THE DESIGN AND EVALUATION OF A DRY-ICE JUMPSUIT

BY

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Acknowledgement

I wish to express my sincere gratitude to my major professor, Dr. Stephan A. Konz for his guidance, creative suggestions and encouragement during the development of this research project.

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To Mr. T. Shrimplin who helped me in constructing or preparing equipment, I am grateful.

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Introduction and Problem

Industrial workers may have to do their jobs in a hot environment. Examples are found in maintenance work in boiler rooms or near hot steel furnaces, manual work in deep mines, fire fighting, tanks in the sun, construction, cotton industry, refineries, etc. To solve these problems, either the hot environment has to be cooled or the body of the individual worker. The later seems to be more desirable. Konz (1974) has shown that personal cooling is an economical and effective means of reducing heat storage and extending working time in heat stress environments.

Both air-cooling and liquid-cooling techniques have been developed rapidly in recent years for providing heat relief to a worker. Laboratory garments using liquid heat transfer were first tried at Royal Aircraft Establishment (Farnborough) in 1962; high rates of heat transfer can be maintained at a very little cost in weight. Veghte (1965) determined that a water-circulation cooling system (consisting of tubes carrying flowing water at a temperature below skin temperature in contact with the skin) was superior to comparable air-circulating systems.

Konz and Morales (1968) developed a water cooled hood, which provided a cooling effect when placed over the head. Gold and Zornitzer (1968) used long underwear, lined with

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plastic tubes carrying water at 20°C. The system cooled the chest, back, upper arms, and thighs. Duncan (1969) used a water cooled helmet to reduce the heat stress. Gandhok (1970) got comparable results with a PVC jacket supplied with cold air from a vortex tube. Byrnes (1970) found a jacket to be more effective than a hood from a physiological viewpoint..

Shvartz, et al. (1974) circulated water at 10 different body regions (neck, face, upper arms, lower arms, hands, chest, back, thighs, lower legs, and feet). Three subjects were used in the experiment performing moderate work at 21.3°C and in heat (49.3°C DB, 31.4°C WB), without cooling and while cooling each of the above body regions. Cooling of the back, chest, or thighs had the highest reduction in body heat storage (66%), while face cooling had the lowest (19%).

Another method of conduction cooling is the use of ice in pockets of a garment. When water ice changes from solid to liquid it picks up 80 kcal/kg of ice melted. When dry ice sublimes it picks up 137 kcal/kg of dry ice evaporating, and an additional 23 kcal from gas going from -79°C to 35°C. Since it picks up more heat, it can be used instead of water ice.

Cooling with dry ice was first reported in a Belgian mining journal by Petit et al (1966). Their cooling garment was made of leather; eight (10x10x3 cm) pockets were attached to the garment --- four in front and four on the back. Each pocket, opened at the top, had approximately 50 holes of 3 mm diameter in the inside surface which permitted the cold carbon dioxide gas to flow next to the skin. A round slab of dry ice (10 cm diameter, 3 cm thick) was inserted in each pocket. Eight male subjects walked for 20 minutes on a treadmill at 6 km/hr and 10% grade, with and without the cooling garment, in an environment of 46°C dry bulb temperature and 50% relative humidity. With the cooling garment, heart rate was 16 beats/min lower, oral temperature was 0.5°C lower and skin temperature was 1.8°C lower. No significant differences were found between conditions of cooling versus no cooling for measurements of oxygen consumption, rectal temperature, and sweat loss. The mean sublimation rate of each of the eight slabs was 8.8 gm/min.

Konz and his associates in the Department of Industrial Engineering of Kansas State University have been developing dry ice cooling garments since 1972. As a result, dry ice cooling jacket model B1 (which was tested by Duncan in the field), dry ice cooling jacket model B2 and dry ice cooling jacket model C (which was not tested by anyone) were developed. Model D, which was similar to model C except that the two vertical pockets at the back were changed to horizontal, was tested by Techapatanarat (1976). The dry ice locally cools the torso which was a desirable place for cooling since it contributed 22% of the total heat produced during working (Aschoff and Wever, 1958). The KSU-Stolwijk thermoregulatory model predicted that the total heat produced during working by the torso was 30%.

The model C dry ice cooling jacket, developed by Konz and Duncan (1975), was made of a quilted nylon outer shell (nylon facings with polyster fill) and blended cotton for the inner shell. There were four vertical inside pockets, two in the front and two at the back. Each pocket was 45 cm long, 18 cm wide, and 5 cm thick. All the four pockets were opened at the top; Velcro fastener was used for closing the pockets. Inside each pocket there was a removable plastic air bubble liner, and inside the liner there was a nylon net which was divided into three compartments; one slab of dry ice was placed into each compartment. The two long sleeves were of a light, permeable, loose-weave nylon. Cold carbon dioxide gas was pumped into two sleeves by the movements of the arms. Elastic was sewn around the end of the sleeves. The bottom edge of the jacket was also sewn with elastic, to prevent the cold carbon dioxide from escaping. In the front of the jacket, Velcro fasteners were used.

Duncan (1975), using the model B1 and model B2 dry ice cooling jacket, found the sublimation rate in the top compartments (1.9 gm/min/slab) was significantly faster than the lower compartments (1.2). This was because carbon dioxide was 1.5 times heavier than air, and the cold carbon dioxide was trapped by the elastic at the bottom of the jacket. As a result the lower part of the jacket (near the waist) was much cooler because of higher carbon dioxide concentration; hence the sublimation rate was lower. Therefore the temperature of the whole body could be divided into three ranges (see Figure 1), namely, cool, cold and hot.

Duncan (1975) also found that when the subject wore the dry ice cooling jacket that there was a significant increase in oxygen consumption (from a mean of 313 kcal/hr to 387). He believed that a "non-shivering thermogenesis" or a "chemical thermogenesis" had taken place instead of shivering because the subjects reported that they did not feel any shivering.

Techapatanarat (1976) modified the model C dry ice cooling jacket by changing the two pockets at the back from vertical to horizontal. He also changed the insulation from two layers (Duncan's experiment) to three to investigate the effect of insulation on sublimation rate of dry ice. The three insulation levels were 11, 7 and 5 gcal/sec-^{o}C-cm^{2}x10^{-5} respectively. The modified jacket was called model D. He found that slabs of dry ice in horizontal pockets sublimed more uniformly than in the vertical pockets. This implies that the subject was more comfortable by getting a uniform cooling from the horizontal pockets, as well as the dry ice in horizontal pockets could last longer due to more efficient use of the dry ice. He used an increasing straight line to approximate heat production due to non-shivering thermogenesis; it was determined from the difference between the oxygen consumption rate under cooling and no-cooling conditions.

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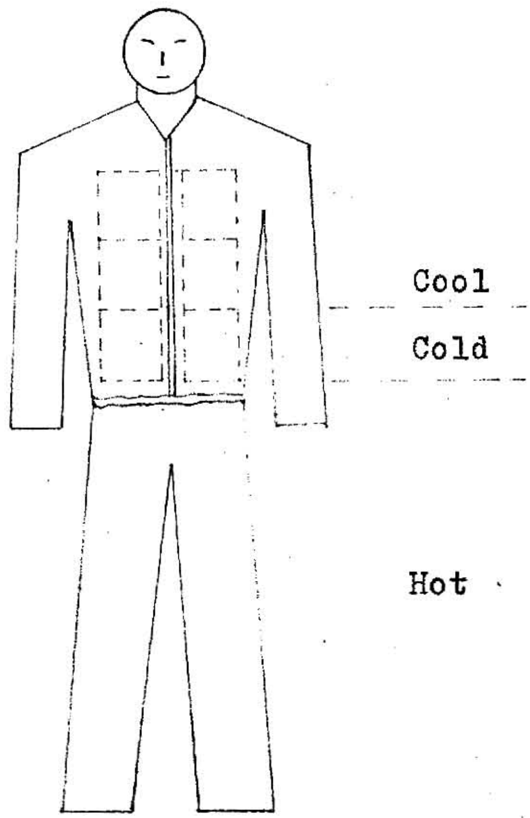


Figure 1. Three Ranges of Temperature When the Subjects Wore Model C and D.

The purpose of this experiment was to design a new garment that would give a better overall body cooling instead of having the body with three ranges of temperature. So a jumpsuit was designed with eight dry ice pockets at the upper part of the suit (see Figure 2). Since carbon dioxide was 1.5 times heavier than air, and because of the gravitational force, the cold carbon dioxide subliming from the pockets was able to come to the lower part of the torso as well as to the two legs. Moreover, when the worker was working, the movements of the two arms and two legs helped the cold carbon dioxide to move to the sleeves and the trousers. Thus a more general overall individual body cooling situation was established, rather than partial cooling. The objectives of this experiment were to:

(1) measure the heart rate, beats/min

(2) measure the oxygen consumption rate, ml/Kg-min

(3) measure the rectal temperature, ^{o}C

(4) measure the skin temperature (at 11 places), ^{o}C

(5) measure the sublimation rate of dry ice for each slab, gm/min/slab

(6) compare the results against previous data

(7) compare the results against computer simulation.

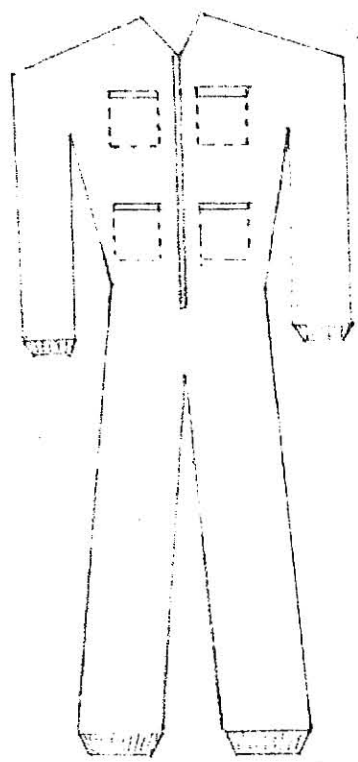


Figure 2. The New Personal Dry-Ice Cooling Garment (jumpsuit).

Method

Design of Garment

A jumpsuit with long sleeves was designed. There were four pockets in the front and four at the back. All the pockets had the openings at the outer shell of the garment, so the worker could load the dry ice without taking off the garment. Velcro fasteners were used for closing each opening of the pockets. Three kinds of material were used in making the jumpsuit. "Surfline" (50% polyster and 50% cotton) was used for sleeves and trousers. "Satinyl quilt" (three layers with the face layer of 100% nylon-batt, the middle layer of 100% polyster and the back layer of 100% nylon-durable water repellant finish) was used for the torso. "Ski Di" (50% kodel polyster and 50% cotton durable water repellant finish) was used for the inside layer of the torso. All the materials were purchased at Wal-Mart Discount Store in Manhattan, Kansas.

Two layers of insulation were used, namely, air bubble and rubber sheet (see Figure 3). All the eight pockets had the same insulation ($6.gcal/sec\text{-}^{o}C\text{-}cm^{2}x10^{-5}$) during the whole experiment.

Clothing

On experimental days without a cooling garment, each subject was clothed in tennis shoes and socks, boxer shorts, slacks and a long sleeved, cotton-twill shirt. The clothing clo

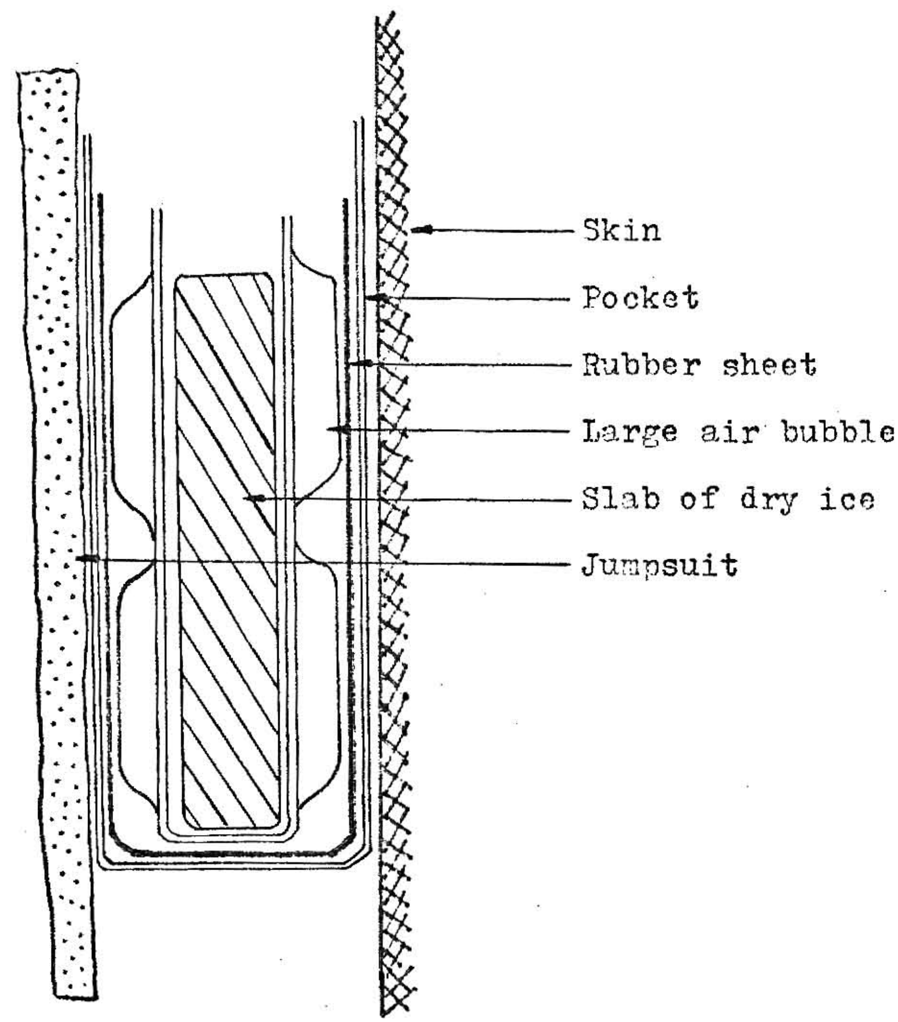


Figure 3. Insulation Inside the Dry Ice Pocket.

value was estimated to 0.49. On days when a cooling garment was worn, the same clothing was worn plus a dry ice cooling jumpsuit but without the long sleeved shirt and the slacks. The clothing value was estimated to be 0.68 clo.

Task

Each subject pedaled the Monark bicycle ergometer at a constant speed of 60 rpm at a 1 kp load for 60 minutes without stopping. The conditions (60 rpm, 1 kp and 60 min) used in this experiment were the same as Duncan's and Techapatanarat's experiments to facilitate comparison of the experimental results.

Subjects

Two males were subjects. Each was paid a total of $50 for the completion of six experimental sessions. The characteristics of the two subjects are shown in Table 1.

Before participating in any session of the experiment, the subjects took the physical fitness test from the Physical Education Department of Kansas State University.

Procedure

Each experiment session began when the ECG surface electrodes and the 11 skin temperature sensors were attached and held in position (see Figure 4) by applying 'Collodium'

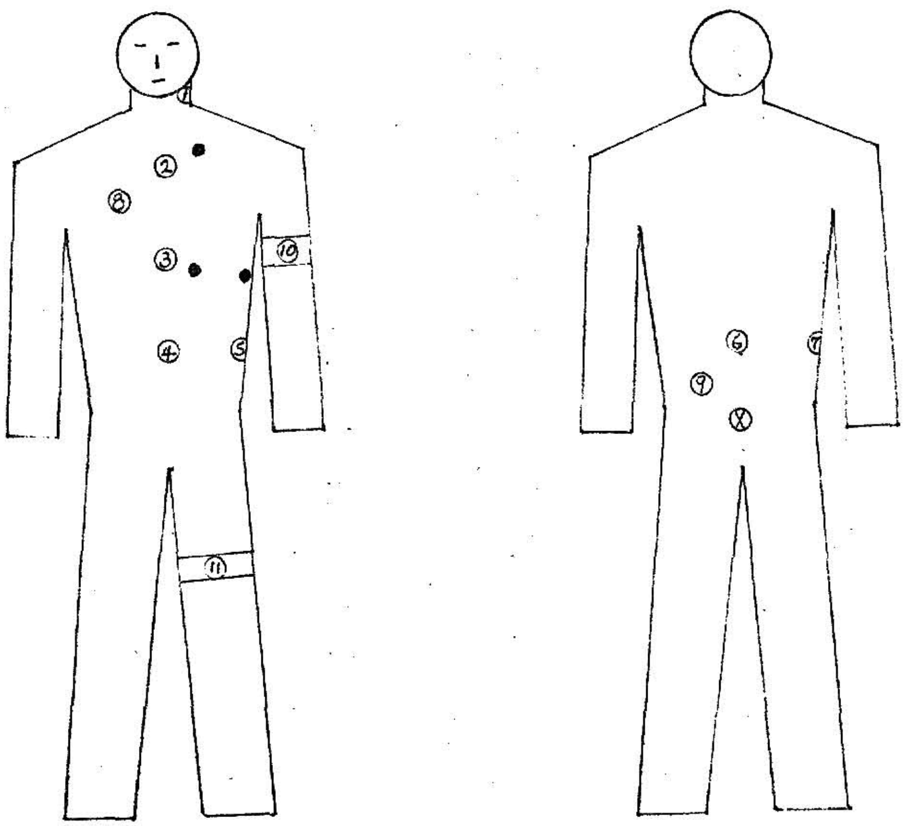
Table 1. The Characteristics of the Subjects.

	Subject YF	Subject RP
Age (years)	24	32
Weight (kg)	57.27	61.36
Height (cm)	167	172
Surface Area (m^2)	1.76	1.84
Skinfold Thickness (mm)		
1 Triceps	3	6
2 Pectoral	4	9
3 Abdominal	16	16
Percent of Body Fat	3.78	6.67
Blood Pressure (mm Hg)		
Systolic	132	118
Diastolic	88	70
Max VO_2 (ml/kg-min)	43	34

Surface Area = $.208 + .945((7.184 \times 10^{-3})(\text{Height in cm})^{.725}(\text{Weight in kg})^{.425})$, (Mitchell, 1971)

Percent Body Fat = $100\left(\frac{5.548}{\text{Specific Gravity}} - 5.044\right)$, (Consolazio, et al., 1963)

Specific Gravity = $1.1017 - 2.82 \times 10^{-4}(\text{Abdominal skinfold, mm}) - 7.36 \times 10^{-4}(\text{Pectoral skinfold, mm}) - 8.33 \times 10^{-4}(\text{Tricep skinfold, mm})$



• ECG electrodes
○ Skin temperature sensors
⊗ Rectal temperature probe

Figure 4. Sensor Locations.

(a chemical solution) around and over the 1" by 1" gauze which covered each electrode. Then they were covered with crossing strips of surgical tape and then 'Collodium' applied over the tape touching the skin. This application method insured a water tight seal around the electrodes and guaranteed a good recording throughout the period in which the skin was covered with sweat.

Then a YSI 401 rectal thermister probe was inserted 13 cm. When the subject was ready to perform the experiment with the jumpsuit (model E), slabs of dry ice (10 cm wide, 10 cm long and 2.5 cm thick) were weighed and placed into the eight pockets.

Then the subject entered the conditioned chamber and started to pedal the bicycle. Oxygen consumption was measured every 10 minutes for 120 seconds.

After pedalling for 60 minutes, the subject stopped and sat in the chamber for 15 minutes with all the sensors on until his heart rate became less than 100 bpm. Heart rate and skin temperature were recorded during the recovery period. Then the subject walked out of the chamber, and the slabs of dry ice were weighed immediately.

Experimental Design

There were 6 sessions in the experiment. The sequences of the 6 sessions of the experiment for subject number one were: (1) wearing shirt and slacks, (2) wearing the jumpsuit with no dry ice, (3) wearing the jumpsuit with dry ice, open cuff, (4) wearing the jumpsuit with dry ice, closed cuff, (5) wearing the jumpsuit with no dry ice, and (6) wearing shirt and slacks. The sequences for subject number two were same as subject number one except changing the order of (3) and (4). For all the 6 sessions in the experiment, the environment was controlled at 35°C dry bulb, 31.6°C wet bulb, 70% relative humidity and 0.3 m/sec air velocity.

Instrumentation

The apparatus and materials used in this experiment consisted of:

(1) The dry ice cooling jumpsuit

(2) dry ice

(3) Hansen spring scale (model 1440)

(4) Monark bicycle ergometer

(5) Collins 9 liter respirometer

(6) Sherer-Gillett (model CER 812) environmental chamber

(7) YSI 709 rectal thermister probe

(8) Beckman recorder

(9) ECG surface electrodes

(10) YSI 409 thermisters

(11) Digital thermometer

(12) 691 Digital printer

(13) 24 hour digital clock

(14) alcohol

(15) Collodium

(16) surgical tape

(17) 1" x 1" gauze

The dry ice cooling jumpsuit was designed by the experimenter. There were eight pockets in the upper part of the suit, four in the front and four at the back. All the openings of the pockets were at the outer shell; Velcro fasteners were used for closing.

Dry ice, cut into slabs, was inserted into each of the pockets. The reason of using slab dry ice was because it was easy to handle and it was very convenient to put the ice into the pockets.

A Hansen spring scale (model 1440) was used for measuring the weight of each slab of dry ice before and after the experiment for the calculation of the sublimation rate.

The Monark bicycle ergometer had a speedmeter and a load meter. In this experiment, all the subjects pedalled at 1 kp load at a constant speed of 60 rpm for 60 minutes.

A Collins 9 liter respirometer was used for measuring the oxygen consumption rate for 120 seconds in every 10 minute interval.

A Sherer-Gillett (model CER 812) environment chamber was used as a closed chamber in carrying out the whole experiment.

A YSI 709 rectal thermister probe was used to measure the rectal temperature.

A Beckman recorder with ECG surface electrodes was used in measuring the heart rate throughout the experiment at a five minute interval. Three ECG surface electrodes were pasted and taped to the left side of the chest, near the heart. The leads of these electrodes were connected to a Cardiotachometer (model 9857). The output appeared as a series of peaks on a continuous roll of graduated paper, moving at a speed of 5 mm/sec.

YSI 409 thermisters were used for measuring skin temperature.

Digital thermometer, 691 digital printer and 24 hour digital clock were built in one piece, and all the temperatures were printed automatically in every 5 minute interval.

Alcohol was used for cleaning those parts of skin where the sensors were attached.

Collodium insured a water-tight seal around the electrodes and guaranteed a good recording throughout the periods in which the skin might be covered with sweat.

Surgical tape and 1" x 1" gauze were used to help keep the sensors in position.

Measurements

As mentioned in the introduction and problem, the objectives of this experiment were to measure the heart rate, the rectal temperature, the skin temperature, and the sublimation rate of dry ice, and then compare the results against previous data and the computer simulation.

Heart rate was recorded every five minutes for approximately 20 seconds, starting with the first reading at time zero (0^+).

All the temperatures were also measured at five minute intervals, with the first reading at time zero (0^+).

Oxygen consumption rate was measured at every 10 minutes for 120 seconds.

Sublimation rate of the dry ice was measured by subtracting the final weight from the initial weight and dividing by the interval time in minutes between the two weighings.

Results

The results were analysed using the Wilcoxon Matched-Pair Signed-Rank Test (Siegel, 1956) and a computer analysis of variance program to search for significance among the main effects.

Heart Rate

The mean heart rate of 120 beats/minute with the cooling jumpsuit was significantly ($p < .01$) lower than the 131 beats/minute for the no-cooling condition. Thus, wearing the cooling jumpsuit reduce the heart rate 11 beats/minute. The mean heart rate at 60 minutes for the no-cooling condition was 143 beats/minutes and for the cooling condition it was 126 beats/minute, a difference of 17 beats/minute; showing that the difference was increasing with exposure time. Figure 5 shows the mean heart rate and the range of the heart rate for the cooling and no-cooling conditions.

Oxygen consumption rate

The mean oxygen consumption rate was 24.1 ml/kg-min when the subjects wore the cooling jumpsuit and was 23.8 ml/kg-min for the no-cooling condition; there was no significant difference. Table 2 shows the mean oxygen consumption rate of the two subjects.

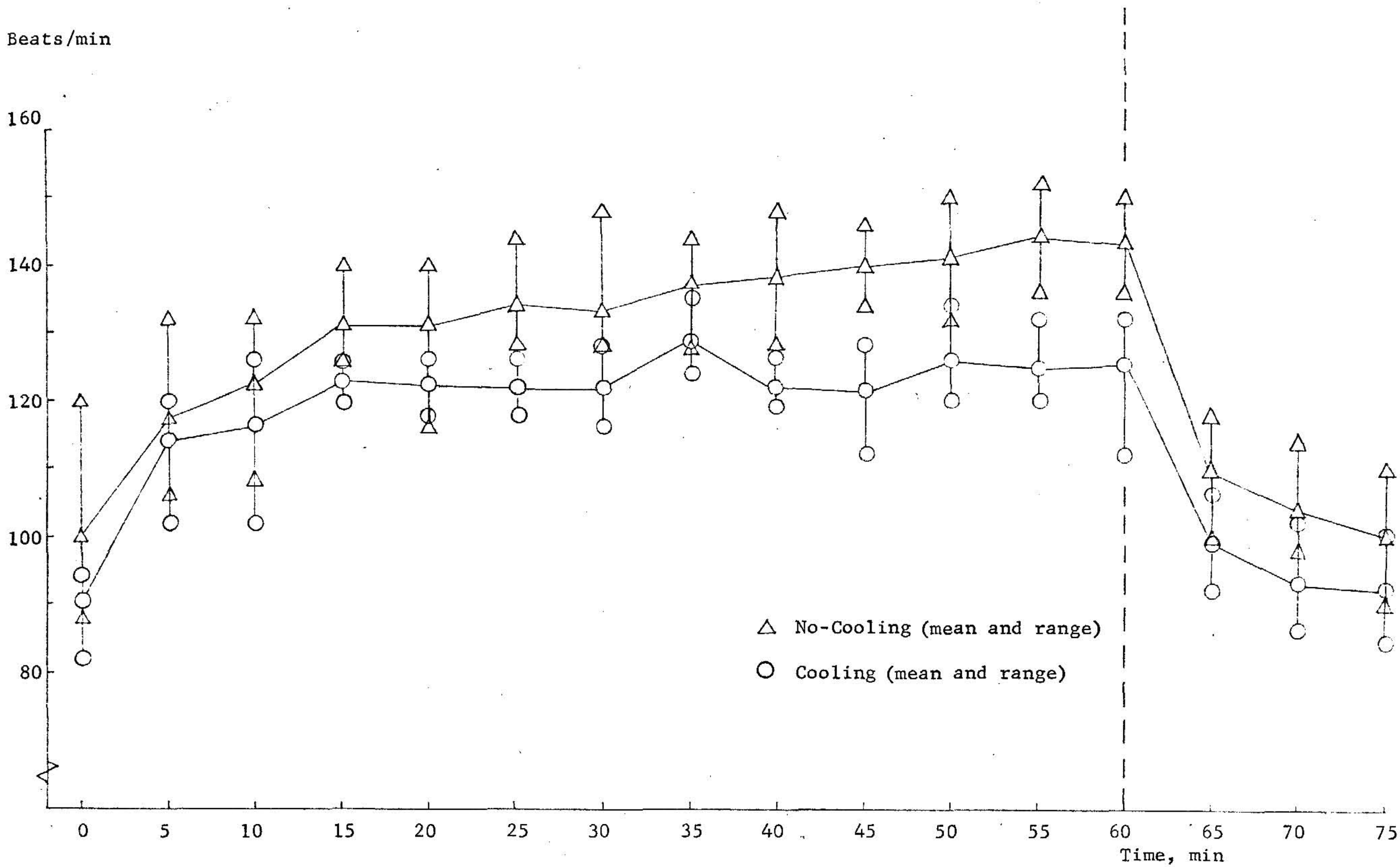


Figure 5. Mean Heart Rate vs Time.

Table 2. Mean Oxygen Consumption Rate.

Subjects	Y.F.	R.P.	Mean
Body Weights (kg)	57.27	61.36	
Mean Oxygen Consumption Rate (liters/min)			
No-Cooling	1.366	1.462	
Cooling	1.338	1.523	
Mean Oxygen Consumption Rate (ml/kg-min)			
No-Cooling	23.852	23.827	23.840
Cooling	23.363	24.813	24.088

Rectal temperature

The mean rectal temperature at 60 minutes was 37.4°C when subjects wore the cooling jumpsuit and was 37.9°C for the no-cooling condition. The overall mean rectal temperature for the 60 minutes exposure was 37.3°C when subjects wore the cooling jumpsuit, which was significantly ($p < .01$) less than the 37.5°C for the no-cooling condition (see Figure 6).

Skin temperature

Skin temperature was measured at 11 locations on the body: 1 on the neck, 8 on the torso, 1 on the left upper arm, and 1 on the leg at the thigh (Figure 4).

The weighted mean skin temperature when no-cooling jumpsuit was worn was:

mean skin temperature (°C) = .07(neck temperature)
+ .049(each of the 8 temperature on the torso)
+ .18(arm temperature) + .36(leg temperature)

The weighted mean skin temperature when cooling jumpsuit was worn was:

mean skin temperature (°C) = .07(neck temperature)
+ .022(left-front-top chest temperature + left-back-bottom temperature)
+ .058(each of the remaining 6 torso temperature)
+ .18(arm temperature) + .36(leg temperature)

The coefficients used for the mean skin temperature were

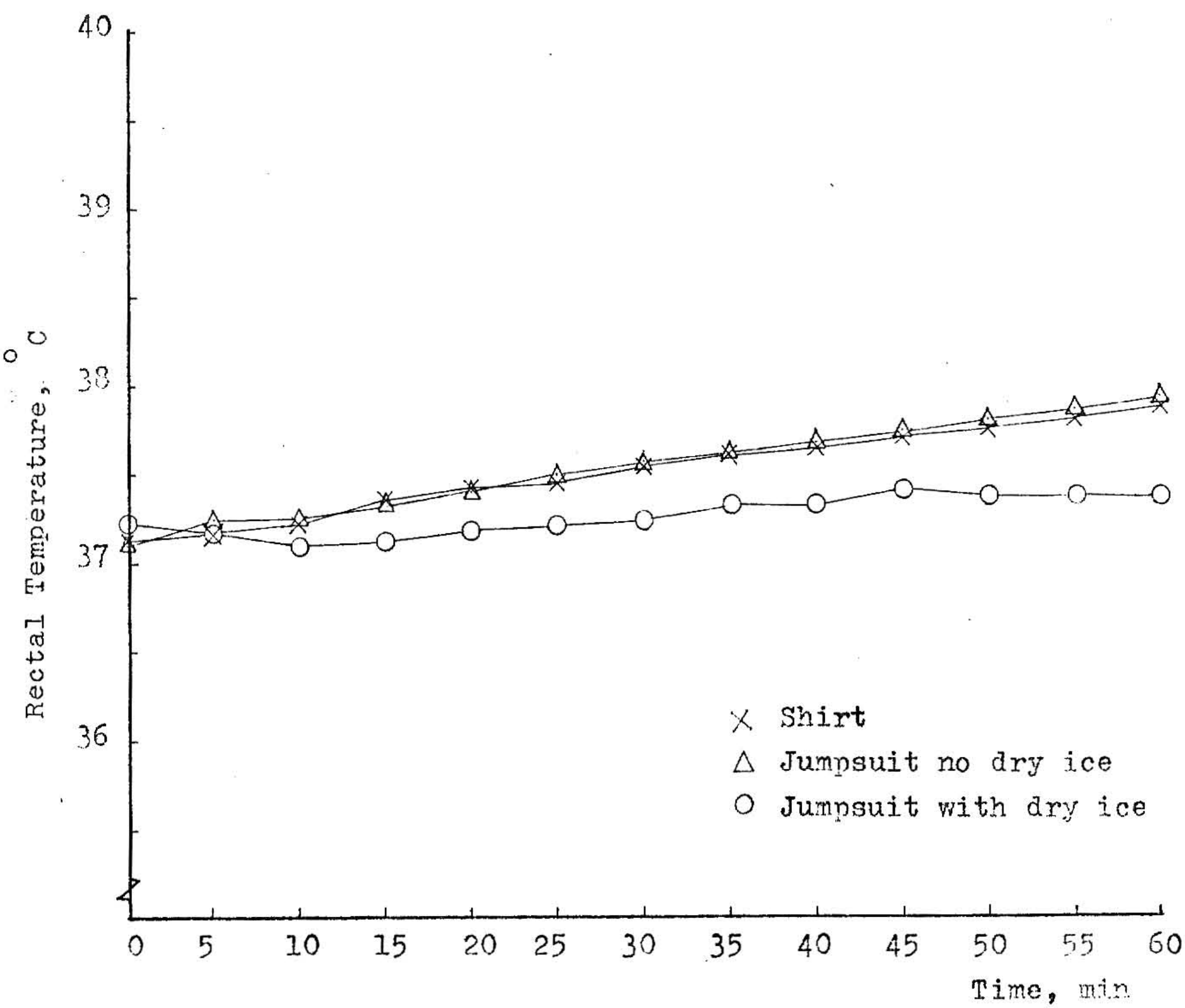


Figure 6. Mean Rectal Temperature vs Time

based on a weighting factor of 7% for the head, 39% for the torso, 18% for the two arms, and 36% for the 2 legs. Therefore for the no cooling condition, all 8 torso temperatures were weighted equally, that is .39/8 = .049.

For the 800 cm^2 cooling area condition, the 8 torso temperatures were weighted by considering the ratio of cooled area and non-cooled area. The area directly under the 8 dry ice cooling pockets was .08 m^2. The total torso area was approximated by the mean total body surface area (1.76+1.84) $m^2/2$ = 1.8 m^2. So the torso area was estimated to be 1.8 m^2 x .39 = .702 m^2. The proportional area under dry ice pockets was .08/.702 = .114. The proportional area under no dry ice pockets was .886. Therefore the 2 temperature locations under the dry ice pockets were each given a weight of .114(.39)/2 = .022. The 6 temperature locations not under the dry ice were each given a weight of .886(.39)/6 = .058.

Figure 7, 8, 9, 10, 11, 12, 13, 14, 15, 16 and 17 show the mean skin temperature vs time for each location when the subjects wore shirt and slacks, jumpsuit with no dry ice, and jumpsuit with dry ice. Table 3 shows the mean skin temperatures during the 60 minutes exposure for each location, each subject, and each experiment. The arm and leg temperature were affected by the closing and opening of the cuffs of the cooling jumpsuit. By closing the cuffs, the arms had better cooling, while opening the cuffs gave the legs better cooling.

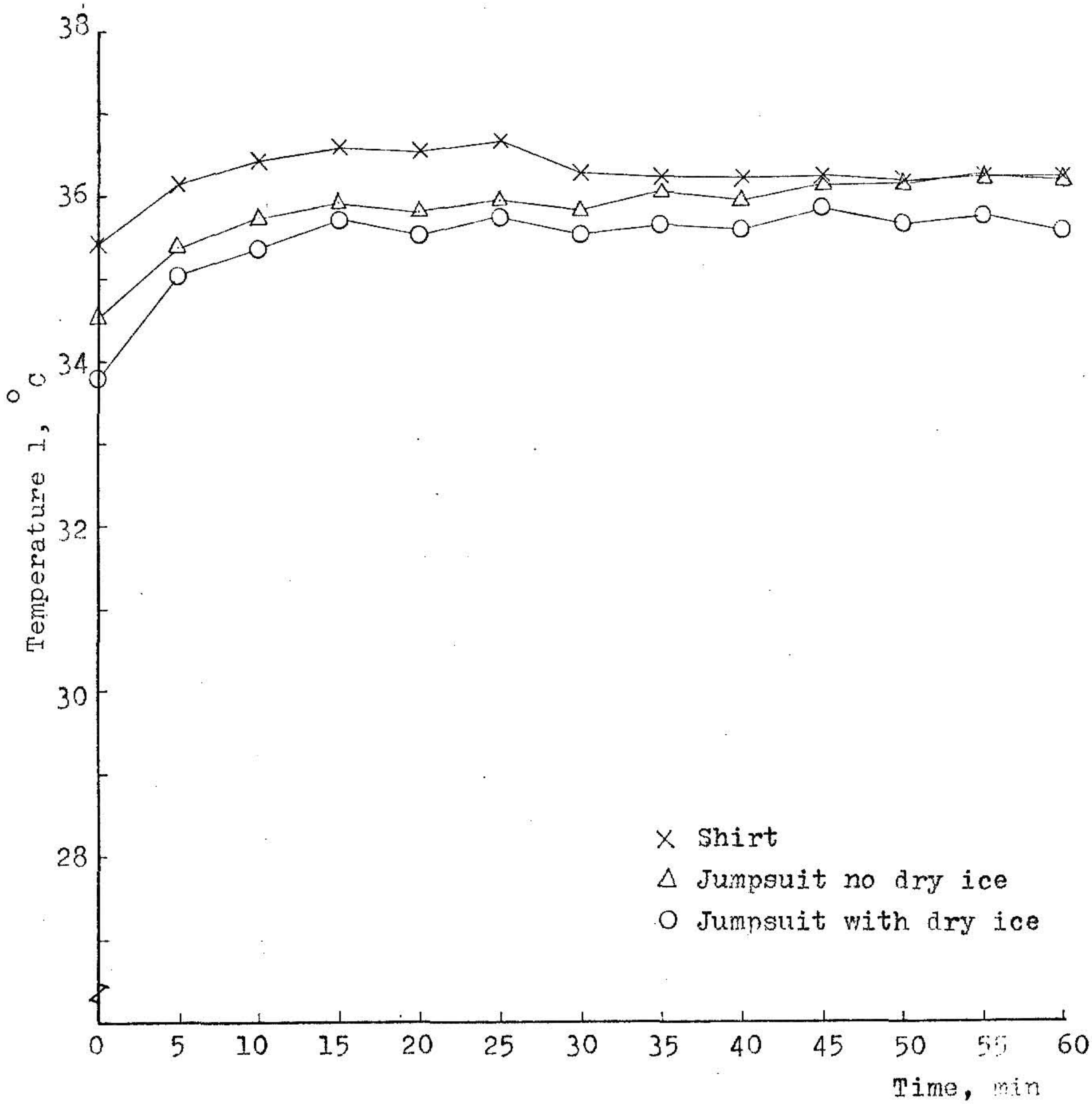


Figure 7. Mean Temperature 1 vs Time.

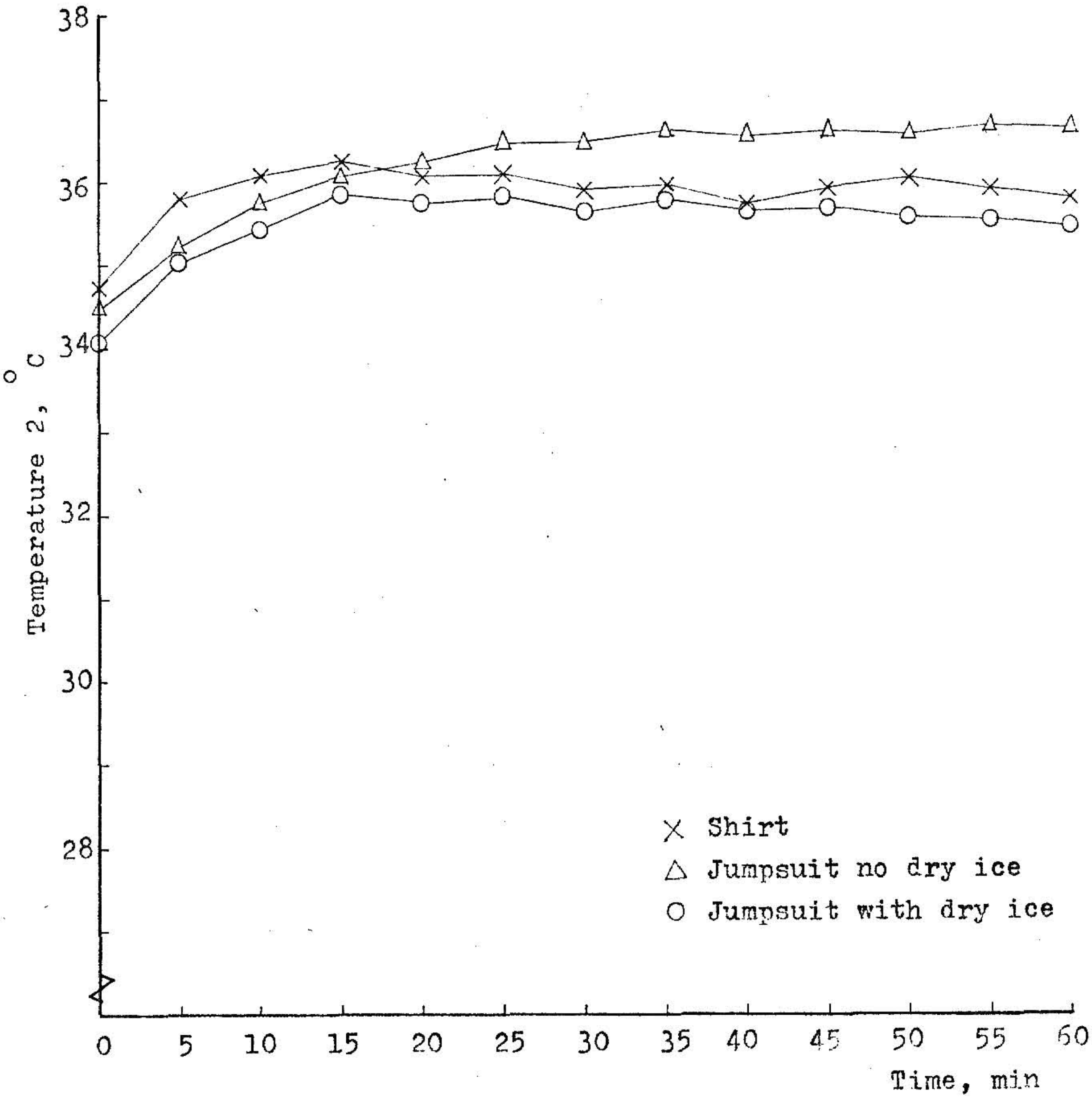


Figure 8. Mean Temperature 2 vs Time.

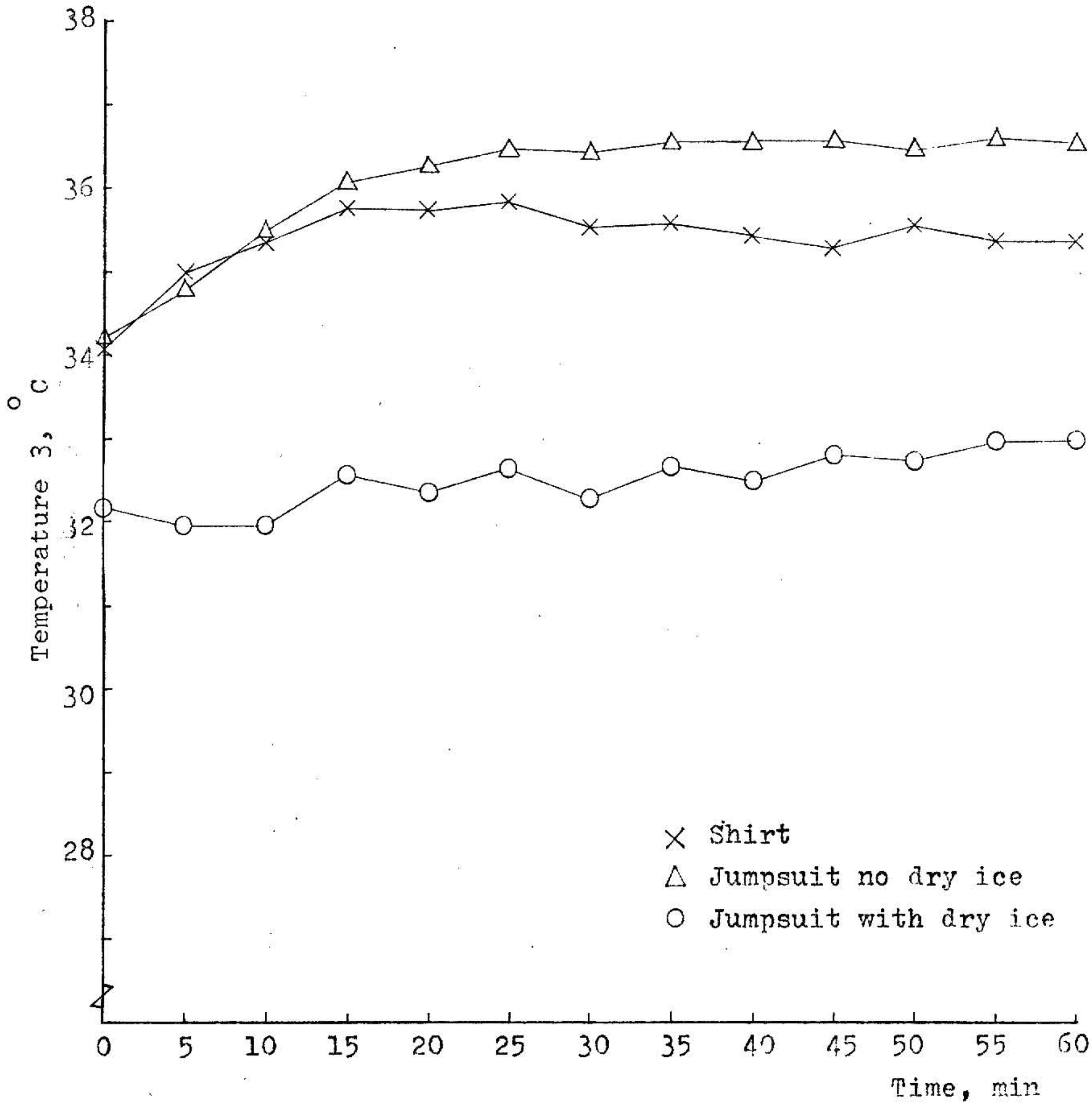


Figure 9. Mean Temperature 3 vs Time.

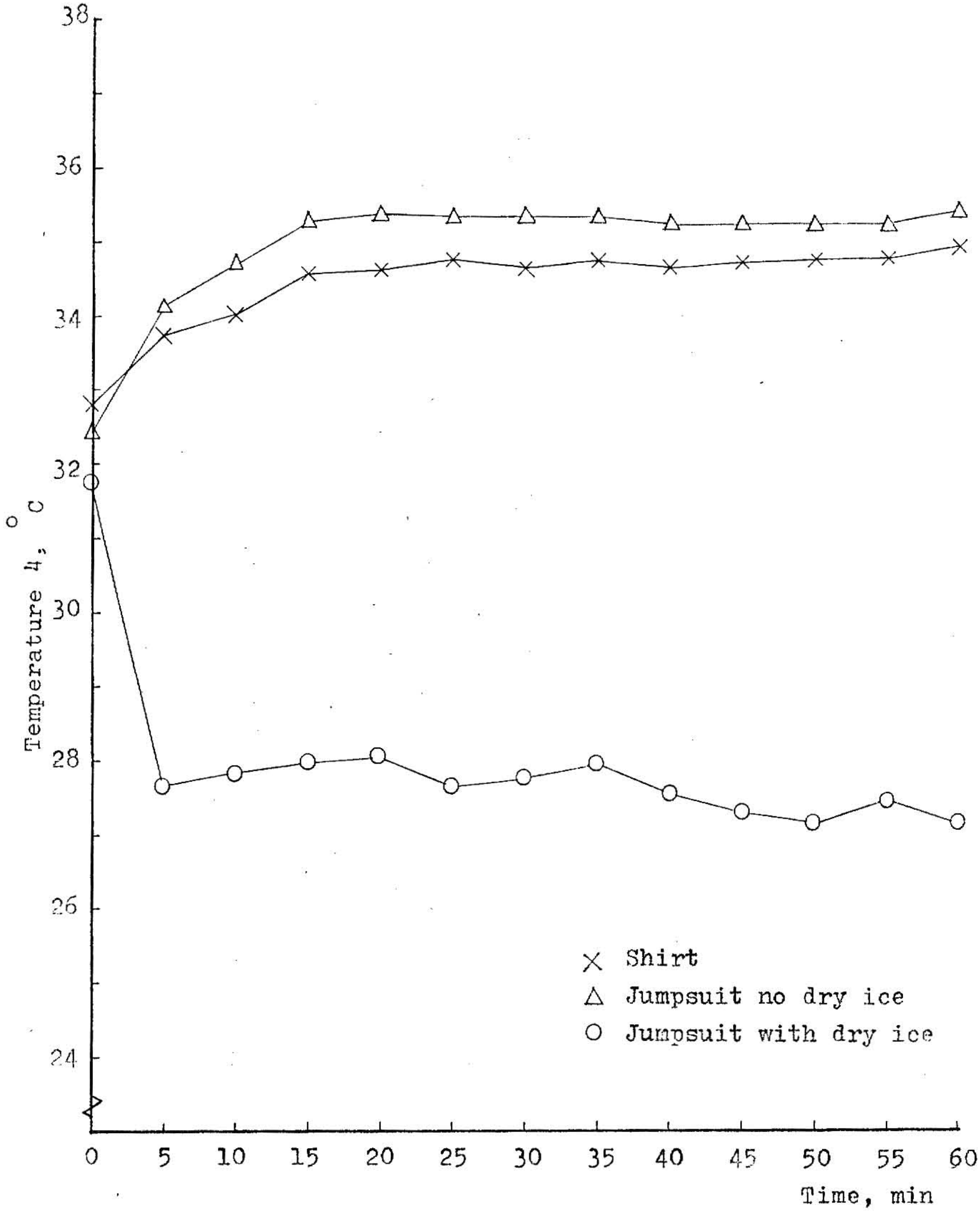


Figure 10. Mean Temperature 4 vs Time.

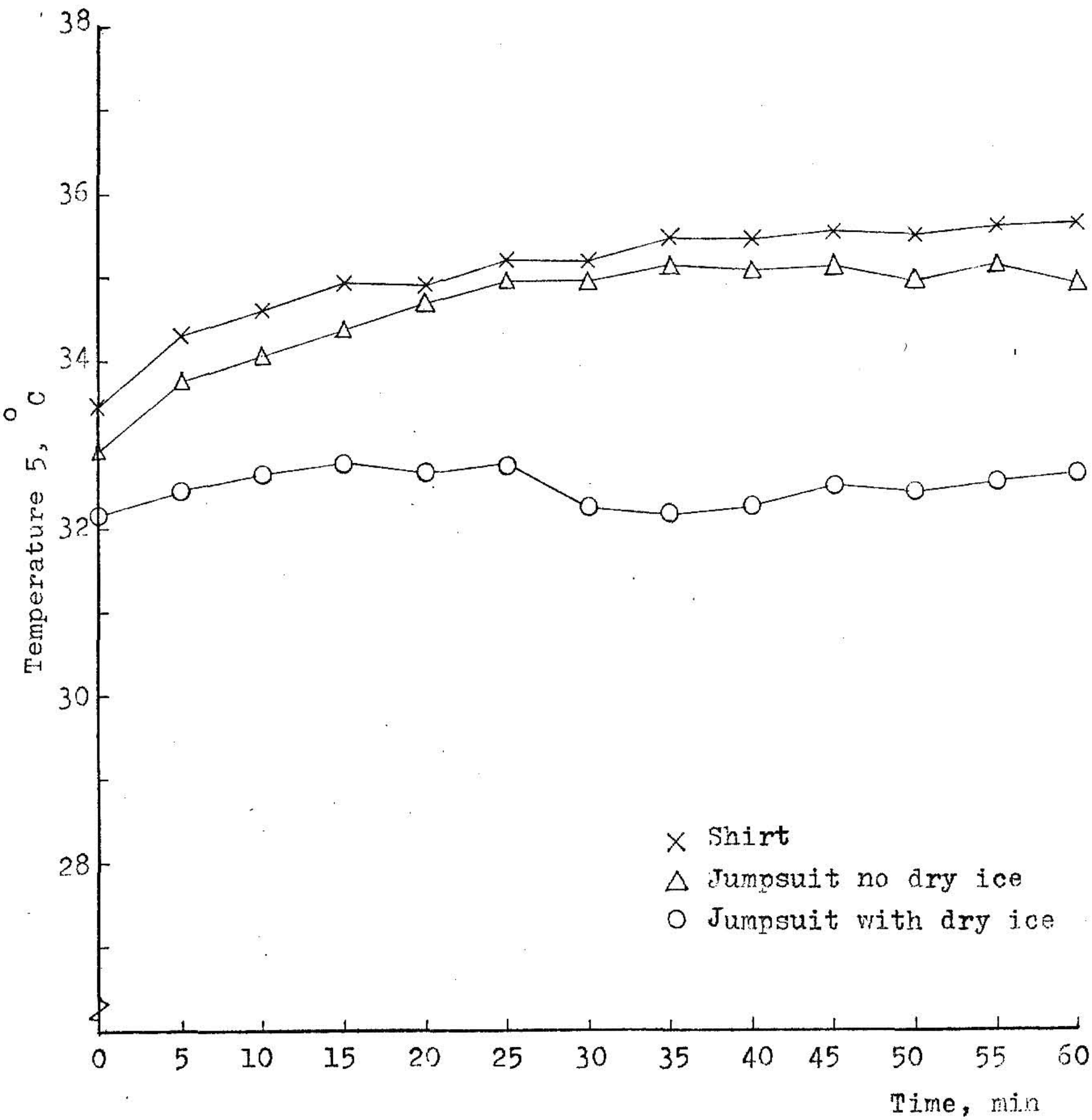


Figure 11. Mean Temperature 5 vs Time.

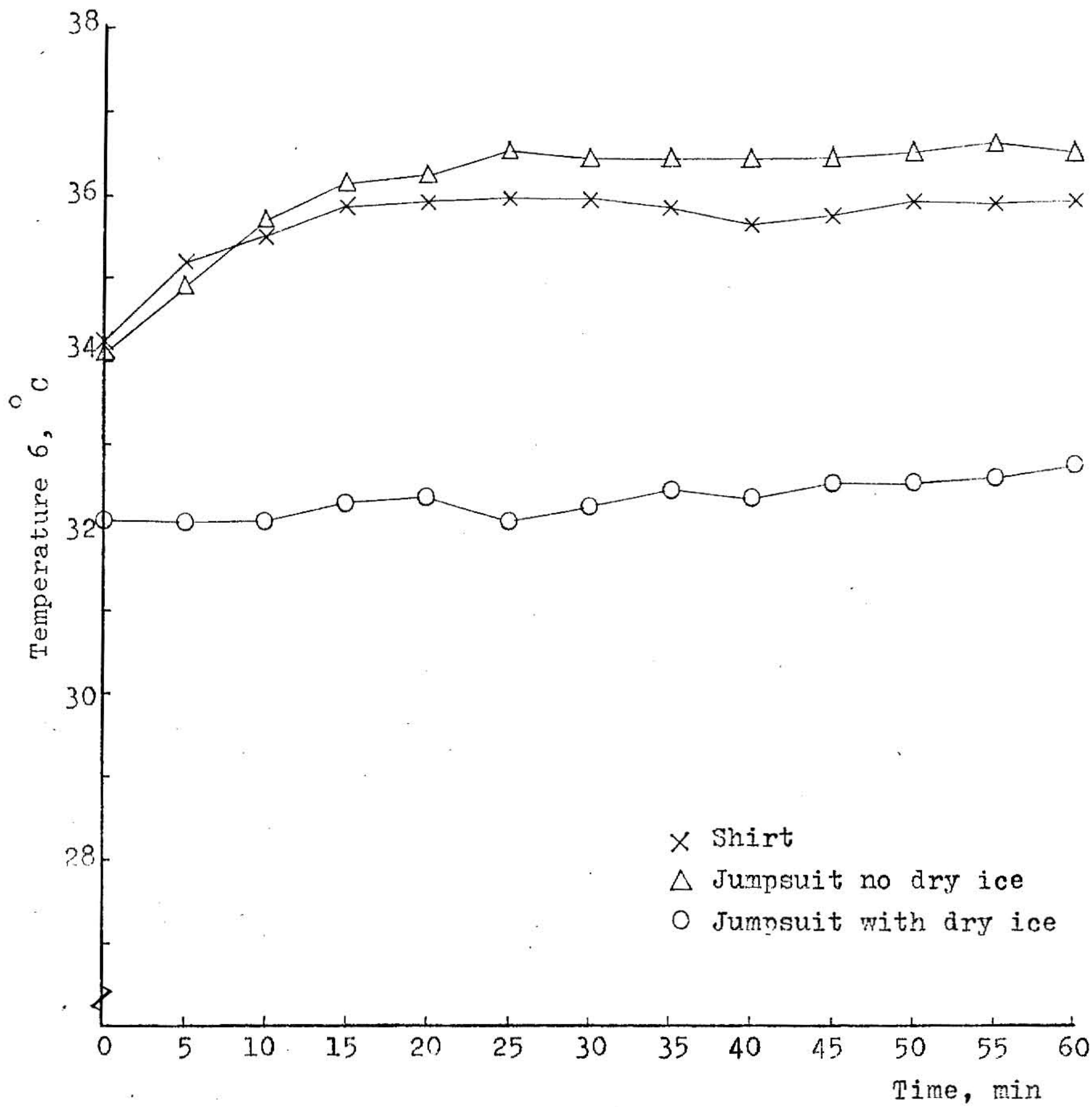


Figure 12. Mean Temperature 6 vs Time.

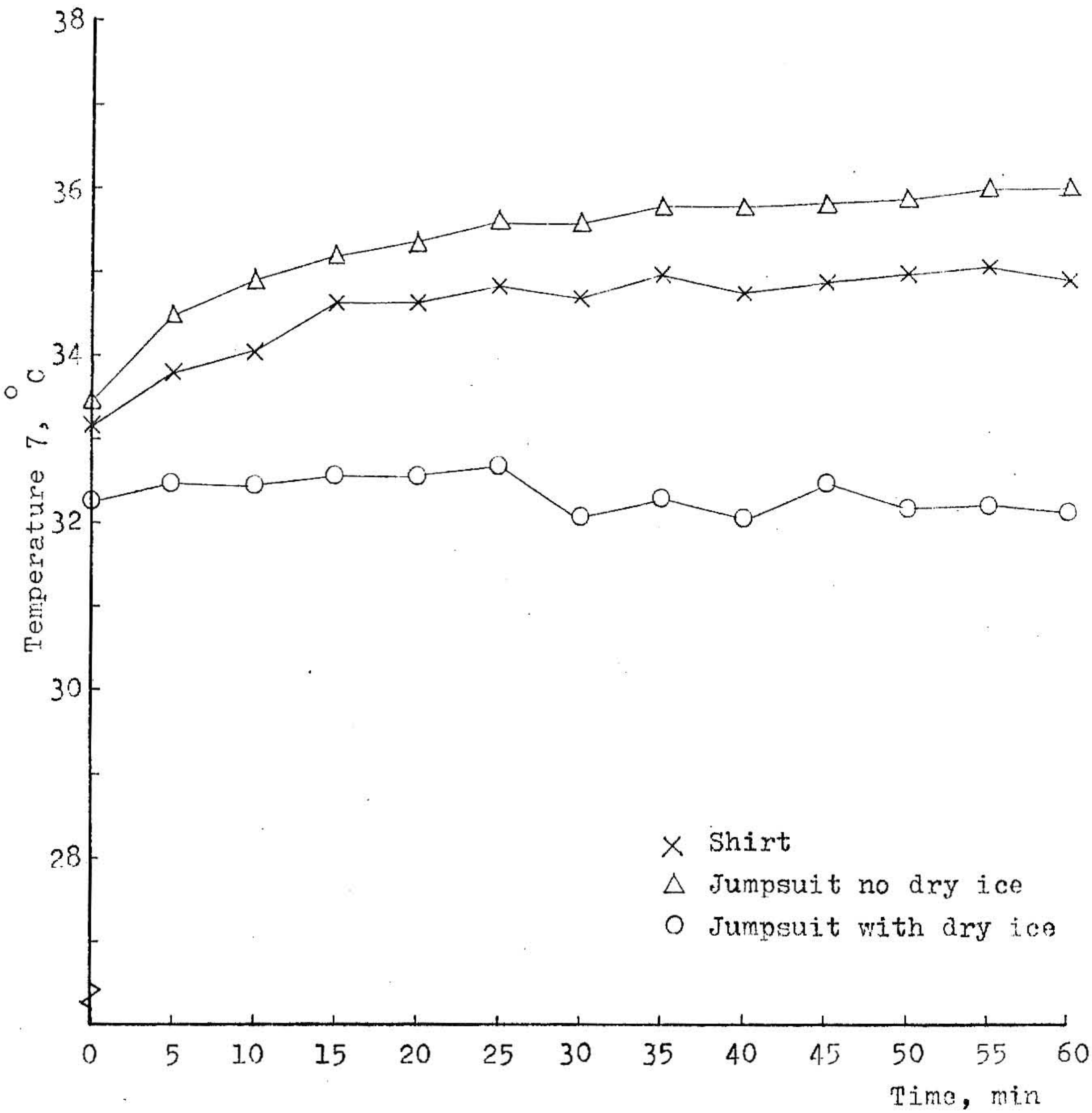


Figure 13. Mean Temperature 7 vs Time.

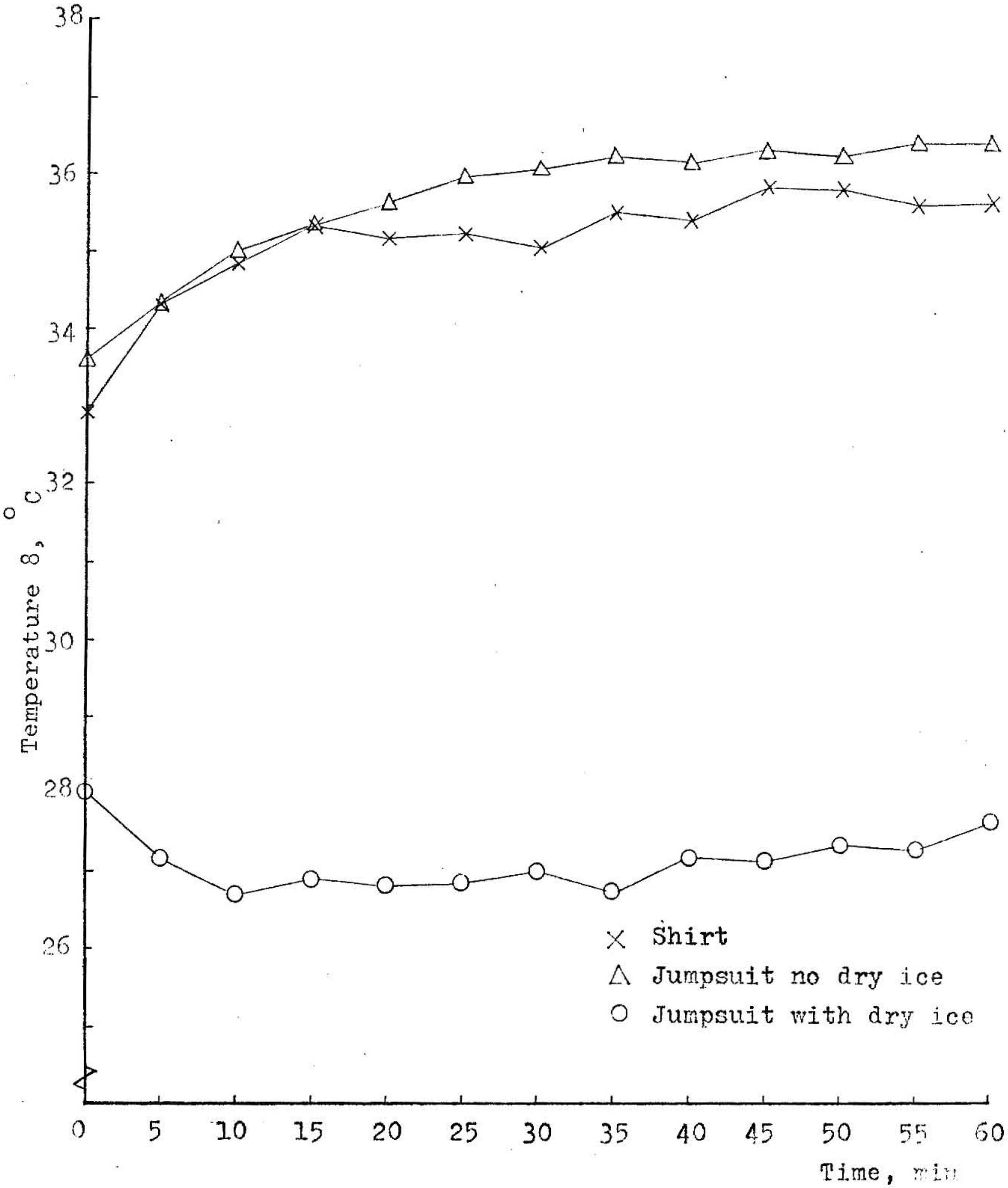


Figure 14. Mean Temperature 8 vs Time.

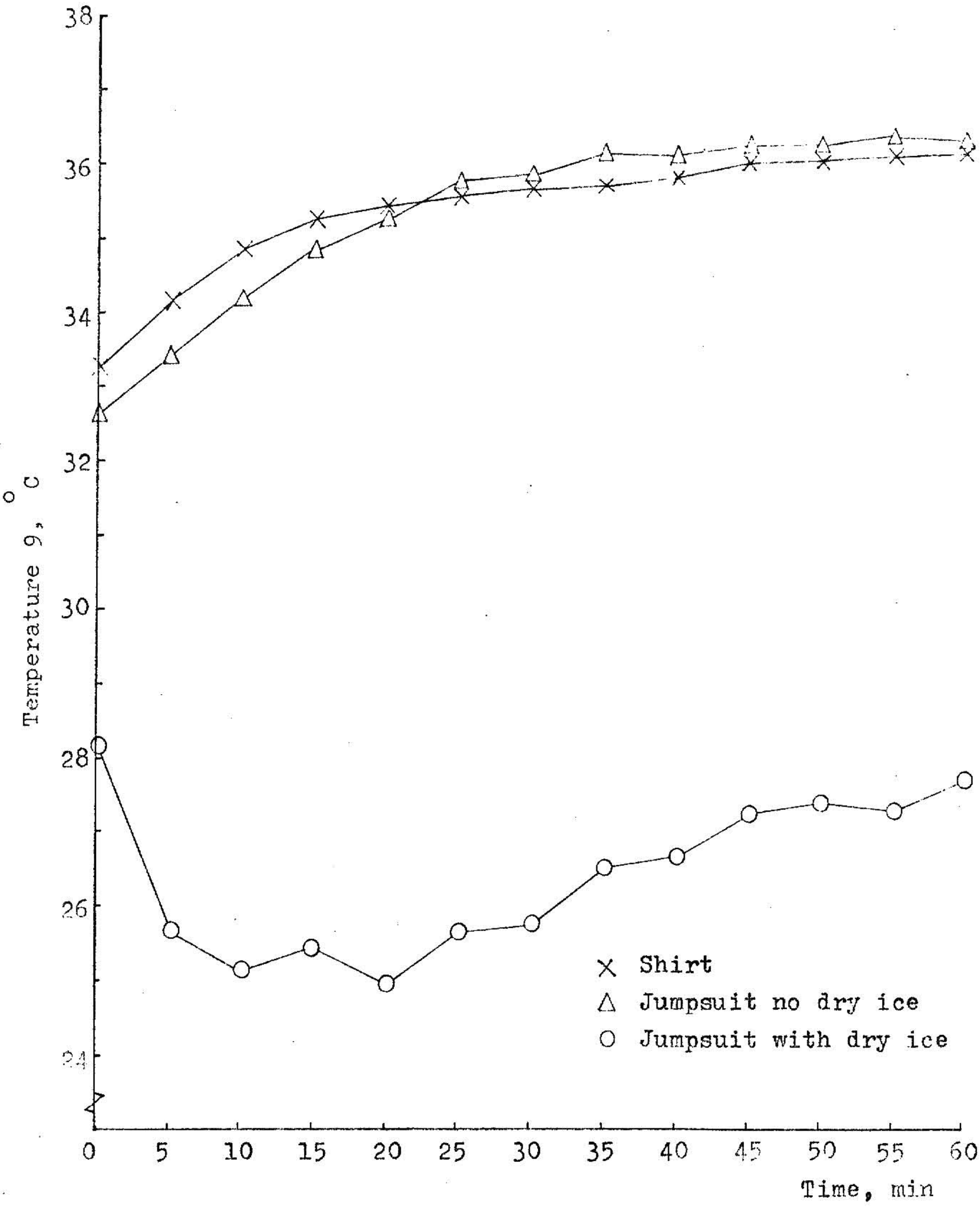


Figure 15. Mean Temperature 9 vs Time.

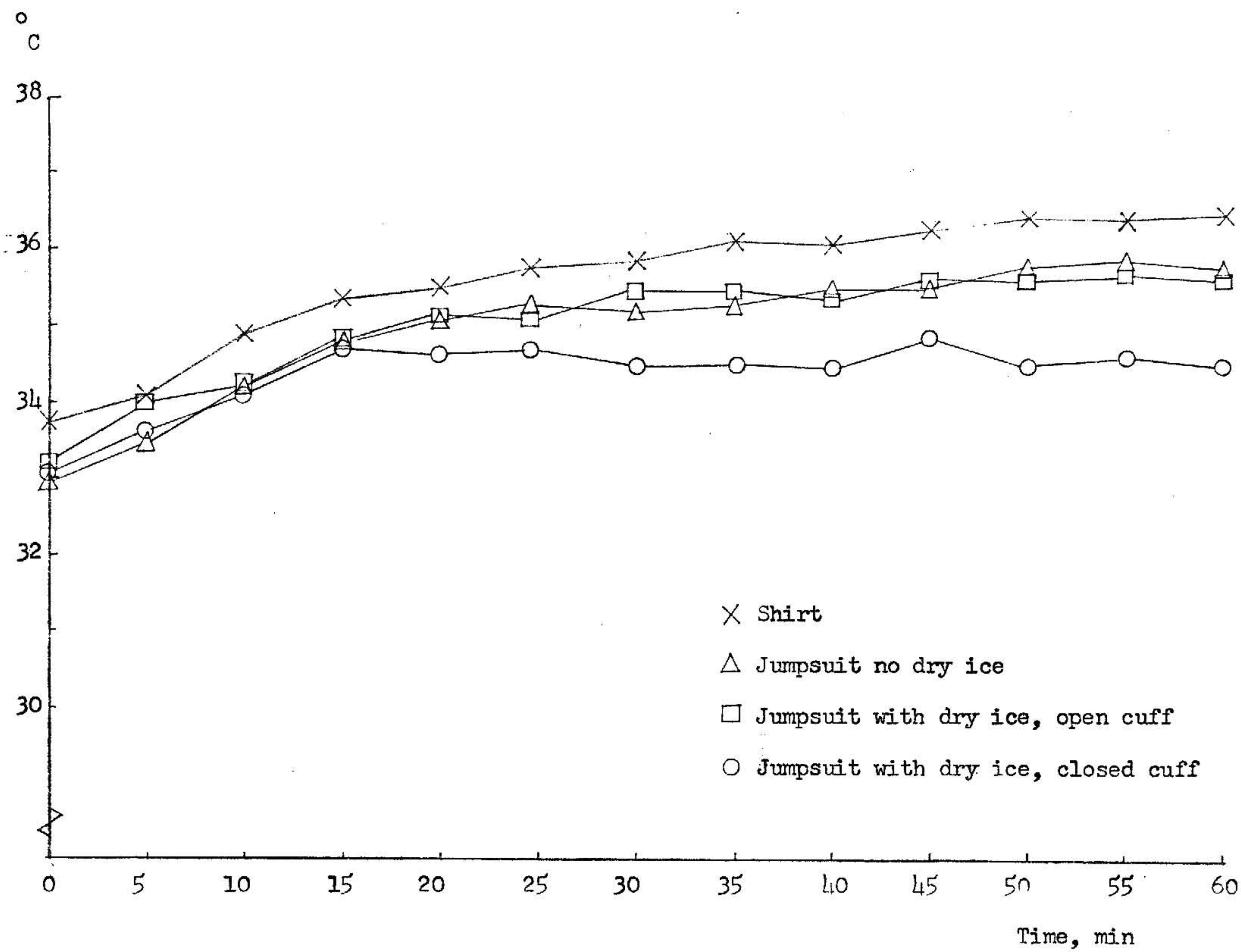


Figure 16. Mean Arm Temperature vs Time.

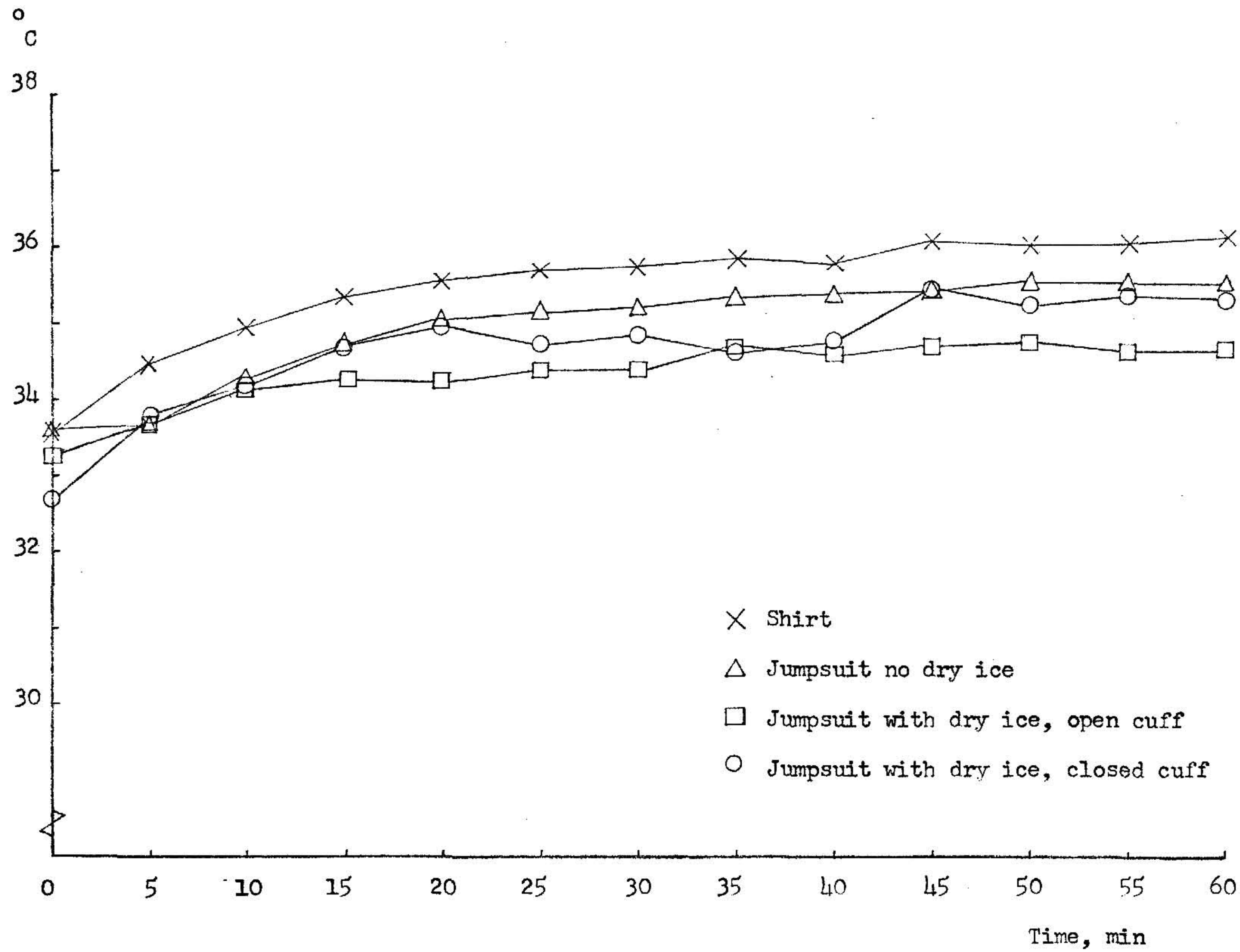


Figure 17. Mean Leg Temperature vs Time.

Table 3. Mean Skin Temperature During the 60 Minutes Exposure for Each Location, Each Subject, and Each Experiment.

Location	Subject	Experiment	Mean (°C)	Overall Mean (°C)	Overall Mean of Two Subjects (°C)
1	Y.F.	1	36.40		
	Y.F.	6	36.48	36.44	
	R.P.	1	36.14		
	R.P.	6	35.98	36.06	36.25
	Y.F.	2	36.37		
	Y.F.	5	35.80	36.09	
	R.P.	2	35.68		
	R.P.	5	35.51	35.60	35.85
	Y.F.	3	35.68		
	Y.F.	4	35.82	35.75	
	R.P.	3	35.54		
	R.P.	4	34.79	35.17	35.46
2	Y.F.	1	35.70		
	Y.F.	6	35.80	35.75	
	R.P.	1	35.92		
	R.P.	6	36.08	36.00	35.88
	Y.F.	2	35.75		
	Y.F.	5	36.24	36.00	
	R.P.	2	36.30		
	R.P.	5	36.45	36.38	36.19
	Y.F.	3	34.93		
	Y.F.	4	35.77	35.35	
	R.P.	3	35.49		
	R.P.	4	35.77	35.63	35.49
3	Y.F.	1	35.65		
	Y.F.	6	35.22	35.44	
	R.P.	1	34.79		
	R.P.	6	35.84	35.32	35.38
	Y.F.	2	35.18		
	Y.F.	5	36.40	35.79	
	R.P.	2	36.54		
	R.P.	5	36.15	36.35	36.07
	Y.F.	3	32.01		
	Y.F.	4	33.17	32.59	
	R.P.	3	31.91		
	R.P.	4	32.87	32.39	32.49

Location	Subject	Experiment	Mean (°C)	Overall Mean (°C)	Overall Mean of Two Subjects (°C)
4	Y.F.	1	34.29		
	Y.F.	6	34.28	34.29	
	R.P.	1	34.01		
	R.P.	6	35.17	34.59	34.44
	Y.F.	2	34.52		
	Y.F.	5	35.57	35.05	
	R.P.	2	34.58		
	R.P.	5	35.14	34.86	34.96
	Y.F.	3	25.63		
	Y.F.	4	29.90	27.77	
	R.P.	3	26.85		
	R.P.	4	29.38	28.12	27.95
5	Y.F.	1	35.02		
	Y.F.	6	35.08	35.05	
	R.P.	1	35.26		
	R.P.	6	34.94	35.10	35.08
	Y.F.	2	33.89		
	Y.F.	5	35.24	34.57	
	R.P.	2	34.97		
	R.P.	5	34.38	34.68	34.63
	Y.F.	3	33.06		
	Y.F.	4	30.54	31.80	
	R.P.	3	32.87		
	R.P.	4	33.43	33.15	32.48
6	Y.F.	1	35.60		
	Y.F.	6	35.19	35.40	
	R.P.	1	35.56		
	R.P.	6	36.35	35.96	35.68
	Y.F.	2	35.58		
	Y.F.	5	35.72	35.65	
	R.P.	2	36.65		
	R.P.	5	36.38	36.52	36.09
	Y.F.	3	31.70		
	Y.F.	4	33.66	32.68	
	R.P.	3	31.88		
	R.P.	4	32.12	32.00	32.34

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Location	Subject	Experiment	Mean (°C)	Overall Mean (°C)	Overall Mean of Two Subjects (°C
7	Y.F.	1	34.26		
	Y.F.	6	34.51	34.39	
	R.P.	1	34.20		
	R.P.	6	35.27	34.74	34.57
	Y.F.	2	34.88		
	Y.F.	5	35.56	35.22	
	R.P.	2	35.82		
	R.P.	5	35.19	35.51	35.37
	Y.F.	3	33.64		
	Y.F.	4	32.97	33.31	
	R.P.	3	33.02		
	R.P.	4	29.70	31.36	32.34
8	Y.F.	1	34.87		
	Y.F.	6	34.62	34.75	
	R.P.	1	35.50		
	R.P.	6	35.65	35.58	35.17
	Y.F.	2	34.79		
	Y.F.	5	35.90	35.35	
	R.P.	2	36.19		
	R.P.	5	35.87	36.03	35.69
	Y.F.	3	29.78		
	Y.F.	4	33.31	31.55	
	R.P.	3	21.26		
	R.P.	4	24.26	22.76	27.16
9	Y.F.	1	35.63		
	Y.F.	6	35.01	35.32	
	R.P.	1	35.51		
	R.P.	6	35.43	35.47	35.40
	Y.F.	2	34.46		
	Y.F.	5	34.95	34.71	
	R.P.	2	36.26		
	R.P.	5	35.72	35.99	35.35
	Y.F.	3	26.22		
	Y.F.	4	27.86	27.04	
	R.P.	3	24.11		
	R.P.	4	27.45	25.78	26.41

Location	Subject	Experiment	Mean (°C)	Overall Mean (°C)	Overall Mean of Two Subjects (°C
10	Y.F.	1	35.35		
	Y.F.	6	35.66	35.51	
	R.P.	1	35.79		
	R.P.	6	35.71	35.75	35.63
	Y.F.	2	35.16		
	Y.F.	5	34.97	35.07	
	R.P.	2	34.83		
	R.P.	5	34.84	34.84	34.96
	Y.F.	3	33.81		
	Y.F.	4	34.84	34.33	
	R.P.	3	35.06		
	R.P.	4	34.86	34.96	34.65
11	Y.F.	1	35.21		
	Y.F.	6	36.05	35.63	
	R.P.	1	35.45		
	R.P.	6	35.24	35.35	35.49
	Y.F.	2	35.00		
	Y.F.	5	34.81	34.91	
	R.P.	2	35.08		
	R.P.	5	35.11	35.10	35.01
	Y.F.	3	35.19		
	Y.F.	4	34.74	34.97	
	R.P.	3	33.99		
	R.P.	4	34.27	34.13	34.55

Figure 18 shows the overall weighted mean skin temperature vs time for cooling and no cooling conditions. Table 4 shows the differences in weighted mean skin temperature for cooling and no cooling conditions at every 5 minute interval.

Sublimation rate of dry ice

The sublimation rate (gm/min) of each slab of dry ice was determined by subtracting the final weight from the initial weight and dividing by the time interval in minutes between the two weighings.

An analysis of variance was used to analyse the main effects, the two subjects, the two kinds of jumpsuit (open cuff and closed cuff), and the eight pocket locations. Table 5 shows the results of the analysis of variance. A Duncan's New Multiple Range Test with .05 type 1 error was used to find the significant differences between the means of the three effects. The 1.267 gm/min sublimation rate of dry ice for subject R.P. was significantly ($p < .05$) greater than the 1.172 gm/min for subject Y.F. This was because the subjects have different body weights and different body shapes. R.P. was 61.36 kg and Y.F. was 57.27 kg, so R.P. had a closer fit to the jumpsuit, hence the sublimation rate was higher.

The sublimation rate of the 8 separate pockets are shown in Table 6; non-significant groupings are connected by a column of asterisks. The dry ice in the left-back-top pocket and the right-back-top pocket have the highest sublimation rate. This

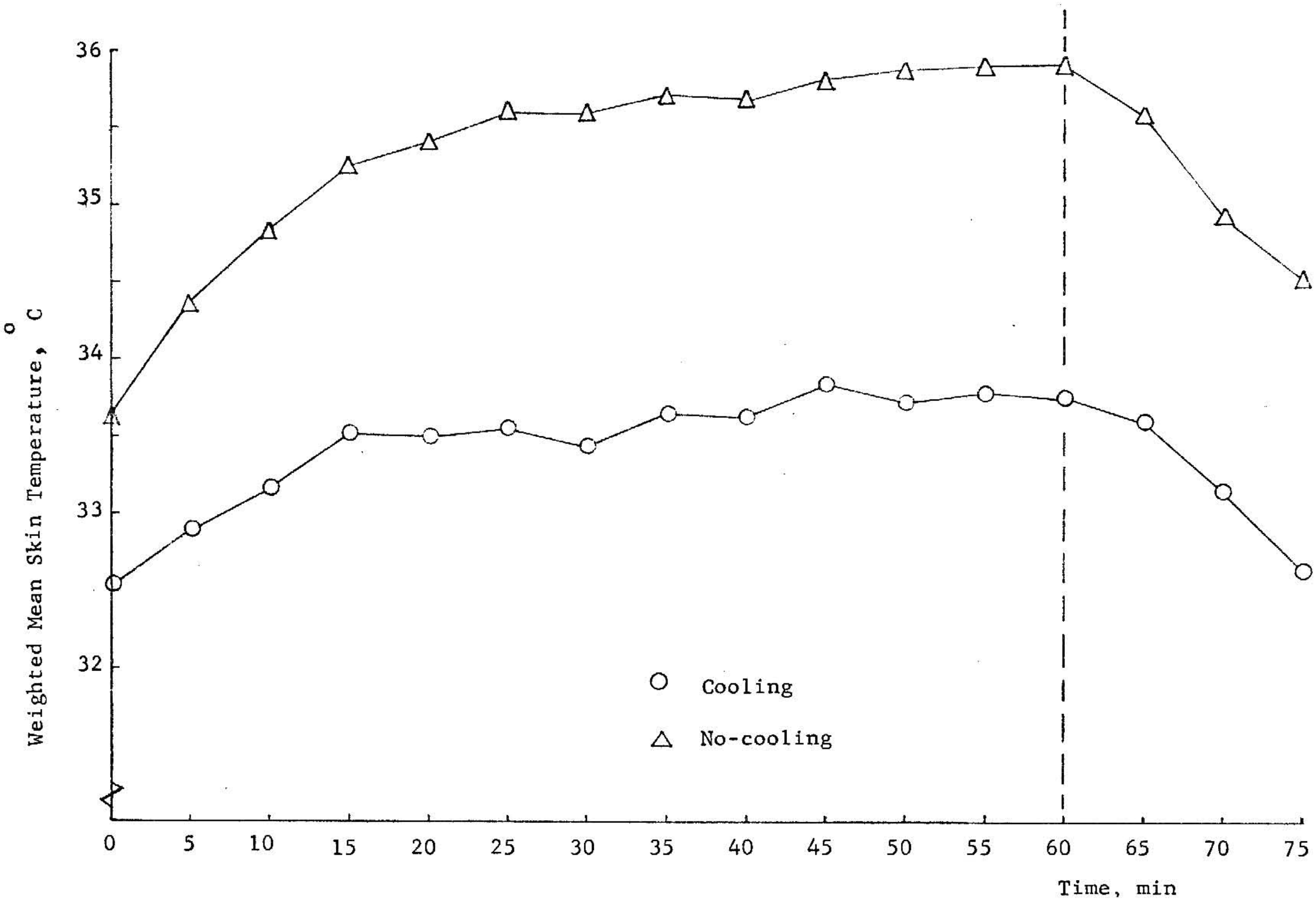

Figure 18. Mean Skin Temperature vs Time.

Table 4. The Differences in Weighted Mean Skin Temperature for No Cooling and Cooling Conditions at Every 5 Minutes Interval.

Time (min)	No Cooling (°C)	Cooling (°C)	Difference (°C)
0	33.61	32.65	0.96
5	34.36	32.89	1.47
10	34.83	33.16	1.67
15	35.25	33.51	1.74
20	35.42	33.50	1.92
25	35.60	33.55	2.05
30	35.59	33.44	2.15
35	35.71	33.65	2.06
40	35.69	33.62	2.07
45	35.82	33.83	1.99
50	35.89	33.71	2.18
55	35.92	33.78	2.14
60	35.93	33.75	2.18

Table 5. Analysis of Variance of Dry Ice Sublimation Rate.

Source of Variation	Degree of Freedom	Mean Square	F
Subjects (S)	1	0.072	79.11 *
Jumpsuits (J)	1	0.002	2.45
Pockets (P)	7	0.030	33.33 *
S x J	1	0.000	0.02
S x P	7	0.001	0.65
J x P	7	0.001	0.76
Error	7	0.001	
Total	31		

* $p < .05$

Table 6. Mean Dry Ice Sublimation Rate (gm/min) for the Eight Pockets.

Pocket Location	Dry Ice Sublimation Rate (gm/min)
Left-Back-Top	1.369 *
Right-Back-Top	1.350 *
Left-Front-Bottom	1.188 *
Right-Back-Bottom	1.184 *
Left-Front-Top	1.178 *
Right-Front-Bottom	1.175 *
Right-Front-Top	1.168 *
Left-Front-Bottom	1.147 *

was due to the posture; when the subjects are pedalling the bicycle, these two pockets have better contact with the skin.

The thermal conductance value of the insulation was measured by putting a slab of dry ice inside the insulation and measuring the heat flow with a heat flow meter, and the temperature at the external surface of the insulation.

The thermal conductance was calculated from:

$$U = \frac{Q}{t}$$

U = thermal conductance, gcal/sec-^{o}C-cm^{2}x10^{-5}

Q = heat flow, gcal/sec-^{o}C-cm^{2}x10^{-3}

t = external surface temperature - sublimation temperature of dry ice (-78.5^{o}C)

Since the measurements were taken inside the chamber, therefore the external surface temperature was 35^{o}C.

The thermal conductance values were:

Jumpsuit with dry ice, being worn by subject
= 6.35 gcal/sec-^{o}C-cm^{2}x10^{-5}

Jumpsuit with dry ice, not being worn by subject
= 4.76 gcal/sec-^{o}C-cm^{2}x10^{-5}

Table 7 shows the thermal conductances for different insulations.

Table 7. The Thermal Conductance for Different Insulations. (gcal/sec-^{o}C-cm^{2}x10^{-5})

Insulations	Model B2	Model D	Model E
small air bubble	17.10	-	-
large air bubble	5.35	11.57	-
large air bubble + rubber sheet	-	7.36	6.35
large air bubble + rubber sheet + plastic sheet	-	5.02	-

Discussion

There were 8 separate dry ice pockets on the jumpsuit. The sublimation rate of the left-back-top and the right-back-top pockets were significantly higher (Table 6) than the other 6 pockets. The mean sublimation rate for these two pockets was 1.4 gm/min. Considering the sublimation rate of 1.4 gm/min as 100%, then the sublimation rate of the other 6 pockets ranged from 87.4% to 84.4%, having an average of 86%.

To predict the sublimation rate of each pocket, the following formula was modified from Duncan's and Techapatanarat's experiment:

$$S = K_1K_2K_3K_4K_5K_6K_7(31.4 + .132(IW))$$

S = sublimation rate/slab, grams/hour

IW = initial weight of the slab, grams, $150 < IW < 400$

K_1 = thickness factor

= 1.00 for 16 mm thick slab

= 0.93 for 22 mm thick slab

= 1.39 for 5 mm thick slab

K_2 = pocket location factor

= 1.00 for top pocket compartment

= 0.69 for middle and lower comaprtment

K_3 = jacket vs vest factor

= 1.00 for jacket

= 1.04 for vest

K_4 = dry bulb environment temperature

= 1.00 for 35°C

= 1.07 for 45°C

K_5 = water vapor pressure in environment

= 1.00 for 33 mm Hg

= 1.04 for 16 mm Hg

K_6 = environment time factor

= 1.085 for time from 0 to 60 minutes

= 1.00 for time from 0 to 120 minutes

= 0.83 for time from 0 to 240 minutes

K_7 = insulation factor

= 0.94 for low insulation (11 Kcal/sec-°C-cm^{2}x10^{-2})

= 0.87 for medium insulation (7 Kcal/sec-°C-cm^{2}x10^{-2})

= 0.83 for high insulation (5 Kcal/sec-°C-cm^{2}x10^{-2})

Techapataranat modified the pockets of the cooling jacket by moving the two vertical pockets at the back into a horizontal position. Therefore, the formula predicting the sublimation rate of the slabs in the vertical pocket was modified to predict the sublimation rate of the slabs in the horizontal pocket as follows:

K_2 = pocket location factor

= 1.00 for vertical top slab and right horizontal compartment

= 0.89 for horizontal left slab

= 0.81 for horizontal middle slab

= 0.69 for vertical middle and lower slab

The average error of prediction was 7.2%.

For this new designed cooling jumpsuit, the pockets location were different from the previous developed cooling jackets and vest. In addition, the jumpsuit was different from jacket and vest. Therefore, K_2 (pocket location factor) and K_3 (jacket vs vest factor) were modified as follows:

K_2 = pocket location factor

= 1.10 for the left-back-top and right-back-top pockets

= 0.95 for all the other 6 pockets

K_3 = vest vs jumpsuit vs jacket

= 1.04 for vest

= 1.01 for jumpsuit

= 1.00 for jacket

Table 8 shows the differences between the experimental and predicted sublimation rate of the 8 pockets.

Table 9 shows the comparison for Model B2 (cooling jacket with 2 vertical pockets in the front and 2 at the back), Model D (cooling jacket with 2 vertical pockets in the front and 2 horizontal pockets at the back), and Model E (cooling jumpsuit with 8 separate pockets, 4 in the front and 4 at the back). For Model B2 and Model D, 12 slabs of dry ice were used, each pocket held 3 slabs separated by a nylon net. For Model E (jumpsuit), each pocket held 1 slab of dry ice, a total of 8 separate pockets holding 8 slabs of dry ice.

Table 8. The Differences Between the Experimental and Predicted Sublimation Rate of the 8 Pockets.

Pocket Location	Experimental Sublimation Rate (gm/min)	Predicted Sublimation Rate (gm/min)	Difference (gm/min)	Error (%)
Left-Back-Top	1.369	1.355	0.014	1.023
Right-Back-Top	1.350	1.341	0.009	0.667
Left-Front-Bottom	1.188	1.155	0.033	2.778
Right-Back-Bottom	1.184	1.207	-0.023	-1.943
Left-Front-Top	1.178	1.152	0.026	2.207
Right-Front-Bottom	1.175	1.184	-0.009	-0.766
Right-Front-Top	1.168	1.138	0.030	2.569
Left-Back-Bottom	1.147	1.171	-0.024	-2.092
Total	9.759	9.703	0.056	4.443
Mean	1.220	1.213	0.007	0.555

Table 9. The Comparison of Model B2, Model D and Model E.

	Model B2	Model D	Model E
Heart Rate Reduction (beats/min)	18	10	11
Rectal Temperature Reduction (°C)	0.49	0.17	0.27
Skin Temperature Reduction (°C)	2.59	-	1.89
Mean Sublimation Rate (gm/min/slab)	0.86	0.91	1.22
Mean Sublimation Rate (gm/garment)	10.32	10.92	9.96
Increase Oxygen Consumption Rate (%)	24	27	1

The sublimation rate of Model E was 3% lower than Model B2 and was 9% lower than Model D. This was because there were only 8 slabs of dry ice in the jumpsuit while the other two models had 12. A decrease of 4 slabs of dry ice was about 33% less dry ice loaded initially, so a decrease of 3-9% in sublimation rate seems to be reasonable. Moreover, the jumpsuit gave a more even overall cooling than Model B2 and Model D, because carbon dioxide was 1.5 times heavier than air, therefore the cool gas would come down by gravitational force and hence cooling the two legs as well. Since it gave a better gas flow inside the jumpsuit, therefore the sublimation rate was lower.

Oxygen consumption rate with the cooling jacket was 24% higher than without it for Model B2, and was 27% higher for Model D. But, for the new jumpsuit, the oxygen consumption rate was only 1% higher, which had no significant difference as compared to the no cooling condition. Duncan's explaination for the increase in oxygen consumption when subject wore the cooling jacket, was due to non-shivering thermogenesis. So the jumpsuit was more desirable than the previous models, because it would not overcool the subject. The mean rectal temperature with the cooling jacket Model B2 was 0.49°C less, and the mean skin temperature was 2.59°C less, while the cooling jumpsuit Model E were 0.27°C and 1.74°C less respectively (Table 8).

A computer program, under development in the Industrial Engineering Department of Kansas State University, simulates a mathematical model of the thermoregulatory system. A comparison of physiological responses between the mathematical model and the experimental data was made for each individual subject under both no cooling and cooling conditions. The input data for each subject are shown in Table 10..

The comparison between the experimental and the simulated heart rate are shown in Figure 19 and 20 for the no cooling condition, and Figure 21 and 22 for the cooling condition. The mean deviation for the two subjects for the no cooling and cooling conditions were 10 beats/min and 0 beat/min respectively.

The comparison between the experimental and the simulated rectal temperature are shown in Figure 23 and 24 for the no cooling condition, and Figure 25 and 26 for the cooling condition. The mean deviation of the two subjects for the no cooling and cooling conditions were $0^{o}C$ and $-0.2^{o}C$ respectively.

The comparison between the experimental and the simulated skin temperature are shown in Figure 27 and 28 for the no cooling condition, and Figure 29 and 30 for the cooling condition. The mean deviation of the two subjects for the no cooling and cooling conditions were $0^{o}C$ and $-1.9^{o}C$ respectively. Under the cooling condition, the predicted result was higher than the experimental data; this was because the model over estimated the torso and leg temperatures.

Table 10. The Input Data for Each Subject.

Subject	1	2
Sex	Male	Male
Age (years)	24	32
Weight (kg)	57.3	61.6
Height (cm)	167.6	172.7
Physical fitness	2	3
Total metabolism (Watts)	400.00	420.00
Relative humidity (%)	70.0	70.0
Dry bulb temperature (^{o}C)	35.0	35.0
Air velocity (m/sec)	0.3	0.3
Job	Pedaling	Pedaling
Sublimation rate (gm/hr)	70.32	76.02

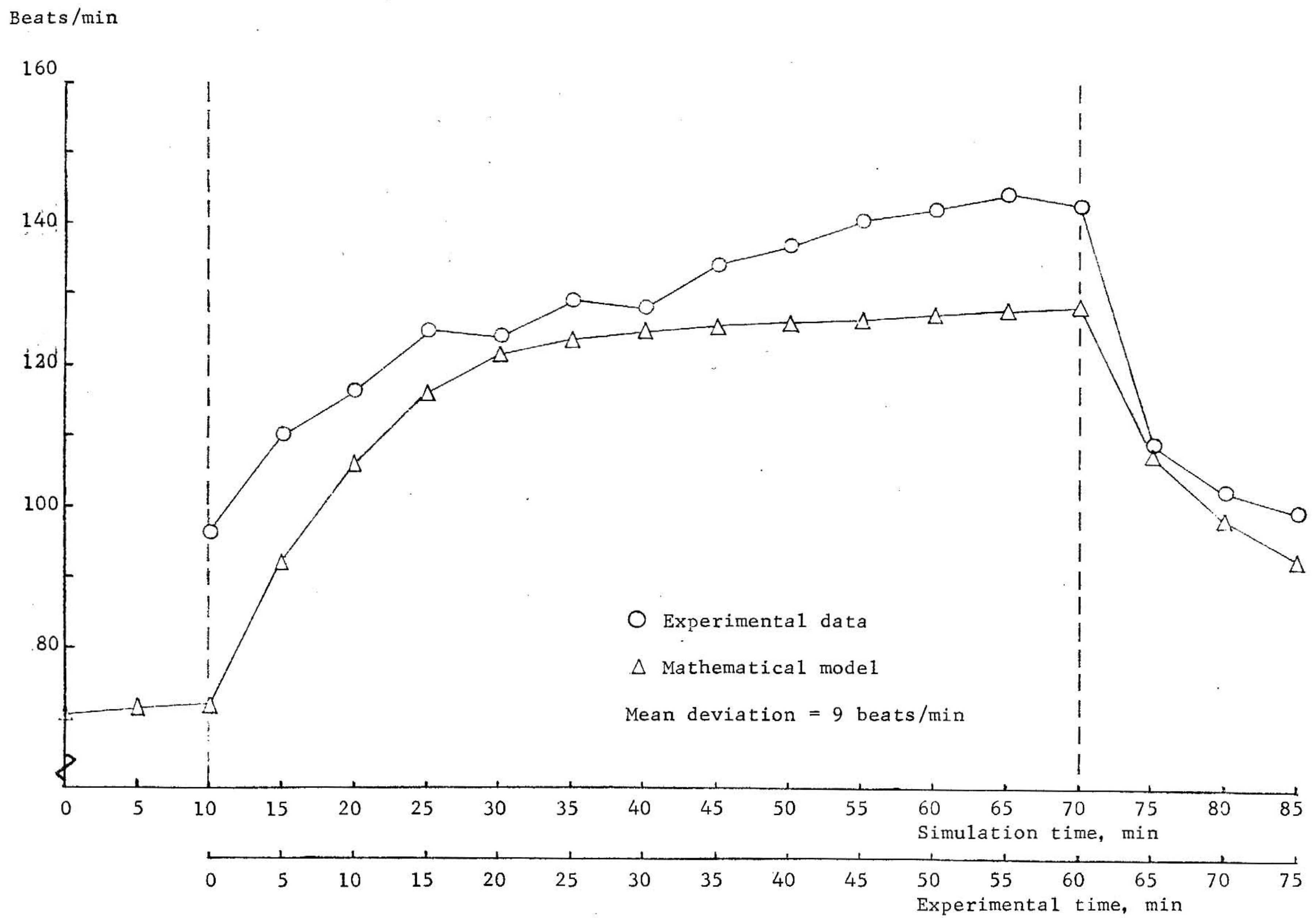

Figure 19. Comparison of Heart Rate for Subject 1 for No-Cooling Condition.

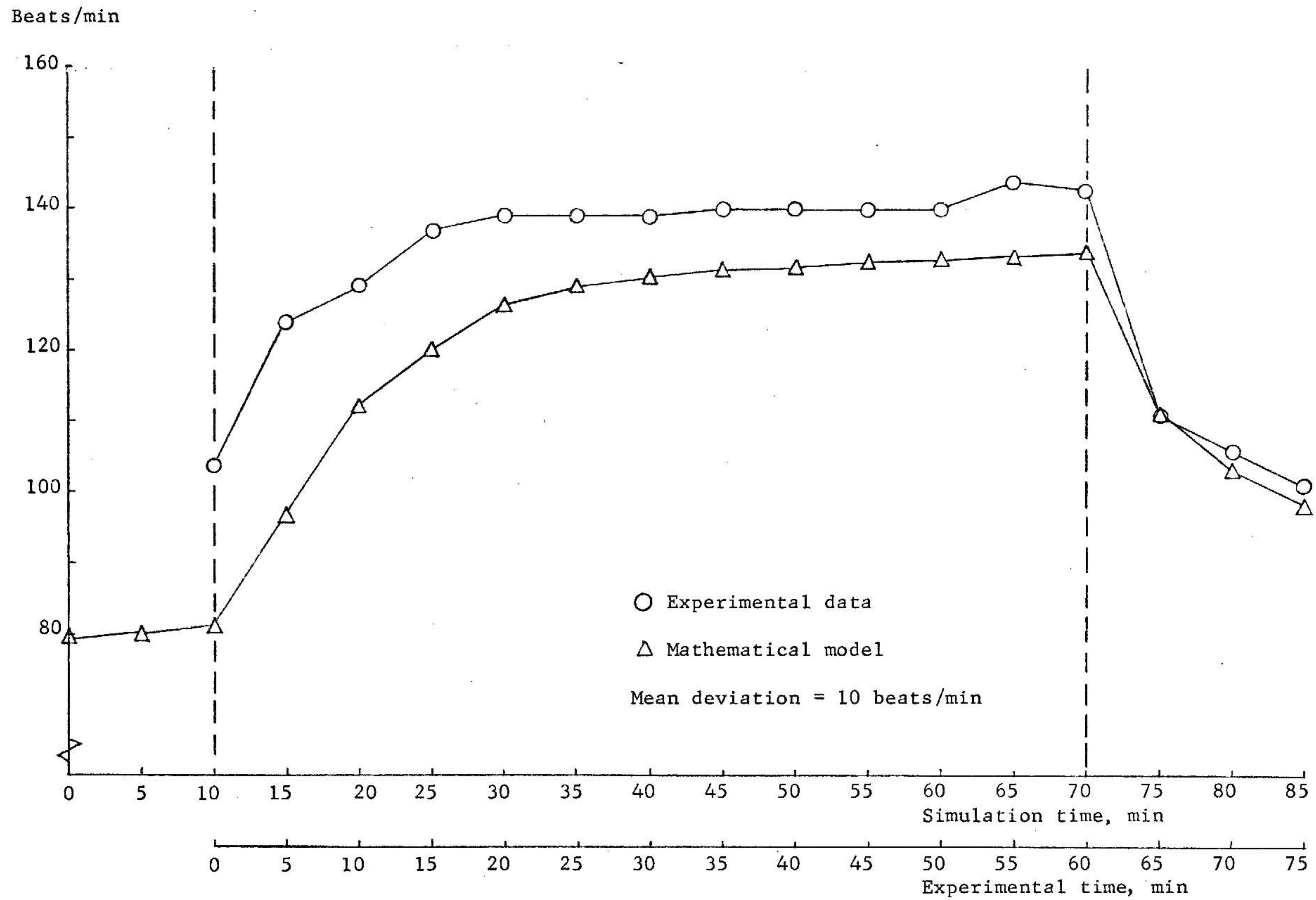

Figure 20. Comparison of Heart Rate for Subject 2 for No-Cooling Condition.

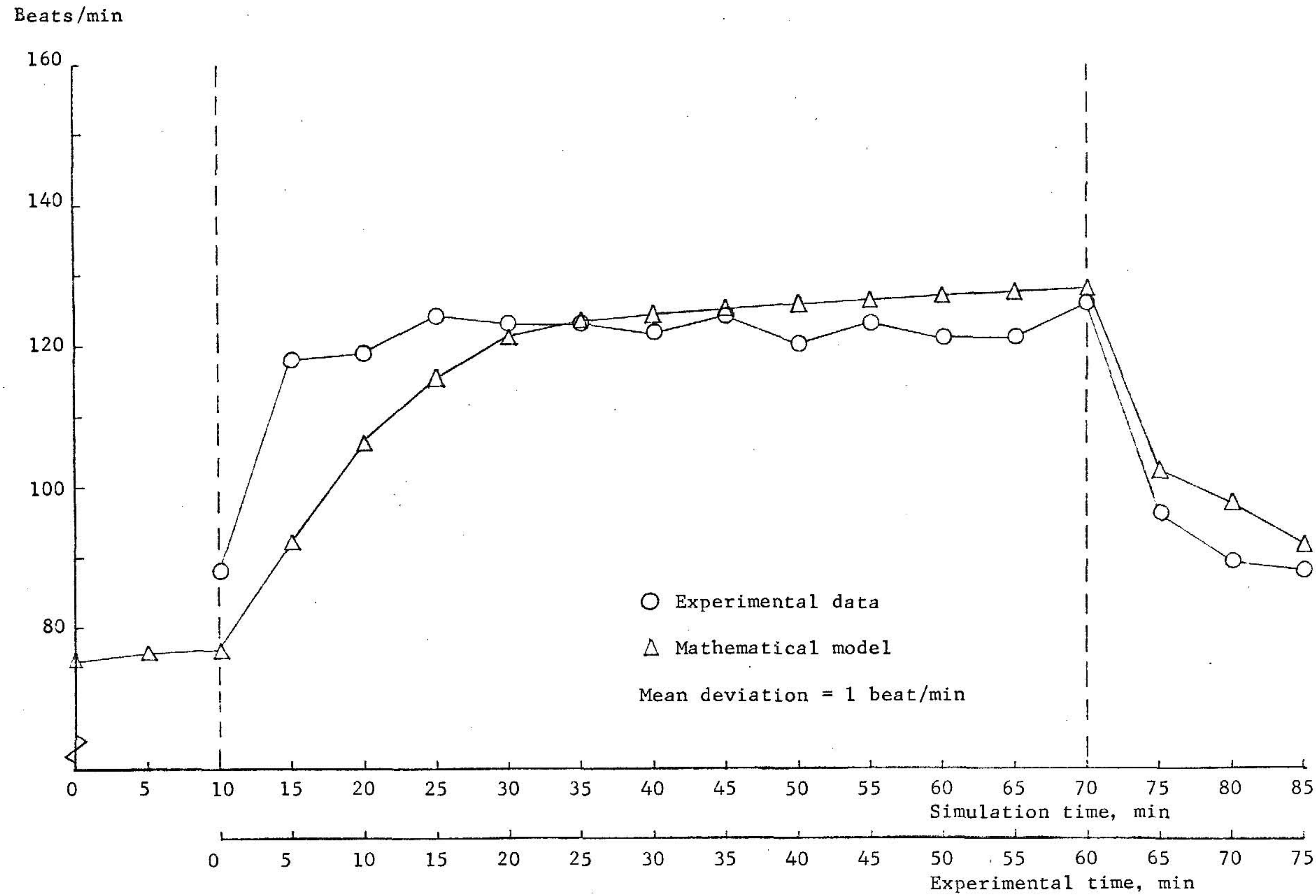

Figure 21. Comparison of Heart Rate for Subject 1 for Cooling Condition.

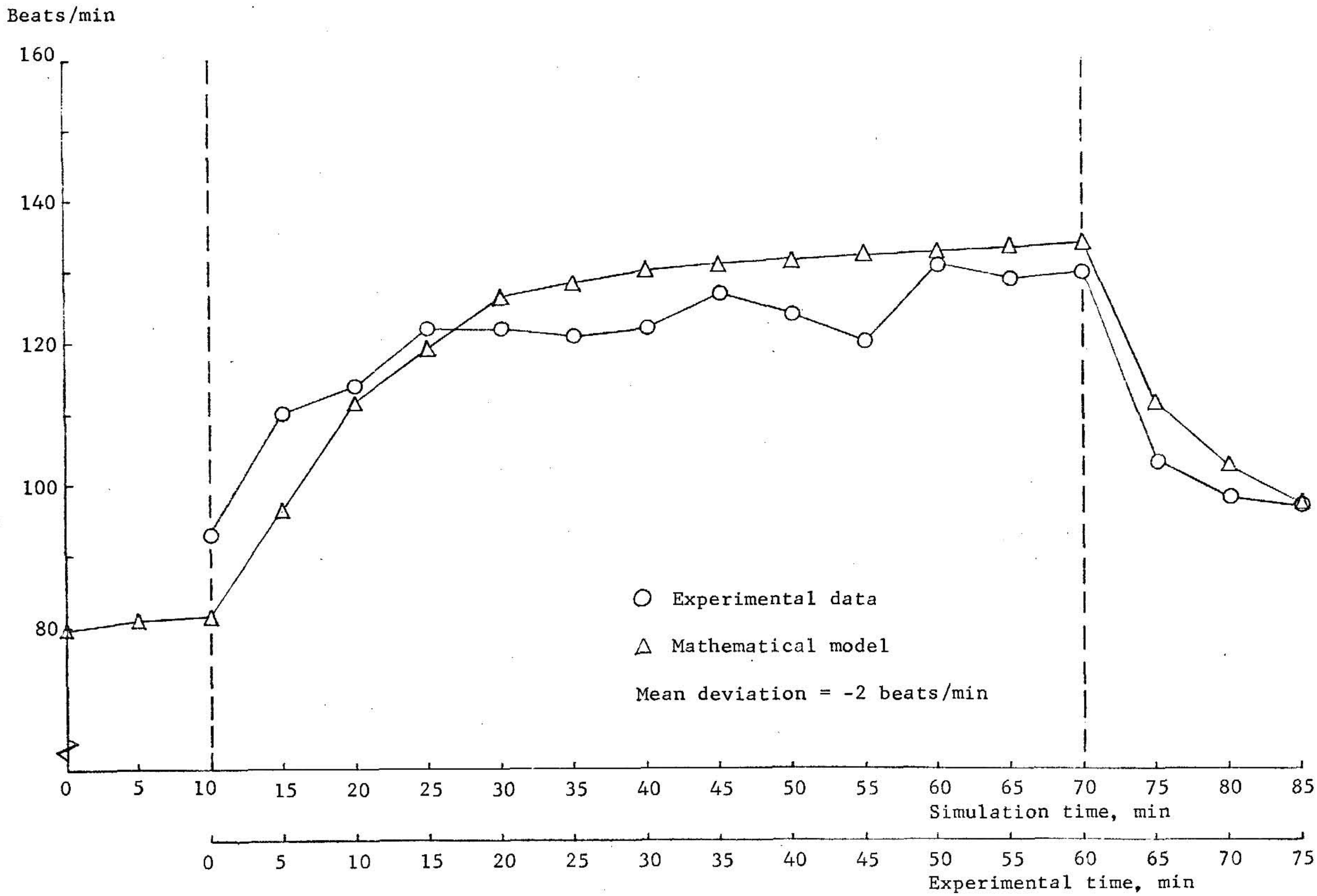

Figure 22. Comparison of Heart Rate for Subject 2 for Cooling Condition.

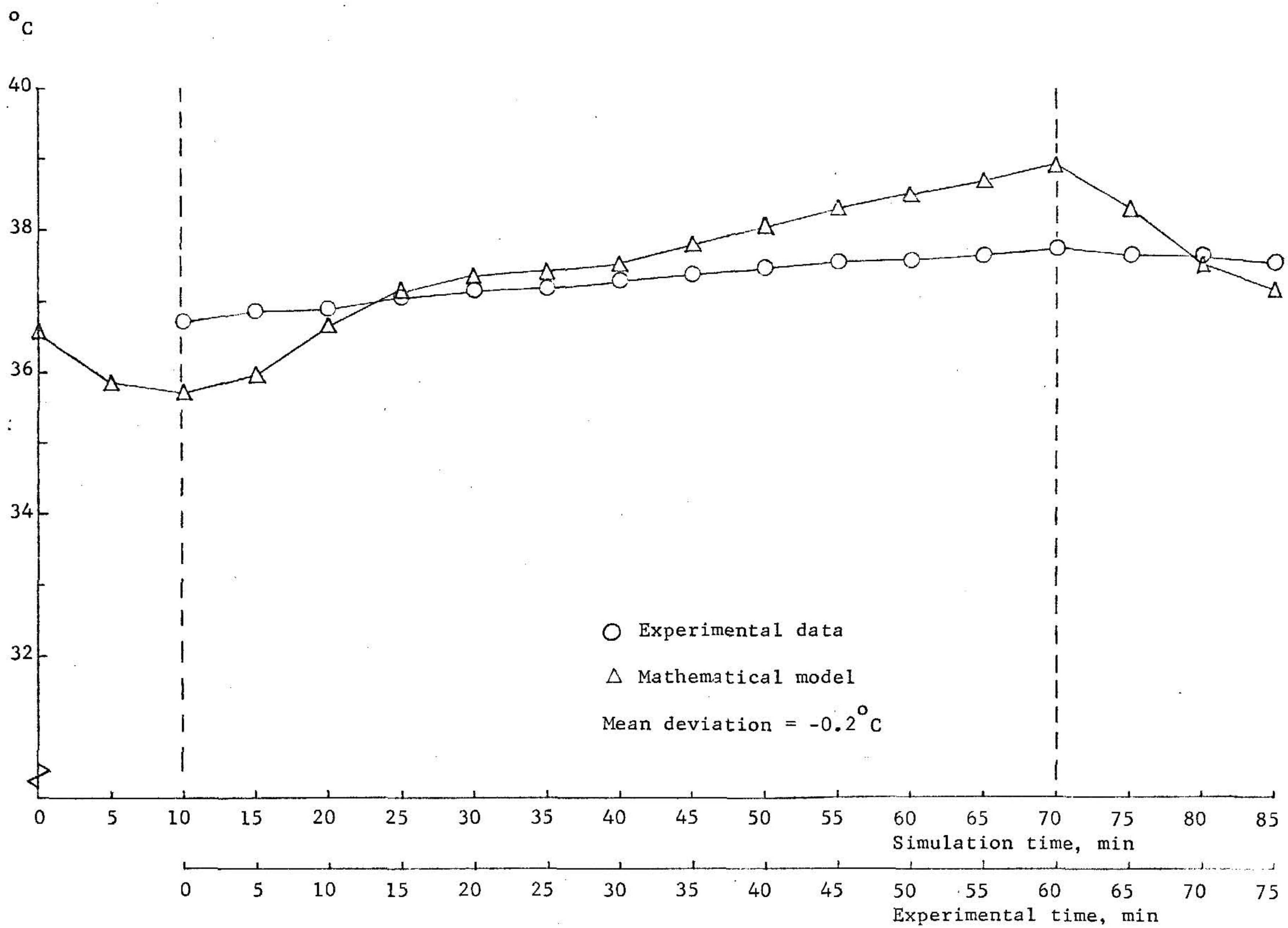

Figure 23. Comparison of Rectal Temperature for Subject 1 for No-Cooling Condition.

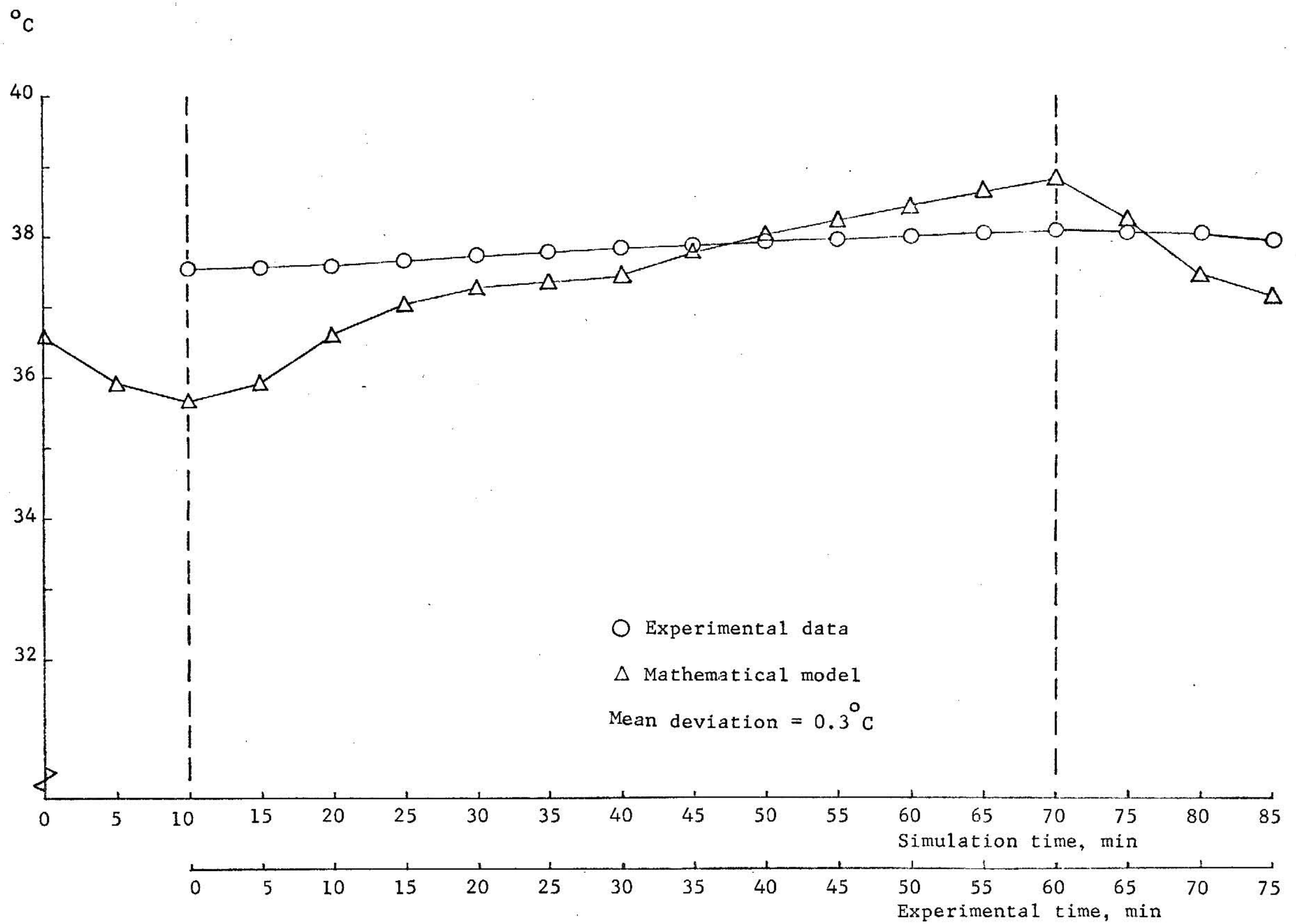

Figure 24. Comparison of Rectal Temperature for Subject 2 for No-Cooling Condition.

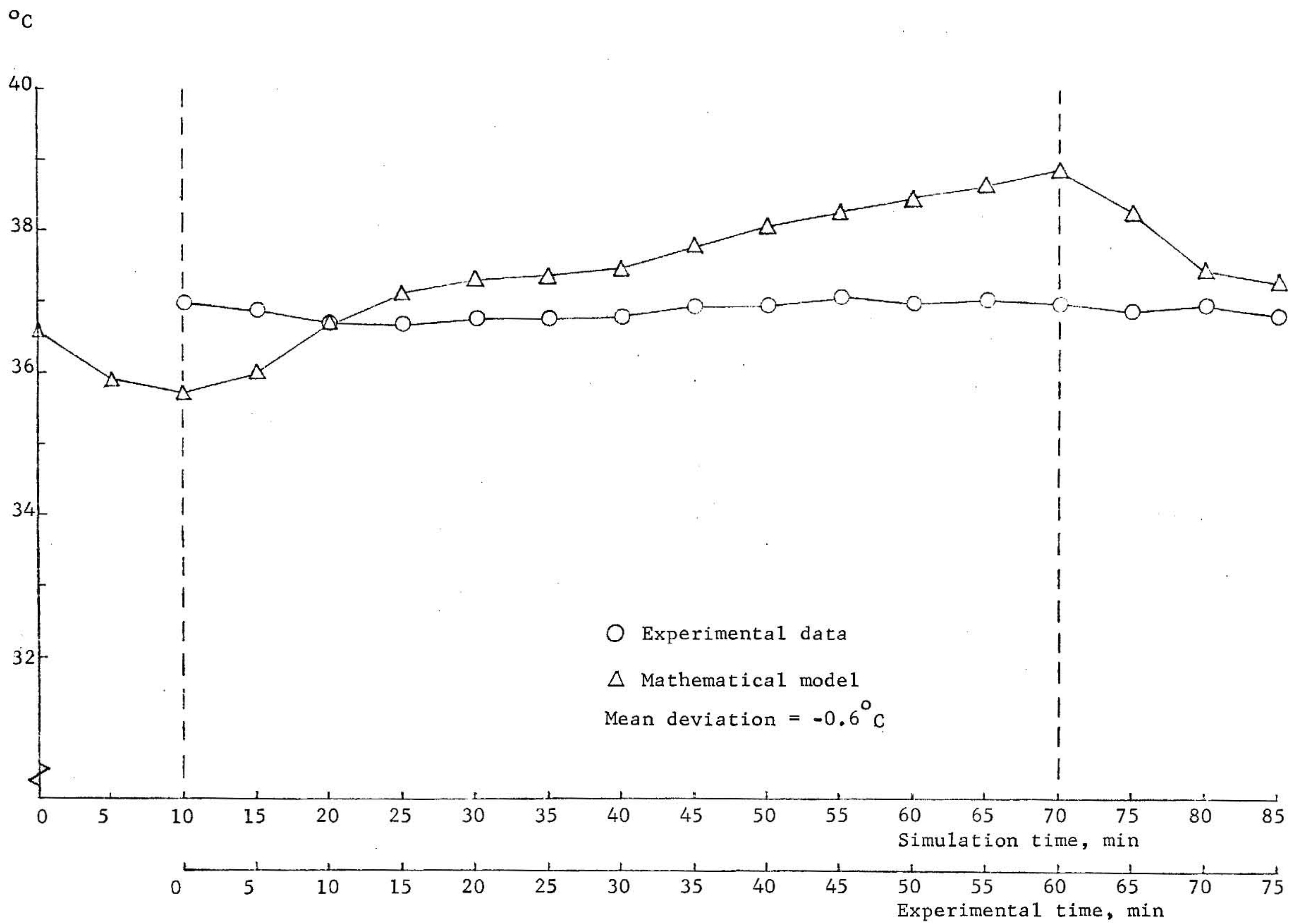

Figure 25. Comparison of Rectal Temperature for Subject 1 for Cooling Condition.

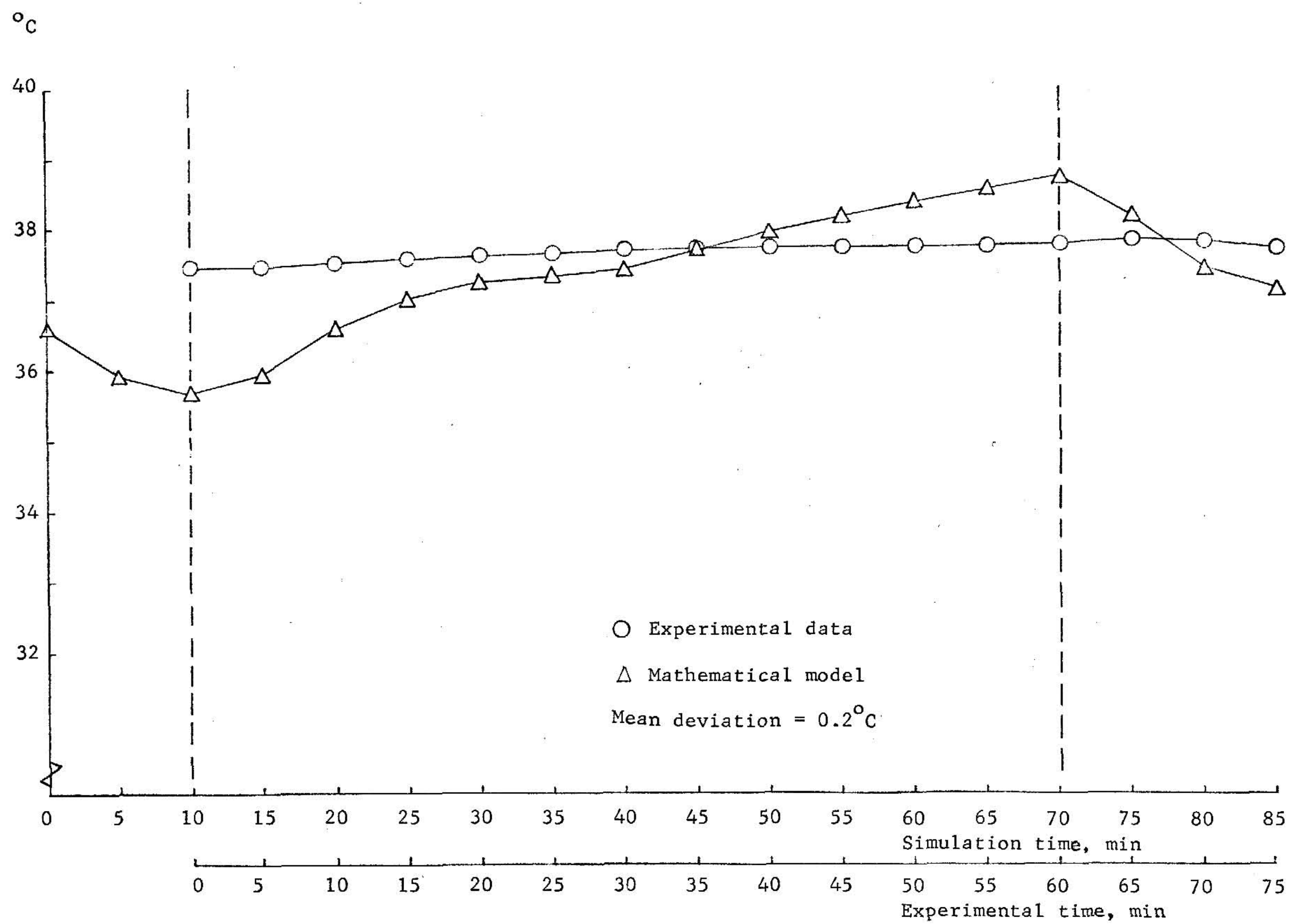

Figure 26. Comparison of Rectal Temperature for Subject 2 for Cooling Condition.

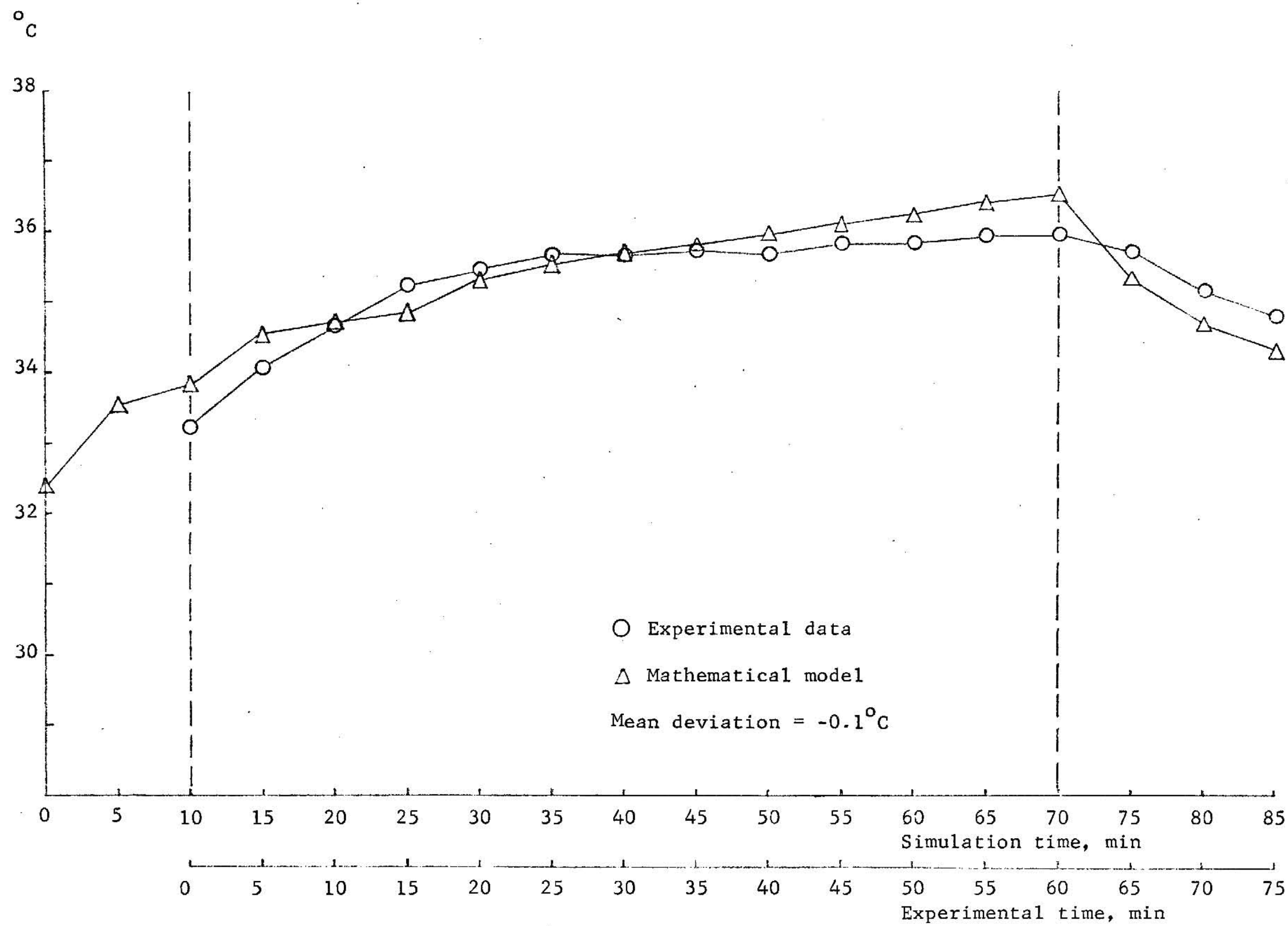

Figure 27. Comparison of Skin Temperature for Subject 1 for No-Cooling Condition.

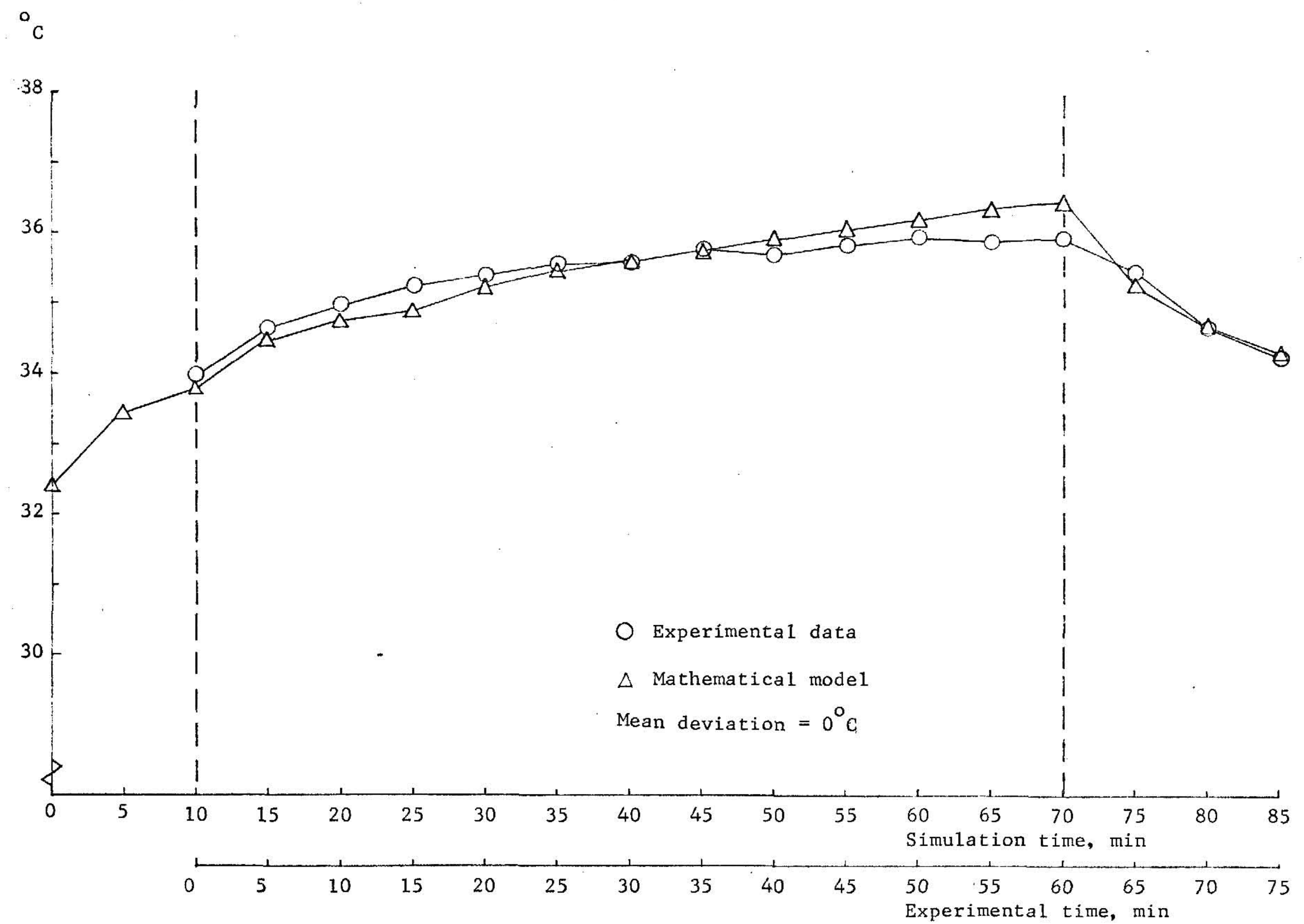

Figure 28. Comparison of Skin Temperature for Subject 2 for No-Cooling Condition.

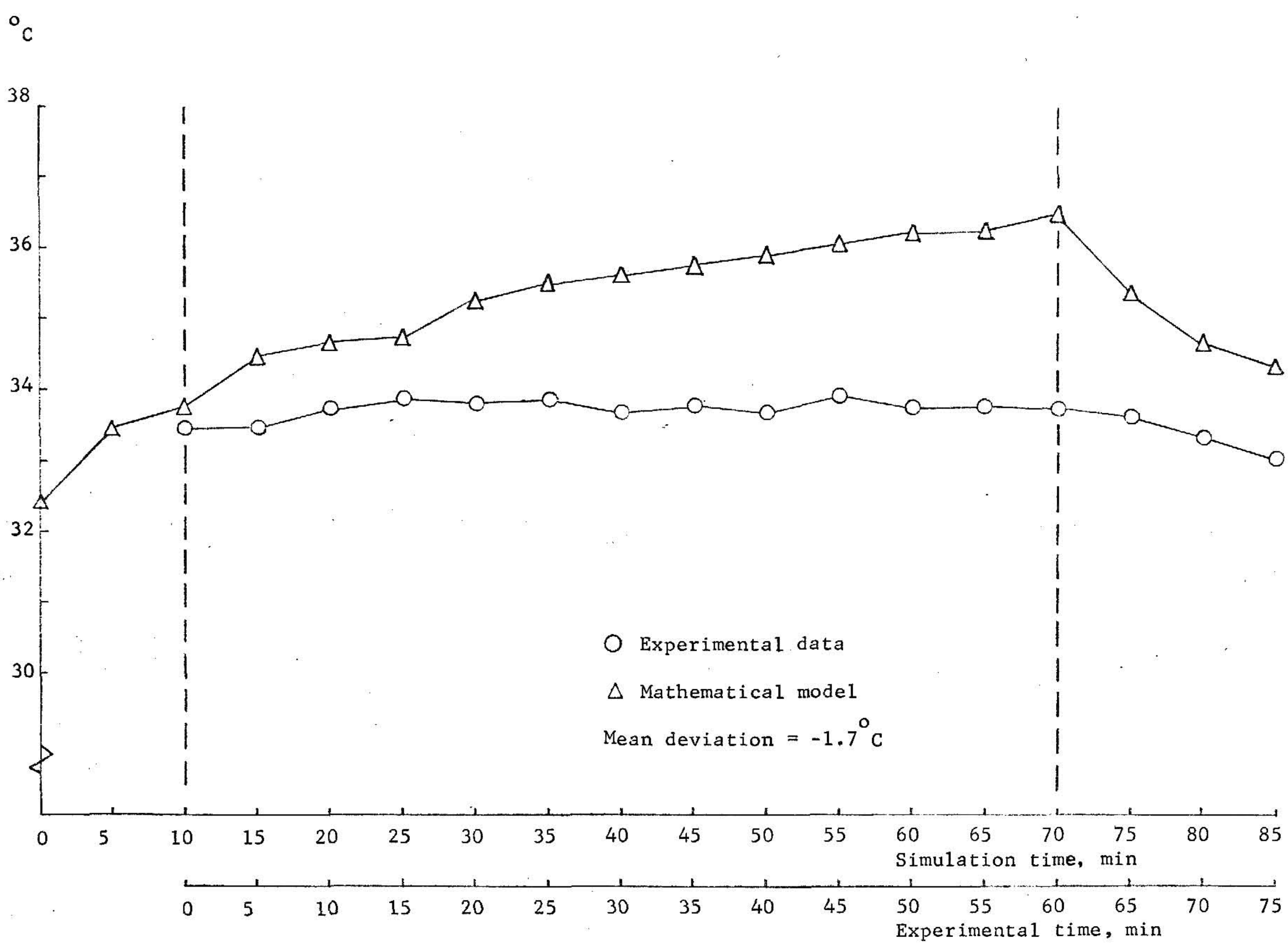

Figure 29. Comparison of Skin Temperature for Subject 1 for Cooling Condition.

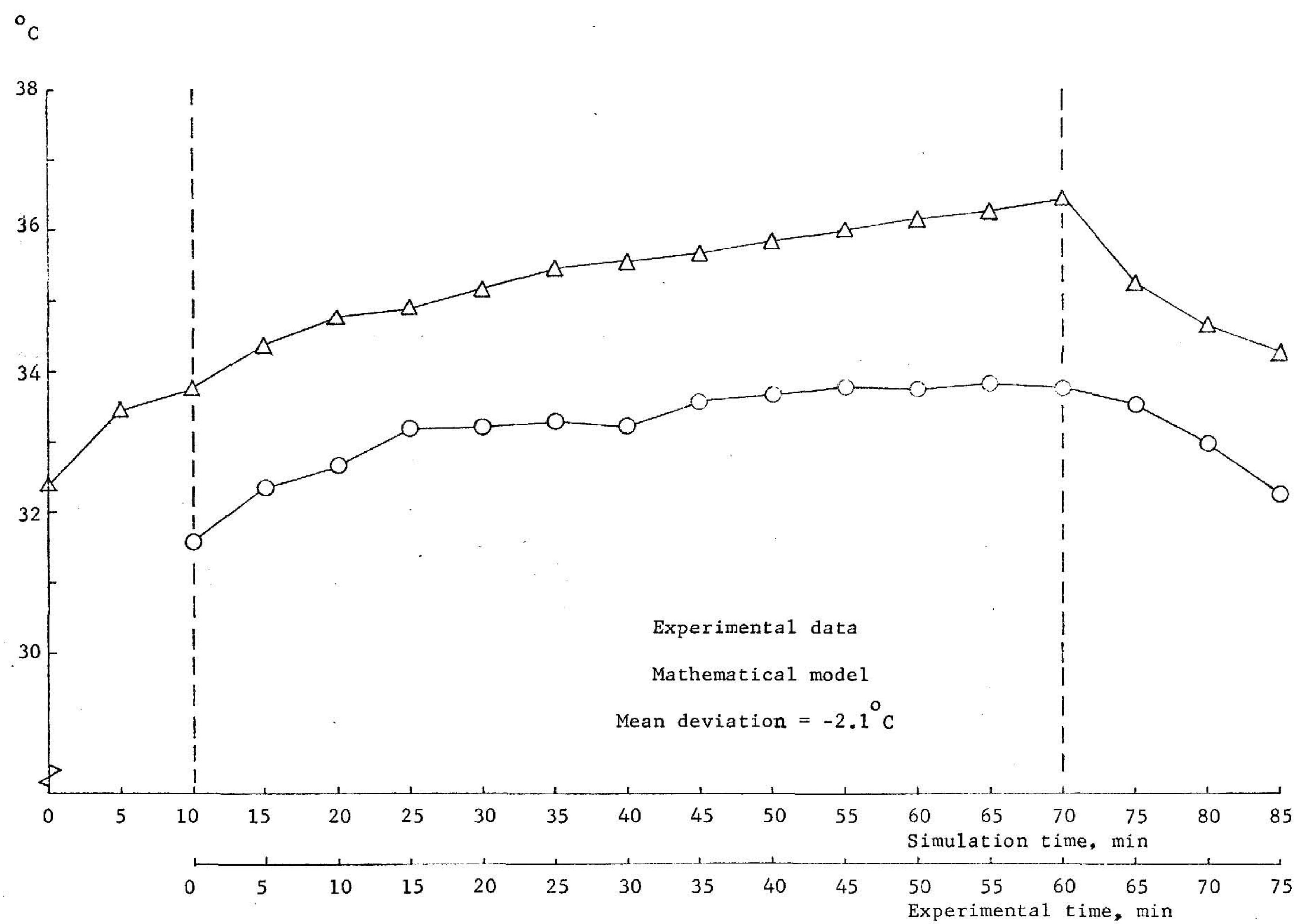

Figure 30. Comparison of Skin Temperature for Subject 2 for Cooling Condition.

Conclusion

The new design jumpsuit was proved an effective means of reducing physiological strain (heart rate, rectal temperature and skin temperature), as well as an improvement over the previous jackets. It gives a more even overall cooling of the individual, instead of just cooling the upper part of the body.

The oxygen consumption rate was only 1% higher when the subjects wore the cooling jumpsuit as compared to the no cooling condition.

The sublimation rate of the jumpsuit is 3% lower than the jacket.

The open cuff and closed cuff do have a slight difference; the open cuff cools the legs better while the closed cuff cools the arms better.

The sublimation rate is different for each individual. In order to have a better fit for each individual, different sizes of jumpsuit are desirable.

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THE DESIGN AND EVALUATION OF A DRY-ICE JUMPSUIT

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AN ABSTRACT OF A MASTER'S THESIS

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Manhattan, Kansas

1976.

Abstract

A personal dry ice cooling jumpsuit for workers in heat stress environments was developed at Kansas State University. It had 8 separate pockets, 4 in the front and 4 at the back.

The cooling jumpsuit was evaluated by 2 male subjects who pedalled on an ergometer for 60 minutes in a laboratory heat stress environment (dry bulb temperature 35°C, relative humidity 70%). The mean heart rate throughout the 60 minutes exposure was 120 beats/min with the cooling jumpsuit and 131 beats/min without cooling. Oxygen consumption rate was not significantly different between the cooling and no cooling conditions. Mean rectal temperature was 37.27°C when subjects wore the cooling jumpsuit, significantly ($p < .01$) less than the 37.54°C for the no cooling condition. Mean skin temperature was 1.74°C less when the subject wore the cooling jumpsuit. The sublimation of the dry ice was more uniform than the previous model, so it gave a more even cooling to the subject. Physiological responses of a subject were simulated by a computer model of human thermoregulation.