LIQUID CRYSTAL THERMOGRAPHY OF TORSO SKIN TEMPERATURES FOR DRY-ICE COOLING

by

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INTRODUCTION AND PROBLEM

The use of cholesteric liquids as a tool for temperature measurement has made possible many innovations in the industrial and medical world. The mapping of skin temperatures in human and animals is now a matter of routine. The use of liquid crystals for non-destructive testing (6) of electric components is one of the many applications of liquid crystals.

The most striking feature of liquid crystals is the ability to display changes in color over discrete temperature bands. The color changes are due to circular dichroism (2,3). An incident beam of light, on striking the liquid crystals, splits into two components having electrical vectors rotated in opposite directions. One component is transmitted through the material while the other is reflected. The reflected light has a wavelength peak that is a strong function of the temperature of the liquid crystals. Temperature changes in the crystals result in a change in the molecular structure, thereby causing a shift in the peak wavelength of the reflected light. When the temperature of the liquid crystal material is in an appropriate range, this peak wavelength becomes visible. The light then passes through the entire visible spectrum (red, yellow, green, blue) as the temperature is increased.

Pick, Fabijanic and Stewart (9) reported that light has a deleterious effect on the stability of the liquid crystal tapes. Degradation of the liquid crystals is due mainly to ultraviolet light; thus packaging material such as opaque papers and black polyethelene should be used to provide protection against the effect of light. Pick and Fabijanic (10) state that, when the temperature of the object is controllable, the liquid crystal tape system is not affected by the ambient temperature. However, if the temperature of the object tends towards equilibrium with the ambient temperature, the liquid crystal system records a value between ambient and source temperatures.

There are many potential applications of liquid crystals in the medical field.

Selawry, Selawry, Holland, Neubaurer and Hoffmeister (11, 12) used liquid crystals for "thermographic measurement of skin temperature over tumor lesions for measurement of size, vasculor physiology and response to the treatment".

Davison, Ewing, Fergason, Chapman, Can and Voorhis (4, 5) used liquid crystal thermography for the detection of breast cancer. "The results of mamography and the results of physical diagnosis were available following liquid crystal thermographic interpretation. Comparison of these results showed liquid crystal thermography to be more reliable than either mamography or physical examination in this study".

The problem for this thesis was to measure skin temperatures under slabs of dry-ice. However, if the dry-ice touched the crystals, the crystals would be removed. Thus a protective shield was needed. Liquid crystals were put on the following films as a base material.

1. Double backed "Scotch" tape (1/2" wide): It gives fair color response to temperature differences (within a range). Acetone on the back of the tapes is recommended by Fergason (7); for us the color response with acetone was not as good as it was without acetone.

2. Black cloth: Thin, elastic, stretchlon black cloth was chosen so that it could fit the subject's body. It did show some colors but, due to the rough surface of the cloth, incident light was not reflected properly and the colors shown were not prominent. Moreover, black cloth soaks up more liquid crystals than tapes.

3. Plain "Scotch" tapes (1/2" wide): Regular "Scotch" tape was also used as base material. These show a fine even color response within a temperature range. Acetone on the back of these tapes did not change the color response. But when these tapes were used for the pilot experiment, due to the glossy surface of the tapes, there was too much glare on the tapes in the photograph; therefore colors could not be detected properly.

Then I tried liquid crystals directly on the skin without any protection. I tried this the following ways.

1. First the skin was dried with alcohol (Lavacol, rubbing alcohol; 70% ethyl alcohol by volume). Then I sprayed the Lix Kit black base coating (washable black paint in a aerosol solvent) directly on the skin. A homogeneous black paint coating was obtained by applying two layers of black paint. Liquid crystals (Pressure Chemical Co.; LC type) were applied with a brush (3/8" wide; M. Grumbacher, N.Y., No. 4116). Liquid crystals showed a good color response in a pilot experiment. I could run the experiment for 60 minutes for the 75° F environment. But the black base coating and the liquid crystals were drained off by sweating especially on the back, in a 95° F environment.

2. New Skin spray: To reduce the sweating problem, I used the "New Skin" water proof material (New Skin Spray-on, Newskin Co. Inc., N.Y.).

I used this material two ways: A) First I sprayed the "New Skin", then I applied the black base, then liquid crystals. The black base and liquid crystals were drained off by sweat dripping from above.

B) First the black base was applied, then liquid crystals and then the "New Skin". Air bubbles came up from under the black base coating, so I could not get good colors.

Finally it was decided to use a different protective layer—sandwich wrap paper (polyethylene, 0.2 mm thick). In the meantime it was discovered that Tempera's black color (1559 Black) could be used as the base with a brush at very low cost. Colors were superior to those using the aerosol black.

METHOD

Task

Black base coating (Prang, instant powder Tempera, 1559 Black) and liquid crystals were brushed on the skin of the chest, stomach and back of the subjects. Then sandwich wrap paper was used over the liquid crystals. After wearing the vest, the subjects pedalled an ergometer (Monark, GIH, Stockholm, Sweden) for 10 minutes at the rate of 60 revolutions per minute (estimated metabolic rate = 200 Kcal /hr). Then he opened the front of the vest and a photo was taken. Then he slid the vest onto the arms and a photograph of the back was taken. The subject then resumed pedalling until the next photo. Photos were taken at 10,20,30,40,50 and 60 minutes. There was a 5 minutes difference for the starting time for the two subjects to permit the photography. On the fourth day, photos were taken of subject 1 after he removed the dry-ice garment to determine the persistance of the cooling.

Subjects

Two male subjects were used. They were paid $50.00 each upon completion of the experiment. Their age, weight and height were 24 years, 115 lbs and 66 inches and 24 years, 145 lbs and 67 inches.

Procedure

The subjects did one session per day. Table 1 and Fig. 1 give the five conditions for the experiment.

Plastic material with air bubbles was used as an insulation for the pockets. Two different thicknesses were used (low-3 mm, high-10 mm). Estimated conductance values for the low and high insulation are 17.1×10^{-5} and 5.35×10^{-5} gm-cal/sec-sq.cm-^{o}C.

Two dry-ice slab sizes were used: 10 sq. inches (3.2 x 3.2 x 0.5) and 20 sq. inches (4.4 x 4.4 x 0.5).

The first four conditions were done on first four days. The sequence of conditions followed was 3,1,4 and 2 (Table 1). On the 5th day, the experimental condition was in a neutral environment (75^{o} F), no cooling, sitting for 60 minutes and then exercise for 60 minutes.

Measurement and Instrumentation

Temperature changes on the liquid crystals were recorded with the help of a 35 mm Contaflex Zeiss Ikon camera with F2.8 lens. For taking the photographs, the flash holder (flash bulbs were Sylvania, blue dot M2B) was held about 4 feet away from the skin and 5 feet above the floor at about a 50-55^{o} angle and was directed towards the center of the liquid crystal belts. The camera was focused by hand and was held 2 1/2 - 3 feet away from the subject. Glare was reduced by a Vivitar polarizing filter (27 mm) on the lens.

After every 10 minutes of exercise, front and back photos were taken. There were 12 photos per subject for each condition.

Table 1: Experimental Conditions

Condition	Cooling	Conductance between ice and skin ($x10^{-5}$gm-cal/sec-sq.cm.-^{o}C)	Facing surface area of dry-ice/slab (sq.in.)
1	yes	17.1	10
2	yes	5.35	10
3	yes	5.35	20
4	yes	17.1	20
5*	no	0	0

*sitting 60 min.; exercise 60 min.

THIS BOOK CONTAINS NUMEROUS PAGES WITH DIAGRAMS THAT ARE CROOKED COMPARED TO THE REST OF THE INFORMATION ON THE PAGE.

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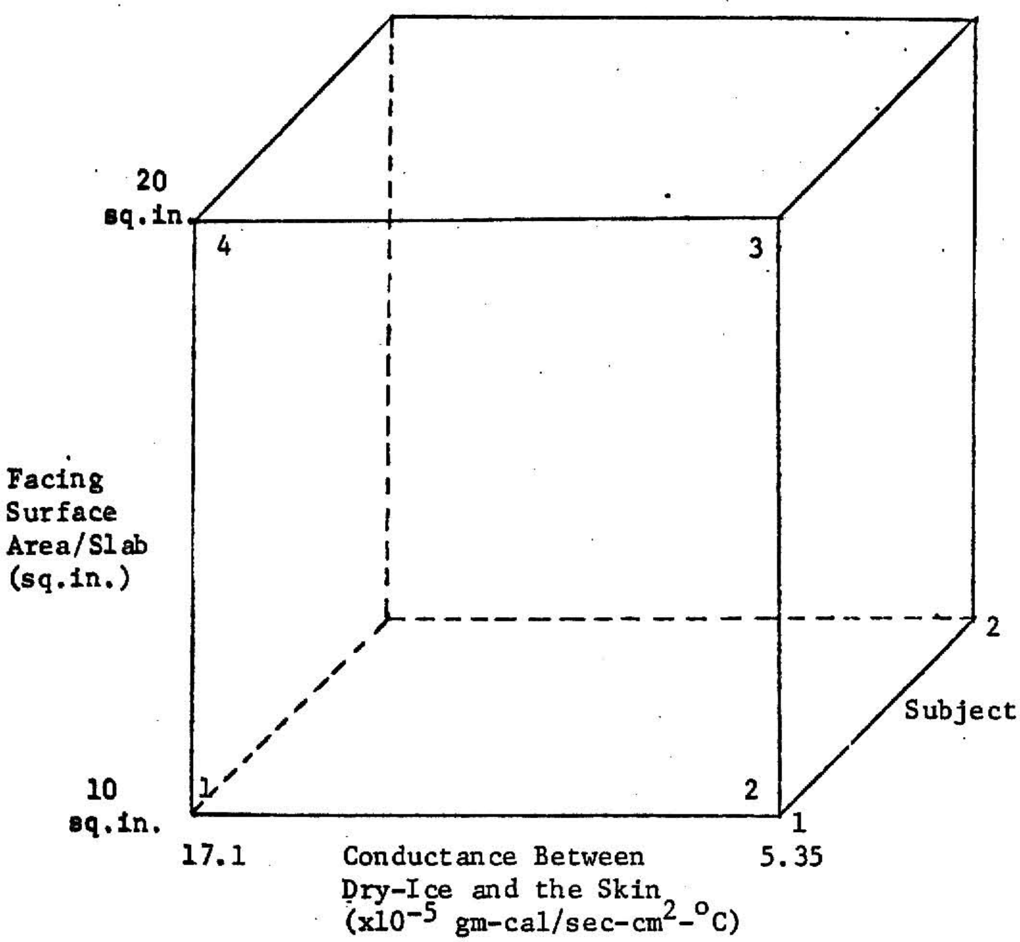

Fig. 1: Experimental Conditions

Liquid crystals were applied as follows:

There were two series of strips each on the front and back of each subject. Each series consisted of seven different ranges as shown in Fig. 2. First the skin, where the liquid crystal was to be applied, was washed with alcohol to dry the skin. Then the seven black strips (1/2" wide) were painted with black watercolor paint (Prang, instant powder Tempera, 1559 Black) with a brush. There was approximately a 1/8" gap between each strip and 1 1/2" gap between each series. The black paint was dried with the help of a hair dryer (Lady Sunbeam, Vista). A homogeneous black paint coating was obtained by applying two layers of black paint. Then the appropriate liquid crystal was applied on each black strip with a brush (Fig. 2). Different brushes were used for different liquid crystal ranges. Then each series was masked separately by polyethelene which was held to the body by applying "Scotch" tapes at the ends.

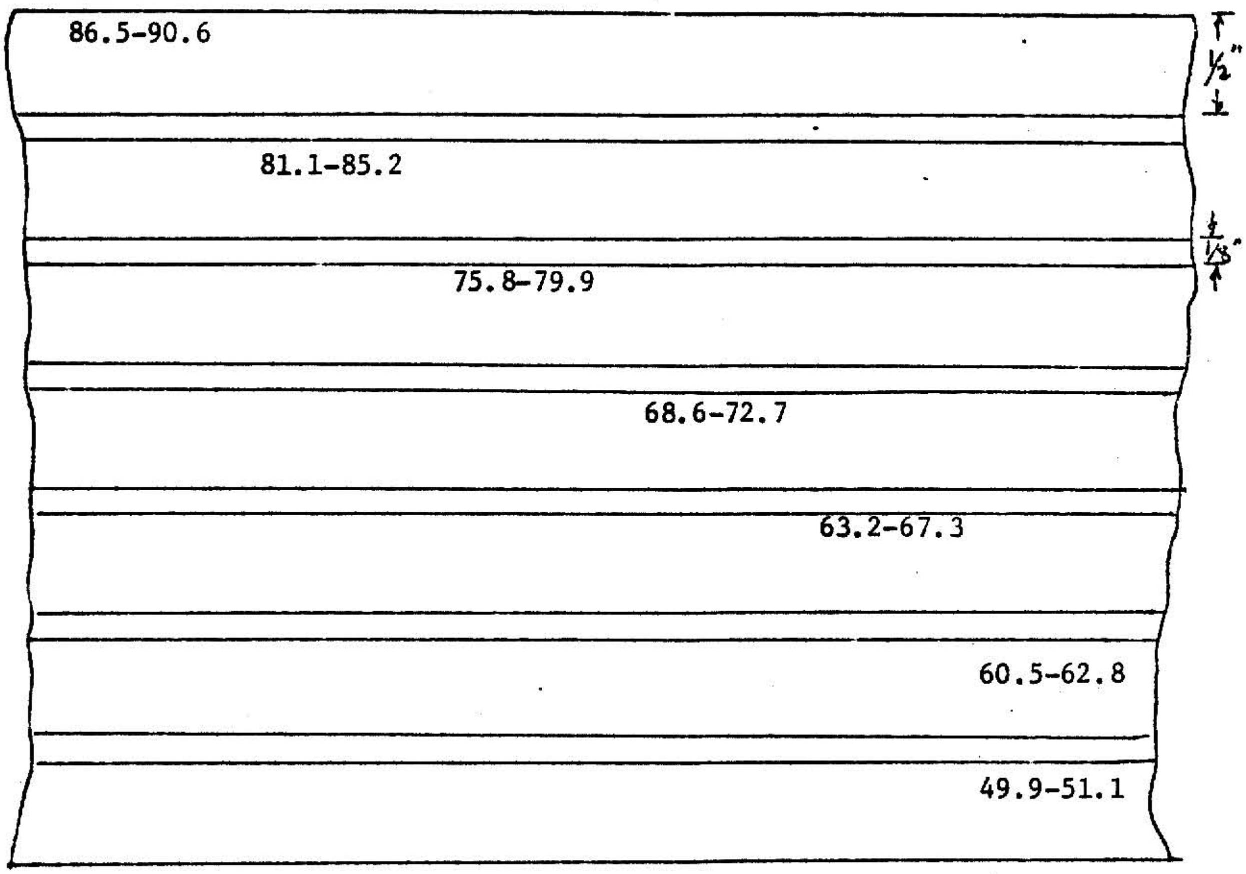

Fig. 2: Portion of the Liquid Crystal Series Showing Different Liquid Crystal Ranges (°F)

RESULTS

The actual length (13") of each liquid crystal strip on the chest and back of each subject was known. Then using a proportionate scale for location of a color, each color on each of the liquid crystal strips from the photo (for example, Fig. 3 and Fig. 4.) was converted to the respective temperature (from Table 2). In this way all possible temperatures were plotted (Fig. 5 to Fig. 17). Then the contours were drawn by eye for 50, 60, 70, 80 and 90° F. As shown in Fig. 5 to Fig. 17, numbers in the bracket indicate the respective areas between the contours in sq. inches (measured with a planimeter).

Fig. 5 to Fig. 10 show the thermograms for 10, 20, 30, 40, 50 and 60 minutes for the experimental condition number 2 (conductance = 5.35×10^{-5} gm-cal/sec-sq.cm-°C, surface area = 10 sq. in.; Table 1). All these thermograms are drawn for the front left pocket for subject 1.

Fig. 11, 12 and 13 show the thermograms for the front right, back left and back right pocket respectively for the same experimental condition (time = 20 min.).

Fig. 14, 15 and 16 show the thermograms for the experimental condition numbers 4, 1 and 3 (Table 1). All these thermograms are drawn for subject number 1 and for the front right pocket. Fig. 17 gives the thermogram for the second subject's front right pocket for the experimental condition number 2 (time = 20 min.).

How the area for the different contours for different pockets change with the time in an experiment are shown in Fig. 18, 19, 20 and 21. Binomial equations to these points are shown on the graphs (Fig. 18, 19, 20 and 21).

Fig. 3: Front Photograph for Experimental Condition #2 (t = 20 min.)

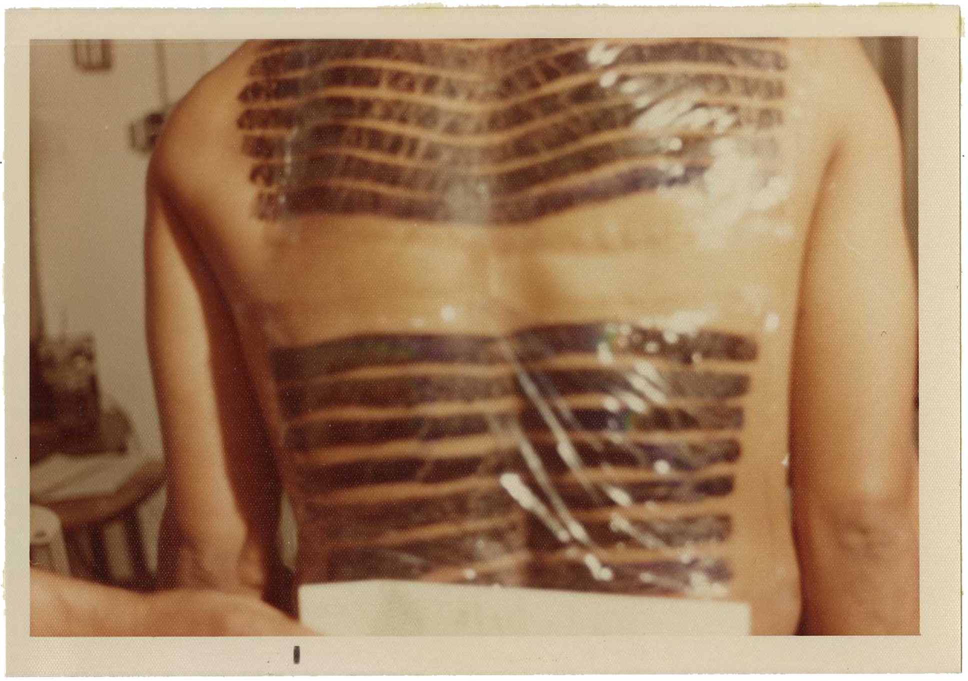

Fig. 4: Back Photograph for Experimental Condition #2 (t = 20 min.)

Table 2: Calibrated Temperatures (^{o}F) for Different Colors for Different Liquid Crystal Ranges.

Strip Number (from top)	Color			
	Red	Yellow	Green	Blue
1	86.5	87.4	88.8	90.6
2	81.1	82.0	83.4	85.2
3	75.8	76.7	78.1	79.9
4	68.6	69.5	70.9	72.7
5	63.2	64.3	65.5	67.3
6	60.5	61.4	62.4	62.8
7	47.9	48.8	49.7	51.1

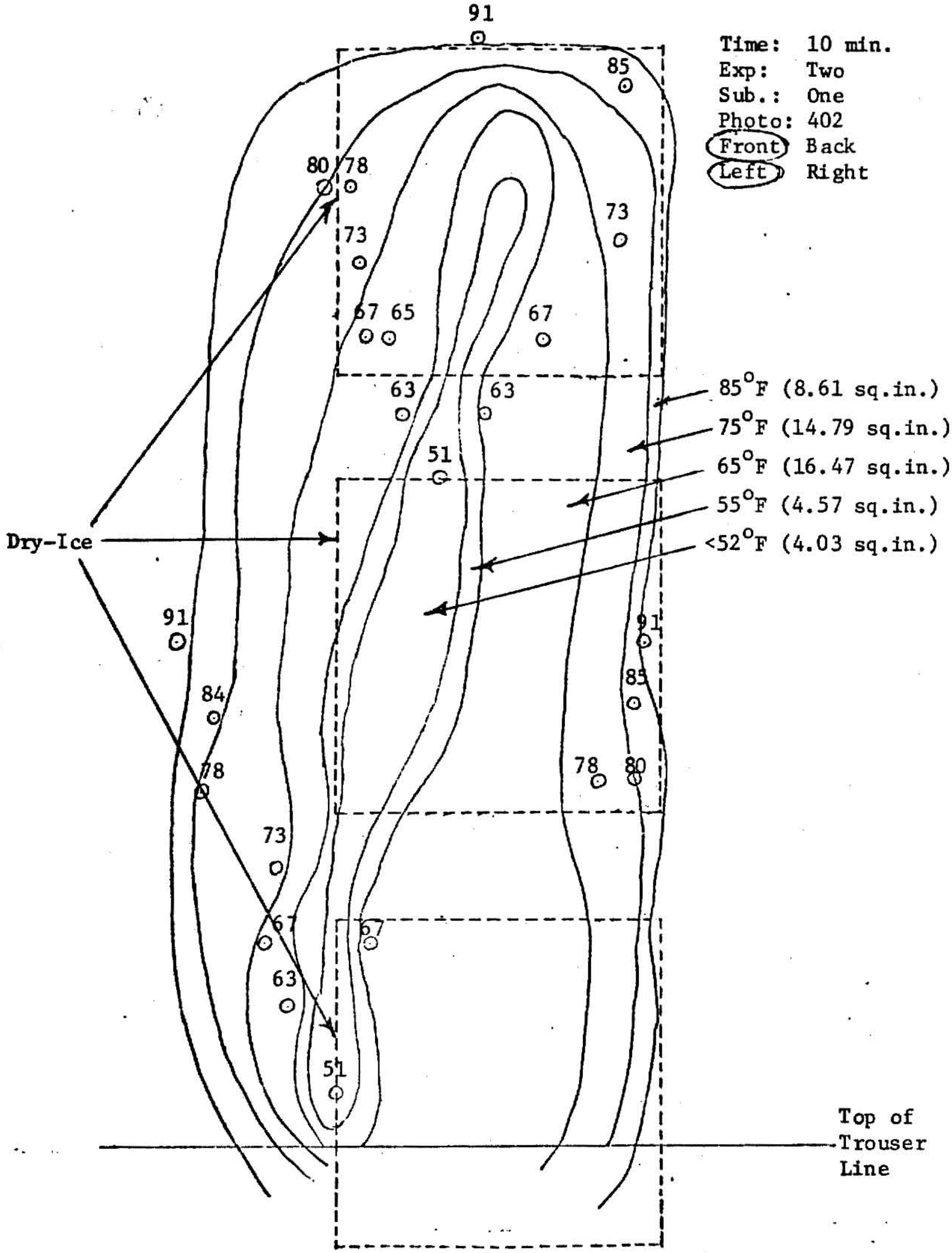

Fig. 5: Thermogram for Experimental Condition Number 2. (time = 10 min.)

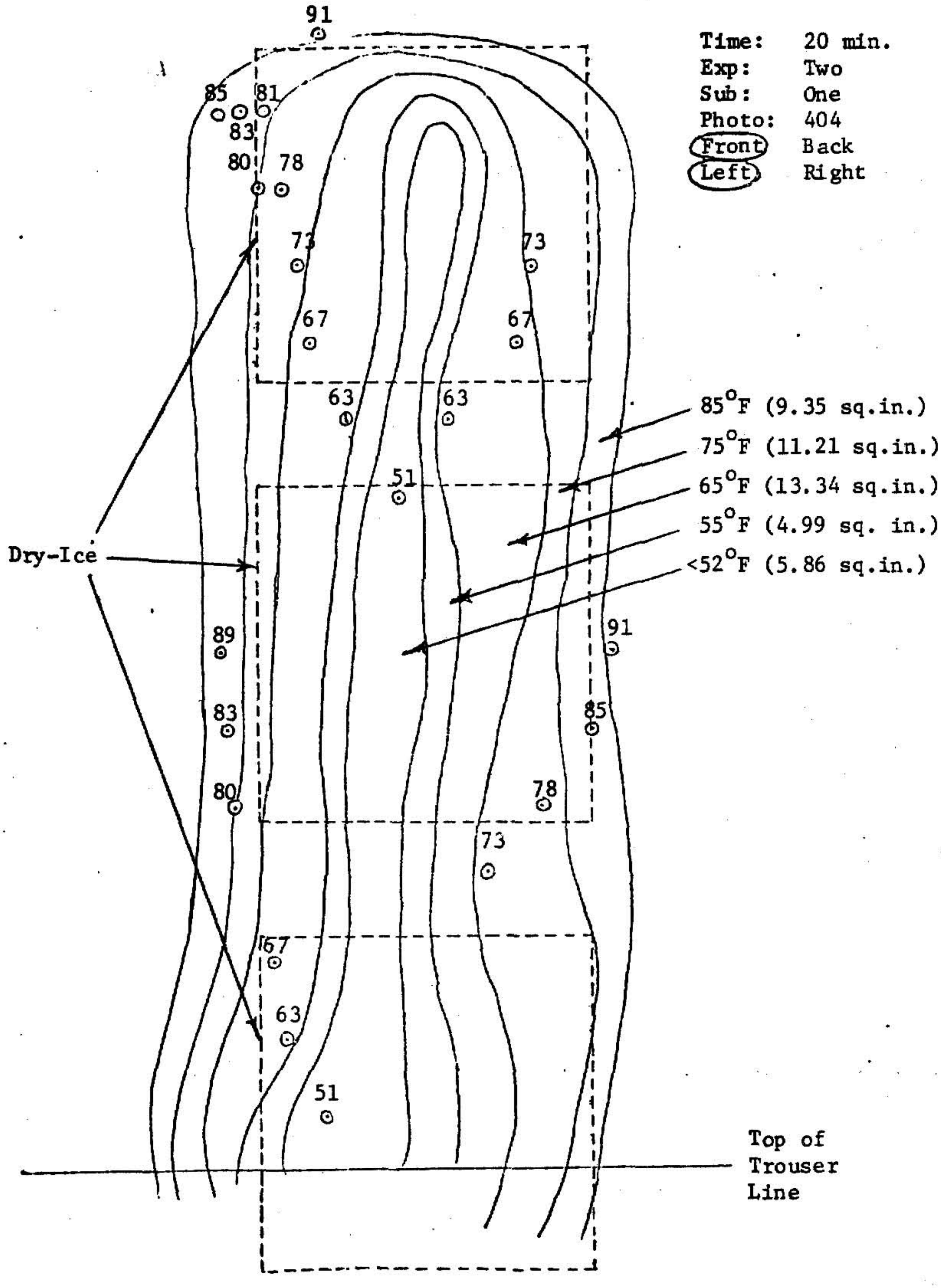

Fig. 6: Thermogram for Experimental Condition Number 2 (time = 20 min.)

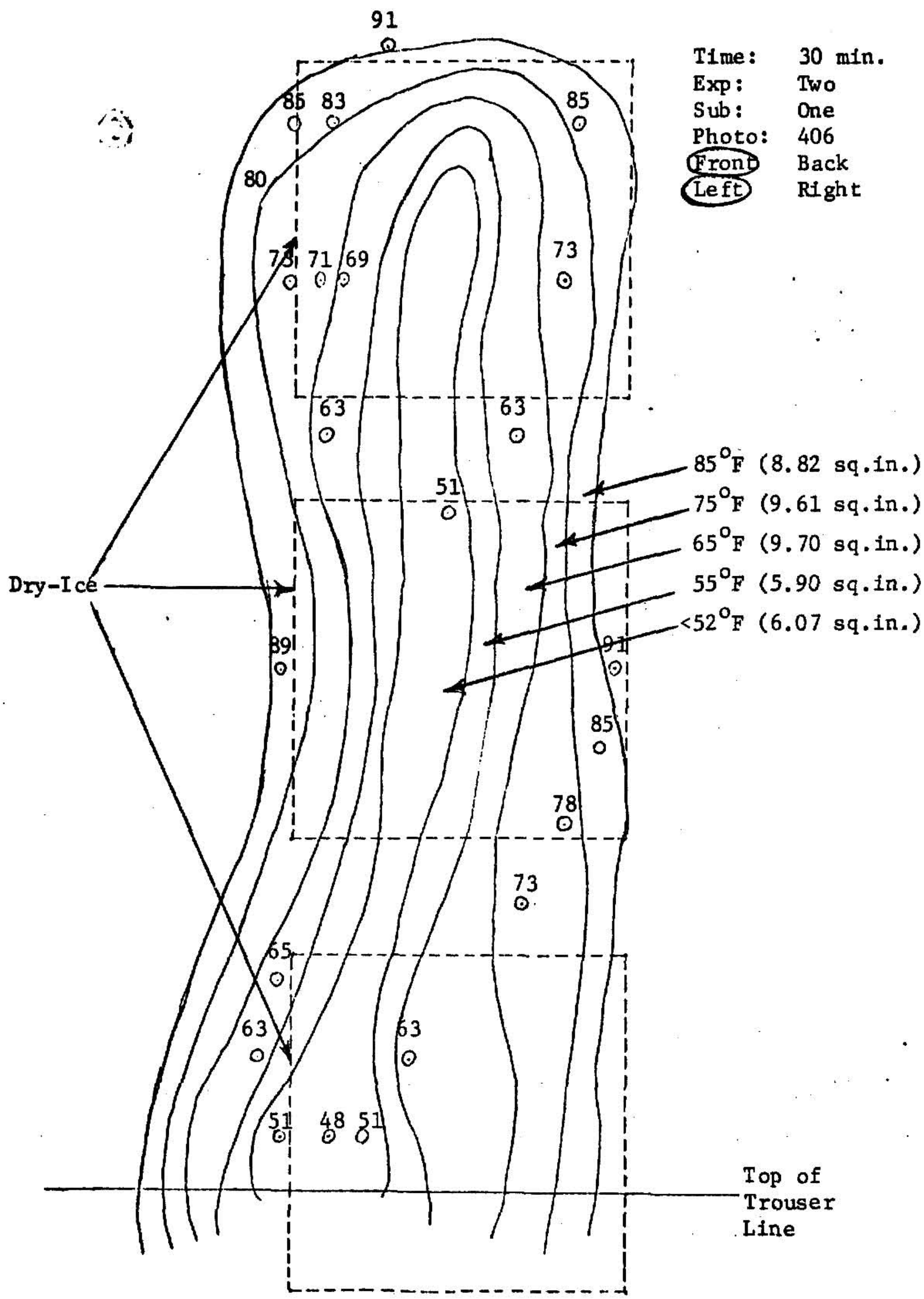

Fig. 7: Thermogram for Experimental Condition Number 2 (time = 30 min.)

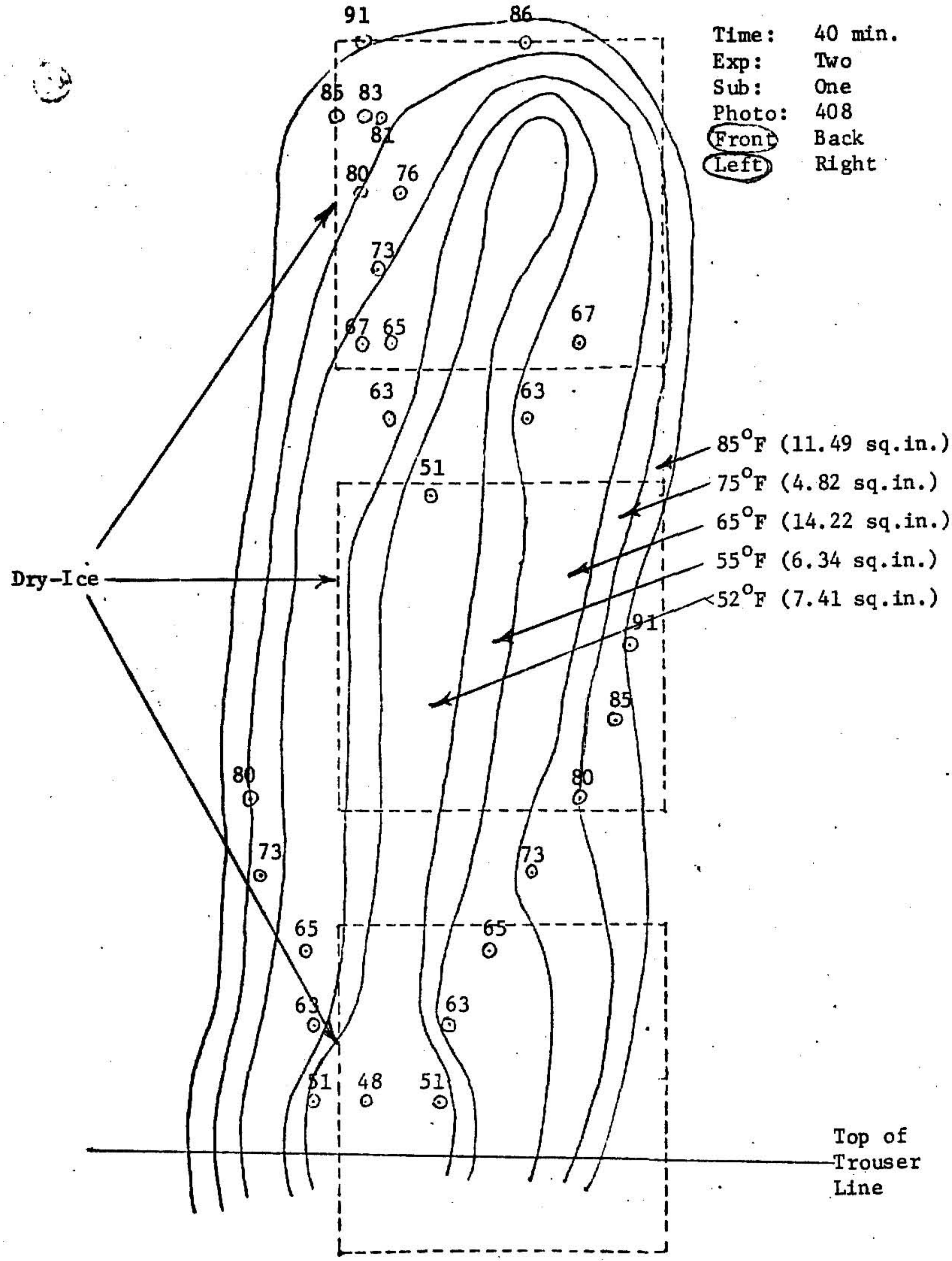

Fig. 8: Thermogram for Experimental Condition Number 2 (time = 40 min.)

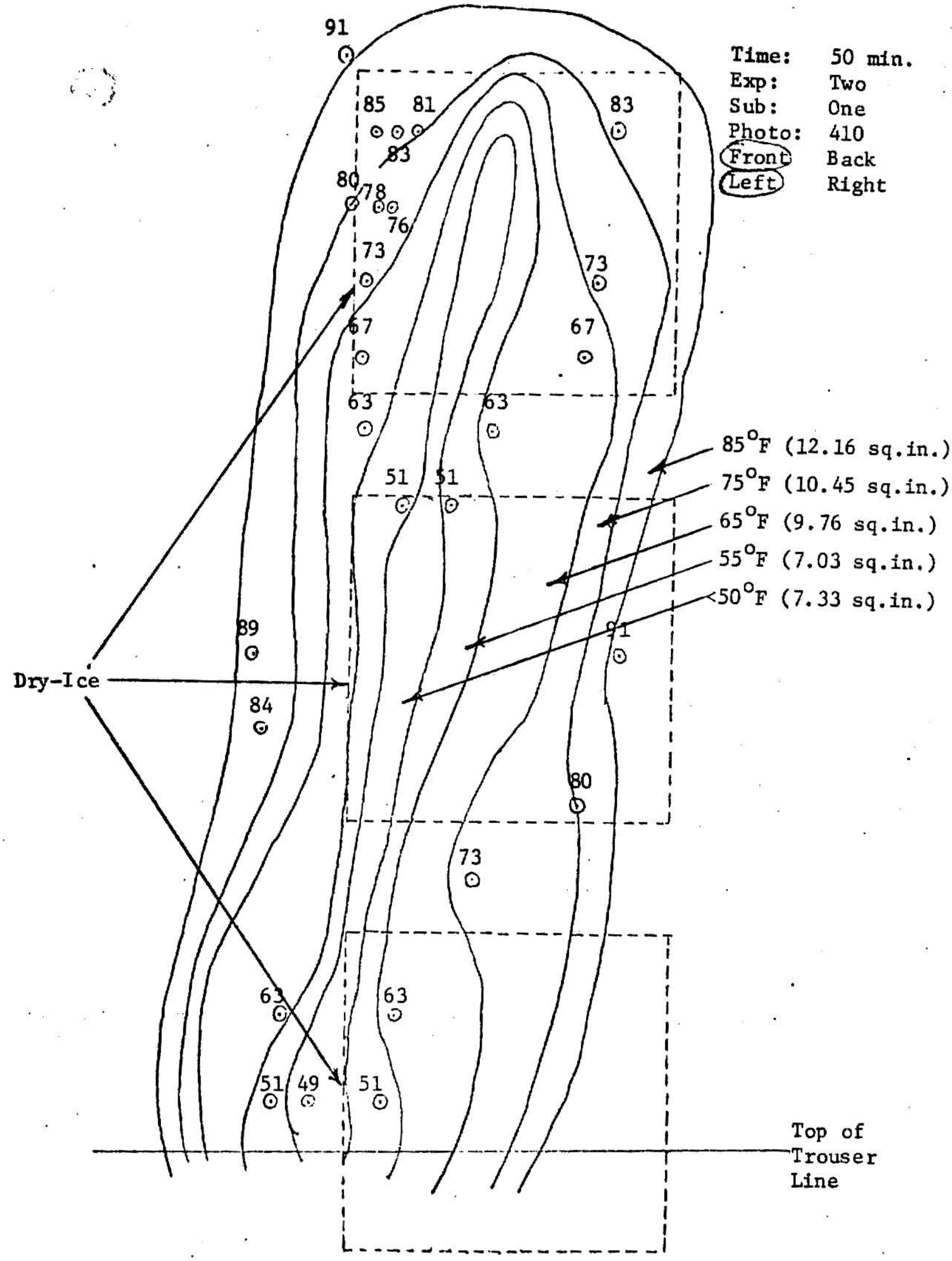

Fig. 9: Thermogram for Experimental Condition Number Two. (time = 50 min.)

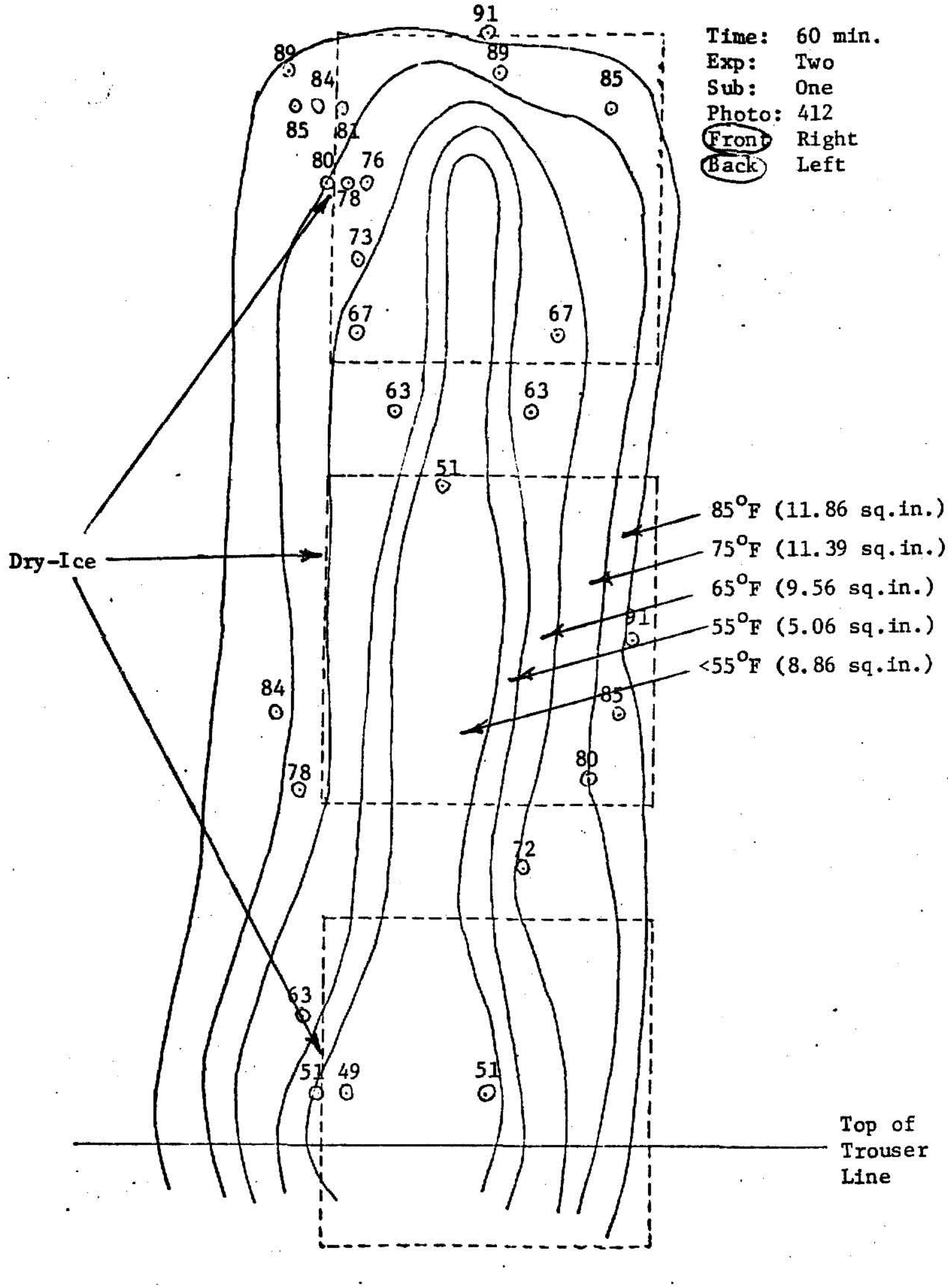

Fig. 10: Thermogram for Experimental Condition Number Two. (time = 60 min.)

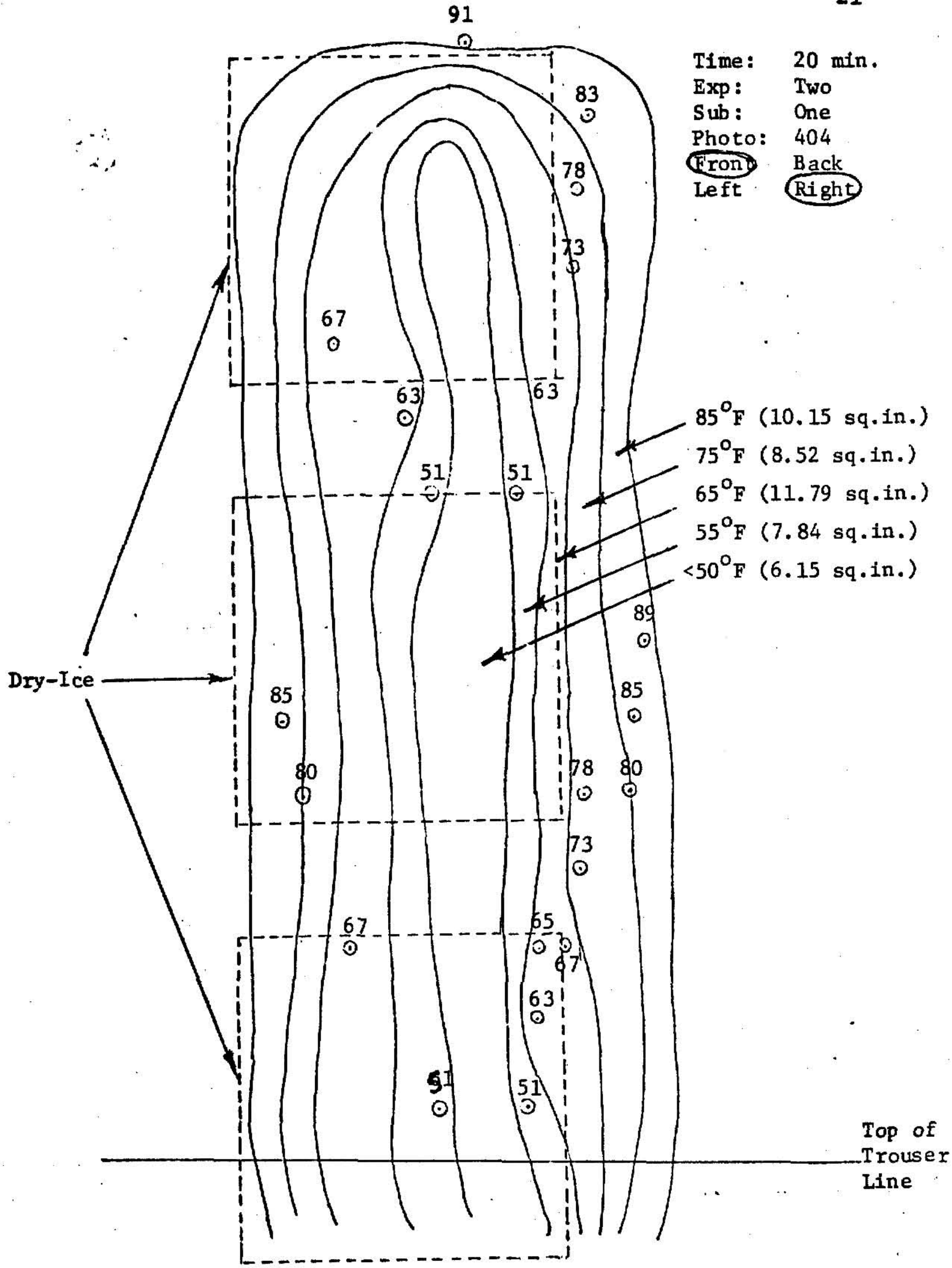

Fig. 11: Thermogram for the Front Right Pocket (time = 20 min.)

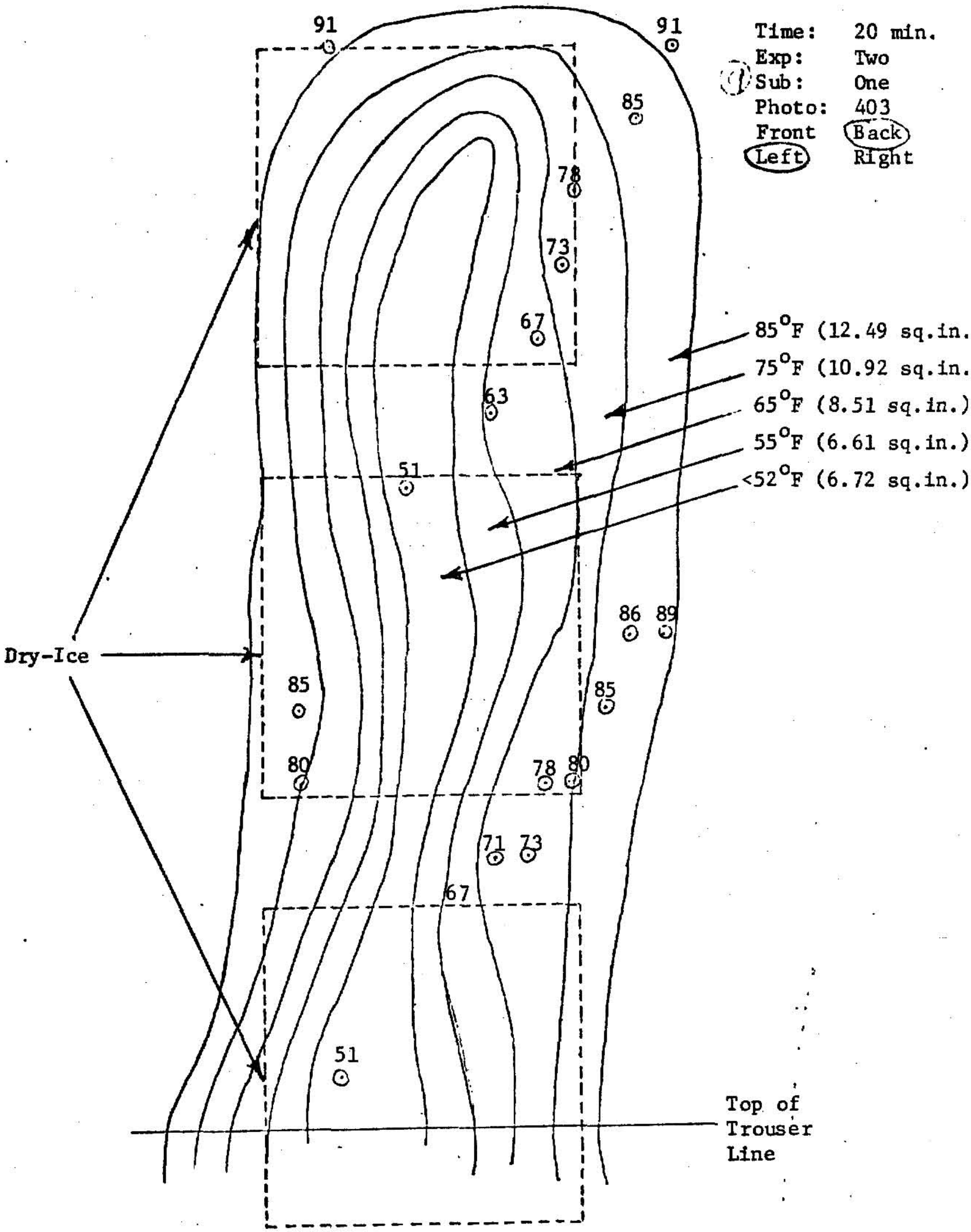

Fig. 12: Thermogram of the Back Left Pocket
(time = 20 min.)

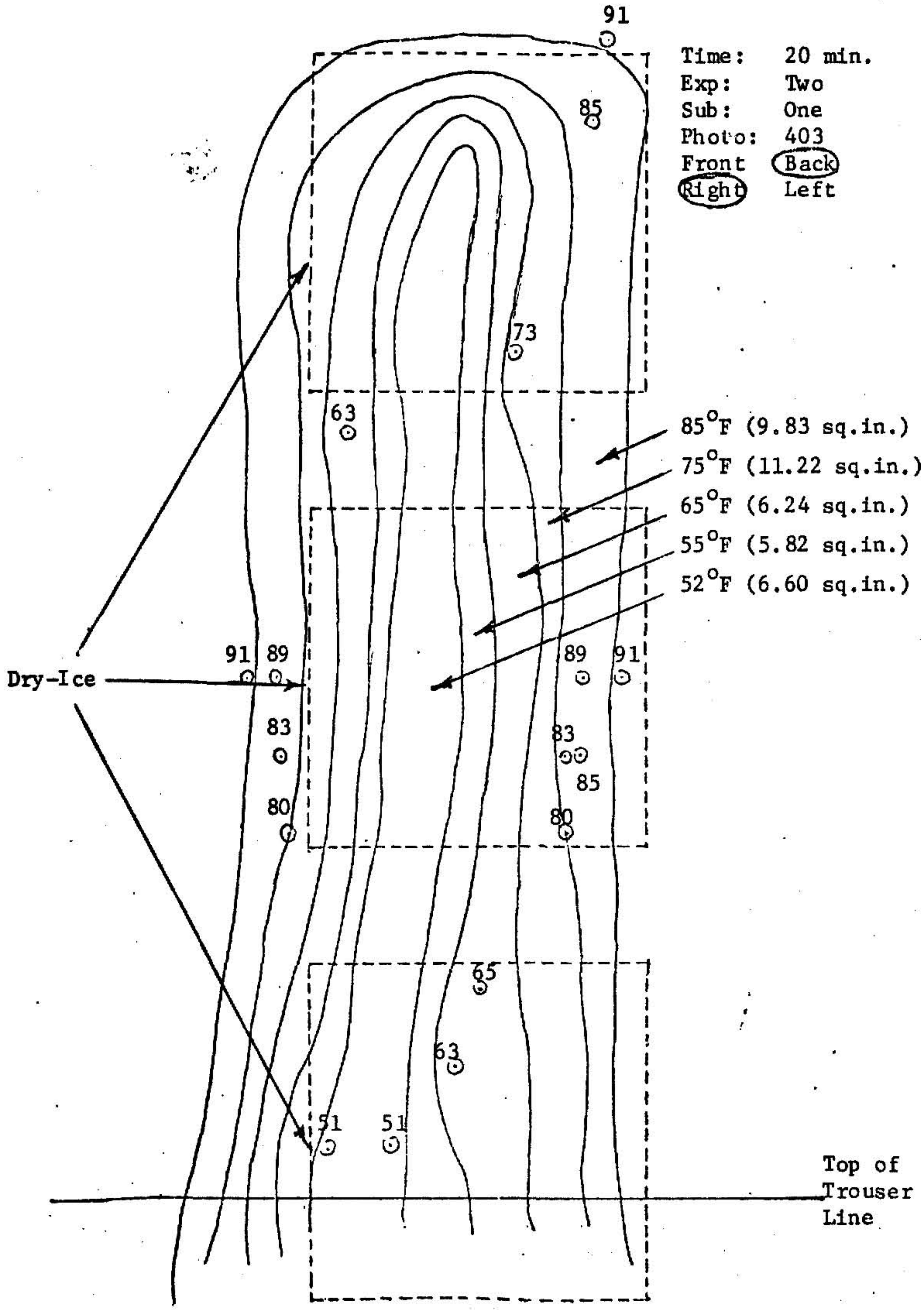

Fig. 13: Thermogram for the Back Right Pocket
(time = 20 min.)

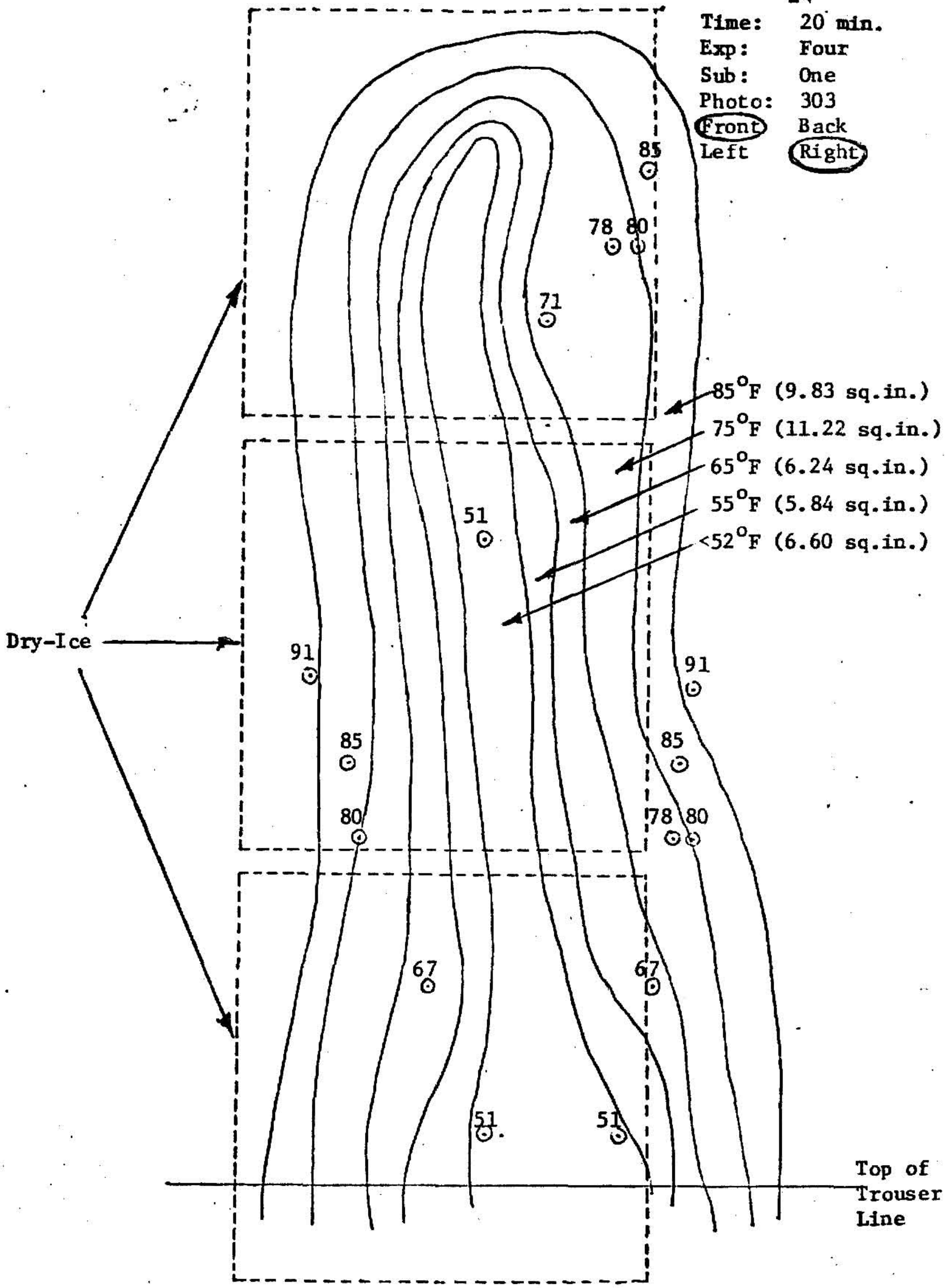

Fig. 14. Thermogram for Experimental Condition Number 4 (time = 20 min.)

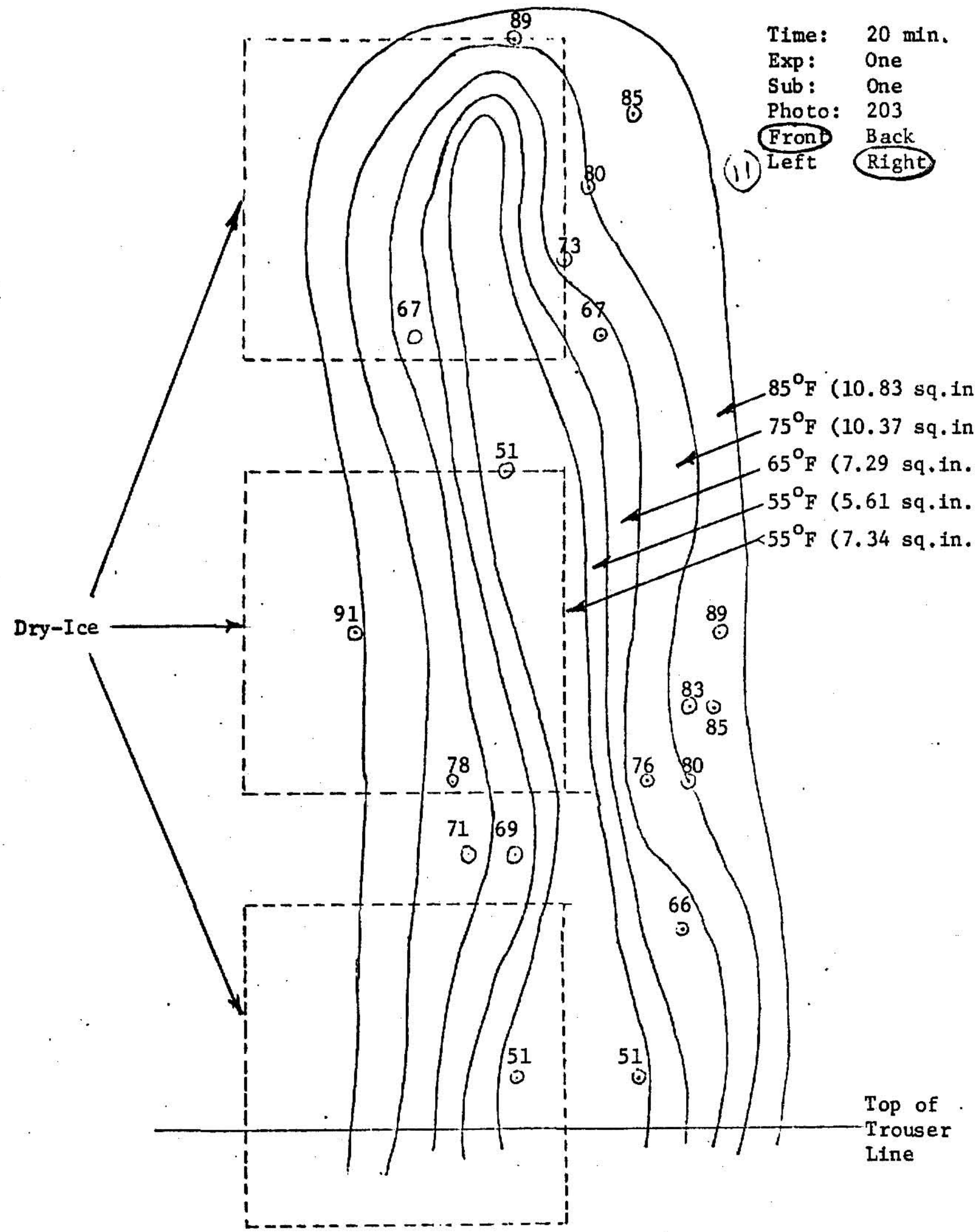

Fig. 15: Thermogram for Experimental Condition Number One (time = 20 min.)

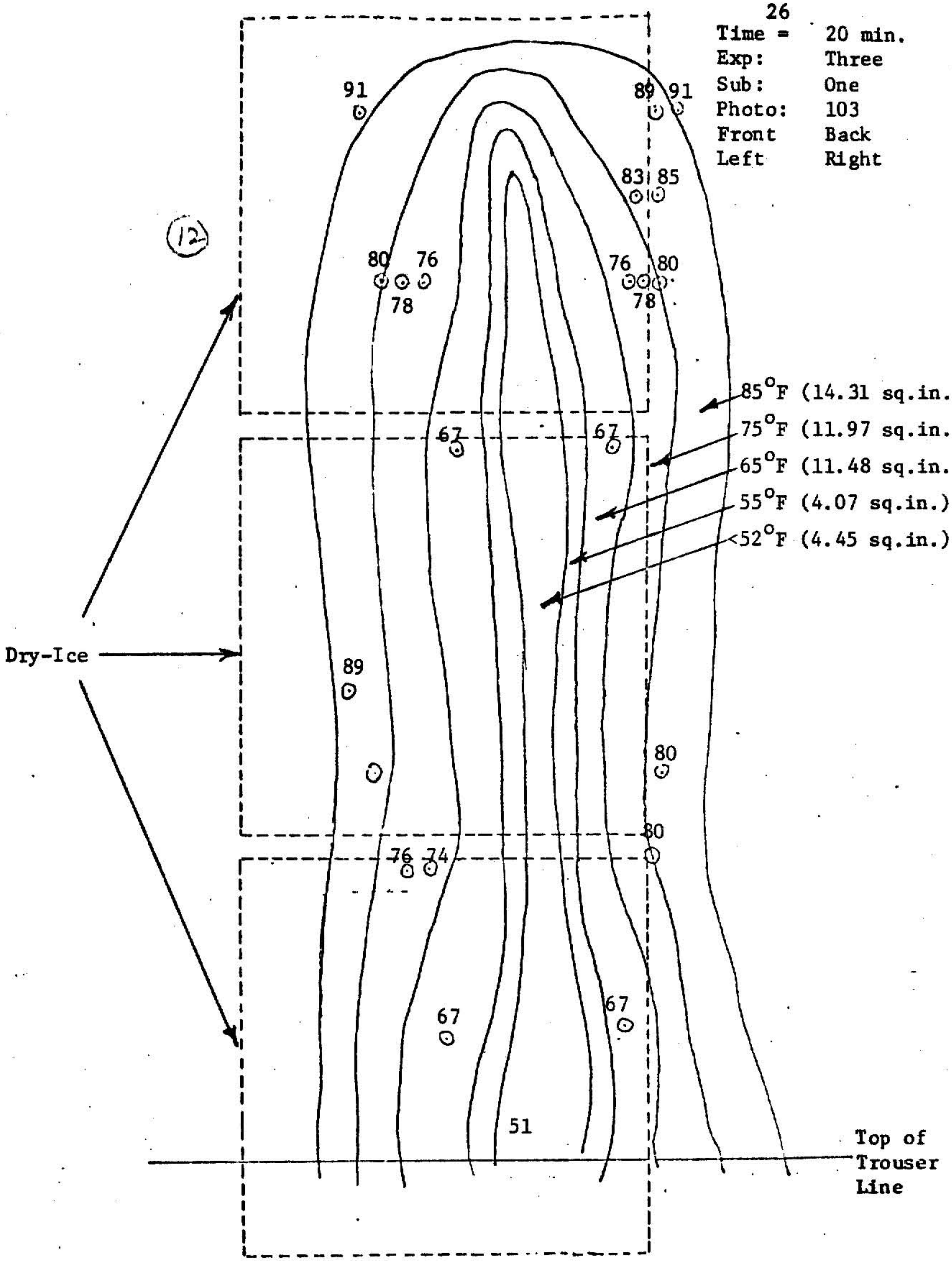

Fig. 16: Thermogram for Experimental Condition Number Three (time = 20 min.)

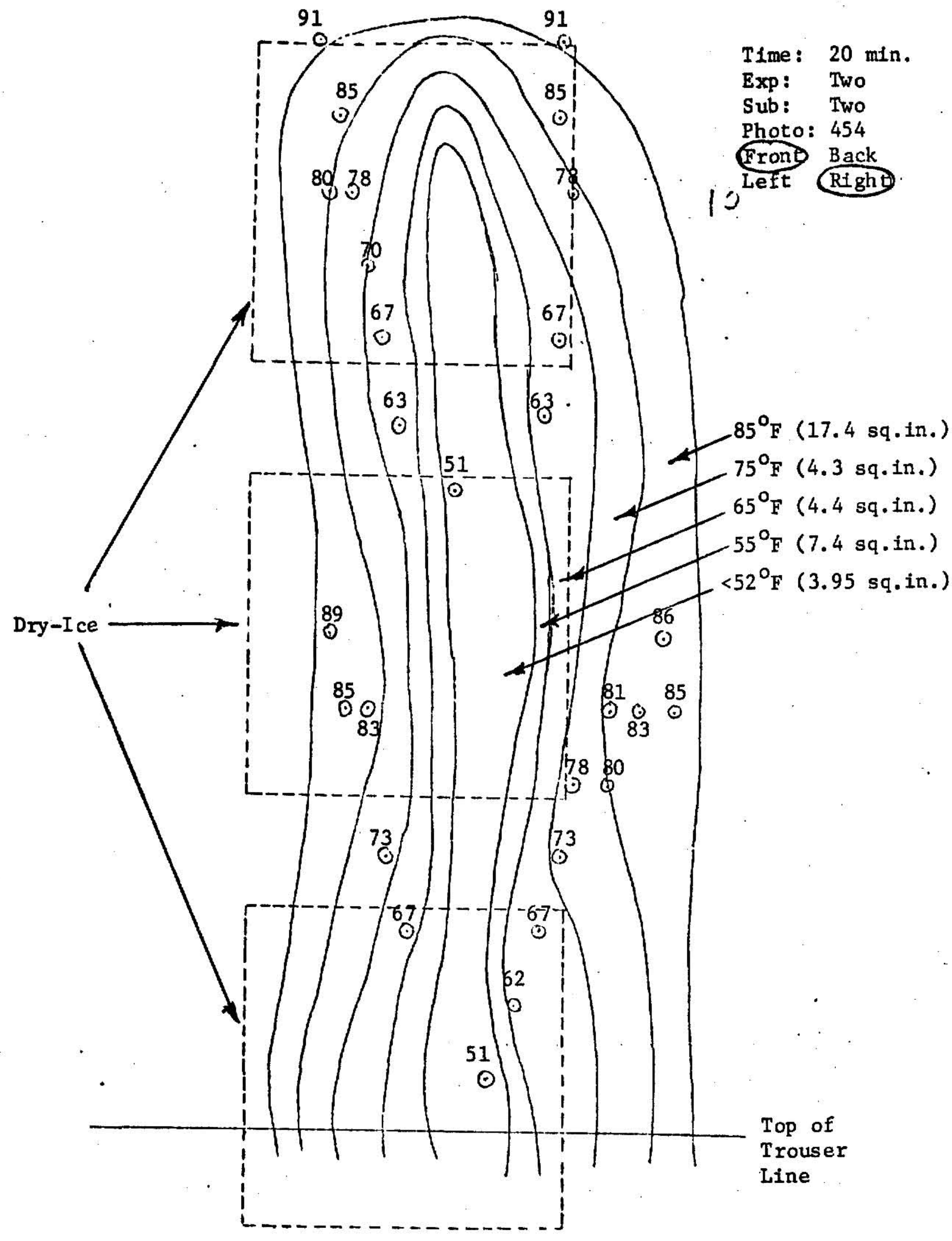

Fig. 17: Thermogram for Subject #2
(time = 20 min.)

Table 4 : Areas for Different Pockets Shown in Figures 18 to 21.

Temp. (°F)	Pocket	Time (min) 10	20	30	40	50	60	Average
90	Front Left	8.61	9.35	8.82	11.49	12.16	11.86	10.38
	Front Right	8.56	10.15	9.97	11.46	13.08	12.62	10.97
	Back Left	9.39	12.49	11.44	13.09	12.04	11.98	11.74
	Back Right	8.78	9.83	10.47	12.27	11.96	12.39	10.95
	Average	8.84	10.46	10.18	12.08	12.31	12.21	11.01
80	Front Left	14.79	11.21	9.61	4.82	10.45	11.39	10.38
	Front Right	9.76	8.52	8.04	7.73	9.03	8.36	8.57
	Back Left	10.21	10.92	9.41	11.29	10.03	10.78	10.44
	Back Right	10.46	11.22	9.37	10.79	9.93	10.56	10.39
	Average	11.31	10.47	9.11	8.66	9.86	10.27	9.95
70	Front Left	16.47	13.34	9.70	14.22	9.76	9.56	12.18
	Front Right	14.43	11.79	11.23	9.46	10.02	9.23	11.03
	Back Left	9.81	8.51	10.42	11.99	11.41	10.77	10.35
	Back Right	10.36	6.24	9.46	11.93	10.87	10.49	9.71
	Average	12.77	9.97	9.95	11.68	10.52	10.01	10.82
60	Front Left	4.57	4.99	5.90	6.34	7.03	5.06	5.65
	Front Right	6.23	7.84	8.07	8.34	7.98	8.50	7.83
	Back Left	5.98	6.61	7.41	8.96	9.03	8.33	7.72
	Back Right	5.02	5.84	7.39	8.42	8.68	7.98	7.22
	Average	5.45	6.32	7.19	8.02	8.18	7.47	7.11
50	Front Left	4.03	5.86	6.07	7.41	7.33	8.80	6.59
	Front Right	5.15	6.15	6.78	7.52	7.83	8.79	7.04
	Back Left	6.01	6.72	7.31	8.19	7.84	9.86	7.66
	Back Right	5.31	6.60	7.06	7.86	8.09	8.94	7.31
	Average	5.13	6.33	6.81	7.75	7.77	9.11	7.15

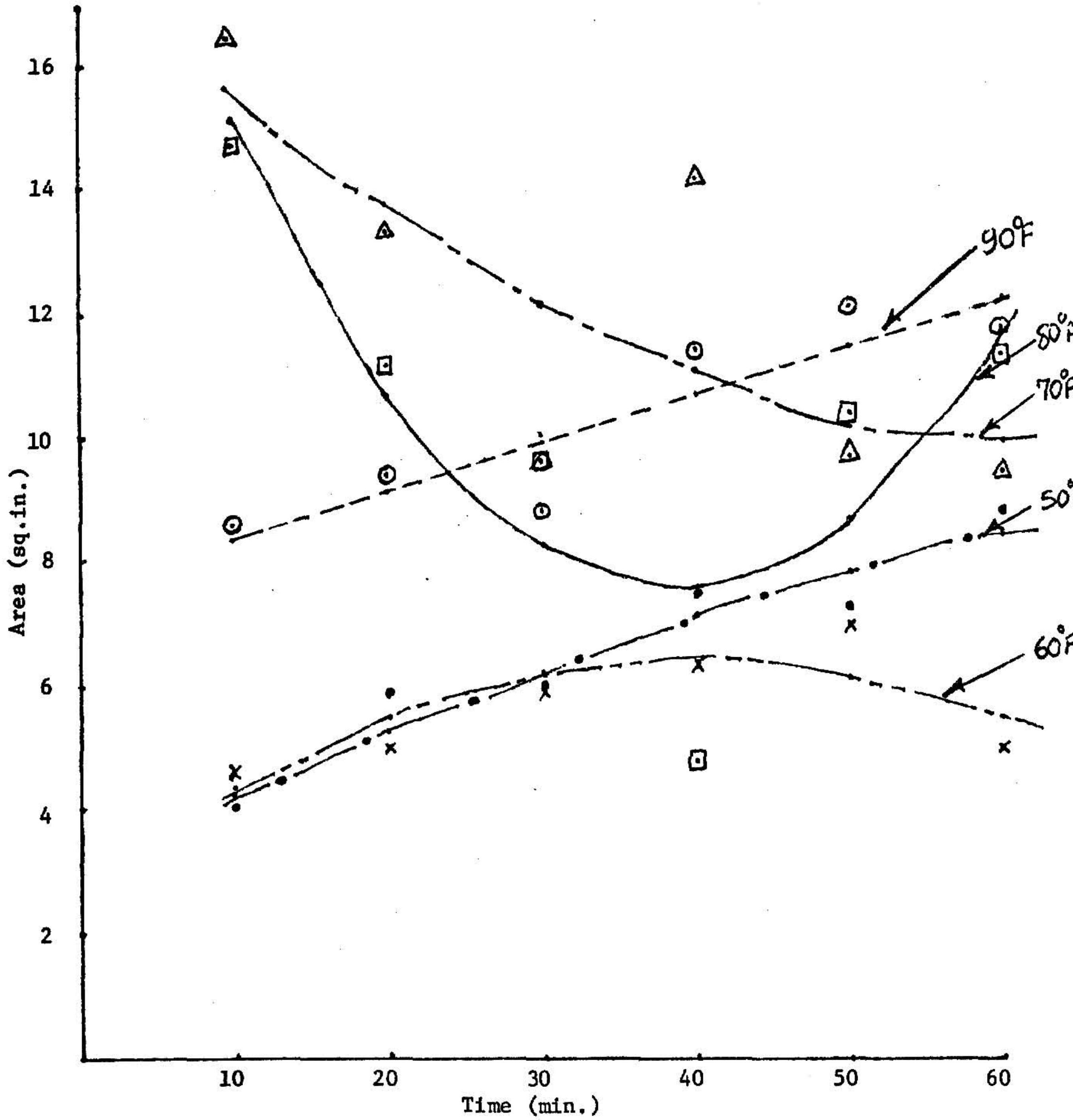

Fig. 18: Areas for Front Left Pocket

	S.E
$90^{o}F$ $(y = 7.5 + 0.08x)$	0.874
$80^{o}F$ $(y = 21.4 - 0.72x + 0.009x^2)$	1.130
$70^{o}F$ $(y = 18.1 - 0.25x + 0.002x^2)$	4.180
$60^{o}F$ $(y = 2.6 + 0.19x - 0.003x^2)$	3.580
$50^{o}F$ $(y = 3.2 + 0.12x - 0.0004x^2)$	1.590

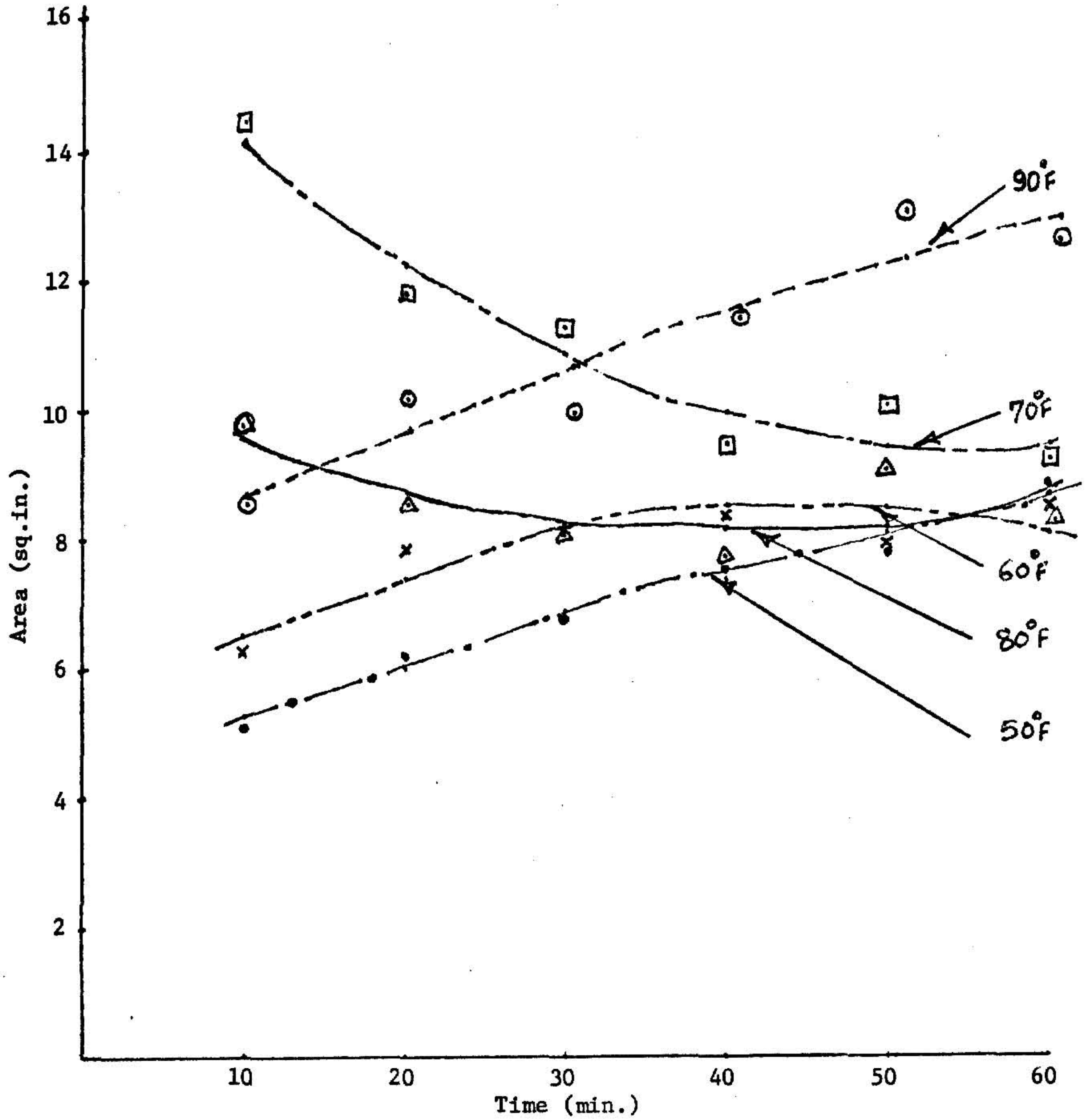

Fig. 19: Areas for Front Right Pocket	S.E.
90°F ($y = 7.4 + 0.13x - 0.0005x^2$)	0.33
80°F ($y = 10.8 - 0.14x + 0.002x^2$)	0.74
70°F ($y = 16.6 - 0.27x + 0.003x^2$)	1.01
60°F ($y = 5.3 + 0.13x - 0.001x^2$)	1.00
50°F ($y = 4.4 + 0.09x - 0.0003x^2$)	1.19

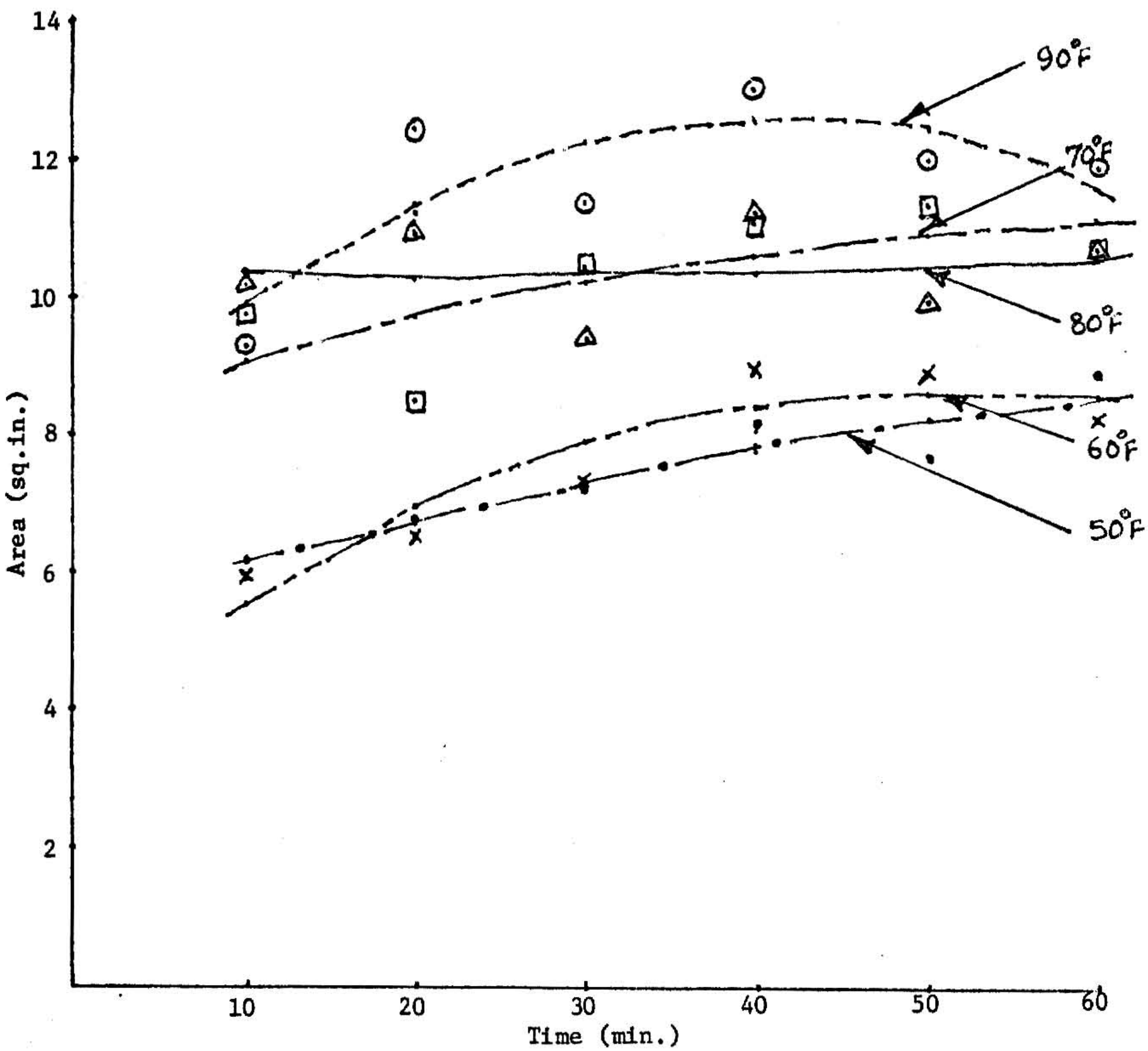

Fig. 20: Areas for Back Left Pocket

	S.E.
90°F ($y = 7.8 + 0.24x - 0.003x^2$)	0.60
80°F ($y = 10.4 - 0.01x - 0.0003x^2$)	0.93
70°F ($y = 8.5 + 0.09x - 0.0006x^2$)	1.62
60°F ($y = 4.1 + 0.17x - 0.002x^2$)	1.51
50°F ($y = 5.3 + 0.08x - 0.0004x^2$)	1.63

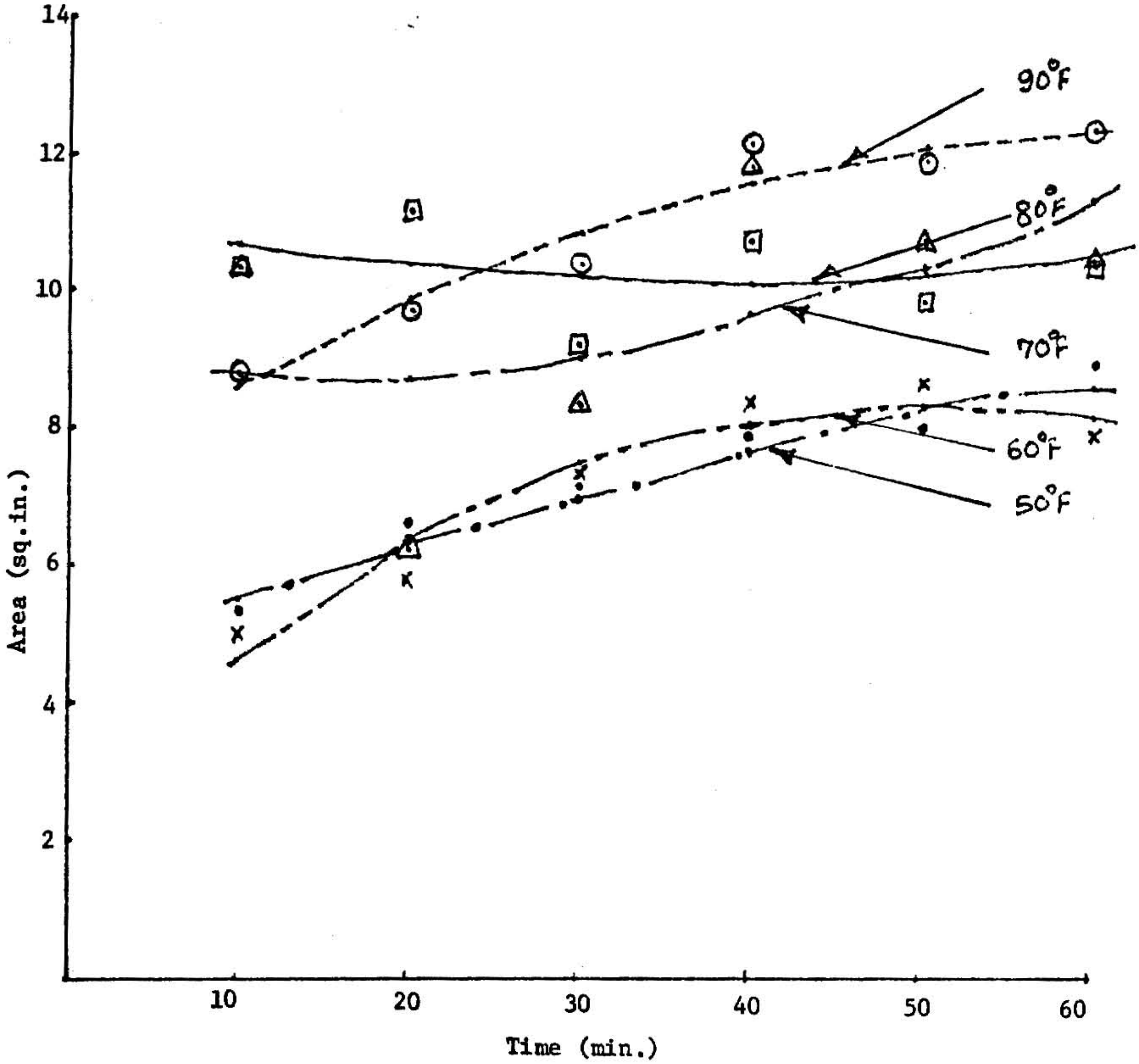

Fig. 21: Areas for Back Right Pocket

	S.E.
90°F ($y = 7.2 + 0.16x - 0.001x^2$)	0.43
80°F ($y = 11.1 - 0.05x + 0.0006x^2$)	0.72
70°F ($y = 8.9 - 0.03x + 0.001x^2$)	3.93
60°F ($y = 2.7 + 0.23x + 0.002x^2$)	1.40
50°F ($y = 4.4 + 0.12x - 0.0006x^2$)	0.79

DISCUSSION

As shown in Fig. 5 to Fig. 17, the general shape of the thermogram, irrespective of the experimental condition, is restricted to only under the pocket. Temperatures are coldest at the center of the thermogram (less than 50°F) and increase away from the center. Whenever there is a gap between the pocket and skin, the shape of the coldest temperature (less than 50°F) narrows.

Fig. 22, 23 and 24 show how the temperatures vary (for a 10 sq. inch slab) from the center of the pocket for upper, middle and bottom dry-ice compartments. These temperatures are plotted by taking the cross section at the center of each compartment for 10, 30 and 60 minutes (from Fig. 5, 7 and 10). To compare with a geographic situation, the temperature changes under the pocket are more like a "canyon" than a valley (the coldest temperatures being at the bottom of the "canyon"). As can be seen from Fig. 22, there is not much change in the colder areas (at the bottom of the graph) as the time increases from 10 to 60 minutes. But compared to the upper compartment, the bottom compartment has a significant increase in the colder areas. It is interesting to note that the total spread of colder temperatures is greater for the bottom compartment than the other two. After 60 minutes, there is a 400% increase in the spread of colder areas for the bottom compartment over upper compartment. As the dry-ice sublimes with time, carbon dioxide settles to the bottom of the vest and therefore it gives the colder temperatures and increased area for the "less than 50°F" contour for bottom compartment and 60 minutes (Fig. 24).

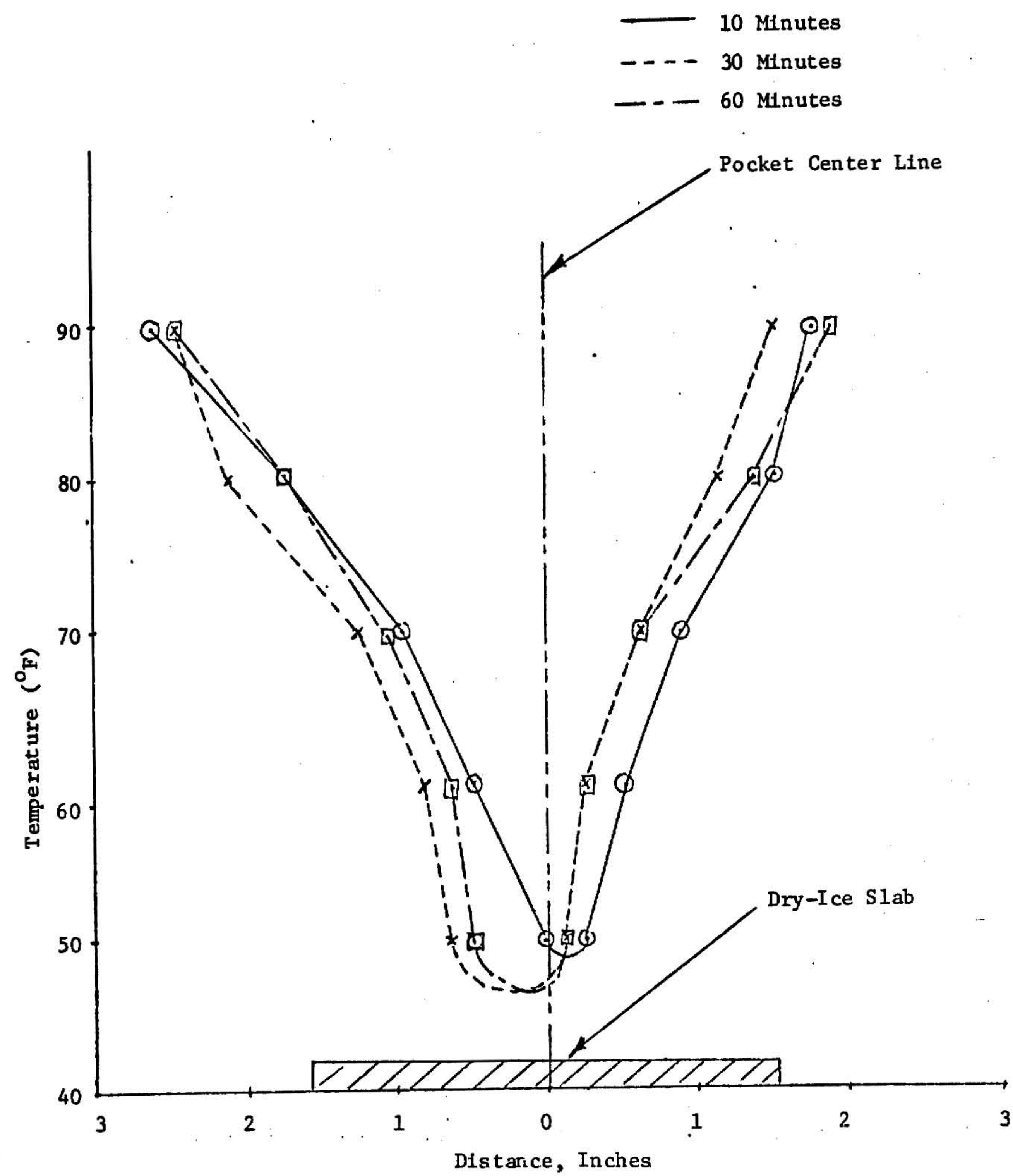

Fig. 22: Temperature Distribution at the Center of the Upper Pocket

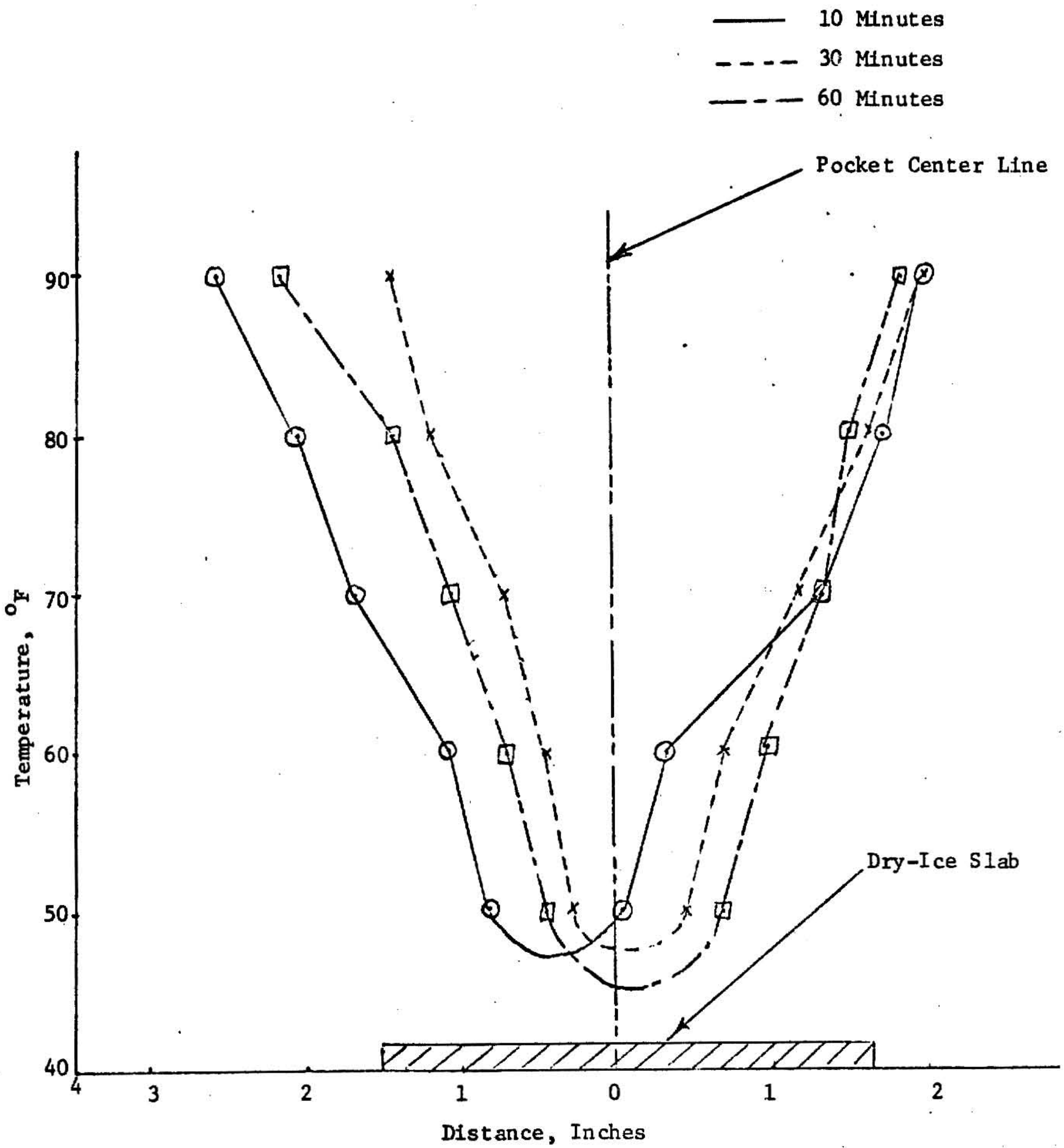

Fig. 23: Temperature Distribution at the Center of the Middle Pocket

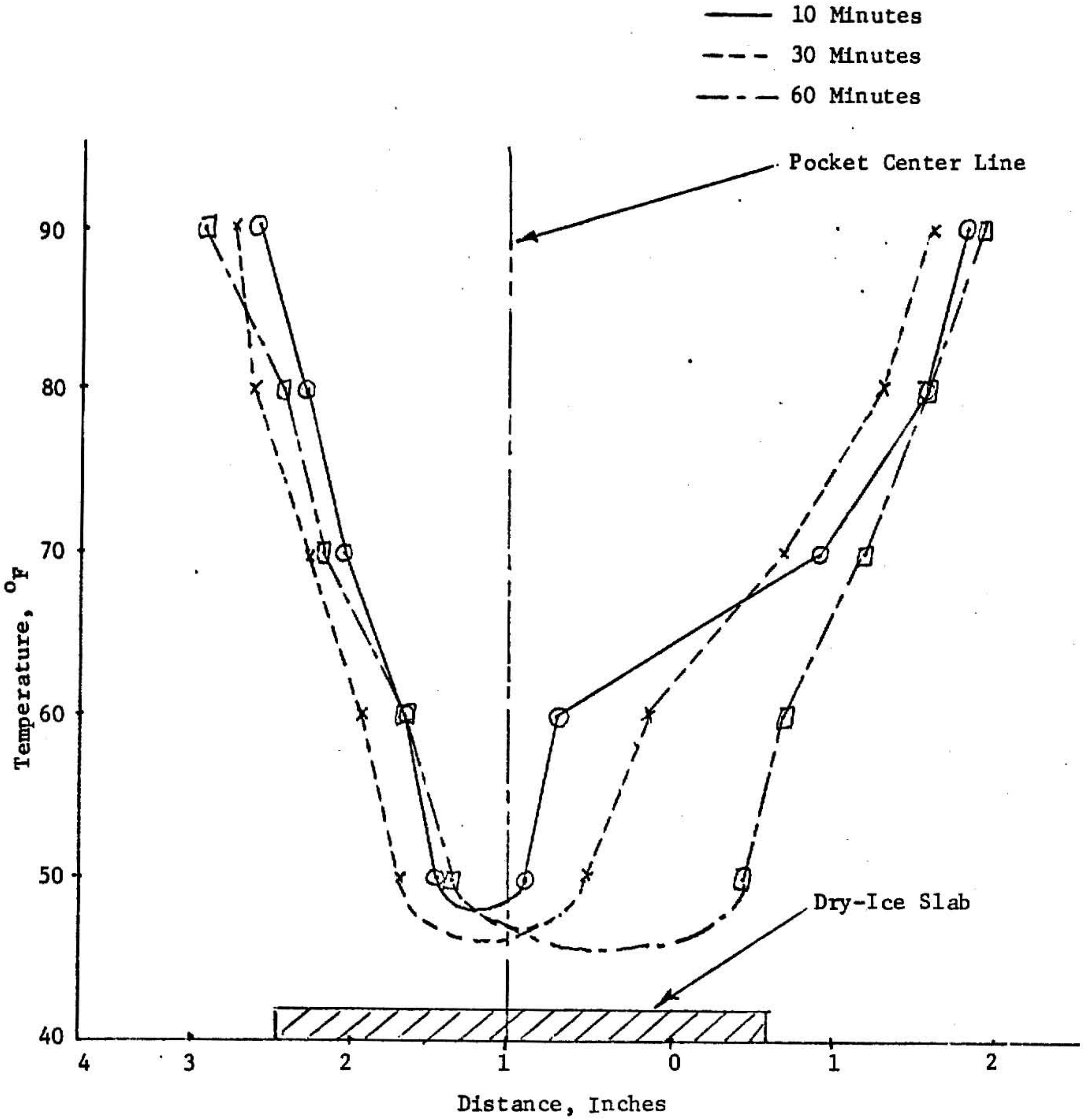

Fig. 24: Temperature Distribution at the Center of the Bottom Pocket

Front and Back Pockets

Fig. 6 (left front), 11 (right front), 12 (left back) and 13 (right back) show the thermograms for time = 20 minutes and for subject #1. There is not much change in the shape of the thermograms. The areas for different temperature contours are almost the same. Some variations, it seems, in the areas for different contours may be due to the variation in the area of contact between dry-ice and the skin.

Low and High Insulation

Table 3 shows the comparisons between 1) Low insulation and high insulation and 2) Low and high surface areas with respect to areas for different temperature contours. It can be seen from the average area values for Δ insulation, that, as the insulation is changed from high insulation to low insulation, areas under the 50°F and 55°F contours increase but area between 60 and 70°F contour decrease very much; the outer areas (for 85 and 95°F contours) do not change appreciably. That is, insulation does not affect the outside areas of the thermogram. Low insulation just makes the center cold area larger with less area at the 65°F contour.

Low and High Surface Area

Again, from the average area values (Table 3) for Δ surface area, it can be seen that as the surface area is changed from high surface area to low surface area, that there is not much change in the center cold area, but it decreases the outer area. In other words, large chunks of dry-ice do not make the center cold area larger, they just increase the outer cooled area.

Table 3: Comparison Between 1) Low and High Insulation; 2) Low and High Surface Area.

Surface Area	Insulation	Temp (°F) 50	55	65	75	85	Total
		Area (sq. inch.)					
High	Low	8.0	6.5	8.7	11.7	12.6	47.5
Low	Low	7.3	5.6	7.3	10.4	10.8	41.4
High	High	4.4	4.1	11.5	12.0	14.3	46.3
Low	High	5.9	5.0	13.3	11.2	9.3	44.7

Δ Insulation (Low-High)

Surface Area	50°F	55°F	65°F	75°F	85°F
High	+3.6	+2.4	-2.8	-0.3	-1.7
Low	+1.4	+0.6	-6.0	-0.8	+1.5
	5.0	3.0	-8.8	-1.1	-0.2
Average	+2.5	+1.5	-4.4	-0.5	-0.1

Δ Surface Area (Low-High)

Insulation	50°F	55°F	65°F	75°F	85°F
High	1.5	0.9	1.8	-0.8	-5.0
Low	-0.7	-0.9	-1.4	-1.3	-1.8
	+0.8	0	0.4	-2.1	-6.8
Average	+0.4	0	+0.2	-1.05	-3.4

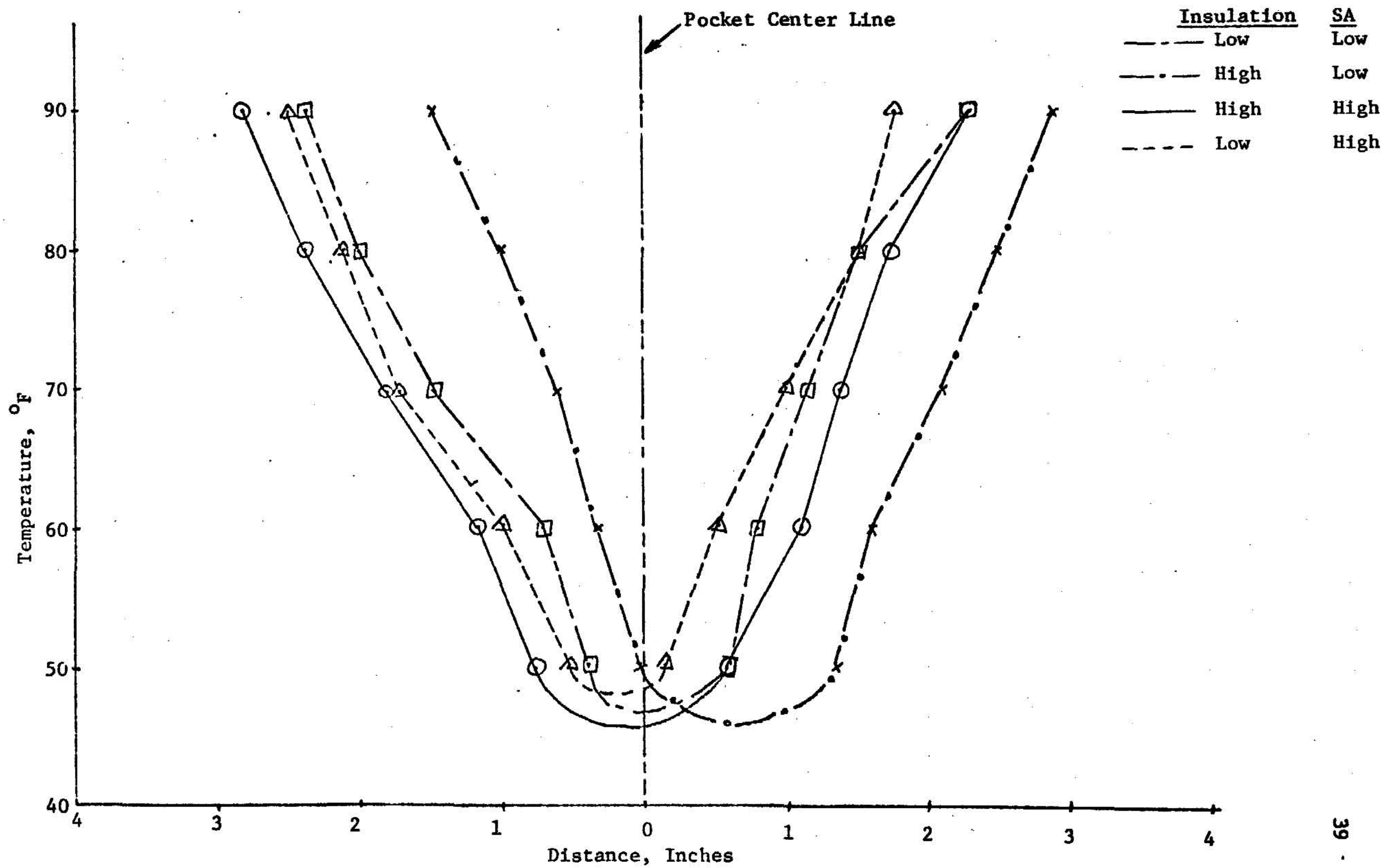

Fig. 25: Temperature Distribution for Different Insulations and Surface Areas (time = 20 min.)

The desirable temperatures for the human torso should be between 65-85°F rather than having <50°F. Therefore, from the above discussion, it is recommended to have high insulation and high surface area of dry-ice for the pocket so that the temperature will not go undesirably low and outer cooled area will be increased.

Subject Number 1 and 2.

Fig. 17 shows the thermogram for the front right pocket for the subject #2 for experimental condition #2 (low conductance and low surface area). From Fig. 26, it can be seen there are variations between the areas for different contours for two subjects. Approximately 40% of the total thermogram area for subject #2 is for the 85°F contour. It seems this is because of the more fat body, hence more ups and downs on the chest of subject #2 (fat % = 11.2%) compared to the relatively flat body of the subject #1 (fat % = 9.3%). This in effect reduced the contact area between dry-ice pocket and the skin for subject #2. Therefore there is less area for the colder temperatures and hence less total thermogram area. It also could be that fat has less conductivity than "flesh".

Persistance of the Cooling

Before starting the experiments, it was assumed that after 60 minutes of dry-ice cooling, skin temperatures would return to normal temperatures (95°F) within 4 to 5 minutes.

To check this assumption, on the 4th day, after 60 minutes of dry-ice cooling, photographs of the front and back were taken for subject #1 every five minutes for an additional 20 minutes. Thermograms for all the

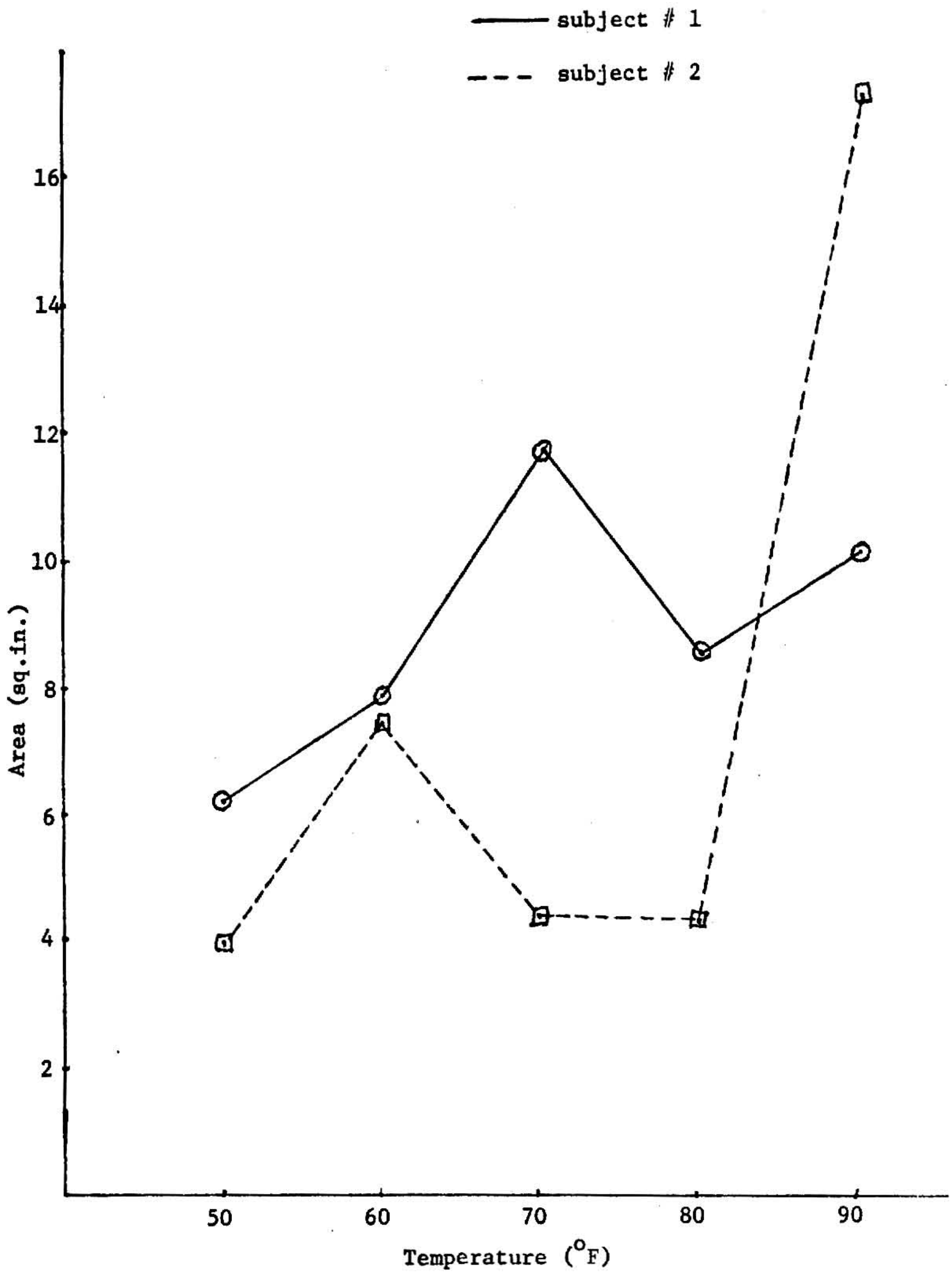

Fig. 26: Contour Areas for Two Subjects

front and back pockets were almost the same. There was no appreciable difference in the thermograms for the front and back pockets. Fig. 27 shows the coldest temperatures of the front left pocket from minute 60 to 80. The skin temperatures came to normal after 20 minutes.

Control Day

Condition #5 (Table 1) with no cooling was performed on the 5th day. Fig. 28 shows the thermogram for the front. The position of the (would be) dry-ice is shown by the dotted line. Fig. 29 and 30 show the photograph of front and back for the control day.

Suggested Method

Since I had used seven different liquid crystal ranges at a time, I was unable to get the exact nature of the temperature contours. The contours I have drawn are estimated. Herewith I suggest a new but lengthy method by which we can get exact thermograms.

Use one liquid crystal range at a time for the entire torso. We can get the exact thermogram for the same range (see Fig. 29 and 30 for a dry run). Then, keeping the experimental conditions the same, use the next liquid crystal range for the entire torso and get the exact thermogram for that range and so on for the remaining liquid crystal ranges. Then superimpose all the thermograms together, which will give an exact thermal mapping of the torso. This method is lengthy, but it will give the exact thermogram.

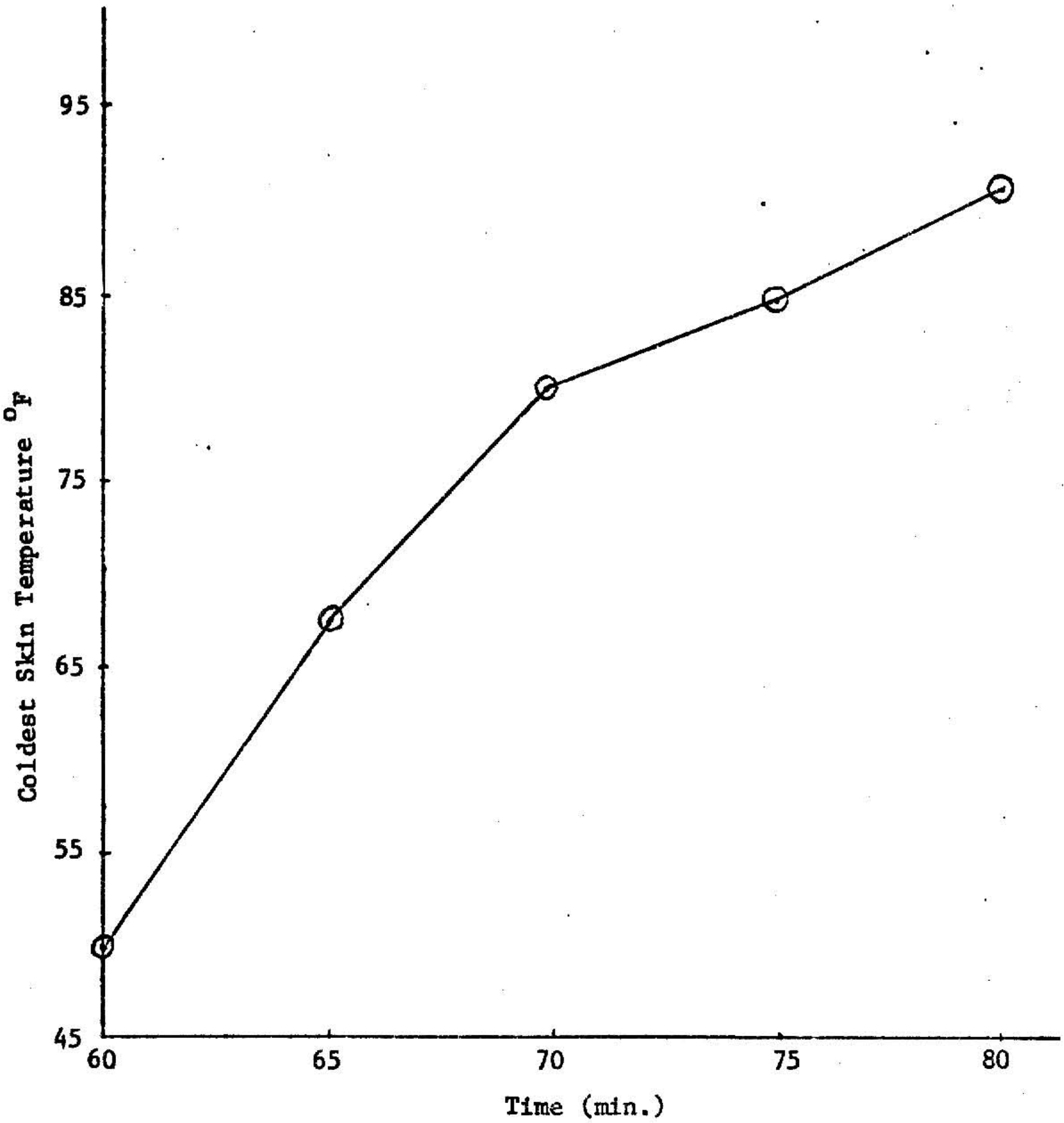

Fig. 27: Persistance of Cooling

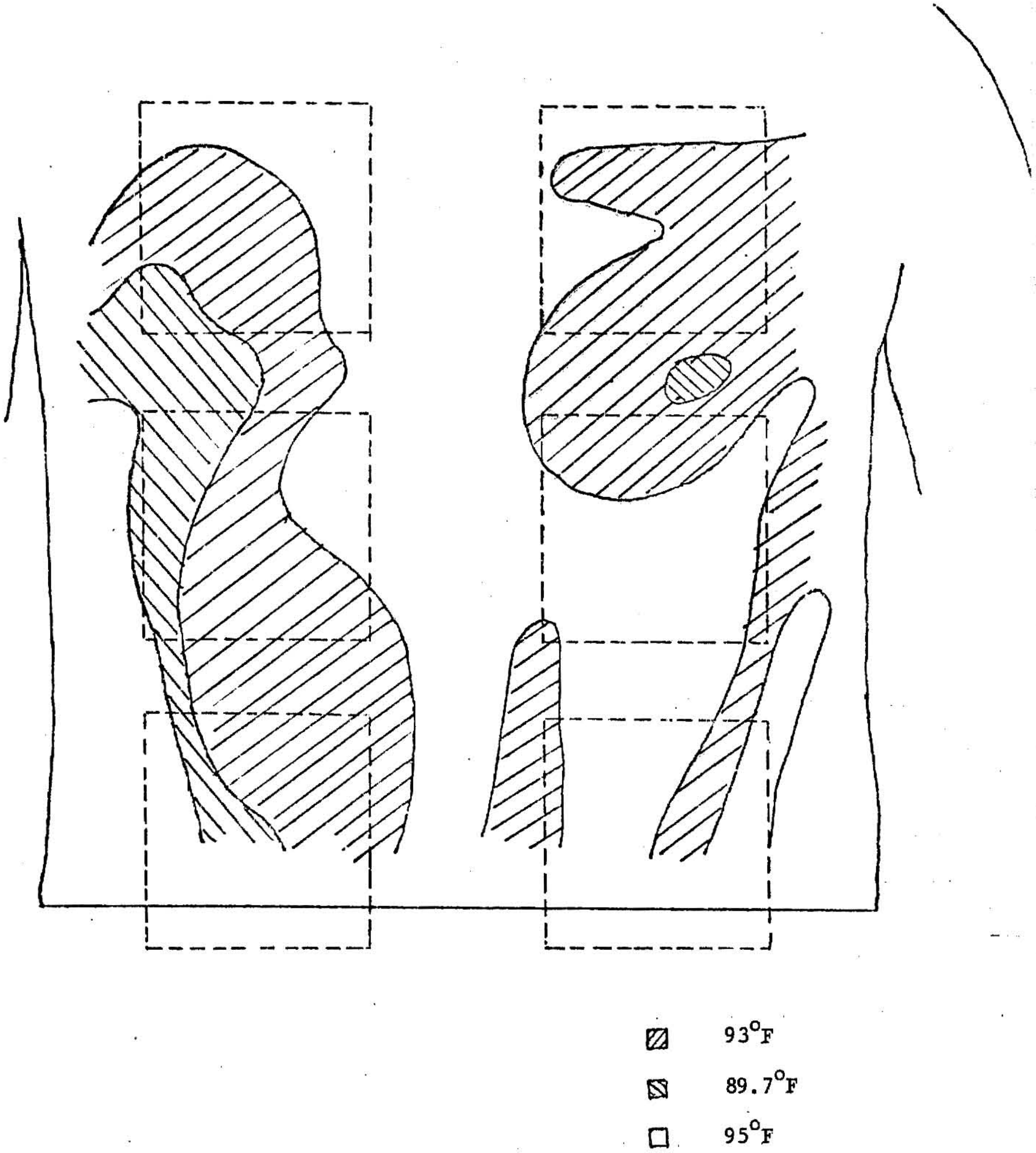

Fig. 28: Thermogram for the Front (Control Day)

Fig. 29: Front Photograph (Control Day)

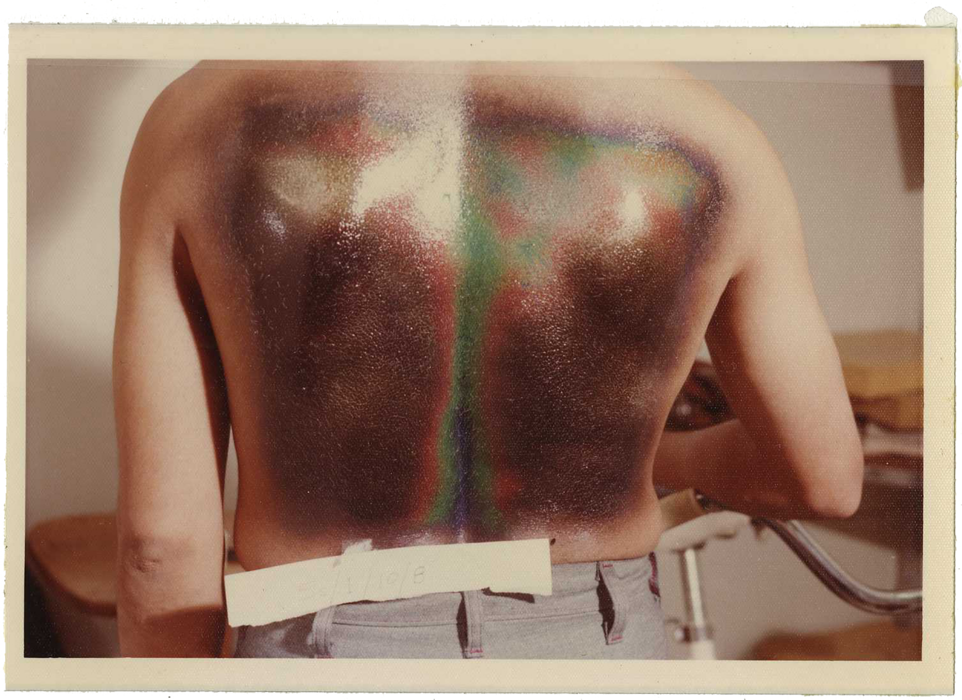

Fig. 30: Back Photograph (Control Day)

CONCLUSIONS

1. The shape and area of the thermogram due to dry-ice cooling depends upon a) the design of the pocket, b) the area of contact between dry-ice pocket and the skin.
2. Insulation does not affect outside area of the thermogram. Low insulation just makes the center cold area larger with less area at 65°F.
3. Large chunks of dry-ice do not make the center cold area larger, they just increase the outer cooled area of the thermogram.
4. When the dry-ice cooling garment is taken off after 60 minutes, it takes approximately 20 minutes to normalize the skin temperatures.

REFERENCES

1. Consolozio, J. P.: Physiological Measurements of Metabolic Functions in Man. McGraw Hill, 300-308.

2. Cooper, T. E. and W. K. Petrovic: An Experimental Investigation of the Temperature Field Produced by a Cryosurgical Cannula. ASME Publication 73-WA/Bio 20, 1-9, 1973.

3. Cooper, T. E. and J. P. Groff: Thermal Mapping, Via Liquid Crystals, of the Temperature Field Near a Heated Surgical Probe. ASME Trans May 1973, 250-256.

4. Davison, Thomas A., K. Ewing, J. Fergason, M. Chapman, A. Can and C. Voorhis: Detection of Breast Cancer by Liquid Crystal Thermography. Cancer, May 1972, 1123-1132.

5. Davison, Thomas A.: Applications of Liquid Crystal Thermography in Clinical Medicine and Applied Physiology. Ph.D. Dissertation, Kent State University, 1972.

6. Fergason, J. L.: Liquid Crystals in Nondestructive Testing. Applied Topics, Sept. 1968, Vol 7, No. 9, 1729-37.

7. Fergason, J. L.: Experiments with Cholesteric Liquid Crystals. American Journal of Physics, April 1970, Vol 38, No 4, 425-28.

8. Konz, S., C. Hwang, R. Perkins and S. Borell: Personal Cooling with Dry-Ice. American Industrial Hygiene Association Journal. March 1974, Vol 35, No 3, 137-146.

9. Pick, P. G., J. Fabijanic and A. Stewart: The Effect of Ambient Light on Liquid Crystal Tapes. Molecular Crystals and Liquid Crystals, 1973, Vol. 15, 371-76.

10. Pick, P. G. and J. Fabijanic: Cholesteric Liquid Crystal: Ambient Temperature Effects. Molecular Crystals and Liquid Crystals. 1972, Vol 15, 371-76.

11. Selawry, O. G., H. Selawry and J. Holland: The Use of Liquid Crystal for Thermographic Measurement of Skin Temperature in Man. Molecular Crystals. 1966, Vol 1, 495-501.

12. Selawry, O. G., H. Neubaurer, H. Selawry and F. Hoffmeister: Cholesteric Thermogrpahy in Tumors of the Head and Neck. American Journal of Surgery, Vol 112, Oct 1966, 537-40.

LIQUID CRYSTAL THERMOGRAPHY OF TORSO SKIN TEMPERATURES FOR DRY-ICE COOLING

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ABSTRACT

Seven different liquid crystal ranges were used on two male subjects to measure the effect of dry-ice cooling on the human torso. Insulation between dry-ice and the skin (conductances of 17.1 and 5.35 x 10^{-5} gm-cal/sec-sq.cm-^{o}C) and surface area per slab of dry-ice facing the skin (10 and 20 sq. inches) were varied. Subjects pedalled an ergometer at an (estimated) metabolic rate of 200 Kcal/hr for 60 minutes. Front and back photos were taken after every 10 minutes to record the colors.

Thermograms were drawn for the different conditions. Areas for different temperature ranges were measured from the thermogram with a planimeter.

The shape and area of the various temperature bands due to dry-ice cooling under the pocket depends upon 1) the design of the pocket, 2) the area of contact between the dry-ice pocket and the skin. High insulation and high surface area increase the outer cooled area and reduce the center cooled area of the thermogram.