THE DESIGN AND ANALYSIS OF TWO DRY ICE PERSONAL COOLING JACKETS

BY

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INTRODUCTION

Industrial work situations may involve hot environments. Some common examples are found in mines, heavy construction, oil rigs in desert lands or off shore, boiler rooms and furnaces. To reduce the heat stress conditions, either the environment or the operator may be cooled. Economy would dictate, in several cases, that the operator be cooled. Thus, personal cooling has been developed as an effective and economical way of reducing heat storage and extending working time in heat stress environments.

Liquid cooling has been developed rapidly in the last few decades. Laboratory garments using liquid cooling were first tried at the Royal Aircraft Establishment (Farnborough) in 1962. Veghte (1965) noted that tubes carrying cold water over the human body produced a good liquid personal cooling system. Water temperatures lower than that of the skin were used.

Konz and Morales (1968) developed a water cooled hood. This was a helmet shaped object that had plastic tubes on the inner surface. Cold water produced the cooling as it flowed through the tubes. Gold and Zornitzer (1968) used long underwear, lined with plastic tubes carrying water at 20°C. Duncan (1969) used a water cooled helmet. Byrnes (1970) found a water-cooled jacket to be more effective than a water-cooled hood from a physiological viewpoint.

Another method of conduction cooling is the use of ice slabs in a garment. Water ice takes up 80 kcal/kg when changing from a solid to a liquid form. Dry ice sublimation needs 137 kcal/kg for the sublimation plus 24 kcal/kg for the gas to rise to the skin temperature (35°C) from the dry ice temperature (-79°C). Since it picks up more heat than water ice, dry ice cooling has been studied at Kansas State University.

Petit et al (1966) were the first to attempt dry ice cooling. Their cooling garment was made of leather; eight (10 X 10 X 3 cms) pockets were attached to the garment -- four in front and four on the back. Each pocket had about 50 small holes on the surface closest to the skin to permit cold CO_2 gas to flow close to the skin. The dry ice slabs were round (10 cm diameter X 3 cm). Eight male subjects walked for twenty minutes on a treadmill at 6 km/hr and a 10% gradient. Environmental conditions were 46°C dry bulb and 50% rh. Dry ice cooling produced a heart rate of 16 beats/min and skin temperature 1.8°C lower than the no cooling condition. Rectal temperatures, oxygen consumption and sweat loss showed no significant changes. The sublimation rates were 8.8 g/min-slab.

Konz and his associates at Kansas State University have been developing various garments for dry ice cooling since

1972. Duncan (1975), using models B1 and B2 dry ice cooling jackets, observed that the dry ice slabs sublimated faster in the upper compartments (1.9 g/min -slab) than the ones in the lower compartments (1.2 g/min -slab). This was because CO_2, being heavier than air, flowed down from the top pockets to the regions of the lower ones. Being trapped there by the garment, it reduced the heat transfer to the lower slabs. So, with a cooling jacket on, the body could be roughly divided into three sections (Fig. 1) -- cool, cold and hot. When the subjects wore the cooling garments, oxygen consumption increased from a mean of 337 kcal/hr to 387 kcal/hr. Since the subjects reported no shivering, this was attributed to non shivering thermogenesis.

Konz and Duncan (1975) developed the model C dry ice cooling garment. This jacket had an inner shell of blended cotton and quilted nylon for the outer shell. Four vertical pockets were used. All the pockets had top velcro fasteners. Permeable nylon was used for the long sleeves.

Techapatanarat (1976) used model D which was very much like model C, except that the two back pockets were made horizontal. He used three different insulation levels 11, 7 and 5 g cal/(sec-c-cm^2 X 10^{-5}). His horizontal pockets showed a more uniform sublimation than that in the vertical pockets.

Horizontal pockets would enable a more efficient use of

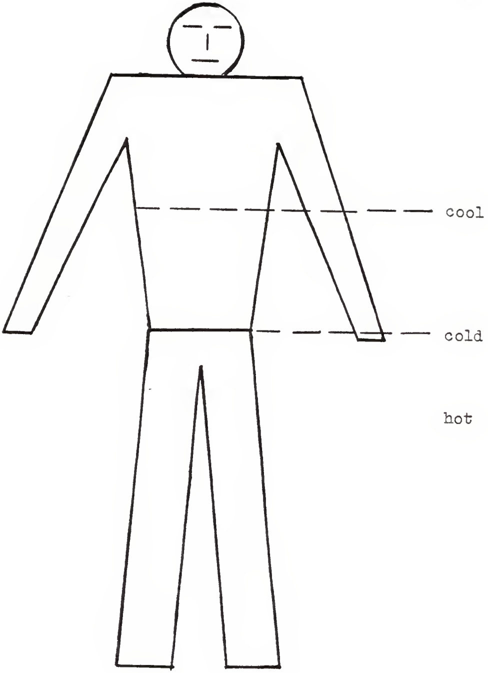

Figure 1. Cooling Zones When Models C and D Were Used.

the dry ice. As a result of these experiments it was determined that the torso region was a desirable place for cooling. Aschoff and Wever (1958) concluded that the torso produced 22% of total heat expended during work. The KSU-Stolwijk thermoregulatory model predicted a value of 30%.

Tang (1976) used a nylon jumpsuit. There were cuffs on the sleeves and legs. Eight pockets, four in front and four on the back, carried the dry ice. A cowl neck was used to prevent air flow across the top of the jumpsuit. The dry ice slabs were 10 X 10 X 1.5 cm. Environmental conditions were 35°C dry bulb, 31.6°C wet bulb, 70% rh and 0.3 m/s air velocity. Metabolic loads were pedalling a bicycle ergometer at 60 rpm and 1 kp load. The cowl neck and cuffed sleeves and legs helped contain the CO_2 within the garment. This enabled a uniform cooling by means of convection because the cold CO_2 was where the dry ice slabs were not. In the cooling condition, the oxygen consumption rose only 1% higher than that in the no-cooling condition. The mean sublimation rate was 1.22 g/min -slab, which was 3% lower than that in model D. This was attributed to the CO_2 being contained within the jumpsuit. The cooling condition produced a mean rectal temperature (37.27°C) which was significantly lower than the no cooling mean (37.54°C). Tang also compared the heart rate, rectal, skin and oral temperatures between the experiment and a computer simulation of the human thermoregulatory system.

PROBLEM

The purpose of this experiment was to analyse two new dry ice cooling jackets. Models E1 and E2 were developed. Model E1 (Fig. 2) was very much like Model D except that D had a nylon layer outside and denim on the inside, whereas E1 had quilted nylon closest to the skin and denim on the outside. The dry ice pockets were of cotton with top pocket openings and flaps that were fastened by velcro fasteners. Dry ice slabs were put into nylon bags that then were put into single layer bags of large plastic air bubbles and then contained in a cotton bag. This insulation (Fig. 4) was 7 $g cal/(sec\text{-}^{\circ}C\text{-}cm^2 X10^{-5})$ for each pocket and was constant for each experiment. The four dry ice pockets were located at upper chest (2 pockets) and upper back (2 pockets) regions. Both E1 and E2 were designed with two more lower pockets each but only the upper pockets were filled with dry ice for the experiment. The denim sleeves were cuffed at the wrist. The cuffs helped contain the sublimated CO_2 within the garment. The plastic zipper was to the left side of the jacket. The waist was snugged by an elastic band.

The construction details of E2 are the same as that of E1. E2 (Fig. 3) is made entirely of denim. Only the four upper pockets of E2 were loaded with dry ice for this experiment. The insulation level for E2 is the same as that of E1.

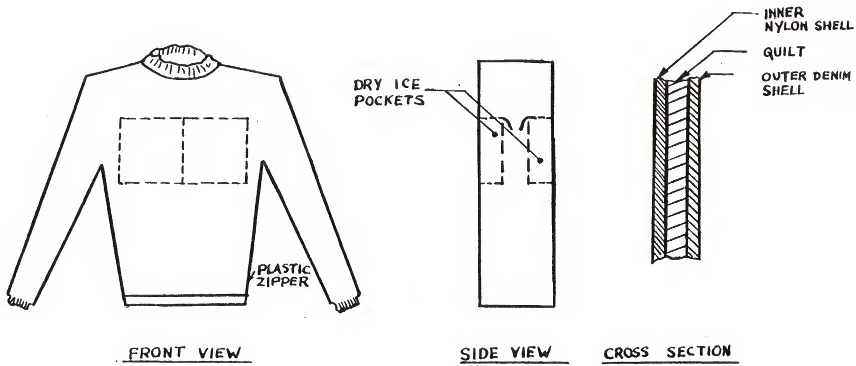

Figure 2. Model E1 Dry Ice Cooling Jacket.

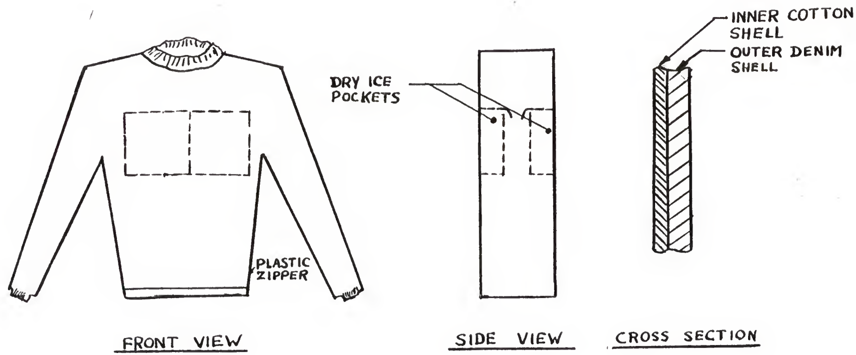

Figure 3. Model E2 Dry Ice Cooling Jacket.

Cowl necks on both the jackets help prevent air circulation across the neck region.

Only the upper four pockets of each jacket were used for the dry ice. This was prompted by Techapatanarat's (1976) study which reported an uncomfortable cold band of CO_2 collecting at the stomach region. Duncan (1975) also suggested that the cooling is preferred around the upper back and chest regions. Another point of significance is that models C and D were designed assuming a four hour supply of dry ice. However, in the case of E1 and E2 it was assumed that in most industrial situations the operator is under heavy heat stress conditions for shorter periods of time, possibly an hour or so. So, even though the jackets are capable of handling larger amounts of dry ice, for this experiment, smaller amounts (15 X 15 X 2.5 cms X 4 slabs) were used. Conduction cooling at the chest and upper back regions and CO_2 convection cooling at the stomach and lower regions of the back was expected.

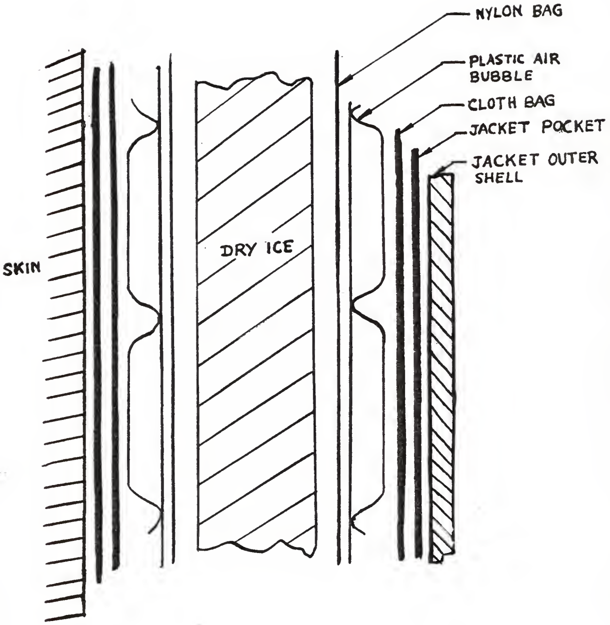

Figure 4. Cross Sectional View of Dry Ice Pocket.

METHOD

Environment

The heat stress environment was simulated in an environmental chamber at the Institute of Environmental Research at Kansas State University. The condition was 35°C dry bulb, 31.6°C wet bulb, 70% rh, and 1.3 m/s air velocity. The above conditions are the same as Tang's (1976) to facilitate comparisons.

Subjects

Two male students from Kansas State University were chosen for the experiment. They had to undergo a physical examination. A participation fee of $75 was paid to each subject. Table 1 gives the subject characteristics.

Task

One Monark bicycle ergometer from the Department of Industrial Engineering and one Schwinn exerciser from the Department of Physical Education were used. These were placed inside the conditioned environmental chamber. For part of the task (Fig. 5), the subjects pedalled the ergometers at 60 rpm with a 1 kp load. These conditions were chosen to facilitate comparisons with earlier experiments. For thirty minutes preceding and 30 minutes following the pedalling, the subjects just sat inside the chamber. During this non-pedalling time, they wore a pair of trousers, socks, tennis shoes, boxer shorts and a long sleeved shirt,

Table 1. Characteristics of Subjects.

	Subject YF	Subject AK
Age (yr)	26	25
Weight (kg)	58	67
Height (cm)	167	178
Surface Area (m^2)*	1.77	1.84
Heat Acclimitisation (%)	0	0
Skin Fold Thickness (mm)		
1. Triceps	4	7
2. Pectoral	4	5
3. Abdominal	13	30
Percent of Body Fat**	7.41	9.70
Seated Blood Pressure (mm Hg)		
Systolic	120	124
Diastolic	80	50

*Dubois Surface Area = 0.007184 x $(\text{Height})^{0.725}$ x $(\text{Weight})^{0.425}$

Surface Area = 0.208 + 0.945 x Dubois Surface Area

** Percentage of Body Fat = ((4.570/Density) - 4.142) x 100

Density = 1.092300 - (Tricep x 0.002030)

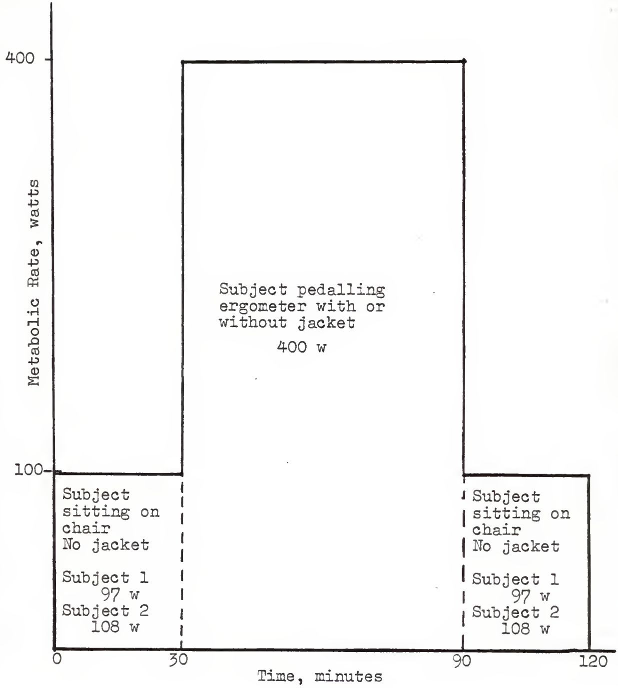

Figure 5. Task Conditions Compared With Time.

estimated clo 0.65. If the experimental session required a dry ice cooling jacket, then after the first 30 minutes, the jacket with dry ice slabs already added was put on the subject.

When the jackets were worn, the subjects wore tennis shoes, socks, boxer shorts, slacks and the jacket. The jacket was worn only for the 60 minutes duration of pedalling (Fig. 5). When using the jackets, the estimated clo value was 1.05 for E1 and 0.95 for E2. Without the jackets the clo value was 0.65.

As soon as the pedalling session was completed, the jackets were removed; the subjects sat in the chamber for another 30 minutes.

Measurements

Yellow Springs model YSI 709 sensors were used to measure the fifteen skin temperatures and a YSI 62728-10 sensor measured the rectal temperature. Heart rate was measured by a sensor attached to the forefinger and digitally displayed on the external console by a Meditron VITAL 1. The temperatures were measured via the sensor, through a junction box and on the console by a United Systems Corporation digital display scanner (model 636) and were simultaneously printed on paper by a 691 Digital Printer. Although the measurements were continuous, the printout was obtained every five minutes.

Oxygen consumption was measured every ten minutes. The apparatus used for this was by Parkinson Cowan. Tubed mouthpieces piped the exhaled air into a rubber bag. The air then was pumped through anhydrous calcium sulphate to the Beckman CO_2 and O_2 analysers. An intermediate flow meter tank measured the flow in litres/min. These then were digitally displayed on the external console by the Beckman O_2 analyser OM-11 and the Beckman Medical Gas Analyser LB-2.

The dry ice slabs (15 X 15 X 2.5 cm) were weighed individually and then put into the insulating bags and installed in the jackets. This weighing was done immediately prior to the pedalling sessions that required dry ice cooling. As soon as the 60 minutes of pedalling was completed, the jackets were removed and the slabs weighed again, in the same order as they were before being loaded. A Hansen Dietetic scale was used for the weighing.

The clothing of each subject was weighed before and after each session. The subjects themselves also were weighed before and after each session.

Procedure

Each experimental session (Table 2) was started by weighing the subjects and their clothing. Then the sensors were placed on them (Fig. 6). The locations of the skin temperature sensors first were coated with a thin coating of plastic bandage. This produced an adhesive base on which

Table 2. Sequence of Experimental Sessions.

Session	Subject 1	Subject 2
1	With E1 and dry ice slabs	With E2 and dry ice slabs
2	No jacket	No jacket
3	With E2 and dry ice slabs	With E1 and dry ice slabs
4	No jacket	No jacket
5	With E2 and dry ice slabs	With E1 and dry ice slabs

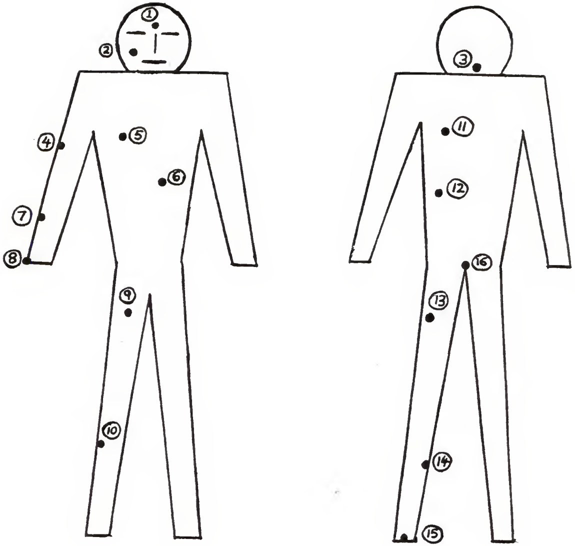

Figure 6. Location of Temperature Sensors.

the sensors could be well secured by strips of 3M surgical tape. The oral temperature sensors each were covered by disposable sanitary plastic covers, which were discarded after each session. The terminals of all these sensors were plugged into two junction boxes and the temperature readout was triggered to assure that all the sensors were plugged in correctly and securely.

Then, the subjects were taken into the controlled environmental chamber. As soon as they entered the chamber, the measurements were started. The subjects were seated on chairs and the blood pressures measured.

The photo electric heart beat sensor was secured to the middle finger of the right hand of each subject.

The first part of the task required that the subjects be seated in the chamber for 30 minutes (Fig. 5). After this preparatory period, the subjects pedalled the ergometers for 60 minutes.

If the experimental session (Table 2) required the use of a jacket, then the jackets were worn just before the start of the pedalling and removed immediately after. The jackets, as well as the individual slabs, were weighed before and after the pedalling.

After the pedalling task was completed the subjects sat on their chairs (Fig. 5) for another 30 minutes. This recovery period was to enable the physiological conditions of the subjects to return to normal. At the start of this period blood pressures were measured to ascertain that the subjects had not over exerted themselves as a result of the pedalling.

At the end of the recovery period, the measurements were stopped, the sensors removed and the subjects and their clothes weighed again.

If, during any session, a subject wanted a drink of water, 200 cc cups of water maintained within the chamber at 35°C were provided.

RESULTS

The data was analysed using the Wilcoxon Signed Rank Test. The statistical level of significance was $\alpha \leq 0.05$.

As an illustration of the procedure, the data for E1 and no cooling on Ventral Equivalent of Subject 1 are shown. The Δ values are the values over the reading at 30 minutes. As the temperatures were measured every 5 minutes, there are 18 Δ values for each condition of cooling.

E1 Cooling lit/min	No Cooling lit/min	Pair Number	(No Cooling - E1) lit/min	Rank
0.7	1.5	1	0.8	11
1.7	2.0	2	0.3	5.5
2.9	2.5	3	-0.4	-8.5
3.0	2.7	4	-0.3	-5.5
3.2	3.5	5	+0.3	+5.5
4.0	4.0	6	0	1
4.0	5.0	7	1.0	12.5
3.9	5.8	8	1.9	16
3.5	5.8	9	2.3	17
2.8	5.8	10	3.0	18
2.2	4.0	11	1.8	15
1.4	2.6	12	1.2	14
1.0	2.0	13	1.0	12.5
0.7	1.2	14	0.5	10
0.5	0.7	15	0.2	2.5
0.2	0.0	16	-0.2	-2.5
0.1	-0.2	17	-0.3	-5.5
0.0	-0.4	18	-0.4	-8.5

normal deviate $Z = (|\mu - T| - \frac{1}{2})/\sigma$

$\mu = n(n+1)/4 \qquad \sigma = \sqrt{(2n+1)\mu/6}$

if $Z \geq 1.96$ reject the null hypothesis

Here $n = 18$

so, $\mu = 85.5$; $\sigma = 22.96$

T is the sum, sign ignored, of the smaller of the rank totals. Here $T = 30.5$

$$\therefore \quad Z = 2.37 > 1.96$$

So, reject null hypothesis.

This meant that ventral equivalent of the no cooling was greater than the ventral equivalent of jacket E1 cooling. All the following results were obtained after similar tests on the data.

Skin Temperatures

Figures 7 through 21 are plots of the mean skin temperatures at all the fifteen sensors. Table 3 shows the mean changes in skin temperatures, over the values at 30 minutes. The time period for these means was 90 minutes--the pedalling period (60 min) plus the recovery period (last 30 min).

From Fig. 7, forehead skin temperature, E1 (-0.56°C) and E2 (-0.56°C) were both significantly cooler than no cooling (-0.27°C). E1 and E2 were not significantly different.

From Fig. 8, the cheek temperature, E1 (-0.78°C) was significantly cooler than E2 (-0.60°C); both E1 and E2 were significantly cooler than no cooling (-0.34°C).

From Fig. 9, the back neck temperature, both E1

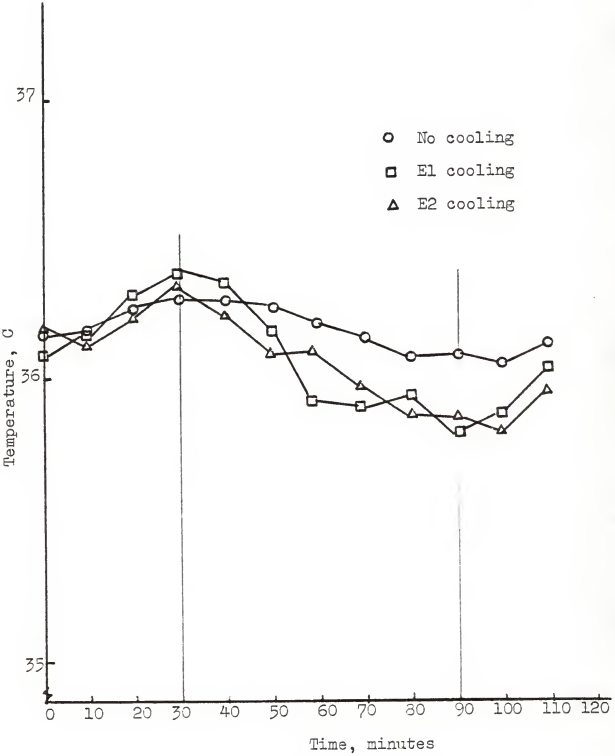

Figure 7. Mean Skin Temperature at Forehead vs Time

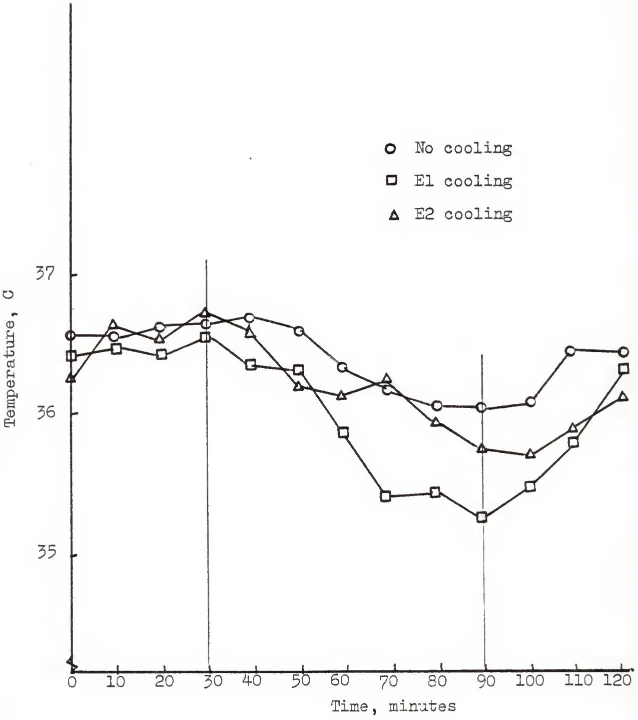

Figure 8. Mean Skin Temperature at Cheek vs Time

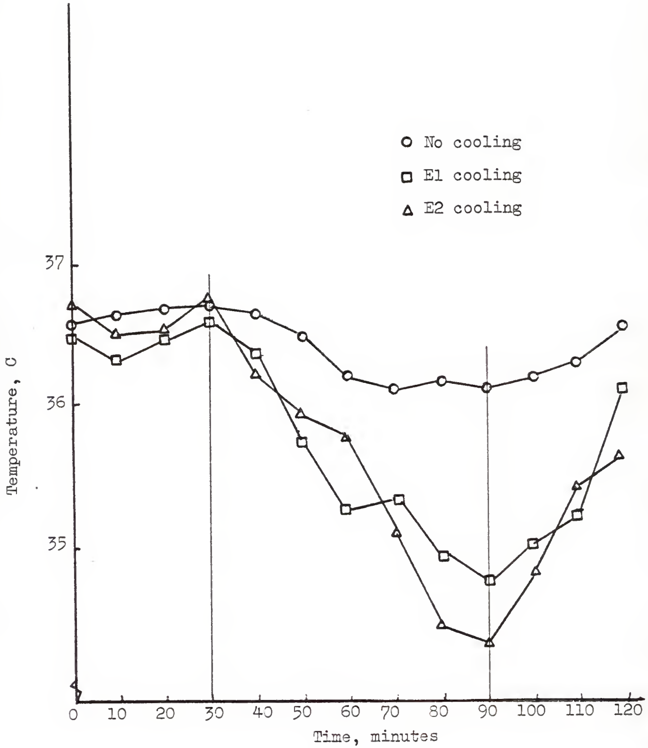

Figure 9. Mean Skin Temperature at Back of Neck vs Time

Table 3. Mean Increases (+) or Decreases (-) in Skin Temperatures (°C) at All Sensors, Over the Readings at 30 Minutes.

Sensor	CONDITIONS: CONTROL Subject 1	CONTROL Subject 2	CONTROL Mean	E1 COOLING Subject 1	E1 COOLING Subject 2	E1 COOLING Mean	E2 COOLING Subject 1	E2 COOLING Subject 2	E2 COOLING Mean
1 forehead	-0.27	-0.27	-0.27	-0.40	-0.71	-0.56	-0.81	-0.31	-0.56
2 cheek	-0.36	-0.32	-0.34	-0.99	-0.57	-0.78	-0.55	-0.65	-0.60
3 neck	-0.47	-0.27	-0.37	-0.80	-1.28	-1.04	-0.78	-0.96	-0.87
4 arm	-0.75	-0.59	-0.67	-0.62	-0.84	-0.73	-0.55	-0.85	-0.70
5 chest	-0.48	-0.66	-0.57	-2.10	-2.30	-1.65	-1.47	-1.83	-2.20
6 lower chest	-0.84	-0.31	-0.58	-1.12	-0.18	-0.65	-1.47	-0.51	-0.99
7 forearm	-0.36	+0.11	-0.31	-0.41	-0.71	-0.56	-0.16	-0.22	-0.19
8 rear palm	+0.21	+0.57	+0.39	+0.26	+0.02	+0.14	+0.64	-0.12	+0.26
9 front thigh	-0.40	+0.73	+0.17	+0.32	-0.64	-0.32	+0.28	-0.22	+0.06
10 calf side	+0.68	+0.84	+0.76	+0.63	-0.07	+0.28	+0.46	+0.30	+0.38
11 top back	-0.25	-0.37	-0.31	-0.62	-0.26	-0.44	+0.31	+0.13	+0.22
12 lower back	+0.52	-0.04	+0.24	-0.16	-0.28	-0.22	-0.31	-0.21	-0.26
13 rear thigh	-0.36	-0.24	-0.30	+0.64	-0.06	+0.29	-1.64	-1.06	-1.35
14 calf	-0.26	-0.02	-0.14	+0.35	+0.17	+0.26	+0.95	+0.37	+0.66
15 foot	+0.55	-0.19	+0.18	+0.71	-0.18	+0.27	+0.12	+0.34	+0.23
	Mean		-0.14			-0.38			-0.39

E1 (-1.04°C) and E2 (-0.87°C) were significantly cooler than no cooling (-0.37°C). E1 also was significantly cooler than E2.

From Fig. 10, the right arm temperature, E1 (-0.73°C) was significantly cooler than no cooling (-0.67°C), E2 (-0.70°C) was not significantly cooler than no cooling (-0.67°C).

From Fig. 11, the right chest temperature, both E1 (-1.65°C) and E2 (-2.20°C) were siginificantly cooler than no cooling (-0.57°C). E2 also was significantly cooler than E1.

From Fig. 12, the lower chest temperature, both E1 (-0.65°C) and E2 (-0.99°C) were significantly cooler than no cooling (-0.58°C). E2 also was significantly cooler than E1.

From Fig. 13, the right forearm temperature, E1 (-0.56°C) was significantly cooler than no cooling (-0.31°C) and E2 (-0.19°C). E2 (-0.19°C) was significantly warmer than no cooling (-0.31°C).

From Fig. 14, the rear palm temperature, both E1 (+0.14°C) and E2 (+0.26°C) were significantly cooler than no cooling (+0.39°C). E2 also was significantly cooler than E1.

From Fig. 15, the front thigh temperature, E1 (-0.32°C) was significantly cooler than both E2 (+0.06°C) and no cooling (+0.17°C). E2 also was significantly cooler than

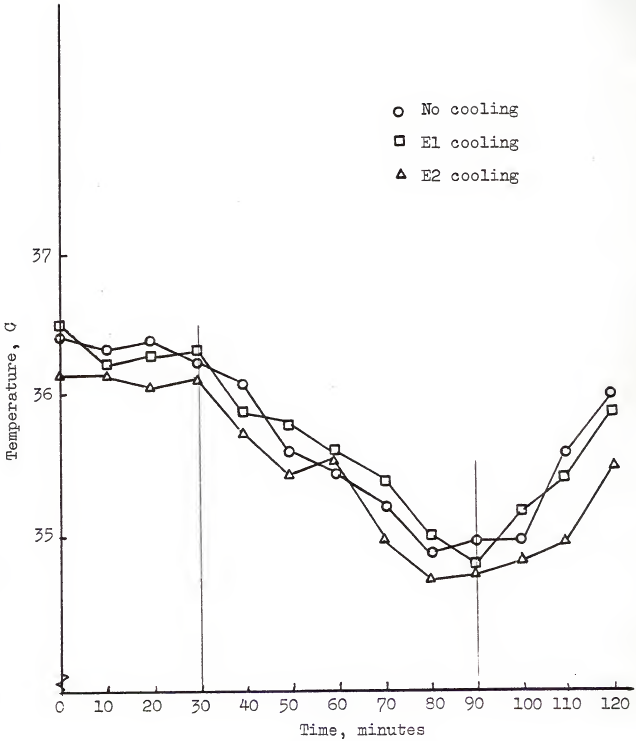

Figure 10. Mean Skin Temperature at Arm vs Time

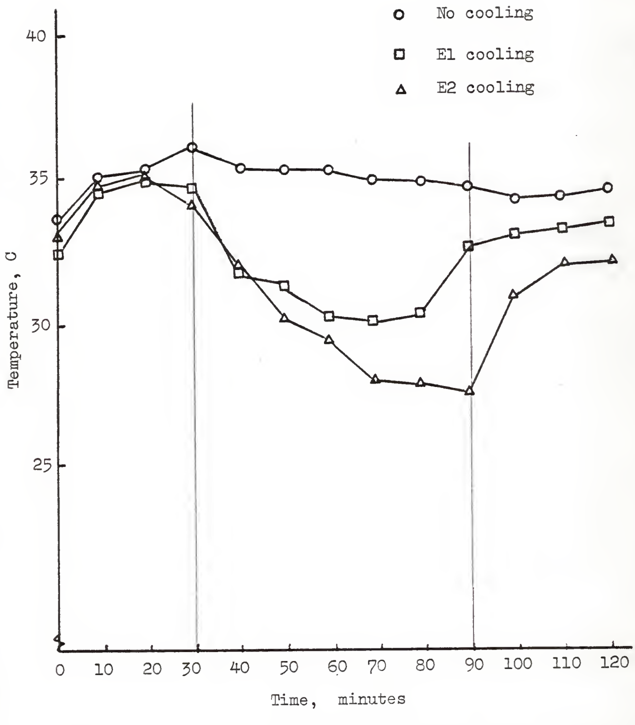

Figure 11. Mean Skin Temperature at Right Chest vs Time

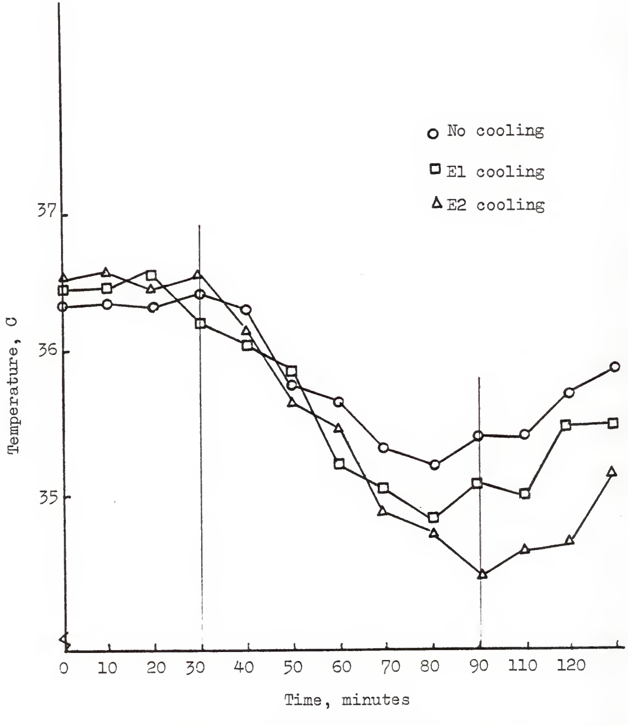

Figure 12. Mean Skin Temperature at Lower Chest vs Time

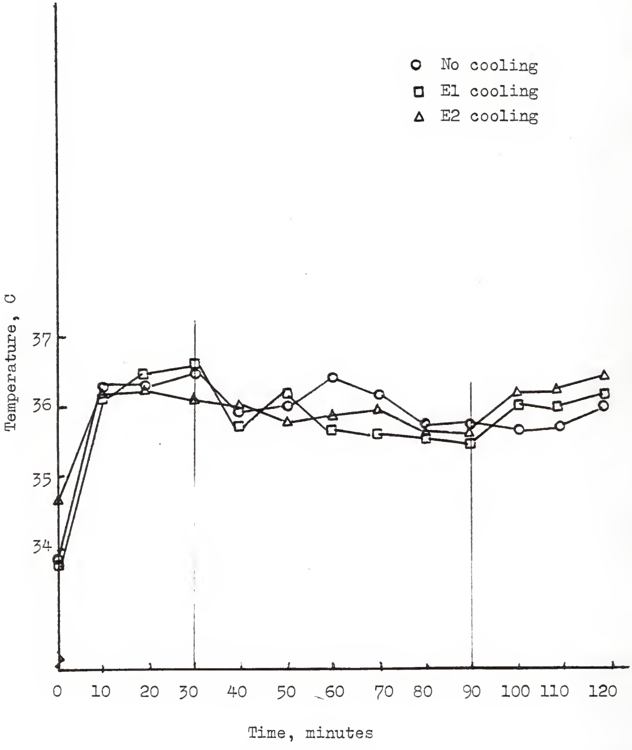

Figure 13. Mean Skin Temperature at Forearm vs Time.

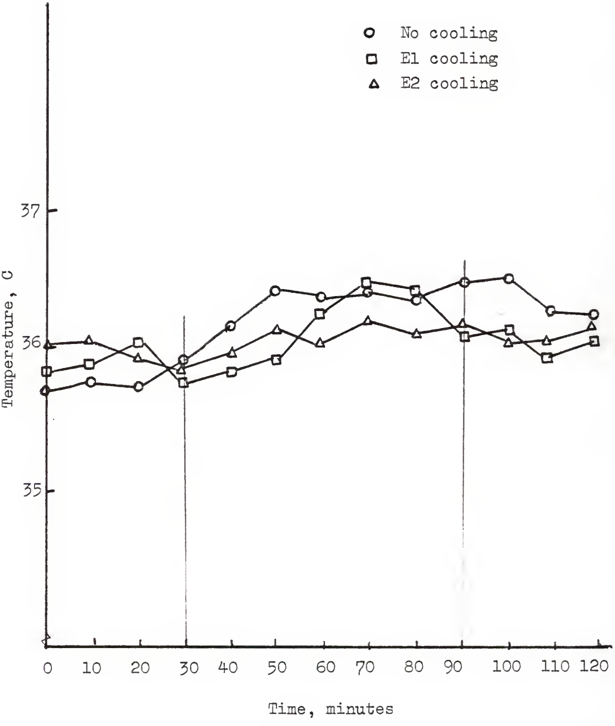

Figure 14. Mean Skin Temperature at Back of Palm vs Time.

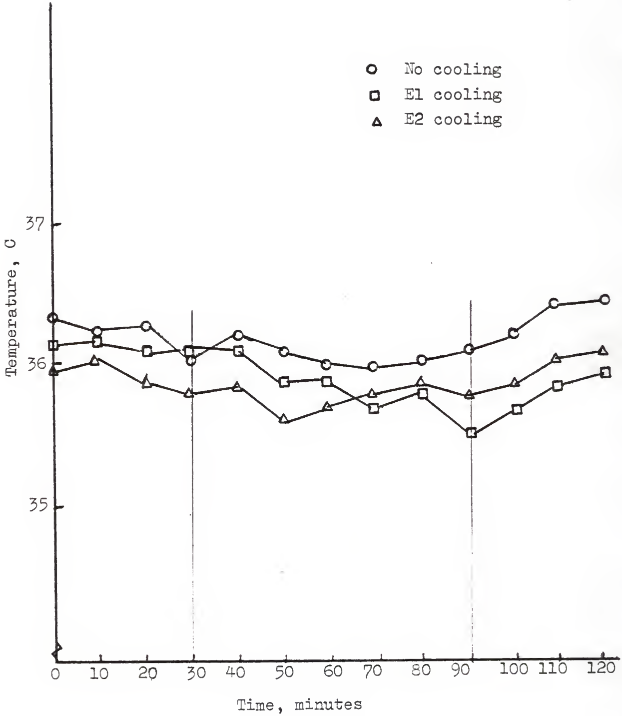

Figure 15. Mean Skin Temperature at Front of Thigh vs Time.

no cooling.

From Fig. 16, the side of the calf temperature, both E1 (+0.28°C) and E2 (+0.38°C) were significantly cooler than no cooling (+0.76°C). E1 also was significantly cooler than E2.

From Fig. 17, the top of the back temperature, E1 (-0.44°C) was significantly cooler than no cooling (-0.31°C); E2 (+0.22°C) was significantly warmer than no cooling (-0.31°C) and E1 (-0.44°C).

From Fig. 18, the lower back temperature, both E1 (-0.22°C) and E2 (-0.26°C) were significantly cooler than no cooling (+0.24°C). E2 (-0.26°C) was not significantly different from E1 (-0.22°C).

From Fig. 19, the rear thigh temperature, E1 (+0.29°C) was significantly warmer than no cooling (-0.30°C); E2 (-1.35°C) was significantly cooler than both E1 (+0.29°C) and no cooling (-0.30°C).

From Fig. 20, the calf temperature, both E1 (+0.26°C) and E2 (+0.66°C) were significantly warmer than no cooling (-0.14°C); E2 also was warmer than E1 (+0.26°C).

From Fig. 21, the foot temperature, E1 (+0.27°C) was significantly warmer than no cooling (+0.18°C); E2 (+0.23°C) and no cooling (+0.18°C) were not significantly different; E1 (+0.27°C) and E2 (+0.23°C) were not significantly different.

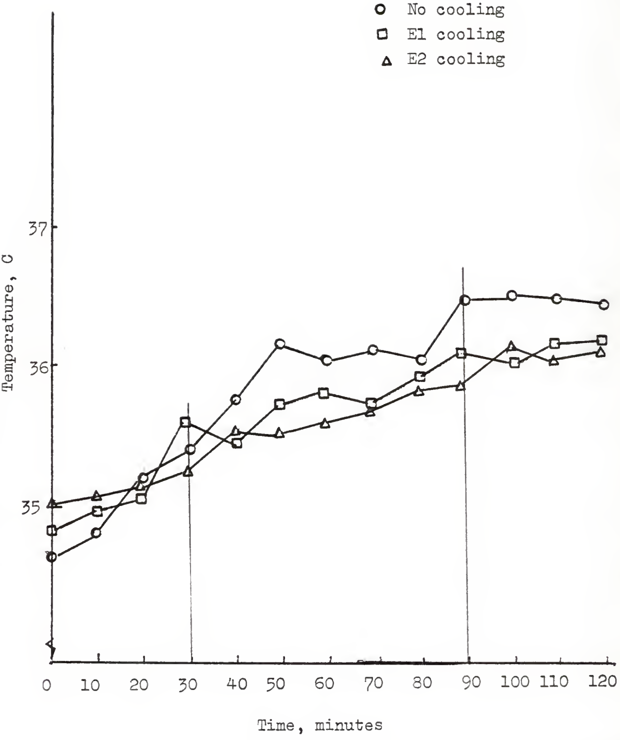

Figure 16. Mean Skin Temperature at Side of Calf vs Time.

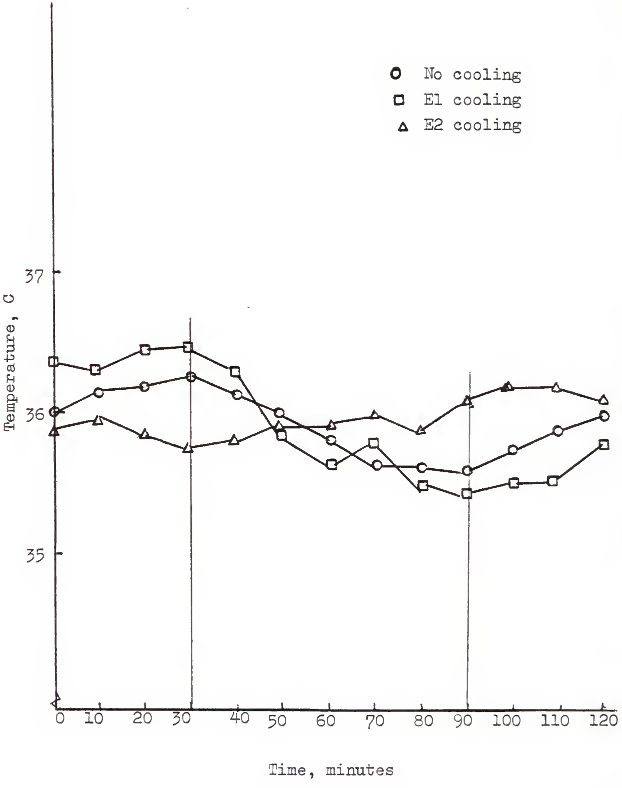

Figure 17. Mean Skin Temperature at Top of Back vs Time.

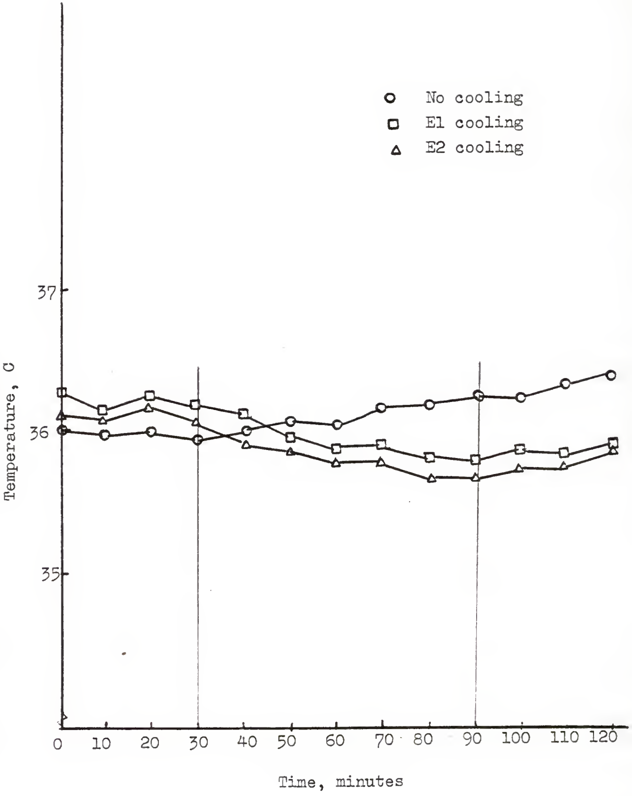

Figure 18. Mean Skin Temperature at Lower Back vs Time.

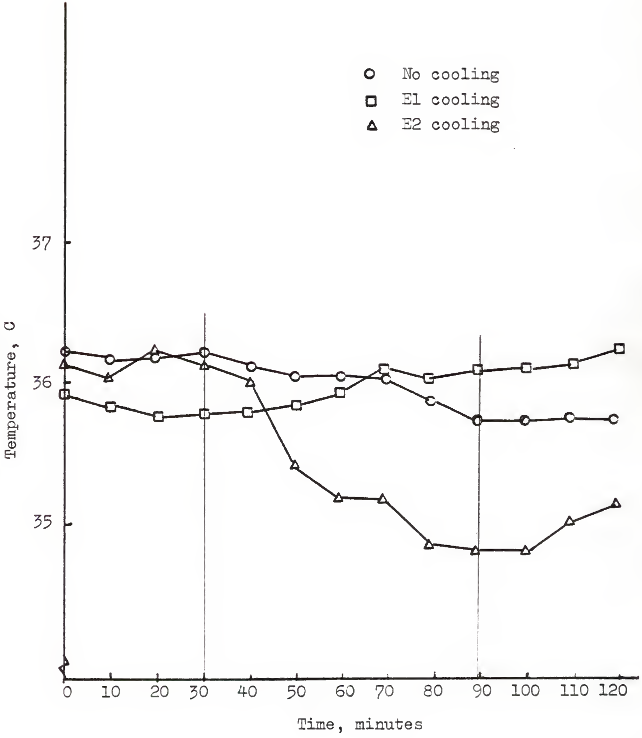

Figure 19. Mean Skin Temperature at Rear of Thigh vs Time.

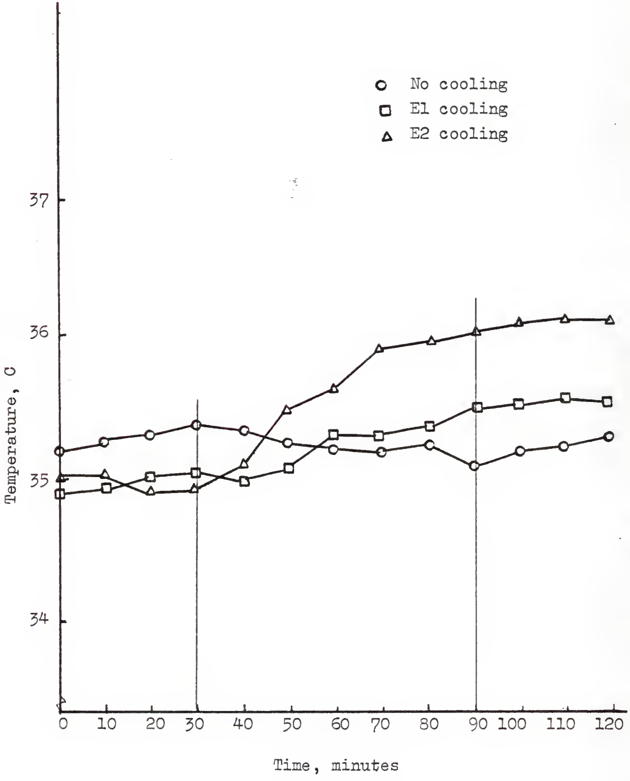

Figure 20. Mean Skin Temperature at Calf vs Time.

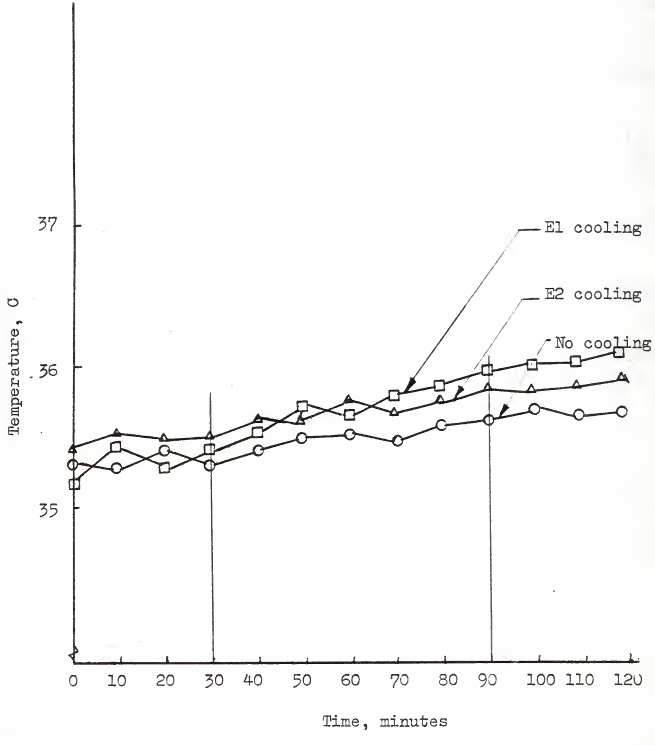

Figure 21. Mean Skin Temperature at Foot vs Time.

The mean skin temperatures (see Table 3) which were the mean of all 15 sensors, were E1 (35.4°C), E2 (35.1°C) and no cooling (36.0°C). Both E1 (35.4°C) and E2 (35.0°)) were significantly cooler than no cooling (36.0°C); E1 (35.4°C) and E2 (35.1°C) were not significantly different.

Rectal Temperature

Fig. 22, shows the individual rectal temperatures with E1 and E2 cooling. Fig. 23 shows the three mean temperatures of no cooling, E1 cooling and E2 cooling. Table 4 shows the mean changes over the 30 minute values. The time interval for the means is 30 min. to 120 min.

E2 cooling (+0.17°C) was significantly cooler than no cooling (+0.27°C). There was no significant difference between E1 (+0.25°C) and no cooling (+0.27°C). E2 (+0.17°C) was significantly cooler than E1 (+0.25°C).

Heart Rate

Fig. 24, shows the mean heart rates for the no cooling, E1 cooling, and E2 cooling conditions. Table 4 shows the mean changes in heart rates over the values at 30 minutes. The duration for these means was 30 to 120 minutes.

The no cooling mean heart rate change (+27.5 b/min) was significantly higher than E1 (+17.5 b/min) and E2 (+14.0 b/min). However, E1 (+17.5 b/min) and E2 (+14.0 b/min) were not significantly different.

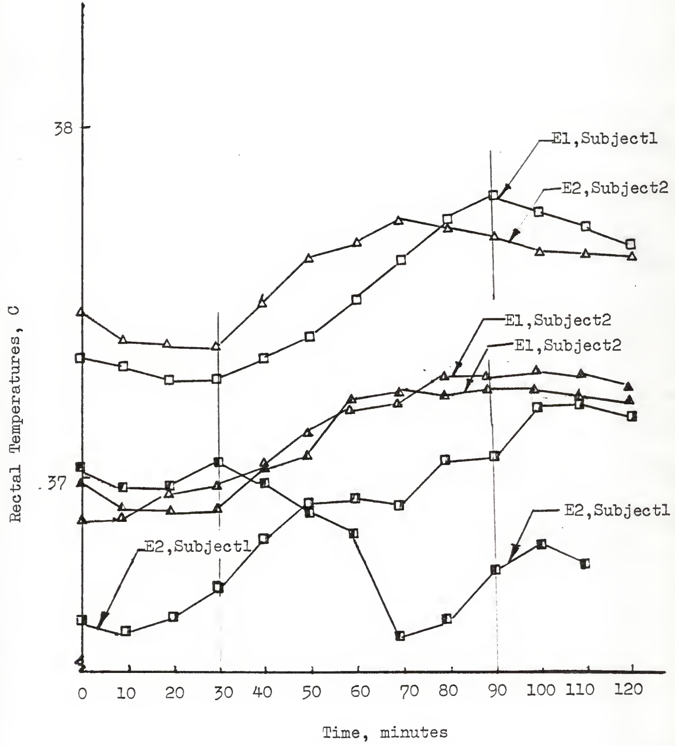

Figure 22. Individual Rectal Temperatures vs Time.

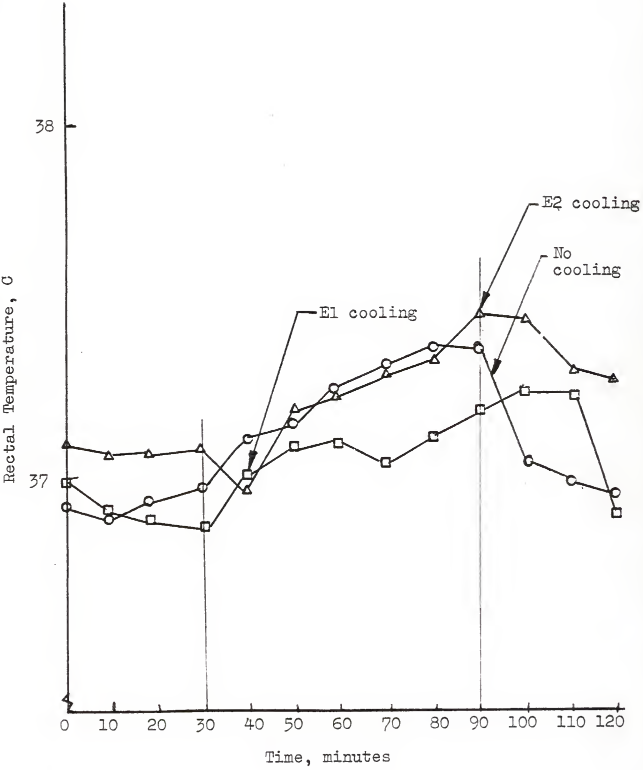

Figure 23. Mean Rectal Temperatures vs Time.

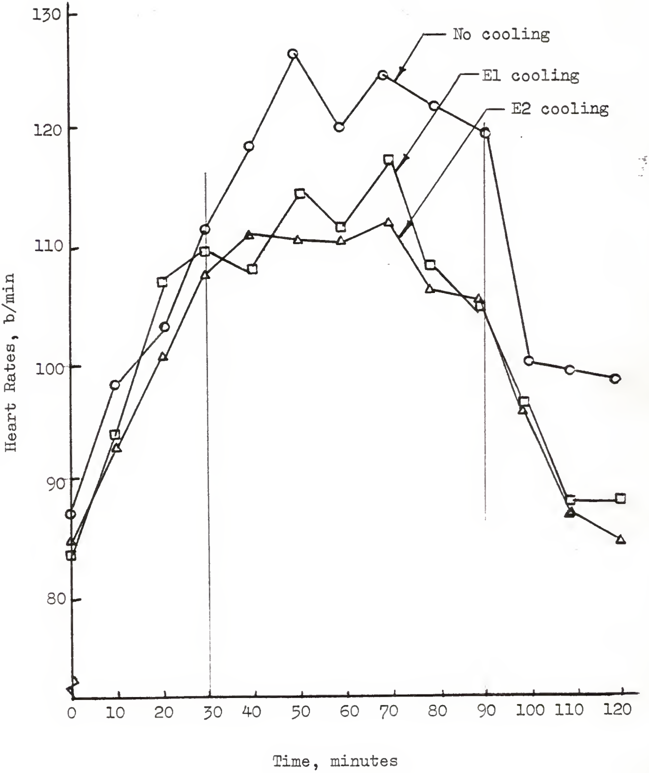

Figure 24. Mean Heart Rates vs Time.

Table 4. Mean Changes in Heart Rate, Rectal Temperature and Ventral Equivalent Over Readings at 30 Minutes.

Condition	Heart Rate, b/min			Rectal Temp., C			Ventral Equiv., lit/min		
	Subject 1	Subject 2	Mean	Subject 1	Subject 2	Mean	Subject 1	Subject 2	Mean
No cooling	22	33	+ 27.5	0.25	0.28	+0.27	2.7	2.9	+ 2.80
E1 cooling	14	21	+ 17.5	0.27	0.22	+0.25	2.2	2.3	+ 2.25
E2 cooling	10	18	+ 14.0	0.14	0.19	+0.17	2.8	2.6	+ 2.70

Ventral Equivalent

A computer program was used to calculate the Ventral Equivalents (VE) and the oxygen pickup percent (VO_2). The volume of air breathed by the subjects and the barometric and water vapor pressure constituted the input data. Fig. 25 and Fig. 26 show the VE for both the subjects, under conditions of no cooling, E1 cooling and E2 cooling. Table 4 shows the mean changes in VE for 90 minutes over the values at 30 minutes.

VE for no cooling (+2.80 lit/min) and E2 (+2.70 lit/min) were both significantly higher than E1 (+2.25 lit/min). No cooling (+2.80 lit/min) and E2 (+2.70 lit/min) were not significantly different.

Figures 27 and 28 show the oxygen pickup percent. The oxygen pickup percent mean for no cooling (38%) was significantly higher than both E1 (33%) and E2 (33%) cooling. However, E1 (33%) and E2 (33%) were not significantly different from each other.

Body Weight

Table 5 shows the changes in body weights of the subjects during the experimental session. Changes in clothing weights were treated as negligible. Fig. 29 shows the changes in body weights over the sessions. The mean losses were no cooling (0.59 kg), E1 (0.40 kg) and E2 (0.37 kg). No cooling (0.59 kg) was significantly higher than both E1 (0.40 kg) and E2 (0.37 kg). However, E1 (0.40 kg) was not

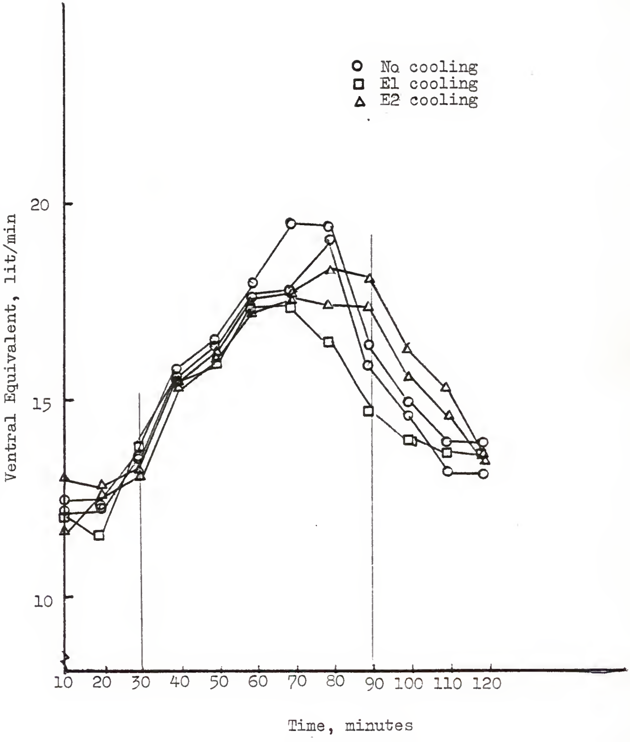

Figure 25. Ventral Equivalent vs Time for Subject 1.

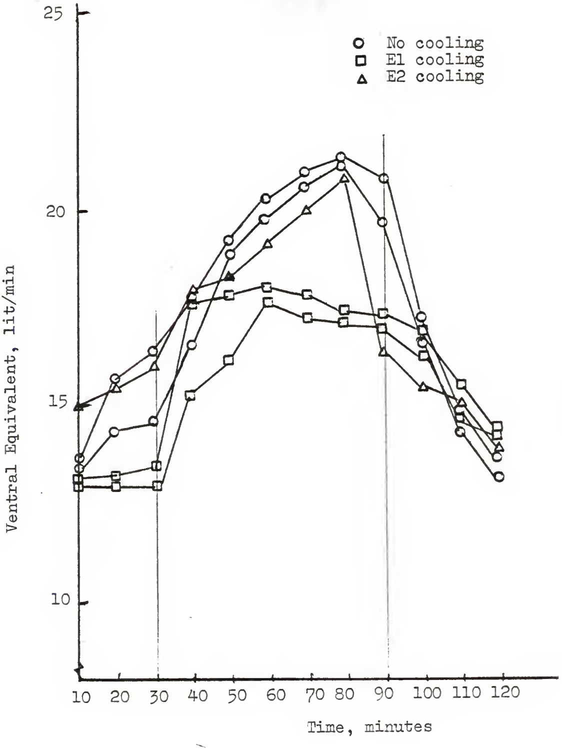

Figure 26. Ventral Equivalent vs Time for Subject 2.

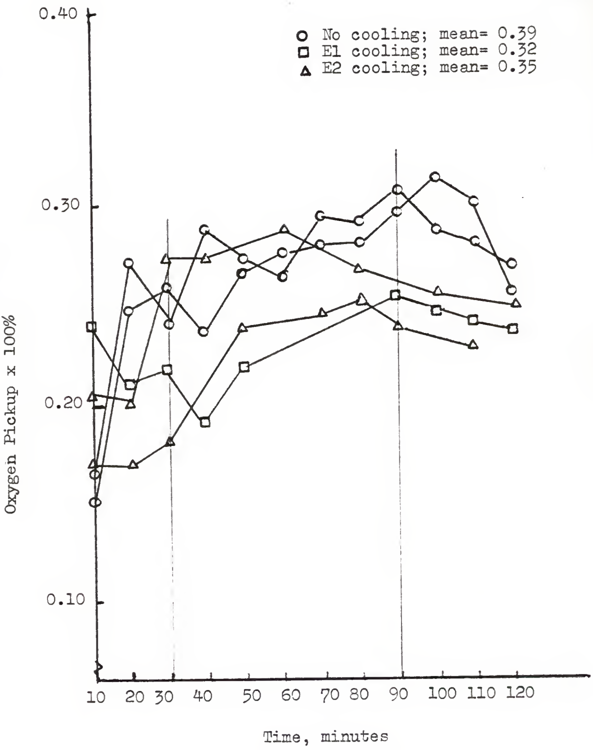

Figure 27. Oxygen Pickup vs Time for Subject 1.

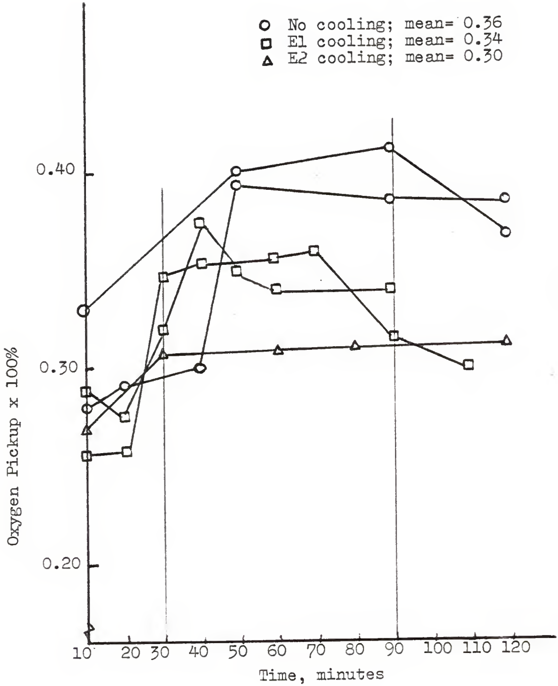

Figure 28. Oxygen Pickup vs Time for Subject 2.

Table 5. Loss in Body Weight of Subjects During Experiments.

Session	Subject 1 (A) Initial Body Weight kg	Subject 1 (B) Water Intake kg	Subject 1 (C) Final Body Weight kg	Subject 1 A-(C-B) Body Weight Loss kg	Subject 2 (A) Initial Body Weight kg	Subject 2 (B) Water Intake kg	Subject 2 (C) Final Body Weight kg	Subject 2 A-(C-B) Body Weight Loss kg
1	57.90	-	57.50	0.40	66.80	0.40	66.75	0.45
2	58.10	-	57.60	0.50	66.90	0.60	66.85	0.65
3	57.85	0.20	57.75	0.30	67.10	0.40	67.10	0.40
4	57.80	0.60	58.00	0.40	67.00	0.60	66.90	0.70
5	58.20	0.20	58.05	0.35	67.10	0.40	67.00	0.50

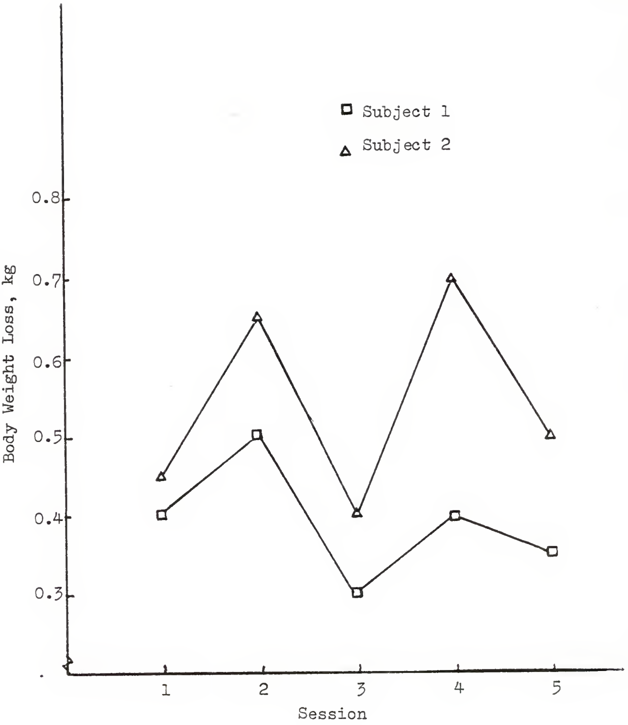

Figure 29. Losses in Body Weights of Subjects vs Sessions.

significantly different from E2 (0.37 kg).

Blood Pressures

Table 6 shows the pre and post pedalling blood pressures of both the subjects.

Sublimation

Konz et al (1975) developed a formula to predict the sublimation of a dry ice slab in a personal cooling garment:

$$S = K_1\ K_2\ K_3\ K_4\ K_5\ K_6\ \left[31.4 + 0.132\ (IW)\right]$$

where

S = sublimation rate/slab, g/hr

IW = initial weight of the slab, g

K_1 = slab thickness factor
= 0.93 for 25 mm slab

K_2 = pocket location factor
= 1.00 for top pockets

K_3 = jacket vs vest factor
= 1.00 for jacket

K_4 = dry bulb environmental temperatures
= 1.00 for 35 °C

K_5 = water vapor pressure in environment
= 1.00 for 30 mm of Hg

K_6 = environmental time factor
= 1.00 for up to 120 minutes

Table 7 and 8 report the sublimation of the dry ice slabs. Table 7 gives the mean sublimation per pocket as 91 g/hr.

The mean sublimation rate of E1 (87 g/hr) was significantly lower than E2 (95 g/hr).

Table 6. Blood Pressures of Subjects Before and After Pedalling.

Session	Subject 1 Before	Subject 1 After	Subject 1 Change systolic	Subject 1 Change diastolic	Subject 2 Before	Subject 2 After	Subject 2 Change systolic	Subject 2 Change diastolic
1 E1 Subject 1 E2 Subject 2	124/92	104/76	-20	-16	124/68	106/92	-18	+24
2 No cooling	122/78	120/74	-2	-4	104/74	102/70	-2	-4
3 E2 Subject 1 E1 Subject 2	130/82	120/80	-10	-2	112/72	100/60	-12	-12
4 No cooling	116/78	110/68	-6	-10	122/80	103/60	-19	-20
5 E2 Subject 1 E1 Subject 2	110/70	108/58	-2	-12	106/68	110/70	+4	+2

Table 7. Mean Sublimation (g/hr) of Dry Ice Slabs.

	E1 COOLING			E2 COOLING			
Pocket	Subject 1	Subject 2	Mean	Subject 1	Subject 2	Mean	Mean
1 left chest	94	88	91	84	90	87	89
2 right chest	84	78	81	88	102	95	92
3 right back	86	90	88	89	112	100	94
4 left back	80	93	87	85	108	97	92
	Mean		87			95	91

Table 8. Sublimation Rates - Predicted vs Experiment.

Jacket	Subject	Pocket	Initial Weight, g	(A) Predicted Sublimation, g/hr	(B) Experimental Data, g/hr	(A)-(B)	$\frac{(A)-(B)}{(A)}$ %
E1	1	1	410	87	94	-7	-8
		2	420	88	84	+4	+4
		3	400	85	86	-1	-1
		4	410	87	80	+7	+8
	2	1	414	87	88	-1	+1
		2	403	85	78	+7	+8
		3	410	87	90	-3	-3
		4	400	85	93	-8	-9
E2	1	1	405	86	84	+2	+2
		2	395	84	88	-4	-5
		3	405	86	89	-3	-3
		4	403	85	85	0	0
	2	1	380	82	90	-8	-10
		2	395	84	102	-18	-21
		3	405	86	112	-26	-30
		4	405	86	108	-22	-25

Error Mean = -6%

Table 8 compares the experimental values of the sublimation rates against the predicted values. The predicted values were 6% lower than the experimental values.

Computer Simulation

A computer program in FORTRAN, under development in the Industrial Engineering Department at Kansas State University, simulates a mathematical model of the human thermoregulatory system on a time scale. A comparison of the physiological responses between the simulation results and the experimental data was made under the no cooling condition for both the subjects. Table 9 shows the input data for each subject. They were both rated at three in cardiovascular fitness which would specify their health as fair. The job times 30, 90, 120 indicate that the subjects sat in the chamber for 30 minutes, then pedalled the ergometer for the next 60 minutes and then again sat in the chamber for 30 minutes. There were no jackets used during the no cooling sessions, so the clothing was 0.65 clo.

Figures 30 through 35 compare the computer simulation against the experimental values. Figures 30 and 31 are heart rates; Figures 32 and 33 are rectal temperatures and Figures 34 and 35 are oral temperatures. Only the values of the no cooling sessions were plotted. Since each subject had two no cooling sessions, the vertical lines joining the two experimental values indicate the

Table 9. Input Data for Each Subject.

Subject	1	2
Sex	male	male
Age (yr)	26	25
Weight (kg)	58	67
Height (cm)	167	178
Cardio-vascular Fitness	3	3
Total Metabolism (watts)	97,400,97	108,400,108
Relative Humidity (%)	70	70
Dry Bulb Temperature (C)	35	35
Air Velocity (m/s)	0.3	0.3
Job	3,4,3	3,4,3
Job Times (min)	30,90,120	30,90,120
Clothing (clo)	0.65	0.65
Clothing Allocation	0.0,0.20,0.15, 0.0,0.20,0.10	0.0,0.20,0.15, 0.0,0.20,0.10

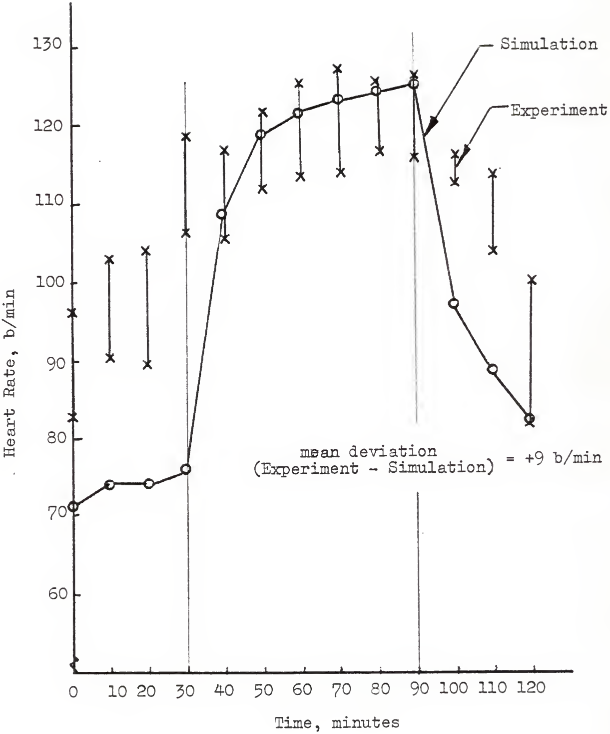

Figure 30. Subject 1 Heart Rates - Simulation vs Experiment.

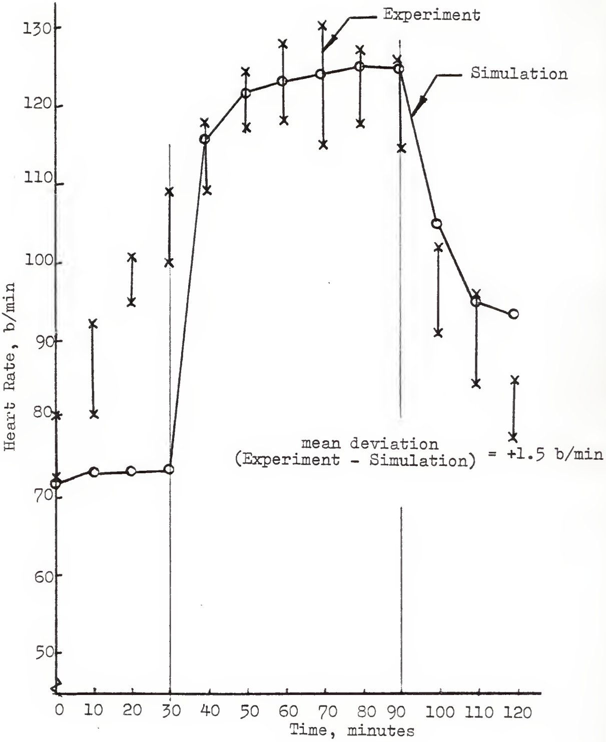

Figure 31. Subject 2 Heart Rates - Simulation vs Experiment.

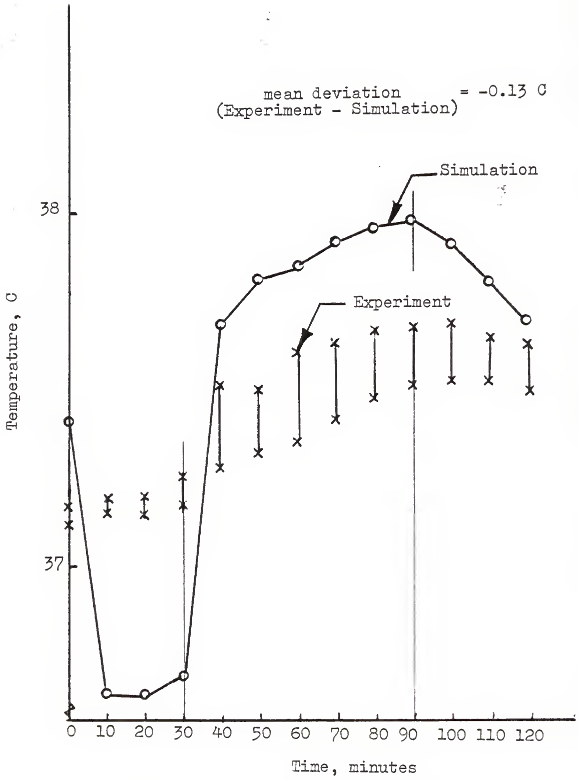

Figure 32. Subject 1 Rectal Temperatures - Simulation vs Experiment.

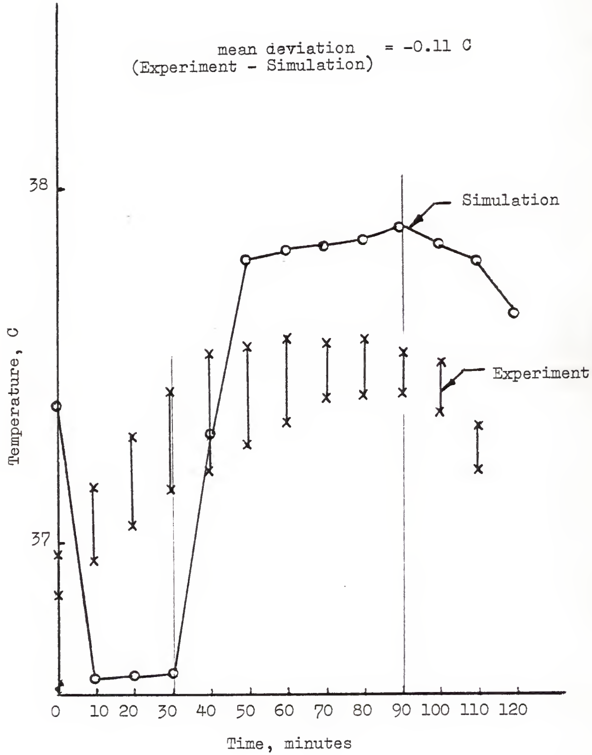

Figure 33. Subject 2 Rectal Temperature-
Simulation vs Experiment.

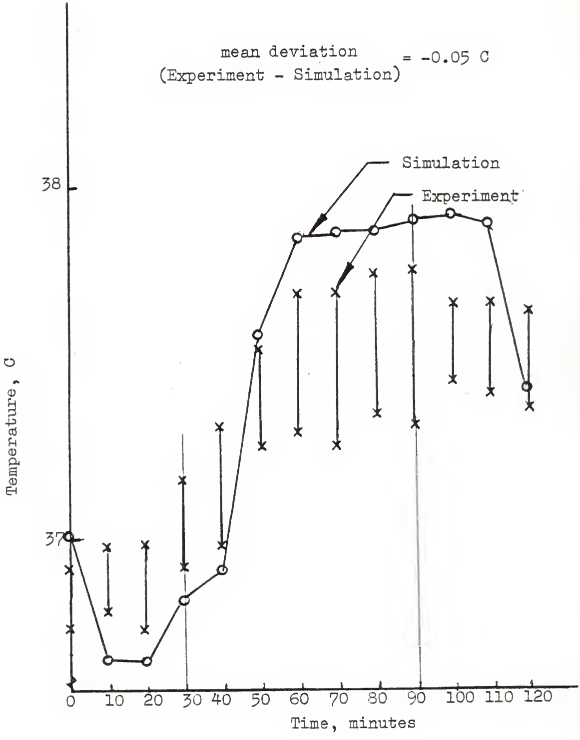

Figure 34. Subject 1 Oral Temperatures-
Simulation vs Experiment.

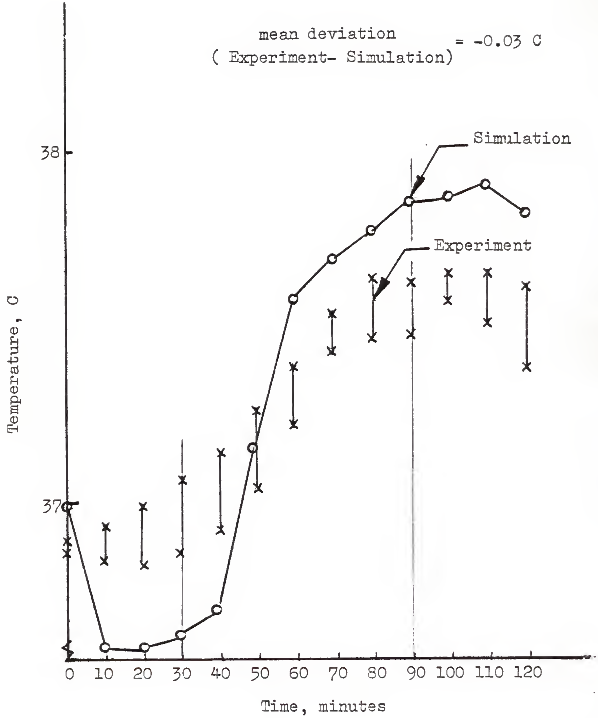

Figure 35. Subject 2 Oral Temperatures-
Simulation vs Experiment.

range of values.

From Figures 30 and 31, the heart rate from the experimental data average 5 beats/min greater than the values from the simulation data.

From Figures 32 and 33, the rectal temperature from the experimental data average 0.12°C lower than that from the simulation results.

From Figures 34 and 35, the mean oral temperature from the experimental data average 0.04°C lower than that from the simulation results.

Though these deviations do not indicate a strong disagreement between experimental values and simulation results, the figures suggest that there is good agreement between the values particularly in the 60 minutes of pedalling. However, for the first 30 minutes, the simulation values are lower than the experimental values and for the last 30 minutes they are too high.

DISCUSSION

As a general trend, most skin temperatures dropped during the pedalling period and tended to rise during the recovery period. Jacket E2 cooled the most with a mean skin temperature of 35.1°C and with a mean decrease of -0.39°C. Jacket E1, with a mean skin temperature of 35.4°C, produced a mean skin temperature decrease of -0.38°C. No jacket produced a higher skin temperature (36.0°C) amd lower cooling (-0.14°C).

Some regions (calf and foot for example) seemed to register an increase in temperature in spite of the dry ice cooling effects in other areas. This could possibly be attributed to internal metabolic heat in the legs while performing the task. E2 (Fig. 17) produced an increase in temperature while both E1 and no cooling caused a decrease. The reason for this anomaly is not known.

As expected, the chest region (sensor 5) was cooled the most by proximity of the dry ice pockets. Convection cooling at the lower chest regions (sensor 5) was noticed.

The uncomfortable cold band of dry ice and cold CO_2 at the stomach region of previous designs was eliminated by the use of dry ice only in the upper pockets.

Both the jackets produced a smaller increase in rectal temperature than the no cooling condition. E2 (+0.17°C) was cooler than E1 (+0.25°C).

Use of the dry ice jackets also reduced the heart rates by about 10 b/min. The values were E1(+ 17.5 b/min), E2 (+14.0 b/min) and the no cooling (+27.5 b/min).

Both the jackets produced lower ventral equivalents than the no cooling conditions. This signified that the dry ice did physiological good for the body, thereby not necessitating an over exertion on the lungs. Both E1 and E2 produced the same (33%) lower oxygen pickup percent while the no cooling produced 38%.

Lack of dry ice cooling caused a significantly higher body weight loss (0.59 kg) than both E1 (0.40 kg) and E2 (0.37 kg). Loss of body fluids by sweating were lower when dry ice cooling was used.

With the amount of dry ice initially loaded in the jackets, there were sufficient amounts left at the end of each session to prolong the use of the same load, if the situation called for it.

The results from the computer simulation and the experimental data do not agree very well during the non-exercise period. The disparity is small during the pedalling.

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THE DESIGN AND ANALYSIS OF TWO DRY ICE
PERSONAL COOLING JACKETS

BY

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B.Tech., Indian Institute of Technology, India, 1974

AN ABSTRACT OF A MASTER"S THESIS

submitted in partial fulfillment of the
requirements of the degree

MASTER OF SCIENCE

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Manhattan, Kansas
1979

Abstract

Two personal dry ice cooling jackets for operators in heat stress environments were developed at Kansas State University. Four pockets (2 in front and 2 at the back) were used for dry ice slabs.

The jackets were tested on two male subjects who pedalled a bicycle ergometer at 60 rpm and 1 kp load. The environmental chamber conditions were 35°C dry bulb; 31.6°C wet bulb, 70% relative humidity and air velocity 0.3 m/s. The dry ice jackets significantly reduced the mean heart rate by about 10 b/min. Use of the jackets significantly reduced (by a mean of 0.8°C) the mean skin temperature from a no cooling mean of 36.0°C. No cooling caused a higher loss in body weight (0.59 kg) compared to the cooling loss (0.38 kg).

One of the jackets produced a significantly lower (+0.17°C) rise in the mean rectal temperature compared with the other (+0.25°C) and no cooling (+0.27°C). A computer model was used to simulate the physiological responses of the subjects.