DECEMBER 1969

MDC G1220

# EMERGENCY EVAPORATIVE COOLANT GARMENT SYSTEM/LIQUID-COOLED GARMENT (EECGS/LCG)

PREPARED UNDER CONTRACT NO. NAS-9-7207 BY McDONNELL DOUGLAS ASTRONAUTICS COMPANY – WESTERN DIVISION FOR NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

## PHASE II FINAL REPORT



MCDONNELL DOUGLAS ASTRONAUTICS COMPANY

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NASA CR 102153

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PREPARED UNDER CONTRACT NO. N[illegible]-9-7207
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# FOREWORD

McDonnell Douglas Astronautics Company--Western Division (MDAC-WD) gratefully acknowledges program support provided by the NASA-Manned Spacecraft Center. In particular considerable technical assistance and advice was provided by Messrs. Larry E. Bell, William J. Huffstetler, and Fred A. Spross of the NASA-MSC, Crew Systems Division. Thanks are also given to Ward E. King and S. Benn of the USAF Plant Representatives Office who were observers on the final design verification test.

Also participating via exchange of technical information and comments on skin thermophysiology was Dr. Allen Chambers of the NASA-Ames Research Center. On the MDAC-WD team, special thanks are due Mrs. Alice Chatham for her diligent work in the EECGS garment fabrication; and also to test engineers R. C. Richards and R. C. Ventonis.

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CONTENTS

## FIGURES

## Section 1
## INTRODUCTION AND SUMMARY

This report presents the results of the second phase overall effort to develop a new concept high-performance Evaporative Cooling Garment System (ECGS) (see Figure 1). The first phase (Reference 1) was devoted to proof of principle, and a test program to determine the maximum heat transfer performance for a full ECGS comprising cooling of arms, legs, torso, and the head. The first suit (Figure 2) was integrated with the Apollo A-6L space pressure suit and showed that an astronaut with sustained metabolic rates of at least 5,000 Btu/hr could be cooled in full comfort with this suit.

The second phase covered an investigation of the potential of the ECGS concept as applied to an emergency cooling system to supplement the current Liquid-Cooled Garment (LCG). The requirements further stipulated that the presence of the Emergency Evaporative Cooling Garment System (EECGS) should not affect the normal operation and/or effectiveness of the LCG.

The only exposed areas of the body not covered by the LCG were the collar, head, hands, and feet. These locations were the most difficult to utilize, but available; the only other possible heat transfer areas were those already covered by the LCG. Since the LCG was not to be compromised in any way, the only possible way to obtain maximum cooling potential was to cool through the LCG along with cooling the unused body surface areas.

The EECGS, therefore, had to be integrated with the LCG forming an EECGS/LCG. The target performance was to provide cooling for 30 minutes at 3,000-Btu/hr metabolic rate, all on ECGS self-contained internally stored expendables (water); and to operate with the LCG at zero cooling rate.

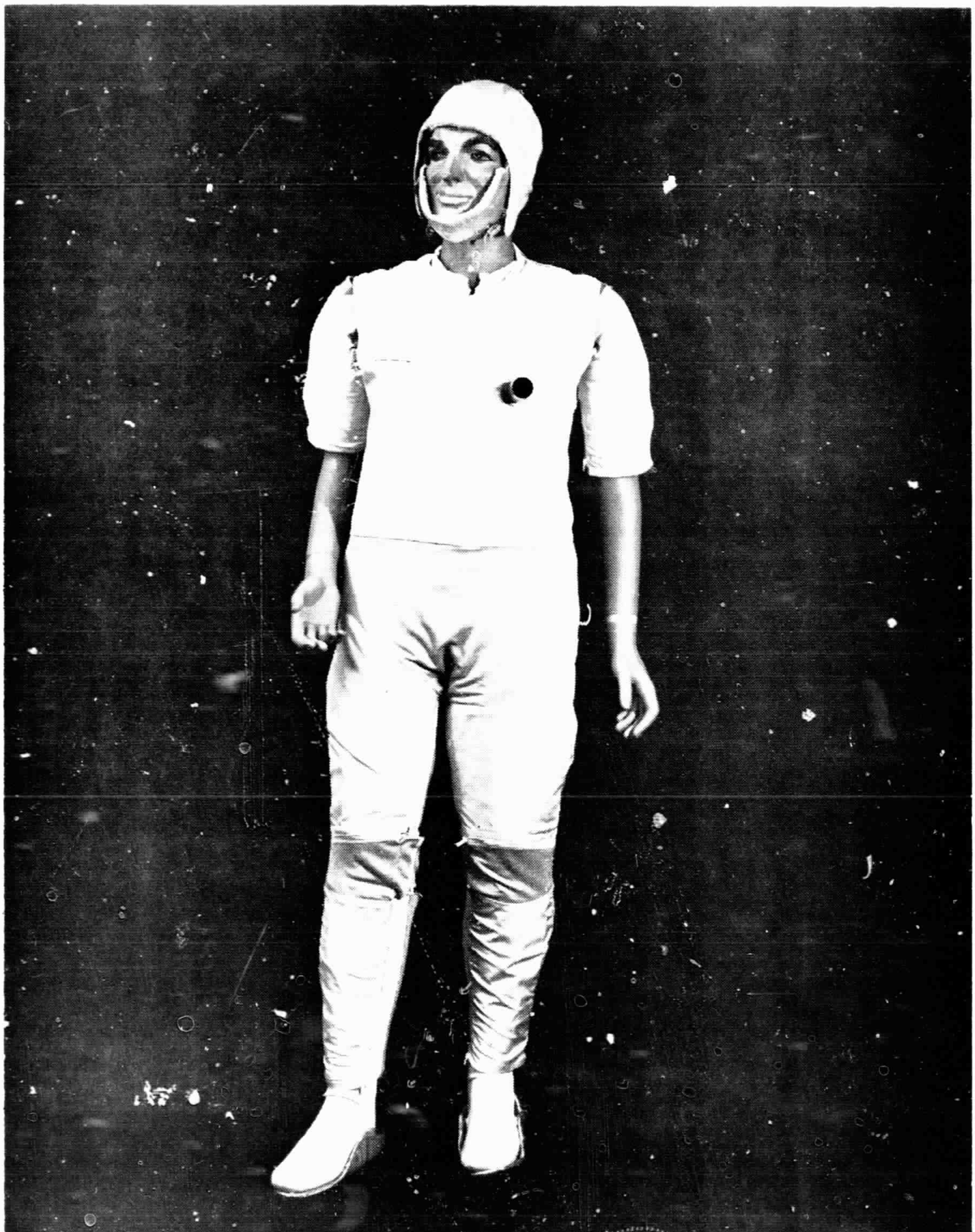


Figure 1. EECGS/LCG Suit

Figure 2. ECGS Garment

The EECGS/LCG configuration evolved included an ECGS collar fastened to and located under the LCG, but not interfering with its operation; redesigned Phase I ECGS cooling segments worn over the arms and legs of the LCG; an ECGS Phase I helmet; and new ECGS foot cooling segments. Torso, neck, and hand cooling was not needed.

Early in the program, it was desired by NASA to provide higher cooling capability to an increased level of 4,000-Btu/hr metabolic rate (not by contractual requirement however). Test results from the Phase I program indicated that thermal balance heat rejection rates of 2,290 and 2,980 Btu/hr would be required for metabolic rates of 3,000 and 4,000 Btu/hr respectively.

The contract target cooling performance was 2,290 Btu/hr, and it was desired that this level could be eventually be raised to 2,980 Btu/hr. The final design verification test mission cooling results gave 2,430-Btu/hr average cooling for the full half hour in the EECGS/LCG configuration described, and further indicated that over 3,000-But/hr total cooling would have resulted if the Phase I torso segments were integrated into the suit.

Other results of the program indicated that EECGS cooling can be apportioned as follows: head - 10 percent; collar - 12 percent; arms - 25 percent; legs - 44 percent; and feet - 9 percent. It was also determined that a moderate training program can produce over 45 minutes nonstop endurance at over 4,000-Btu/hr metabolic rates.

## Section 2
## ECGS DESCRIPTION AND OPERATION

The LCG and the ECGS are shown in Figure 3. In the LCG there are two major loops -- the water circulation subsystem and the backpack water-sublimation heat exchanger. The liquid circulating loop has been eliminated in the ECGS as it serves no function, and the water sublimator was placed directly into the cooling segments, thus eliminating the need for a water pump and its associated battery power requirements. The ECGS has no dependence upon the backpack.

Figure 4 presents the essential functional components of the ECGS. These include the following (Reference 2):

1. A next-to-the-body skin membrane which encloses the entire cooling segment and forms a vacuum-tight enclosure.

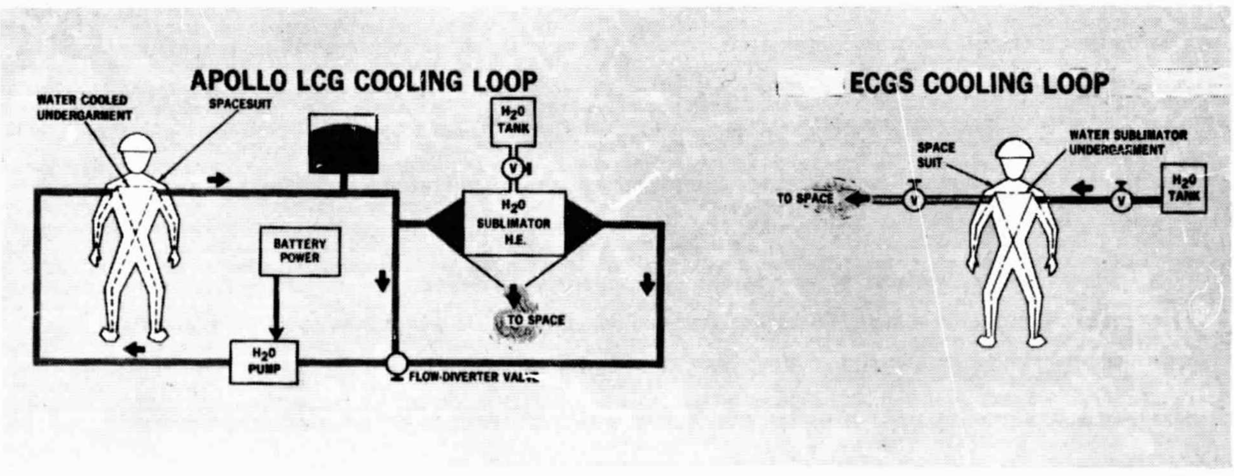



Figure 3. State-of-the-Art Cooling System

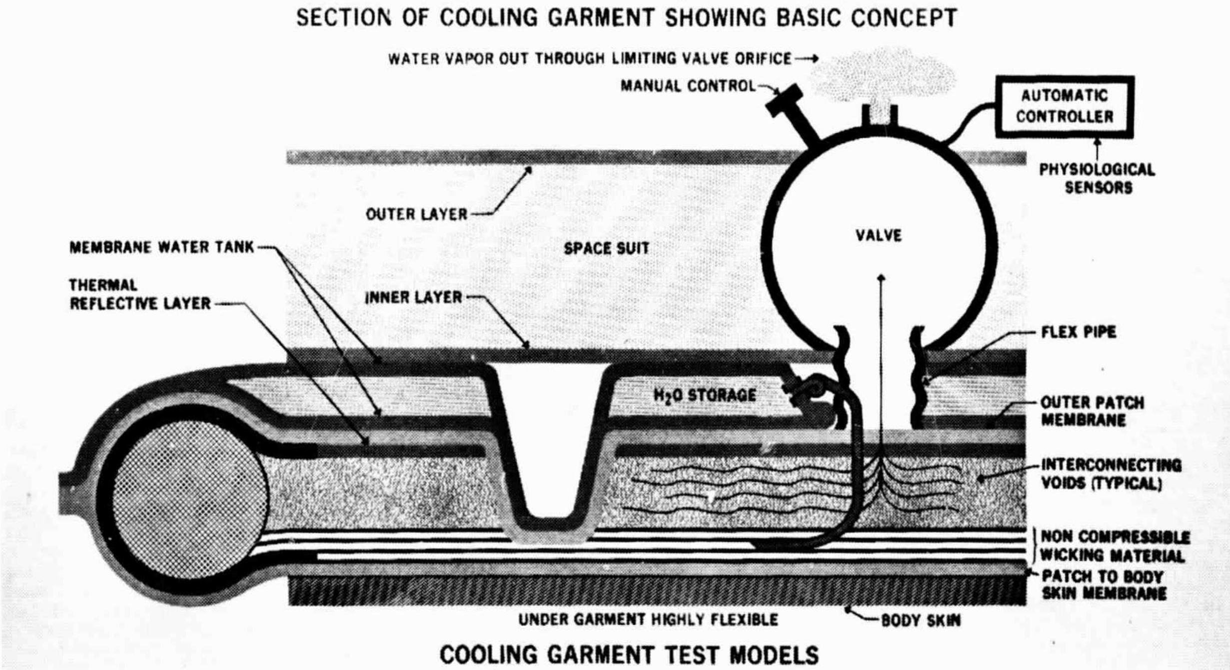



**Figure 4. ECGS Major Functional Components**

2. A wicking layer placed within this bag next to the skin side.
3. A flexible interconnecting void, adjacent to the wicking layer, which allows gas to flow freely through the structure.

A valve-controlled vacuum line, through which gas containing skin-heat energy is ejected through the space suit to space, penetrates the outer membrane. Also included is a fluid supply line which, via a control valve, transmits expendable water to the wicking layer from an integral plastic water container.

The suit operates as follows: heat from the skin is transmitted through the skin membrane to the moistened wicking layer; the interior is exposed to vacuum via the exterior control valve; a phase change takes place by conversion of the expendable water from liquid to gas within the wicking and void structure; and the gas containing skin-heat energy is ejected directly to space. This phase change removes the heat energy in the form of cold steam (Reference 3). The cooling segment as shown in Figure 4 is less than 1/10 inch (2. 54 mm) thick and is extremely flexible to conform to any curved surface of the body with full wearing comfort.

The several cooling segments comprising the ECGS garment are interconnected as shown in Figure 5. It should be noted that the articulation areas such as the hips, knees, and elbows are not cooled, but these areas do connect the cooling segments together; this assures maximum flexibility of the suit, through which excellent wearing comfort has been accomplished. The vacuum lines are all commonly ported to a single outlet located at the LCG fitting which is the only penetration through the space pressure suit. No connection with the backpack is required. An ECGS outer liner covers all segment penetrations to make a smooth outer surface that enables ease of entry into the space suit.

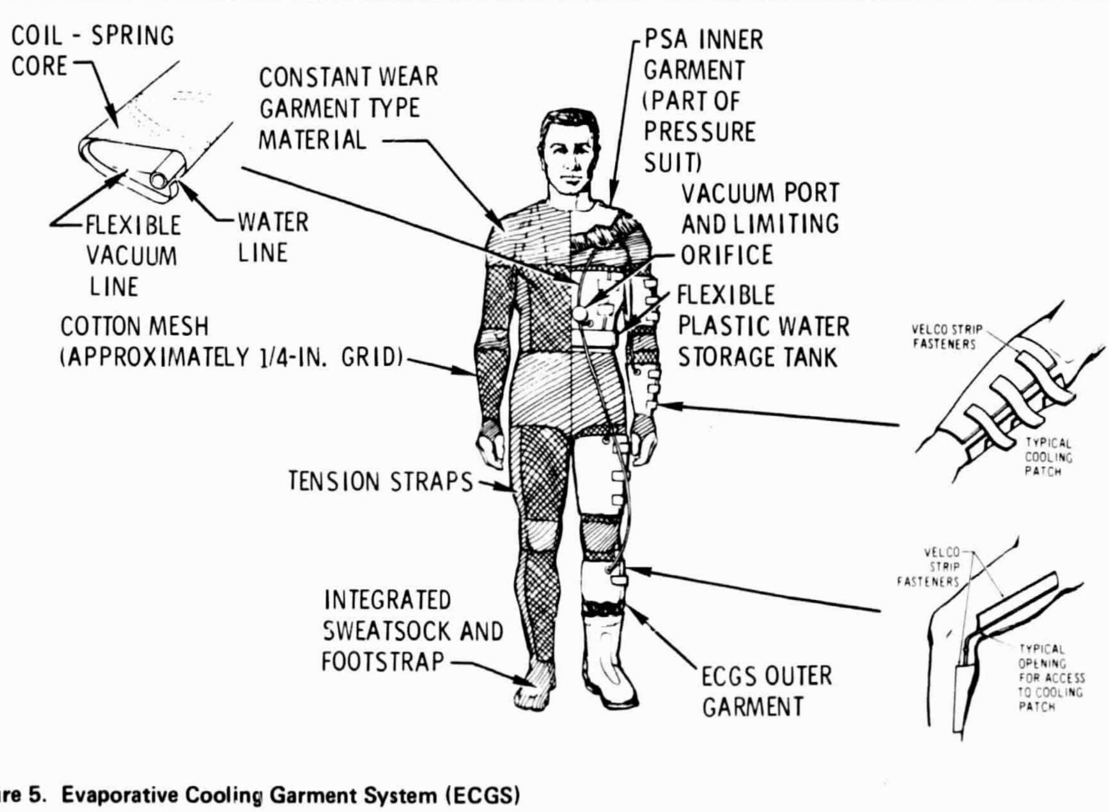



**Figure 5. Evaporative Cooling Garment System (ECGS)**

# Section 3
# UPGRADING OF ECGS

## 3.1 BROAD OBJECTIVES

The ECGS delivery hardware developed in Phase I was highly effective in heat removal capability; however, the active test program in both phases indicated areas for improvement on this engineering model. Many cooling segments were subjected to hard use for hundreds of hours. This use was found to be highly productive in pointing out minor weaknesses. For example, if the interior segment only was exposed for many hours to vacuum, the constant external pressure had a tendency of producing permanent set in the plastic water injection lines, thus reducing feed flow rate (solution: new materials and re-routing lines). Sufficient wearing comfort for tests up to 4 hours required that the cooling segments be removed time after time from the suit proper. This wear emphasized by the presence of engineering and physiological instrumentation aggravated the minor problems.

During Phase II, the same type of problems kept showing up and subsequent solution of these minor difficulties resulted in a general upgrading of the entire suit. This improvement process was limited only by the budget available and time priority.

## 3.2 INTERNAL ASPECTS OF COOLING SEGMENTS

Some of the minor difficulties encountered in the ECGS cooling segments include the following; each will be discussed in later paragraphs:

1. Water line restriction (discussed above)
2. Fungi growth on the wicking layer
3. Wicking layer cracking
4. Water outlets on wicking layer
5. Three-dimensional material edging
6. Membrane leaks

3.2.1 Water Line Restriction

The pinching problem is caused by a local discontinuity in the cooling segment over which the water line is placed. The line is 0.053 inch ID with 0.016-inch wall Resinite Super Heat 125 vinyl tubing, and its characteristics are a plastic deformation with a constant applied load. Bridging over the projection has temporarily solved the difficulty; however, new materials and/or re-routing should be the permanent solution.

3.2.2 Fungi Growths

The cooling segments have always been charged with tap water, and no attempt has ever been made to maintain sterile conditions. Occasionally fungal growths will take place on the paper wicking layer, and at times will cover at least 10 percent of the visible area adjacent to the skin side membrane. Many tests have shown that the cooling segment performance has not been affected by these fungi colonies; however, since the growth when it occurs is always on the paper surface, it would seem that the fungal digestion of some portions of the paper might be expected. This perhaps may explain some of the paper cracking that results from long use. The remedy to this has not been sought up to this time, since performance degradation was not experienced. Biostatic agents should eventually be applied to the cooling segments, which would solve this problem.

3.2.3 Wicking Layer Cracking

The occasional cracking or splitting of the ECGS paper wicking layers has been observed; but again, as with fungi, no appreciable performance degradation has been observed. A possible permanent solution might be to have the paper sandwiched adjacent to and cemented on a rip-stop grid of about 1/4-inch spacing nylon threads. Up to this time, damage to the wicking layers has been solved simply by replacement.

3.2.4 Wicking Water Outlets

Each ECGS cooling segment has an internal water distribution system with multiple outlets terminating on the wicking layers. The initial segments of Phase I had a simple point source outlet opening at each terminal hole. In an effort to increase the wicking speed, the point source outlet concept was modified and improved to the extent that the largest cooling segment could be fully wicked with the full charge of water in less than 10 seconds. This was accomplished by an MDAC patent pending concept which provides the outlet water to be distributed from the center of a plastic sandwich to its periphery by a virtually instant capillary flow. This increases the point outlet to a line outlet of any complex shape, with the result of exceedingly fast wicking to any large two-dimensional object. All cooling segments of the ECGS and the EECGS have been converted to include this feature.

3.2.5 Three-Dimensional Material Edging

The sharp frayed edging of the three-dimensional material has been covered by several methods to protect the vacuum membrane enclosure. These methods include split PVC tubing, Spirap sewed to the edge, felt covering edge, and wicking paper covering any of the prior. In addition to covering the edge, it was found that the added channel was a convenient supplemental vacuum passageway that would increase the segment maximum heat removal level. All of the techniques work, but the best configuration is not yet known. All segments have some type of edge covering.

3.2.6 Membrane Leaks

For convenience, almost all ECGS and EECGS segments were covered by PVC membranes which were easy to heat seal. PVC has the disadvantage, however, of poor abrasion resistance and is quite porous to a hard vacuum. Vacpac, on the other hand, had much better physical properties but is more difficult to heat seal. Therefore the foot segments were eventually converted to Vacpac because of abrasion on the shoe and plastic fatigue, and the rest of the EECGS used PVC. It is felt that Kapton is the best material now known, but special chemical sealing agents may have to be developed for this material. Membranes like Kapton and Mylar would provide much higher maximum heat transfer characteristics as the membrane thickness could be greatly reduced for the same strength.

Membrane heat transfer is crucial to the ultimate cooling performance of any cooling garment system. Figure 6 presents the ECGS membrane performance; the data are presented as a family of curves, each with a constant ΔT (temperature difference between skin and boiler). It can be seen, from observation of the most adverse curve, that a membrane thickness of 0.003 inch will provide over 12,000-Btu/hr heat transfer. This far exceeds any requirement that may be imposed on a cooling system. The upper physiological boundary is that which would result from a skin temperature of 105°F and a boiler temperature of 40°F; in this case no hindrance under any condition can be anticipated for any cooling limit whatsoever. A performance in this warm region of skin temperature is, therefore, far greater than any requirement that can be conceived, particularly since the membrane thickness of the ECGS is approximately 2 mils. If a membrane thickness of 0.03 inch (as used in the LCG tubing wall) is considered, it is obvious that the heat transfer degradation process is quite extreme. Systems operating in this category should be avoided if high-performance heat rejection is required.

### 3.3 SEGMENT VACUUM FITTINGS

The final vacuum fittings developed in Phase I had two primary weaknesses; one structural and the other functional. The former problem was a strength situation at the pressure line instrumentation penetration through the fitting and the same for the water line. Rough handling of the cooling segments would break the solder connection of these fine hypodermic size tubings. The remedy for this failure was to provide a tin-silver soldered A-frame brace just outside of the fitting so that any bending of the tubing would be supported by the A-frame and not the solder joint sealing the tube to the vacuum fitting. No further difficulty was experienced after this remedy was installed on all fittings. Figure 7 depicts two types of ECGS fittings.

The external vacuum fitting shown in Figure 7 is screwed into a male adapter which is in turn secured to the cooling segment. The straight threaded joint was not adequate for vacuum, and was sealed in Phase I by Silastic rubber on the threads; this worked except for the many instances when the segment was roughly treated and the fitting was inadvertently twisted, resulting in a vacuum leak through the threads. An O-ring was placed between these two parts and a backup nut locked the two tightly together, thus providing a good vacuum seal. Although the fittings now work well, they have too great a projected area above the cooling segment and therefore should be redesigned in the next phase of development.

### 3.4 SEGMENT EXTERNAL VACUUM LINES

The external vacuum lines provided in Phase I were fabricated from flexible bellows tubing. The lines were shaped to an elliptical cross-section in a wood die in an attempt to reduce the external projected area above the ECGS segments. The tubing worked well; however, it soon developed vacuum leaks after several hours of flexing. This was solved by placing the flexible lines in PVC sleeve tubing; however, additional hours of flexing caused parting fractures of the brass flexible lines, integrity being maintained only by the sleeve. In summary the lines were poor in fatigue and they were also very heavy.

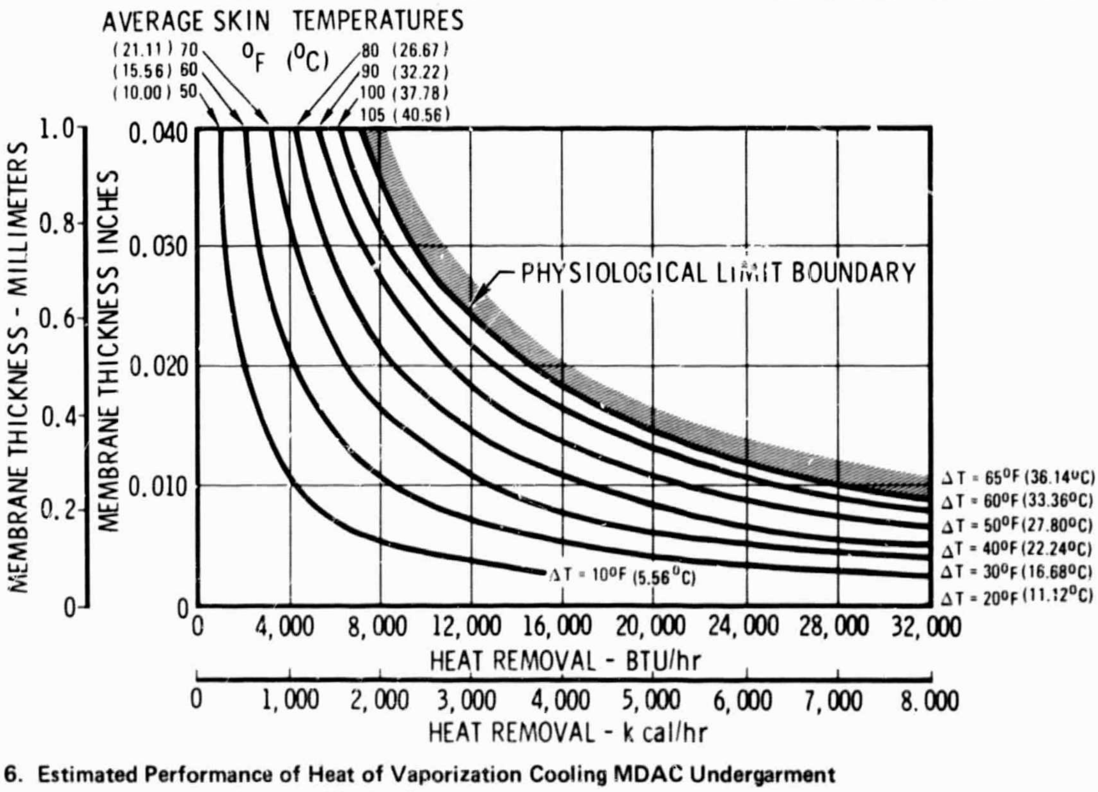
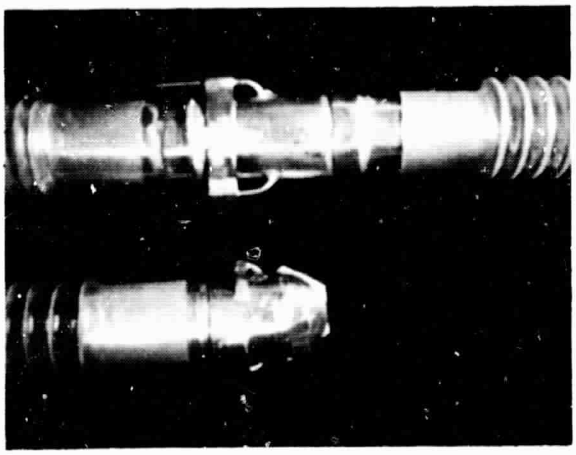
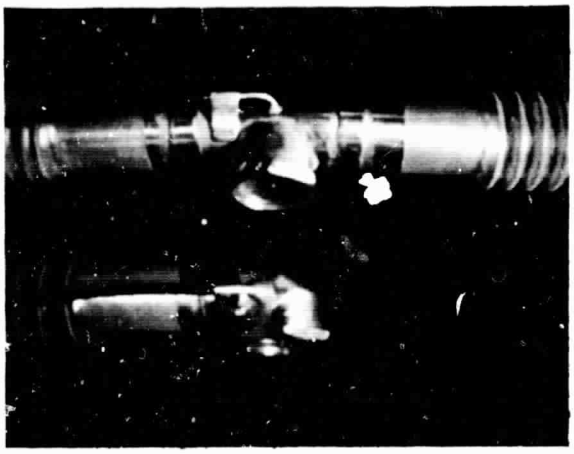


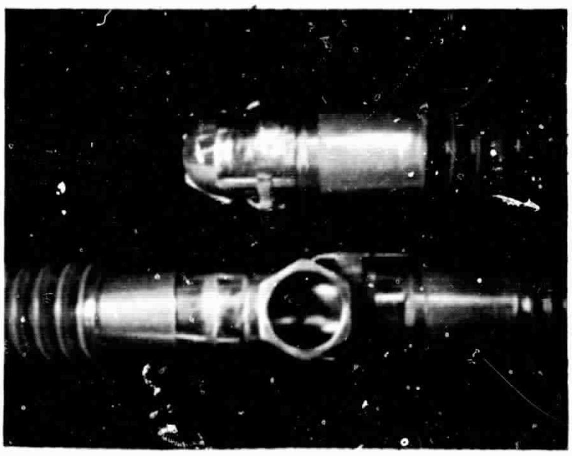

**Figure 6. Estimated Performance of Heat of Vaporization Cooling MDAC Undergarment (Skin Thermal Conductance Limited)**



TOP VIEW



SIDE VIEW



BOTTOM VIEW

Figure 7. Vacuum Outlet Fittings (Elbow Type - **Single Segment; Tee Type - Double Segment)**

The Penntube Division of the Pennsylvania Fluorocarbon Company was contacted regarding a new product called flexible corrugated Teflon tubing, No. 400 CT-FLEX. This tubing can be extended or retraced without affecting the inner diameter, can be bent into a radius one-half its inner diameter, and withstands continuous flexing. Appropriate lengths of this transparent tubing with constant-diameter end sections were ordered and installed in the ECGS and the EECGS/LCG. The product proved excellent for the purpose, was considerably lighter, but had a larger projected cross-sectional area than the elliptical section brass flex tubing. The vendor was contacted and is willing to form the tubing into an elliptical cross-section on special order; this is recommended for Phase III.

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## Section 4
## DEVELOPMENT OF EECGS COOLING SEGMENTS

### 4.1 OBJECTIVES AND BACKGROUND

The primary purpose of Phase II was a feasibility program to determine if the ECGS could provide cooling for a full half hour on an emergency operation basis without affecting the operation of the LCG. This required that the LCG be worn as normal and all cooling possibilities be either added to or worn over the LCG. The Phase I full-suit delivery hardware was available for modification as required to serve this purpose. The leg, arm, and helmet ECGS cooling portions were the most easily removable segments; and therefore represented the first candidates for the EECGS/LCG. The front and rear torso would have required extensive modifications if applied to Phase II; and if done would then destroy the original ECGS configuration which was not desired.

The upper and lower arm and leg segments and the helmet comprising also the cooling chin strap were modified internally so that more stored water could be contained. The extra storage was accomplished by increasing the number of wicking layers. This was an iterative process as the exact performance or heat removal required through the inactivated LCG could only be guessed because of the many heat transfer unknowns, and more particularly to the thermophysiological variables. For example, a very thick layer would hold a greater quantity of water; but on the other hand, this thick layer would lower the maximum thermal conductance (Figure 6). A compromise had to be chosen for each segment, with the hope for the highest performance consistent with the cooling endurance of 30 minutes.

To make matters even more difficult, the performance varied with metabolic rate: and full work rates required about 3-month training, all in a 6-month test program. It was first felt that every unused cooling part of the LCG would be required to attain compliance with the work statement. Patterns were made of the British LCG Beaufort produced by Frankenstein, to see which areas could be directly covered by the ECGS. Figures 8, 9, and 10 show the unused areas as a dark pattern coverage. Subsequently, an Apollo short-sleeved LCG was provided by NASA-MSC, and this showed even less area was available for direct cooling.

It was soon decided that the coverage typically shown in Figure 9 was not the solution; instead, cooling through the LCG seemed to be the only technique to get a sufficient area for heat transfer. Figures 11, 12, and 13 show the basic patterns selected, except that the torso would be used only as a last resort. In place of the torso, a collar comprising the lower neck, partly on top of the shoulders, and a narrow strip about 1 inch wide extending down the spine and sternum was selected. Subsequently, the soles of the feet shown in Figure 14 were extended along each side of the foot for greater cooling.

The fabrication program which also included upgrading of the ECGS was pursued at the same time as laboratory testing. The test program first started with subjects at rest to obtain basic cooling data; and as training progressed, subjects wearing different parts of the EECGS were tested at higher and higher metabolic rates, culminating at the 4,000-Btu/hr level for 30 minutes.

## 4.2 COOLING THROUGH INACTIVATED LCG

The first question to be answered on cooling through the inactivated LCG was the loss of thermal conductivity. The LCG was filled with water, and the circulating tubes were sealed at the outlet in a manner that allowed no air entrainment in the system. Constant heat rejection runs were made using the lower leg ECGS applied directly to the skin. A constant heat rejection, q, was established by throttling the ECGS exit vacuum valve. This produced a given $\Delta T$, which is the skin temperature minus the boiler temperature. As the skin temperature was driven down, the boiler temperature was also

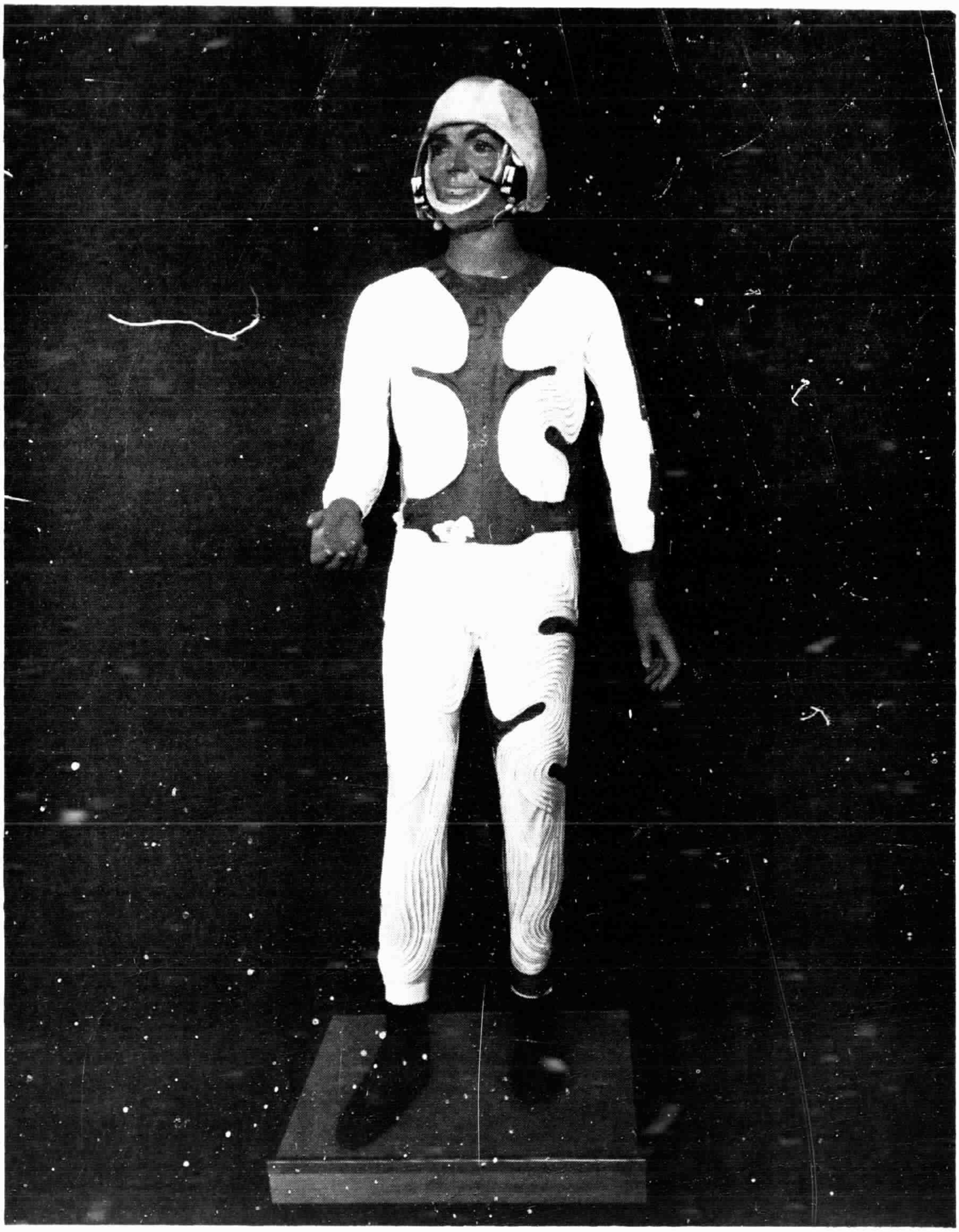

Figure 8. Unused Body Contact Areas British Frankenstein Beaufort LCG
Type 1 Series 5 - Front View

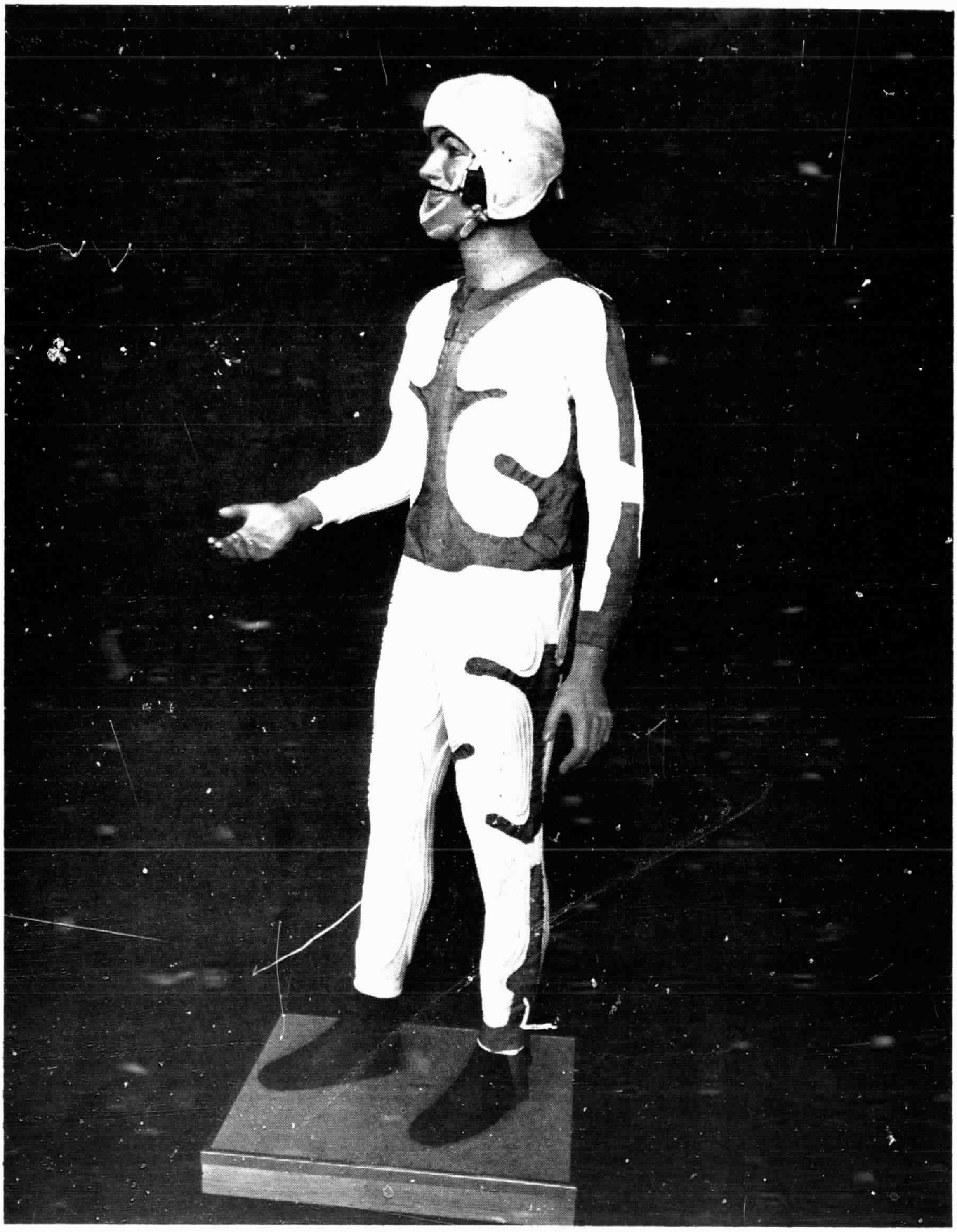

Figure 9. Unused Body Contact Areas British Frankenstein Beaufort LCG
Type 1 Series 5 - Side View

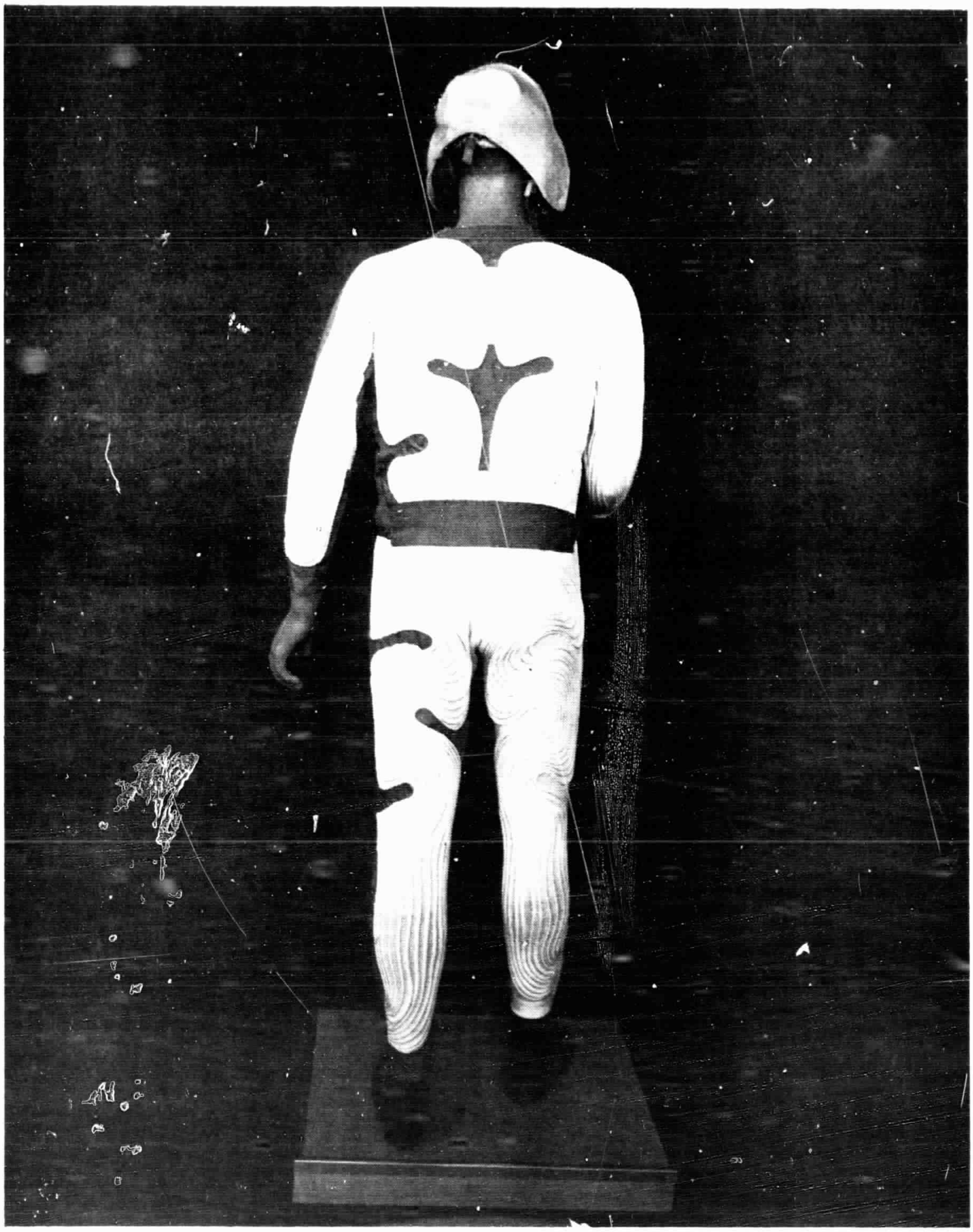

Figure 10. Unused Body Contact Areas British Frankenstein Beaufort LCG
Type 1 Series 5 - Back View

**Figure 11.** EECGS Patterns over Apollo LCG - Front View

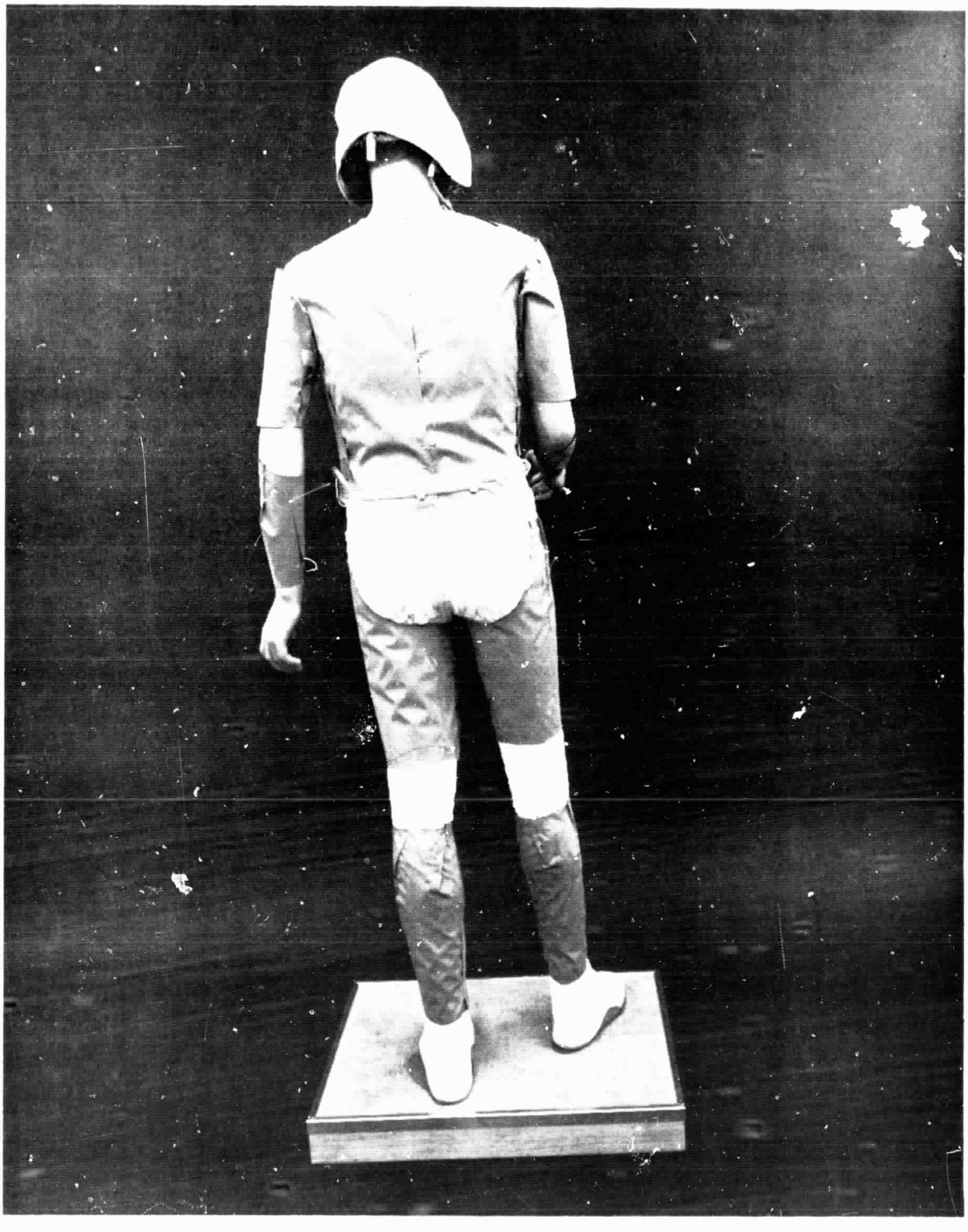

Figure 12. EECGS Patterns over Apollo LCG - Back View

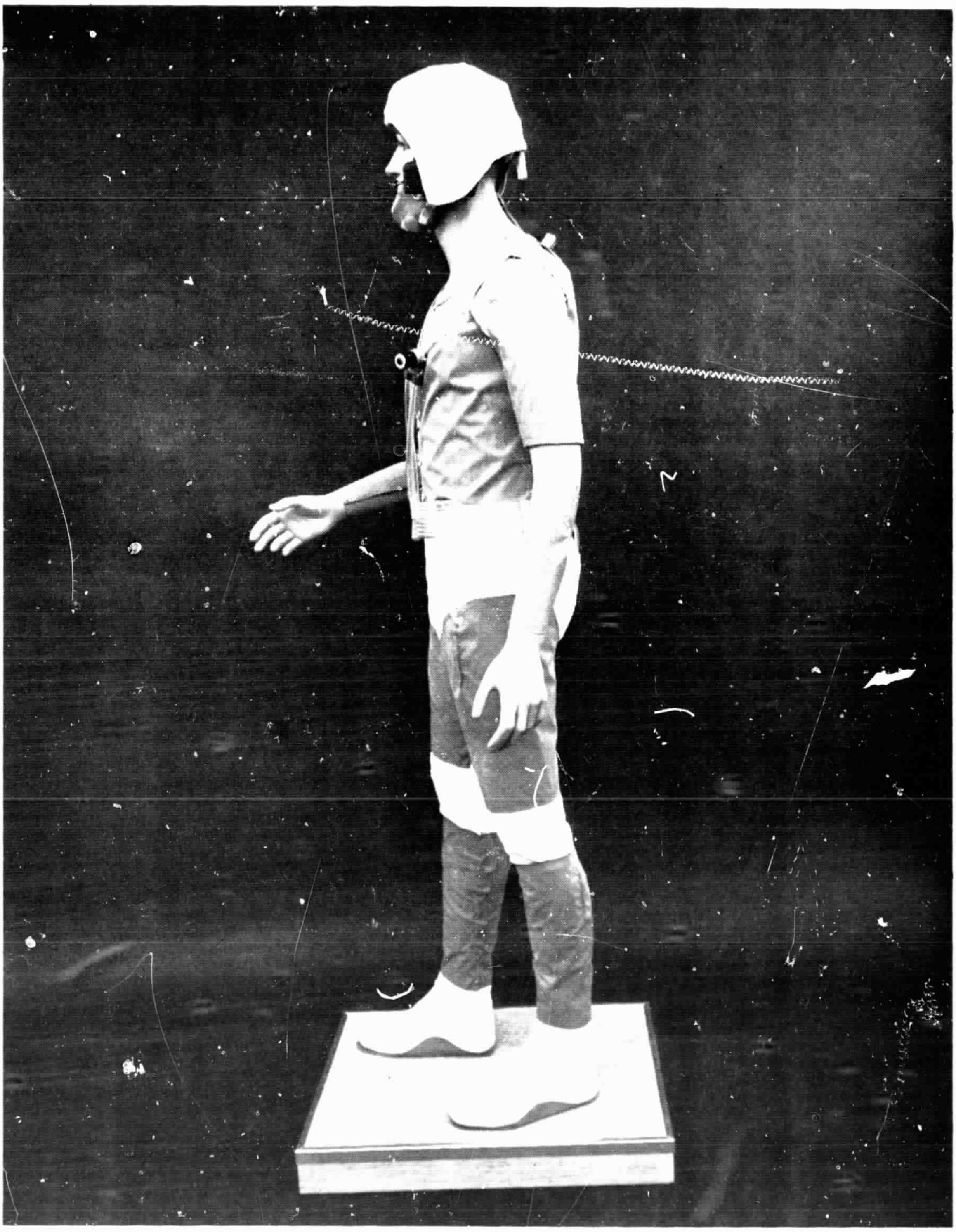

Figure 13. EECGS Patterns over Apollo LCG - Side View

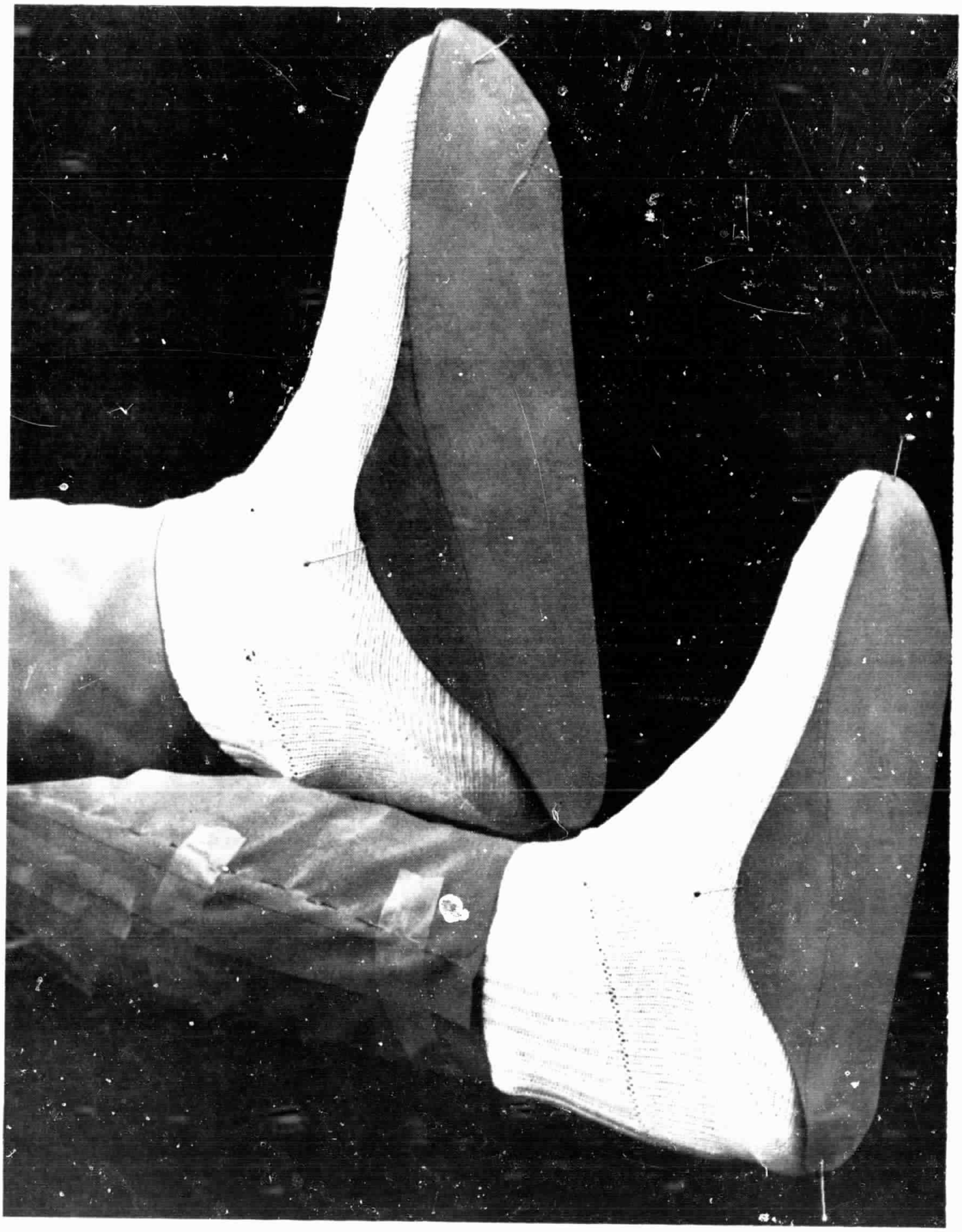

Figure 14. EECGS Foot Cooling Patterns

lowered by opening up the valve while maintaining constant q (the resultant $\Delta T$ also remained constant). The heat removed can be described by the following equation:

$$q = U A \Delta T \qquad (4-1)$$

where

U = conductance
A = contact area

During each run there was a point in time where the preselected q value could not be sustained because of a reduction in the original $\Delta T$. At this point, the run was terminated and a data value of q versus time was recorded. A sufficient number of such tests was conducted to establish a boundary curve of q versus time. Any point outside this boundary would then represent an impossible performance situation for the specified cooling configuration. Whenever skin temperature reaches equilibrium, the run time for this constant heat rejection approaches an infinite value.

The same series of tests was performed for the ECGS cooling segment placed directly over the inactivated leg of the LCG, while a test subject was wearing the assembly sitting at rest. The boundary curve produced by these tests could then be compared with the prior case. The difference between these two boundaries was then directly comparable to the loss in conductance resulting from the presence of the LCG.

Figure 15 summarizes 16 of these runs into two boundary curves, also the difference in thermal conductance as a percent loss in heat removal due to the LCG. The loss was found to vary from a high of about 18 percent at 10 minutes, down to 13 percent for 30 minutes. The variability of the loss with time can probably be explained by the thermal lag in cooling the static water in the LCG. Cooling this water first by conductance would be necessary before cooling the skin. Two other pathways of cooling now become

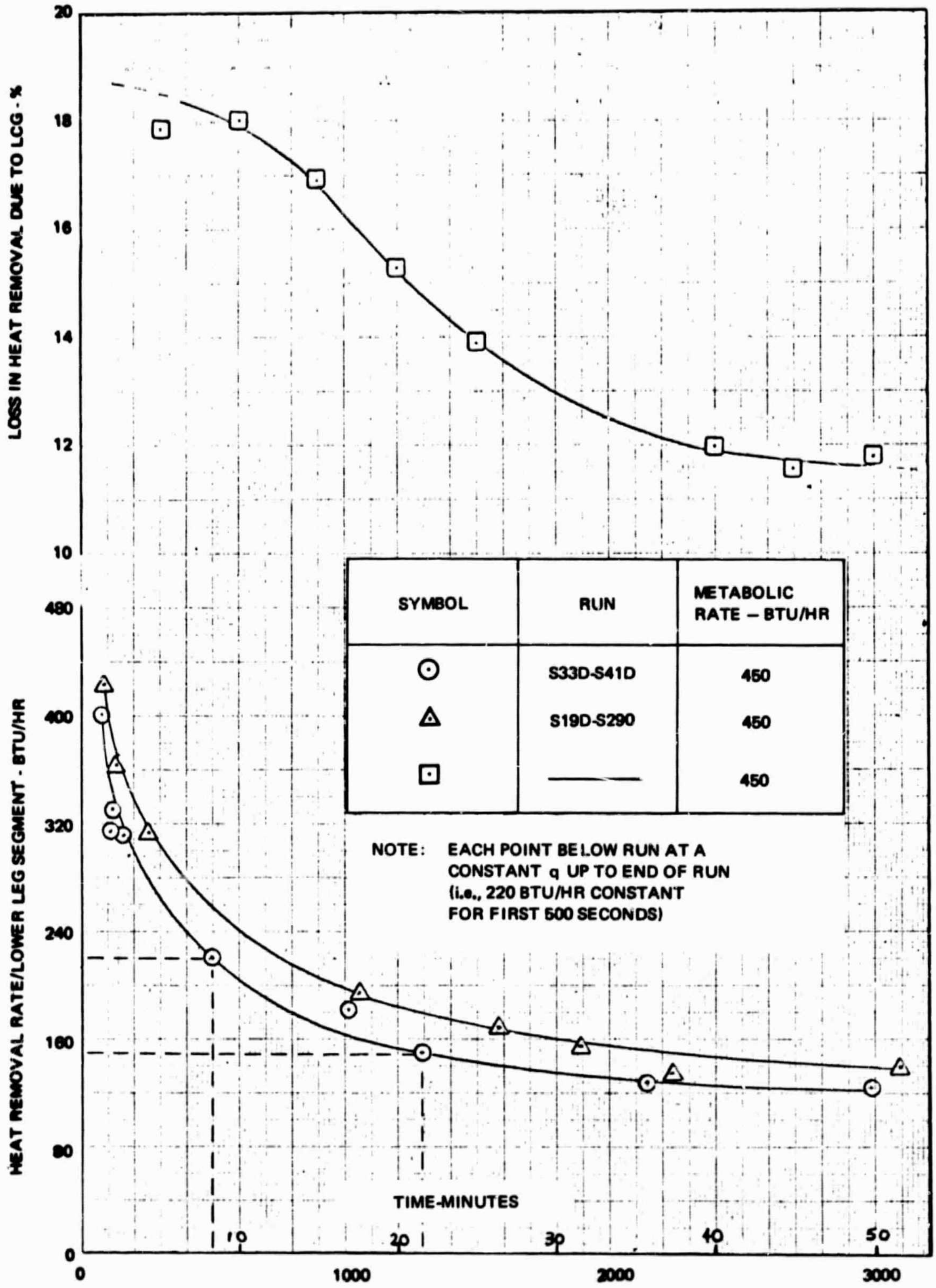


Figure 15. ECGS Cooling Through Inactivated LCG (Subject Sitting at Rest)

apparent from these data and also from subjective comments of the test subjects. Radiation cooling primarily between the LCG tubes would be virtually instantaneous, while conduction cooling of the dead air space caused by the presence of the LCG would be relatively slow. The test subjects reported instant cooling, which indicates that a significant portion of cooling can be derived from radiation, and this also could explain why the losses through the LCG were much lower than expected.

Figure 16 presents the equivalent skin temperature that would result from operating precisely on these two boundary curves. The data show that the temperatures are lower when the ECGS is placed directly on the skin as would be expected.

The next test series was conducted to establish upper and lower leg cooling through the LCG during high rate exercise. These tests were performed on the treadmill at 4.5 mph at a grade sufficient to attain a metabolic rate of 4,000 Btu/hr. (The grade angle depended upon the subject, but averaged about 6.3 percent.) All tests were run for exactly 30 minutes with full cooling on; at the 30-minute point, the cooling was shut off by a pneumatic valve and the subjects continued exercise to obtain the rise in skin temperature. Occasionally the subject went more or less time than 10 minutes after cooling cutoff, depending upon heat stress conditions without cooling.

Figures 17 and 18 present average leg skin temperatures and cooling rates versus time. Leg cooling even through the LCG is most effective, producing a 22°F average drop in surface temperature during the run, down to a low of about 68.5°F. One would think this would be too cold for comfort; however, such was not the case. Another point should be brought out, that no pre-exercise warmup on any runs in the program was allowed to preclude difficulty in data analysis. Yet in the leg cooling runs, the skin temperature stayed nearly constant for the last 20 minutes of the test at these very low levels. The leg muscle mass on the other hand must have been about normal temperatures because cramps, numbness, after effects, or inability to exercise at these very high metabolic rates would have shown up. In fact, subjects have stated that it is uncomfortable after cooling cutoff if exercise is continued.

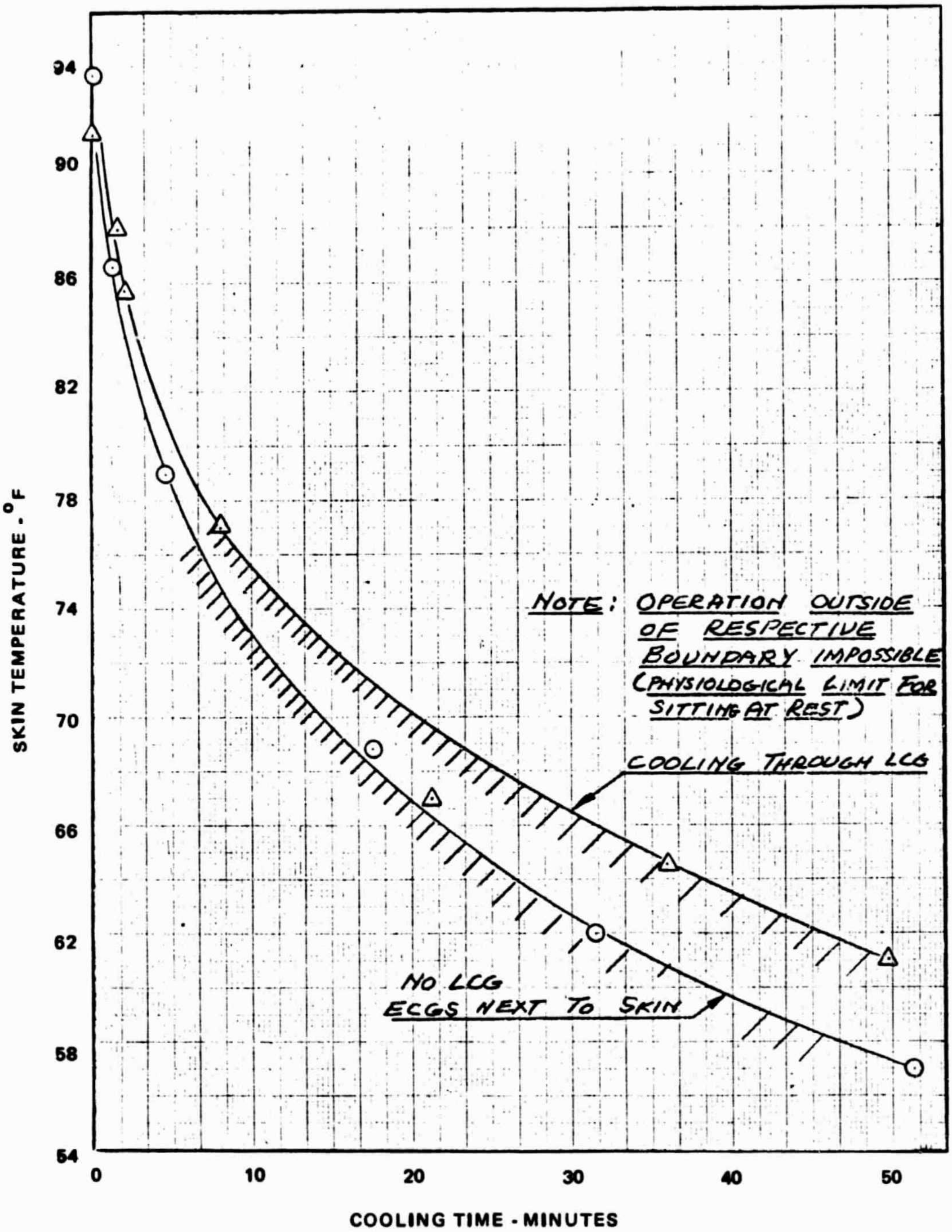


Figure 16. ECGS Cooling Through Inactivated LCG - Lower Leg (Subject Sitting at Rest)

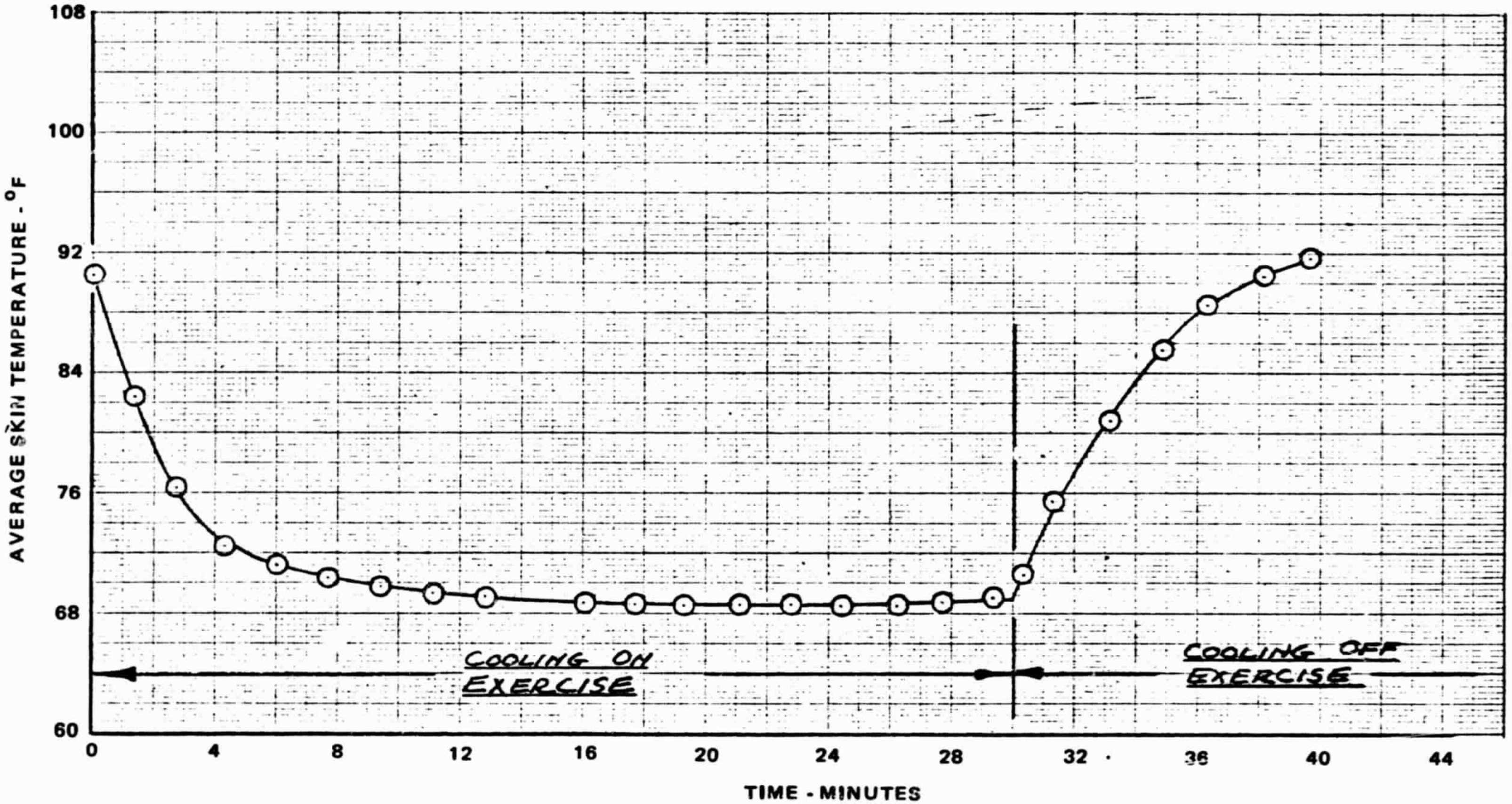


Figure 17. EECGS/LCG Leg Temperatures – ECGS Worn Over LCG on Legs Only (4,000 Btu/Hr Metabolic Rate)

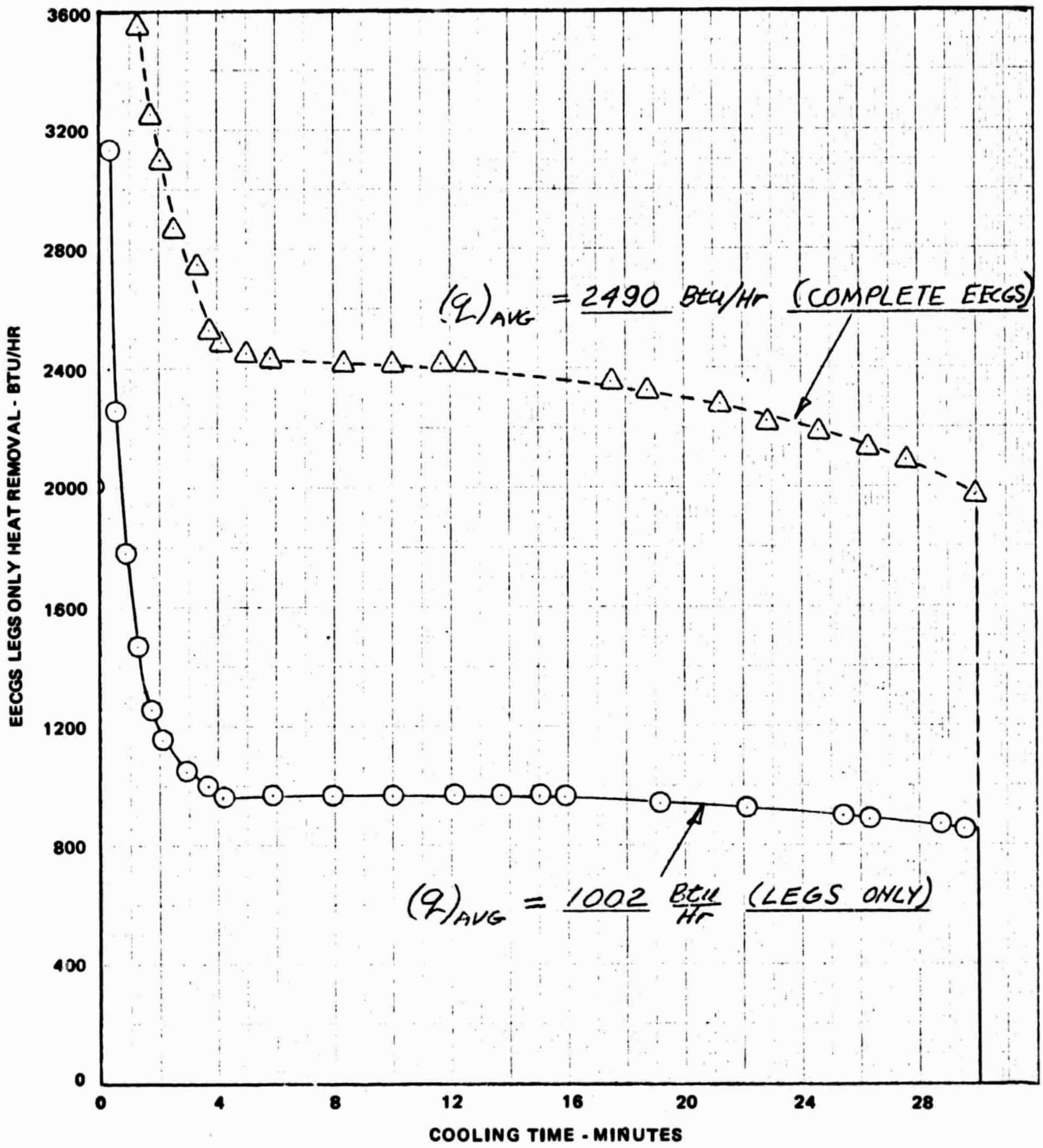


Figure 18. EECGS Legs Cooling Through Inactivated LCG (4,000 Btu/Hr Metabolic Rate)

Exercising at these high rates without cooling in the treadmill training runs produces profuse sweating. If the air circulation is stopped and/or if the room ambient temperature reaches near 80°F, the run endurance at 4,000 Btu/hr is reduced by at least 30 percent, and signs of severe heat stress can be observed. The forearm exercise tests (hand squeezing) conducted during Phase I have also indicated that fatigue limit is nearly coincident with the time it takes for the skin surface temperature to reach the core values.

These results are beginning to indicate that comfort, and more important, work efficiency at high metabolic rates require very low skin temperatures. It is strongly recommended that research programs be specifically conducted to establish comfort zones of skin temperature, as related to work efficiency.

Figure 18 shows that the leg cooling averaged about 1,000 Btu/hr during the 30-minute run, and remained quite steady during the last two thirds of the test. No attempt was made to hold heat removal constant, because maximum performance was of prime interest. Therefore, this and other similar runs were made with fully open vacuum valve. A mathematical summation of each individual cooling capacity of the various cooling segments consistently shows less cooling than when all such segments are run simultaneously. This is not fully understood; it may be thermophysiological and/or thermomechanical; further tests are needed for verification.

Right and left upper arm only cooling runs were performed as in the prior test series. The cooling segments were obtained, as with the legs, from the Phase I delivered ECGS hardware. The arms were attached to a light vest which was worn over the LCG. Tests leading to the final configuration were not conducted on the lower arms since the GFE LCG was a short-armed suit. All data in this report relating to the arms were extrapolated upward to include the effect of the absent lower arms. The performance prediction was obtained simply by ratioing their areas, the lower being 16.2 percent smaller than the upper arm.

Figure 19 presents average arm skin cooled temperature during 4,000-Btu/hr metabolic rate versus time. Arm cooling was about as effective as the leg per unit area, producing a 13°F average drop in surface temperature during the run, down to a low of about 81°F. Again this was comfortable, but the relatively small area covered by the upper arm gave more apparent cool contrast than with the legs.

Figure 20 shows that the arm cooling average, about 470 Btu/hr during the 30-minute run. The heat removal shows a trend of slightly increasing rate from the 6-minute value to the end. This trend was noted also on the collar, helmet, and shoe which is contrary to what the temperatures indicated. This may perhaps result from a slightly higher thermal conductance value within the cooling segments as caused by a gradual depletion of water stores.

## 4.3 DIRECT COOLING OF LCG UNUSED AREAS

The only area under the LCG believed practical for an ECGS segment is the collar which was extended over part of the shoulder, and includes strips down the spine and sternum. The complex shape of this segment gave serious doubts about whether it could be made to function efficiently. Considerable care was given to its design as helped from several years past experience, and fortunately the first model worked most effectively.

The most difficult design problem was to provide sufficient internal vacuum pathways to vent the boiled water under high heat removal loads. Temperatures measured at the extremities of the spinal and sternum strips under constant heat source were very close, indicating good design.

Figure 21 presents average collar skin temperature versus time. This cooling segment produced a 13°F average drop in surface temperature during the run, down to a low of about 80°F. The test subject's remarks about the full-cooling collar was that the entire torso felt cooled, instead of only about 30 percent of the Phase I torso area actually covered by the ECGS.

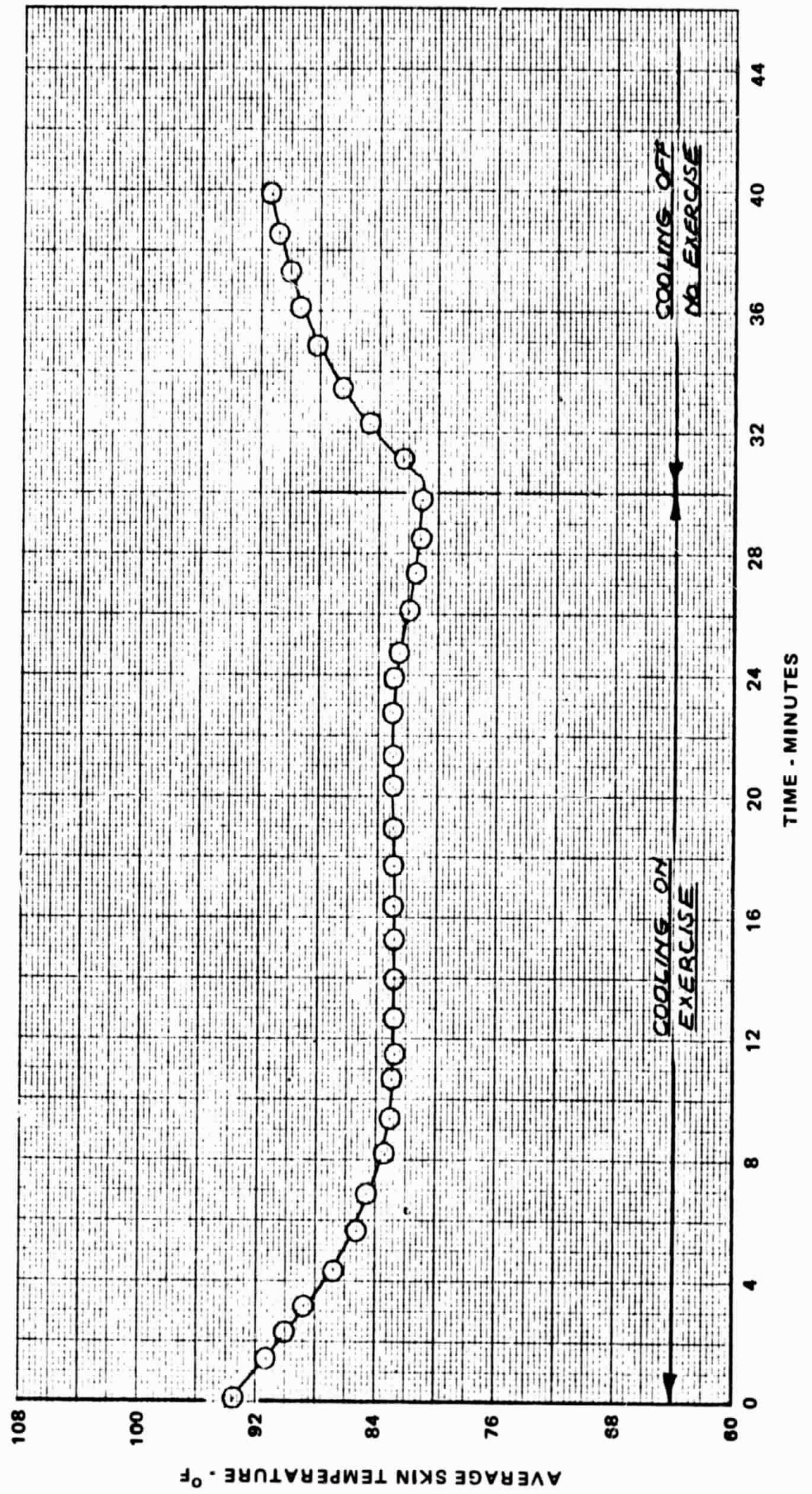


Figure 19. EECGS/LCG Arm Temperatures – ECGS Worn Over LCG on Upper Arms Only (4,000 Btu/Hr Metabolic Rate)

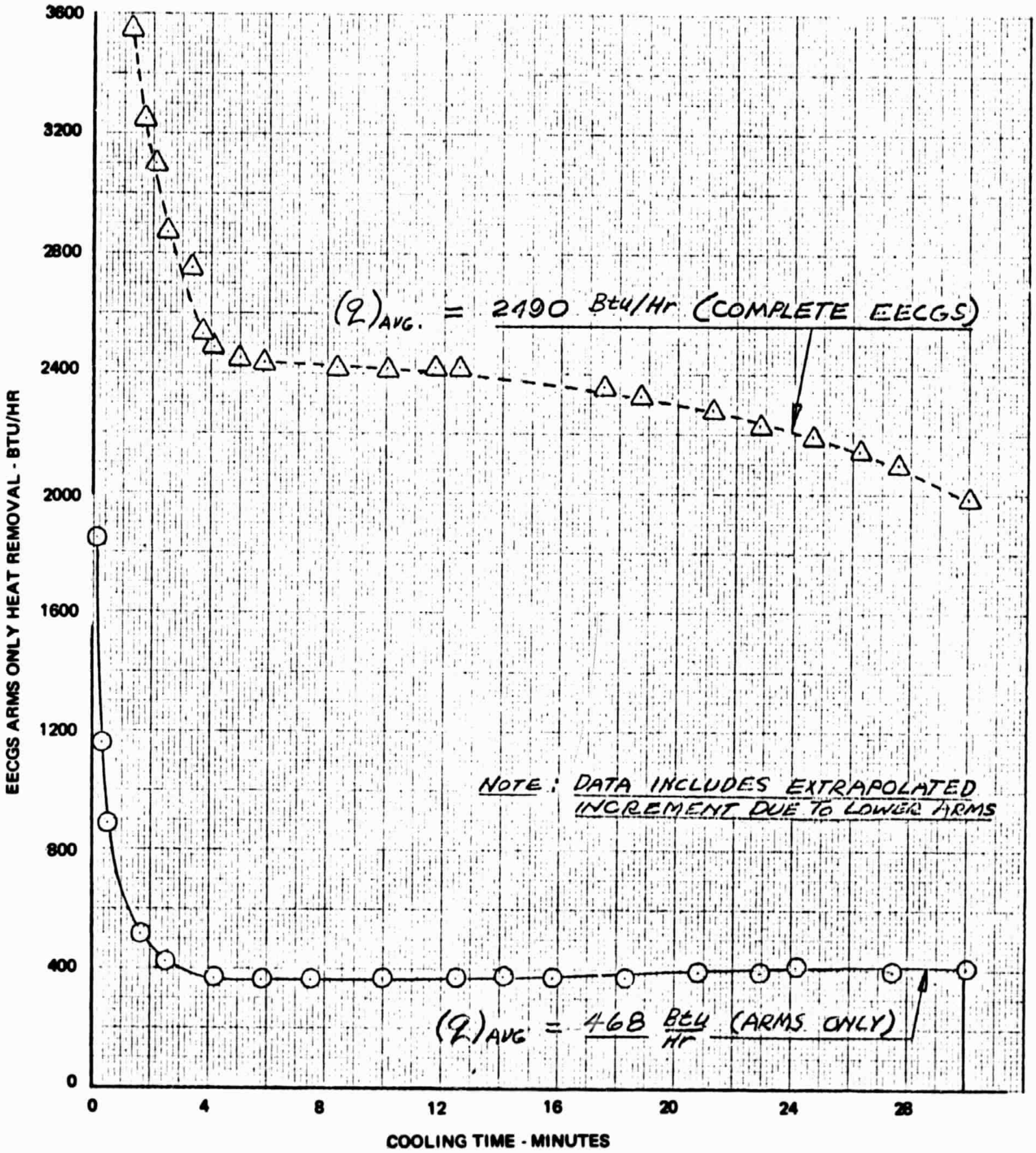


Figure 20. EECGS Arms Cooling Through Inactivated LCG (4,000 Btu/Hr Metabolic Rate)

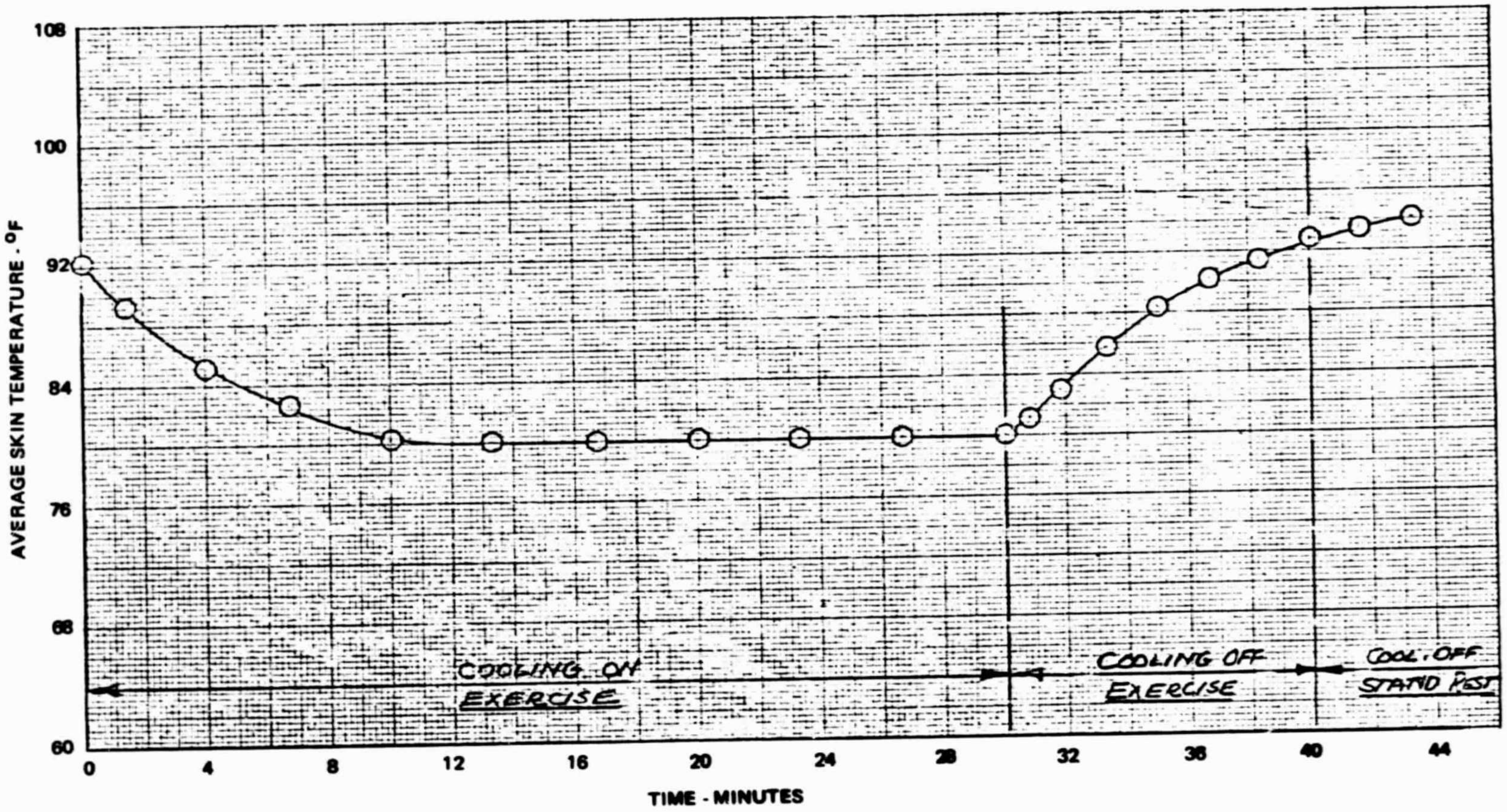


Figure 21. EECGS/LCG Collar Temperatures — ECGS Collar Under LCG (4,000 Btu/Hr Metabolic Rate)

Figure 22 shows that the collar cooling averaged about 225 Btu/hr during the 30-minute run. The lowest cooling rate occurred at about 5 minutes into the test and thereafter actually increased to 121 percent at the vacuum shutoff point (100% being the average total body cooling per unit area).

## 4.4 DIRECT COOLING OF NEW BODY AREAS NOT COVERED BY LCG

The head and feet are the only fully exposed areas not covered by the LCG. The head cooling was initiated in Phase I as a cooling helmet and lower chin strap; this cooling segment was a part of the full ECGS configuration. The foot cooling segments are new; they presented some unique problems and most interesting results.

### 4.4.1 Head Cooling

The helmet comprises six cranial gores and a wide under-chin holding strap (see Figure 23). Each gore is form fitted to the natural shape of the head, and all are flexibly mounted within a soft skull cap. The design is such that several head sizes can use the same helmet. The cooling chin strap is also form fitted to the lower jaw. Each of the seven segments has its own vacuum and water feed line, and these lines terminate in two manifolds; one for vacuum, and one for water. The vacuum manifold has a single outlet which is flex hose connected to the "octopus" collector mounted at the LCG inlet-outlet fitting location near the heart. The entire helmet can be folded up into a compact, soft, flexible package for storage. The helmet also incorporates aircraft or space earphones and microphone for intercom (see Figure 1).

The numerous high metabolic rate training runs without cooling have shown that the entire head is flushed with blood and profuse sweating is prevalent. These conditions are increasingly aggravated when the heat stress fatigue point is reached. When this point is eminent, an electric fan or air hose high rate circulation will extend the endurance. This applies to metablic rates in the 3,500- to 5,000-Btu range and is most prominent at the higher rates (Reference 4).

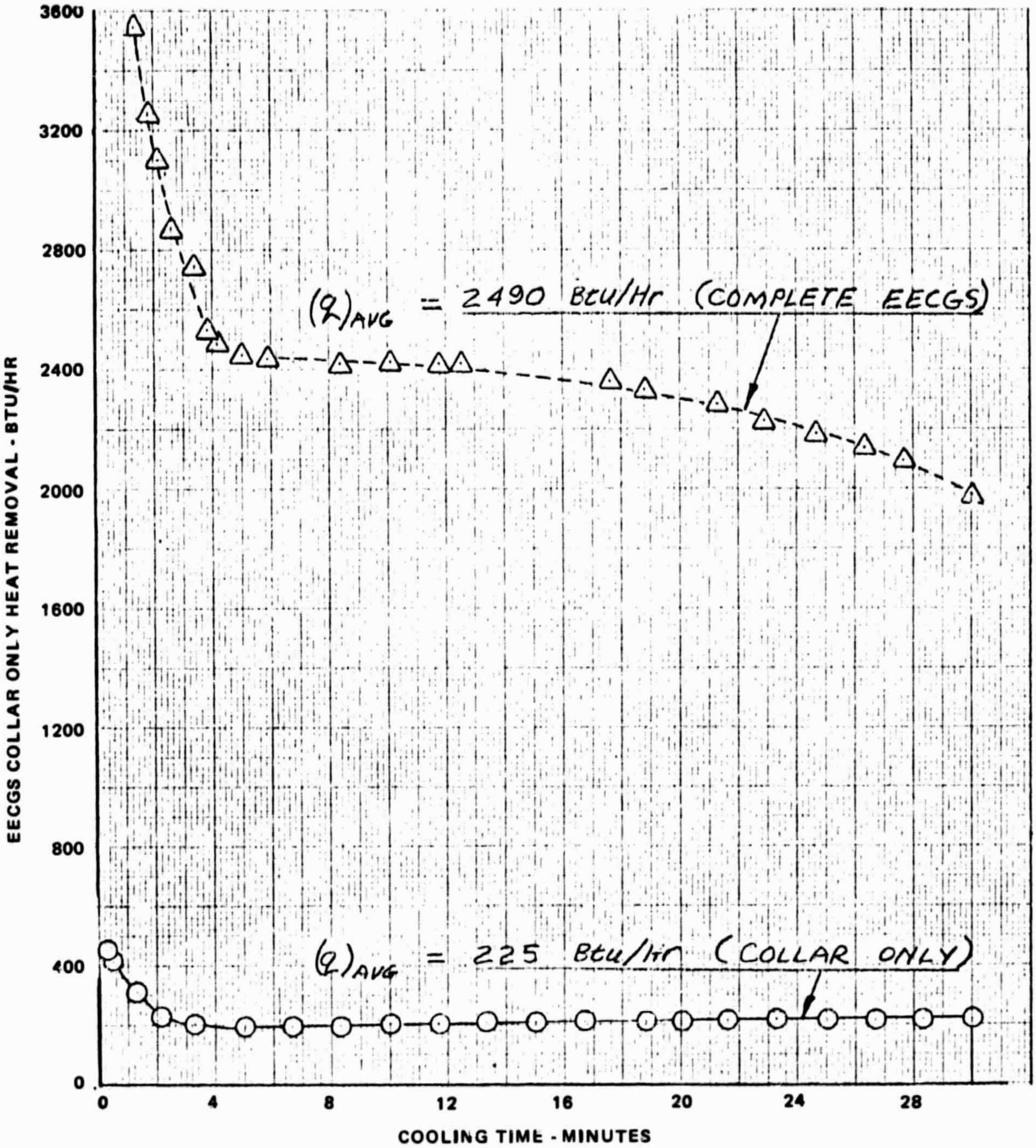


Figure 22. EECGS Collar Cooling – ECGS Collar Under LCG (4,000 Btu/Hr Metabolic Rate)

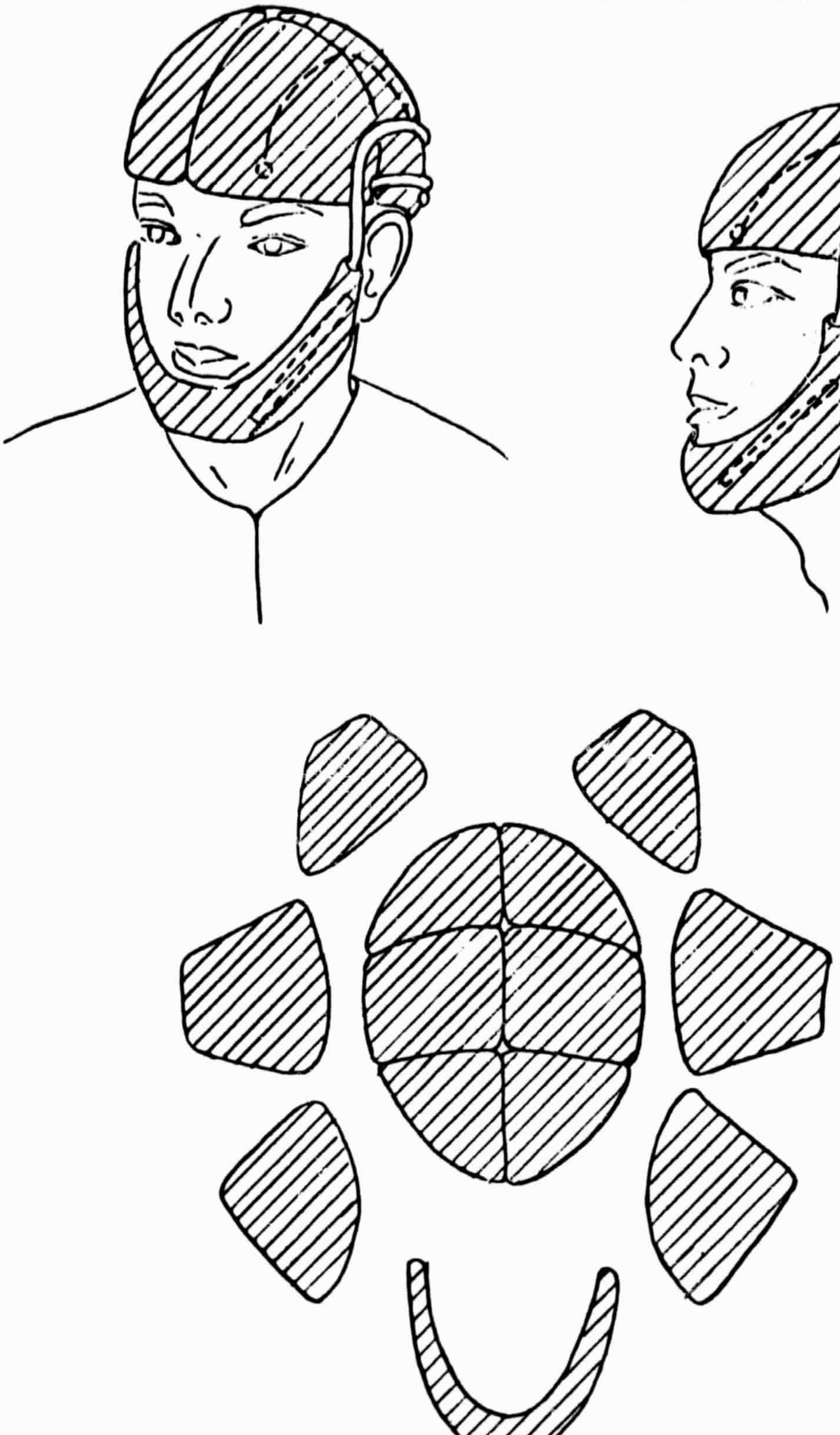

**Figure 23. ECGS Cooling Helmet Segments (Helmet Gores and Chinstrap)**

The cooling helmet, when worn at high work rates, is most welcome to all test subjects without exception. In fact the general request is for even higher cooling than the current designed helmet can provide. The maximum helmet heat removal rate per unit area covered is greater than any other ECGS segment located anywhere on the body. In fact the helmet heat removal flux is 20 percent greater than the EECGS full-body coverage average. These values are relevant even with the thermal insulation of the hair. It is believed that a custom-fit helmet, with a crew-cut haircut and optimized cooling segments, could give considerably higher performance values.

Figure 24 presents an average between the cheek (located under the cooling chin strap) and the forehead skin cooled temperatures, during a 4,000-Btu/hr metabolic rate versus time run. The minimum temperature reverses direction at the 10-minute time point, and rapidly climbs up to a slowly rising plateau at the 16-minute point. This is believed to be caused by one or more of the ECGS segments running out of water resulting from the high cooling rates. It was discovered from other runs that the helmet had only about 6 percent of the initial charge of water left at the end of a 30-minute run. This remaining percentage is the lowest of any segment in the entire EECGS, and further indicates the exceedingly high heat flux from head to helmet. Note also the rapid rise in temperature at the cooling cutoff point, an incremental value of about 7-1/2°F in 4 minutes This again is the highest dT/dt ever recorded on recovery temperatures, indicating extremely high vascular flow in the blood capillaries. Again this further points out that helmet heat transfer is of vital importance in total body high rate cooling.

Figure 25 presents the head heat removal rates versus time during high rate exercise. The cooling averages 207 Btu/hr for the 30-minute run. It is believed this value could be designed upward by about 50 percent with an optimized cooling segment design.

4.4.2 Foot Cooling

Treadmill exercise experiments were conducted at 4.5-mph walking speeds at various grades to determine basic foot temperatures. The range in temperature increase from standing at rest at about 88°F, varied from a

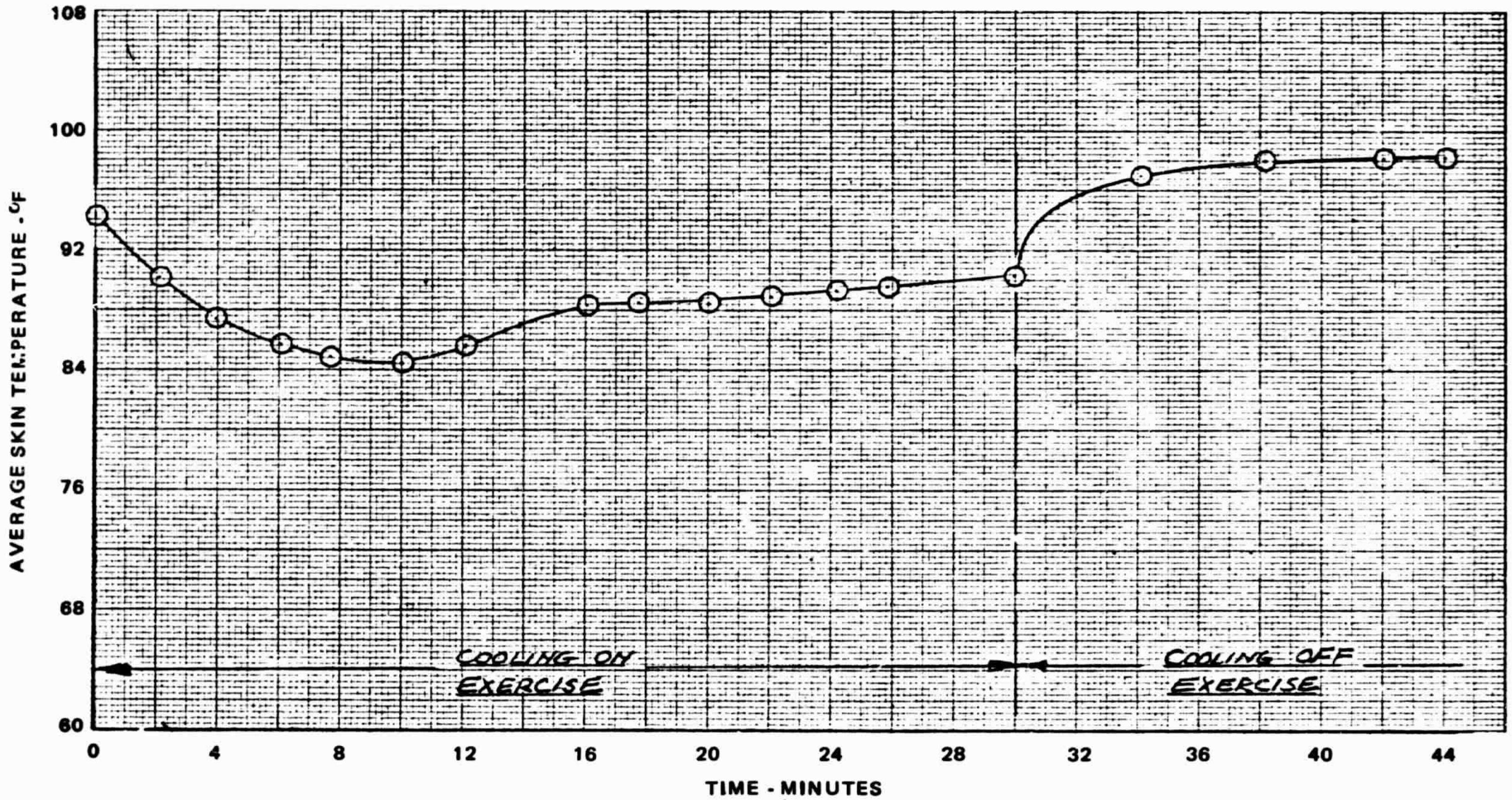


Figure 24. EECGS/LCG Heat Temperatures (4,000 Btu/Hr Metabolic Rate)

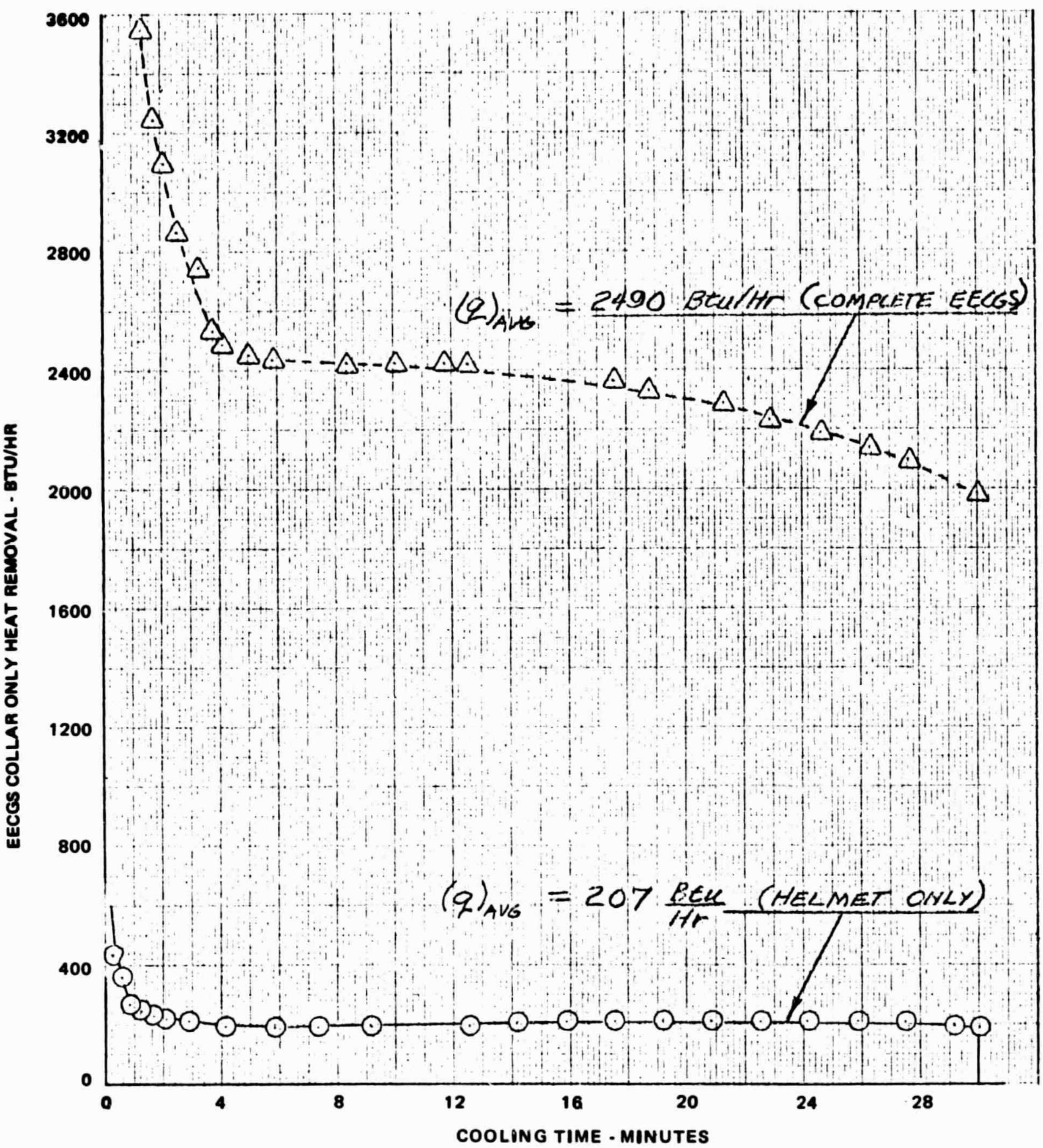


Figure 25. EECGS Helmet Cooling (4,000 Btu/Hr Metabolic Rate)

$\Delta T$ of 8°F to a maximum of 13°F in a 1-hour walk of 4.5 miles. The foot skin temperature usually reached body core values or even up to 5°F higher. The higher values can probably be explained by the conversion of mechanical shoe flexing energy to heat which is transmitted to the ground and also to the soles of the feet.

One of the greatest problems of the treadmill training program was the healing time required from the formation of foot blisters. These blisters primarily started on the ball of the foot, and to a lesser degree on the toes. It is interesting to note that blister formation starts at about the 1-hour point in heavy exercise. It is postulated that the sustained near to, or higher than, core temperature tends to weaken the local flexing skin pressure points on the foot and enhances the formation of blisters.

Metabolic rates have been taken numerous times before and after blister formations, and have shown increase from 10 percent to 30 percent during a single training run. This increase is caused by ineffective walking muscles taking over the exercise load and the change of a smooth gait to an awkward hunched and loping walk. These points are brought out to show that foot comfort is absolutely mandatory at high exercise levels. Long lunar walks may eventually require foot cooling, since the space pressure suit boots provide very high thermal insulation. This insulation will prevent the conduction of foot heat energy away, and result in excessive foot temperatures at high work rates.

The development of a satisfactory foot cooling segment required that the wearing comfort be optimized. It was felt that at least 7 miles of non-stop walking at 4.5 mph was necessary to show endurance comfort. The first prototypes worked, but comfort qualities were lacking, particularly in the heel area. The back of heel also produced leaks in one of the main areas where foot blisters frequently formed during training runs. It should be pointed out that this is the only area of the entire ECGS where a fatigue or abrasion leak has occurred. A typical test run will have over 2,500 cycles of heavy wear on the foot segment, and this kind of trouble was anticipated. Numerous design changes, new models, and subsequent tests have led to the solution of this problem.

Foot comfort is now considered good for the engineering model, since long duration runs of at least 9 miles on the treadmill have been accomplished, in addition to high work rates of at least 4,500 Btu/hr for 30 minutes.

The progression of foot cooling performance has steadily increased from an initial low of 70 Btu/hr up to three times this value.

Figure 26 shows the average foot skin temperatures versus time for 30-minute cooling 4,000-Btu/hr treadmill run, while wearing the final ECGS foot segment configuration. Temperatures dropped from the 88°F level, while standing at rest, to a low of 82°F at the 6-minute point; after which a gradual rise of 2°F took place up to the end of cooling. The temperatures were quite stable indicating a good design had been reached.

Foot cooling had reduced the no cooling exercise condition by 12.5°F at the 30-minute point. It is interesting to observe the effects of high exercise rate on cooling. The same figure also shows the full-cooling standing at rest curve; where the temperatures dropped to a low of 73°F, which is over 10°F lower than the stabilized exercise temperature. This shows the effect of increased blood circulation in the feet as a result of exercise. The rapid rise in temperature after cessation of cooling can be observed.

Figure 27 shows the variation of heat removal rate versus time for the 30-minute test. Heat transfer was constant after the first 2 minutes; this indicates the cooling process was self-limited by the cooling segment vacuum outlet orifice. It is believed that a redesigned fitting will increase performance, even considering that the final design verification run showed that nearly 9 percent of the total ECGS body cooling was derived from the feet.

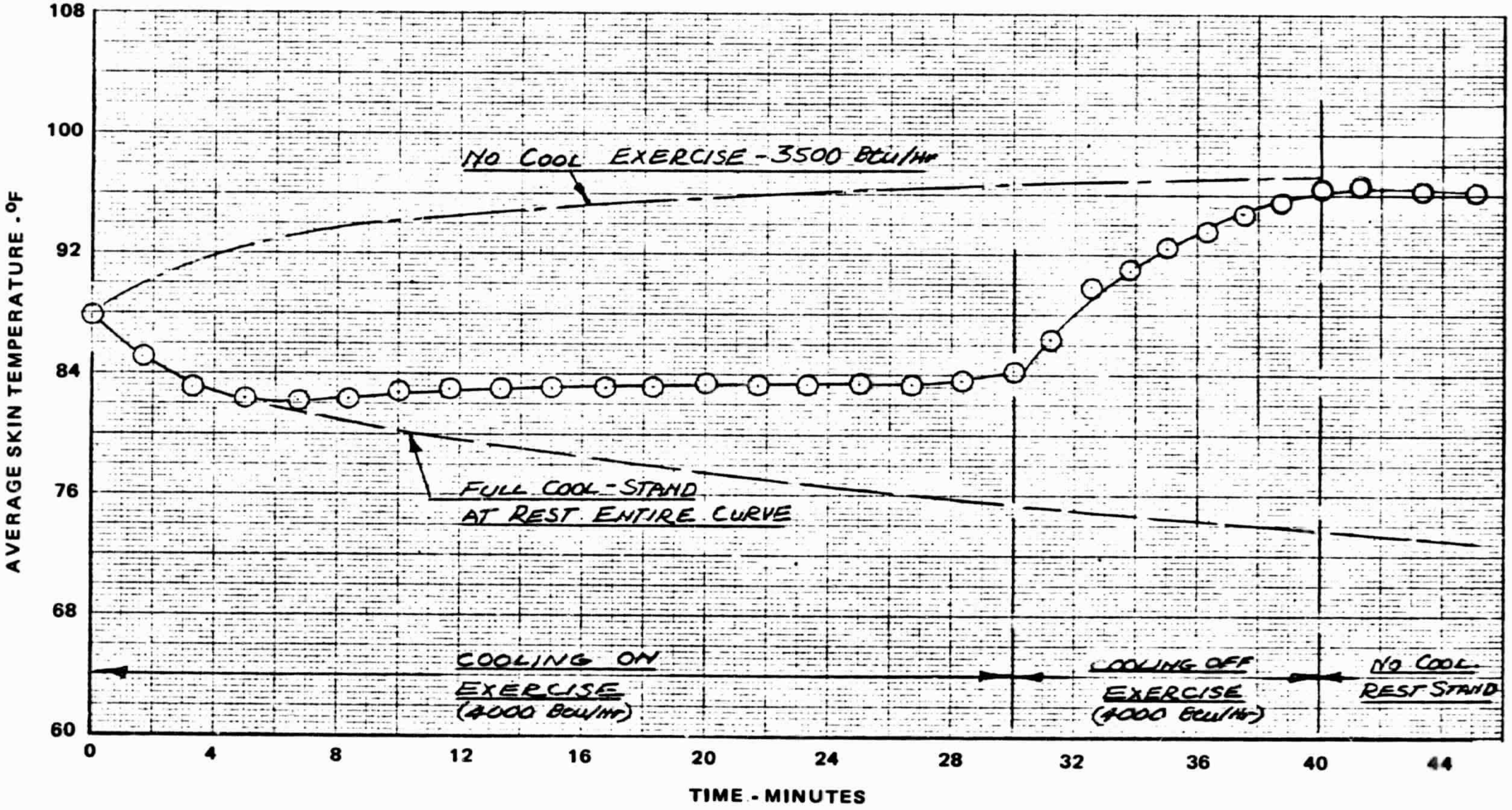


Figure 26. EECGS Foot Temperatures

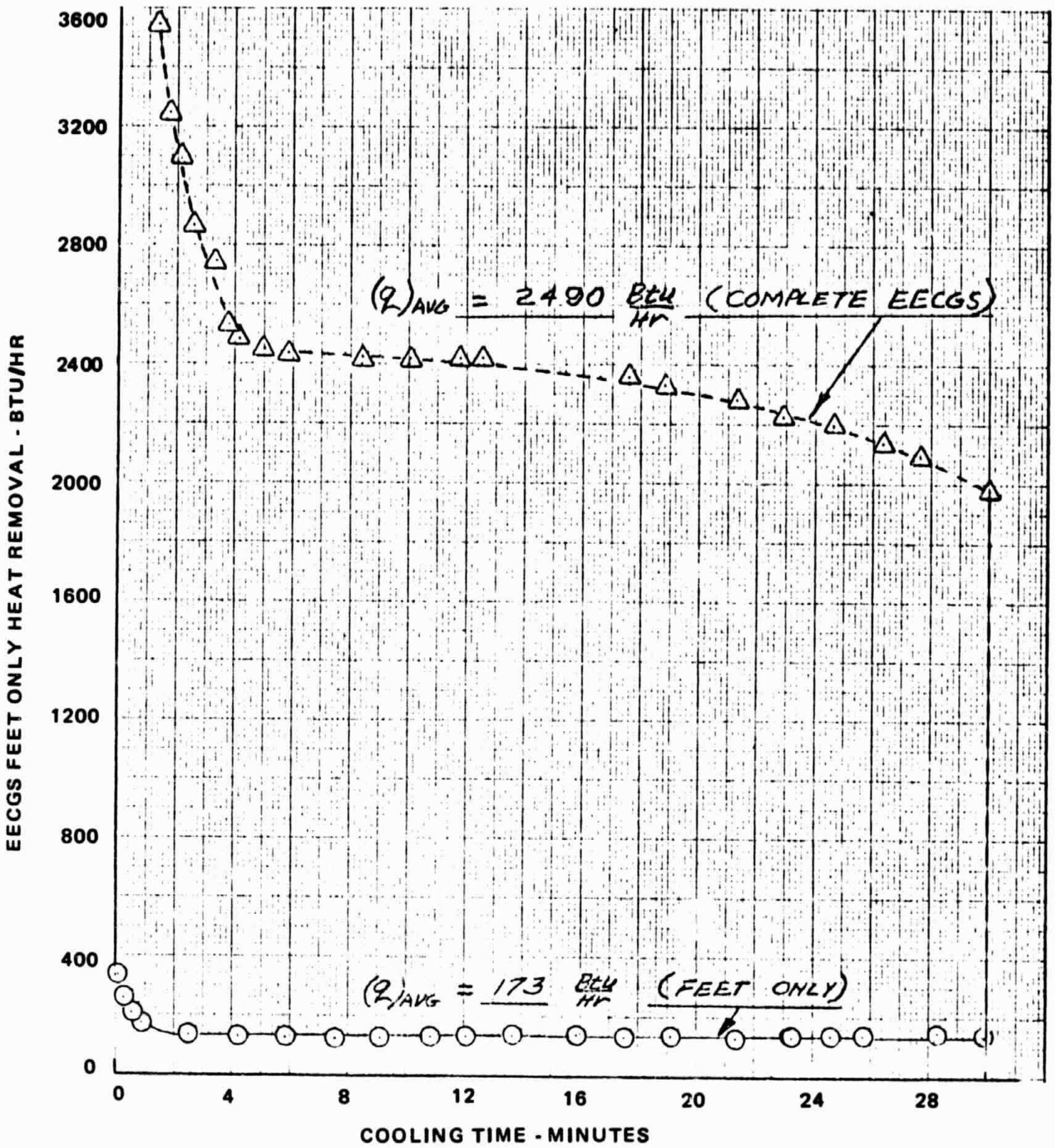


Figure 27. EECGS Foot Cooling (4,000 Btu/Hr Metabolic Rate)

## Section 5
## EECGS/LCG INTEGRATION AND FINAL CONFIGURATION

### 5.1 OBJECTIVES

The prime objective was feasibility, without compromising the normal operation of the LCG. The secondary aim was to integrate the ECGS with the LCG into a configuration that showed promise of leading to a combined cooling garment system that would be compatible, lightweight, and be able to provide emergency performance under an ECGS operating mode.

### 5.2 EECGS/LCG INTEGRATION

The cooling collar, discussed earlier, was designed such that it could be Velcro attached to the LCG, both garments could then be donned as one. The LCG has a front zipper for entry; therefore, the ECGS sternum strip was split vertically so that each side could match the LCG. The LCG is put on normally, the collar can be zipped up first or simultaneously with the LCG. The ECGS arm and leg cooling segments are enclosed in a separate garment to be worn over the liquid-cooled suit. The outer garment will be described in the following paragraphs.

The arm and leg segments are permanently joined together via Spandex at the articulation areas to a lightweight vest that zips up the back. The vest contains the final outlet vacuum manifold called the "octopus", which is located at the same LCG inlet-outlet space pressure suit penetration fitting position. This provides for testing the EECGS without modifying the current Apollo space suit. All vacuum lines from each cooling segment are routed underneath an integrally attached final smooth outside lightweight cover.

The EECGS arm-leg-vest garment is donned through the back, then zipped up; and the torso, arm, and leg seams are Velcro joined together. The collar vacuum line is attached to the "octopus", and the smooth outer cover is dropped over the outlet valve and zippered to the lower torso. The cooling shoes and helmet are finally donned and connected by three vacuum fittings. (These will eventually be redesigned as quick disconnects.)

Thermistors and pressure instrumentation lines are all permanently installed and are protected by the outer cover.

## 5.3 FINAL CONFIGURATION

Figure 28 shows all of the EECGS cooling segments, as joined at actual length vacuum lines to the final "octopus" collector manifold. Each segment fits into its own pocket, all lines are normally secured to the connective garment, and the octopus is permanently bolted to the vest. The circular segment at the top center is the helmet, adjacent to which are the upper and lower arms, followed by the lower legs and the larger upper legs. The lower right shows the foot cooling segments. The collar is "fork" shaped; the "handle" covers the spine, and the "tines" are joined to cover the sternum.

Figures 29 and 30 show how all ECGS cooling segments are configured to the man. The shaded areas are cooled with a total coverage of 10.54 sq ft, which is about half of the body exposed area. Of this total only 29.4% is in direct contact with the skin. The remaining 70.6% is cooled by the EGGS directly through the LCG, which acts as a semi heat insulator. The vacuum lines from each cooling segment are routed according to Figures 31 and 32. The thermistor pattern is shown in Figures 33 and 34. The helmet is detailed in Figure 35 and the complete EECGS/LCG is shown in Figure 36.

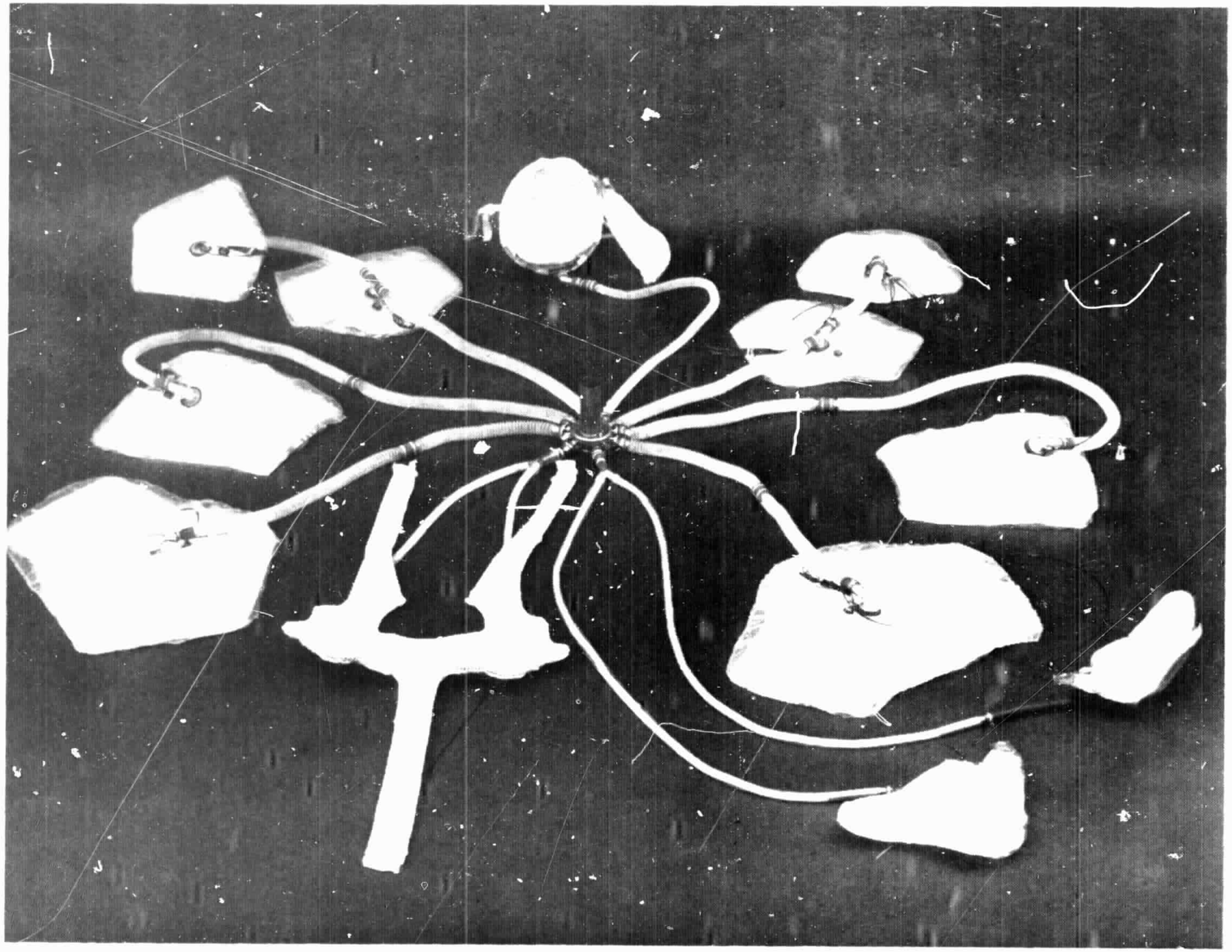

Figure 28. EECGS/LCG Segment and Vacuum Lines Connected to Octopus Collector

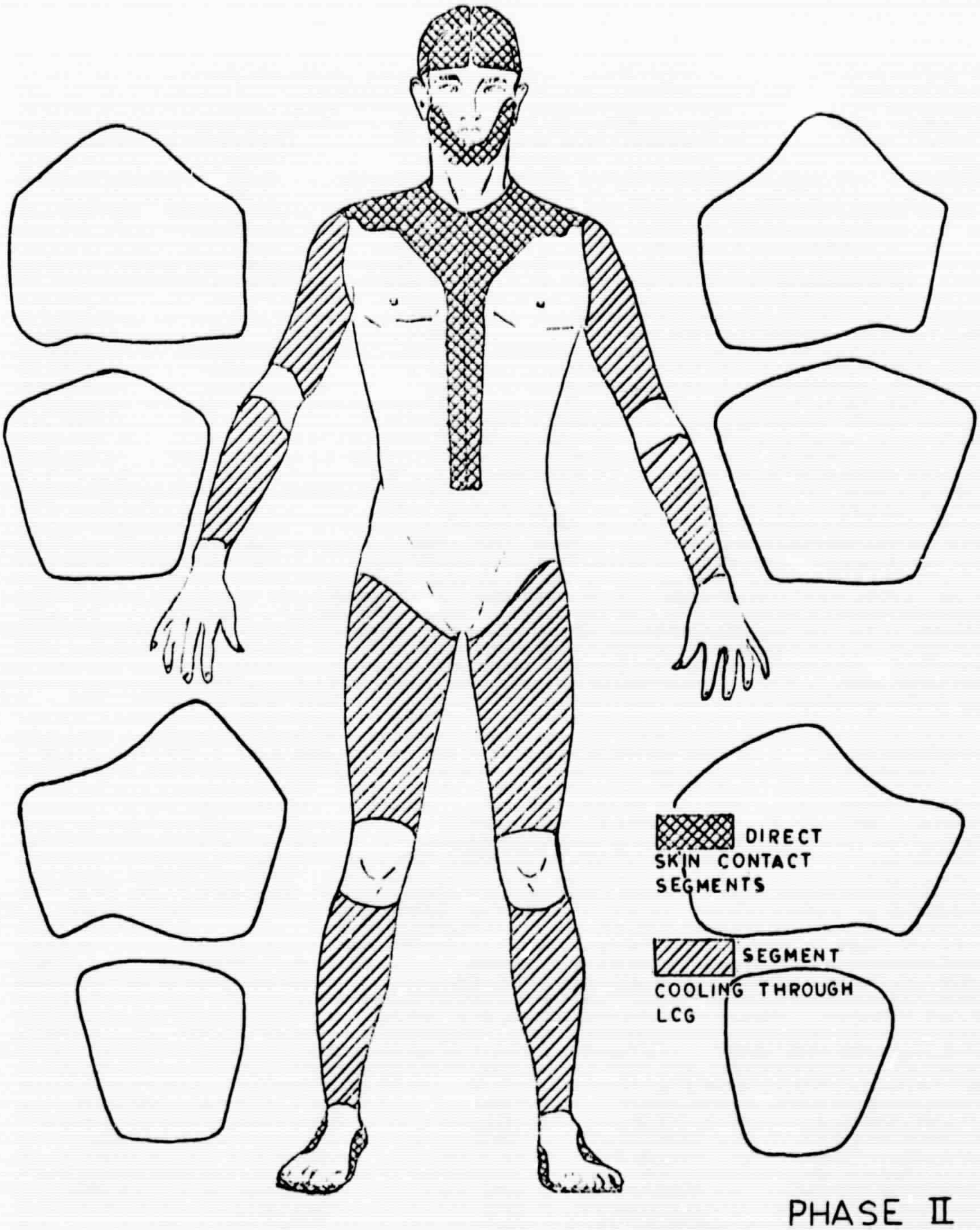


**Figure 29. EECGS/LCG Segment Contact Areas - Front**

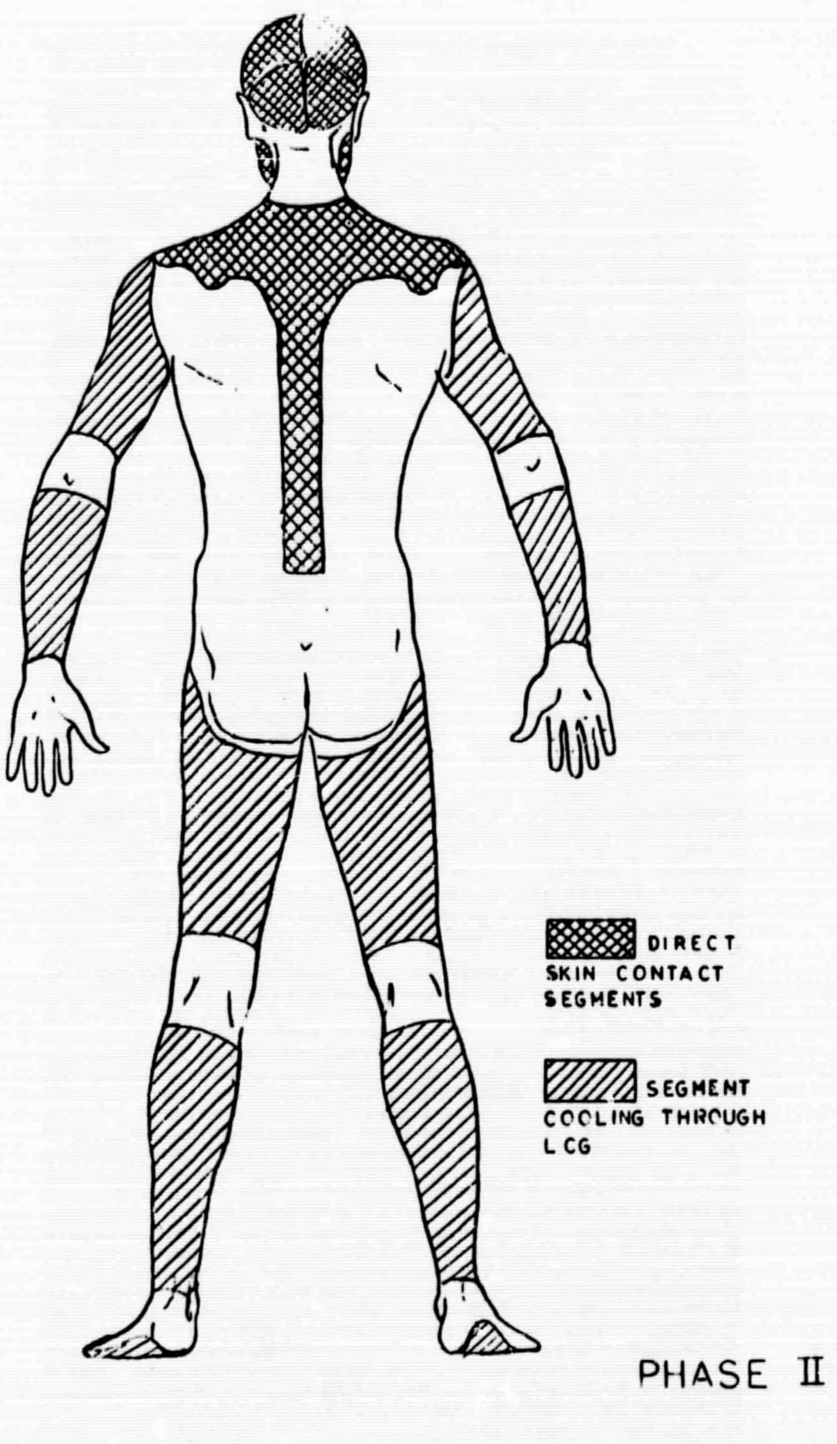


**Figure 30. EECGS/LCG Segment Contact Areas - Back**

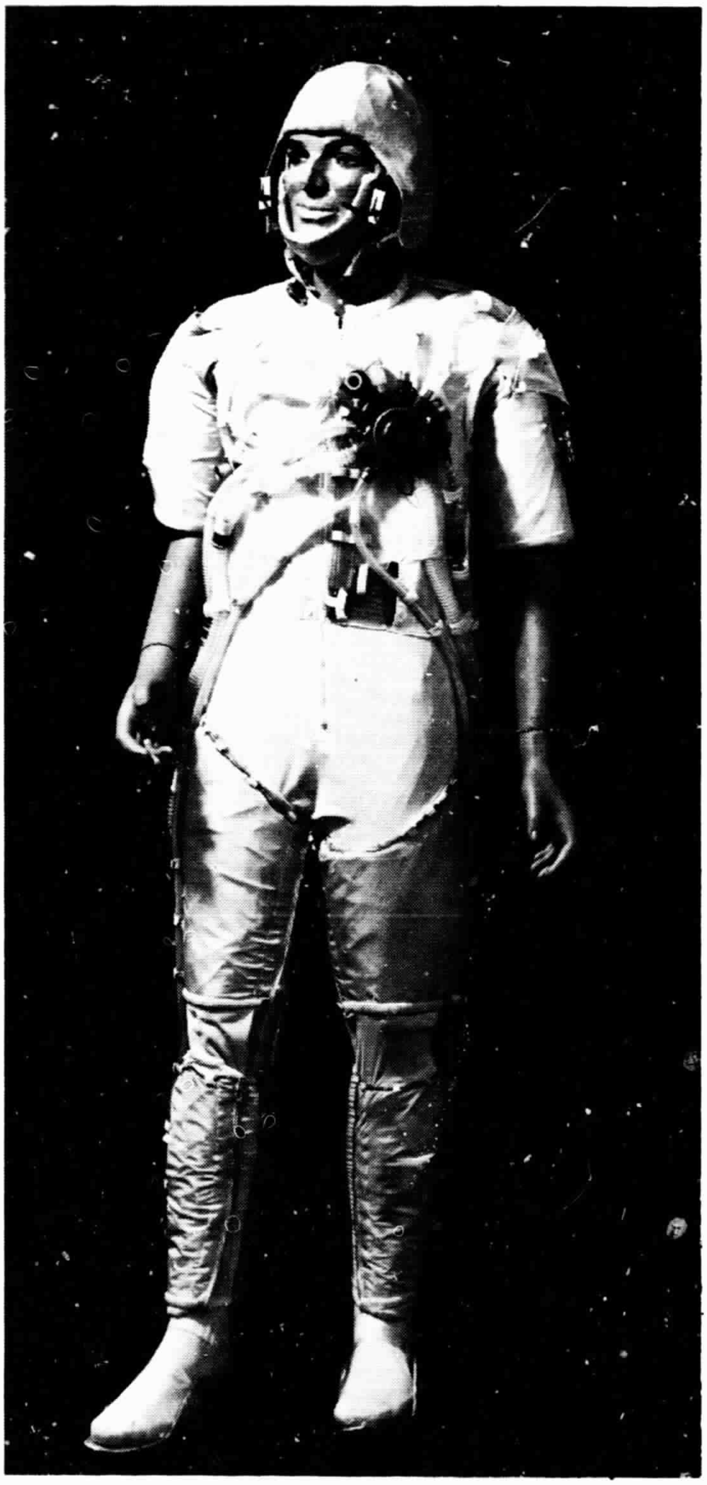

**Figure 31.** EECGS/LCG Vacuum Lines

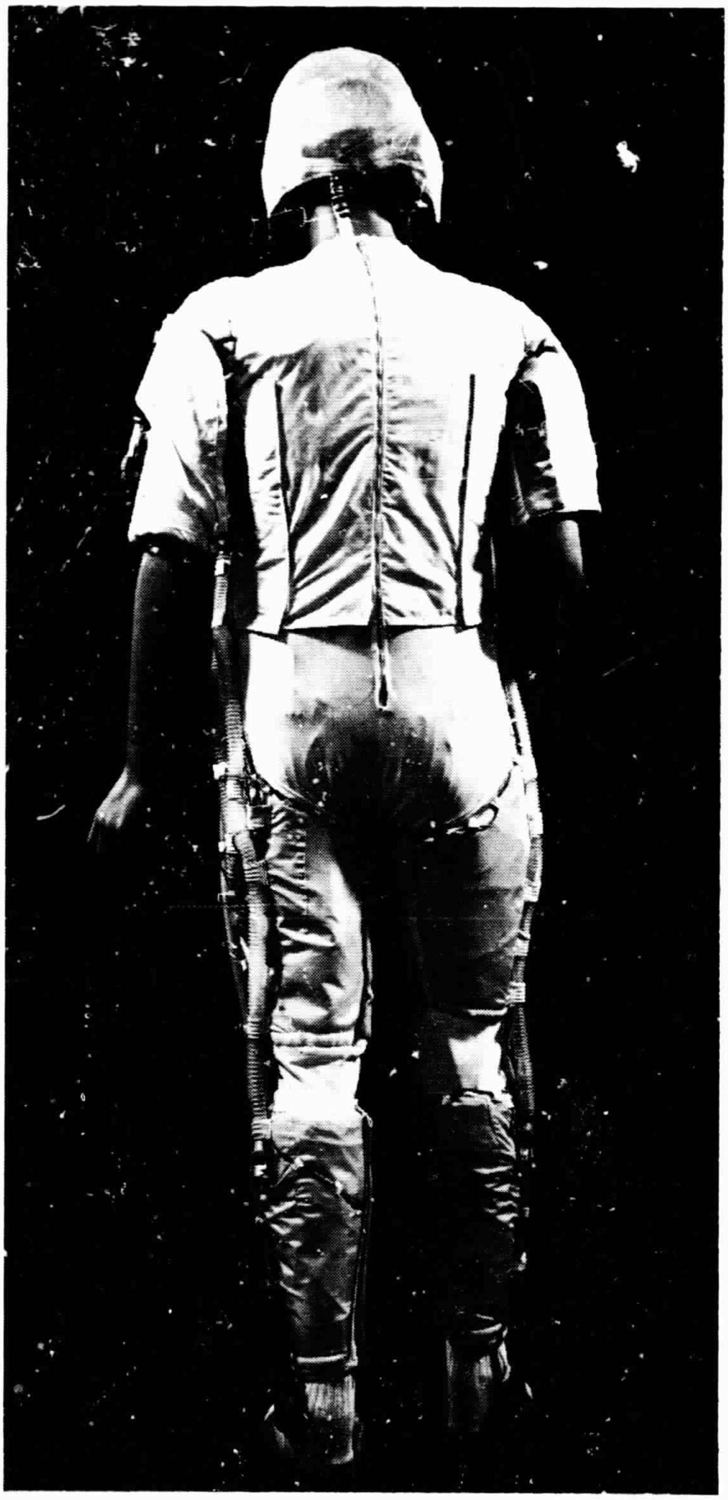

**Figure 31. EECGS/LCG Vacuum Lines (Continued)**

**Figure 31.** EECGS/LCG Vacuum Lines (Continued)

Figure 31. EECGS/LCG Vacuum Lines (Continued)

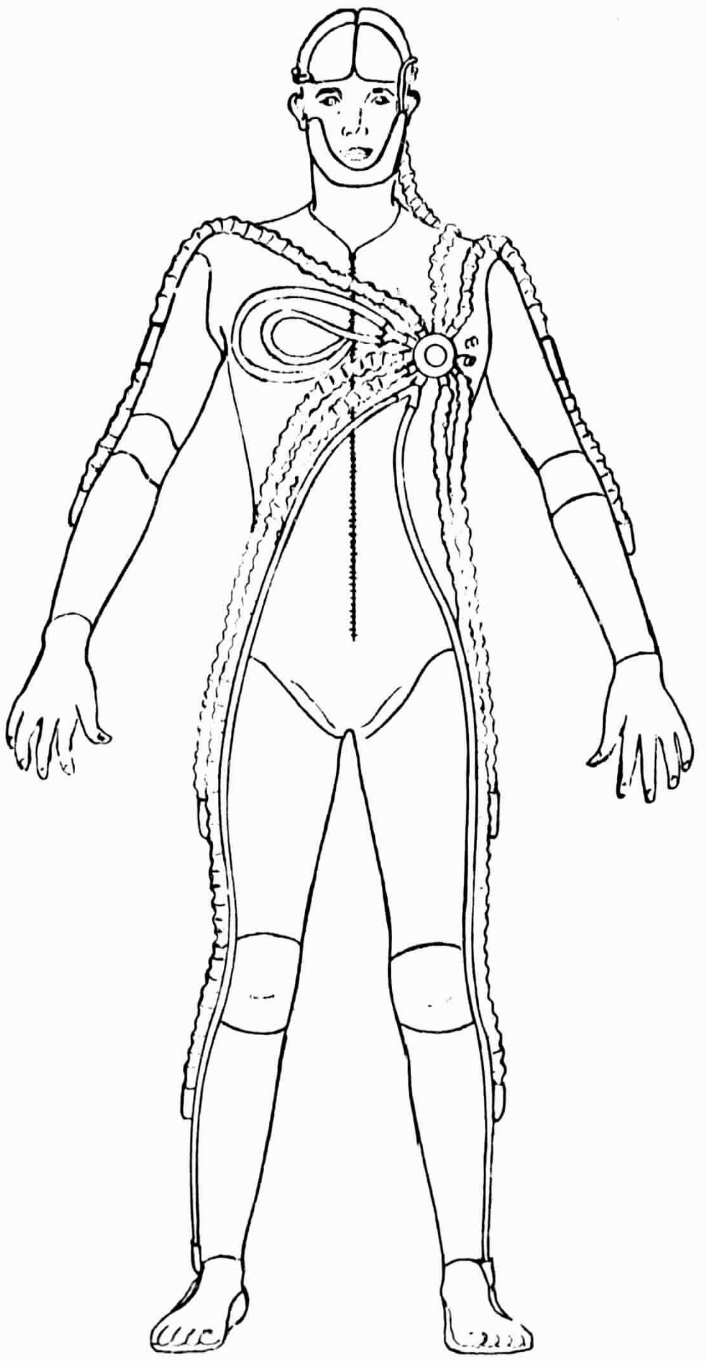

Figure 32. EECGS/LCG Vacuum Lines - Installed

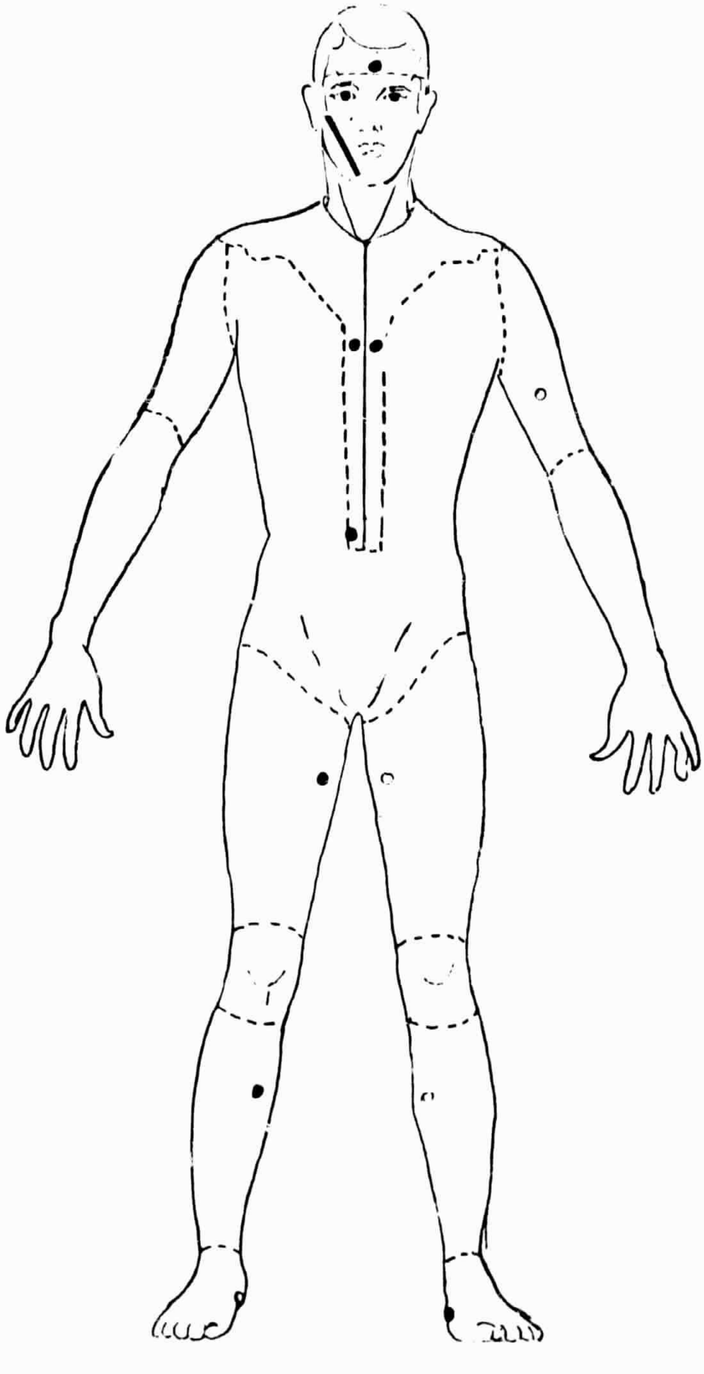

Figure 33. Thermistor Pattern - Front

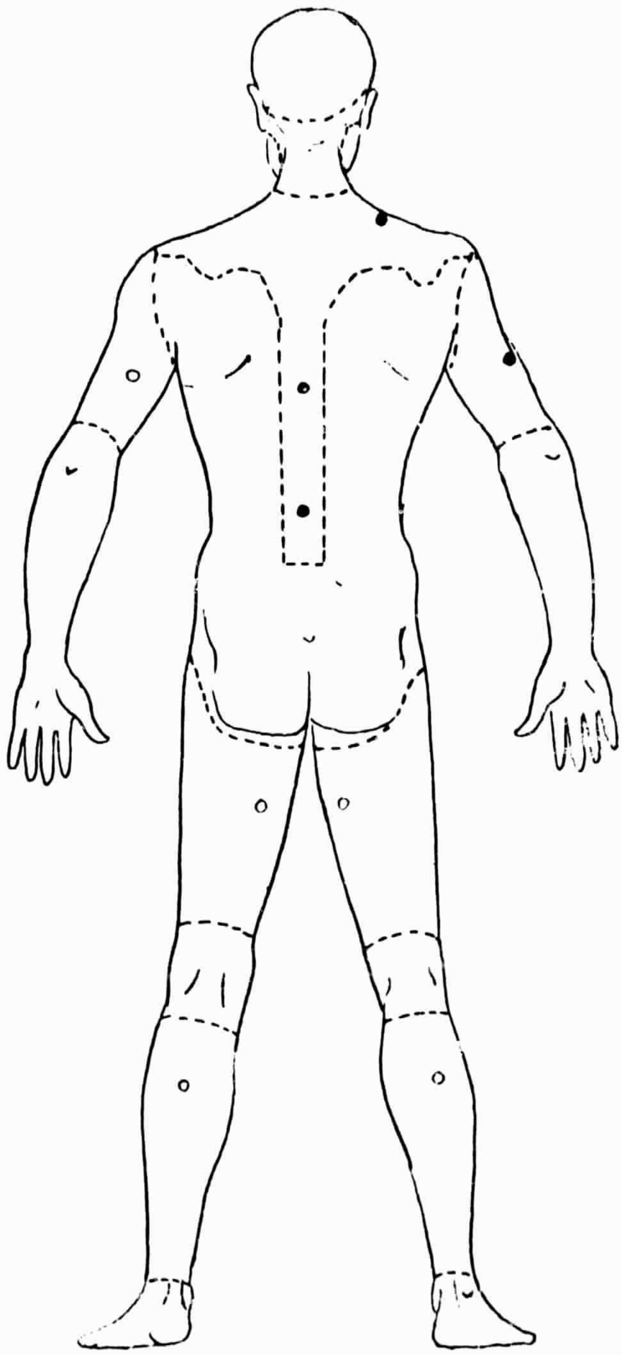

Figure 34. Thermistor Pattern - Back

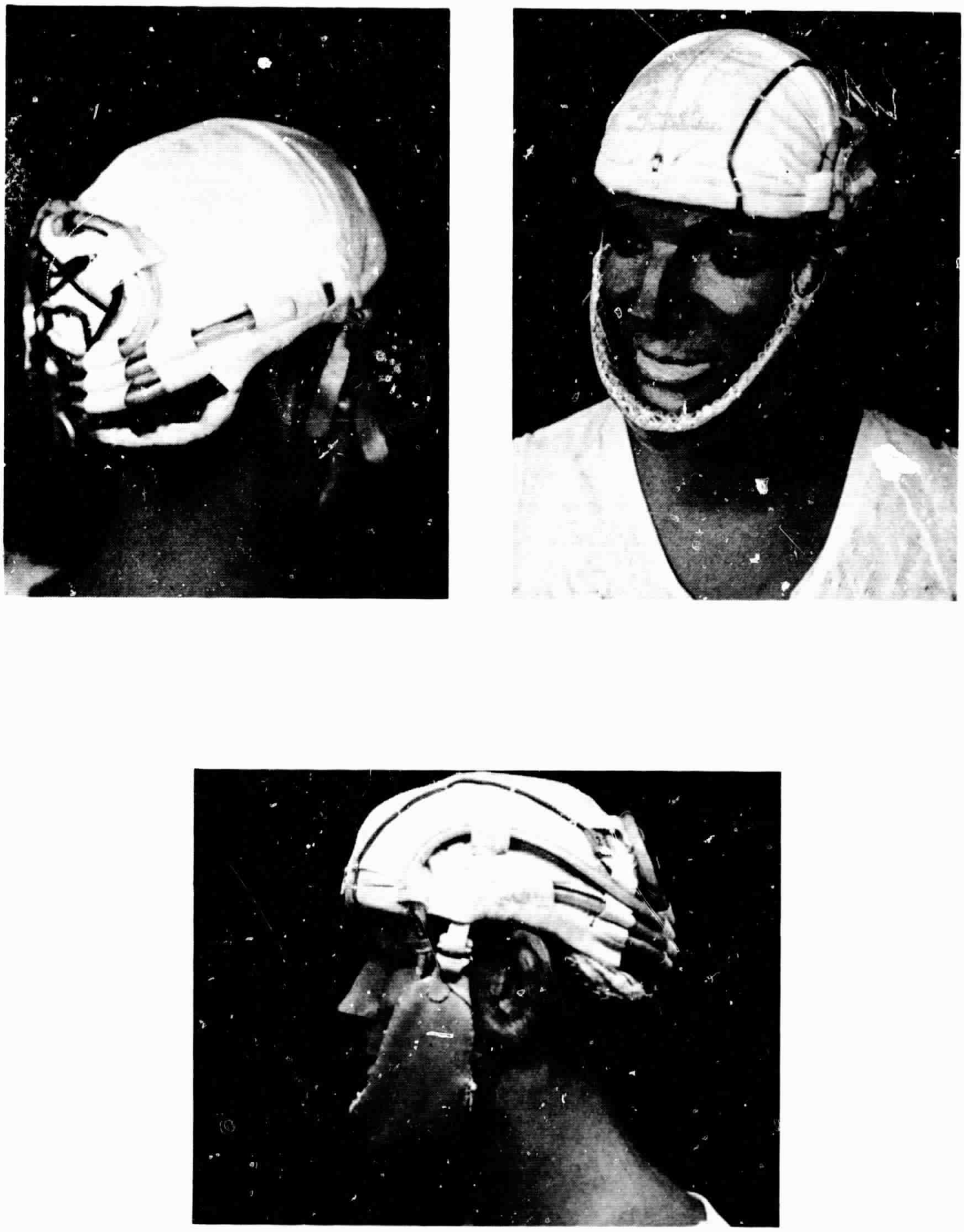

**Figure 35. ECGS Cooling Helmet with Outer Cover Removed**

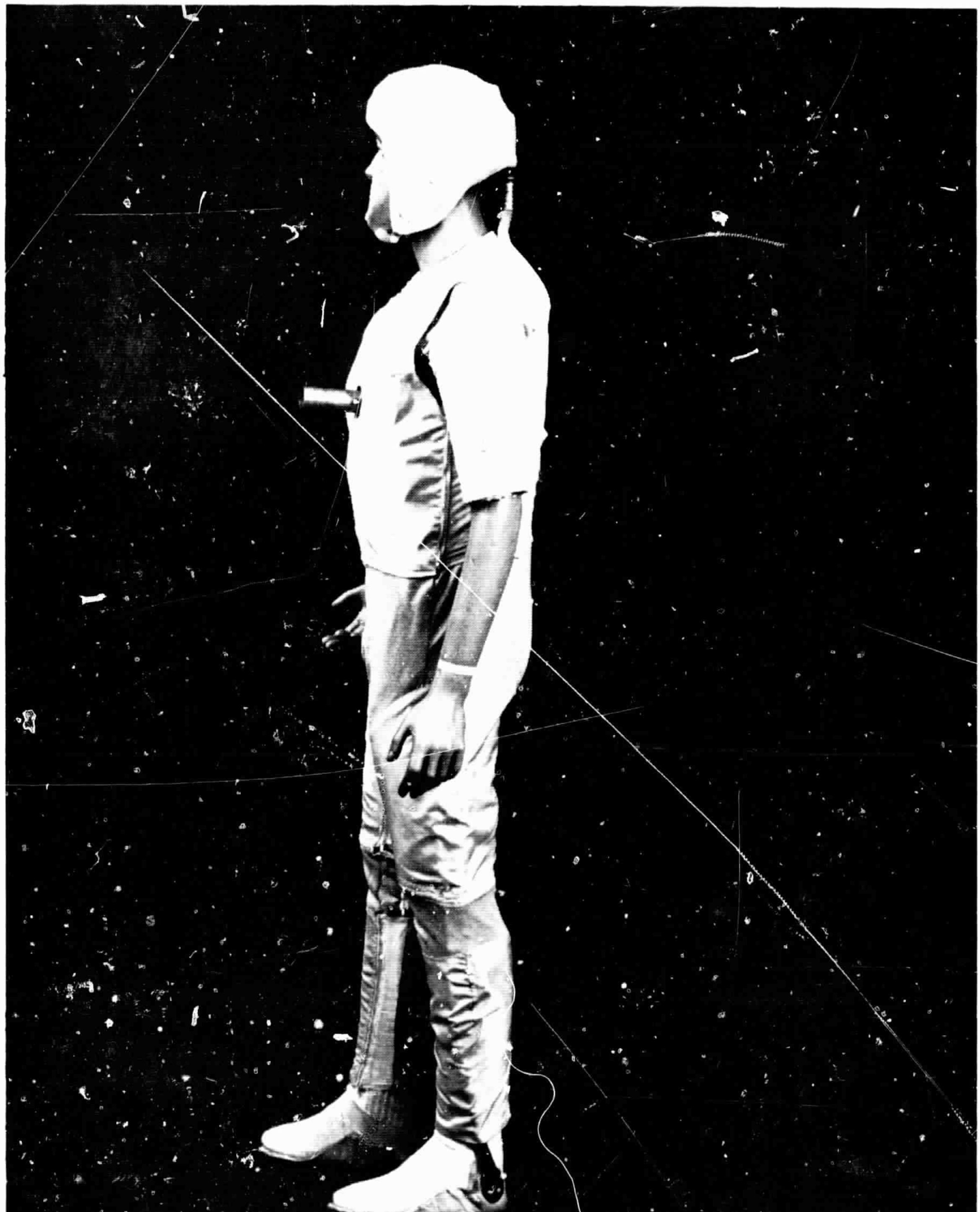

Figure 36. EECGS/LCG Complete Suit

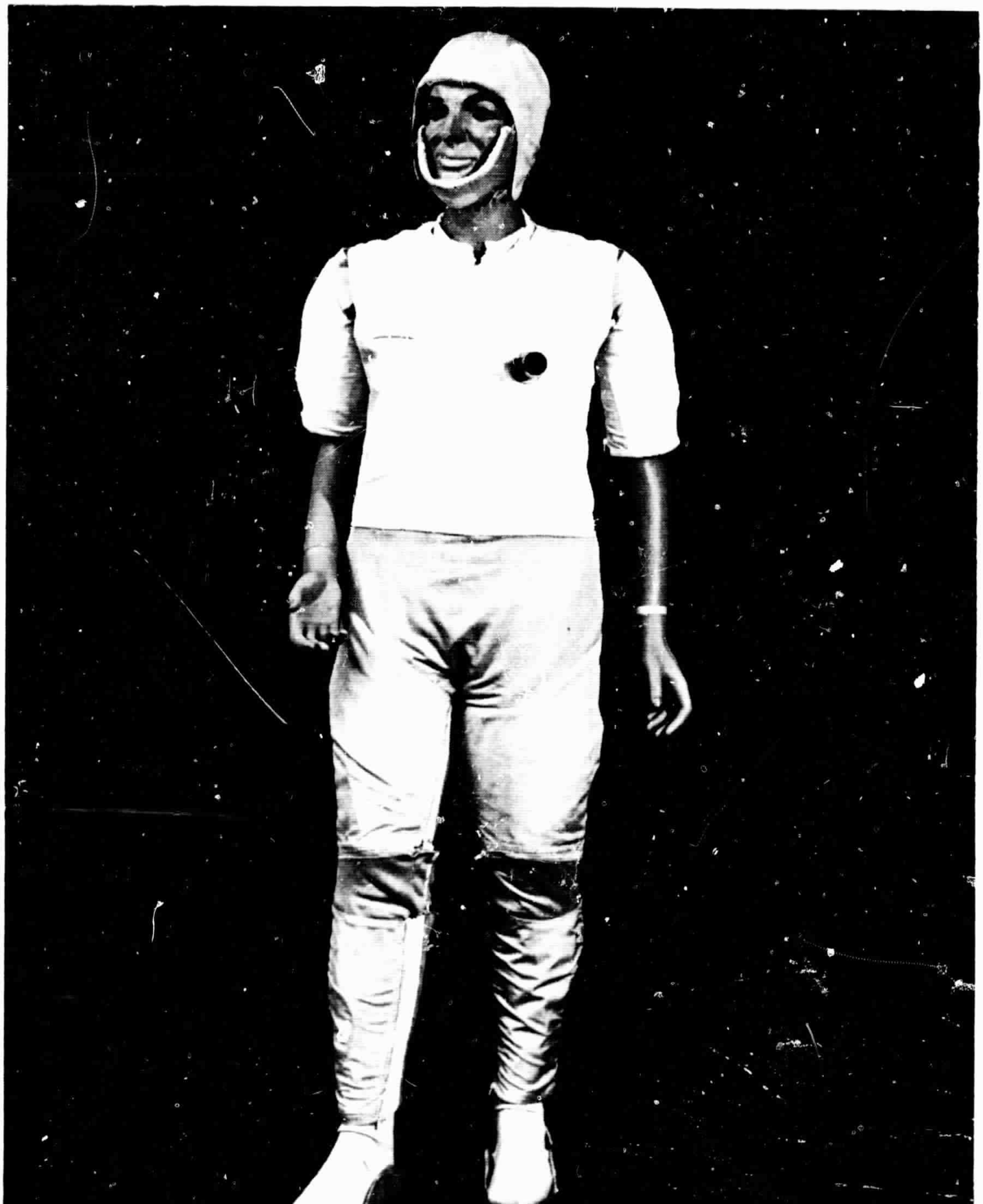

Figure 36. EECGS/LCG Complete Suit (Continued)

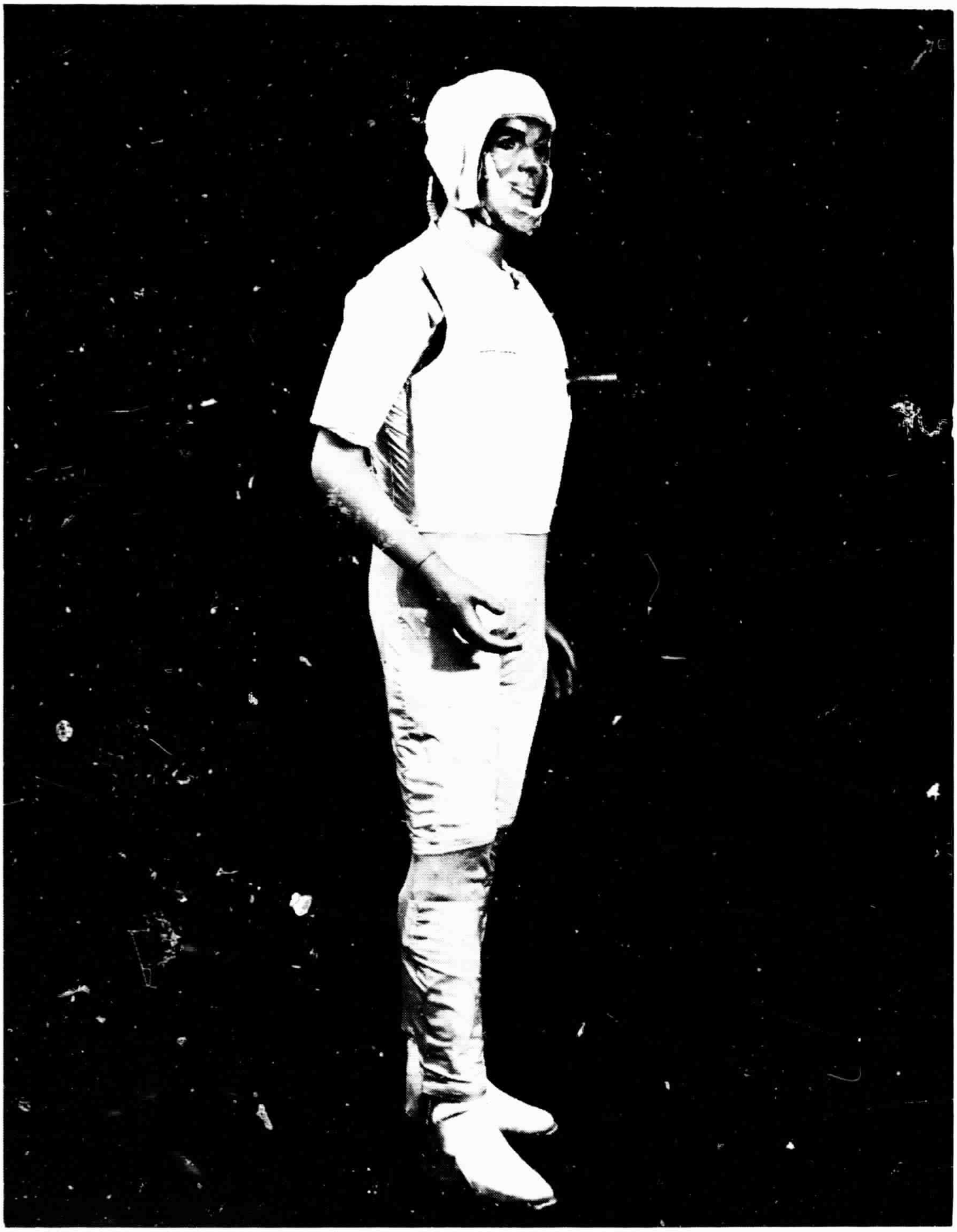

Figure 36. EECGS/LCG Complete Suit (Continued)

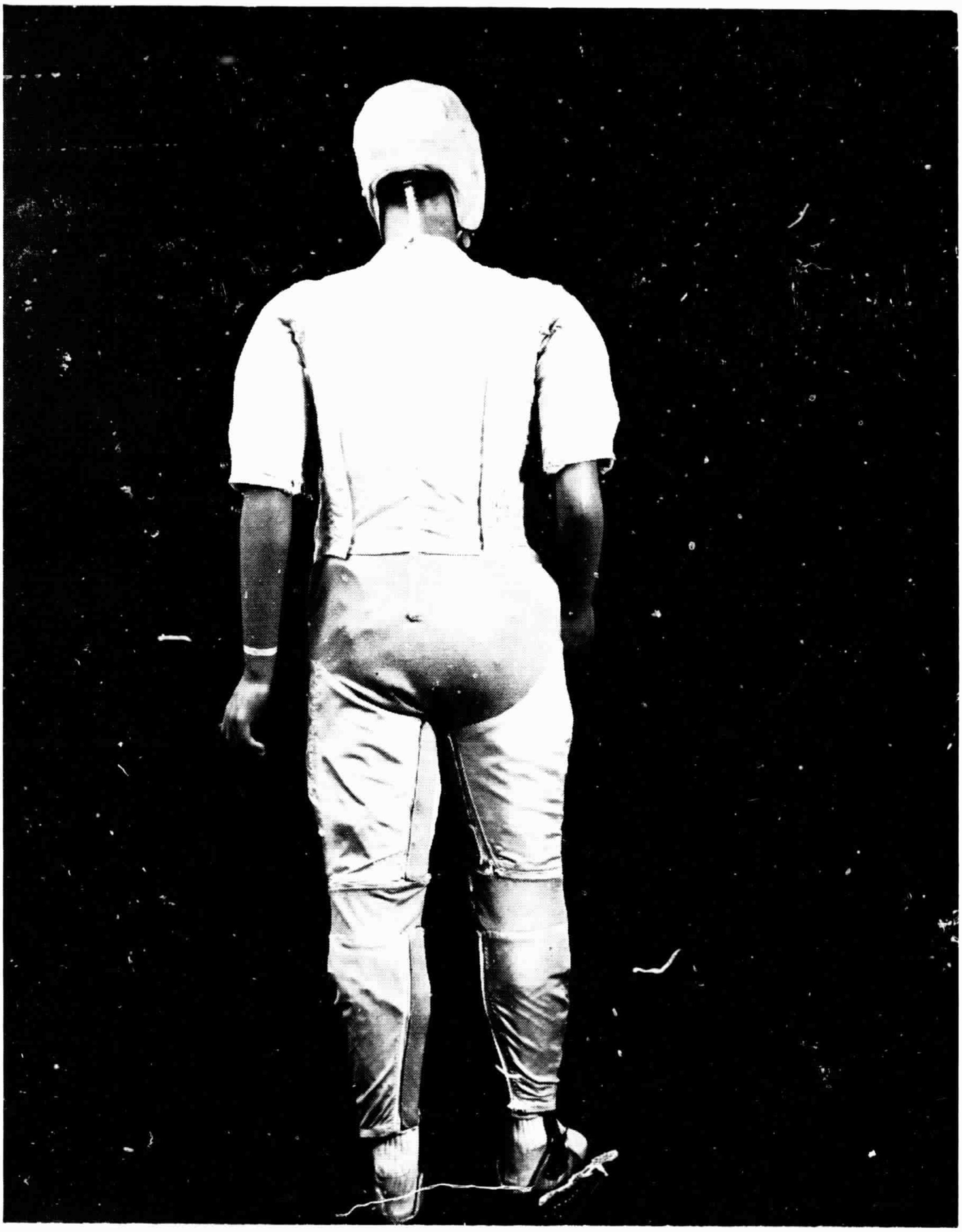

Figure 36. EECGS/LCG Complete Suit (Continued)

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# Section 6
# FORMAL DESIGN VERIFICATION TEST

## 6.1 SIMULATED MISSION PROFILE

The work rates established by NASA-MSC were to simulate a lunar emergency mode of operation, wherein the LCG was rendered inoperative. The ECGS would take over the cooling in the configuration of the EECGS/LCG as described in Section 5.3.

The work rates established by contract were 3,000 Btu/hr to be held constant for an uninterrupted 30 minutes of operation. The emergency mode was to operate on a prestored single charge of internal ECGS cooling segment of expendable water, and was to require no power or dependence on the backpack for cooling. Shortly after Phase II was initiated, it was requested to raise the metabolic rate to 4,000 Btu/hr as a "best-effort" target. The full half hour average cooling heat exchange for 3,000- and 4,000-Btu/hr work rates were 2,290 and 2,980 Btu/hr, respectively. The lower value was easily demonstrated and the feasibility of the higher value was assured with existing hardware.

## 6.2 TEST SUBJECT TRAINING ON TREADMILL

### 6.2.1 Training Background

The Phase I program required metabolic rates of 5,000 Btu/hr for 20 minutes without rest. It was then determined that training for these high work rates was necessary, and a training procedure was developed empirically. The training program was duplicated in Phase II with some minor refinements, with the objective of 4,000 Btu/hr for 30-minute duration.

Three young subjects of normal build and weight were selected as candidates for training between the ages of 22 and 26. All were required to take an Air Force Class A flight physical, which they all passed. None of the trainees were college athletes or smokers. A fourth subject, age 50, was selected as a backup because he had gone through the Phase I contract and had become one of the two primary subjects for that program's highest work rates. Nine months had elapsed between the finish and the start of the two training programs; therefore, this latter subject was required to repeat the training and did so with relative ease, as compared to the first time through.

A constant treadmill training speed of 4.5 mph was again selected, because all data could then be compared with the first phase. This speed is well into the vigorous walk range, but is sufficiently below the run transition range of 5.5 mph, so that all subjects end up with a fast walking gait. Before every training run, the subject was prepared with three ECG electrodes with the ground lead at the sternum and the other two symmetrically placed at the side of the third rib. No signal artifacts were observed even during the heaviest prolonged exercise. An oscilloscope was provided for visual inspection of the ECG; strip-chart recordings could be taken, and simultaneously, pulse rates and time to the nearest hundredth of a minute were printed out on paper tapes.

The subjects were dressed in track shorts only and wore canvas rubber-soled shoes and socks of their own liking. Two of the four subjects had a high skin impedance, and the electrodes were attached in these cases about 1 hour prior to each test. The conducting paste then fully reacted, and the resulting noise gradually went away. The other two subjects could start even violent exercise immediately after electrode placement with no noise problem.

A basic body weight to the nearest 0.01 lb was acquired before obtaining basic resting heart rates. The pre-exercise standard procedure was to get by means of the digital pulse rate recorder the following information:

A. A prone resting pulse-time history on the stationary treadmill for 15 minutes to remove any effects due to minor excitement, and to obtain a good basal rate. (No communicaction with the subject was allowed on any pretest or posttest recordings.)

B. Immediately following the prone position was a sitting at rest recording for 10 minutes.

C. The last pre-exercise test was a 5-minute recording while standing at rest, immediately followed by the preselected full-rate step function exercise.

It was very interesting to note that if any subject's pulse rates were slightly higher than his normal on the three resting tests, his physical performance for that day would be below normal. A good steady low pulse of about 60 while standing at rest would lead to a prediction of good endurance, high performance, and a feeling of vigor even when pushing to the fatigue limits. Usually the higher than normal resting rate increases of 3 to 7 beats per minute could be traced to a prior evening of minor dissipation or stress. Each exercise run was followed by a 15-minute sitting at rest recovery recording, and then body weight was taken to obtain an accurate weight loss.

A training run could be terminated for any of the following reasons:

A. Medical monitor observations.

B. Test subject fatigue or discomfort.

C. Limiting pulse rate of 180 (mandatory termination).

D. Any of the program personnel observing difficulties by the test subject or in his recordings, for any reason.

Endurance at high work levels was the goal, the training protocol was to have test subjects work out to nearly the fatigue limit, at least 1 to 2 days each week on the treadmill at 4.5 mph. Exceptions to this were when a subject was too sore, ill, or had foot blisters which were common. Any given run was continuous, with no rest allowed. Endurance was built up at each grade to a point of apparent diminishing returns, and then the next higher grade angle jump of 2 percent was instigated. The lower grades resulted in endurance up to 2-1/2 hours at 3,000 Btu/hr (11-1/4 miles), which culminated at training peaks of about 4,400 Btu/hr for 40 minutes. Training to higher levels could easily have been accomplished, if desired, but 4,000 Btu/hr was the goal for Phase II.

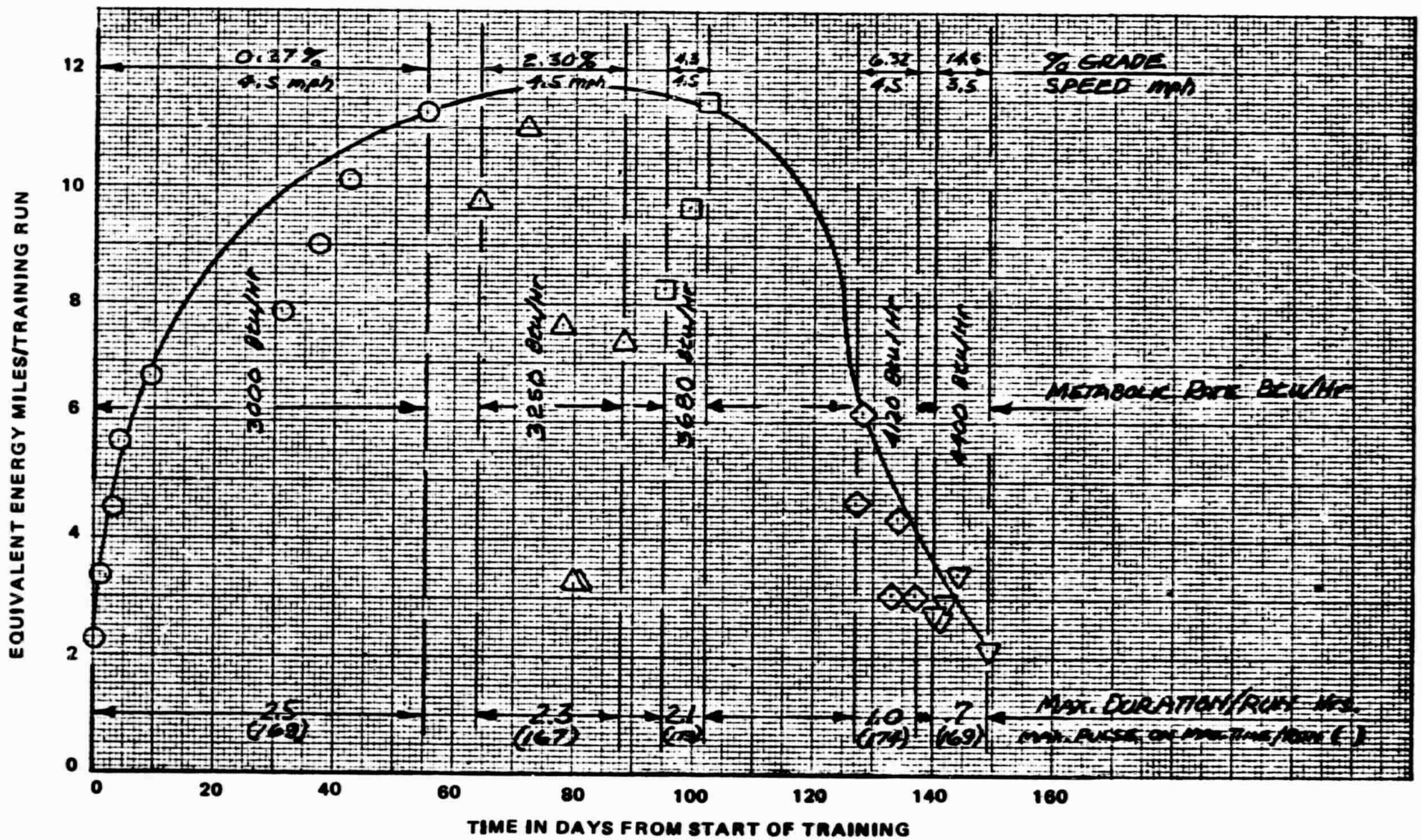
The typical treadmill training profile is presented in Figures 37 and 38. The physical conditioning time was chosen to be 150 days, as required to coincide with the design verification test. The exercise regimen was leisurely accomplished along with other duties, and it is believed the same results could have been obtained in 90-day elapsed time, if really necessary.

Pulse rate versus time plots were prepared for all training runs. The spectacular advantages of a proper exercise protocol in producing a progressive lowering of pulse rate at a given work level were observed for all subjects. A complete pulse rate training history from beginning to end for all four test subjects is presented in Figures 39 through 42. In each case the improvement is shown by both increased endurance and higher work capabilities.

Figure 43 shows data of all four subjects compared on a metabolic rate per pound basis, each doing the same task on the treadmill, thus indicating that all were conditioned close to the same level.

Two of the four test subjects were selected for the design verification tests at 4,000-Btu/hr metabolic rate. Both of these men could easily maintain this work rate for at least 1 hour without rest. The third subject continued training at these higher levels as a backup, and the fourth subject terminated employment to accept a university fellowship. Foot blisters were not a problem at about the program half-way point, even on the longest and most vigorous training runs. Resting heart rates declined steadily during the training period to the point where they all averaged about 60 beats per minute. Sitting at rest heart rate recovery within 10 minutes after cessation of treadmill runs averaged a drop over 60 beats per minute from the maximum exercise level of 170/minute.

The greatest weight loss during the most strenuous training runs was 4.39 lb in 2 hours; this produced no particular distress except for a great thirst after the run which continued for several hours. The intake of fluids after a high




EQUIVALENT ENERGY MILES = [TRUE MILES] $\frac{\text{(BTU/HR) GRADE } n\%}{\text{(BTU/HR) GRADE } 0\%}$
(SUBJECT JB)

**Figure 37. Treadmill Training Profile**

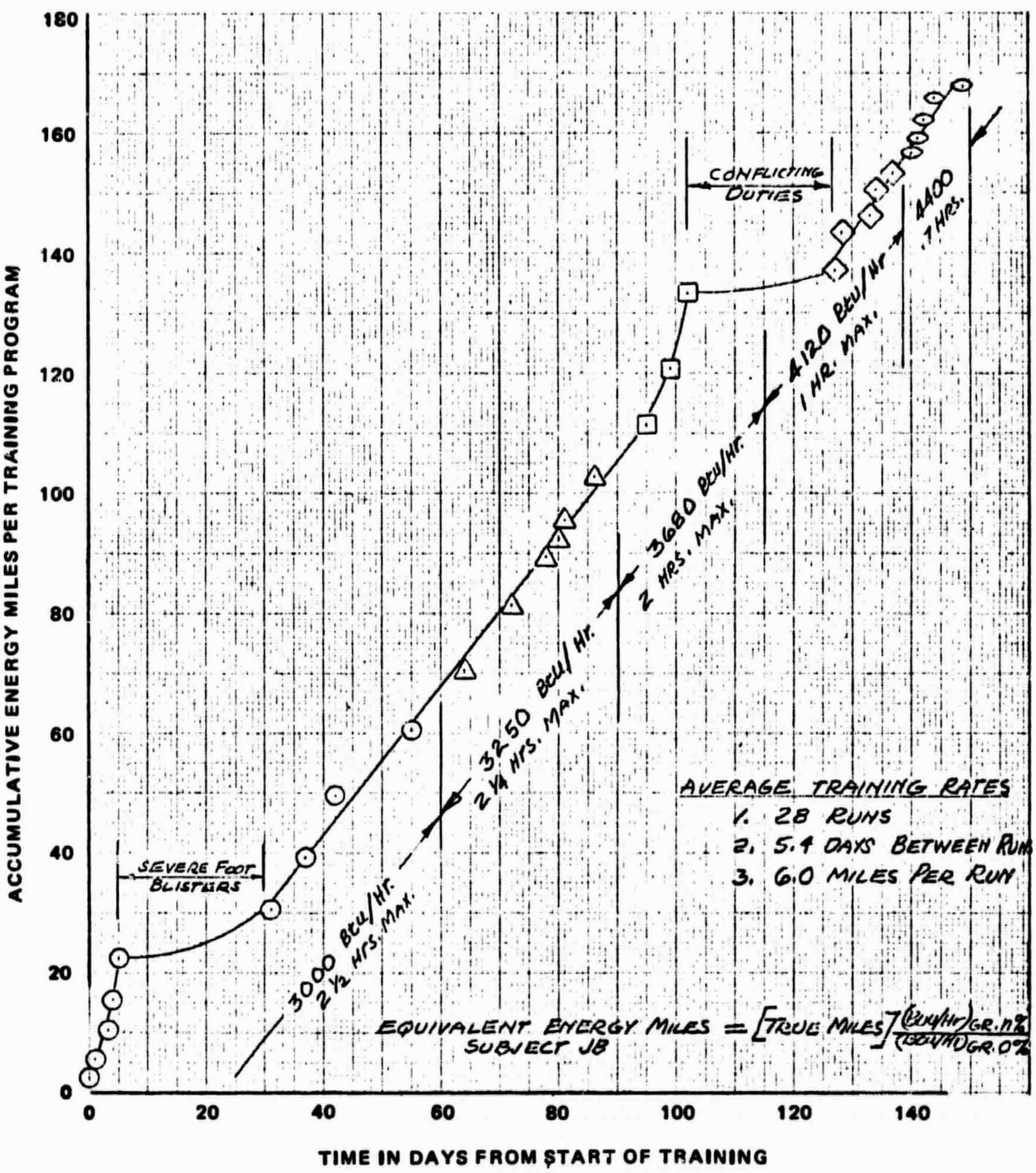
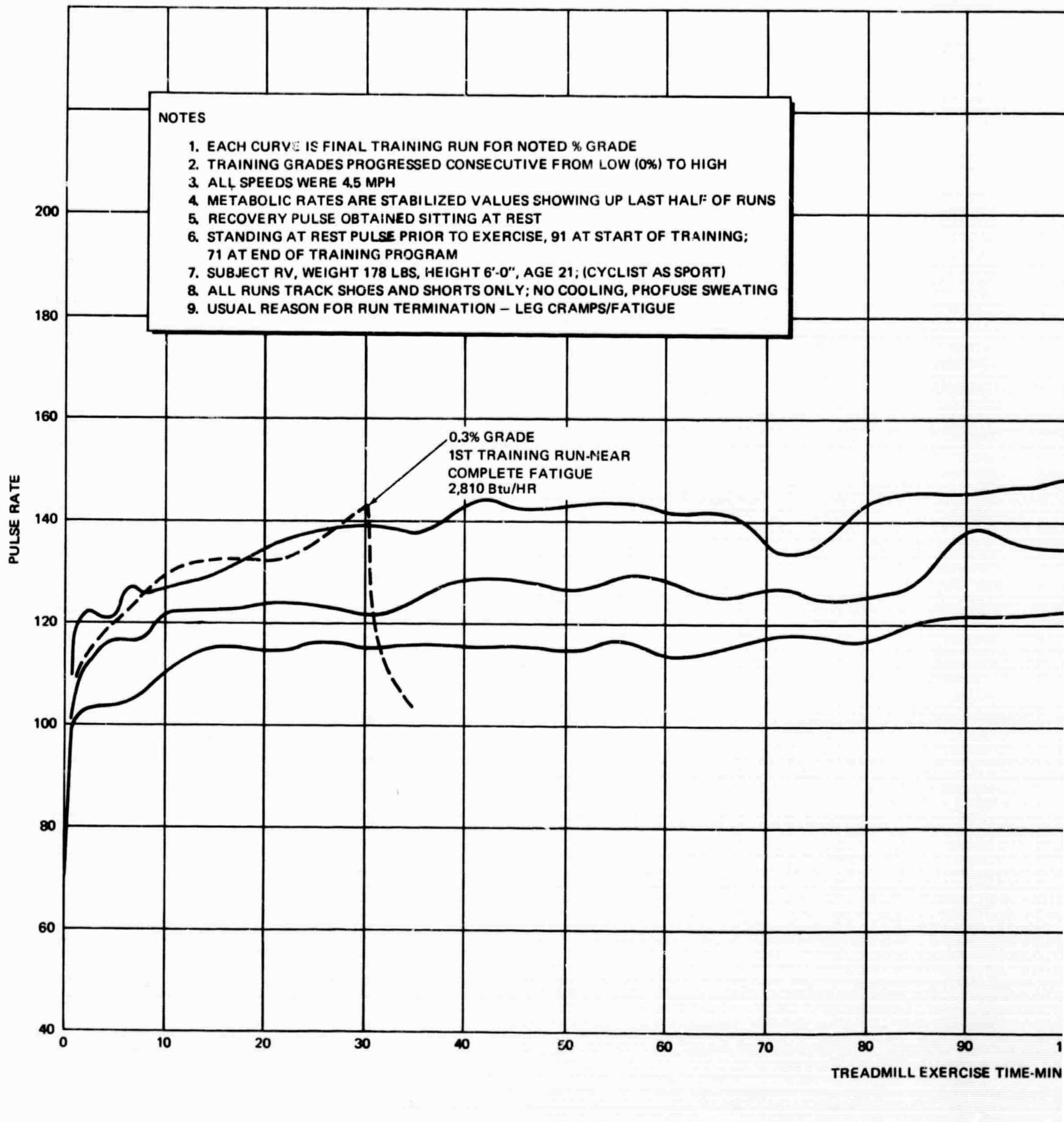



Figure 38. Treadmill Training Miles for Conditioning Program




FOLDOUT FRAME 1

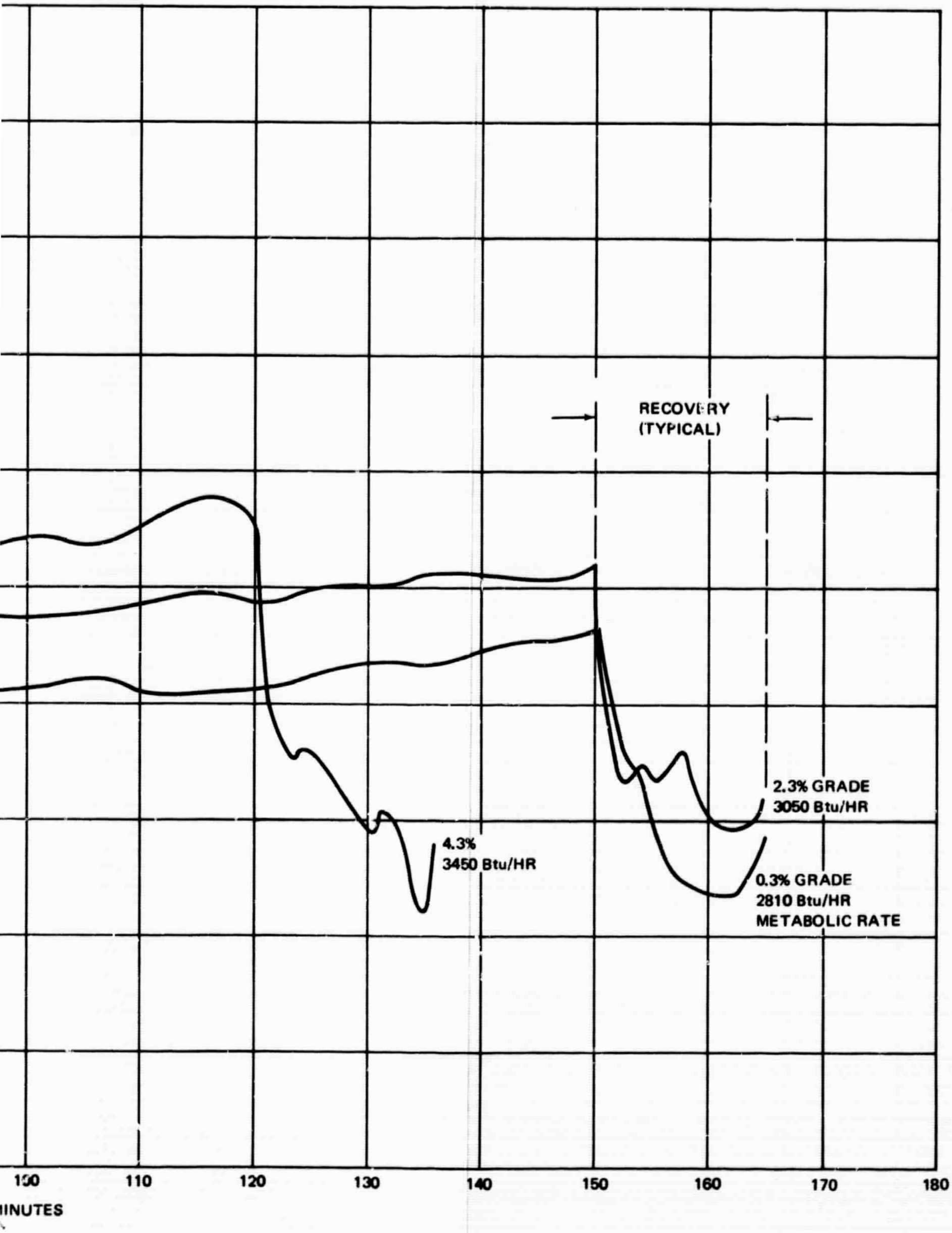
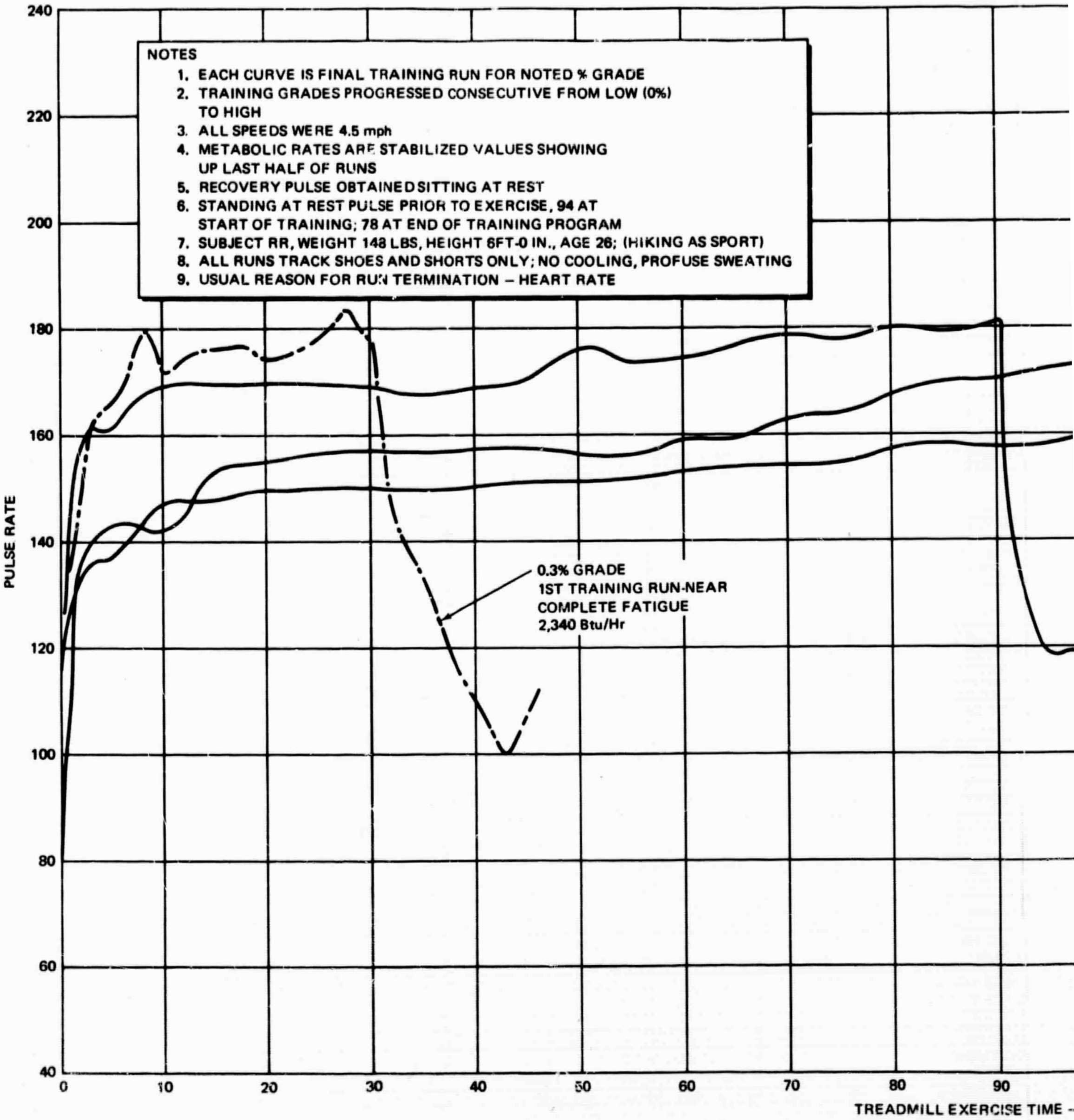


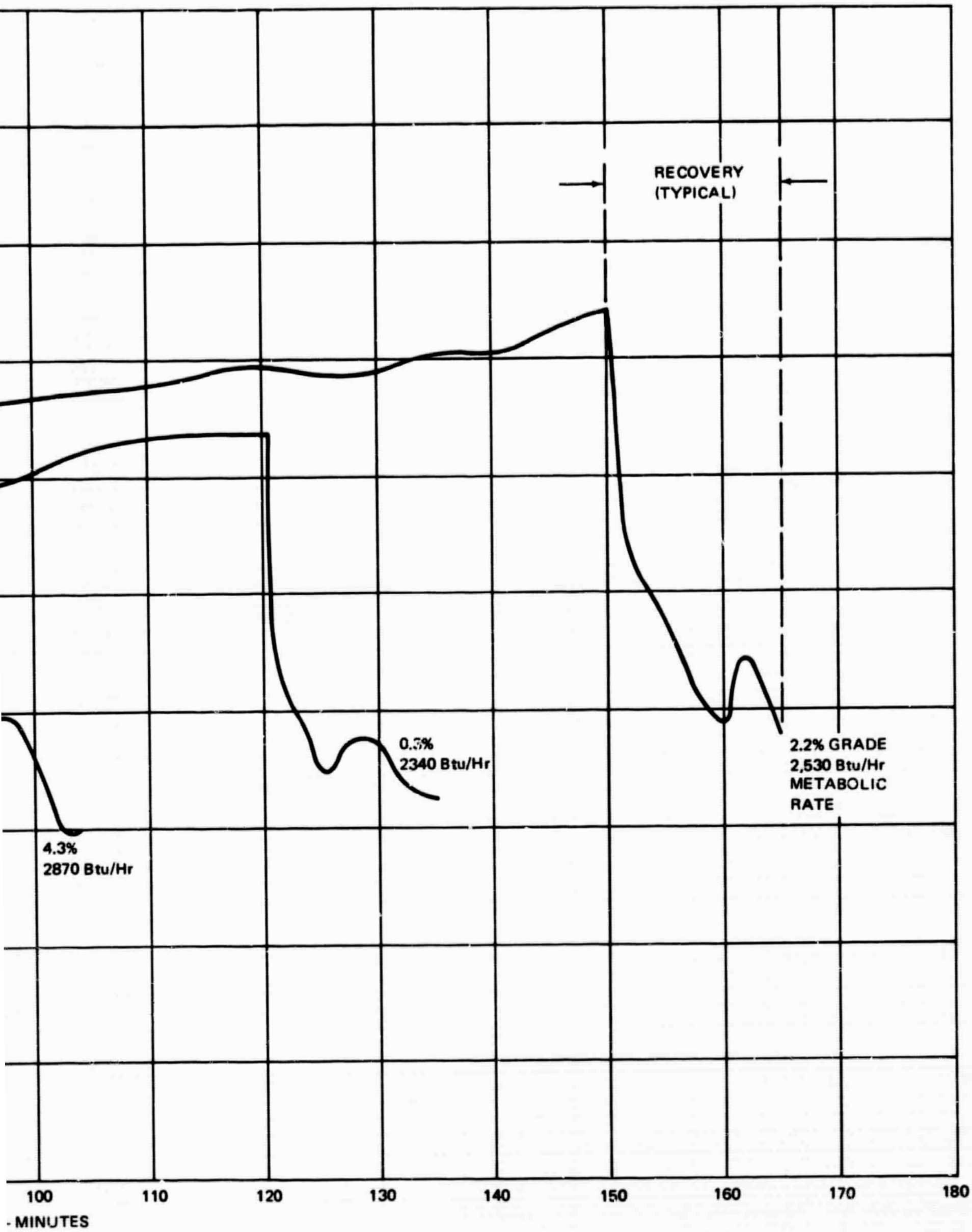

Figure 39. Treadmill Training



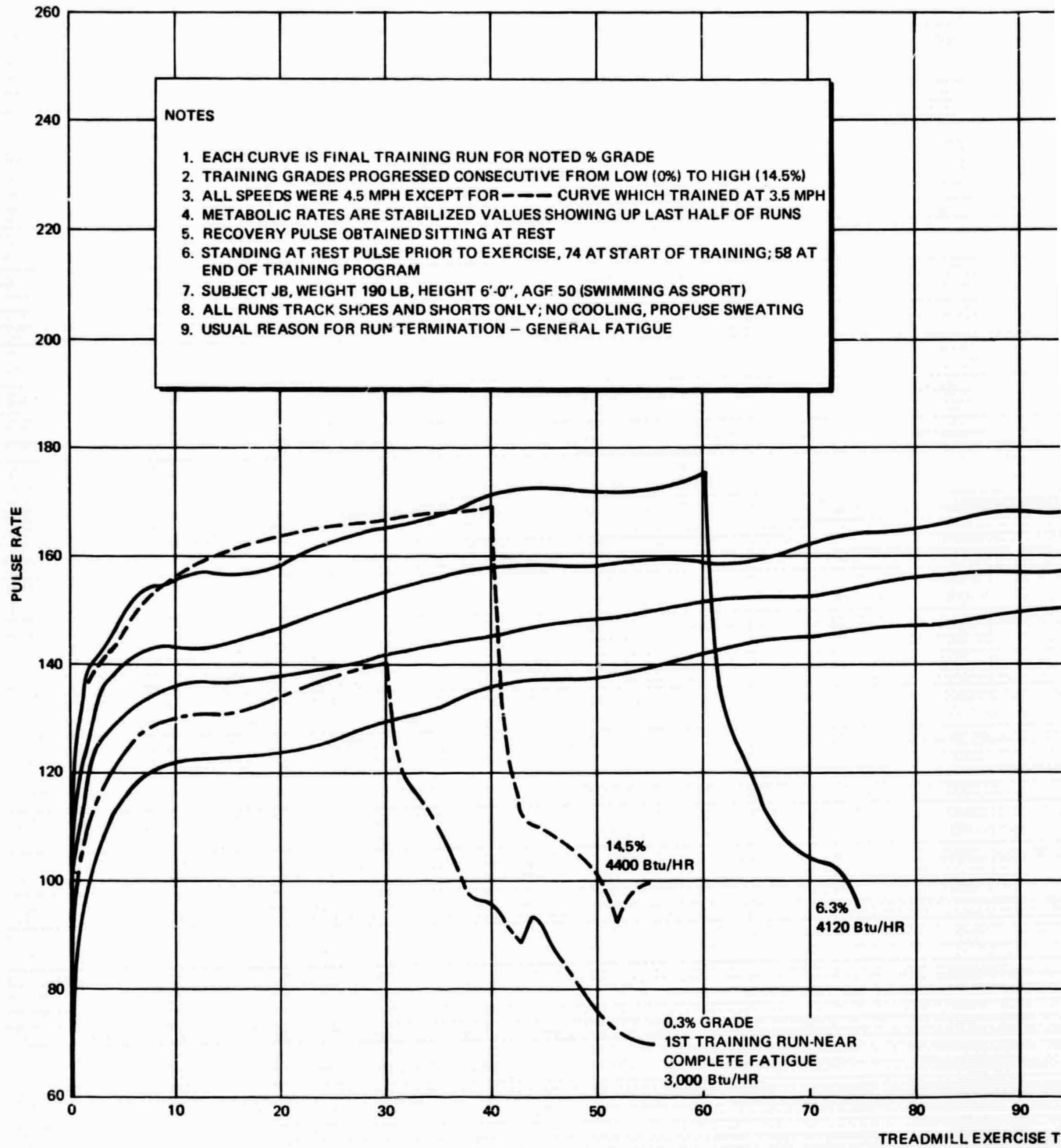

F ure 40. Treadmill Training

[redacted]

FOLDOUT FRAME 1




FOLDOUT FRAME 2




FOLDOUT FRAME

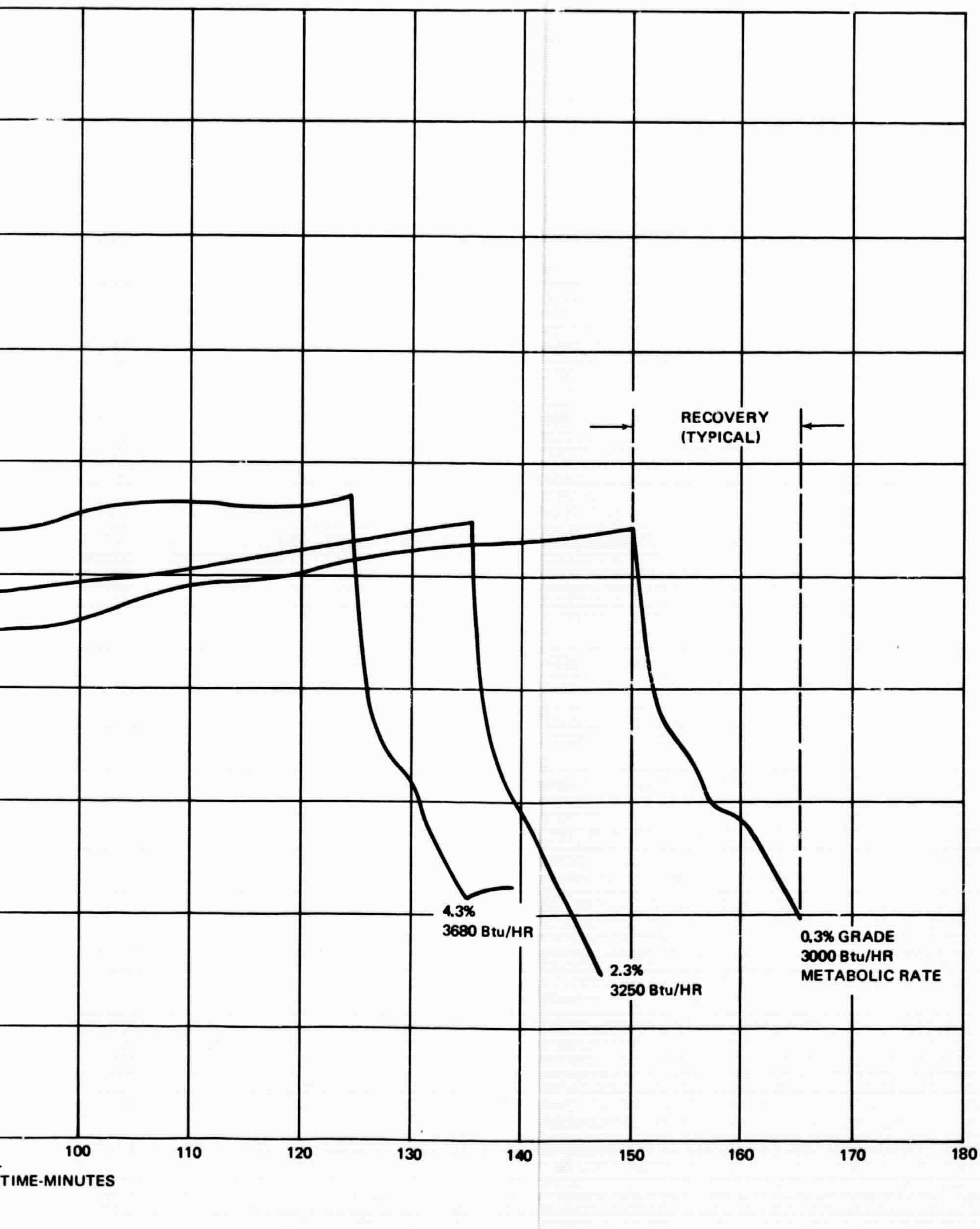



Figure 41. Treadmill Training

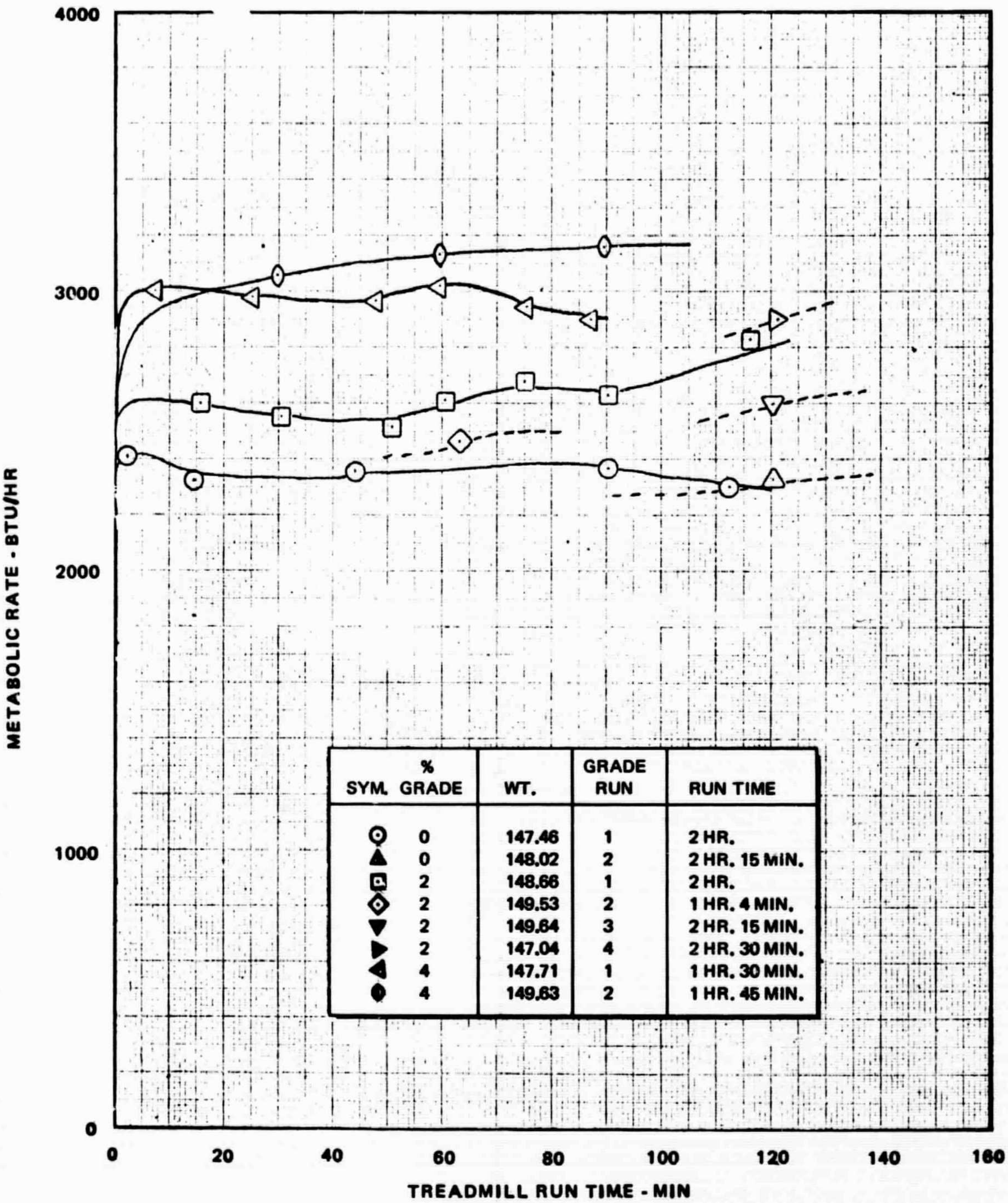



**Figure 42. Training Effect - 4.5-mph Subject RCR**

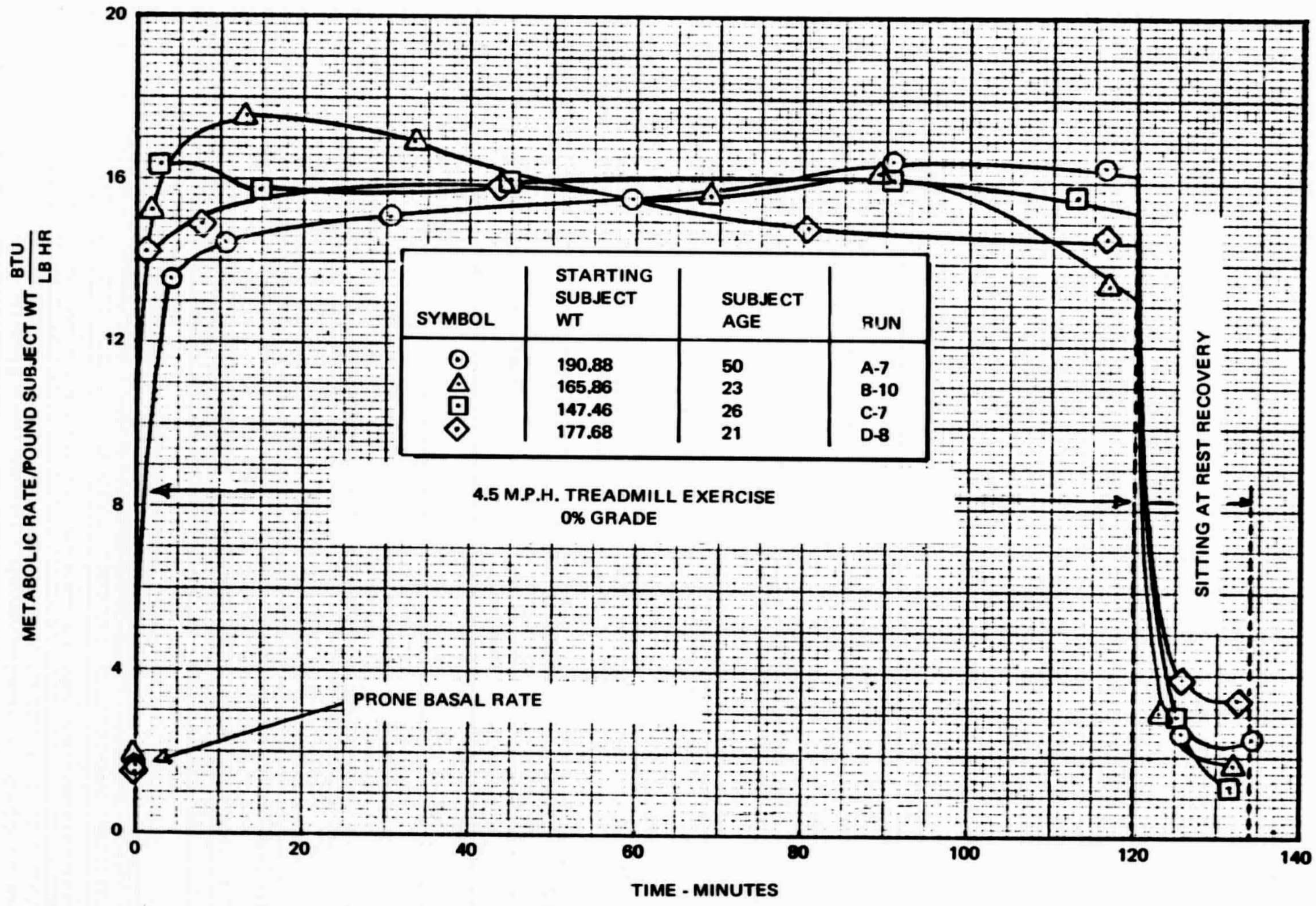



Figure 43. Subject Conditioning on Treadmill

rate exercise is quite variable; however, a typical posttest example is presented as follows for a 2-hour test at 3,680 Btu/hr, completed 1:00 p.m.:

| | | |
|---|---|---|
| 1. | Cold lemonade consumed within a few minutes, starting at the half-hour point past run | 0.83 lb |
| 2. | Warm tea during the next half hour | 1.46 lb |
| 3. | Miscellaneous fluids during the next 3 hours | 1.75 lb |
| TOTAL | | 4.04 lb |
| 4. | Weight loss during run | 4.39 lb |
| 5. | Dehydration and body stores metabolized (deficit) | 0.36 lb |
| 6. | The subject was exactly back to his usual weight at 7:00 a.m. the next morning, feeling completely normal. | |

Figure 44 presents the average loss in weight for each treadmill run for one of the subjects during the whole training program. The values appear high; however, two other subjects had higher losses for the same speed and grade condition, and they each were about 20 lb lighter in body weight.

Figure 45 presents the culminating training series on one of the two final test subjects. The data show resting, exercise, and recovery heart rates; exercise metabolic rates, respiration rates and exhaled oxygen consumption; and weight losses. The same subject repeated the 3.5-mph, 14.5 percent grade run at NASA MSC Crew Systems Division laboratory as a check of Contractor's metabolic rate determination. The symbols marked "X", and "(the values noted)" show the data taken at NASA. The MSC treadmill area had much lower air ventilation, consequently a 35 percent greater sweat rate resulted; heat stress terminated the run at 25 minutes. Other values such as heart rate reflect this. Respiration rate checks quite well; however, oxygen consumption was considerably lower for some unknown reason. The 20-minute MSC metabolic rate was determined to be 3,962 Btu/hr.

A prior discussion on treadmill training and weight loss indicates three important conclusions on high work rates with only ambient laboratory air

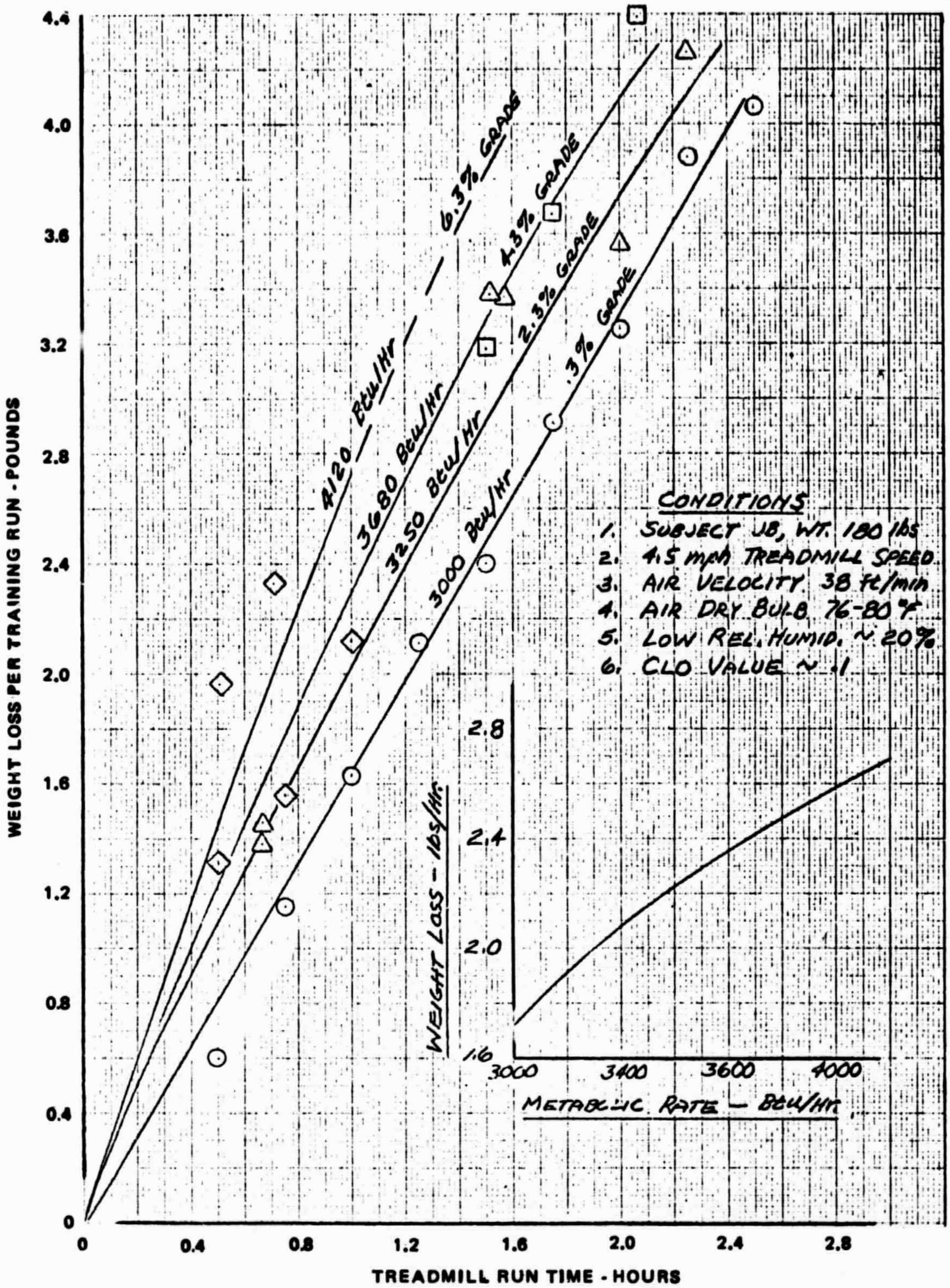



Figure 44. Exercise Weight Loss

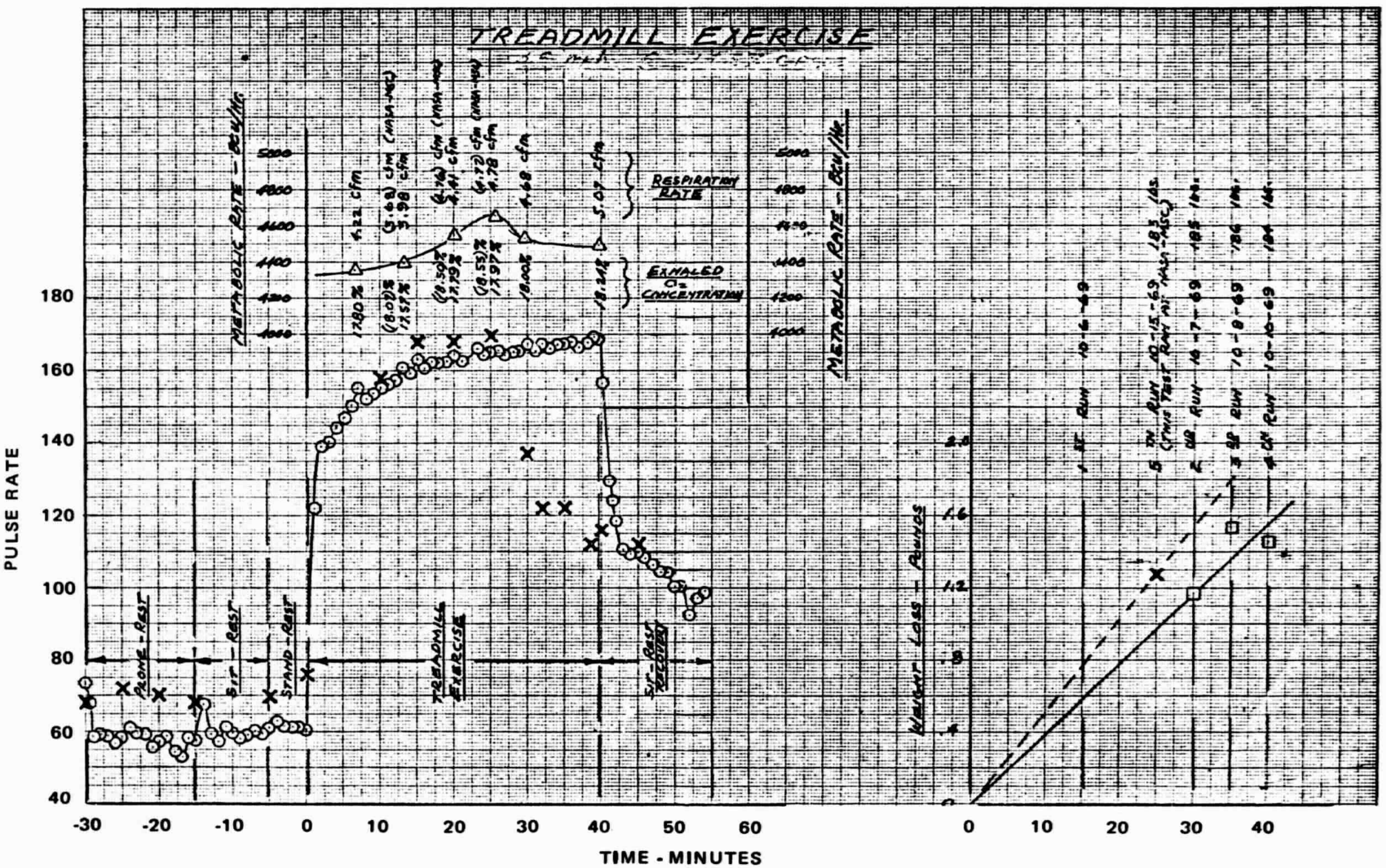



Figure 45. Treadmill Exercise - 3.5 mph at 14.5% Grade

cooling (air conditioning temperature maintained at about 78°F and a relative humidity of around 20 percent):

A. Eighteen training runs have boosted the physical condition of a nonathletic average subject from a starting point of 2, 750 Btu/hr at a 30-minute endurance to nearly 3, 700 Btu/hr for nearly 2 hours. This represents a total energy expenditure increase of 5.5 times (comparing runs 1 and 16).

B. Significant training effects showed up clearly to the end of the program, and from past experience all test subjects could easily have reached 5, 000 Btu/hr for at least one-half hour duration.

C. Heat stress in the uncooled high rate runs can only be negated by profuse sweating (at least 4-lb water loss), a low humidity, and an average air circulation velocity of at least 38 ft/min not exceeding 80°F dry bulb temperature.

High cooling means have been demonstrated by the ECGS to sustain body thermal balance in the 5, 000-Btu/hr range. The following advantages could be anticipated with the ECGS complete suit in a lunar environment space pressure suit, as compared to a low cooling level garment:

A. Average walking or climbing work rates of 4, 000 Btu/hr could be sustained for at least 2 hours in full comfort, while carrying heavy work loads or working in emergency situations consistent with producing that high metabolic rate.

B. The incremental increase in heart rate caused by heat stress would approach zero.

C. High sweat rates and the resultant dehydration would not occur.

D. Supplemental drinking fluids to balance dehydration would not be required.

E. Space pressure suit relative humidity could be raised without affecting sweat rate, since sensible water losses would approach zero.

F. Space pressure suit ventilation in the body region could be reduced or eliminated as sensible water loss would approach zero.

## 6.3 FINAL WORK LOAD CALIBRATION TESTS

Metabolic rate determinations were made on nearly every training run. The progression of work levels could be followed with actual measured energy consumptions; as a rule, the first training run for a given subject and grade angle was checked for oxygen consumption at about each 10-minute interval. Subsequent tests were spot checked to determine training effects, see Figure 42 for typical example.

As the program progressed, the test subjects wore more parts of the EECGS/LCG and metabolic determinations were made. By the time the final design verification runs were to be made, training included the actual garments, and the metabolic rates could be predicted quite well.

## 6.4 TEST FACILITY, INSTRUMENTATION, AND CALIBRATIONS

The ECGS Biotechnology Laboratory was established before the Phase I contract and has since been expanded in capability. The basic areas covered include biomedical (primary physiology) and engineering (high-vacuum technology). The physiological equipment covers a large treadmill with programmed grade control, pulse rate digital recording system, the usual biomedical instrumentation systems, and gas analyzers. The high-vacuum facility includes a two-stage vacuum pump comprising a rotary ballast pump downstream and a Roots blower for high vacuum. Both units are able to pump 2, 500 cfm at a basic pressure of 5 microns Numerous high-vacuum gate valves, pneumatic valves, and manual throttle valves are tied into the system covering size ranges from tiny needle type to 10-inch remote operating gates. Also integrated with the system are many sensors and recorders covering pressure, temperature, time, and vacuum. Data can be recorded by a variety of ways, such as single channel, multi-channel; analog, and/or digital. Much of the equipment is automatic in operation to save time.

For example, Douglas bag gas volumes are determined to better than 0. 5 percent accuracy by the following:

A. Connect bag to the measuring and recording equipment via a quick-disconnect plug and throw a switch.

B. When the bag is empty, an alarm sounds and the bag volume is indicated and stored digitally, and the system shuts itself off.

The laboratory vacuum manifold was again recalibrated, as was originally done in Phase I (see Reference 2); such that EECGS heat removal rates could be directly measured on a real time basis via vacuum pressure instrumentation. All thermistors were also calibrated against a master standard, as was any other pertinent instrumentation.

Figures 46 through 48 show the EECGS/LCG suit being checked out on a subject, a general view of the laboratory and a typical test being conducted on the treadmill.

## 6.5 TYPICAL TEST OPERATION

A typical complete suit EECGS/LCG test operation can be described as follows (see Figures 46 and 48):

A. The test subject is weighed to ±0.01 lb, then attaches the ECG electrodes, and is assisted in attaching the various body thermistors.

B. The subject is helped into the LCG, which is followed by the EECGS, and weighed again.

C. All physiological instrumentation is plugged into the recording system and checked out.

D. The EECGS is attached to the flexible vacuum line and leak checked.

E. The basic ECGS/instrumentation leak rate is established prior to injection of the feed water charge. This determines which heat rejection calibration curve is to be used.

F. An exact measured quantity of water is added to each ECGS cooling segment via hypodermic syringes.

G. The subject is then measured for ECG and pulse rate in the resting positions of prone, sitting, and standing (see Section 6.2).

H. All instruments start recording.

I. The treadmill exercise starts, usually at 4.5 mph at a 6 percent grade.

J. The ECGS cooling and recording is turned on at the onset of exercise.

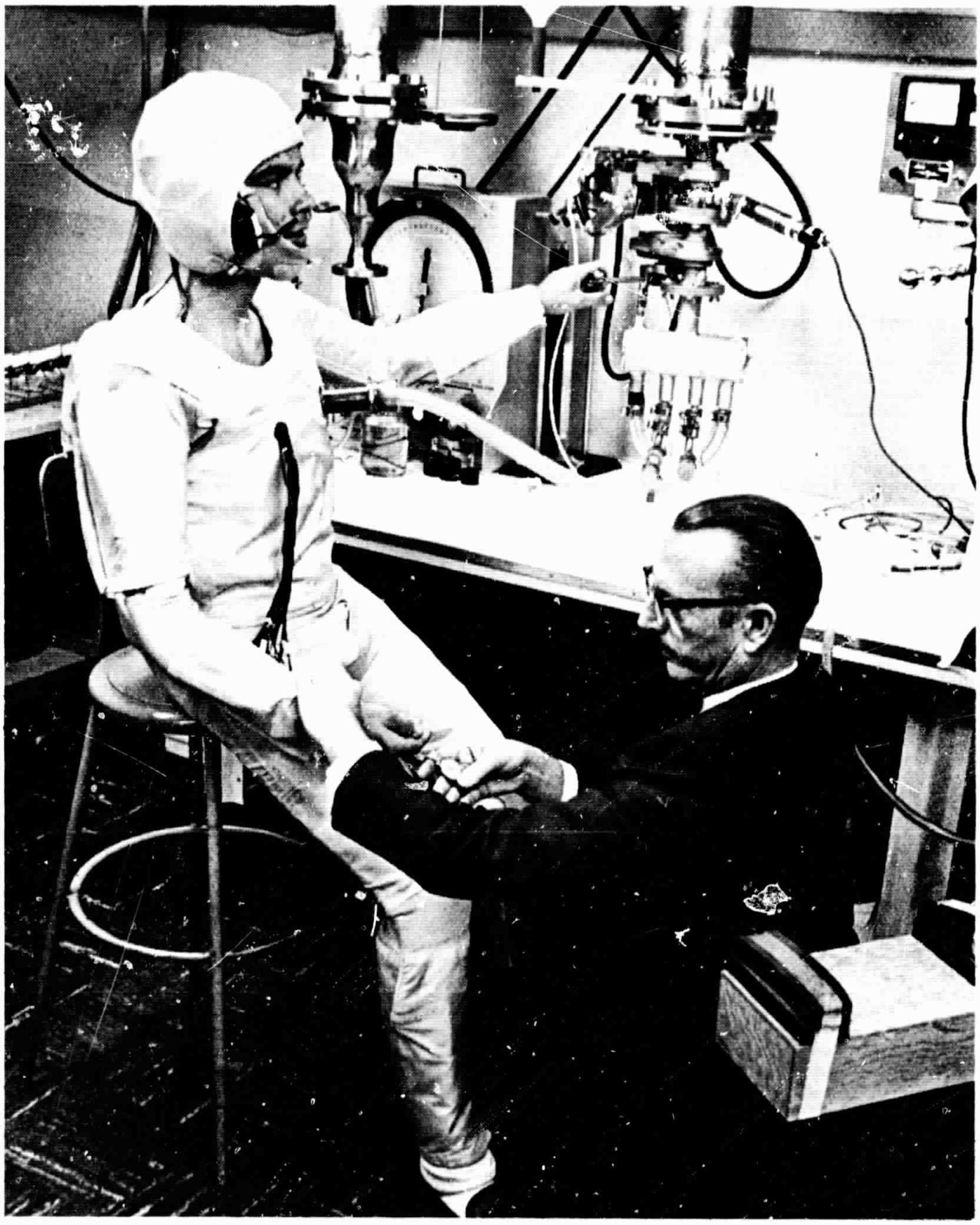


Figure 46. EEGS/LCG Being Checked on Subject

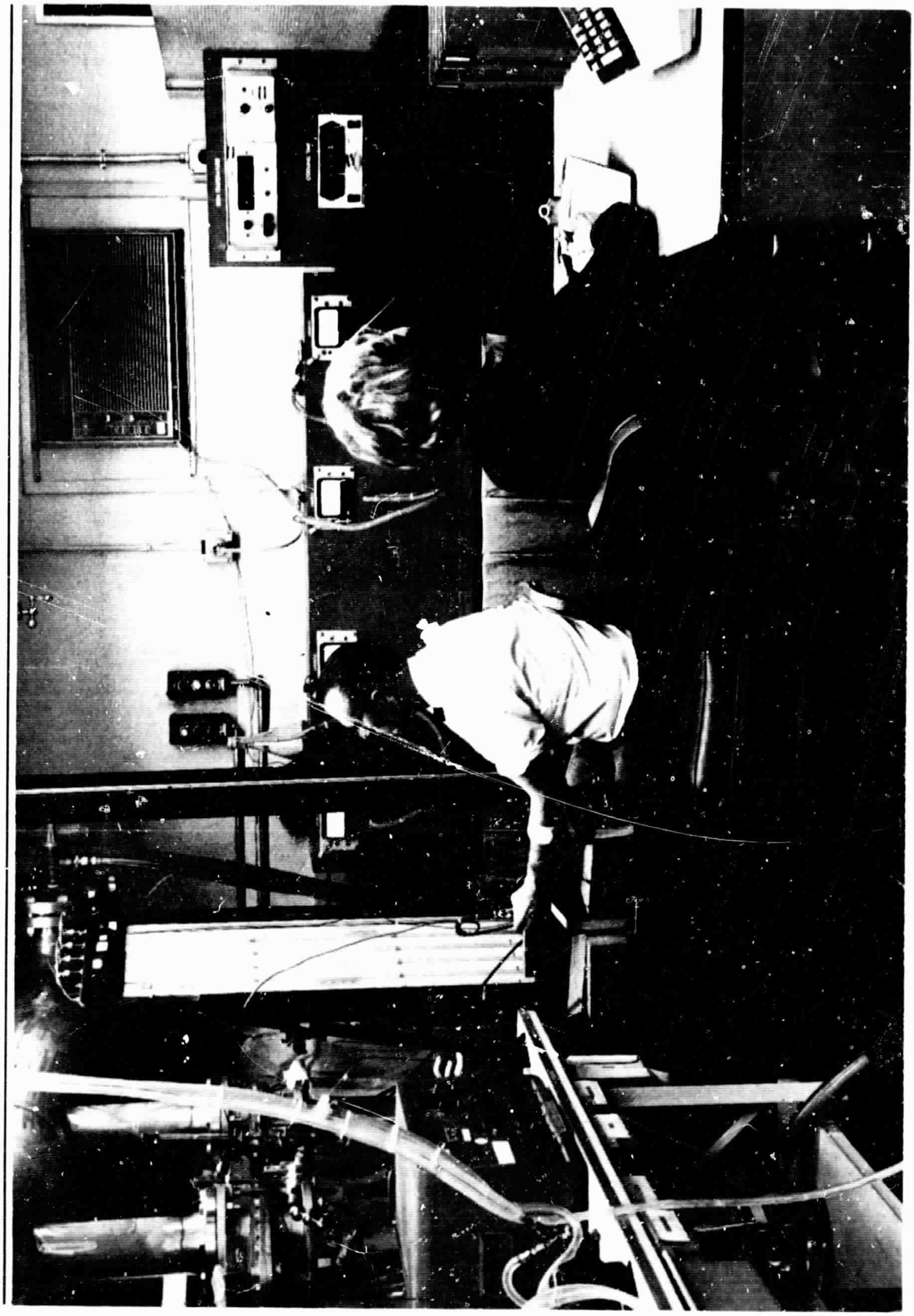


Figure 47. General Views of Laboratory

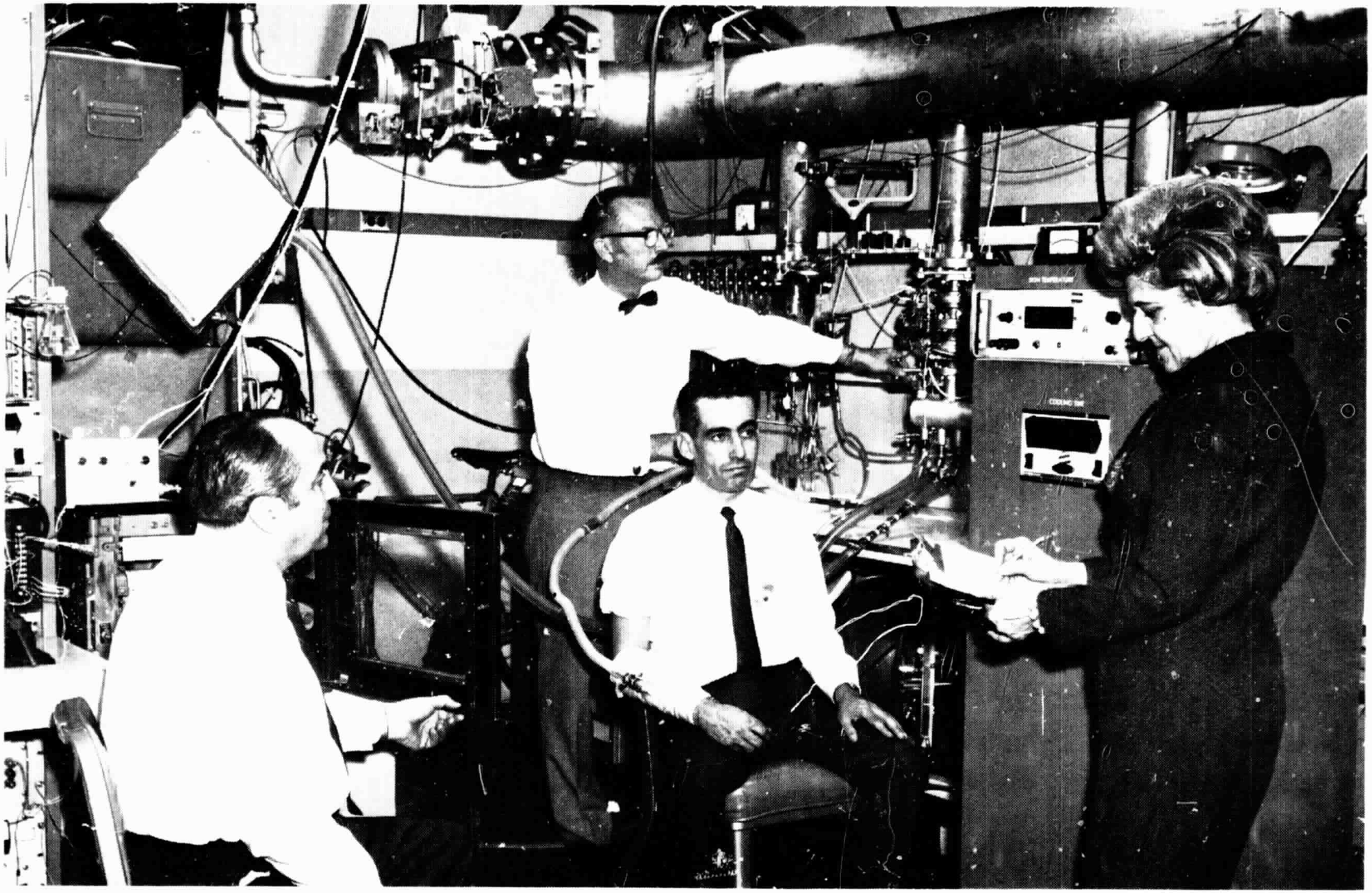


Figure 47. General Views of Laboratory (Continued)

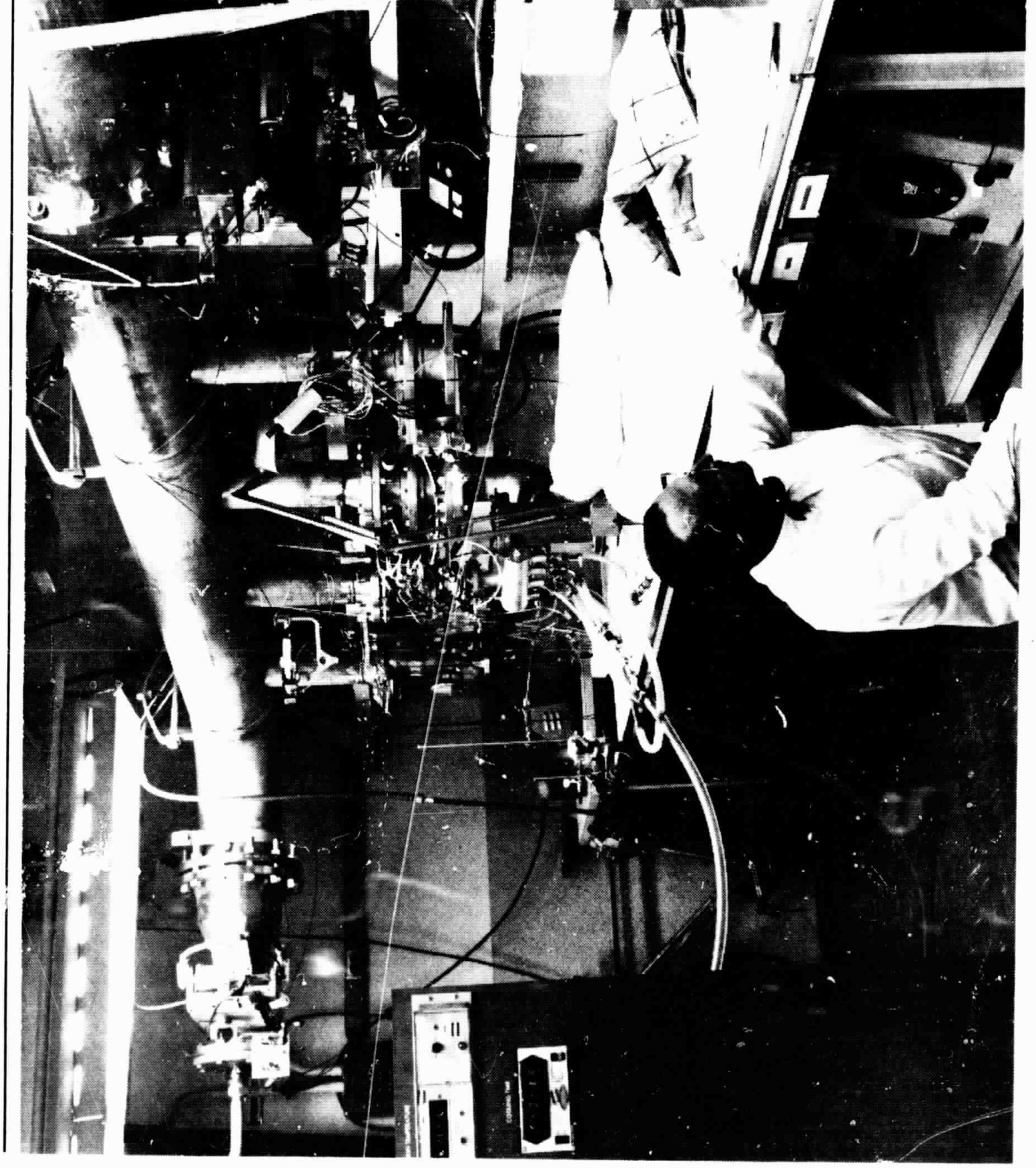


Figure 47. General Views of Laboratory (Continued)

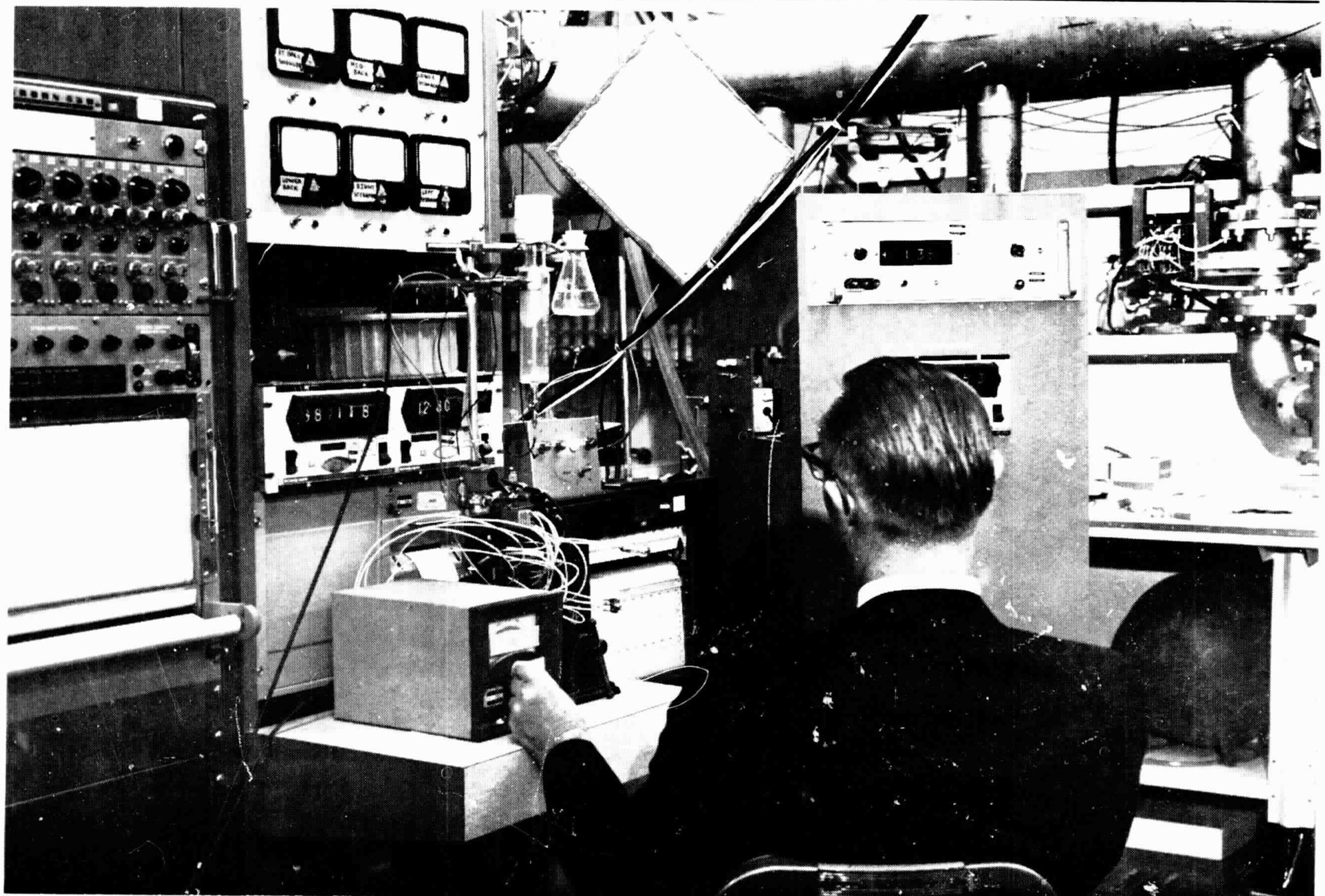


Figure 47. General Views of Laboratory (Continued)

Figure 47. General Views of Laboratory (Continued)

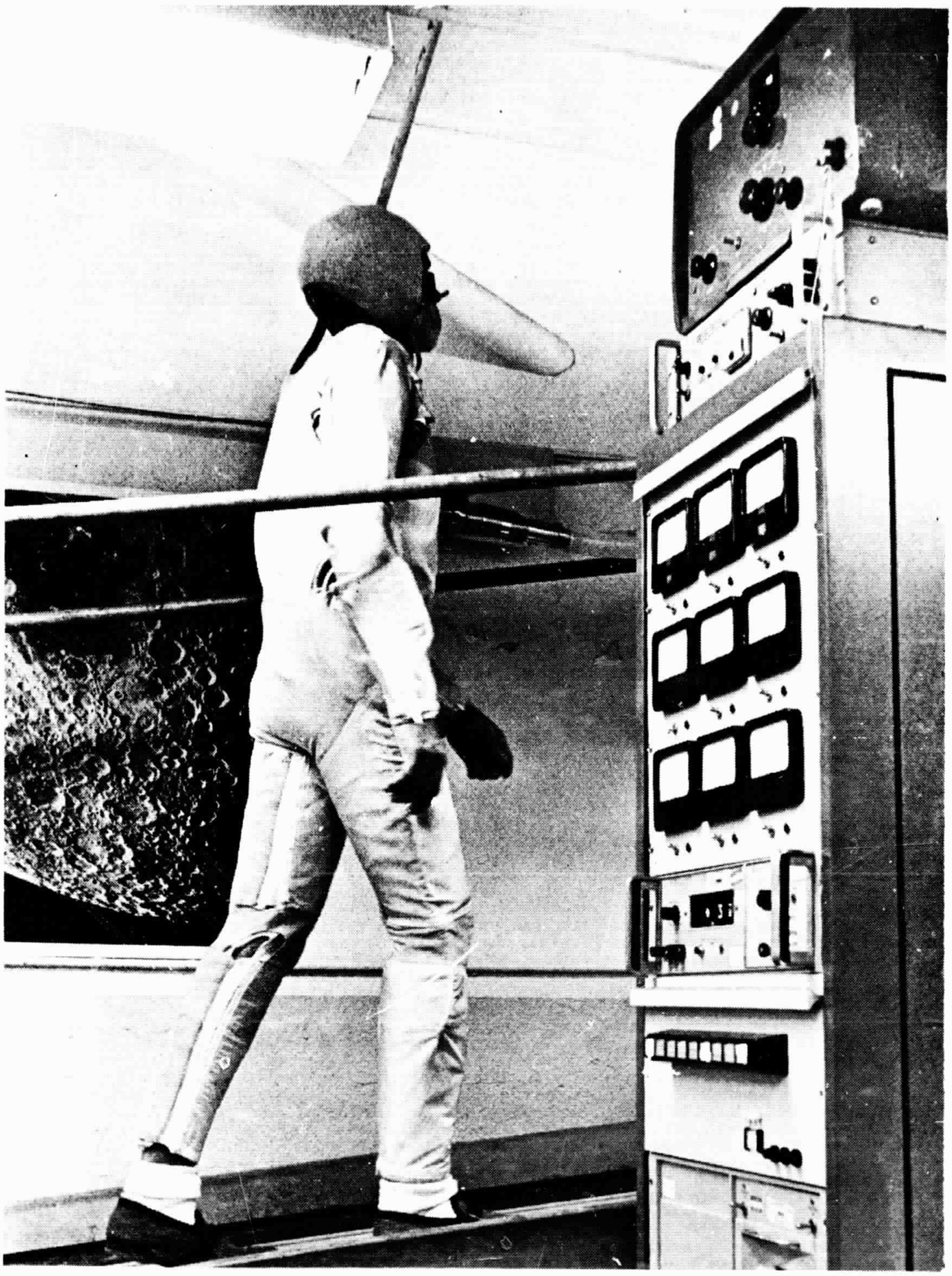


Figure 48. Typical Treadmill Test

K. Several samples of expired air are obtained during the exercise period by Douglas bags which are then stored for later analysis.

L. Subject comments are recorded during run; heart rates are observed by the medical monitor as are other visual functions for subject safety.

M. The treadmill run is carried to completion while the test crew monitors all recordings.

N. At run conclusion at the 30-minute point the treadmill is stopped, the cooling is shut off, vacuum lines plugged and a standing at rest temperature rise of all thermistors is observed, along with recovery pulse rates.

O. The subject is weighted fully suited, and with parts of the ECGS/LCG removed to obtain condensate water absorbed; the subject is finally weighed nude to obtain a total body sensible and insensible weight loss.

At this time each of the cooling segments is removed, securely corked up and weighed when dry externally. All segments are then dried internally by exposure to vacuum, and reweighed to obtain the volume of internal water that remained at the conclusion of the cooling test. This procedure provides the basic information necessary to precisely compute the total heat removed by each ECGS cooling segment during the design verification runs. The summation of each segment cooling quanta can be checked against integrating the heat removed with time as indicated by the vacuum manifold pressures.

In other words expressing this mathematically, the solution to the following equation should be an identity if all data were valid:

$$\sum \Big[ (q)_w \Big]_{1 \text{ to } n}^{30} = \int_0^{30} (q)_p dt$$

where

$\left[(q)_w\right]_n$ = $n^{th}$ segment heat removal, based on weight of water evaporated.

and $(q)_p$ = instantaneous heat removal rate of all segments put together, based on manifold pressure calibration.

The heat removal results presented in Section 6.6 were checked by the above technique to within 5 Btu/hr of each other. In other words, the accuracy is better than 0.3 percent agreement.

On this basis, we are confident that the EECGS performance is correct, and higher than that required of the Contract Work Statement.

## 6.6 30-MINUTE SIMULATED EVA MISSION RUN

### 6.6.1 Water Storage

The 30-minute simulated mission run required internal cooling segment water storage with no additive amounts permitted during the run. It was known earlier that the proper quantity could be held in the EECGS, but not if this specified amount could all be used up. For example, if 1,040 Btu of heat needs to be removed, the 1 lb of water within the ECGS must change phase; however, 1 lb injected could result in some areas of the body using up their quanta earlier and therefore that area would not be cooled at the end of the specified cooling time. This required that an excess be injected, such that some reserve would always be left in every segment at the end. The optimum design appeared that of where all segments would run dry the same instant, and was the goal for optimum design.

The iterative design of the wicking system described in Section 4.1 eventually came up with individual quantas of water that was different for each cooling segment. Figure 49 shows these results in grams. For example, the upper left leg (ULL) can store a maximum of 100 ml of water; it was found that roughly 37 percent or 37 grams were left after the simulated EVA mission run.

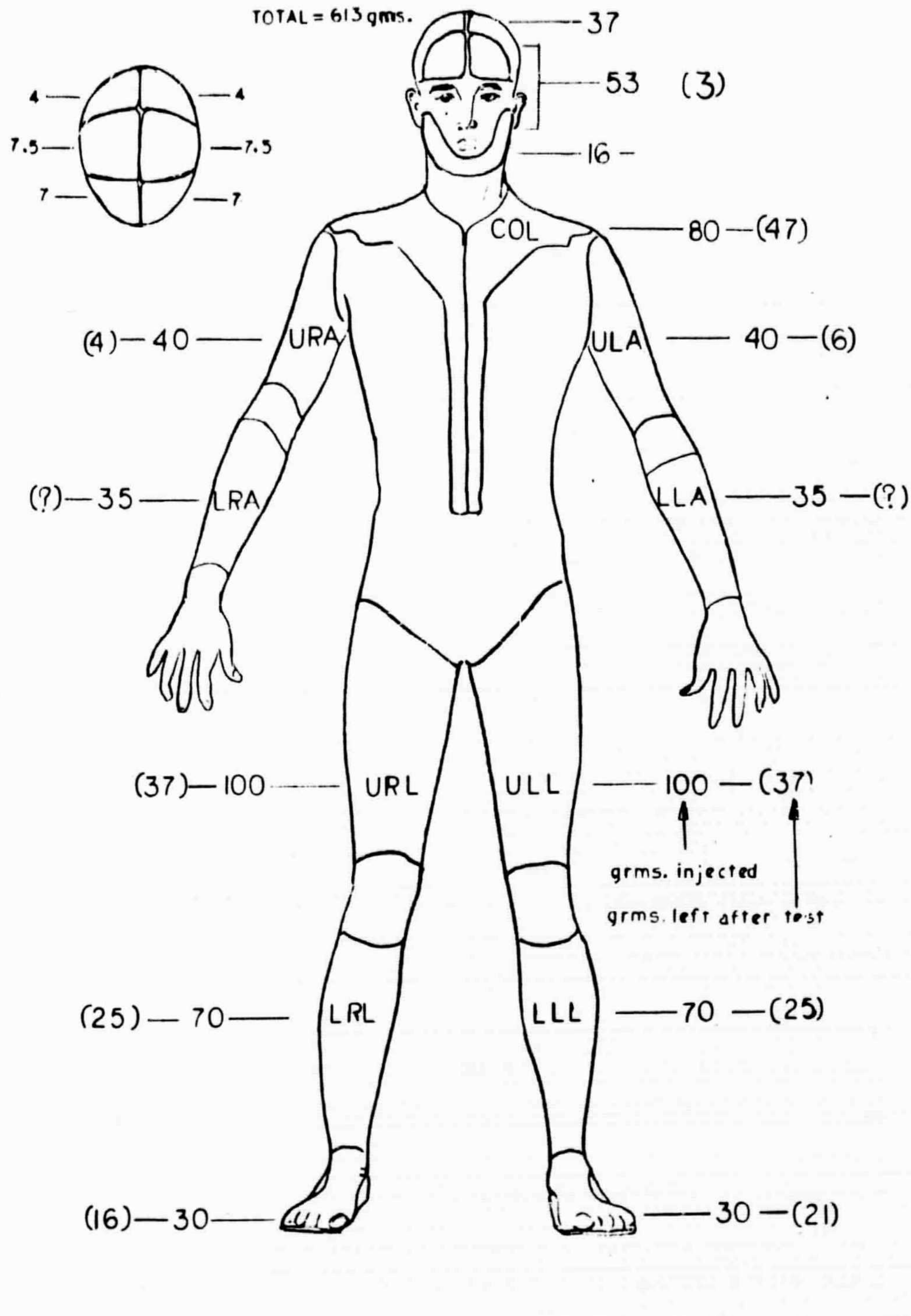



Figure 49. Segment - Water Storage

The formal run therefore was set up with the water quantas shown in Figure 49, and the water remaining to the nearest gram is also noted.

If much higher duration runs are required, it may be desirable to provide extra water tankage integral with the cooling segments. In this approach the extra water stores would be contained as a "sheet tank" such as that shown in Figure 3. A parameter design chart relating to this concept is shown in Figure 50. For example if a single mission charge to cool 1,500-Btu/hr work rate average for 12 hours was desired the chart shows the "sheet tank" thickness to be 0.17 inch, and this would weigh 13.4 lb. In other words, the ECGS could be made this much thicker which is about half the thickness of the LCG tubing diameter (Reference 5).

6.6.2 Formal Design Verification Run

The test was conducted according to the procedure described in Section 6.5, and the results are as follows:

A. Head Temperatures (Figure 51) -- The forehead thermistor was the only temperature-measuring location on the cranium because of the difficulty in measuring temperatures through the hair. The subject felt uniformly cool on the top of the head. The temperature shows a rather sudden rise after 6 minutes 88°F low and then approaches the starting value by the end of the run. This behavior is indicative of running out of water, and matches comments of the subject that he could stand more head cooling.

   The chin cooling, on the other hand, exceeded the low limits of the recorder that was set up prior to the test. The data are extrapolated, but could never have been higher than 80°F during the cooling portion of the test. The chin segment felt very comfortable and remained so until the cooling was shut off.

   Even with running out of water early (only 6 percent remained compared to 26 percent for all other segments), the head cooling accounted for 9.6 percent of the total EECGS cooling, and the

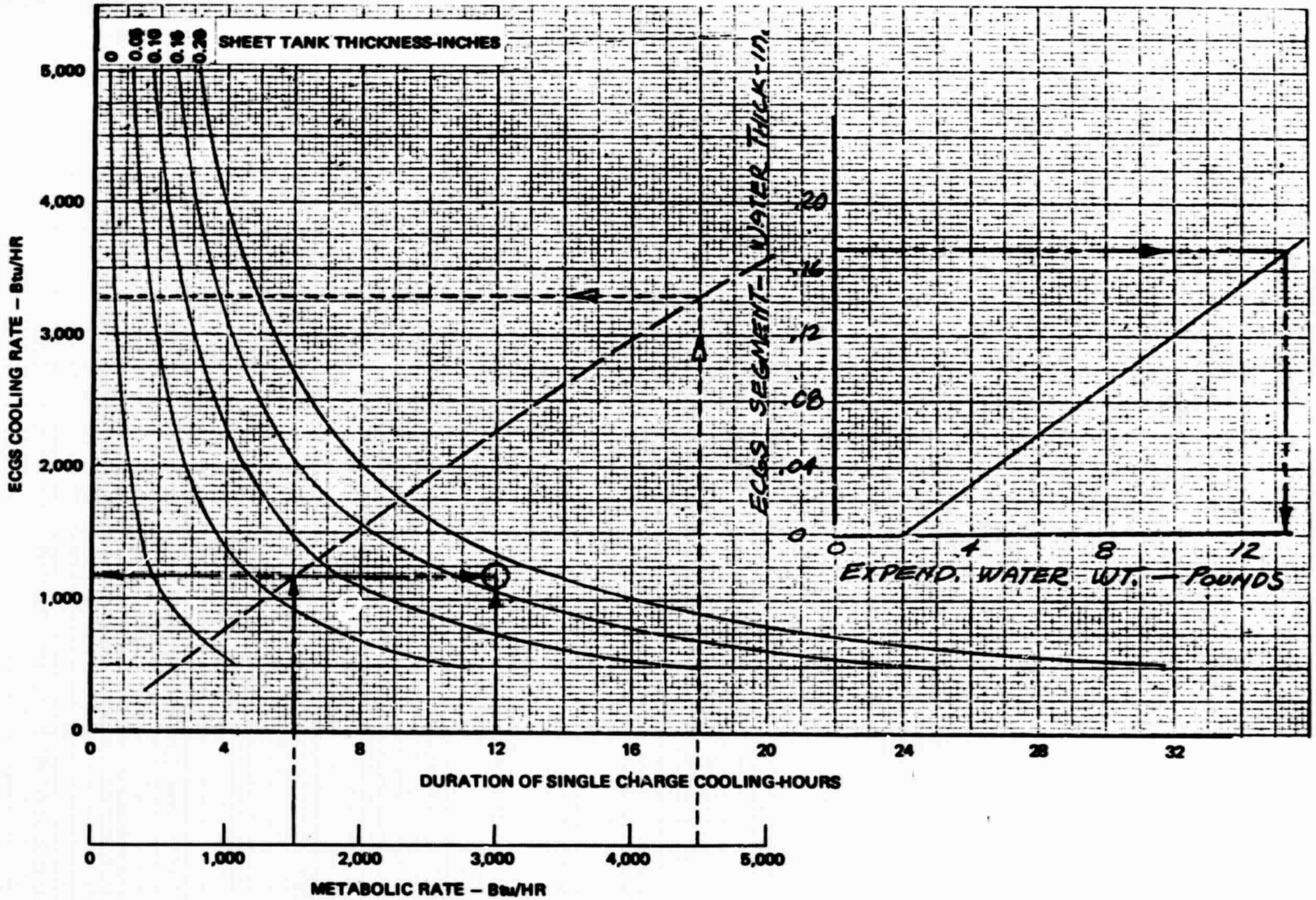



Figure 50. ECGS Single Charge Performance Duration

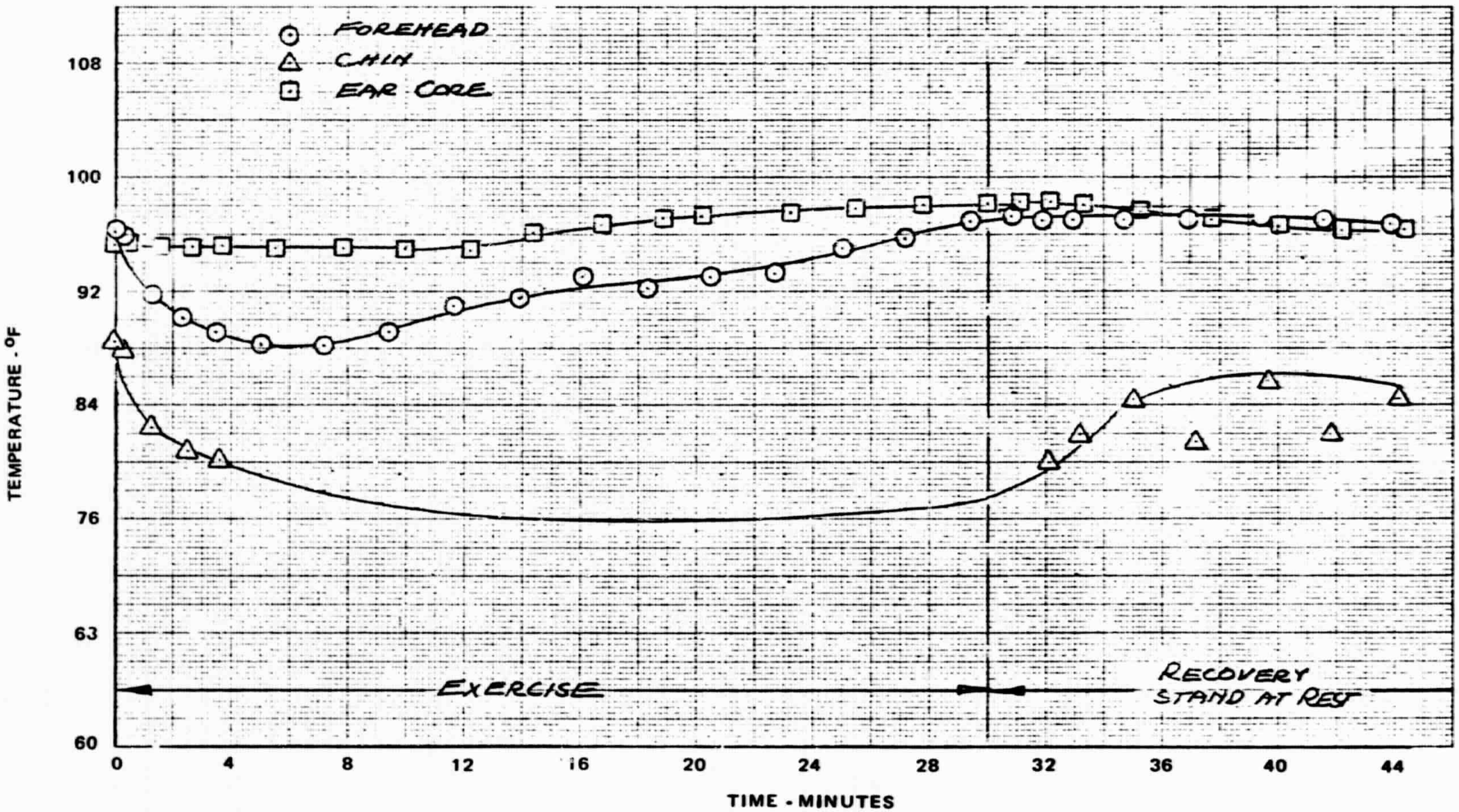



Figure 51. EECGS/LCG Head Temperatures (4,000 Btu/Hr Metabolic Rate)

cooling flux average per unit area was 20 percent higher than the average of all segments. It would appear then that head cooling is the most important and effective area of the entire body for high work rate heat transfer. This is borne out in the treadmill training where the absolute fatigue limit under heat stress can be suddenly relieved by a blast of cool air directed at the freely sweating head.

Ear core temperatures fell slightly during the first 10 minutes, then rose about 2°F during the last two-thirds of the test, and were back to normal 14 minutes after test. The temperature variations followed the forehead. One might easily postulate that these were not really core temperatures at all, but head temperatures, which is always debatable as to where it should be measured (Reference 6).

B. Collar Temperatures (Figure 52) -- The cooling collar performed quite well and all locations where temperatures were measured followed the same trends but at different levels, with the exception of the midriff location. It was experienced in our laboratory many times in the past that the fatty layers around the navel are poorly supplied with blood; as temperatures can be rapidly lowered in this region and recovery will occur at a very slow rate. The collar behaved much like the torso segments of Phase I; in fact, the subject remarked that the collar felt as though the whole torso was cooled. The results were generally as expected.

The collar provided 12.6 percent of the total body cooling, and had a heat removal flux of 238 Btu/hr as compared to 276 Btu/hr for the helmet. Over 18 percent of the initial charge of water was left, which could have maintained good cooling for about 6 minutes more.

C. Arm Temperatures (Figure 53) -- Data on the upper arms only were obtained as the LCG was short sleeved. Cooling the lower arms on the available ECGS segments would have produced values much too high and would have given erroneous answers.

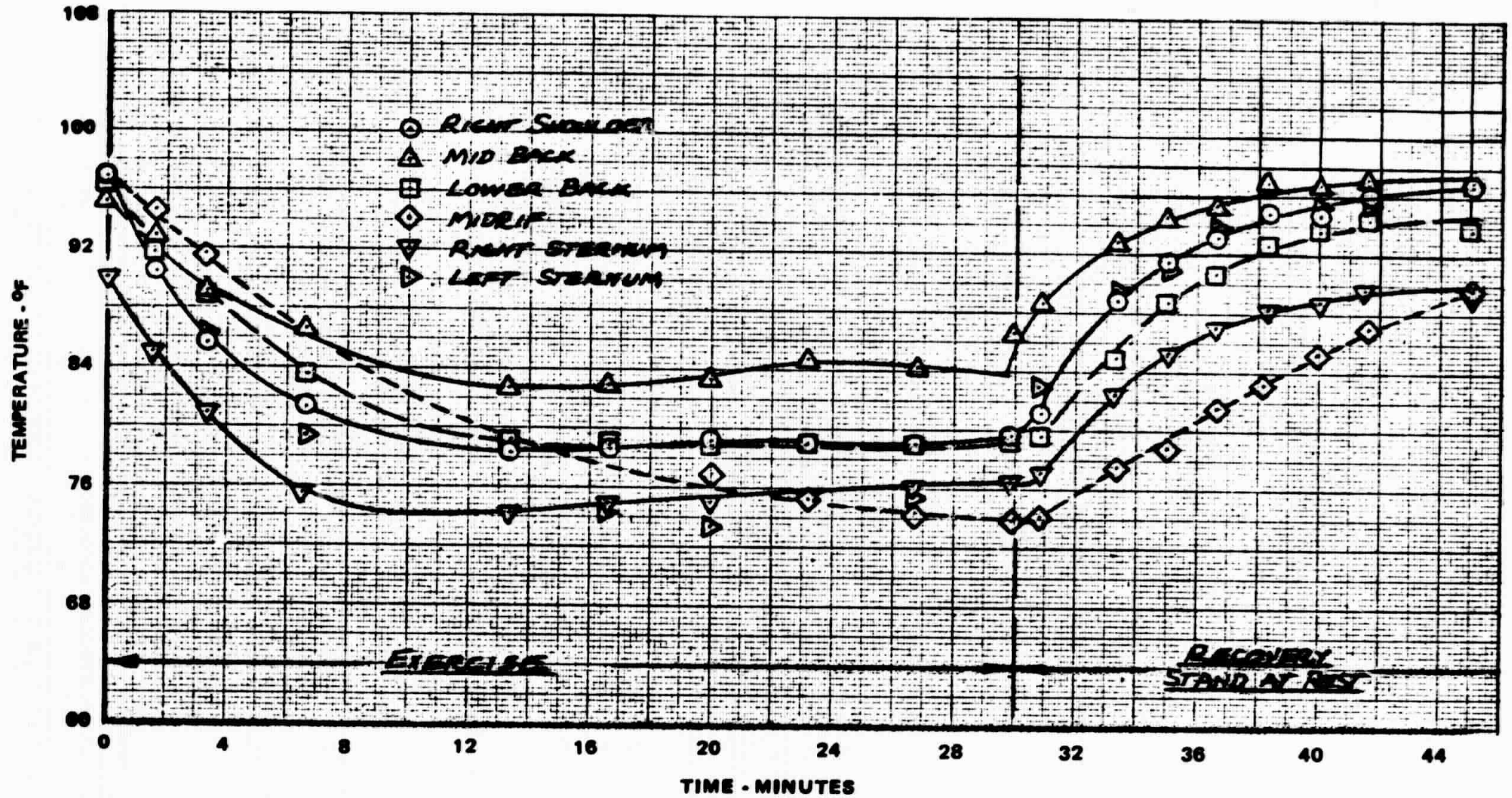



Figure 52. EECGS/LCG Collar Temperatures (4,000 Btu/Hr Metabolic Rate)

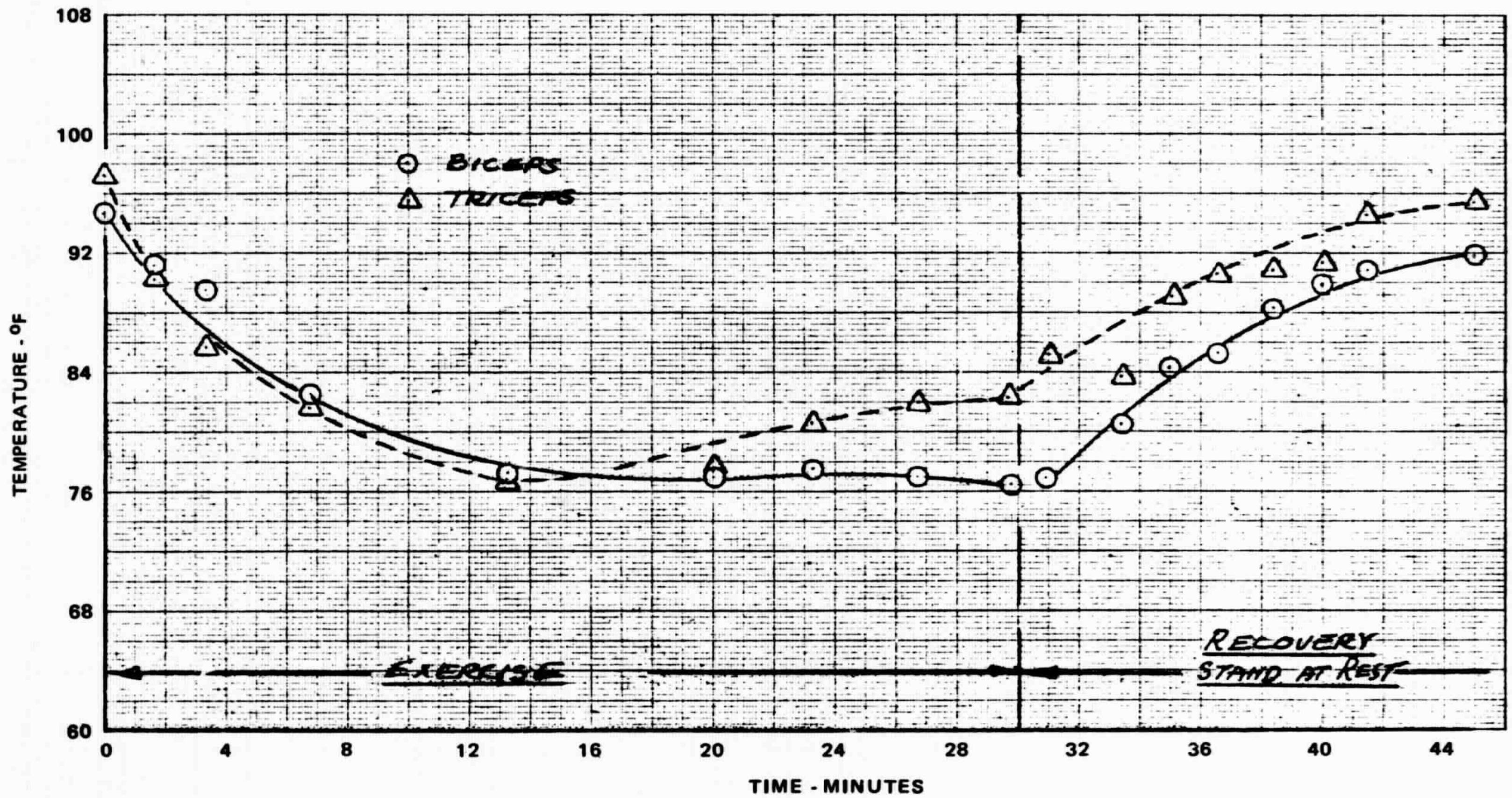



Figure 53. EECGS/LCG Arm Temperatures (4,000 Btu/Hr Metabolic Rate)

The right arm bicep and tricep temperatures followed almost identical values up to 20 minutes, where it appeared that the tricep area blood supply started to increase, or that part of the cooling segment started to dry out. The latter presumption is believed to be the case because the reserve water remaining in that arm at the cutoff time was only 10 percent. Arm temperatures reduced 19°F to a low of 77°F, heat flux was 256 Btu/hr/ft$^2$, which was second in performance only to the cooling headpiece. The average upper and corrected lower arm heat removal values accounted for 25 percent of the total EECGS/LCG cooling as compared to 23 percent of the area cooled.

D. Leg Temperatures (Figure 54) -- Leg cooling represented the greatest total heat exchange area of the body, by virtue of the 48 percent area coverage. The heat flux was the lowest at an average value of only 212 Btu/hr/ft$^2$. This low value could have resulted from poor conductance caused by the high insulation of the LCG, or reduced blood circulation in the legs, or some combination of both. These reasons are contradictory upon careful examination of the data as the temperature rise during recovery is rapid, indicating high blood flow to the capillaries. The extremely rapid drop in temperature at the onset of cooling would indicate high conduction and/or particularly high radiation. More testing and analyses are needed to understand these phenomena, which are further complicated by the unknowns of thermophysiology (Reference 7).

The data also indicate much lower average temperatures were reached in the upper legs than were experienced in the lower region. Again this is the opposite to expectations.

E. Foot Temperatures (Figure 55) -- The high and continuing rise in no cooling foot temperatures, with excercise, should be referred to when looking at the cooling performance. It can be seen from the data and also from the discussion in Section 4.4.2 that the very high rise in no cooling, exercise foot temperature will influence

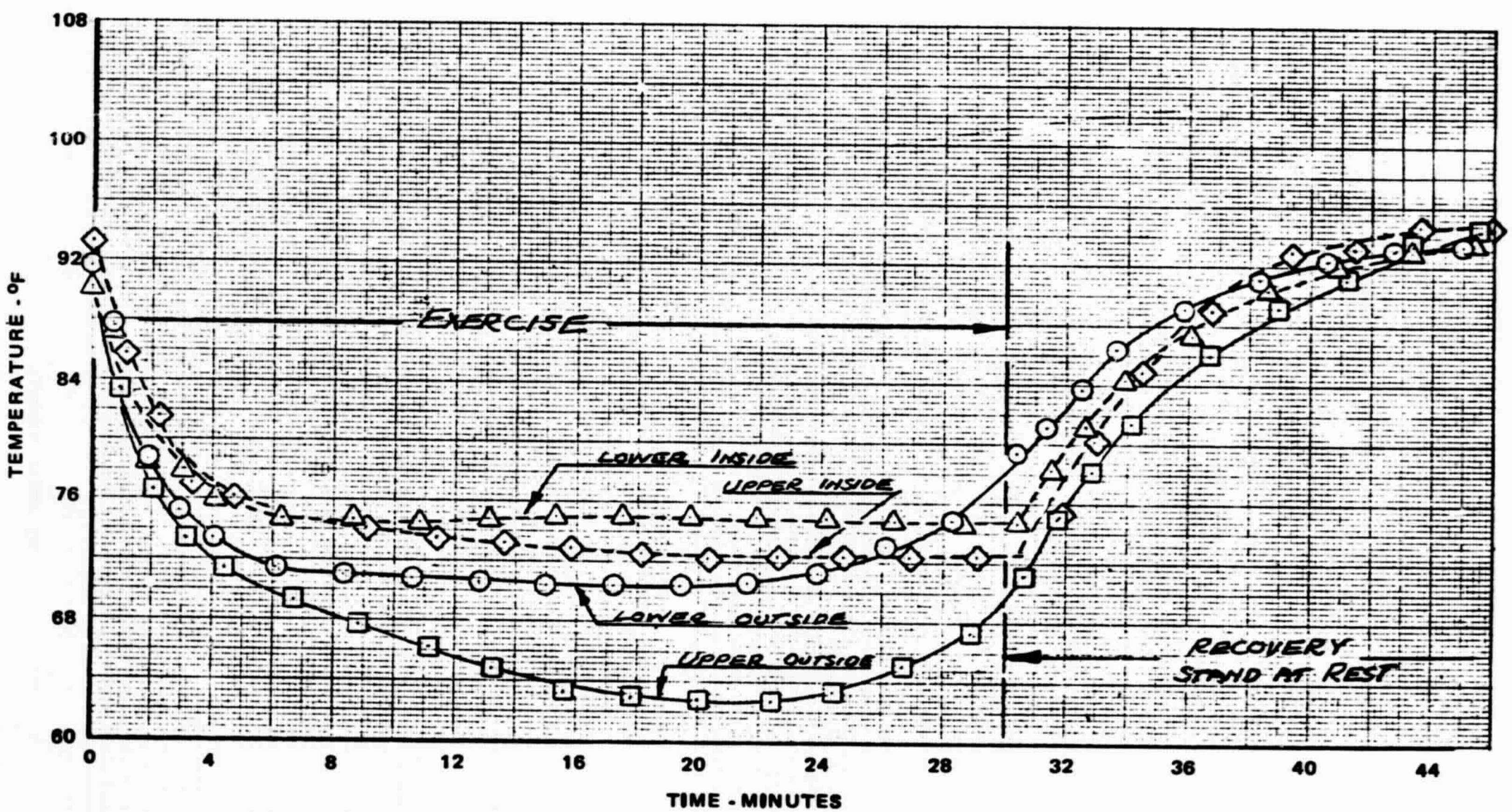



Figure 54. EECGS/LCG Leg Temperatures (4,000 Btu/Hr Metabolic Rate)

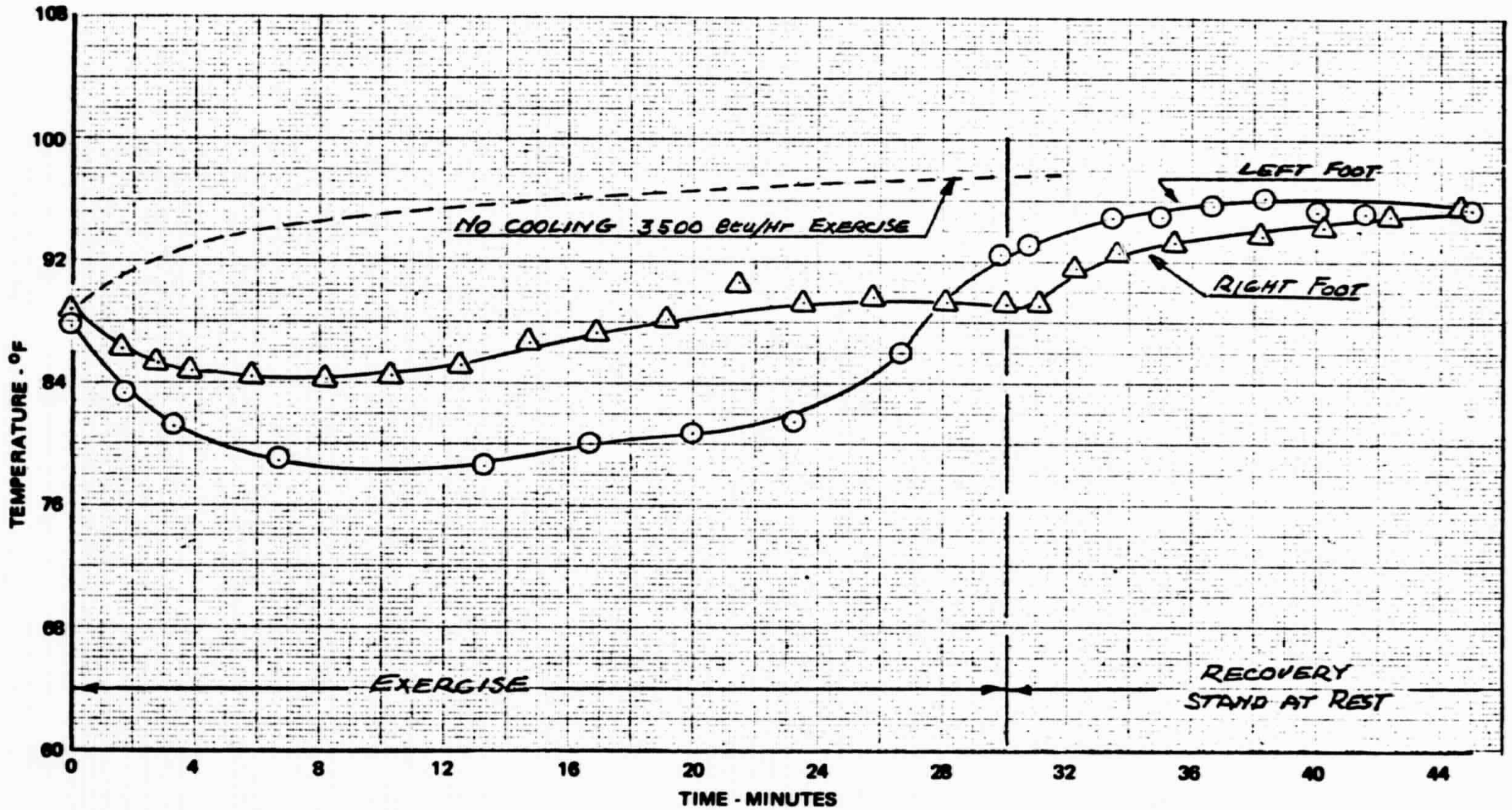



Figure 55. EECGS/LCG Foot Temperatures (4,000 Btu/Hr Metabolic Rate)

the performance in the cooling case. The data show the trend of a constant ΔT as measured by the uncooled and cooled averages with time. The constant ΔT would indicate an unchanging heat transfer, which is suggested by the data in Figure 27.

Figure 55 also indicates the left foot performance to be better than the right, which is borne out in the respective heat flux values of 240 and 197 Btu/hr/ft$^2$. Both feet contribute 8.7 percent of the total EECGS cooling, and this value is about equal to the helmet or a lower leg in magnitude. On the basis of percent residual water remaining, the left foot appears to be running low on water, this can be seen at the 25-minute point.

F. Total EECGS/LCG Cooling (Figure 56) -- The final performance time history for the complete suit shows that over 4,000 Btu/hr in cooling takes place in the first minute and gradually levels off at about 2,400 Btu/hr at the 16-minute point, with an average for the entire run of 2,429 Btu/hr. This final number exceeded contract requirements, and if projected to what the ECGS torso would have added to the collar contribution, would result in over 3,000-Btu/hr average for the full 30 minutes. This high cooling rate more than verifies the feasibility of using the ECGS as a backup emergency garment to the LCG. In fact this configuration provides more heat removal than the primary system, and does not require any moving parts, uses no power, has no dependence on the backpack, and has been integrated with the Apollo A-6L space pressure suit.

G. Cardiopulmonary Performance During Design Verification Run (Figure 57) -- This figure shows the resting, exercise, and recovery heart rates, exercise metabolic rates, respiration rates and exhaled oxygen consumption, and weight losses. The data were obtained at a treadmill speed of 4.5 mph at a 6.3 percent grade. The results are similar to the 3.5 mph and 14.5 percent grade test presented in Figure 45.

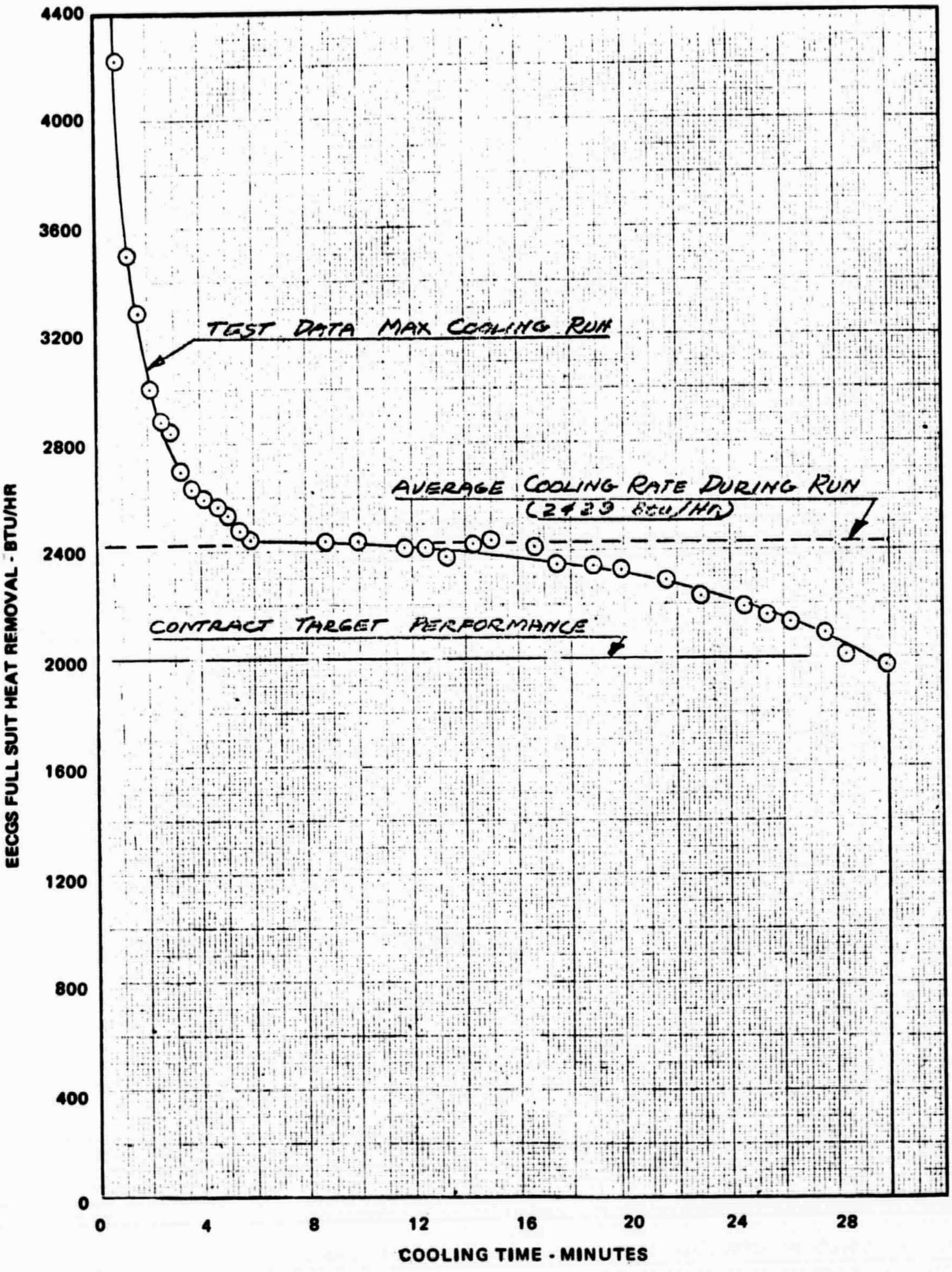



Figure 56. EECGS Complete Suit Cooling (4,000 Btu/Hr Metabolic Rate)

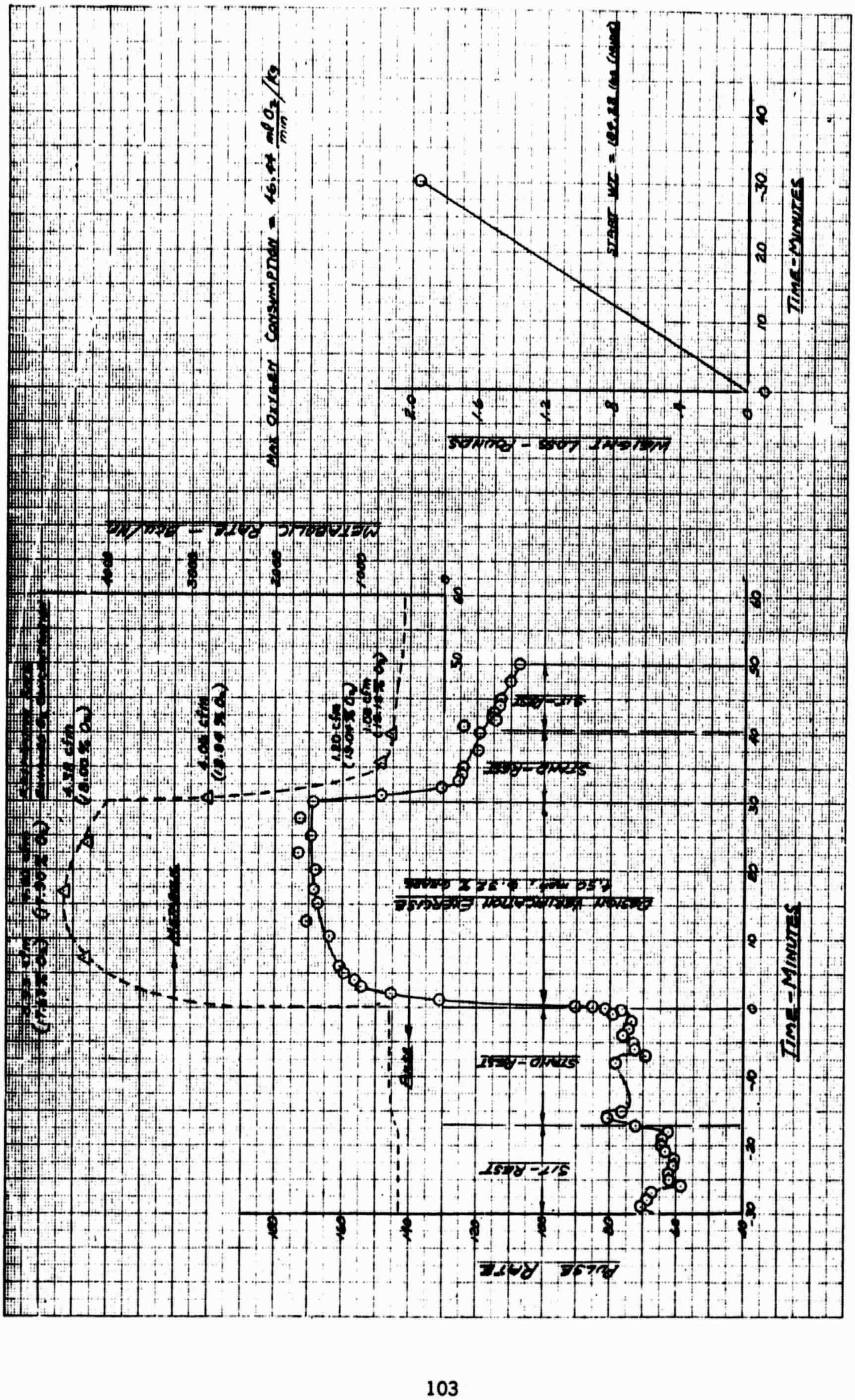



Figure 57. Design Verification Test: Cardiorespiratory Data Wearing Full EECGS/LCG

H. Tabular Data on Design Verification Run (Table 1) -- This table shows the detailed results of the final design run for reference purposes and for future analyses.

## 6.7 GOVERNMENT REPRESENTATIVES WITNESSING FINAL TEST

The final design verification test was observed by two members of the USAF Plant Representatives Office:

Ward E. King, Industrial Specialist

S. Been, Industrial Engineer

Table 1

DATA ON DESIGN VERIFICATION RUN

| Segment Location | Segment Area | | Segment Dry Wt | | $H_2O$ Store per Segment | | $H_2O$ Used per Segment | | Heat Removed per Unit Area | | Heat Removed per Unit Wt | | Total Heat Removed | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Each $ft^2$ | % Total | Each lb | % Total | Each lb | % Total | Each lb | % Total | $\frac{Btu}{hr\ ft^2}$ (Each) | % Avg Total | $\frac{Btu}{hr\ lb}$ (Each) | % Avg Total | $\frac{Btu}{hr}$ (Each) | % Total |
| Helmet | 0.843 | 8.00 | 0.7667 | 12.04 | 0.1153 | 7.70 | 0.1080 | 9.57 | 275.9 | 119.7 | 303.4 | 79.5 | 232.6 | 9.58 |
| Collar | 1.288 | 12.22 | 0.7050 | 11.07 | 0.1739 | 11.62 | 0.1471 | 12.59 | 237.6 | 103.1 | 434.0 | 113.8 | 306.0 | 12.60 |
| Arm, upper right | 0.645 | 6.12 | 0.4963 | 7.79 | 0.0875 | 5.85 | 0.0783 | 6.94 | 261.2 | 113.3 | 339.5 | 89.0 | 168.5 | 6.94 |
| Arm, upper left | 0.645 | 6.12 | 0.4871 | 7.65 | 0.0883 | 5.90 | 0.0748 | 6.63 | 249.8 | 108.4 | 330.7 | 86.7 | 161.1 | 6.63 |
| Arm, lower right | 0.555 | 5.27 | 0.3635 | 5.71 | (0.0753) | (5.03) | (0.0674) | (5.97) | (261.2) | (113.3) | (398.9) | (104.6) | (145.0) | (5.97) |
| Arm, lower left | 0.555 | 5.27 | 0.3979 | 6.25 | (0.0760) | (5.08) | (0.0644) | (5.71) | (249.8) | (108.4) | (348.3) | (91.3) | (138.6) | (5.71) |
| Arms, total | 2.400 | 22.78 | 1.7448 | 27.40 | (0.3271) | (21.86) | (0.2849) | (25.25) | (255.5) | (110.8) | (351.4) | (92.1) | (613.2) | (25.24) |
| Leg, upper ri[illegible] | 1.460 | 13.86 | 0.7608 | 11.95 | 0.2190 | 14.63 | 0.1478 | 13.10 | 217.9 | 94.5 | 450.1 | 118.0 | 318.1 | 13.09 |
| Leg, upper left | 1.460 | 13.86 | 0.7615 | 11.96 | 0.2183 | 14.59 | 0.1419 | 12.58 | 209.2 | 90.7 | 401.2 | 105.2 | 305.5 | 12.58 |
| Leg, lcwer right | 1.060 | 10.06 | 0.6142 | 9.64 | 0.1559 | 10.42 | 0.1111 | 9.85 | 225.8 | 97.9 | 389.6 | 102.1 | 239.3 | 9.85 |
| Leg, lower left | 1.060 | 10.06 | 0.5952 | 9.35 | 0.1539 | 10.28 | 0.0945 | 8.38 | 192.0 | 83.3 | 341.9 | 89.6 | 203.5 | 8.38 |
| Legs, total | 5.040 | 47.84 | 2.7317 | 42.89 | 0.7471 | 49.92 | 0.4953 | 43.90 | 211.6 | 91.8 | 390.4 | 102.4 | 1,066.4 | 43.90 |
| Foot, right | 0.483 | 4.58 | 0.1871 | 2.94 | 0.0681 | 4.55 | 0.0442 | 3.92 | 196.9 | 85.4 | 508.3 | 133.3 | 95.1 | 3.91 |
| Foot, left | 0.483 | 4.58 | 0.2336 | 3.67 | 0.0651 | 4.35 | 0.0538 | 4.77 | 240.0 | 104.1 | 496.1 | 130.1 | 115.9 | 4.77 |
| Feet, total | 0.966 | 9.16 | 0.4207 | 6.61 | 0.1332 | 8.90 | 0.0980 | 8.69 | 218.4 | 94.7 | 501.5 | 131.5 | 211.0 | 8.69 |
| Total, body | 10.537 | 100.0 | 6.3689 | 100.0 | 1.4966 | 100.0 | 1.1283 | 100.0 | 230.54 | 100.0 | 381.42 | 100.0 | 2,429.2 | 100.0 |

# Section 7
# CONCLUSIONS AND RECOMMENDATIONS

## 7.1 CONCLUSIONS

The EECGS contract was programmed through the research tasks of theory and design, basic laboratory tests, engineering model fabrication, design verification tests, and documentation with hardware delivery. The development was carried out within 7 months from a requirement to functioning hardware that was tested with heavy work loads simulating a lunar emergency mode of operation for 30 minutes. The greatest problem was seeking an ECGS configuration that would satisfy the performance goal and to implement the developed hardware with man in the loop to match the goal.

It was again gratifying to the ECGS project team and management to demonstrate that all aspects of the program were accomplished in accordance with contract requirements, and that the target cooling performance was easily met. It was shown that the EECGS as an emergency backup unit had the capacity to remove a man's metabolic heat at work rates that were double that provided by the LCG, while not hindering the efficiency of the LCG.

Specific conclusions derived from the EECGS program are as follows:

A. The EECGS/LCG has demonstrated its ability to exceed every cooling requirement of the contract specified 30-minute emergency lunar heavy work.

B. Short run cooling rates would exceed 3,700 Btu/hr with the full EECGS configuration; and any duration at this level over 2 minutes is limited only by the cardiovascular system's ability to transmit internal body heat via the bloodstream capillary bed to the skin surface.

C. Maximum heat removal can be instigated within the EECGS in less than 1 second.

D. The ECGS can cool through the inactivated LCG with a loss of only 13 percent for a full 30 minutes.

E. The EECGS can operate at a maximum cooling rate on its own internal wicking water supply for at least 30 minutes.

F. Foot cooling segments have been demonstrated that are thermally and mechanically comfortable for 9 miles of walking; 8.7 percent of the body thermal load can be removed through the feet at high work rates in full comfort.

G. The EECGS can average 230-Btu/hr/ft$^2$ heat flux removal for at least 30 minutes.

H. The EECGS can be recharged with a full load of water in 10 seconds.

I. The EECGS can be stored in space either wet or dry at ambient temperatures and pressure.

J. Entrainment of air in the wet or dry stored state has no effect on its being immediately pressed into service.

K. External heat loads will actually increase the heat removal capacity.

L. The EECGS cooling headpiece was found to be very effective in delaying the onset of heat stress fatigue.

M. It is believed that dry EECGS total system weight can be designed to as low as 6-1/2 lb.

N. The EECGS requires no power, needs no connection with the backpack, does not affect the efficiency of the LCG, nor does it have any moving parts.

## 7.2 RECOMMENDATIONS

The following recommendations are made:

A. Continue the development of the ECGS and/or the EECGS/LCG into space hardware.

B. Optimize all components and materials.

C. Conduct manned tests of the ECGS and/or the EECGS/LCG in a space pressure suit.

D. Redesign all vacuum fittings and lines for minimum protuberances and for minimum weight.

E. Increase mobility and wearing comfort.

F. Investigate thermal comfort zones using ECGS at various high work rates, and relate the results to the control problem.

G. Initiate the study of automatic cooling valves and controls versus the manual mode.

H. Establish the optimum cooling pattern configuration for the ECGS.

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Appendix

CONSTRUCTION FEATURES

The following pages detail the actual construction features of each ECGS cooling segment.

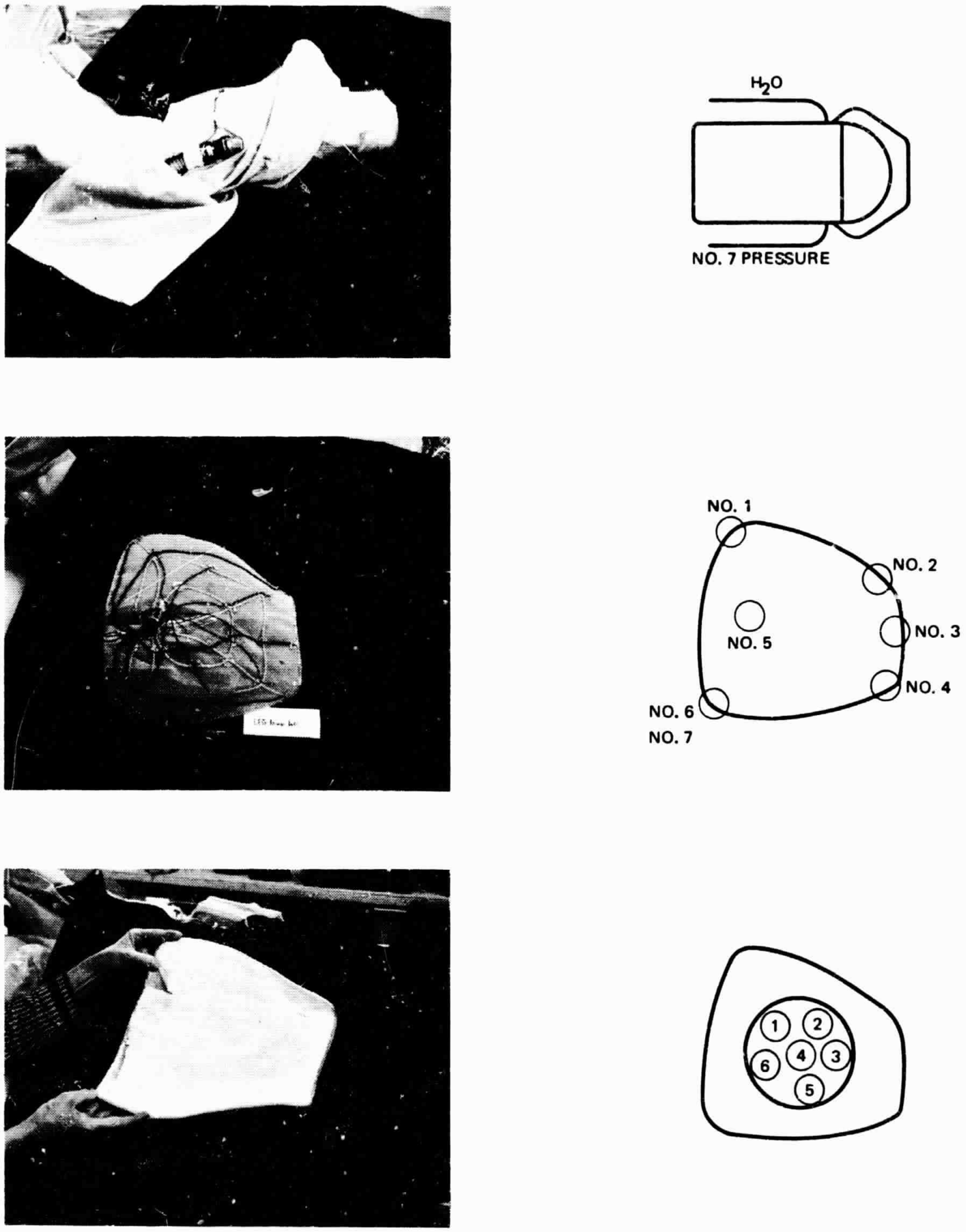


Figure A-1. Leg, Lower Left

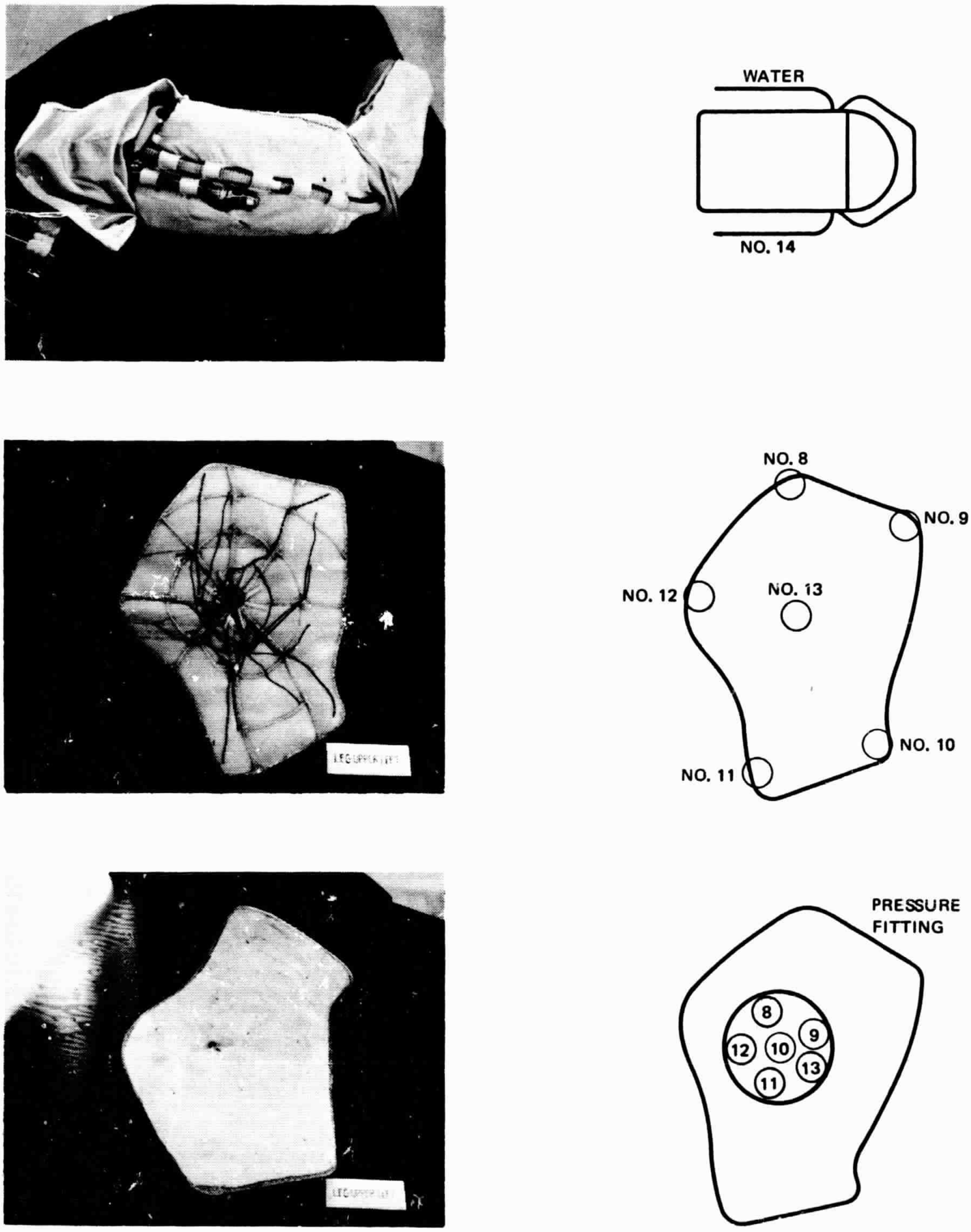


Figure A-2. Leg, Upper Left

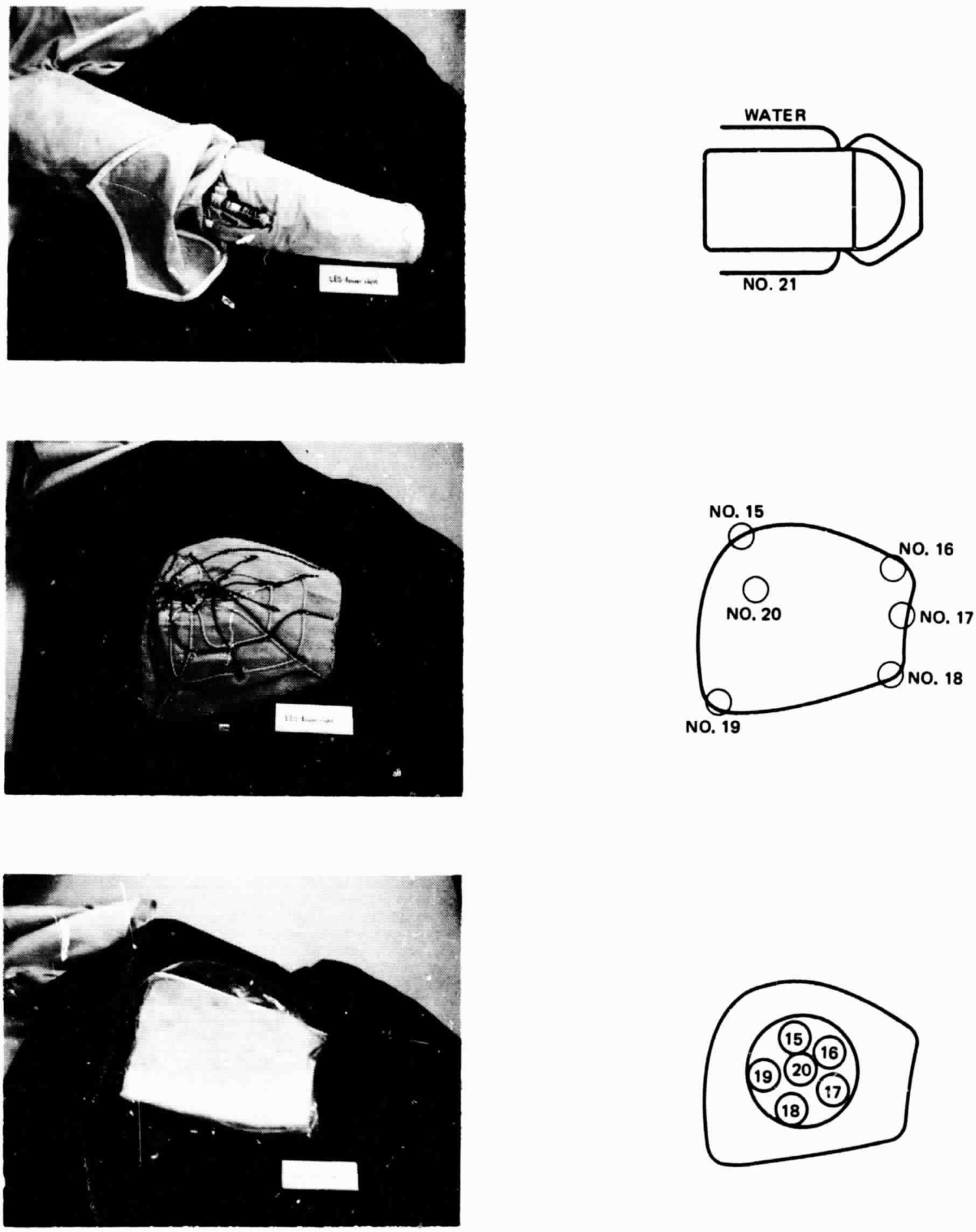


Figure A-3. Leg, Lower Right

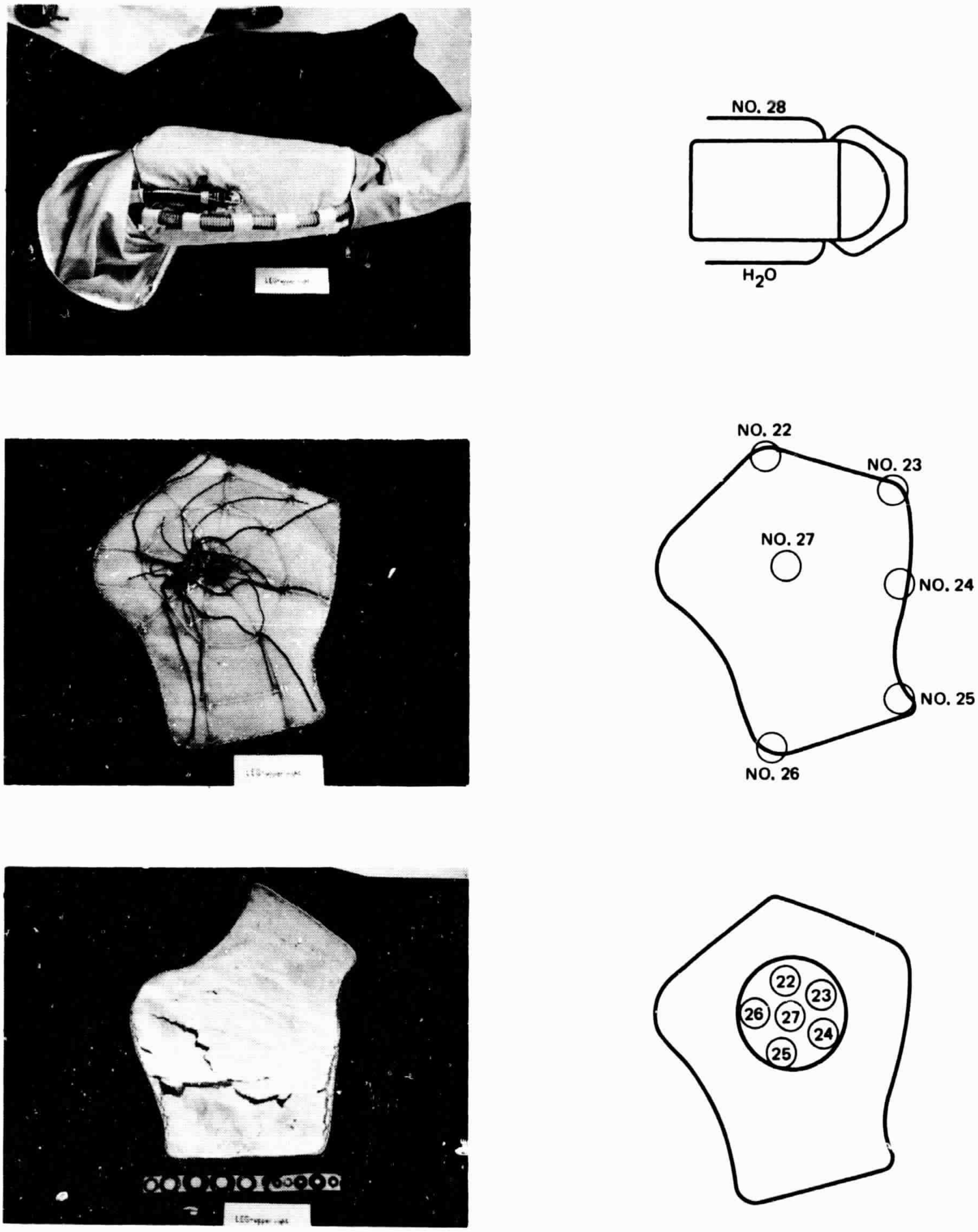


Figure A-4. Leg, Upper Right

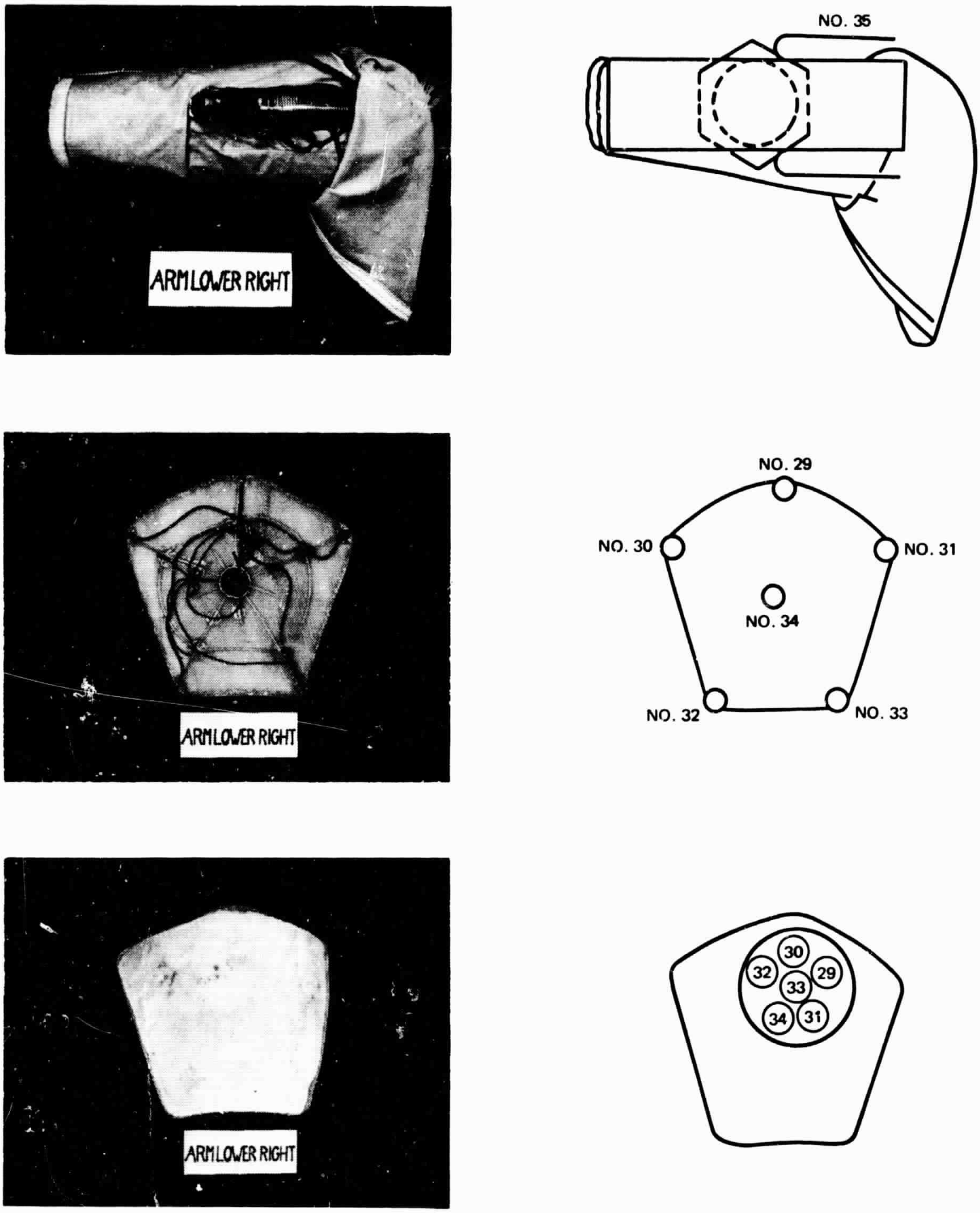


Figure A-5. Arm, Lower Right

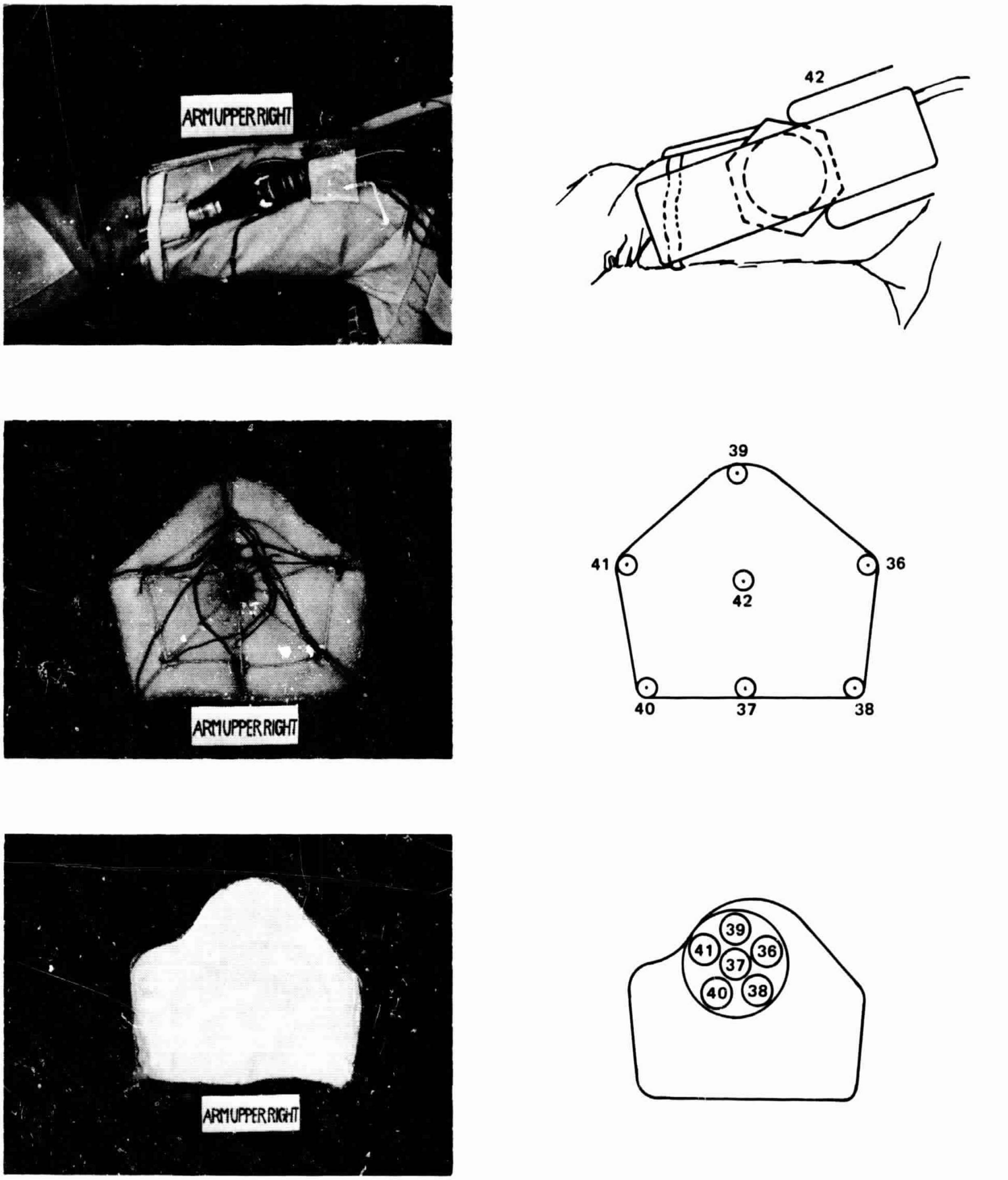


Figure A-6. Arm, Upper Right

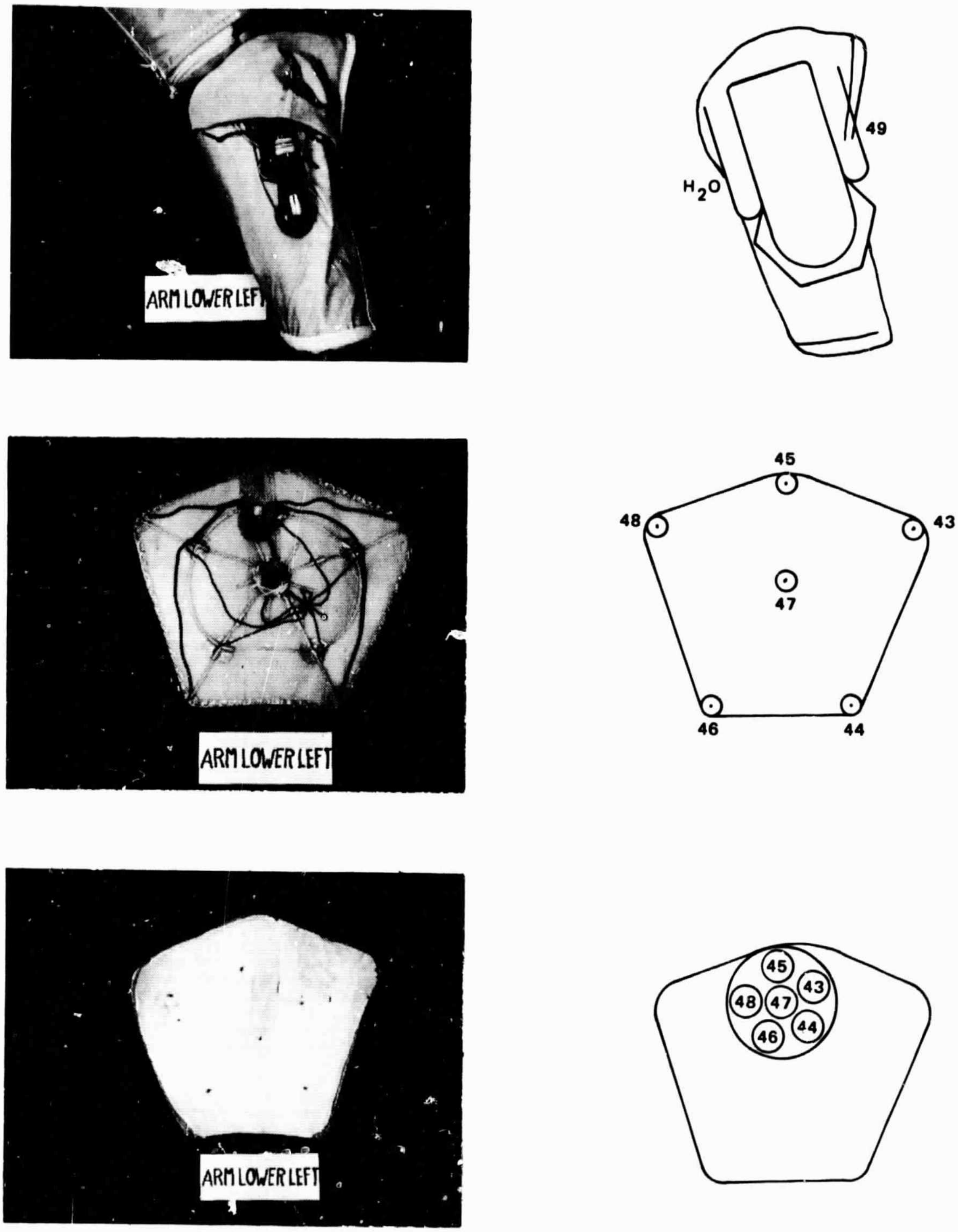


Figure A-7. Arm, Lower Left

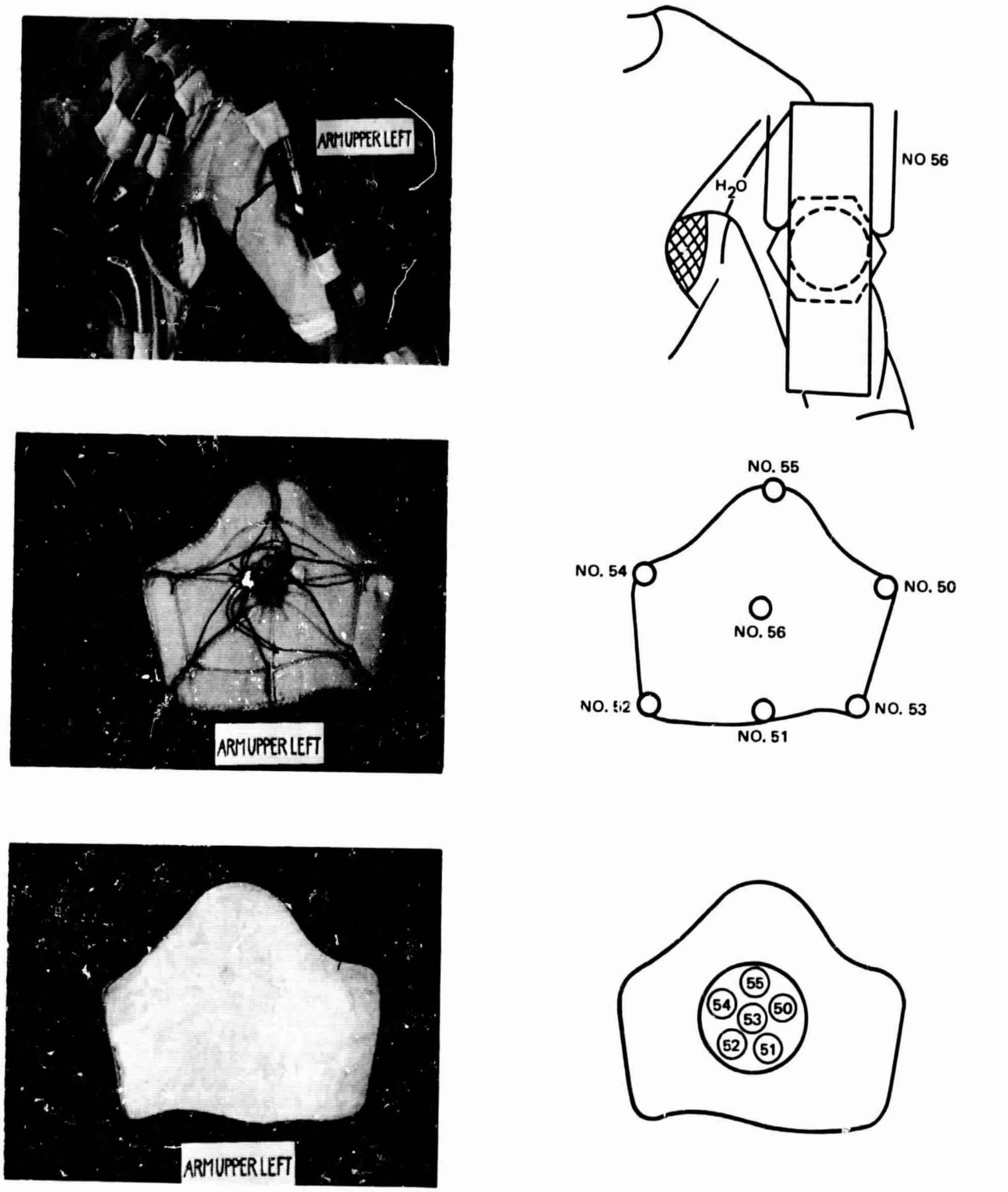


Figure A-8. Arm, Upper Left

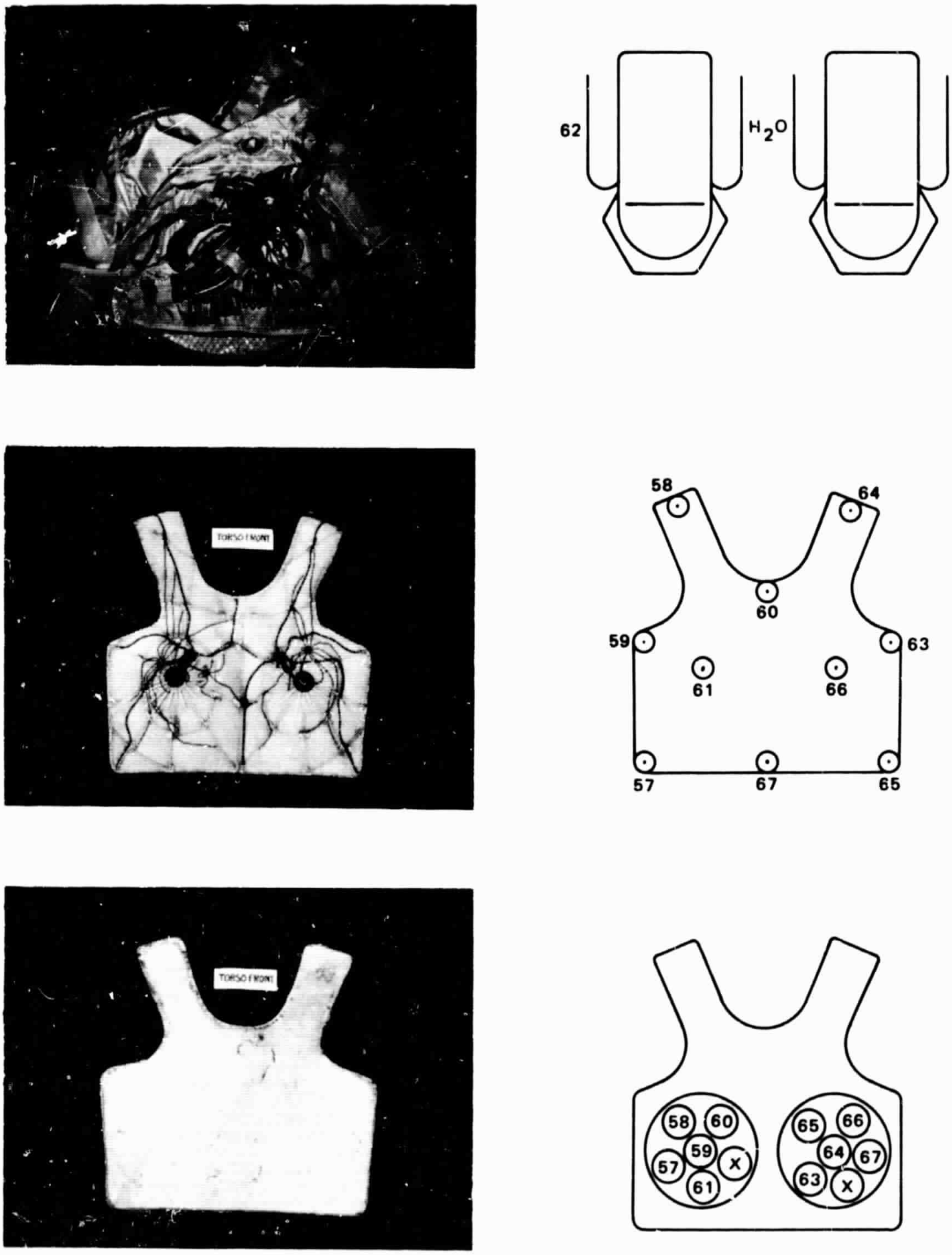


Figure A-9. Torso, Front

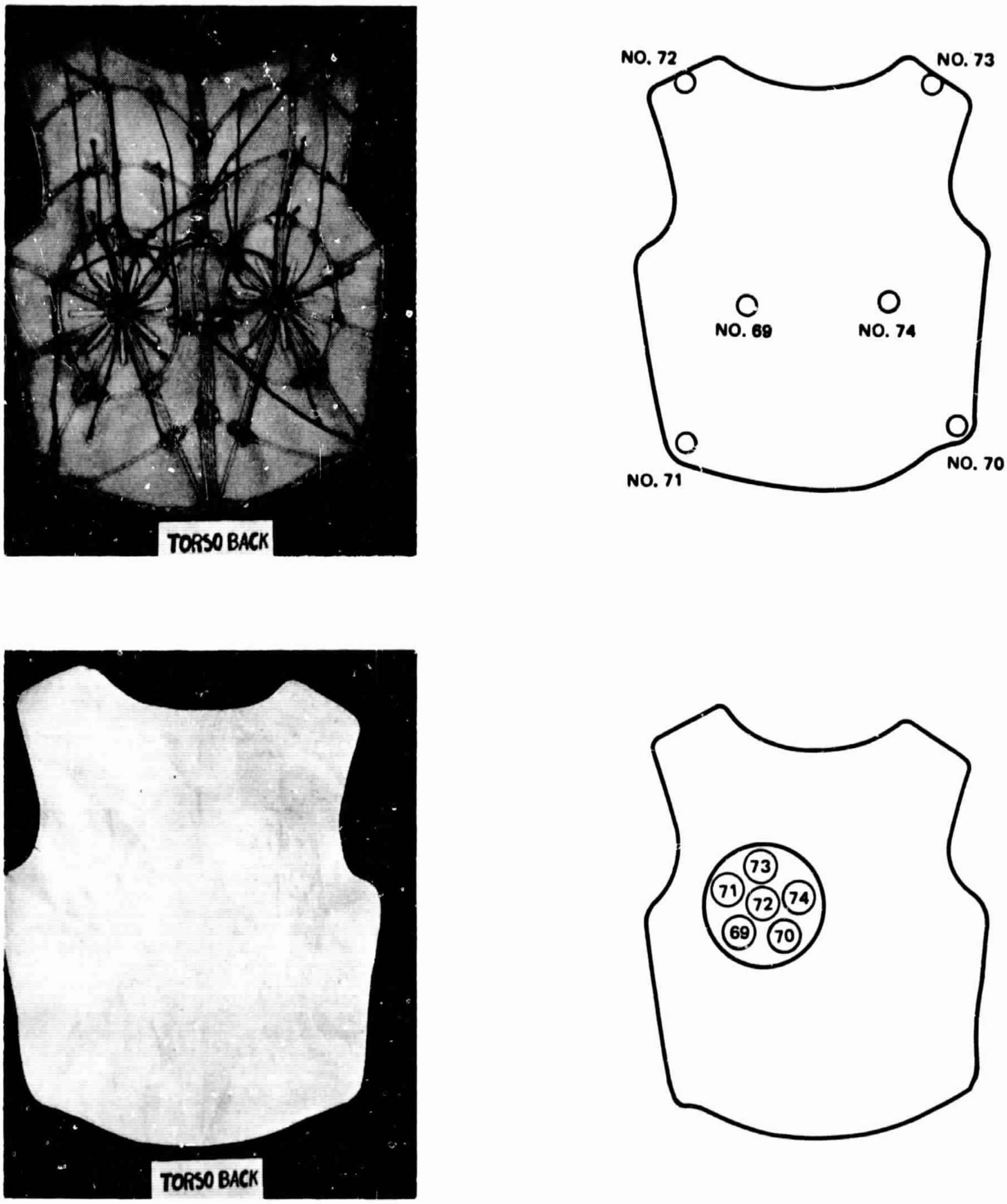


Figure A-10. Torso, Back (Inside)

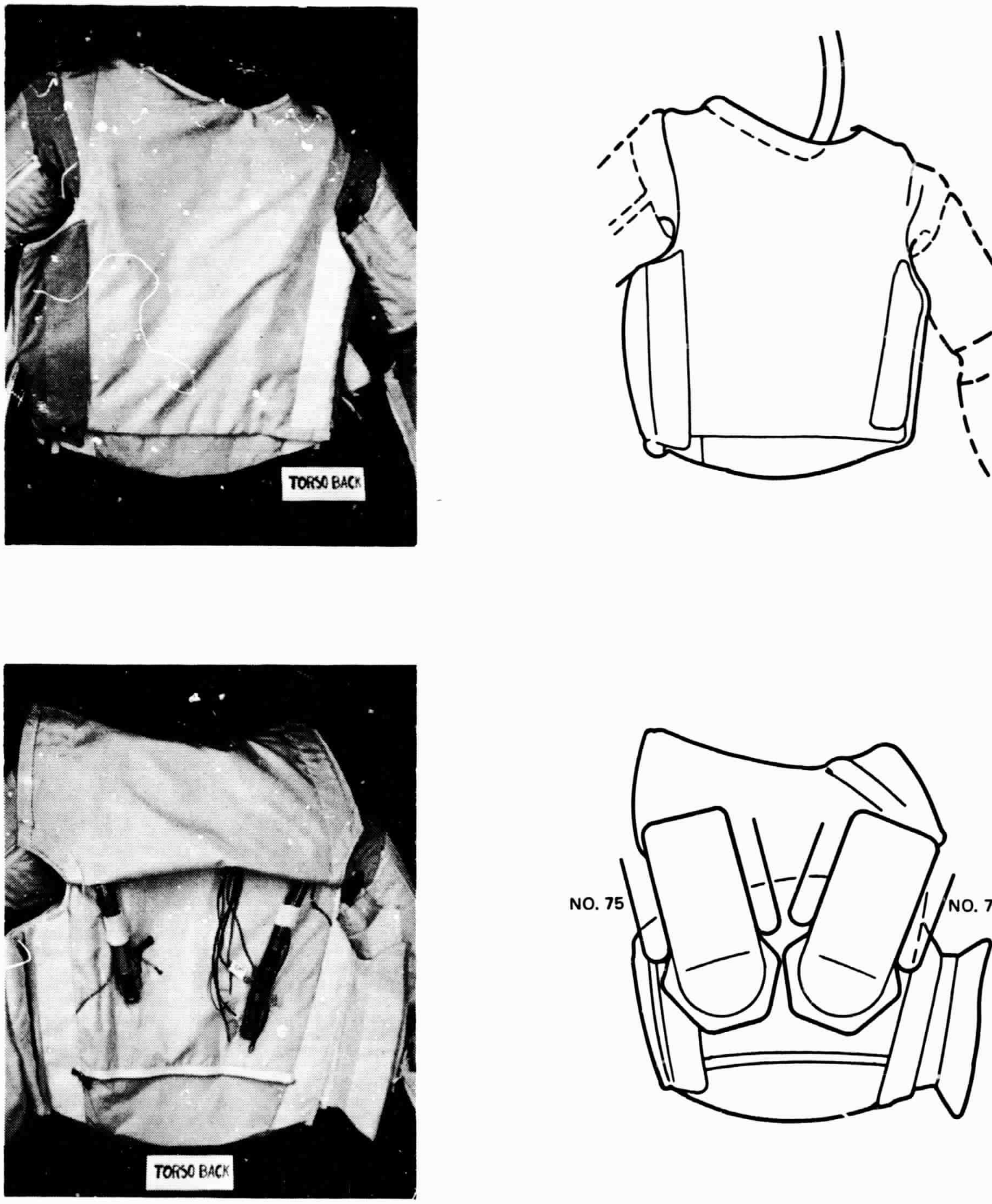


Figure A-11. Torso, Back (Outside)

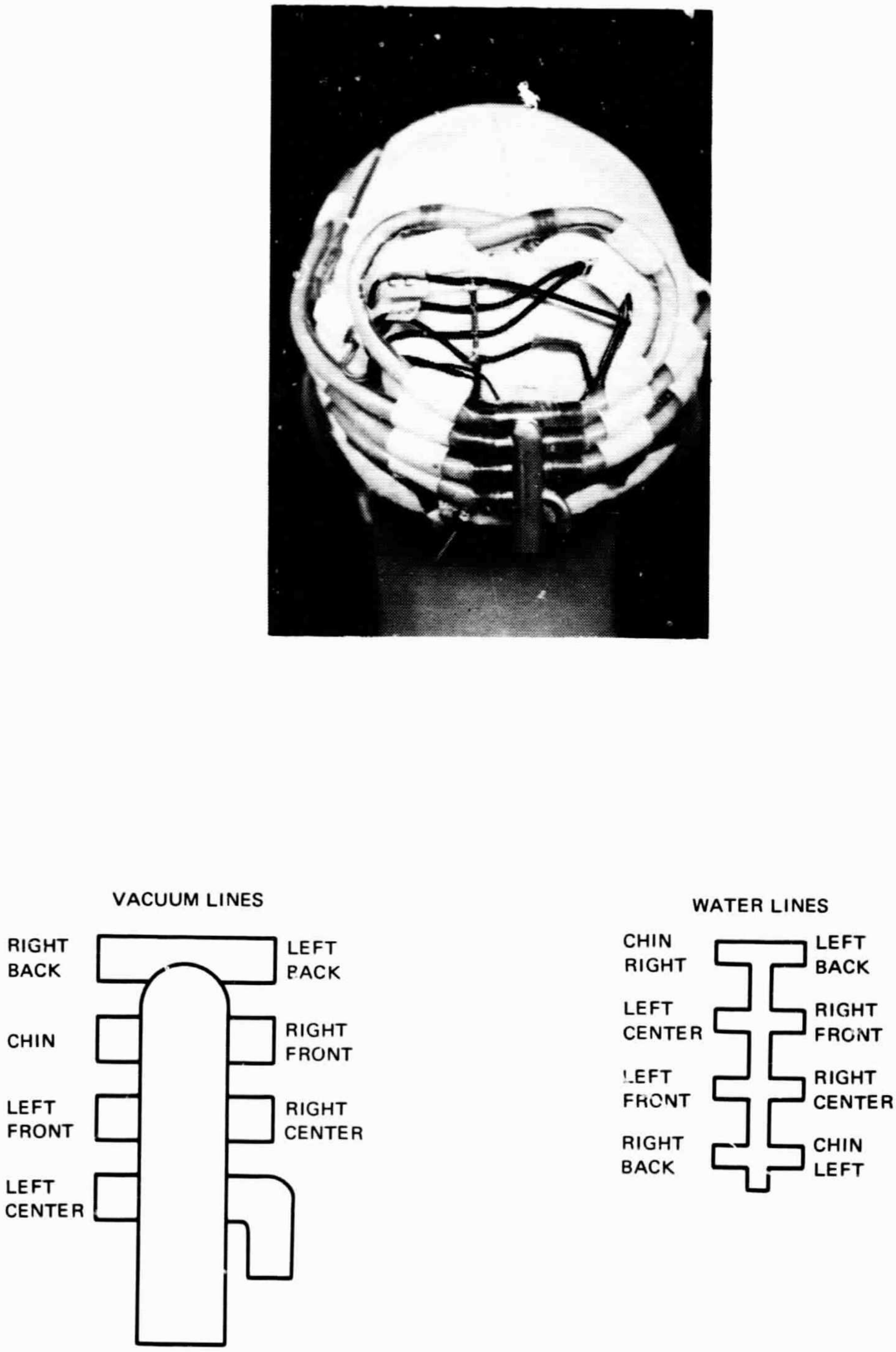


Figure A-12. Helmet, Back

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