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CR-134059

POSTPONEMENT OF INCIPIENT COLLAPSE DUE TO WORK-INDUCED HEAT STRESS BY LIMITED COOLING

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Final Report on Contract
NAS 9-11889

Prepared for

ENVIRONMENTAL PHYSIOLOGY LABORATORY
MANNED SPACECRAFT CENTER
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
HOUSTON, TEXAS

September 1973

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APPENDIX

POSTPONEMENT OF INCIPIENT COLLAPSE DUE TO WORK-INDUCED HEAT STRESS BY LIMITED COOLING

This is the third report in a series of investigations dealing with the limits of heat tolerance in men unable to dispose of metabolic heat, while working, as fast as it is produced within the body.

The first phase of this work (1) was concerned with the simple case of a bout of work started at the moment when the capability of transferring heat from the body to the environment was lost. These first experiments began with a subject in a state of thermal equilibrium at rest; as the man began to work, removal of body heat was stopped completely, forcing the internal storage of the total metabolic heat generated in the course of treadmill walking at various speeds and grades.

In the second phase of the work (2) two factors were studied, namely the effect of metabolic rate (as determined by the rate of work) on the duration of tolerance when a standardized rate of heat storage was maintained and secondly the effect on the tolerance time of achieving thermal equilibrium at the particular work rate before loss of the ability to dissipate heat.

In general, the previous studies showed a very wide range of individual variation in tolerance times, and suggested that men of greater maturity and longer experience as professional fire fighters were more likely to display long endurance times than younger men who scored higher on a standard physical fitness test. The experiments at a fixed rate of body heat storage revealed that men succumbed earlier at the lower work rates than at the higher levels, probably because skin temperature was maintained at a lower value for the high work rates in order to achieve the required efficiency in heat dissipation.

The experiments in which heat loss was terminated after thermal equilibrium had been attained at a steady work rate showed that collapse could occur in as little as 11 minutes at a metabolic rate of 2500 Btu/hr, and reconfirmed the desirability of maintaining skin temperatures as low as possible during all routine LCG activity as a precautionary measure. The most useful parameter for predicting tolerance time in the event of loss of cooling power is apparently the heart rate.

The present phase of the work was designed to test the hypothesis that with a limited amount of refrigeration cooling capability, it might be possible to improve the status of the circulatory system in a subject approaching heat collapse and so extend the duration of his tolerance. The subjects had all participated in the previous studies and were familiar with the experimental routine.

EXPERIMENT DESIGN

Four subjects were used ranging in age from 27 to 39 years. Each man was given the standard NASA test for physical fitness at the beginning and the end of the program, and all completed at least five training sessions, walking uphill on the treadmill in a cool environment at metabolic rates approximating 2000 Btu/hr or more.

The final training session for each man was accomplished while wearing an LCG garment of the early Apollo type covered by a sealed impermeable garment which left only the face exposed, and a thick insulating layer externally. Sufficient cooling was supplied to the LCG to maintain the man in comfortable equilibrium and oxygen consumption was continuously measured on line. The speed and elevation of the treadmill were adjusted until oxygen consumption stabilized at 1.75 L/min., equivalent to 2000 Btu/hr metabolic rate. This was the work load used in all the subsequent heat stress experiments.

Each man received four heat exposures, consisting of a preliminary equilibration phase, during which the LCG was used to maintain a comfort state during the adjustment of rectal temperature to the imposed metabolic demand. At the end of the equilibration period the cooling flow supplied to the LCG was reduced to a level just sufficient to produce a net heat storage of 1000 Btu/hr. The first heat exposure was designed to establish the baseline tolerance limit for each individual subject to 1000 Btu/hr heat storage rate at a work rate of 2000 Btu/hr. In the three remaining heat exposure experiments on each man, a variety of methods for localized or abbreviated cooling were explored, in an effort to find a practical means for extending the duration of tolerable exposure by a significant amount.

In all heat exposure experiments, the following physiological parameters were continuously measured; skin temperature at nine locations, ear canal temperature, rectal temperature, heart rate. Electrocardiograms were taken periodically, and weight loss was recorded for each experiment. Oxygen consumption was measured on line periodically, using a unique valveless open circuit method developed in this laboratory.

Figure 1 shows the general arrangement of the laboratory facilities, the treadmill which is located in the environment control chamber being visible through the observation window at the left of the photograph. The methods and equipment used have been previously described (2).

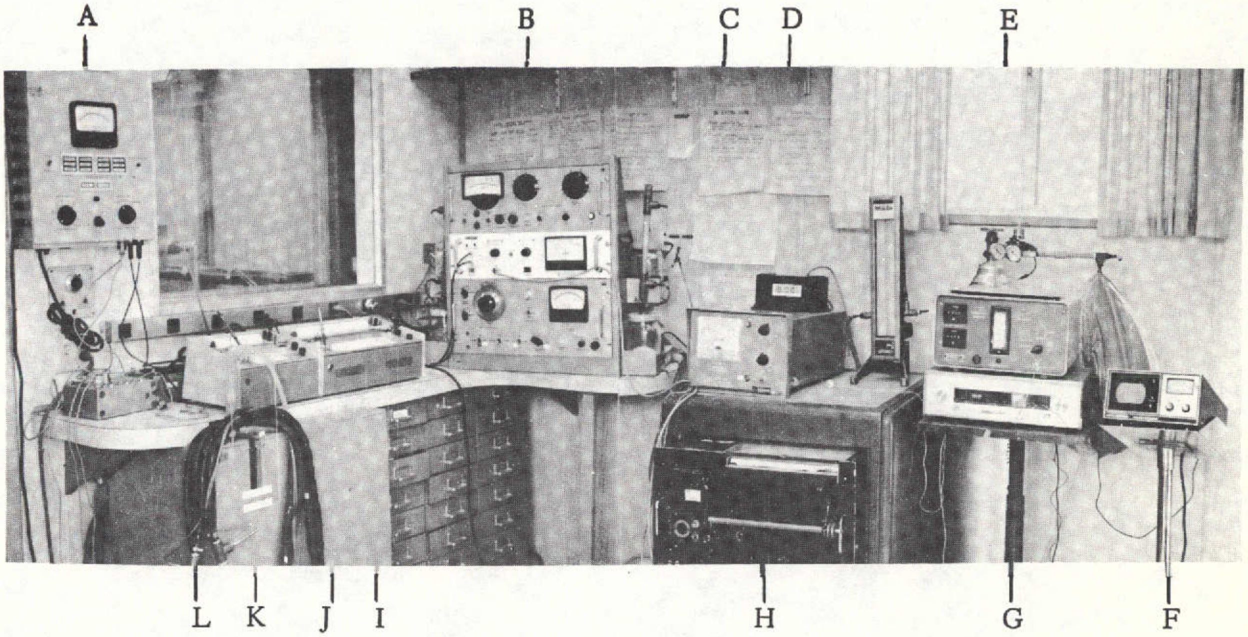


Figure 1. Instrumentation and Control Center

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 cardiotachometer.

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.

RESULTS

SUBJECT FD

The first of the experimental subjects, FD, is 39 years of age, 6' 1" in height and weighs 180 lbs. His fitness rating on the Luft-Balke test in each of the three years that he has served as a subject, has been exceeded only by subject SR, the youngest man in the present group; in a total of 10 tests over the years, his duration has never been less than 16 minutes and has been 18 minutes on three occasions, 19 minutes once. Needless to say, this is a man who is serious about maintaining his physical fitness. He is also highly competitive, and very conscientious about delivering his best possible effort.

In his first baseline heat exposure, marching at 2.6 miles per hour on a 7% grade, he began to have a slight disturbance of equilibrium after 45 minutes of heat storage, which showed up as a tendency to lose balance whenever he looked to the side of the treadmill. 10 minutes later he reported a definite and strong loss of orientation and at 64 minutes heat storage exposure, he stated that "everything fell apart"; he had difficulty in maintaining balance and was forced to hold onto the handrail periodically to remain upright. The experiment was terminated at 70 minutes of heat storage exposure at a rectal temperature of 102.3 and an ear temperature of 102.0, heart rate 181 (down from a high of 186).

FD's second heat exposure was two days later, at the same treadmill speed and grade. A very simple emergency cooling procedure was tried, consisting of the application of a pre-cooled gel-filled pad applied to the bare skin at the base of the neck. The gel pad was taken directly from the freezer compartment of a refrigerator at a temperature of 0°F; its temperature had risen to 16°F at the end of the five minute application. During the application of the cold pack, the subject stood motionless beside the treadmill. He stated that at the time he was taken off the mill he was not tired, although he had noticed a slight amount of disorientation, beginning at about 40 minutes of heat storage exposure. As can be seen in Figure 2, there was no interruption in the rate of rise of rectal temperature during the five minute cooling period, although the ear temperature shows a discontinuity beginning in about the third minute of cooling.

Upon resuming the march, the subject stated that he found the difficulty of the work severely increased, although the heart rate remained below the value which had been attained at 60 minutes for 10 minutes. 7 minutes after the resumption of work, the subject was displaying air hunger, gasping for breath, and stated that there was no improvement in the difficulty of the work load. He began puffing and at 77 minutes the loss of equilibrium was noticeable worse than it had been. The exposure was terminated at 78.5 minutes, with a rectal temperature of 102.6 and ear canal temperature of 102.1, heart rate 172.

The 8.5 minutes of increased duration for this experiment cannot be considered significant when one takes into account the five minute rest. The vasoconstrictive effect of a limited area supercooled pad thus seems to be minimal.

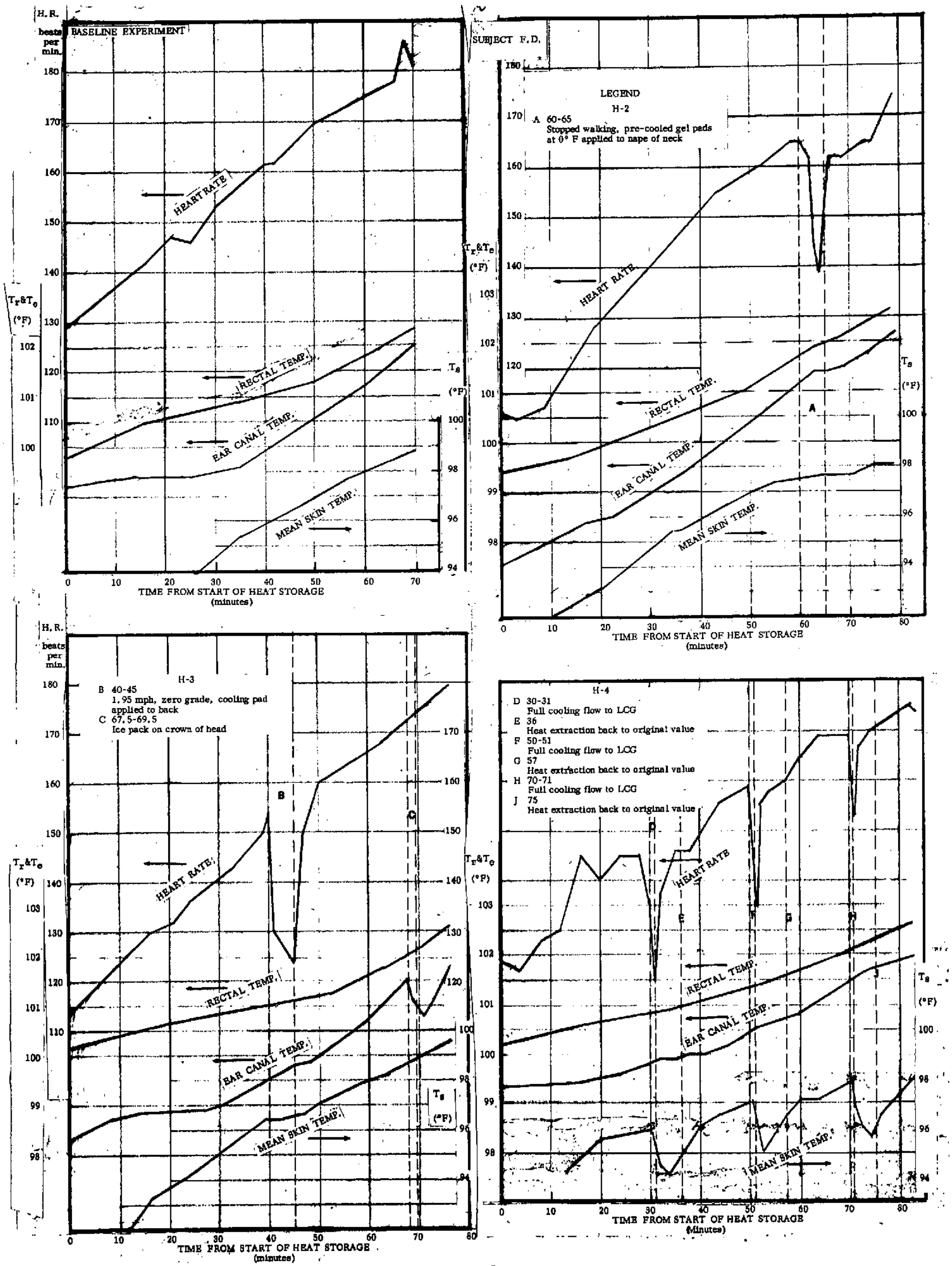

BASELINE EXPERIMENT
H. R. beats per min.
HEART RATE
RECTAL TEMP.
EAR CANAL TEMP.
MEAN SKIN TEMP.
T_r&T_e (°F)
T_s (°F)
TIME FROM START OF HEAT STORAGE (minutes)
SUBJECT F. D.
LEGEND
H-2
A 60-65
Stopped walking, pre-cooled gel pads at 0° F applied to nape of neck
H-3
B 40-45
1.95 mph, zero grade, cooling pad applied to back
C 67.5-69.5
Ice pack on crown of head
H-4
D 30-31
Full cooling flow to LCG
E 36
Heat extraction back to original value
F 50-51
Full cooling flow to LCG
G 57
Heat extraction back to original value
H 70-71
Full cooling flow to LCG
J 75
Heat extraction back to original value

Figure 2

In the third experiment with FD (H-3) the special cooling treatment was applied earlier, after 40 minutes of heat storage, and instead of stopping the work entirely, the treadmill speed was reduced to 1.95 mph and the grade was reduced to zero. The drop in heart rate in response to this reduction in work load was almost identical to that observed in the previous experiment when work was stopped entirely; skin temperature nearly leveled off during the period of cooling and the ear canal temperature showed a slight plateau after the cooling period ended.

The supercooled pad was again applied to various parts of the back during the 5 minute "breather" and again the benefit was short-lived and unimpressive. 7 minutes after resuming work the subject reported slight loss of equilibrium and 3 minutes later his respiration was observed to be noticeably increased in depth and rate. By 66 minutes of exposure time FD reported his equilibrium was "going to pot" although he did not feel particularly tired. At 67 minutes the ventilation face mask was removed and a supercooled pad was applied to the top and sides of the head without any reduction in the work load. This spot cooling was continued for just 2 minutes; the only clearly definable effect was a sharp drop in ear canal temperature. The experiment was terminated at 76 minutes with the subject having difficulty in breathing, disoriented, and with a high heart rate. Again, there was no demonstrable advantage gained from the emergency cooling procedures used.

In the fourth and final heat exposure for subject FD, it was decided to apply more heroic cooling procedures in a determined effort to extend the tolerance time. The general strategy was to give three very brief "shots" of full body cooling, starting early in the heat exposure. The first such 1 minute cooling shot was given at 30 minutes. As will be seen in Figure 2, the thermal lag of the Apollo LCG produced a 5-minute carry over of increased cooling after the increased cooling flow had been shut off.

In each case the mean skin temperature dropped sharply during each cooling session with the net result that at the termination of the heat exposure the skin was only 97°F, a value which was reached in the previous three heat exposures at 50 minutes exposure time.

Although the total exposure duration in experiment H-4 was 83 minutes, the net improvement can hardly be considered impressive when one takes into account the cumulative total of 18 minutes of cooling flow to the LCG in excess of the design value producing a body heat storage 1000 Btu/hr. Subtracting 18 minutes from 83 leaves a net balance of 65, which represents a net loss as compared to the unaided heat exposure H-1.

Immediately before the first special cooling episode at 29 minutes, the subject stated that he felt warm all over but not uncomfortably so, and added that he seemed to be moving fairly easily without much trouble. Immediately after the cooling, he reported "even the extremities seemed to cool off a little", and indicated that walking seemed to be easier. Later, he reported that even 14 minutes after the end of the cooling, he could still feel residual pockets of cooling around his body.

After the second cooling episode, he noted that it didn't seem as cool as before; the extremities did not seem to be noticeably cooled the second time. The tendency to lose equilibrium seemed to have cleared up, and walking seemed easier to him.

In general, the effect of the cooling episode was definite but less dramatic than the first time.

At 68 minutes exposure time, 17 minutes after the second cooling episode, he reported the loss of equilibrium sensation again whenever he looked from side to side.

The third cooling episode from 70 to 71 minutes again produced a mild improvement in the subject's subjective sensations, including easier breathing and easier walking as well as an abatement of the disorientation sensation. 10 minutes later he was having difficulty walking straight, having to concentrate on looking straight ahead in order to do so, and reported a tendency to stumble occasionally. The experiment was terminated at 83 minutes because of high heart rate and lack of coordination.

SUBJECT BD

The second subject to begin his heat exposure series, BD, took his first baseline heat exposure on the same day that FD completed H-4. In the 1969 study (1) subject BD ranked number one of all eight subjects in terms of cumulative endurance time in all heat stress experiments. He is 37 years old, 6'2" in height, and weighed 174 lbs. at the time of the experiments. He follows an organized fitness maintenance program, and seems to have unusual stamina, although his performance on the bicycle ergometer is not impressive because of muscle limitations association with lack of specific training. In his calibration run, subject BD walked at 2.6 mph up a 7% grade for 75 minutes, and never exceeded a heart rate of 107 bpm. The heart rate plateau was established at about 40 minutes, having remained below 100 for the first half of the experiment.

In the baseline heat exposure H-1, subject BD spent 60 minutes in the adjustment phase, with cooling supplied to the LCG adequate to maintain a comfortable skin temperature between 90 and 91°F. The final heart rate was 112 bpm, and when asked about his subjective sensations, he reported no feeling of tiredness in the legs, and a general state of thermal comfort.

After 45 minutes of heat storage, BD reported feeling "very warm all over", heavy perspiration on the forehead, back and arms, but stated that the feet and legs "felt good". His heart rate at this time was 156 bpm. When queried again at 69 minutes, BD reported chills and a tight feeling in the throat and in the area of the diaphragm. He also reported the sensation of desiring to urinate. At 74 minutes exposure time, the sensation of desiring to urinate had become strong, the subject was short of breath, the chills were more frequent, and he reported a lump in the diaphragm area at the center of his chest "like a gas pain". On the basis of these symptoms and a heart rate of 180 bpm, the exposure was terminated at this point. Upon stepping off the treadmill, there was a slight amount of dizziness or unsteadiness, but the "gas pain" in the chest quickly disappeared.

In the second heat exposure for subject BD, the pre-exposure adjustment period was again 60 minutes in length; the final heart rate was 109 bpm, mean skin temperature 88.5°F and the rectal temperature 99.40°F. After the run was started, it was

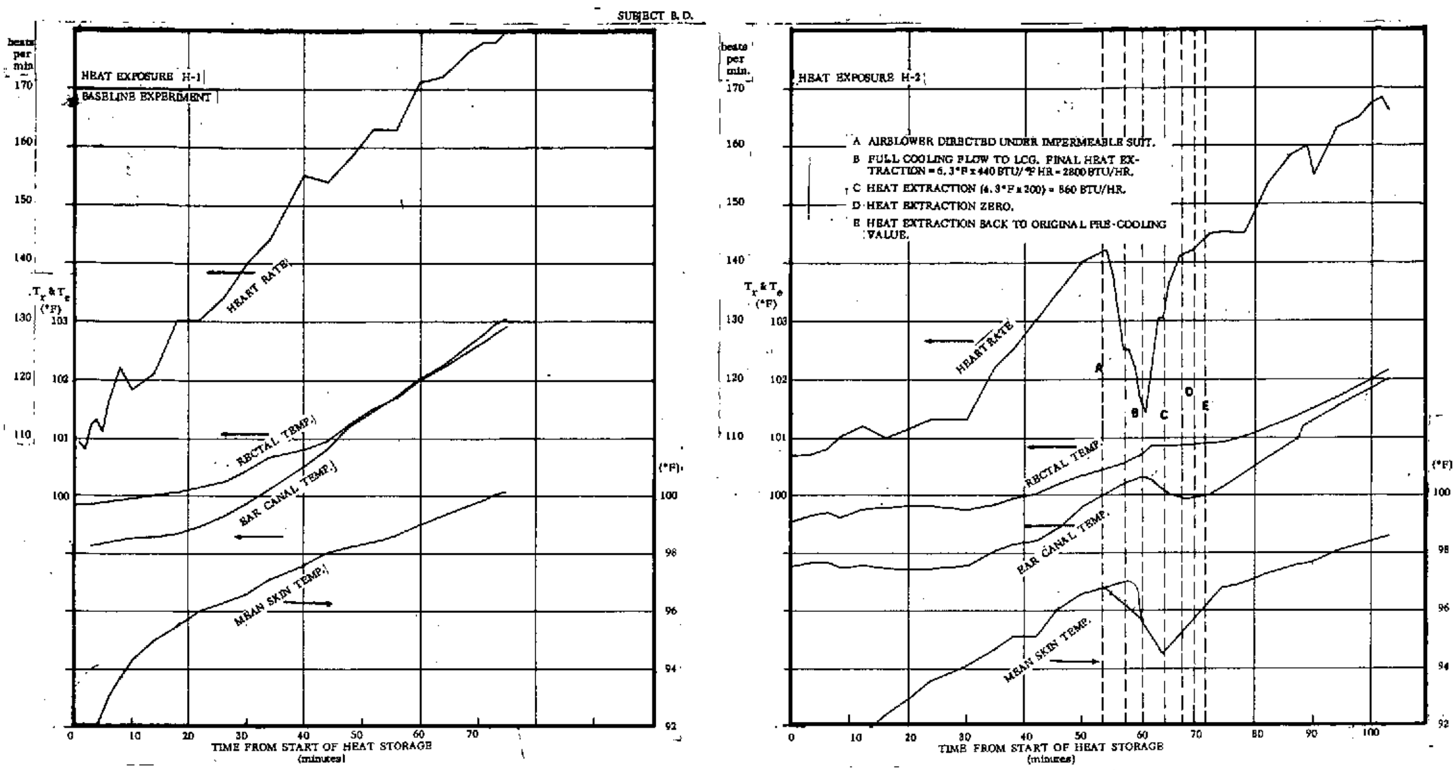
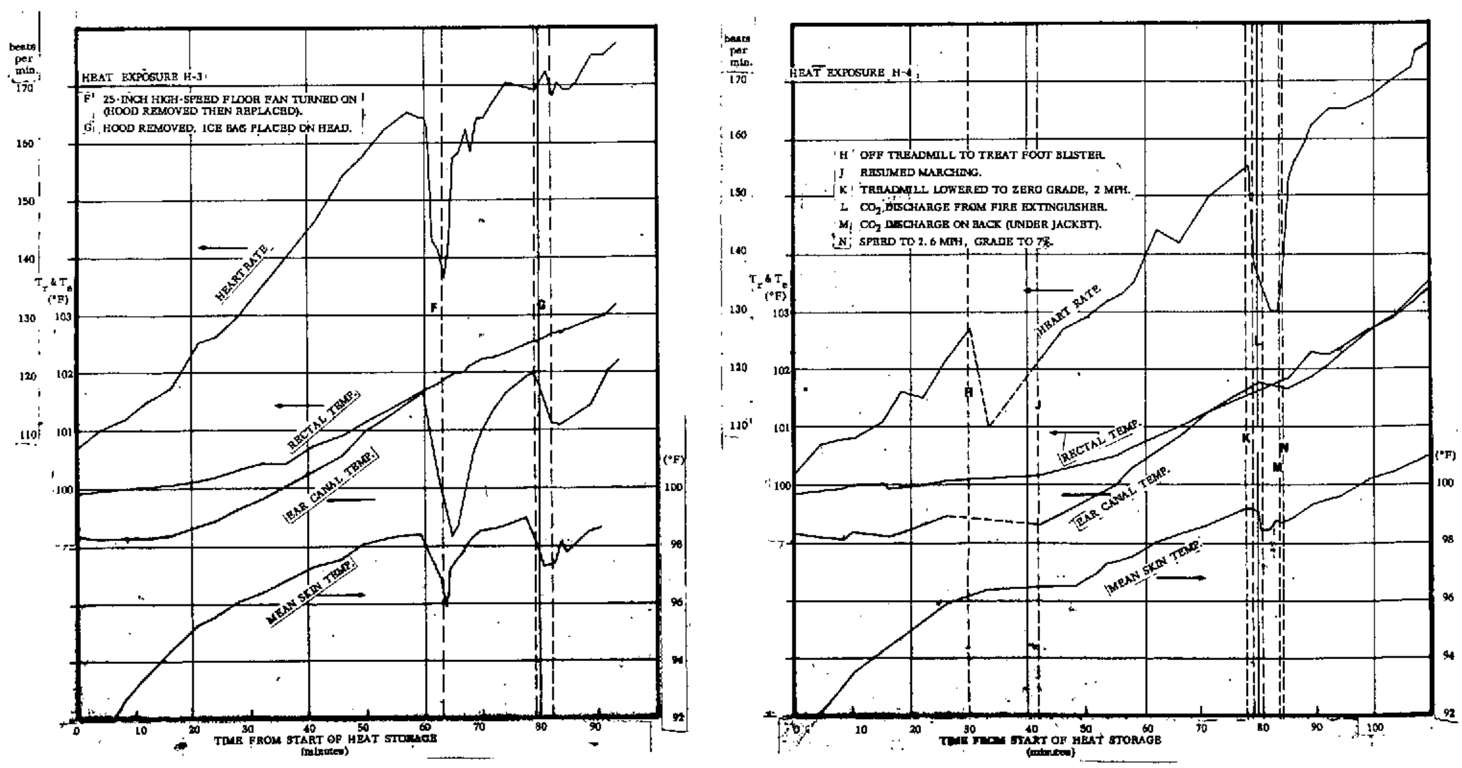


Figure 3

Physiological responses to internal heat stress, baseline and experimental exposures - Subject BD



it was learned that the subject had responded to three separate alarms during the preceding night so that he was up from 10 to 12 midnight and roused again at 2:00 and 4:00 a.m. He had had no breakfast.

The first trial method of emergency cooling for this subject was started at 54 minutes of exposure time; the discharge from a small portable vacuum cleaner blower was directed beneath the impermeable suit after lowering the treadmill grade to zero and the speed to 2 mph. Upon the subject's observing that the degree of cooling sensation seemed to him insignificant, the air blower was removed, and at 58 minutes cooling flow to the LCG was increased to maximum. The cooling flow was reduced again four minutes later, at 62 minutes exposure time, but the rate of heat extraction was still 50% greater than the value required to maintain a body storage rate of 1000 Btu/hr at exposure time 66. At this point the flow was stopped altogether for four minutes, and at 72 minutes exposure time the original heat extraction rate of 500 Btu/hr was re-established. A rough integration of the heat extraction history over this period indicates the net excess heat extraction to be approximately 135 Btu. It may be noted in Figure 3, on the skin temperature curve for heat exposure H-2, that skin temperature did not begin to drop until the increased cooling flow to the LCG was started.

At 96 minutes exposure time, or 25 minutes after the steady storage rate of 1000 Btu/hr had been resumed, subject BD was asked for a report on his sensations; he stated that the small of his back felt tired, that the tightness reminiscent of gas pains was beginning again in his diaphragm area, the desire to urinate sensation was present in slight degree and he "just felt warm all over". At 100 minutes, he stated that he had experienced a couple of severe chills and that the back discomfort was still present. The other sensations had abated slightly. Four minutes later, he reported more frequent chills, disappearance of the urination sensation but a continued feeling of pressure in the throat and abdomen. The subject stated that he was "possibly a little weary, a little staggery", and was observed to be somewhat unsteady on the treadmill. The decision to terminate was made at 104 minutes, with a heart rate of 168.

Although the gross tolerance time in exposure H-2 was 29 minutes longer than the baseline experiment, there was approximately 10 minutes of increased cooling and/or reduced work load halfway through the experiment. One might therefore estimate that the net benefit of this particular cooling treatment was approximately 15 minutes or 20% of the baseline tolerance time.

Heat exposure H-3 for subject BD was started, like the others, after a 60 minute adjustment period, which brought rectal temperature to 99.7°F and mean skin temperature to 90°F, heart rate fo 107 bpm. After 50 minutes of heat storage, the subject stepped off the treadmill and removed the impermeable hood. A high speed, double-bladed 25 inch floor fan was directed at the subject's bare head for 4 minutes. After 1 minute of this high wind, the subject was asked for his sensations; he reported "it feels very comforting; no more heat; - I don't feel that hot and I don't have any shortness of breath, no sensation to urinate, and the tiredness has gone out of my back and legs a little bit".

When queried again at 76 minutes, the subject reported some chills and some shortness of breath again. At 80 minutes, an ice pack was placed on his head for 1.5 minutes without altering the work load. At 92 minutes, subject reported "nothing new, just chills, desire to urinate, moderate chest discomfort, shortness of breath". The experiment was terminated at 93 minutes at a heart rate of 177 bpm, rectal temperature 103.5°, ear canal temperature 102.1°F. Subtracting 6 minutes of special cooling from the total exposure time of 93, leaves a net of 87 minutes, representing a 12 minute or 16% improvement over the baseline experiment.

Exposure H-4 for subject BD again had a 60 minute adjustment period, with a final heart rate of 104 bpm, skin temperature of 91.0, rectal of 99.86, and an ear canal temperature of 99.14° F. After 30 minutes of heat storage, the subject was obliged to step off the treadmill in order to treat a blister. After 11 minutes, the work resumed at 41 minutes exposure time. Between 78 and 83 minutes exposure time, the treadmill speed was lowered to 2 mph and the grade reduced to zero; a fire extinguisher was used to discharge carbon dioxide snow between the insulating garment and the impermeable suit. The nozzle of the extinguisher was directed down the pants legs, over the back, and on the front of the torso.

At 109 minutes exposure time, the subject was staggering slightly, experiencing difficulty in maintaining a straight course on the treadmill. The exposure was terminated at 110 minutes at a heart rate of 175, a rectal of 103.30 and an ear canal temperature of 103.40.

Allowing for the 11 minutes time out for the treatment of the blister and 5 minutes of cooling treatment, we derive a net increment of 19 minutes, a 25% improvement over the baseline heat exposure tolerance time.

SUBJECT RB

The next subject to complete the series of heat stress exposures, RB, was 36 years of age, 6' tall, and weighs 179 lbs. He also was a subject in the previous two studies, and his fitness test scores have varied between 14 and 17 minutes over the three years. In the comfortable cooled calibration run, after 67 minutes of walking at 2.6 mph up a grade of 7%, he said "all of my body feels well cooled where the suit is; a little warm from the wrists down to the hands and a little warm around the ankles. Mainly the warmest spot would be around the neck and the head. Physically, I feel slightly tired in the groin and upper thighs; other than that all the muscles seem fine - not worked at all."

In the first baseline heat exposure, H-1, RB reported at 30 minutes that he felt "pretty hot all over, with the neck and head a little hotter than the rest of the body. A little tired in the groin again and along the shoulders".

In contrast to subject BD, RB developed heart rates in the vicinity of 140 bpm in the latter third of his cool calibration run. His adjustment period for heat exposure H-1 was 30 minutes in duration, and the final heart rate was 140. At the time of the above comments, 30 minutes into the heat storage period, his heart rate had reached 160 bpm.

When questioned again as to his sensations at 54 minutes exposure time, RB reported rapidly increasing fatigue over the general body, an extreme sensation of heat, and a dry throat. He added spontaneously in heartfelt tones, "I must have been out of my bleeping mind to consent to this again".

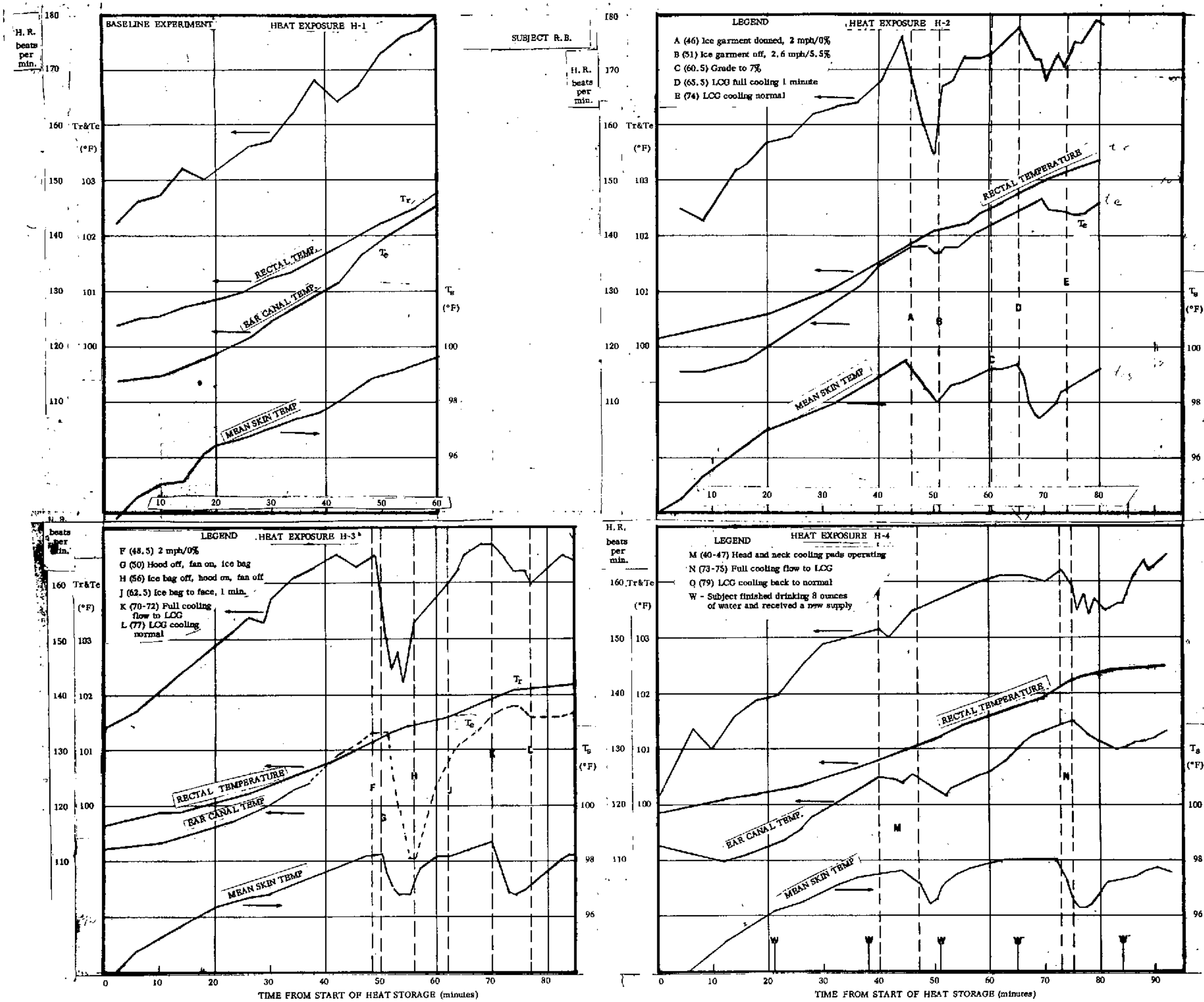


Figure 4

Physiological responses to internal heat stress,
baseline and experimental exposures - Subject RB

By this time the subject was displaying a shambling, shuffling gait and reported a slight loss of equilibrium causing him to stagger slightly. The experiment was terminated at 60 minutes of heat storage exposure time with a heart rate of 180, rectal temperature 102.8, ear canal 102.6, mean skin 99.5.

The second heat exposure, H-2, was preceded by a 40 minute adjustment period with the internal temperatures and the heart rate stabilized at closely similar values to those at the beginning of the baseline heat exposure. The treatment used in this experiment was a torso ice garment consisting of a large number of flat sealed plastic tubes, containing small amounts of water, which had been pre-frozen in the freezer compartment of a refrigerator. The entire frozen garment had an initial temperature of 0°F. Because of the manner in which the plastic compartments are sealed together, the garment is quite flexible even at zero, and is designed to slip over the head and drape down the front and rear of the torso, with the tapes at the sides of the body. In essence it is designed like a double apron with a high neck and a high back, with short extensions reaching part way down the thigh.

This ice suit was slipped between the sealed impermeable garment and the outer insulation garment, at 46 minutes exposure time, after lowering the speed and grade of the treadmill to 2 mph/0%. The ice suit was removed 5 minutes later, and the speed of the treadmill was returned to 2.6 mph; inadvertently, the grade was increased only to 5.5% instead of the intended 7% and this error was not discovered until another nine minutes had passed. As soon as the grade was corrected, heart rate rapidly rose again to approach 180 bpm, suggesting that further emergency action would be necessary if the total tolerance time was to be extended significantly. Accordingly, full cooling flow to the LCG garment was initiated at 65.5 minutes and turned off approximately 1 minute later. It required a further 8 minutes for the rate of heat extraction to fall back to the original value associated with a body storage rate of 1000 Btu/hr. Integration of the heat extraction time history over a 9 minute period yields an estimate of the excess heat extraction of 113 Btu over and above the base rate.

As soon as the original heat storage rate was resumed at 74 minutes, the heart rate again began to rise rapidly and since the rectal temperature had by now risen well above 103°F, and the man was obviously in great distesss and highly fatigued, the exposure was terminated at 80 minutes at a heart rate of 178 bpm, rectal 103.36, ear canal 102.54, mean skin 99.2. Allowing for the 14 minutes of reduced work load and/or special cooling procedure, the net increase in tolerance time was 6 minutes or 10% of the baseline figure.

For RB's third heat exposure, a combination of air cooling and ice pack applications was used to achieve a sharp reduction in scalp temperature for a total of 6 minutes between 50 and 56 minutes of heat exposure. The treadmill was lowered to zero grade and speed reduced to 2 mph at 48.5 minutes. The bag of ice applied to the head weighed slightly under 2 lbs.

The effect of this treatment was not impressive; the subject found the removal and replacement of the hood an ordeal. The heart rate did not fall below 142 bpm during the cooling treatment, having been 165 before the cooling.

At 62.5 minutes the ice bag was applied to the subject's face for one minute; this again seemed to be relatively ineffective and at 70 minutes full cooling flow to the LCG was started and shut down 2 minutes later. By 77 minutes the heat extraction rate had returned to the original value associated with the design body heat storage rate.

The experiment was terminated at 85 minutes exposure time due to extreme fatigue of the subject. Allowing for 16 minutes of reduced work and/or cooling, the improvement in tolerance time relative to the baseline experiment is 9 minutes or 15%.

In the course of the interrogation preceding the decision to terminate, the subject RB observed that under ordinary standards of motivation, there was no way he could be persuaded to subject himself to the kind of abuse he was then experiencing. The only reason for tolerating such conditions was because he felt "morally obligated". This is probably a most significant observation and reflects the fact that this particular group of special firemen subjects have an unusual willingness to drive themselves to the limits of physiological tolerance, in the spirit of scientific investigation, considerably beyond the point at which they would normally give up in the course of their professional duties.

In the fourth exposure for subject RB a combination of procedures was tried. First of all, an attempt was made to maintain a state of constant hydration throughout the period of heat storage by keeping cool water in front of the subject at all times, and encouraging him to sip 8 ounces within a 20 minute period (beginning midway through the 40 minute adjustment period before the start of heat storage). As can be seen in the H-4 panel of Figure 4, the 8 ounce servings of water were finished at 21, 38, 51, 65, and 84 minutes of the heat exposure period. In addition, a further 8 ounces of water was ingested during the adjustment period. Attainment of the objective was indicated by the net change in nude weight of only 0.54 lbs. over the full 2 hours and 10 minutes of the experiment.

In addition to the maintenance of hydration, a further attempt was made to achieve effective cooling of the head and neck, this time by means of a pair of commercial cooling pads, through which cooling water was pumped from the system supplying the LCG. The larger of these, 6 by 16 inches in area, was tied across the top of the head extending down over the temples on either side. The smaller unit, 2.5 inches by 13 inches, was secured around the neck; an insulating hood covered both. These two units, manifolded together, were supplied with cooling water from the LCG circulation system from 40 to 47 minutes of the heat storage period. The system was not very efficient and inlet temperature to the head cooling pads fell relatively slowly from about 90° F at 42 minutes to 81.5° F at 43 minutes, 72°F at 45 minutes, reaching a low of 68 degrees at 47 minutes when rewarming of the circulating water began. When the LCG was reconnected to the circulating system, there was a carryover of extra cooling for the first couple of minutes; normal heat extraction as required to produce the 1000 Btu/hr heat storage rate was re-established at 51 minutes exposure time. Integration of the cooling flow records for the supply of cooling water to the head cooling pads indicates a total extraction of 153 Btu during the 7 minutes of operation, or 83 Btu in excess of what would have been taken out by the LCG under the standard flow conditions. The additional excess heat extraction ascribable to the several minutes of operation of the LCG with a reduced inlet temperature is an additional 23 Btu. As can be seen in Figure 4, the only clearcut effect of this cooling episode was in the ear canal temperature.

When questioned at 68 minutes exposure time, with a heart rate in the range 162 to 165, RB reported that while he felt pretty hot from the neck up, he was still "ok" with only moderate fatigue in the legs and groin. Starting at 72 minutes, he was then given 2 minutes of full cooling flow to the LCG, with the heat extraction rate returning to its original value at 79 minutes, for a total of 7 minutes of excess cooling with a total excess heat extraction of 110 Btu beyond the standard amount producing a heat storage of 1000 Btu/hr. The final inlet temperature during this brief cooling episode was 54°F, with a corresponding outlet temperature of 63°F.

Immediately after the cooling episode RB was asked to comment on the degree of improvement. He answered "It did a lot of good for most of my body. Of course, it didn't help from the neck up. I still have the groin pain and a slight side ache on the left side. All of my body feels cool right now with the exception of the head and hands. The cooling helped my fatigue considerably".

Fourteen minutes later at 89 minutes exposure time the subject had nothing in particular new to report except that his shoulders and neck seemed to be getting tired and he noticed an increased sensation of pressure in the bladder. Objectively, he appeared to be somewhat uncoordinated and in considerable distress. The exposure was terminated at 92 minutes at a heart rate of 165, rectal of 102.5, ear canal 101.35, and mean skin 97.6.

After subtracting 18 minutes for the two sessions of head cooling and LCG extra cooling, the remaining increment over the baseline tolerance time is 14 minutes or 23%.

SUBJECT SR

The last subject to be studied in the current series, SR is a young man of 26 who was the best of the low tolerance group in the original study performed in 1969. He was also the top ranking subject of the original eight with respect to physical fitness, as indicated by the score on the Luft-Balke ergometer test. His mean score for three tests in 1969 was 18 minutes; he scored 19 minutes in both of the tests administered in the present study.

In the hope of resolving the question of whether special attention to head cooling would be effective in achieving the kind of tolerance time extension we were looking for, we borrowed from Webb Associates Yellow Springs a tubing network skull cap which had been utilized in a study of the efficacy of head cooling as a substitute for general body cooling in 1969 (3). These authors had shown that with a cooling water flow of only 350 cc's per minute the skull cap extracted approximately 120 Btu/hr from a subject at rest and up to twice that amount in working subjects in moderate environments. The authors found no upper limit to the cooling capability under 40° C. environment conditions.

The first baseline heat exposure for subject SR had to be terminated at 36 minutes at the request of the subject, at a heart rate of 150, rectal 101.8, ear canal 101.5. The pre-storage adjustment period had lasted 60 minutes and rectal temperature had stabilized at 100.10, which exactly matched the final rectal plateau in the calibration run under cool conditions two days before.

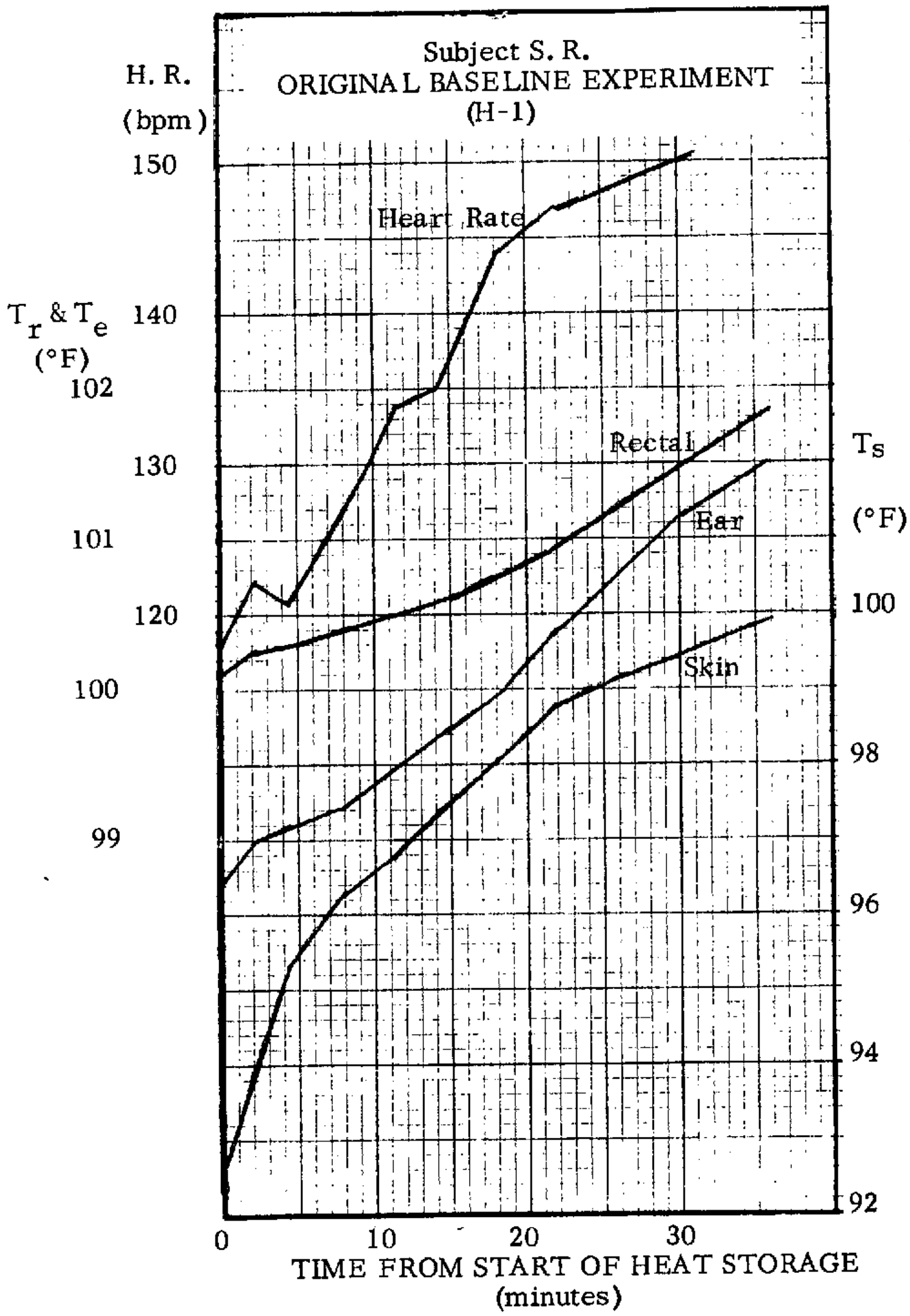


Figure 5

First Baseline Experiment on Subject S. R.

(Abnormally abbreviated heat tolerance time)

On his next visit to the laboratory, SR stated that he "must have had a virus", based on his symptoms on the evening and the day following the experiment, which included intestinal distress and stomach cramps. The physiological response in the H-1 experiment is displayed in Figure 5. After comparing these curves with the data obtained in the three subsequent heat exposures, we decided that there may have been a factual basis to the subject's suspicion that he was not in his normal state of health on the day of the first heat experiment. Accordingly, SR was subjected to a fifth experiment after the others were completed, which was then used as the baseline reference. Thus in Figure 6, the baseline chart in the upper left corner is for experiment H-5, in which the tolerance level was reached at 47 minutes, rather than for H-1. It is interesting to note that the final rectal temperatures were essentially identical in experiment H-5 and H-1, although rectal did not begin to rise until after 20 minutes of heat storage in the later experiment. Similarly, the ear canal temperatures in the two experiments began and ended at almost exactly the same point, although the rise began immediately in H-1 and began at 12 minutes exposure time in H-5. Skin temperatures followed a closely similar course in the two experiments until the thirty-sixth minute, with skin temperature continuing on for an additional 10 minutes at essentially the same slope. It is the heart rate picture which is distinctly different between H-1 and all the other heat exposures including H-5. The slope of heart rate increase was slightly steeper in H-1, and the rates are consistently higher throughout the full exposure time by 9 or 10 beats initially and 20 bpm later on.

The reason for terminating experiment H-5 was the inability of the subject to remain upright and his continued reports of extremely tired legs with a "leaden" feeling. He held onto both side rails and tried to drag his feet by supporting his weight on his arms. The relatively low terminal heart rate suggested that the limit reached by the subject was not a cardiovascular one in the usual sense. During his cool calibration experiment this subject marched uphill for 95 minutes without complaint, attaining a plateau heart rate for the last hour of 114 bpm.

The first experimental cooling run for subject SR, experiment H-2, started out after a 40 minute adjustment period during which heart rate had stabilized at 104 bpm, skin temperature was at 92.8, rectal at 99.6, and the ear canal temperature 98.96. To ensure a minimum of external heat input to the exposed tubing of the Webb Associates skull cap, a down-filled skier's parka was applied at 15 minutes exposure time. In responding to questioning at 20 minutes exposure time, SR stated that he felt a little warm but otherwise fine physically; his heart rate at that time was 125. At 40 minutes, the only changes reported by the subject were that his hands and feet were much hotter than the rest of his body and especially the feet. By this time the heart rate was 145. At 54 minutes exposure time, the cooling water flow was diverted from the LCG to the skull cap; almost immediately the subject complained that his body was "burning up". Agreeing that his head felt good, he objected strenuously to the sudden increase in the sensation of heat in the legs and other parts of his body. Because of limitations in the plumbing arrangements, there was no cooling flow at all for about 30 seconds before the flow started in the head piece, and it took another 30 seconds before the temperature difference across the head piece reached 10°F. Two minutes after the LCG was cut off, the inlet temperature to the skull cap was 62° with an outlet of 73° and a flow rate of 1 L/min., representing a heat extraction rate of 1467 Btu/hr or 24 Btu/min. At 59 minutes, the clamps obstructing the inlet to the LCG were removed, establishing a parallel flow pattern

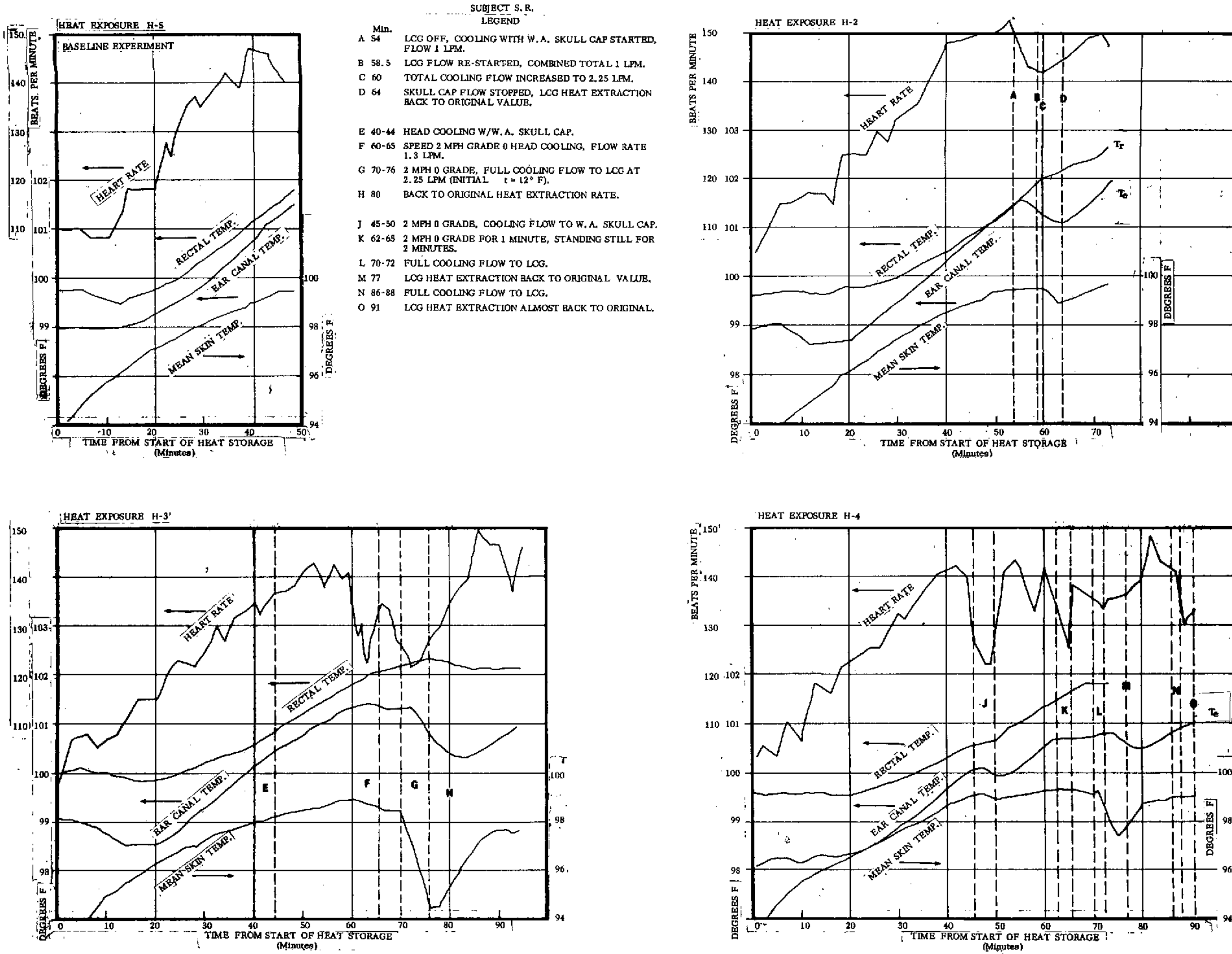


Figure 6

Physiological responses to internal heat stress, baseline and experimental exposures - Subject SR to both LCG and skull cap, whereupon the temperature differential increased to 13 F degrees with an inlet at 51°F, still at a total flow rate of 1 L/min, representing a heat extraction rate of 29 Btu/min. Two minutes later, at 61 minutes exposure time, the inlet temperature had climbed to 61 F, the flow rate having been increased to 2.25 L/min.

At 63.5 minutes, the total heat extraction was back to its original value of approximately 10 Btu/min, and the inlet tubes to the skull cap were closed off. Integration over this full 10 minute period indicates a net heat extraction of 112 Btu, in excess of the nominal 10 Btu/min which was required to maintain a heat storage rate of 1000 Btu/hr.

At about this time the subject complained of feeling "run down" and weak; 5 minutes later, at 69 minutes exposure time, he was leaning on the side rails trying to support his weight on his arms and reiterating the feeling of weakness. In view of the obvious inability of the subject to maintain the work load, despite a heart rate of only 150 bpm or less, the experiment was terminated at 74 minutes exposure time. Allowing for the 10 minutes of the cooling episode the tolerance time in exposure H-2 represents a 17 minute or 36% increase in tolerance as compared with the baseline experiment H-5.

When the insulating parka and the impermeable hood were removed at the end of the experiment, it was discovered that a substantial leakage from the skull cap had occurred, resulting in the accumulation of a quart or so of water within the neck area of the hood, which was sealed around the base of the neck. There was no way of assessing accurately the cooling value of this accumulation of water.

Before undertaking experiment H-3, the skull cap plumbing was repaired and a separate cold water reservoir and pumping facility was provided for the water cooled skull cap. A 40 minute adjustment period was utilized as before, producing a final heart rate of 102 bpm, rectal of 100.0 and ear canal temperature of 99.1.

From 40 minutes exposure time to 44 minutes, cooling water was supplied to the tubing cap at a flow rate of 1.3 L/min and a nominal inlet temperature of 35°F. Heat extraction totalled an estimated 90 Btu, and the subject was conscious of the improvement, commenting that the head cooling was "nice" because he had been sweating on the head. However, he also observed that he felt the heat in his legs severely, and remarked that his legs seemed to be bothering him more than anything else generally in these experiments. He was asked "So you would regard the head cooling as nothing more than superficially pleasant, right?" and his reply was "Right! It just feels nice - it's a very local feeling."

At 49 minutes the subject complained again that the feet and legs felt extremely warm and somehow weak and tired. At 60 minutes, the treadmill speed was reduced to 2.0 mph and the grade to zero and head cooling was started again, without any interruption of the LCG heat extraction which continued at 10 Btu/min. The temperature drop across the skull cap, at a flow of 1.3 L/min, was 5 F degrees, with an inlet temperature of 36°F, ± 1. After 5 minutes of head cooling at this approximate rate producing an estimated heat extraction of 85 Btu, the treadmill was returned to 2.6 mph/7%. During this period, the subject commented that his muscles felt "baked".

At 70 minutes exposure time the treadmill was again lowered and reduced in speed, and maximum cooling flow to the LCG was initiated. The high cooling flow and reduced work load was maintained for 6 minutes; the excess heat extraction lasted a total of 10 minutes, returning to the original 10 Btu/min at exposure time 80. Integration over the 10 minute period indicates an excess heat extraction of 315 Btu. Inlet temperature reached a minimum of 47.5°F, 1.5 minutes after full cooling was started, and stabilized at 51°F from the second minute of full cooling until the cut-off at 76 minutes.

During the above cooling session, the subject compared the sensation of weakness in the legs which was the most prominent feature of his symptom complex, with his typical experience as a high school runner. The following is an essentially verbatim transcript of his comments: "When I was running the mile, my legs would start getting tired as I approached the last quarter, but then they would also begin to feel very heavy; in the last 440 yards my legs would feel just like stones - I had no power or strength in them at all - yet I didn't really feel particularly tired. When I finished the race I really wasn't tired. The coach would bawl me out, seeing that I wasn't at the point of exhaustion, accusing me of dogging it. I had to explain that I simply couldn't make my legs perform towards the end of the race".

The subject also explained that the pain in the groin area which caused him to bend over and lean on the rails seemed to him to be of deep origin, as though it was located in the marrow of the bone rather than in the muscles.

The emergency cooling procedure had eliminated both the deep pain and the leg weakness; at 72 minutes, just before the special cooling was cut off, SR said "I feel fine; right now I'm sure I could go out and run a mile, but at the last quarter it would be the same situation as when I was in high school"- meaning that he knew his legs would give out on him. Two minutes after the heat extraction rate had returned to its design value, SR reported his legs getting weak and heavy again but said they were not yet hot; one minute later his feet were beginning to feel hot. 10 minutes later he was obviously in pain again, hanging on the side rails. He reported his legs were more tired than before the cooling episode, though not as hot as before. At 94 minutes exposure time he stated his legs were too tired to continue and the experiment was terminated at 95 minutes.

Even subtracting the full 19 minutes of special cooling and/or reduced work load, we get an effective tolerance time of 76 minutes, which represents an increase of 62% over the baseline heat tolerance time of 47 minutes. Note that from 76 minutes on, rectal temperature dropped slightly and stabilized at slightly above 102°F, while ear canal temperature fell sharply from about 72 to 82 minutes. The concurrent drop in skin temperature was the greatest seen in any of the current experiments.

Experiment H-4 was conducted five days later. The pre-storage adjustment period was 45 minutes with a final heart rate of 101, a rectal temperature of 99.6 and an ear canal temperature of 98.1. The first special cooling treatment was applied from 45 to 50 minutes, consisting of head cooling at the reduced work load of 2 mph/0%.

The inlet-outlet temperature difference for the cooling skull cap was 3 F degrees with an inlet temperature of approximately 46°F. When questioned at the end of this cooling period, SR remarked that while both the reduction in work load and the head cooling helped, he appreciated the slowing of the treadmill most, because of the opportunity to relax his legs somewhat, which "takes away the pain in the groin and some of the heat". It turned out that the pain had started about 20 minutes after the beginning of heat storage, though it was apparently not as severe as it had been in the previous experiment.

The heart rate had dropped from 140 to 122 during the period of head cooling and quickly returned to 141 when work resumed at the original rate. Five minutes later, SR reported his legs getting hot and tired, and the groin pain continuing to develop. At 58 minutes the subject was leaning on the hand rails, grimacing in pain. When asked about the grimacing, he replied that it was just his painful legs and the general sensation of heat and fatigue.

At 62 minutes the treadmill was again leveled and reduced to 2 mph, without any increase in cooling. After 1 minute, the treadmill was stopped for an additional minute of rest.

By 69 minutes the subject was again leaning on the rail, apparently in considerable distress; the cooling flow to the LCG was turned up to maximum for 2 minutes then returned to the original settings, without any change in work load. When asked "How much good does that do?" SR replied "I'll buy that over the head cooling any day; I feel much better, although my legs are still tired."

In the six minutes of this increased cooling session, the integrated excess heat extraction relative to the nominal 10 Btu/min was 163 Btu, with the inlet temperature attaining a low of 55°F.

One minute after the design heat extraction rate had been reattained, the subject reported he was "starting to get hot again". At 80 minutes SR estimated he could probably go about 5 more minutes, volunteering that his thighs were not yet excessively hot. Three minutes later he was leaning on the rails, trying to control the groin pain which had returned a few minutes earlier after temporarily disappearing. The subject explained that he was trying to drag his right foot in an effort to minimize the pain.

At 86 minutes a 2 minute period of maximal cooling was started in an effort to correct the pain problem. The attempt was essentially unsuccessful, although the subject reported that the cooling provided some amelioration, but not enough to permit continuation. The treadmill was stopped at 91 minutes, and the subject reported that he could not bend his right leg.

With a total of 17 minutes of special cooling and/or reduced work load, the effective tolerance time of 74 minutes is 57.5% greater than the baseline tolerance.

SWEAT LOSS

Table 1 presents the data derived from before and after nude weighings, which gives a reasonable approximation of the total sweat production during the pre-storage adjustment period and the heat stress exposure. The overall average for all 12 experimental heat stress exposures is 3.65 lbs. with a range of 2.88 to 4.41 lbs.

The greater length of the experimental heat exposures with respect to the baseline run shows up for 3 of the 4 subjects as an average difference of 0.44, 0.94 and 1.38 lbs. respectively.

Based on previous experience with men working in compensable heat stress environments, we regard any reduction in body water content of greater than 1% to be thermally significant in altering deep temperature regulation and splanchnic blood flow (4, 5). For these subjects, a 1% dehydration would mean sweat losses of about 1.8 lbs., or half the observed actual loss. Subject RB in his H-4 exposure was the exception, since his net deficit at the termination of the recovery period was only 0.54 lbs., as a result of the repeated ingestion of small amounts of water during the experiment.

TABLE 1

OVERALL SWEAT LOSS (lbs)

Change in before and after nude weight adjusted for water intake

Subject	Cool Calibration Experiment	Baseline Heat Stress Experiment	Experimental Heat Exposure H-2	H-3	H-4	Avg. of H-2, H-3 & H-4	Experimental Avg. minus Baseline Experiment
FD	1.51	3.25	3.32	3.33	3.02	3.22	-0.03
BD	-	3.79	4.38	4.22	4.10	4.23	0.44
RB	1.33	2.20	2.88	2.99	3.54*	3.14	0.94
SR	1.37	2.61	3.49	4.41	4.06	3.99	1.38
Average	1.40	2.56	3.52	3.74	3.68	3.65	

*Water intake 3 lbs, weight change 0.54 lbs.

SUMMARY OF TOLERANCE TIME

Table 2 shows the durations of each pre-storage adjustment period, during which LCG cooling was maintained at comfort levels and each heat stress period, during which LCG heat extraction was adjusted so as to maintain a body heat storage rate of 1000 Btu/hr.

TABLE 2

TOTAL EXPOSURE TIMES

Subject	Baseline pre	Baseline storage	H-2 pre	H-2 storage	H-3 pre	H-3 storage	H-4 pre	H-4 storage
FD	40	70	21.5	78.5	72	76	40	83
BD	60	75	60	104	60	93	60	110*
RB	30	60	40	80	50	85	40	92
SR	40	47**	40	74	40	95	45	91

*Incl. 11 minute rest to treat blister
** Experiment H-5; stress tolerance time in experiment. H-1 was 36 minutes probably due to an intestinal upset.

DISCUSSION OF THE RESULTS

The results for subject FD, displayed in Figure 2, suggest that, whether applied early or late in the heat storage process, the localized cooling of a small area of skin has only minor benefits at best. Although somewhat better results were obtained from three 1 minute periods of increased full body cooling, the gross increase in exposure time tolerated was less than the sum of the duration of the improved cooling episodes. Viewed in the light of later experiments in which the period of maximal cooling flow to the LCG was 2, 3 or more minutes per session, the disappointing results with subject FD suggest the possibility of a thermal lag phenomenon at the LCG-skin interface. Even though one minute of high cooling flow was sufficient to drop the LCG inlet temperature to the vicinity of 50 to 55°F, producing a noticeable drop in mean skin temperature each time, this reduction was not reflected in the ear canal temperature. In contrast, experiments H-2 and H-4 for subject BD and all three exposures on subject RB show definite ear temperature responses to general body cooling where the full cooling episodes were longer.

While the hydration-maintenance experiment with subject RB (H-4) produced a 53% gross increment in tolerance time, it may be that a major share of the credit should go to the two minutes of full flow LCG cooling and the subsequent six minutes of slightly elevated cooling, and the earlier period of relatively inefficient head cooling. However, there was no reduction in work load during this exposure, so that at the peak of the special cooling periods the net heat loss rate was only 380 Btu/hr for 1 minute during the early head cooling episode and 1600 Btu/hr for a moment during the LCG full cooling period. Subject BD, on the other hand, went from a metabolic heat production rate of 2160 Btu/hr to 780 Btu/hr when the treadmill speed and grade were lowered, so that in his experiment H-2, when the peak cooling rate for the LCG was achieved, the net heat loss from the body was 2065 Btu/hr.

One possible explanation for the contrast between the results for FD and for BD is that there is some critical minimum duration for lowering heart rate and reducing skin temperature, which was approached in this group of experiments by the various techniques used on BD.

The data which is most difficult to explain is that for subject SR who showed the greatest increases in tolerance time yet displayed the greatest amount of distress, without ever reaching more than 80 or 85% of his maximum attainable heart rate.

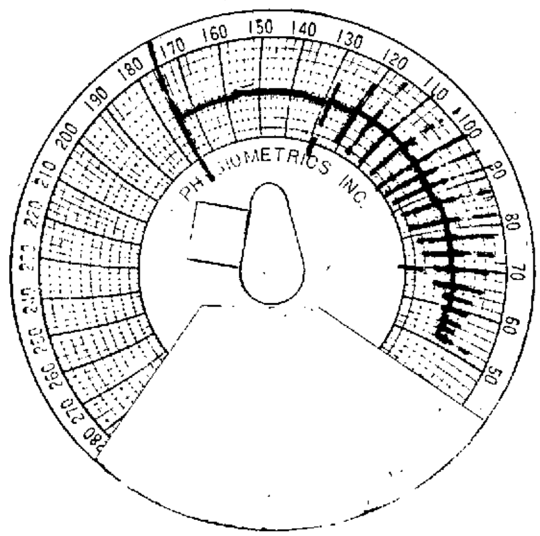
The recurrence of difficulty with the right leg whenever SR began to get hot, seemed to us to suggest some sort of vascular anomaly. The anecdote from the subject's high school track days, which is recounted in the Results section, focused speculation on the possibility that there was some sort of congenital malformation in the arterial system of the right leg. In the hope of shedding light on this possibility we took a series of blood pressure readings in rapid succession, in the supine position above the knee and in the calf on right and left legs. The instrument used was the Physiometrics model USM-105 recording sphygmomanometer, which utilizes an

Figure 7

Left-Right comparison of lower limb blood pressures to identify a vascular abnormality Subject SR, age 26, max. VO_2 3.8 + L/min

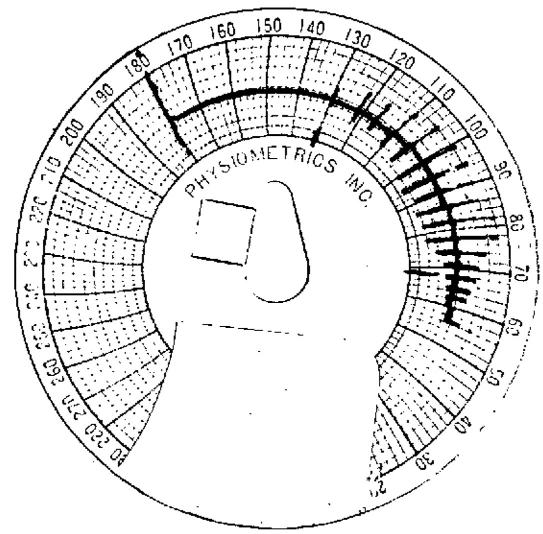
SUPINE POSITION

LEFT LEG



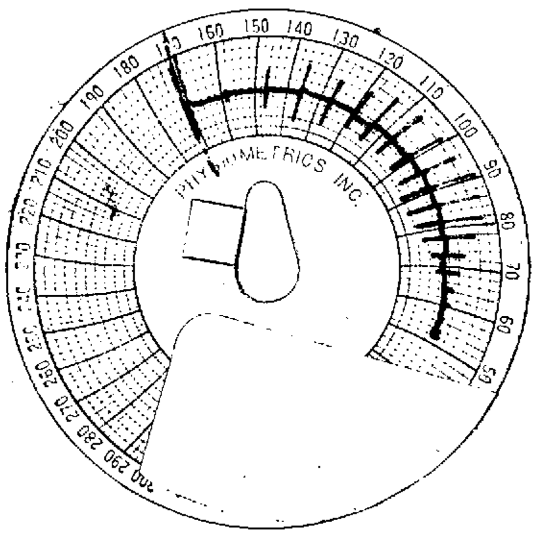
128/70

RIGHT LEG



130/70

Thigh, immediately above the knee, large cuff



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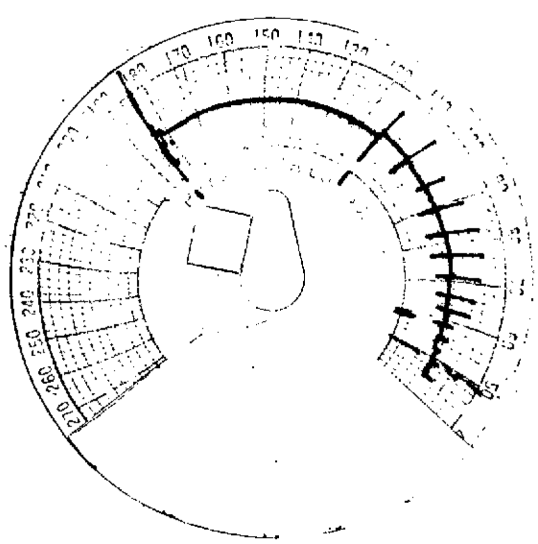

114/58

Mid-calf, standard arm cuff

PHYSIOMETRICS INC.

infrasonic principle to detect the pulse and is able to give accurate measurements in many situations where it is not feasible to hear the conventional Korotkoff sounds. An oversize cuff was placed above the knee with the pulse detection transducer in the popliteal space, and a regular size cuff was placed around the calf. Figure 7 displays the four recordings taken in this series, first on the right leg and then on the left, which clearly reveal a discrepancy between the two legs. In general, one expects the systolic pressure in the more distal part of the extremity to be higher than at a more central location; thus the comparison is between a change of +18 millimeters in the normal left leg to -16 millimeters in the right, with respect to systolic, and +3 on the left versus -12 on the right for diastolic pressure.

The subject was advised to consult a physician regarding the possibility of an anatomical abnormality in the vascular system of the right leg. As of this writing we have no information as to the results of any such examination.

The postulation of a restriction in the arterial outflow from the right thigh into the lower leg would tend to explain the relatively premature attainment of a tolerance limit in the unaided heat exposures H-1 and H-5 despite the outstanding physical fitness status of the individual concerned. Similarly, such a disability might be very susceptible to limited amounts of local cooling, permitting the subject to extend his endurance to more closely approach the usual type of cardiovascular limit seen in the other subjects.

If a useful generalization can be extracted from this rather special case, it might be that any physiological problem which tends to compound the difficulties created by an inadequate rate of heat loss, which is itself responsive to localized, brief, or limited cooling of some sort, may amplify the apparent value or effectiveness of a limited cooling treatment relative to its value in a completely normal and healthy individual.

It is unfortunate that our most sophisticated emergency cooling device, the Webb Associates tubing skull cap, was tried only on the subject whose special problem resided in the right upper leg. Considering the impressive heat extraction rates which are possible with this cooling cap, we strongly suspect that such an arrangement may hold the key to a practical emergency cooling system for future astronaut use. From the vantage of hindsight, we also regret the lack of an opportunity to experiment with intermittent cooling, that is the alternation of periods of zero heat extraction with periods of full cooling whose cumulative sum equals the limited heat extraction rate of the baseline reference exposure. We suspect that a given amount of cooling power deployed in this intermittent manner would yield a substantially longer tolerance time than when it is in effect "dribbled away" in a system with relatively high inlet temperatures to the LCG.

When the relationship between tolerance time extension and heat extraction excess is examined for the five experiments in which it was possible to record the amount of cooling quantitatively, a straight line relationship seems to exist with a slope of roughly 6 minutes of added endurance time for every 100 Btu of extra cooling during the special treatment periods. However, this relationship has an intercept on the zero heat extraction abscissa at about 21 minutes, suggesting that from 44% to 78% of the tolerance increment may be ascribable to the less tangible aspects of the corrective treatment, and to the reduction in work load in those cases where this was used.

The modest tolerance time increments seen in the first subject, who was given local cold pack applications in two runs and one-minute periods of LCG extra flow in his last experiment, were partially offset by the fact that he stopped walking or slowed down for 3-5 minutes during the extra cooling treatments.

The second and third subjects showed increments in tolerance time ranging from 25% to 53%, with an average of 37%. Again, part of the value of the gain would be slightly offset by reduced work load during some of the cooling treatments. The largest gain occurred in an experiment in which the subject was kept fully hydrated throughout by requiring him to continually take small drinks of water.

The importance of dehydration in the determination of endurance is suggested by the average sweat loss of 3 lbs during the baseline experiments and 3.6 lbs during the extra cooling experiments. In the one re-hydration experiment, the subject ingested 3 lbs of water and showed a net change of only half a pound for the 2 hours and 12 minutes between weighings.

Comparing the amounts of extra heat extracted during special cooling treatments with the total stored heat associated with the point of incipient collapse (112 or less to 490 Btu versus 1120 to 1600 Btu) there seems to be little doubt that the main value of the extra cooling procedures used in these experiments arose from their influence on the systemic vasomotor control system. The limited evidence does not support the view that useful re-adjustment of the vascular system can be accomplished by purely local cooling in the neck and head region; but this possibility should be explored further by more rigorous experiments on normal subjects.

One thing which seems quite clear is that the amount of heat accumulated within the body is not of itself a reliable predictor of the tolerable exposure duration. Further study should be made of the ways in which this gross storage and endurance time can be maximized.

As a final observation, it may be worth directing attention once again to the conclusion from our 1971 study that the best way to prolong endurance in the event of cooling system failure is to enter the period of emergency with the lowest possible skin temperature. It seems clear that as in many other problem areas, prevention is the best possible protection, and the essence of protection in the present context is to have the individuals operate at all times at the lowest possible mean body temperature which is compatible with unimpaired muscle function.

SUMMARY

Four subjects, all of whom had previously served in similar heat stress experiments, completed five treadmill training sessions under comfortable to cool conditions and were "calibrated" to find an optimum combination of speed and grade on the treadmill which would produce a metabolic rate of 2000 Btu/hr. Dressed in an Apollo liquid cooling garment (an early model), a vapor-impermeable coverall garment sealed to rubber gloves and rubber boots, and to an impermeable hood sealed around the face, each man underwent a total of four experiments in which the rate of heat extraction from the liquid cooling garment (LCG) was adjusted to an amount which would cause a storage within the body of 1000 Btu/hr. A standardized flow rate to the LCG of 2.25 L/min was used; after accounting for respiratory heat loss and for the external work performed in climbing the treadmill grade, the temperature difference between inlet and outlet of the LCG required to produce the desired heat storage rate was approximately 2 F degrees in each case, sensible heat loss from the body to the environment being essentially zero, and the work rate being 2.6 mph, at a 6 to 7% grade.

In one experiment for each man, designated the baseline experiment, a fixed heat extraction rate as described above was maintained throughout. In the remaining three experiments, a variety of procedures were used at various times to temporarily increase the rate of heat extraction in order to delay the attainment of the heat endurance limit. Initially, these extra cooling treatments involved small localized areas of the body surface, but when this appeared relatively ineffective, emphasis was placed on brief increases in the rate of cooling by means of the LCG itself. A liquid-cooled tubing skull cap (Webb Associates) was also utilized.

In each of the experiments the first 40 to 60 minutes of marching was performed under optimal comfort conditions, with sufficient cooling flow supplied to the LCG to maintain subjective comfort. Physiological measurements included skin temperature at 9 locations, rectal and ear canal probes (the latter inserted through custom molded foam ear plugs) and heart rate. All subjects were required to pass the astronaut's fitness test performed on the bicycle ergometer according to the Luft-Balke technique.

The increases in tolerance time ("time to incipient collapse") for the various subjects and the various methods of emergency cooling, ranged from a low of six minutes to a high of 48 minutes, or from 8 to 102% of the baseline tolerance times. The largest gains were achieved in a subject whose tolerance endpoint was atypical, and whose baseline heat tolerance was unusually low (47 minutes as compared to a range of 60 to 75 for the others). This particular subject was the youngest and the most "fit" of the four, but never reached a maximal degree of cardiovascular strain under the experimental heat stress conditions because of pain and weakness in the legs. This limitation is suspected to be one of functional anatomy, and was probably more sensitive to amelioration by extra cooling by the LCG than the more normal forms of heat strain.

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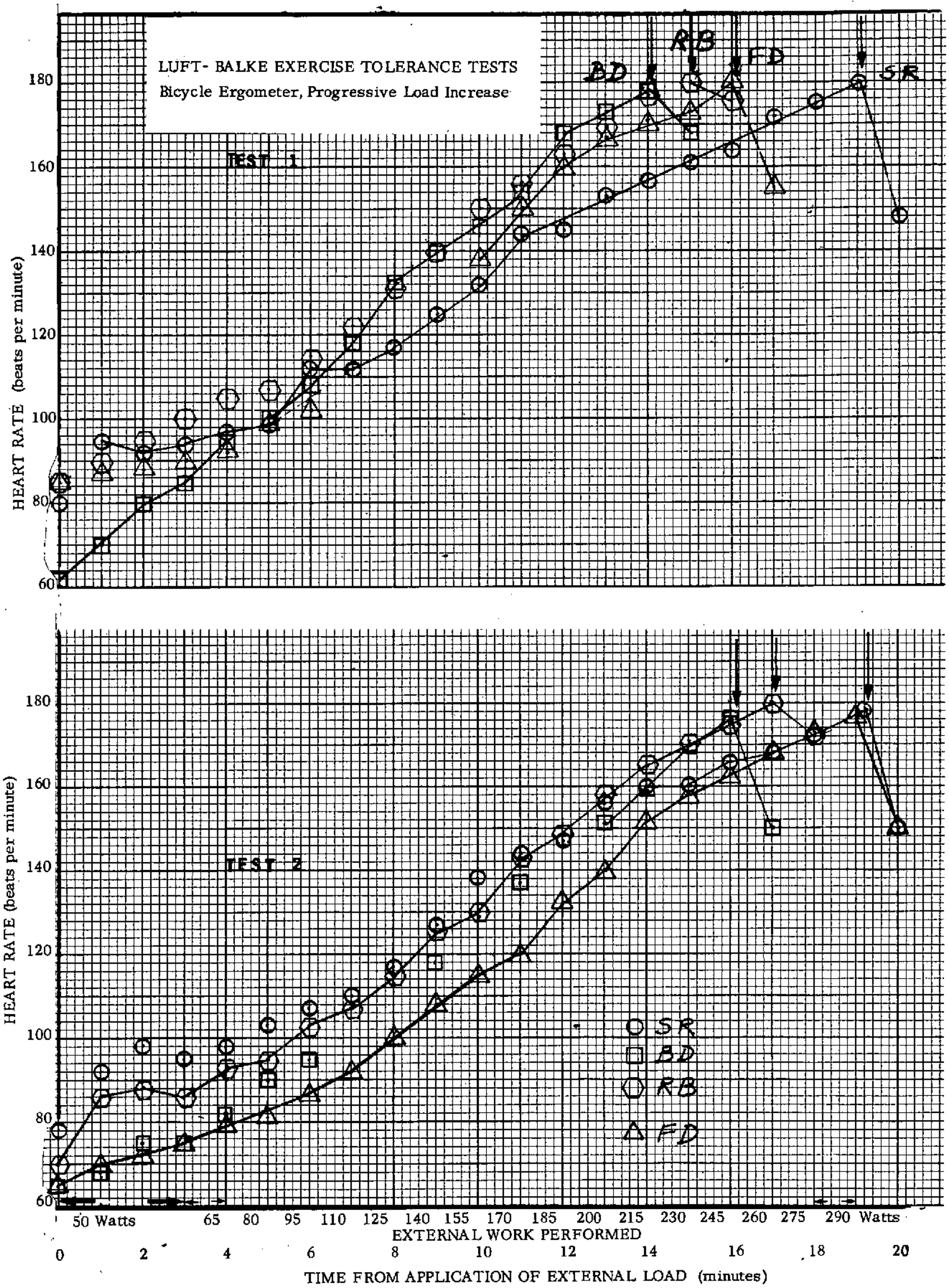


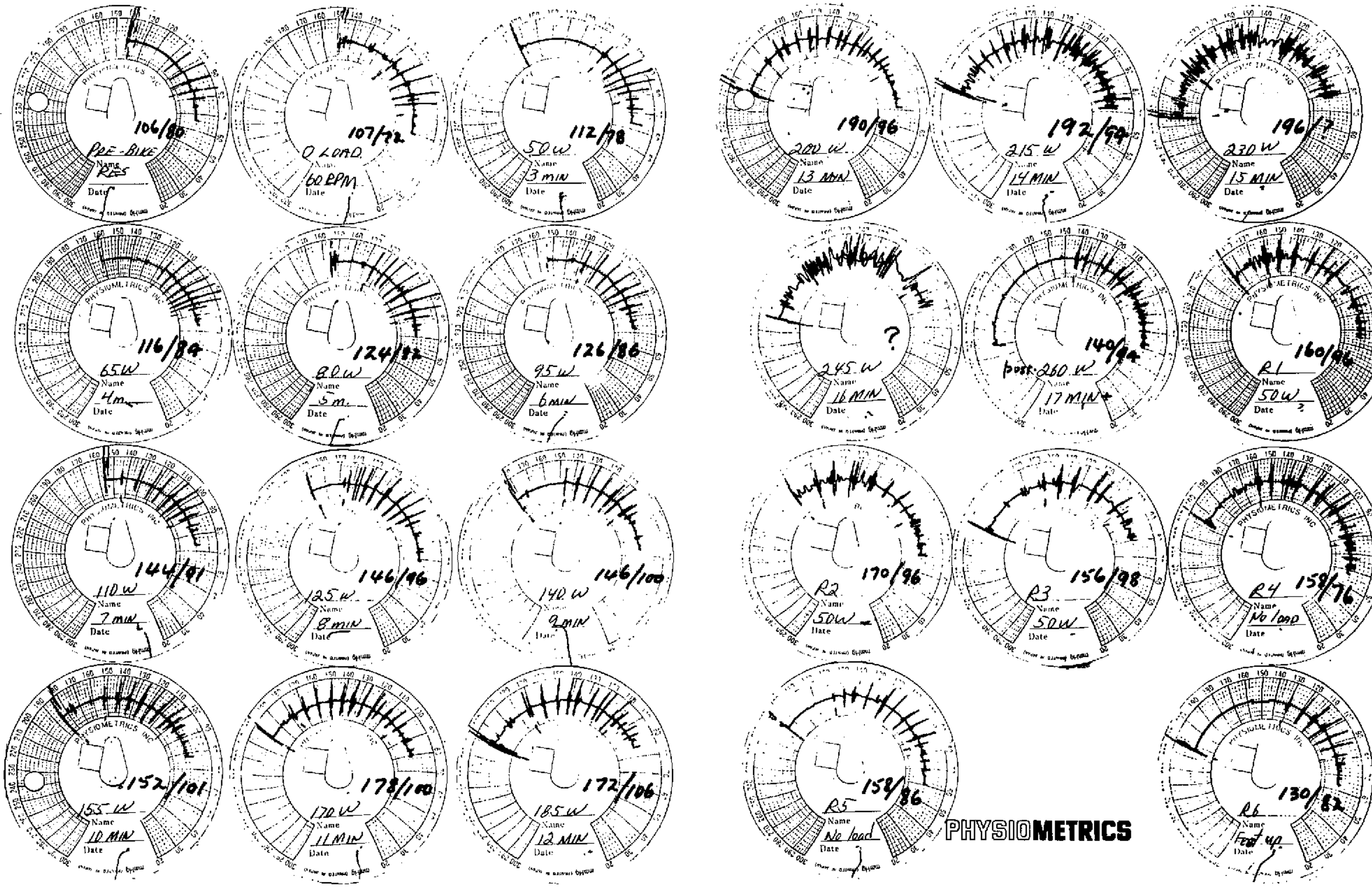
Appendix A

Heart rate response to the Luft-Balke exercise tolerance test for the 4 subjects, before and after the experimental series

LUFT-BALKE BICYCLE ERGOMETER FITNESS TEST

Progressive increments in workload every minute

Subject RB; male, age 36, 175 lbs, 6 feet: 4/10/73



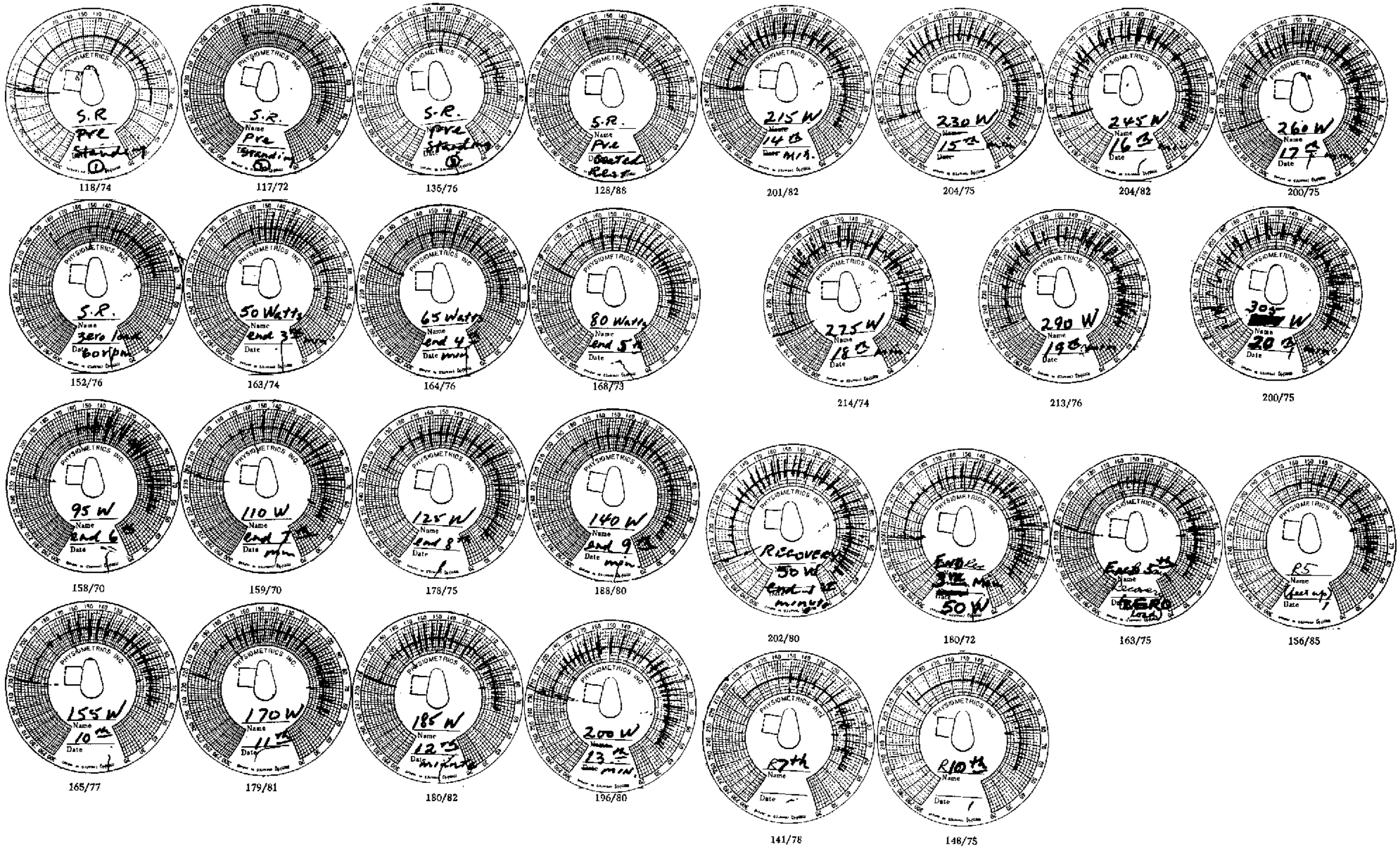
Appendix B (I)

Blood pressure recordings during Luft-Balke exercise tolerance test on a bicycle ergometer - Subject RB

LUFT-BALKE BICYCLE ERGOMETER FITNESS TEST

Progressive increments in workload every minute

Subject SR: male, 28, 175 lbs, 6 feet



Appendix B (II)

Blood pressure recordings during Luft-Balke exercise tolerance test on a bicycle ergometer - Subject SR