat removal was continuously adjusted during the first 41 minutes of each test so as to achieve a subjectively comfortable condition for the man, with minimum ascertainable sweating. Heat removal was then terminated, and heat loss was kept negligible for the rest of the test. Each test was carried to the point of the man's incipient collapse. Work was then stopped and he was rapidly cooled.

As in the previous study, heart rate and temperatures of the ear canal, rectum and 9 skin locations were continuously recorded. Mean skin temperature was also

automatically derived, by the thermistor logger, from the nine separate measurements and recorded each minute. Oxygen uptake was monitored continuously and, in this study, carbon dioxide output was also monitored. Regulation of the heat removed from the body was achieved by a system circulating water at controlled temperatures through the tubing system of a liquid-cooled garment (early model of the Apollo LCG, furnished by NASA) which the man wore under an impervious and insulating clothing assembly.

When heat loss was to be terminated, circulation through the suit was stopped, and the temperature of the climatic chamber was brought as close as possible to skin temperature. Respiratory heat loss was also minimized by supplying, to the face-covering mask of the metabolic system, air substantially saturated at near body core temperature. At other times, respiratory heat loss was estimated from temperature-humidity data, and due allowance made, along with other heat loss parameters, in achieving the desired rate of storage of metabolic heat.

#### SUBJECT SELECTION AND TRAINING

As in the prior study, each subject was required to meet a standard level of physical fitness. The test described in Ref. 1 was administered prior to his entering the program, again after a series of training walks, and at the end of the program. In order to avoid heat acclimatization as a complicating factor, all training sessions prior to the heat stress test proper were conducted in environments within the normal comfort range, and at a metabolic level of about 2000 Btu/hr except during the "calibration" run. This run was used to determine the treadmill grade, at the standard walking speed of 2.6 mph (used throughout) which elicited metabolic levels of 1500, 2000 and 2500 Btu/hr.

The subjects participated in the program on schedules adjusted to their available off-time from fire department duty.

#### LABORATORY FACILITIES AND INSTRUMENTATION

With the exception of the equipment and instrumentation used for control and measurement of the heat removed via the LCG, and addition of an infrared CO<sub>2</sub> analyzer to the metabolic instrumentation, facilities were substantially as described in detail in Ref. 1 (q.v.). Only significant changes or additions will be discussed here. Figure 1 shows the instrumentation and control system in the control center adjacent to the climatic chamber.

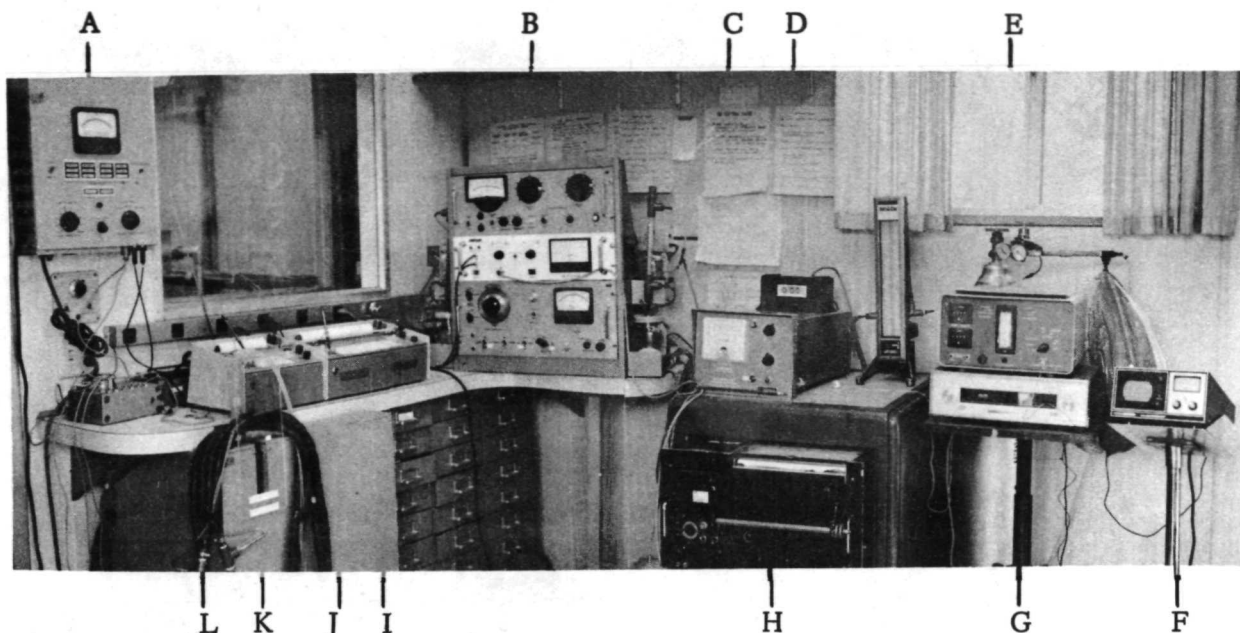


Figure 1. Instrumentation and Control Center

- A: Thermistor Computer-Logger.
- B: Operational Control Center:  
     top panel, LCG cooling controls;  
     middle panel, respiration circuit flowmeter (electronic manometer);  
     bottom panel, metabolimetry controls and  $pO_2$  null balance meter;  
     left and right, dehydrator and  $CO_2$  scrubber columns.
- C: LIRA infrared  $CO_2$  analyzer.
- D: Digital program clock.
- E: Reference gas supply for calibrating  $CO_2$  analyzer.
- F: ECG monitoring oscilloscope with cardiometer.
- G: Heart rate and ECG telemetry units.
- H: 4-channel Sanborn pen recorder.
- I: Rectal and tympanic temperature recorder.
- J: Skin temperature recorder.
- K: LCG circulation and refrigeration cabinet.
- L: LCG cooling circuit connector assembly.

Note: Door to climatic chamber at left, observation window above temperature recorders.

## LCG Thermal Control System

The LCG thermal control system provides quick and precise adjustment of the LCG inlet water temperature over a wide range, and control of the rate of flow. The mean temperature of water entering the LCG tubing system is varied by admitting very cold water, from a refrigerated reservoir, at repeated, frequent intervals whose frequency and duration can be automatically programmed by the controls on the LCG cooling control panel, shown in Fig. 1.

Controls (2) and (3), for the cooling water program, permit choice of an "on" time ranging from 0 to 8 seconds, and an "off" time of the same range. A panel meter (1) with two temperature scales (40 - 90 and 0 - 10 deg. F) enables reading, as desired, of (1) LCG "in" temperature, (2) LCG "out" temperature, and (3) the  $\Delta T$  between suit inlet and outlet. Any one of these 3 temperatures may be recorded, as chosen, on one channel of the 4-channel strip-chart Sanborn recorder. The inlet-outlet  $\Delta T$ , together with the mass flow through the LCG tubing system, and the specific heat of the fluid, define the rate of heat removal from the body. Control 4 regulates flow (measured by a precision glass rotameter) through the LCG tubing system. A standard flow rate of 2.25 liters per minute was maintained throughout these experiments. This value is convenient in that heat extraction in Btu/hr is obtained by multiplying  $\Delta T$  in °F by 300.

## CONTINUOUS MEASUREMENT OF METABOLIC RATE

Changes in this instrumentation from that used in the previous program consist principally of the following:

1. Flow control and measurement. To assure a minimal differential between air pressure in the mask and that of the chamber, a controllable-speed blower assists flow of air from the mask to the flow-measuring and sampling system. This supplements the blower in the supply line to the mask. Coordinated blower adjustments control the flow as necessary for the metabolic measurements, and keep intra-mask pressure essentially equal to that in the chamber.

An improved Greer electronic micromanometer (Mercury Electronics) is used to measure the pressure differential across the linear pneumotachometer, and provides an electrical signal for the multi-channel recorder, indicating exhaust system flow-rate and (with the oxygen sensor in null-balance) the rate of oxygen consumption (i. e., 1/100 the exhaust flow rate). Calibration of flow rates was done by timed collection of measured volumes at several rates of flow within the range used.

2. Gas sampling and analysis. A small, constant-flow sample of the exhaust line gas is passed through drying and CO<sub>2</sub> adsorbent columns before admission to the constant-temperature chamber containing the oxygen partial pressure sensor (General Electric Model 4000). Another portion is admitted to the infrared carbon dioxide analyzer (M. S. A. LIRA Model 300.) The calibration procedure for estimation of oxygen uptake uses fresh air as a reference gas for oxygen, on account of difficulty experienced in obtaining bottled calibration gas mixtures with desired and guaranteed concentrations of both oxygen and carbon dioxide. Calibration of the LIRA for carbon dioxide presented no reference gas problems.

## PROCEDURES

Except for the differences in the programming of the heat stress tests, as outlined above, procedures in the current program were essentially as described in Ref. 1 (q. v.). The two types of heat stress exposure employed in the current program were categorized as (A) Constant Heat Storage and (B) Interrupted Cooling.

### A. Constant Heat Storage Experiments

In these tests, each man walked at each of three treadmill grades which at 2.6 mph resulted in metabolic rates, respectively, of 1500, 2000 and 2500 Btu/hr (V<sub>O2</sub> values of 1.25, 1.68 and 2.08 L/min.) At each metabolic level, suit cooling was adjusted to produce a heat storage rate of 1000 Btu/hr, after allowance for the energy expended as work in ascending the treadmill grade, and for respiratory heat loss, estimated from the enthalpy changes between inspired and expired air. The combined effect of environmental temperature and clothing prevented any other significant exchange of heat with the environment. Thus:

$$\text{LCG Heat Extraction} = (\text{M. R.} - \text{W} - \text{Q rest}) - 1000 \text{ Btu/hr}$$

### B. Interrupted Cooling Experiments

In this test series, also done at the same three metabolic levels, suit cooling was adjusted, during an initial period of 41 minutes\* in each test run, so that the man felt thermally comfortable and sweating was minimal. At the end of the 41st minute, suit cooling was stopped completely. At the same time, respiratory heat loss was substantially stopped by saturation of inspired air at body core temperature by means of a heated "fogger". Further, convective heat loss to the chamber was made negligible by heating the chamber air to the level of mean skin temperature during the first 41 minutes. There was a slight lag in achieving exact balance of radiant heat exchange

\*(the initial period of 41 minutes was used, instead of the intended 40 minutes, due to an inadvertent time over-run in the first test.)

between the man and chamber surfaces, but such imbalance was made negligible by the fact that the subject wore, over the impermeable garment, a "cold-weather" insulating suit comprising jacket and trousers, and wore a pair of bulky lined gloves over the neoprene gloves which were taped to the impermeable suit sleeves to prevent air or water vapor exchange at the wrists.

#### Sweat Loss

Total sweat loss during each test was estimated by taking the nude weight of each subject, before dressing for each test, and after removal of clothing at its end. The fully dressed and instrumented subject was also weighed immediately before and after the treadmill walking in each test.

#### Heart Rate and Core Temperature

Heart rate was read from an averaging cardiometer (Model CT-180 or PM-2 CardioPacer; Physiometrics, Inc.) The cardiometer was calibrated before each run, using known frequency inputs. Heart rate was recorded on the running test log, and also was plotted throughout the course of each test run on a "working graph". The latter was also used to plot rectal and ear canal temperature readings (to 1/100° F, using a Digitec digital thermometer), at similar intervals, to provide a running visual check of the progress of the man's condition throughout the test, as a supplement to automatic recording.

During the "constant storage" tests, this working graph also provided a running check of storage rate, through the slopes of the trend-lines of tympanic and rectal temperatures, plotted against time.

#### ECG Telemetry

A Biocom telemetry unit was used to transmit an ECG signal to a receiver outside the chamber, with an oscilloscope displaying the ECG wave-form and indicating the heart rate on an in-built cardiometer. The ECG was also periodically recorded, especially near the tolerance end-point, on the Sanborn recorder.

#### Procedure in a Typical Test

On arrival at the laboratory, the subject was weighed nude. Skin, rectal and ear canal thermistors were affixed, also electrodes for ECG telemetry and for input to the cardiometer. He was then dressed in the LCG, the vinyl impermeable garment, a skirted, foam-neoprene head covering or "hood", and the insulating suit. Galoshes, gloves and hood were taped at their junctures to the impermeable garment to complete the vapor seal. Readouts of thermal and cardiac instrumentation



were checked, and a final fully-dressed subject weight taken on a Fairbanks platform beam-balance (to 0.01 lb.) adjacent to the treadmill in the climatic chamber. The full face-mask for the valveless respiration system was then donned and this system checked, just before starting the treadmill with the subject standing to one side.

At zero time, the subject started walking, and continued until he reached his tolerance limit, defined by established criteria: (1) inability to continue due to weakness, nausea or loss of equilibrium; (2) rectal or ear canal temperature exceeding 103.5° F for 1 minute; or (3) heart rate exceeding 180 beats per minute for 1 minute (except for one subject in whom ability to sustain a higher heart rate safely had been previously verified).

At the tolerance end-point, the treadmill was stopped, maximum cooling via the LCG was started, and the respiration mask was removed. The subject was weighed and escorted from the chamber to the dressing area, where he was seated, and clothing removed as expeditiously as possible in front of a large fan. When the impermeable garment had been removed, the rapid air flow, directed on the sweat-soaked LCG, assisted in rapid cooling. Substantial recovery, indicated by marked lowering of heart rate and rectal temperature, was usually well along by about 10 minutes in the post-test period. After removal of the LCG and instrumentation sensors, a final nude weight was taken and the subject was allowed to shower and dress.

## RESULTS

The experimental data are presented as individual time histories for the various key parameters, grouped by metabolic rate (work load) and by experiment type. Thus Figures 2 and 3 present the twelve experiments of the constant storage type, arranged for easy comparison of the four subjects as to rectal and ear canal temperatures (Fig. 2), heart rate and mean skin temperatures (Fig. 3). Figures 4 and 5 present the data for these same four parameters in the twelve experiments of the interrupted cooling type (i.e., zero heat loss after attainment of equilibrium).

The scales for these four graphs are carefully matched for all panels, to allow direct comparison of all curves and points. A heavy dot near the upper end of each curve indicates the point at which work was stopped and maximal cooling was started, thus ending the heat storage phase of the experiment and beginning the recovery phase.

During the recovery phase the subjects were being undressed; skin and ear canal temperatures, as well as heart rates fell rapidly, the monitored electrocardiogram returned quickly to the normal resting configuration. Rectal temperature continued to rise for several minutes after cooling was started, presumably as a result of peripheral vasoconstriction and volume shift of heated blood to the central regions.

Presentation of Figures 2 and 3 as facing pages (the same for Figures 4 and 5) permits scanning laterally to compare data on the four graphed parameters, at a given metabolic level, and vertically to observe the influence of metabolic level on each parameter.

Figure 6 graphically summarizes data on the rise of rectal, ear canal and mean skin temperature, and of heart rate, during the experiments, and the maximum heart rate at the end of each. Figure 7 is a graphic presentation of the thermal responses of one subject to the six different combinations of metabolic rate and test protocol type. Figure 8 graphically compares individual and mean values for the time to incipient collapse, in all experiments.

### EXPERIMENTS WITH CONSTANT HEAT STORAGE (1000 BTU/HR.)

#### Rectal and Ear Temperature

All the experiments at the mildest metabolic rate (1500 Btu/hr) and half of those at 2000 and 2500 Btu/hr were terminated before rectal temperature reached 103°F.

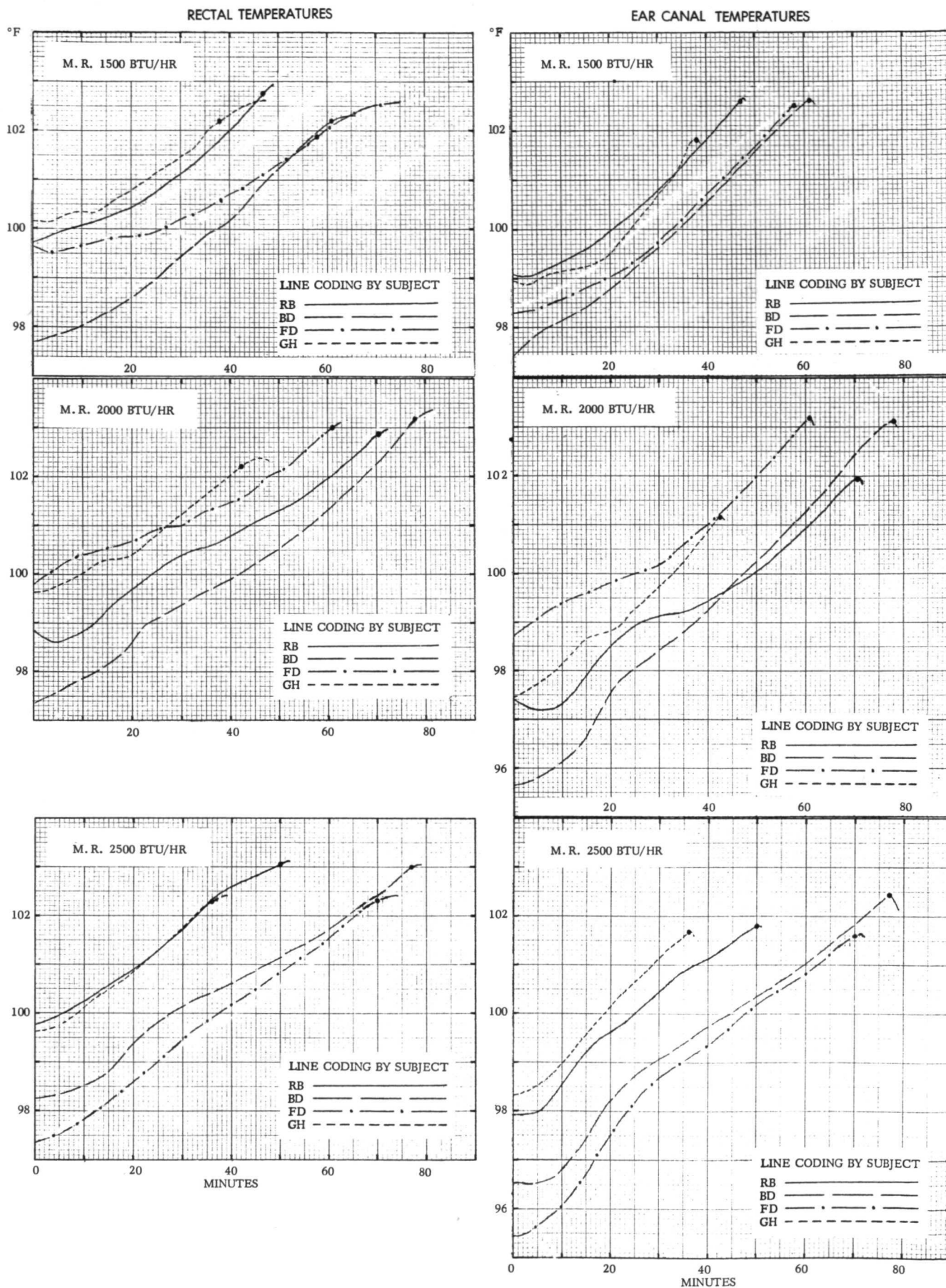
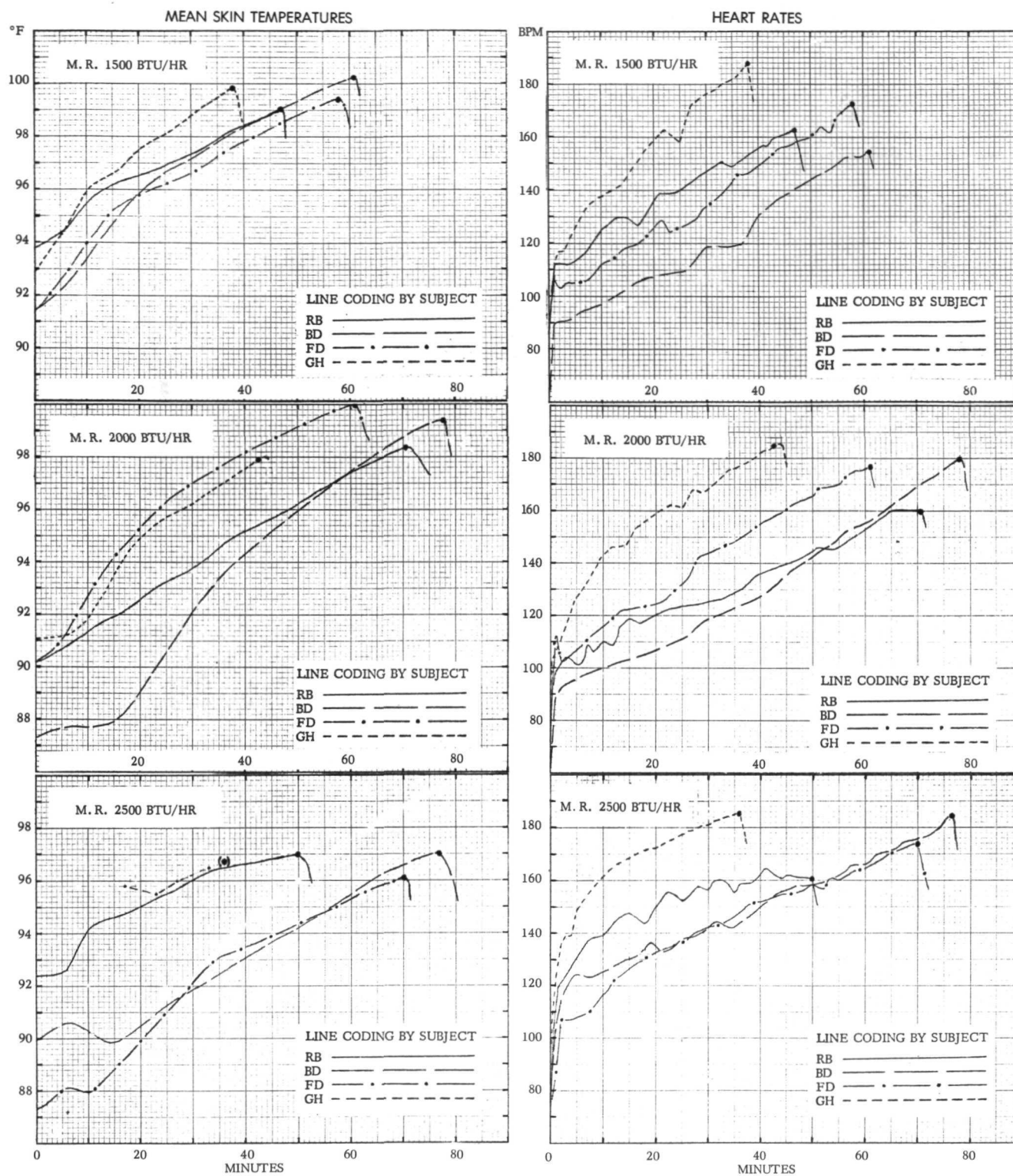


FIGURE 2. RECTAL AND EAR CANAL TEMPERATURES IN EXPERIMENTS WITH CONSTANT HEAT STORAGE (1000 BTU/HR) AT THREE METABOLIC RATES: 1500, 2000 AND 2500 BTU/HR.



( ) Data incomplete (recorder malfunction);  
final  $T_s$  obtained by extrapolation.

FIGURE 3. MEAN SKIN TEMPERATURES AND HEART RATES IN EXPERIMENTS WITH CONSTANT HEAT STORAGE (1000 BTU/HR) AT THREE METABOLIC RATES: 1500, 2000 AND 2500 BTU/HR.

As shown in Figure 6, the overall rise in rectal temperature was quite consistent, amounting to roughly 2.5° F for 3 of the 4 subjects, and 4.5 to 6° F for subject BD. BD also displayed an initial rectal temperature substantially below the others at each metabolic level, and always had a longer tolerance time than them.

Ear canal temperatures tended to run slightly lower than rectal in most cases, and only exceeded 103°F in 2 of the experiments (at 2000 Btu/hr metabolism). A final value of 102° was attained in only 7 out of 12 experiments (3 at 1500, 3 at 2000 and 1 at 2500 Btu/hr).

The change in ear temperature ranged from 3 to 4° in 8 of the experiments, to 5, 6 and 7.5° for subject BD. Subject FD showed a change of 6.1 degrees at M. R. 2500 Btu/hr.

#### Skin Temperatures

In 10 of the 12 experiments initial mean skin temperature was between 90 and 94°. In the two cases where the starting skin temperature was below 88, there was a 10 to 15 minute delay following the start of work before mean skin began rising, but final values were not different from those in the other 10.

Final mean skin temperature was between 99 and 100° F at 1500, between 98 and 100° at 2000, and between 96 and 97° F at 2500 Btu/hr metabolic rate. This pattern of declining final temperatures with increasing work load reflects the decrease in LCG temperature associated with the greater heat extraction necessary to maintain the fixed storage rate of 1000 Btu/hr.

#### Heart Rates

In general, heart rates increased rapidly in the first two minutes of work, then began a slower but steady rise until the termination of the exposure. Three of the four subjects displayed a rate of rise of approximately 1.2 bpm/minute at 1500 Btu/hr M. R. Two of these showed about 1 bpm/min rise at 2000 and 0.75 bpm/min at 2500 Btu/hr. Subject GH, with the shortest tolerance times, had a heart rate increase of 1.7 bpm/min at 1500, 1.25 bpm/min at 2000 and 0.85 bpm/min at 2500 Btu/hr (after the first 5 or 10 minutes).

Again, the probable explanation of the negative correlation between heart rate increase and metabolic rate at constant storage lies in the cooler LCG and resultant skin temperatures.

Final heart rates appear to be determined more by individual characteristics than by the metabolic rate level. Thus GH ended at  $187 \pm 1$  in all three experiments

while RB reached  $161 \pm 1$  bpm at from 9 to 26 minutes later. BD, on the other hand, reached final heart rates of only 154 and 155 in the lower M.R. experiments, but pushed himself to 185 bpm at 77 minutes in the high work load run.

### Discussion of Results

Excluding subject GH, who shows signs of intolerance for this type of heat stress, the tolerance times plotted in Fig. 8 tend to cluster between 45 and 77 minutes, tending to be somewhat greater at the higher metabolic rates. The three-man averages are 55, 70, and 65 minutes for M.R. 1500, 2000 and 2500 respectively, for a grand average of 63 minutes.

The same men in the 1969 experiments with zero cooling and 950 to 1000 Btu/hr storage rate had tolerance times of 48, 49 and 70, or an average of 56 minutes. A comparison between each man's 1969 experiment at 1000 Btu/hr M.R. and his 1971 experiment at 2000 Btu/hr M.R., 1000 Btu/hr storage, shows increases of 21.5, 13 and 8 minutes for RB, FD and BD, respectively, when cooling was involved, despite the higher work load. In contrast, subject GH had almost the same tolerance time in all four situations; viz., M.R. 1000, 1500, 2000 and 2500 Btu/hr.

The origin of GH's limited tolerance appears to lie in his relatively high rectal and ear temperatures and his sharply exaggerated heart rate response, relative to the other three men. Evidence from the Type B experiments, discussed later, suggests that GH's heart rate response is closely tied to the level of his skin temperature, and may resemble the rest of the group when skin temperature is maintained low enough. It may be of some significance that GH is of a more slight build than the other 3 men, and in consequence the LCG did not fit him as well, so that heat extraction efficiency was lower.

### INTERRUPTED COOLING EXPERIMENTS (zero heat loss after 41 minutes)

In the 12 experiments in which heat extraction was terminated after allowing 41 minutes for a thermal quasi-equilibrium to be established, the cessation in cooling produced an immediate rise in the mean skin temperature followed almost immediately by a rise in heart rate, while the rise in ear temperature was delayed by about 10 minutes. There was usually little or no detectable change in the rate of rise of rectal temperature at the 41-minutes point, but there was a tendency for the curve to steepen about 10 or 15 minutes thereafter.

Ear canal temperature, in contrast, tended to reach a plateau by 41 minutes of work under comfortable cooling conditions and began to rise abruptly only after 10 minutes of zero heat loss, except at the highest work load, when the rise began after only 2 to 7 minutes of total storage.



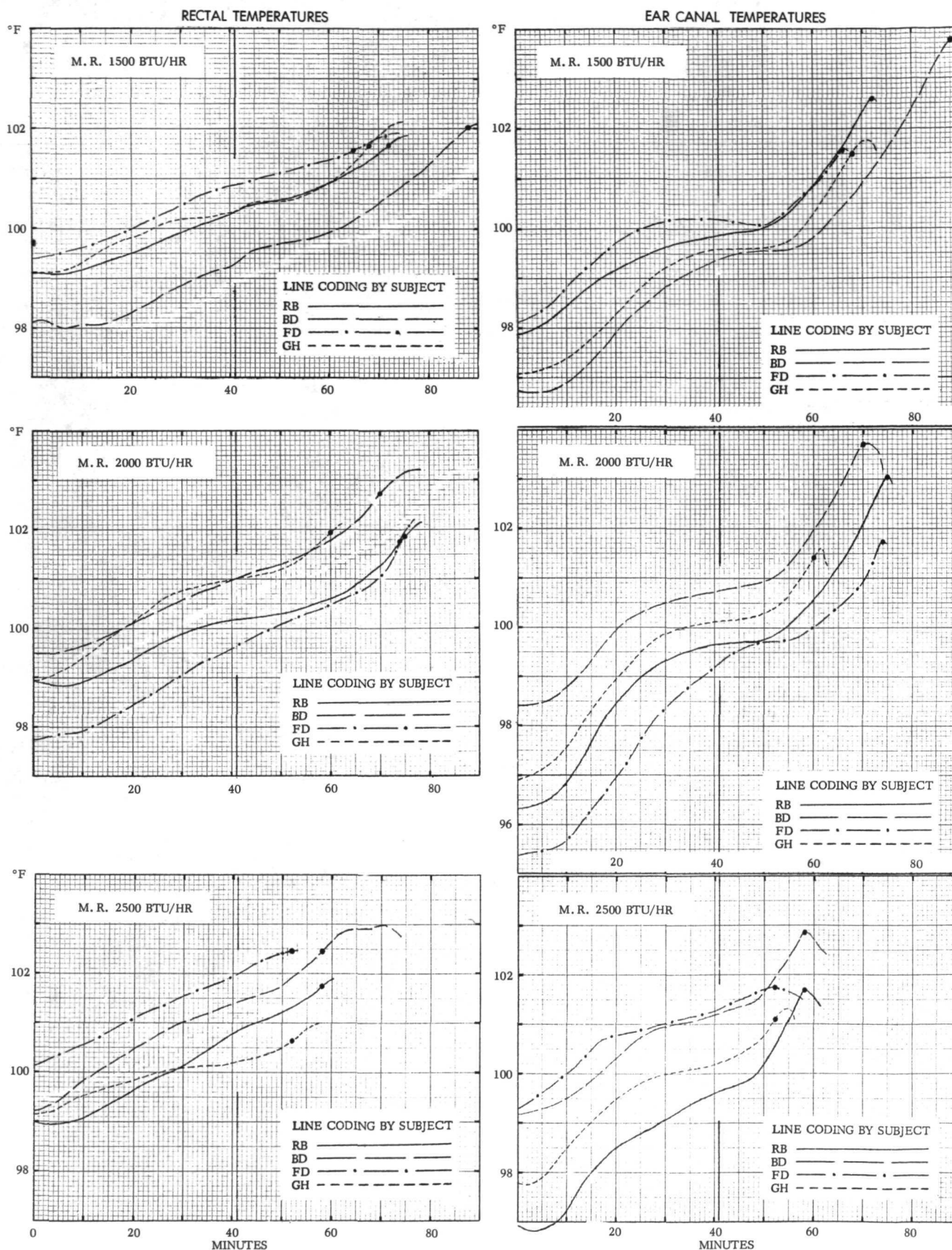


FIGURE 4. RECTAL AND EAR CANAL TEMPERATURES IN EXPERIMENTS WITH ZERO HEAT LOSS AFTER 41 MINUTES, AT THREE METABOLIC RATES: 1500, 2000 AND 2500 BTU/HR. HEAT LOSS PRIOR TO 41 MINUTES ADJUSTED TO SUBJECTIVE "COMFORT" CONDITION.

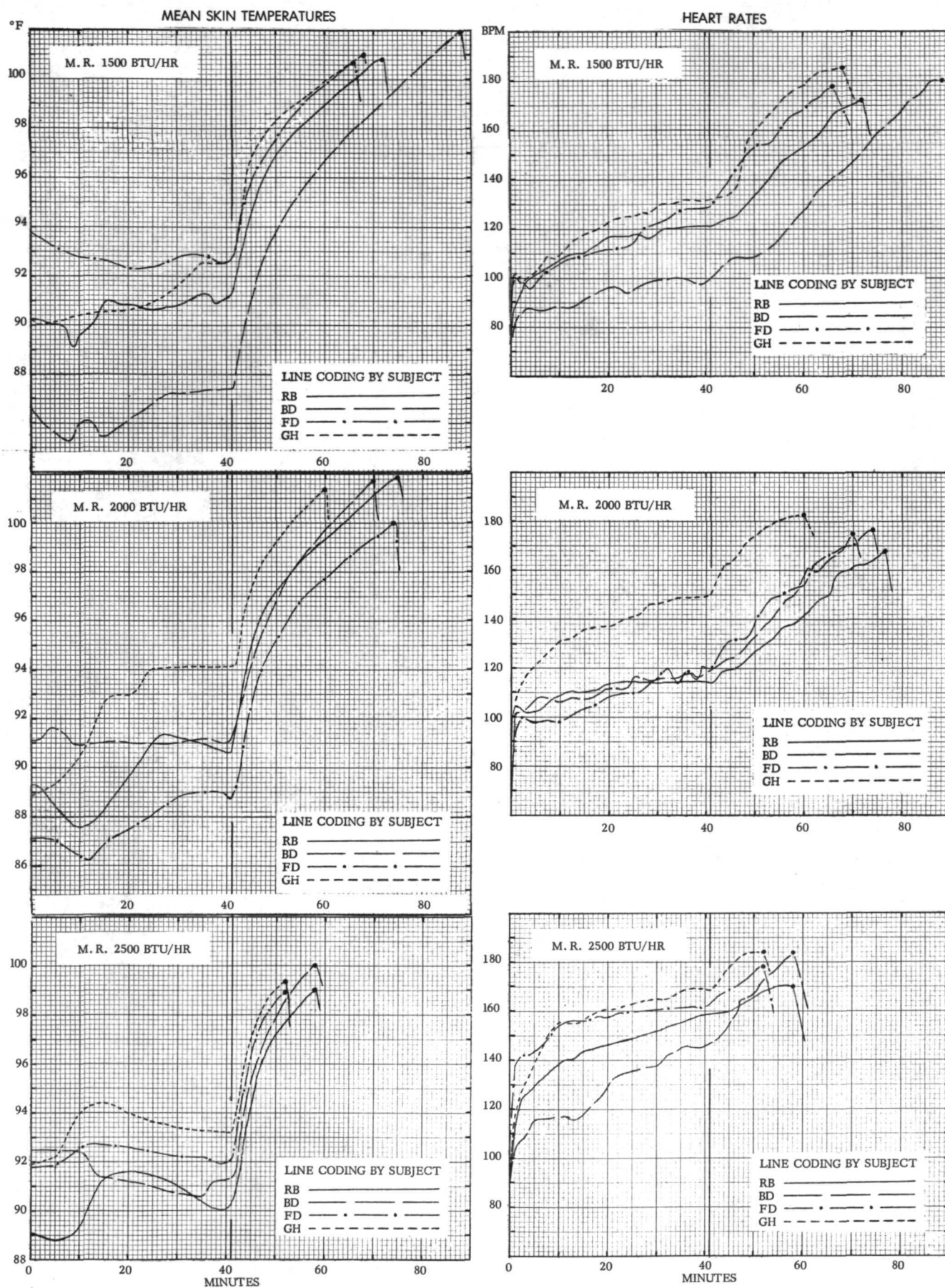


FIGURE 5 MEAN SKIN TEMPERATURES AND HEART RATES IN EXPERIMENTS WITH ZERO HEAT LOSS AFTER 41 MINUTES, AT THREE METABOLIC RATES: 1500, 2000 AND 2500 BTU/HR. HEAT LOSS PRIOR TO 41 MINUTES ADJUSTED TO SUBJECTIVE "COMFORT" CONDITION.



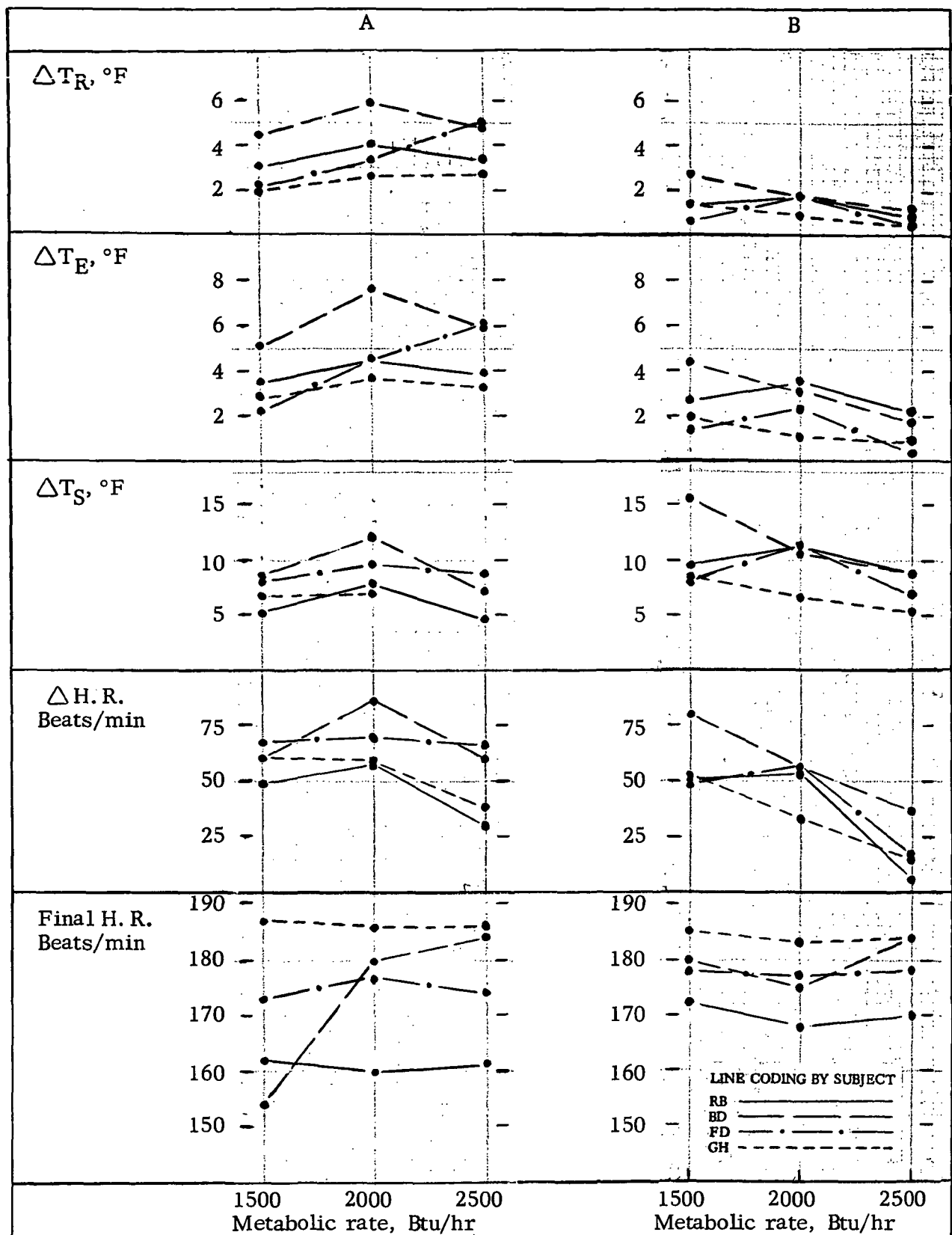


Figure 6. Rise of rectal, ear canal and mean skin temperatures, and of heart rate, during experiments; also final heart rate.

A: Fixed heat storage rate, 1000 Btu/hr.

B: Zero heat loss after 41 minutes of full cooling.

Note: Initial values for all temperatures taken at time zero for Type A experiments, time 41 minutes for Type B. Initial heart rates taken at 5 minutes after start of work (see discussion in text).

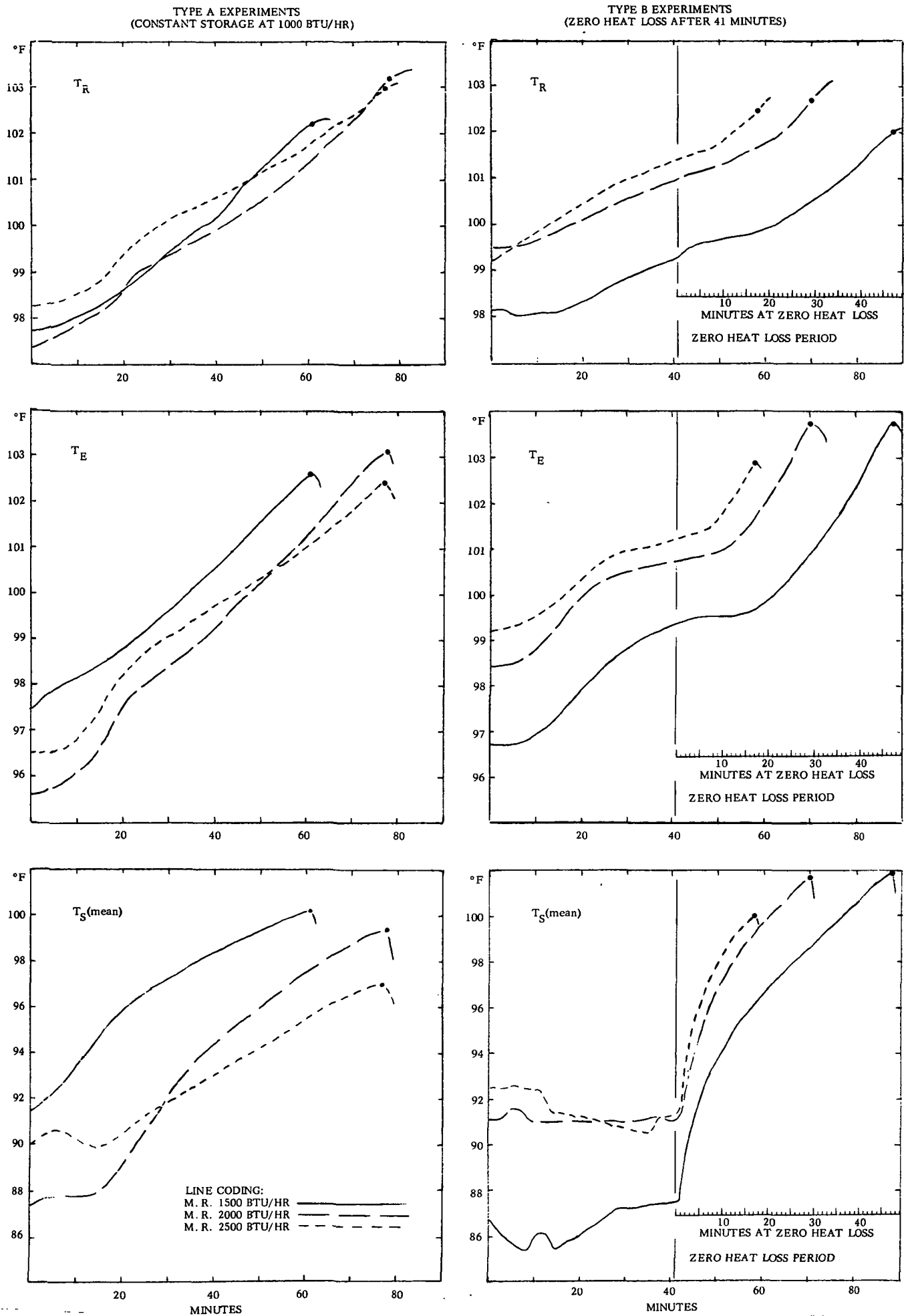
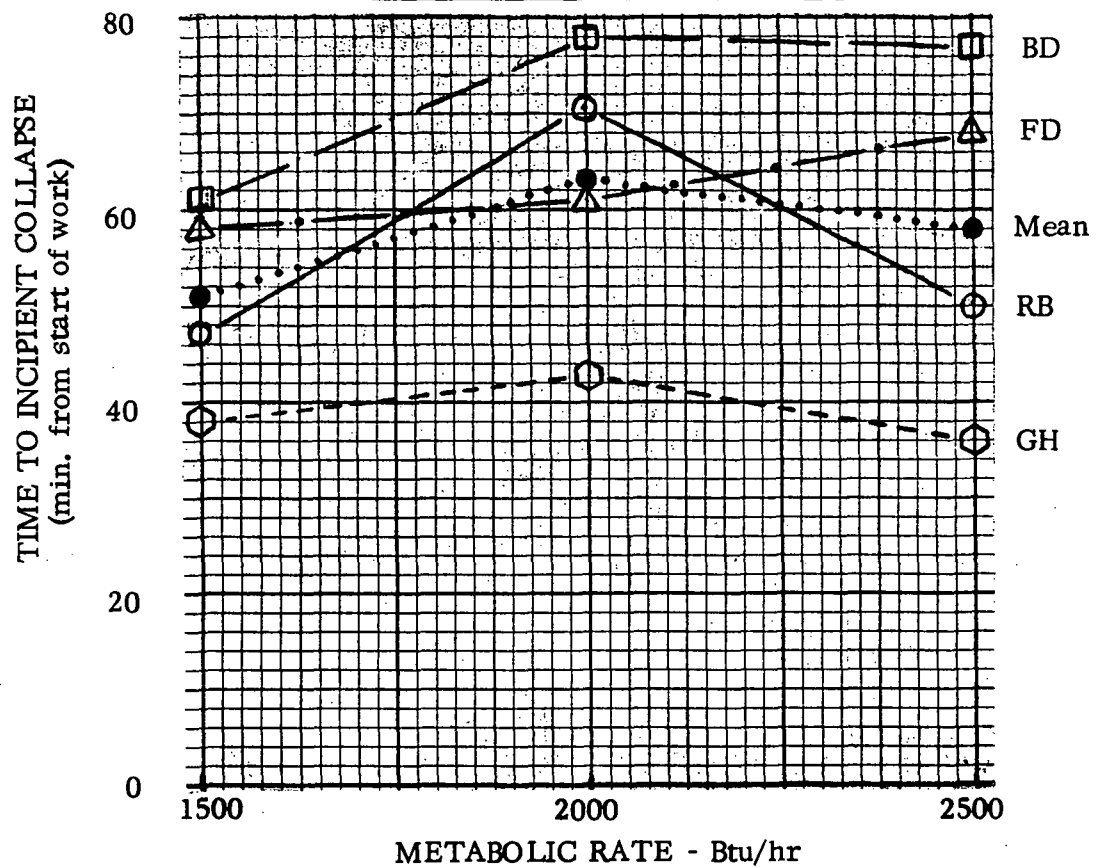


Figure 7. Comparative thermal responses of one subject (BD) at three metabolic levels (1500, 2000 and 2500 Btu/hr), in two types of experimental protocol (A, constant heat storage of 1000 Btu/hr, and B, zero heat loss after 41 minutes of "comfort cooling").

# HEAT STRESS TOLERANCE TIMES

## (A) CONSTANT STORAGE (1000 Btu/hr)



## (B) INTERRUPTED COOLING

(All metabolic heat stored after 41 min.)

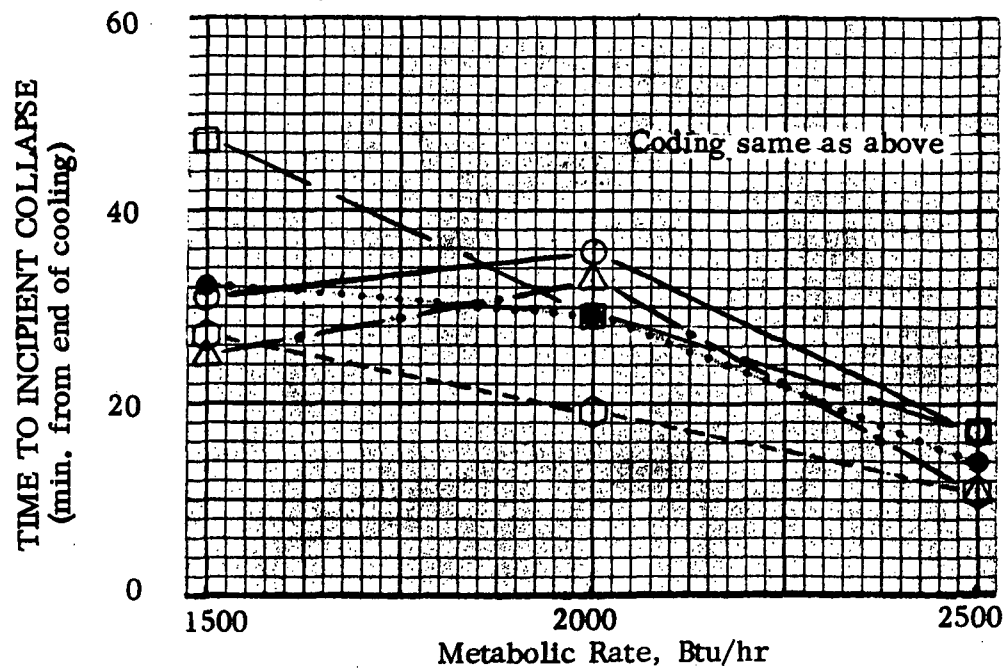


Figure 8. Time to incipient collapse in (A) constant storage tests, and (B) interrupted cooling tests; individual and mean values.

Final heart rates were closely similar for all four subjects, in these zero heat loss exposures, although tolerance times differed by as much as 22 minutes. The very long tolerance time of 47 minutes for BD at the 1500 Btu/hr metabolic load is seen in Figure 5 to be associated with an abnormally low pre-experiment skin and rectal temperature which was maintained during the equilibration period of work. In the 2000 Btu/hr group of experiments subject FD displayed unusually low pre-exposure rectal and skin temperature, giving him a slightly longer tolerance time at this metabolic rate than he had at 1500 Btu/hr. The greater tolerance time of subject RB at 2000 relative to 1500 Btu/hr M. R., is also associated with a somewhat lower rectal, ear and skin temperature at the time heat loss was terminated.

Subject GH, when kept relatively cool during the equilibration period as to working skin temperature (M. R. 1500 and 2500 Btu/hr) had a heat stress tolerance time closely comparable to those of the other men. At 2000 Btu/hr, however, his skin temperature during the equilibration period was allowed to climb to 94° F (a comfortable temperature for the resting individual); the subsequent heart rate response (Fig. 5) suggests an intolerance in this subject for surface blood flow demands, leading to a tolerance time shorter by 10 minutes than the next lowest man.

Subject FD showed an abnormally short tolerance time at 2500 Btu/hr, compared to his other experiments. This is almost certainly associated with the fact that his pre-experimental rectal temperature was above 100° F as a result of multiple immunization injections which he had received in preparation for a trip to the Orient.

The number of uncontrolled variables and the small number of experiments makes hazardous any attempt to derive a predictive equation from these tolerance time data. The generally brief tolerance times following loss of cooling at a metabolic rate of 2500 Btu/hr was unexpected, based on our prior experience at this level of effort with no cooling at all. The mean time to incipient collapse in those previous experiments was 26.5 minutes, compared to the present mean of 14 minutes. The individual differences between the two types of exposure, in order of descending tolerance time in the present series, are: 17, 12, 17 and 4 minutes respectively. Looking back at our 1970 report (Figures 21a and b) we see that heart rate at 10 minutes, in these zero heat loss experiments, was closely comparable in each case to the rate the same man displayed at the end of the 41-minute equilibration period in the current series. Mean skin temperatures were higher by 3 to 6 degrees at the 10 minute point of the no-cooling experiments than at 41 minutes in the pre-equilibration series.

### Heat Storage after the Cessation of Cooling

Figure 9 presents the mean and range of values for body temperature rate-of-change during the terminal portion of each zero heat loss experiment. The parameter plotted is the slope of the linear portion of each man's curve of mean weighted body temperature versus time from the cessation of cooling. Mean weighted body temperature ( $T_b$ ) is computed from rectal and mean skin temperatures, using the arbitrary factors of two thirds and one third, respectively. In all cases, the time history plot of  $T_b$  is linear after the first 8 to 10 minutes, during which sharp increases of from  $1^\circ$  to  $1.5^\circ$  F occurred. The individual variation in these steady-state storage rates is not great, except at the highest metabolic rate, where the initial conditions represented a distinct thermal stress.

There does not appear to be a strong correlation between the terminal rate-of-rise of mean body temperature and tolerance time. Similarly, the computation of enthalpy change from the difference in mean body temperature at the beginning and end of the zero heat loss exposure sheds no particular light on the problem of predicting tolerance time.

A tabulation was made of the total increase in heat content for each subject above an arbitrary reference level of  $94^\circ$  F mean body temperature ( $T_r = 98^\circ$ ,  $T_s = 86^\circ$ ), for all 12 experiments. It was found that the figure ranged from 859 to 1230 Btu, with an overall average of 1106, and a standard deviation of 106 Btu. Of the total, as much as half had already been accumulated, in some cases, when the LCG cooling was stopped. The largest amounts of heat accumulation actually occurring after the end of cooling were 1011 Btu in BD's 1500 Btu/hr experiment, 770 Btu in FD's 2000 Btu/hr run and 705 Btu in RB's 2000 Btu/hr experiment. For the rest, the heat content of the body at the time cooling stopped was such that only 374 to 680 Btu more could be accommodated before the point of incipient collapse was reached.

The foregoing implies that the best way to extend the tolerance time in case of cooling failure is to ensure the lowest possible heat content in the body at all times.

### Individual Variation in Tolerance

The comparison of old (Ref. 1) and new experiments suggests that after the body has reached a quasi-steady state at a given metabolic load, the abrupt cessation of heat loss produces a more immediate deterioration of the circulatory balance than when the body is just beginning to store heat at the time cooling ceases. Reference has been made to the apparent importance of skin temperature at the beginning of the heat stress period in influencing the tolerance time. Figure 10 illustrates this point

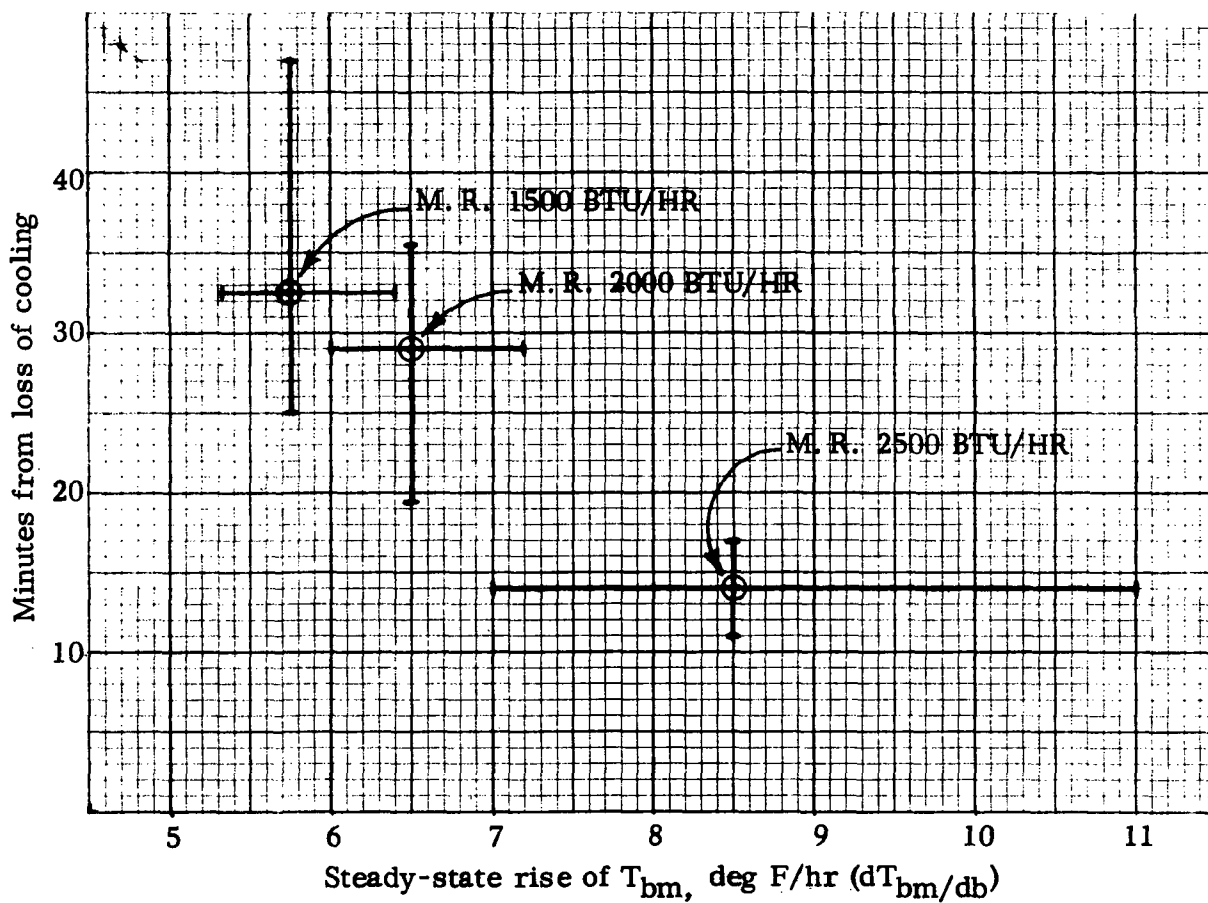


Figure 9. Time to incipient collapse, in interrupted cooling experiments, in relation to the rate of change of mean body temperature ( $T_{bm}$ ) during the final steady state of heat storage. (Mean and range for four subjects at three metabolic rates.)

quite dramatically, and suggests that a major portion of the variance between individuals may have been due to variations in the effectiveness of the LCG in terms of the gradient required between skin surface temperature and water temperature to remove a given amount of metabolic heat. As is well understood by suit designers, it is much more difficult to remove heat efficiently at the higher metabolic rates. A sort of paradox arises, in fact, to the extent that ideally the skin temperature should decrease as metabolism increases, to hold the circulatory load constant, whereas the typical LCG often requires a higher skin temperature to maintain balance as the metabolic rate is increased.

During the training walks, in shorts in a 70° F room, the men typically displayed mean skin temperatures between 82° and 85° F at the typical metabolic level of approximately 2000 Btu/hr, and had sweat losses of roughly 1 lb/hr. This observation is consistent with our earlier work (Ref. 2) which indicated, for a metabolism of 1680 Btu/hr, a skin temperature threshold for sweating of about 82° F and a sweat rate of one-half pound per hour at 86° F skin temperature.

This same 1965 report predicts a sweating threshold of about 81° and 76° F, respectively, for metabolic rates of 2000 and 2500 Btu/hr. Even though these are only approximations, it is clear that sweating must have been substantial at 1500, heavy at 2000 and excessive at 2500 Btu/hr, in spite of our subjects' comments indicating thermal comfort during the 41-minute cooling periods. In only one experiment is there a possibility that sweating was suppressed -- namely subject BD at 1500 Btu/hr. It is noteworthy that this man lasted 16 to 22 minutes longer than the others at this metabolic level after cooling was stopped, yet showed no such obvious superiority at the other two load levels. The implication we feel is clear: skin temperatures above the sweating threshold for the metabolic rate concerned represent a thermal burden which is proportional to the elevation, and tolerance for a suddenly-imposed storage rate due to loss of cooling will be reduced significantly when such a thermal burden is present.

The data presentation in Figure 10 suggests the possibility that an improvement in LCG efficiency, providing lower skin temperatures during the cooled period of equilibration, could probably increase tolerance times following cessation of cooling by as much as 100 per cent. By this line of reasoning, the small difference between the 1500 and 2000 Btu/hr experiments would be ascribed to the opposite effects of initial skin temperature and metabolic load on the circulatory reserve.

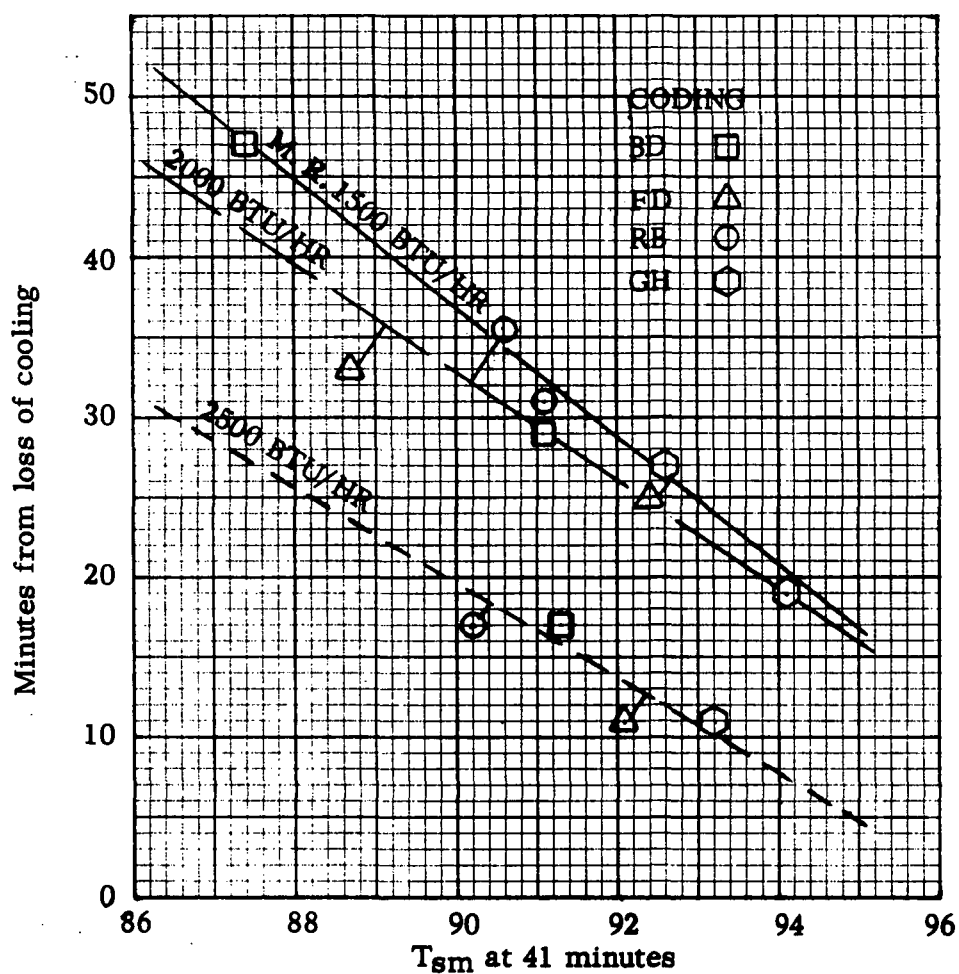


Figure 10. Time to incipient collapse, in interrupted cooling experiments, in relation to mean skin temperature ( $T_{sm}$ ) at start of zero heat loss period. Trend-lines for three metabolic rates, and individual values for four subjects.



### Equilibrium Heart Rate and Tolerance Time

The presence of a thermal burden should be reliably revealed by heart rate. In Fig. 5, the effectiveness of the pre-cooling at 1500 Btu/hr in BD is clearly indicated by the heart rate, which never exceeds 100 until cooling stops, as compared to a plateau of 120 to 130 for the other men.

At 2000 Btu/hr, subject GH, who is obviously undercooled, had an equilibrium heart rate 30 beats/min higher than the others, presaging his abbreviated stress tolerance.

At 2500 Btu/hr, the steady climb of heart rate for all four men reveals that none is being cooled even adequately. Even here, a 50 per cent increase in tolerance time is associated with 30-minute heart rates of 138 and 152, as compared to the two men who were above 160/min at that time during the cooling phase.

Figure 11 summarizes the relationship between the heart rate at the end of the cooled period of work and the endurance time after the cessation of cooling. There is a surprisingly small scatter among the points representing 12 different combinations of individual and metabolic rate, and the suggestion is strong that equilibrium heart rate is an accurate indicator of combined work and thermal burden. The straight line is an eye fit which ignores the single point at 47 minutes. Except for the latter, the scatter about the indicated line of relationship is  $\pm 2.5$  minutes. The slope indicates a loss of 4.5 minutes in tolerance time for every increment of 10 beats per minute in the heart rate at the end of the period of thermal balance.

### Heat Extraction During Equilibration Period

From the continuous record of LCG inlet-outlet temperature difference and flow rate, we can compute the amount of heat picked up from the skin by the water circulated through the suit. As explained earlier, the inlet temperature was gradually lowered at the start of each experiment in an attempt to preclude chilling of the subject, but still keeping him comfortably cool. Flow was kept essentially constant at 2.25 lpm, providing 300 Btu/hr cooling per deg F temperature difference between suit inlet and outlet.

Typically, inlet temperature was around 68° F in the first few minutes, gradually decreasing to 57° in most experiments. On one or two occasions, inlet temperatures as low as 49° to 51° F were attained toward the end of the cooling period. Figure 12 displays the time histories of the heat extraction in the individual

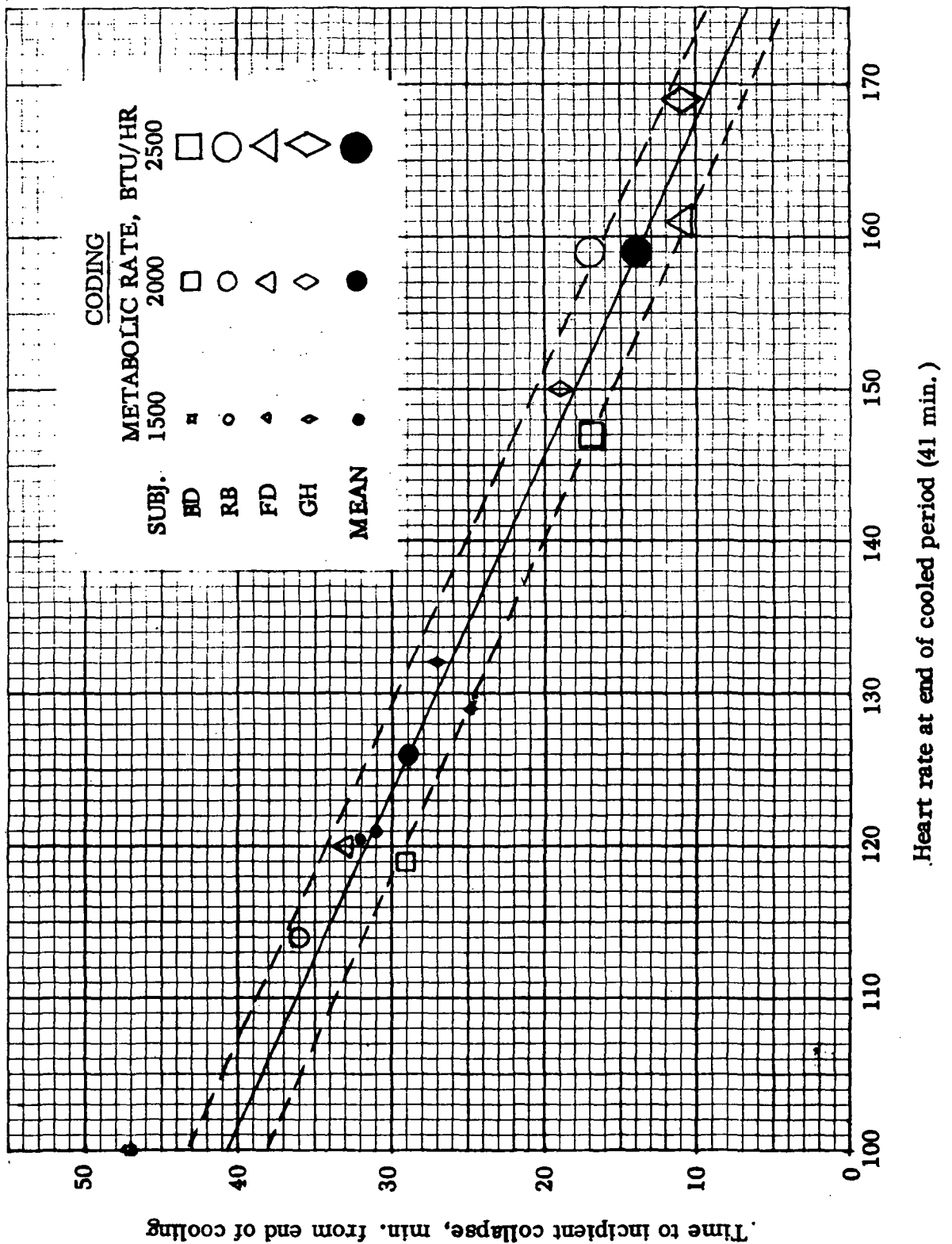


Figure 11. Individual and mean times to incipient collapse, from end of cooling, at 3 metabolic levels, in Type B experiments, as a function of heart rate at the end of the cooled work period (41 minutes).

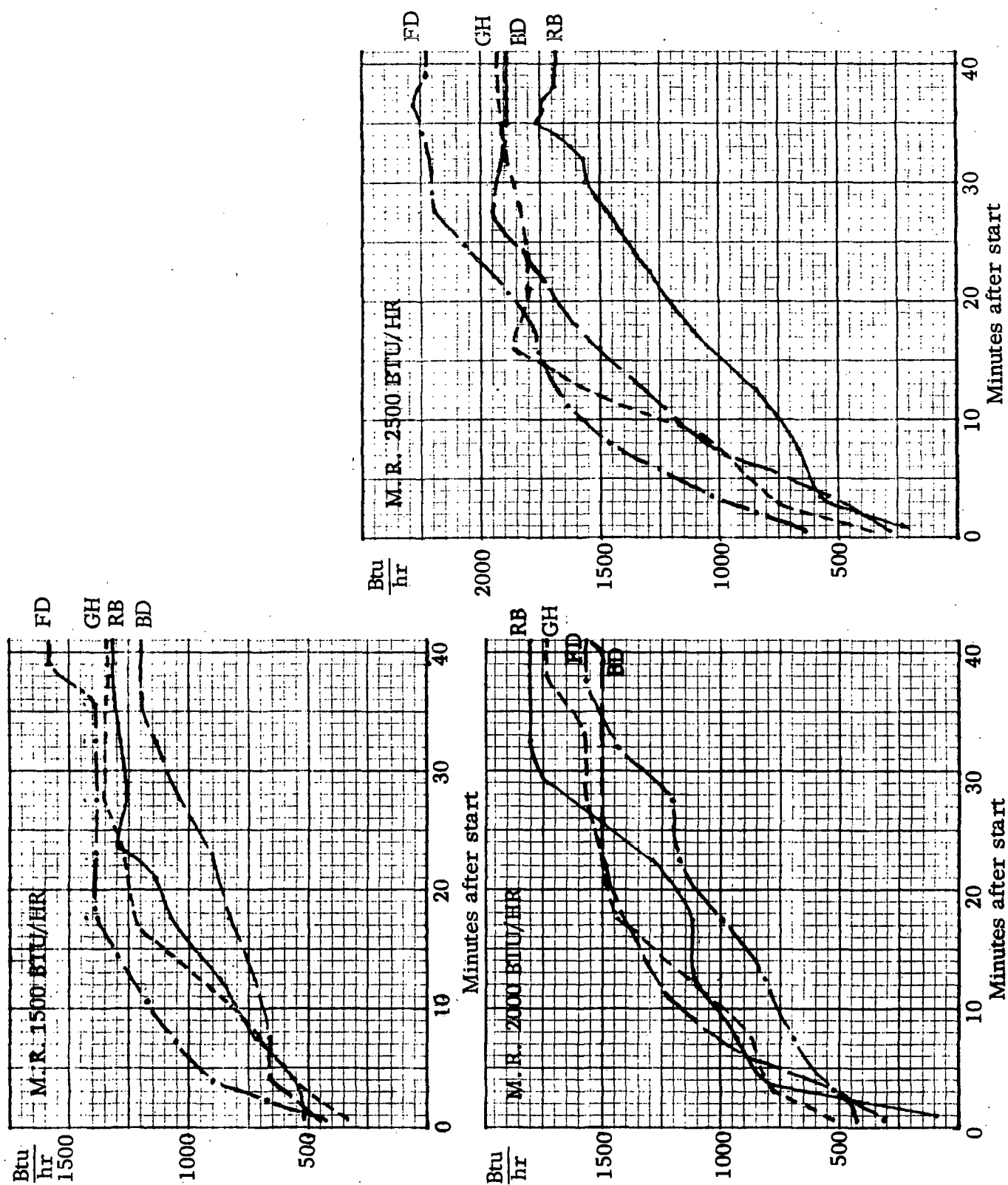


Figure 12. Heat extraction by the LCG during the 41-minute equilibration period.

experiments. The heat removal of the LCG was of course supplemented by respiratory heat loss, and from 200 to 350 Btu/hr was expended in external work.

It is apparent from Fig. 12 that we were relatively slow in attaining a balance between metabolic heat production and heat extraction, as a result of our concern about avoiding excessive chilling. It will be interesting to investigate in the future the consequences of attempting full cooling from the start of work.

The experiment on subject RB at 2500 Btu/hr metabolism is particularly marginal in the cooling program. This was the first experiment of the interrupted cooling type, and the low initial skin temperature caused us to be overly cautious in lowering the inlet temperature to the LCG. When full cooling power was applied, at 36 minutes, it was too late to improve the situation significantly and we were unable to get below 56° F inlet temperature or more than 1740 Btu/hr heat extraction.

The second experiment of this type was with subject FD at the 2500 Btu/hr metabolic level. This time the cooling was increased more rapidly, reaching a value of 1700 Btu/hr at 14 minutes, as compared to 920 Btu/hr at this time on RB. As was mentioned earlier, this subject was exhibiting a low grade fever of pyrogenic origin, which had not been noticed until the experiment was under way. Presumably this fact helps to explain why FD's comments stimulated the attainment of near maximal cooling by the 20th minute. At 35 minutes, the subject called for still more cooling, although he was already losing 2220 Btu/hr to the LCG and 370 Btu/hr in external work, plus a small respiratory loss. Hindsight suggests that the subject was actually calling for a lower skin temperature rather than a higher rate of heat extraction.

#### Sweat Loss Data

Table 2 displays the weight loss data for all 24 experiments, derived from nude weights taken just prior to donning and just after removal of the LCG.

It is noteworthy that the loss of sweat is nearly equal in the two types of experiments at a metabolic rate of 2500 Btu/hr, despite the relatively brief period without cooling. As discussed elsewhere, there must have been extensive sweating during the cooled period.

TABLE 2 - WEIGHT LOSS

Change in nude weight, beginning to end, lbs.

Experiment Type*	A	B	A	B	A	B	
Metabolic Rate (btu/hr)	1500		2000		2500		overall average
RB	3.08	2.05	2.15	2.48	2.08	2.10	2.32
BD	2.50	2.80	2.69	3.04	2.90	3.35	2.88
FD	3.86	2.68	3.97	2.65	2.72	2.71	3.10
GH	2.91	2.09	2.04	1.77	2.20	1.86	2.04
Average	3.09	2.40	2.71	2.48	2.48	2.50	2.6

\*Type A - fixed storage, 1000 Btu/hr

Type B - zero cooling after 41 minutes

Individual Performance (Inter-test comparisons)

The data presentation in Figures 2, 3, 4 and 5 tends to emphasize inter-individual differences in response to the prime experimental variable, metabolic rate in the two types of experimental procedure, constant heat storage and interrupted cooling. It is instructive, however, also to review the pattern of thermal response of a single subject to the six different combinations of metabolism and procedure.

This is done in Fig. 7 for subject BD, who was chosen for several reasons, not the least of which was the fact that he ranked the highest in the high-tolerance group in the previous experimental program (Ref. 1). He was without doubt the most phlegmatic and most physiologically stable of all the 10 original subjects. We therefore consider his responses to be more physiologically determined, and less affected by adventitious or psychological factors, than those of any of the other subjects.

In four of the six experiments on this subject, his pre-experiment rectal temperature was below 98.5° F. This seems to be the key factor in determining BD's superior tolerance time; at 2000 and 2500 Btu/hr metabolism in Type B experiments, where his initial rectal temperature is more normal, his tolerance times matched the mean.

The pattern of the ear temperature history in Type B experiments suggests that equilibrium was almost attained at 40 minutes, although the rise in rectal temperature was uninterrupted by the cessation of cooling.

## CONCLUSIONS

These experiments have established the fact that working men in thermal equilibrium are more vulnerable to the abrupt cessation of heat loss than the same men working at the same rates who were at rest prior to the onset of heat storage.

The data indicate that the amount of thermal sweating associated with heat extraction by an LCG has a powerful influence on the tolerance time available in the event of total cooling system failure. Thus for maximum fail-safety, it appears that the cooling system should operate at the lowest skin temperature which is commensurate with maintaining heat balance and avoiding musculo-skeletal difficulties.

The experiments involving a fixed deficiency of 1000 Btu/hr in heat extraction showed that this shortage tends to be more limiting at a low work rate, where it is a major proportion of the metabolism, than at higher levels of work. The main reason for this somewhat paradoxical situation appears to be the fact that skin temperatures are lower at the high work rates. Again, minimal skin temperatures appear to be associated with increased heat stress tolerance.

The finding that the collapse point may be reached in at little at 11 minutes after the cessation of cooling when a subject has equilibrated to a work rate of 2500 Btu/hr suggests that it would be prudent to undertake protracted work loads of this magnitude only after a period of pre-cooling to lower mean body temperature as much as possible.

The results generally support the view that an automatic control system designed to minimize skin temperature at any metabolic rate would provide the best protection in the event of cooling failure. Predictability of tolerance time at the instant of failure depends on an accurate knowledge of the thermal burden which has been imposed by the operation of the LCG during the preceding metabolic history. Heart rate is probably one of the most reliable of the simple indicators of such thermal burden, especially when the individual has been "calibrated" previously during non-sweating exercise. For the present group of experimental subjects, time to incipient collapse following loss of cooling was a linear function of the final equilibrium heart rate attained in 40 minutes of work with "comfort" cooling.

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