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THE DEVELOPMENT OF AN ADVANCED SYSTEM TO COOL A MAN IN A PRESSURE SUIT

R. B. Olson, J. Felder, and C. F. Lombard

Prepared under Contract NAS9-4925 by

NORTHROP SPACE LABORATORIES
3401 West Broadway
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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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FOREWORD

This report describes the technical tasks performed in developing an advanced system for cooling a man in a pressure suit. This work was sponsored by NASA Manned Spacecraft Center under Contract NAS9-4925, with J. M. Waligora serving as Technical Monitor.

The objective of this program was to determine the feasibility of cooling a man in a spacesuit with a cooling system comprised of wick-filled water boilers in direct contact with the skin, manifolded and ducted to an adjustable differential pressure relief valve which is vented to the vacuum of space.

The ultimate goal is to provide for the comfort of the pressure suit occupant at maximum envisioned peak of 2,500 Btu/hr and steady state of 2,000 Btu/hr metabolic rates during backpack operation in a free space environment with a 3.7-7.0 psia operating pressure range, and during intra spacecraft operation with an unpressurized spacesuit at 5.0-7.0 psia. It is assumed that a vacuum environment is always available.

This study was performed by Northrop Space Laboratories, Hawthorne, California. Dr. C. F. Lombard was Program Manager.

Major contributions to this program were made by Mr. C. A. Reetz and Mr. M. C. Saunders of the Biodynamics Laboratory, and Mr. W. L. Eichelkraut of the Thermodynamics Group, Northrop Space Laboratories.

Northrop Space Laboratories has assigned document control number NSL 66-73 to this report.

ABSTRACT

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In this program a feasibility stuay was conducted and a configuration developed of a conductive cooling system for cooling a man in space. The results of the bench tests and the single man test held at the end of the program demonstrate the feasibility of this concept plus the need for further development work to produce a model having the desired efficiency, reliability, and safety for space use.

AUTHOR

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I. INTRODUCTION

The current approach to thermal transport in a space worker's garment is to use a liquid coolant loop which brings the body heat to a boiler or heat sink on the workers' backpack. This concept adds considerable mass and bulk to the suited worker. If the backpack boiler, with its associated coolant loop, pump and power pack could be replaced by a simplified cooling system requiring neither pump, power pack, nor coolant loop; considerable mass and bulk would thus be eliminated. This predicates minimum mass and bulk constraints on the new system.

Conceivably, a boiler in intimate contact with the man in the space suit and vented to the vacuum of space could provide the thermal transport to meet the minimal requirements for mass and bulk. The conductive cooling system could be made of small, wick-filled water boilers in direct contact with the skin. These would be manifolded and ducted to the vacuum of space through a differential pressure relief valve. Since the pressure adjustment of the valve determines the temperature at which the water boils, it also determines the temperature which the boiler will maintain in contact with the skin.

To determine the feasibility of such a concept, some experiments were required to develop engineering data to design a laboratory prototype for testing. Among the important tasks were the following:

1. Investigation and test of available wicking materials to determine those best suited for the application.
2. Development and test of boiler configurations with high thermal conductivity and combining flexibility (to achieve intimate contact with the occupants' skin) with structural rigidity to resist collapsing pressures when evacuated.
3. Selection of an adjustable differential pressure relief valve, operative at differential pressures less than 0.6 psi at high accuracy without icing when venting water vapor to the space environment.

The data derived in performance of these tasks was used to develop a working laboratory model of a cooling system, which demonstrated the feasibility of this concept when worn by a man walking on a treadmill at a 2,000 Btu/hr metabolic output.

This report describes the experiments, investigations, and tests performed in deriving this concept. From the results of these tasks further refinements were suggested. Recommendation for these are therefore included in this report.

II. INVESTIGATION OF THE PROPERTIES OF AVAILABLE WICKING MATERIALS

The primary function of the wick inside the boiler is to maintain a flow of water to the inner heated surface as the water boils away. The most desired properties of wicking materials for this application are high water storage capability and rapid capillary action coupled with sufficient permeability to permit the flow of water vapor during boiling. A method of comparative testing of available wick materials for this property, was required for selection of an optimum material for use in the water boilers. Therefore, a wick test chamber was designed and fabricated for this purpose. The chamber has a wetted wick in contact with a heated copper plate which is instrumeted to measure the temperature of the plate surface under the wick. With a vacuum source for establishing lower boiling temperatures for the water in the wick and to evacuate the steam generated plus a controlled heat input, comparison tests can be made.

WICK TEST CHAMBER

The wick test chamber (see Figure 1) consists of a long, narrow box of one-inch Plexiglass plate in which a temperature-monitored copper skin analog plate is mounted. A tape heater is attached to the under-surface of the copper plate and is thermally isolated from the bottom of the box. Thermocouples monitor the plate temperature, which is recorded on a Brown Recorder. Thermal inputs to the tape heater were provided by a variable transformer, with the input monitored by a voltmeter and ammeter. Recorded input values were converted to Btu/hr. To reduce additional heat inputs from the surroundings to a minimum, the test chamber was placed in a tubular Plexiglass chamber which was evacuated by a second vacuum system.

Data on water storage capability of a variety of wicking materials was obtained (Table I, Appendix). From this listing, three wick materials were selected for test and comparison of performance characteristics under low pressure conditions. The choice was based upon maximum water storage capability, minimum wick volume change from the dry to the saturated condition, basic strength (a consideration in both fabrication and use), and availability. Materials chosen were polypropylene, Arnel (cellulose triacetate) and viscous rayon.

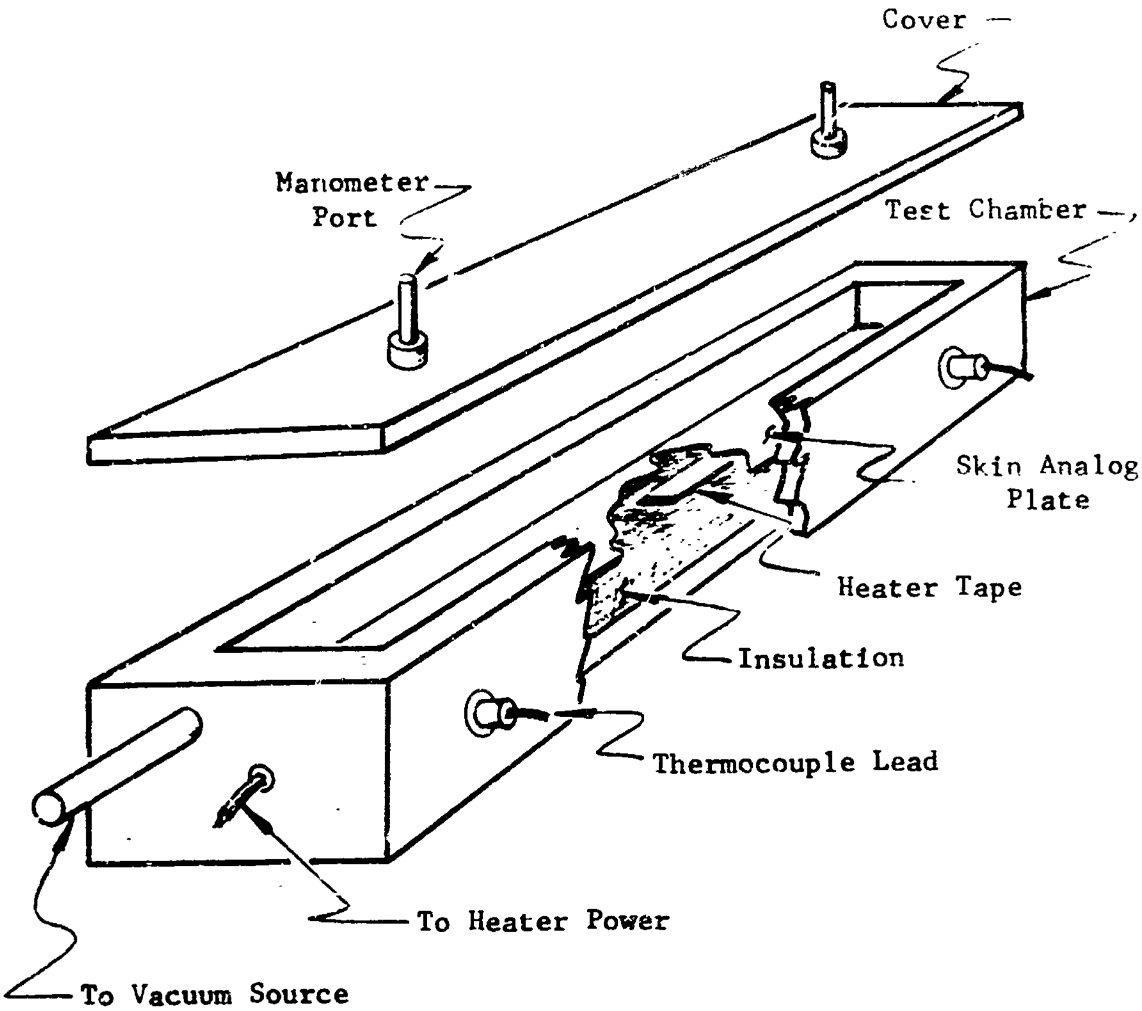


FIGURE 1. WICK TEST CHAMBER

TEST PROCEDURE

The first step in testing the wick materials was to place a dry sample of the wick (24" x 2 1/4" x 1/4", completely covering the copper plate), in the test chamber. To this was added 200 cc of water, which brought the sample close to saturation. A one-half inch spacer of Tri-Lock, a resilient woven plastic matting, was placed between the wick and the lid of the chamber to hold the wick firmly against the copper plate. Without this restraint, the wick was held away from the plate by the boiling action of the water which prevented effective cooling of the copper plate. The lid was then installed and the test chamber placed inside the insulating vacuum chamber. A heat input was then applied and the test and insulating chambers were evacuated. The heat input and the test chamber pressure were then adjusted to obtain a desired plate temperature, after which the heat input was generally held constant for the duration of the test. The plate temperature, chamber pressure and the heat input were measured and recorded throughout the entire test. The tests were not terminated until it was obvious that cooling had stopped.

In another test, the differential relief valuve was used in the system to control the pressure in the wick test chamber and its adjustment varied periodically to determine the thermal response of the system to sudden changes in pressure (Figure 2).

TEST RESULTS

Figures 3, 4, and 5 show that the performance characteristics of these three materials were substantially equal under low pressure conditions. With a fixed heat input, the temperature could be maintained almost constant in each case for the first 90 percent of test duration, after this interval, the temperature rose rapidly. The volume of water in the cold trap downstream from the test chamber showed approximately 90 percent of the water had been lost from the wicks when effective cooling had ceased. Another characteristic indicated by some of these data (Figure 4) is the apparent improvement in cooling efficiency after completion of approximately one-third of the test. This was indicated by the temperature drop which occurred with no change in heat input or pressure, and may be the result of increased vapor flow efficiency through the wick as the available vapor flow passage volume increased with the decline of wick saturation.

Even though the wick surface was covered by the rather tightly woven surface of the Tri-Lock spacer, which also reduced and obstructed the vapor flow passage over the wick the length of the test chamber, anticipated head losses did not materialize. This made it unnecessary to perform flow tests, varying the chamber cross-section, as originally intended. The indication was that head losses did not constitute a major problem area at this stage of the investigation.

In the final selection of wick material for the boiler design, viscous rayon was ruled out because it is attacked by mildew. Polypropylene was chosen in

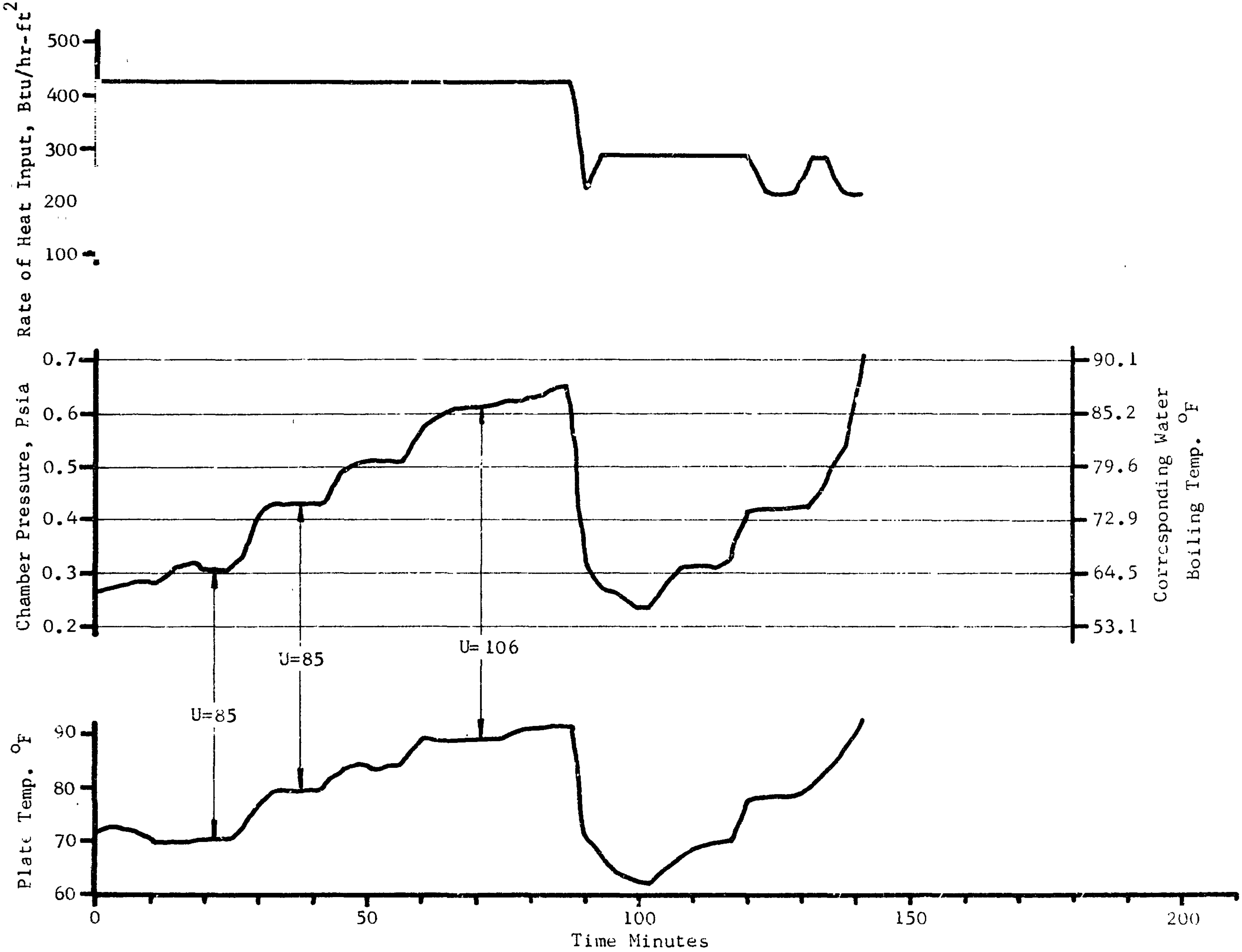


FIGURE 2 POLYPROPLENE WICK TEST USING THERMAL RELIEF VALVE

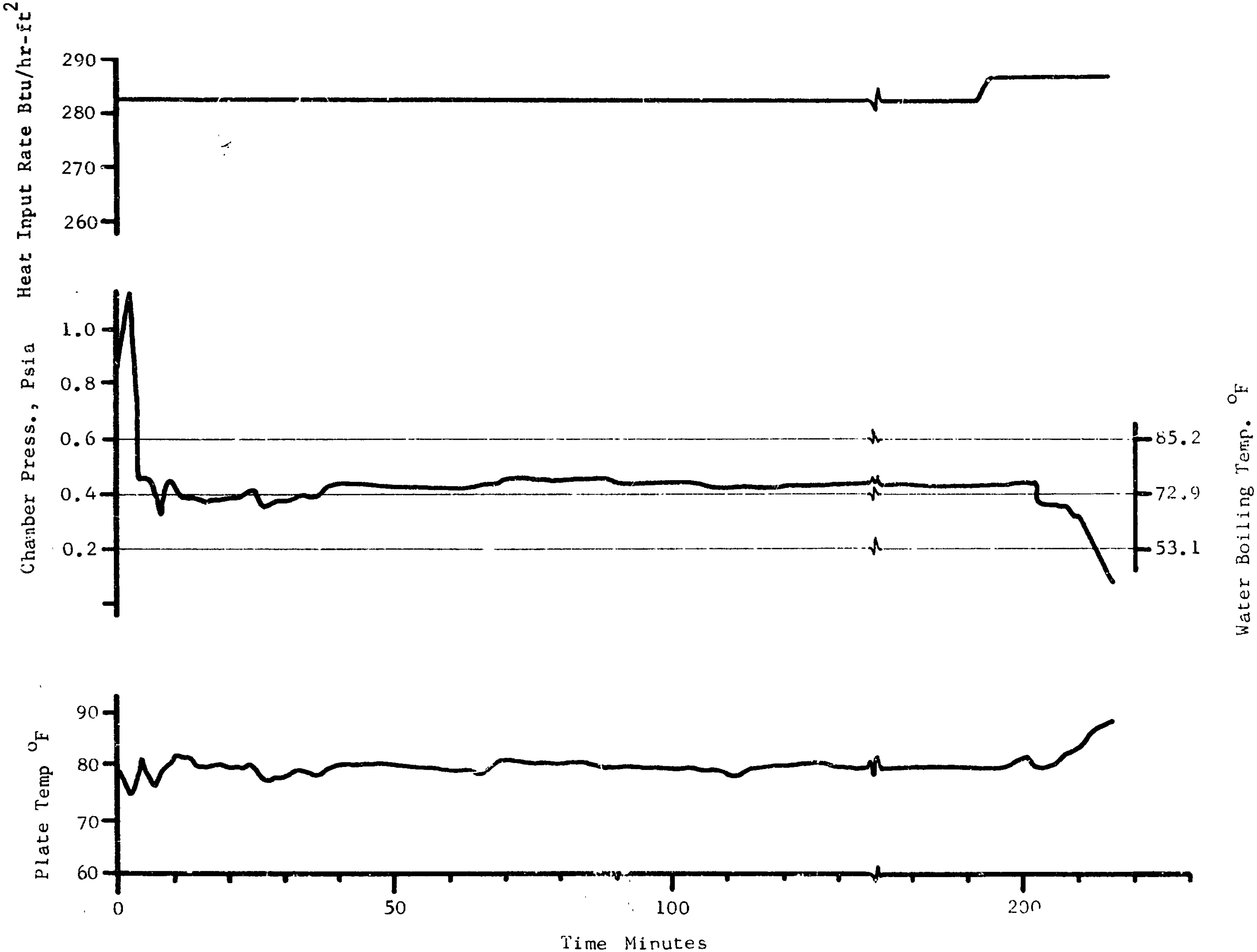


FIGURE 3 ARNEL WICK TEST

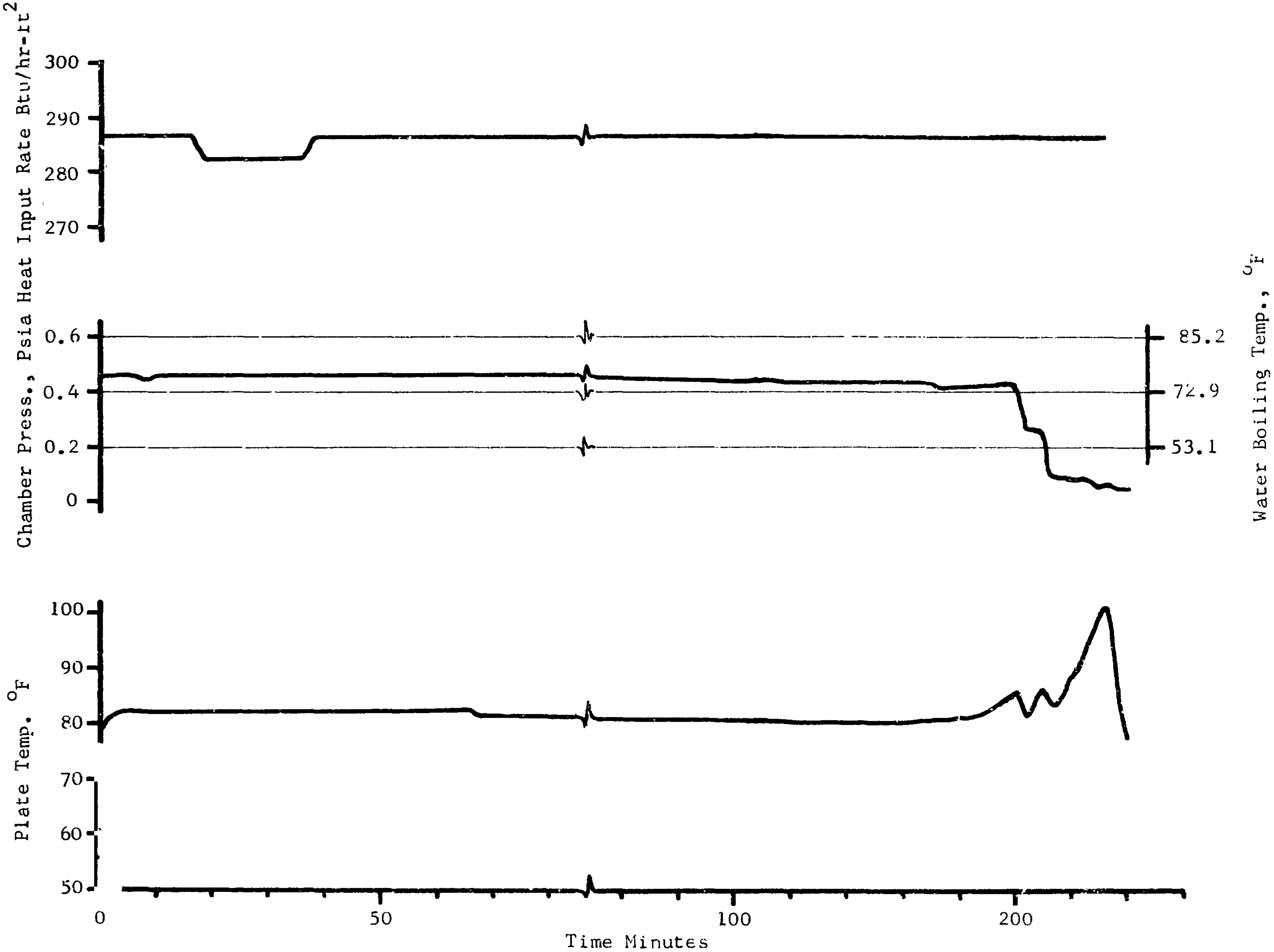


FIGURE 4 VISCOUS RAYON WICK TEST

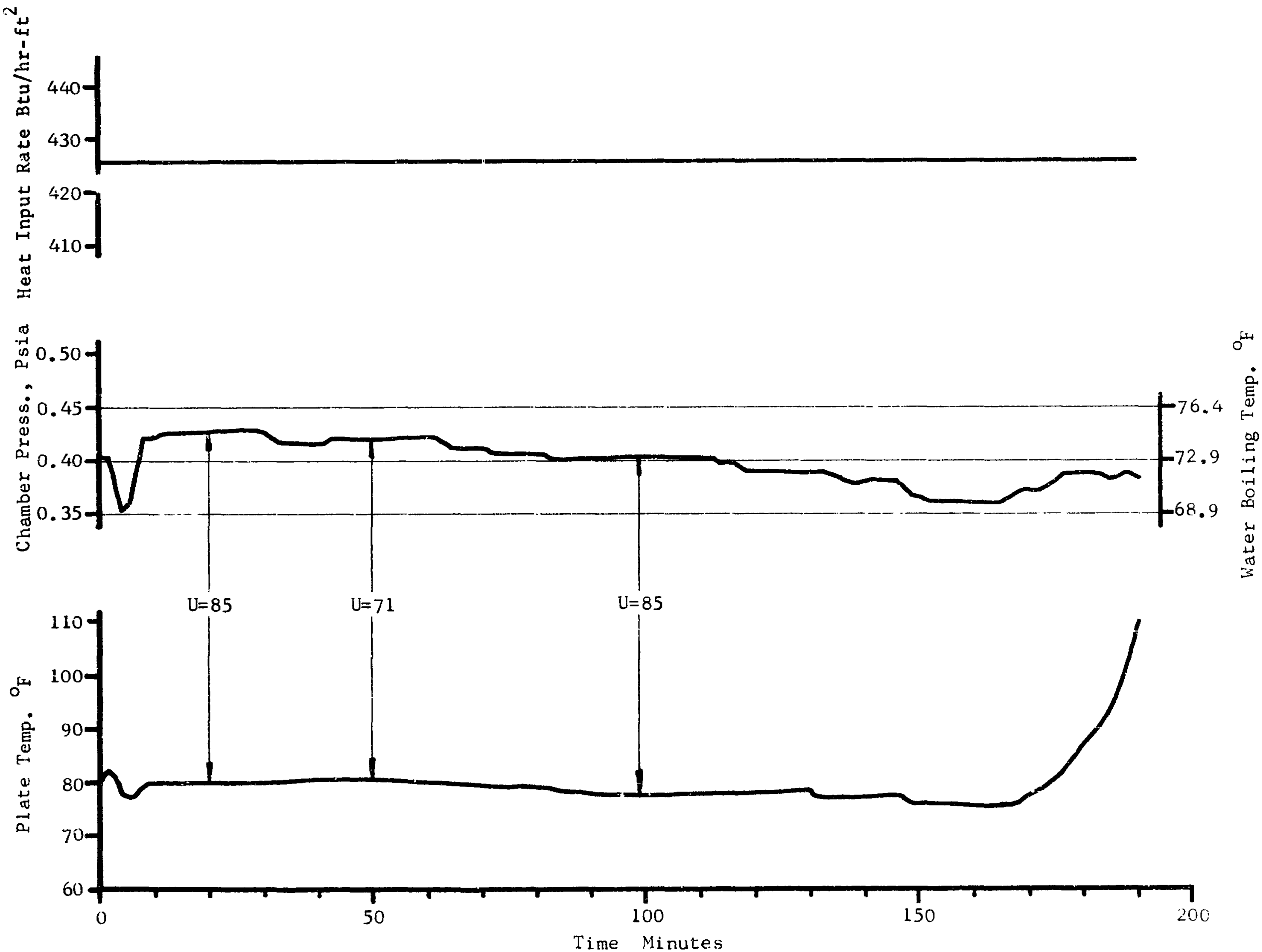


FIGURE 5 POLYPROPYLENE WICK TEST

preference to Arnel because of its ready availability in a variety of densities and configurations.

ANALYSIS

The thermal conductance, U, of the polypropylene wick material had to be determined to evaluate its performance and to predict the performance of proposed boiler configurations in which it would be used. Thermal conductance was calculated from the test data by dividing the heat load by the product of the surface area of the plate and the temperature difference between the copper plate and the water boiling temperature at a given test pressure. The basic relationship is

$$Q = UA(T_1 - T_2)$$

Where:

Q = Heat load, Btu/hr

U = Thermal conductance, Btu/hr-ft^2 - °F

A = Area of conducting surface, ft^2

T_1 = Temperature of heating surface, °F

T_2 = Boiling temperature of water at test pressure, °F

Solving for U,

$$U = \frac{Q}{A(T_1 - T_2)}$$

The resulting U value shows the presence of a thermal resistance which can be attributed only to the boiling action of water creating a vapor barrier between the wick and the copper plate. Those tabulated values of U found in Column 7 of Table III (Appendix) are based on test data shown in Figures 2 and 5 on polypropylene wick at a broad range of pressures and relatively high heat loads. An average value of 85 representing this thermal conductance (U) was combined with the conductivity values of other applicable components used in later configurations to predict their overall performance.

III. WATER BOILER DESIGN, TESTING AND EVALUATION

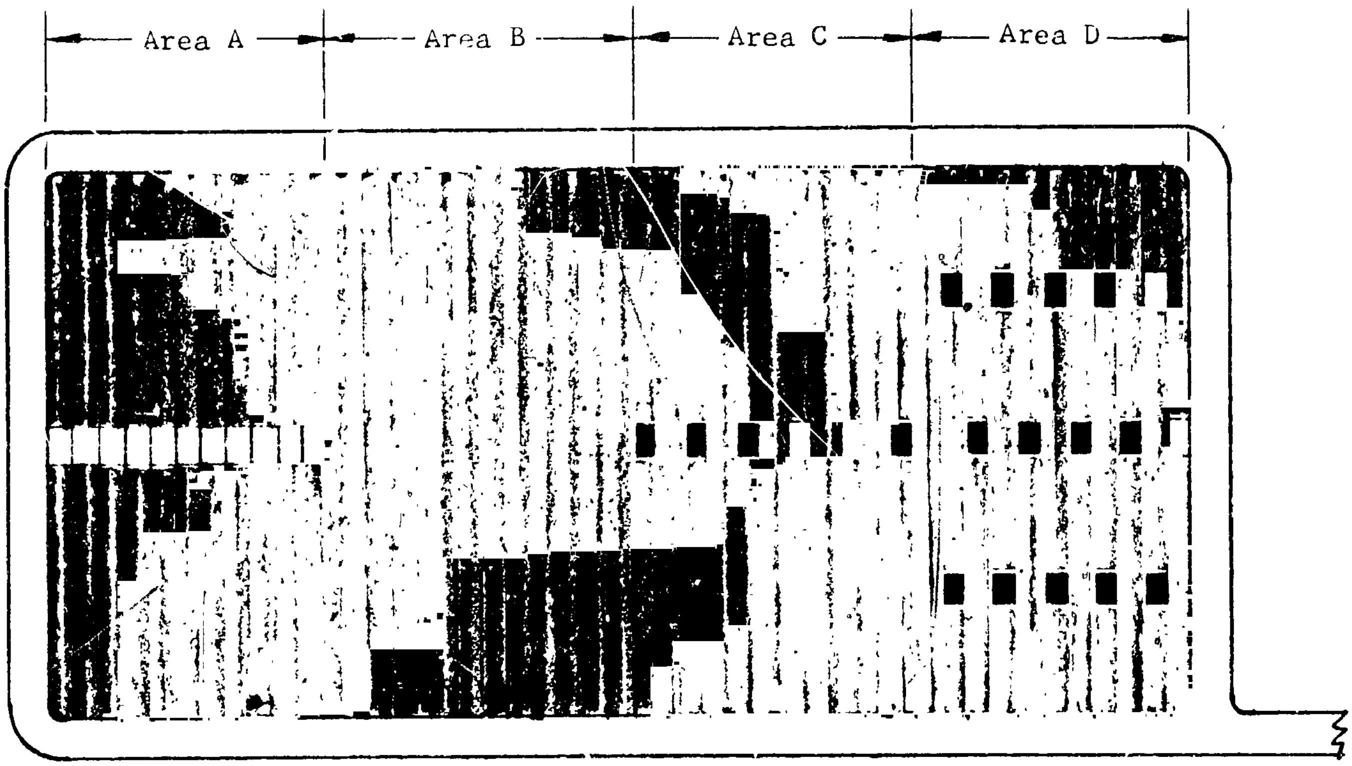
The water boilers used in this study are characterized by an outer gas-tight wall; a water storage section (wick); and space for ducting water vapor. To derive a water boiler design incorporating the structural integrity and the flexibility necessary several concepts were considered and evaluated. Information from the wick material investigation presented in Section II was used in the boiler designs considered and discussed below.

Flexible tubing made of interlocking segments of highly conductive material such as aluminum and sheathed in an impermeable material was considered for the gas-tight boiler wall design, as was a flexible, wire-reinforced, impermeable, silicone tubing. A configurations using Tri-Lock supporting a wall of flexible impermeable material appeared to offer the required structural characteristics but further investigation showed that although this design could withstand the planned operating pressure differential of 7.0 psi, it would collapse at the required sea level demonstration test pressure.

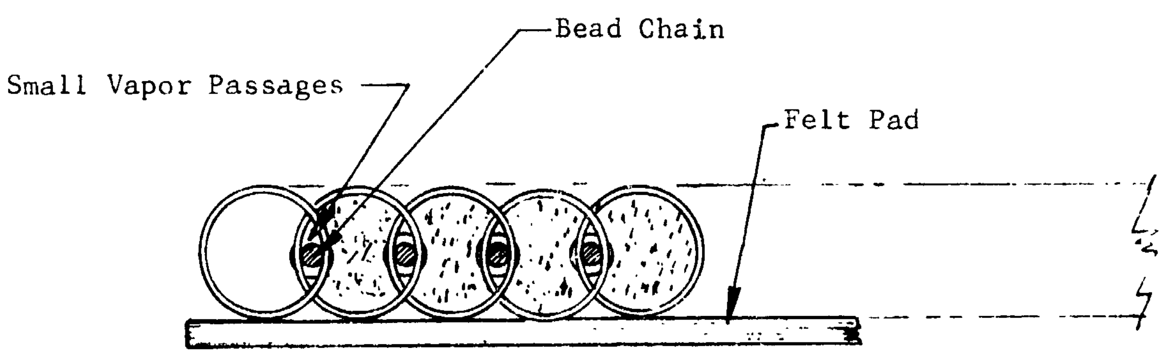
FIRST BOILER DESIGN

The next design approach showed greater promise because it was structurally sound as well as flexible when evacuated in a sea level pressure environment. The boiler consisted of rows of stainless steel springs, some filled with wick and others open for vapor flow, uniquely interlocked with stainless steel bead chain to prevent axial compressive deformation of the springs when subjected to reduced internal pressure. The combination of interlocking bead chain at the neutral axis of the boiler cross-section and continuous bellows-type joint created by the vacuum applied to the encapsulating material results in an extremely flexible boiler design (cross-section of Figure 6). A boiler based on this design was fabricated for testing on the human analog test fixture shown in Figure 7.

Four different wick arrangements were used in this boiler (Figure 6) in an attempt to obtain a quick indication of the relative importance of spacing and size of vapor flow passages in a water boiler of this configuration. Nylon and Dacron fabrics coated with buna-N and neoprene of various thicknesses were considered



Note - Shaded Areas Indicate Wick, Other Areas for Vapor Passage



Typical Cross-Section of Boiler

FIGURE 6
WICK BOILER FOR TESTING ON HUMAN ANALOG

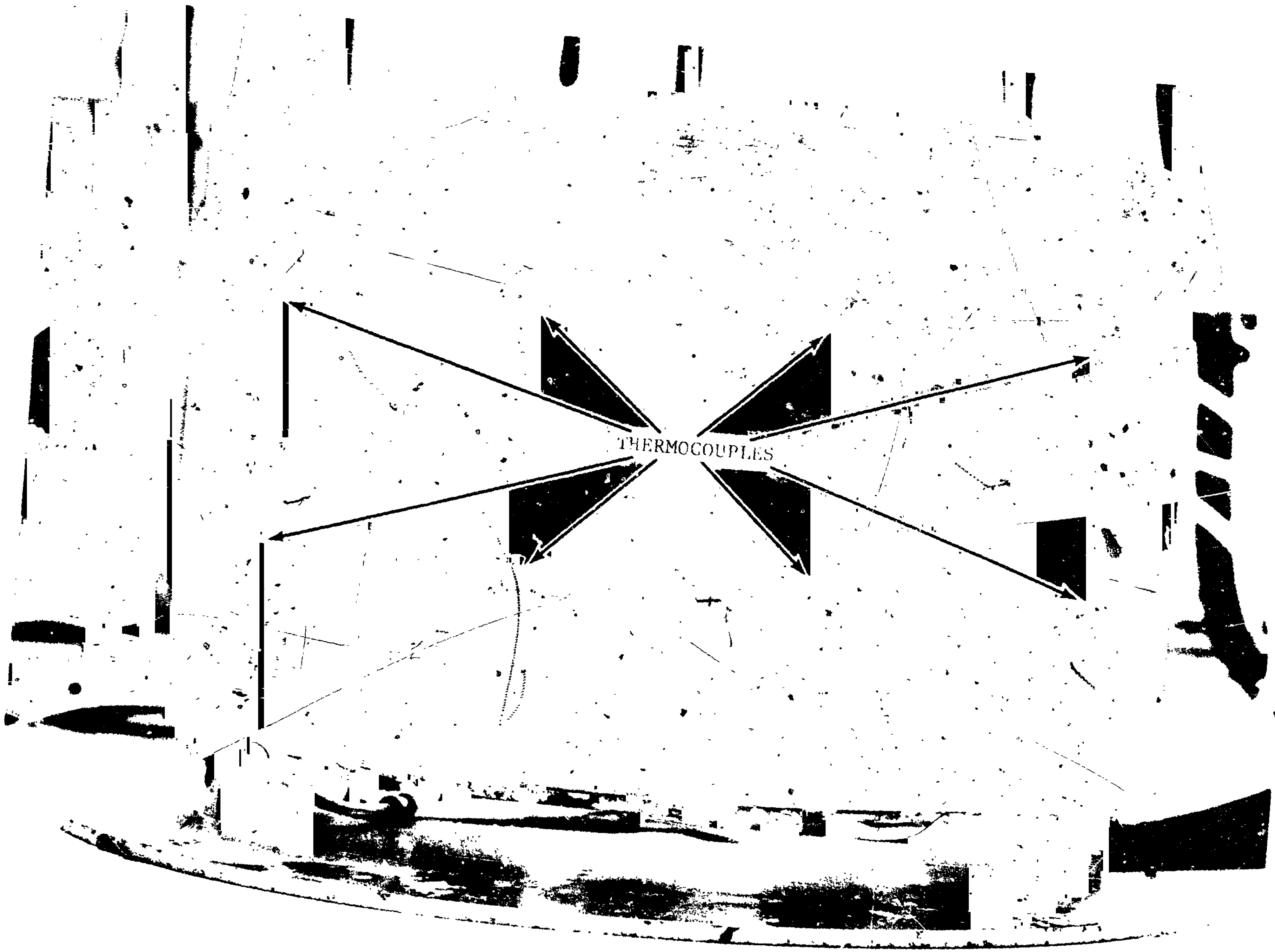


FIGURE 7 HUMAN ANALOG TEST FIXTURE

for the gas-tight encapsulating material required to complete the boiler configuration. Bonding techniques and resulting joint strengths were investigated; from this standpoint as well as abrasion resistance, neoprene-coated Nylon was chosen. The minimum thickness available (.007 inch) was chosen for maximum thermal conductivity. Because of availability problems, it was necessary to use buna-N coated Nylon for this test boiler, an acceptable substitute because the thermal conductivities of both are essentially equal at this thickness and abrasion resistance is not a critical requirement when testing on the inanimate human analog test fixture. The boiler-encapsulating bag was made with an end open to facilitate changes in the wick arrangements during the test program. A temporary sealant was used during testing.

As a basis for evaluating test boiler performance, a theoretical U value was calculated; the predicted value was 54 combining U values obtained from the wick tests with the theoretical conductivity of the encapsulating material.

TEST PROCEDURE

The boiler was first filled with water and allowed to soak for at least one-half hour. Excess water (water not absorbed by the wicks) was then poured out, the boiler weighed, and its weight recorded. It was then taped snugly against the copper plate of the human analog test fixture (Figure 7). The fixture has a heating element on the reverse side of the plate and eight thermocouples mounted on its surface. When mounted on the test fixture the test boiler had two thermocouples centrally located under each of its four different wick arrangements for comparison of their performances if measurable differences occurred. Fiberglass insulation was then wrapped and secured around the test fixture and boiler, the heating element energized, and the test boiler evacuated. The heat input and boiler pressure were adjusted to preselected values and each test was continued until a steady state condition was reached. At the end of each test, the boiler was weighed to determine the quantity of water lost. Many tests were performed with variations in the wick arrangements in an attempt to approach the predicted performance of the boiler. Test results were unfavorable and are discussed below.

TEST RESULTS

The test results shown for Configuration 1 in Table II (Appendix) indicated insufficient contact area was provided by the multiple contact points of the bellows-shaped surface of the boiler. In Configuration 2, a thin wick pad was added between the rubber bag and the spring-wick assembly to increase the contact surface area and improve moisture transport to the heated surface. However, when a vacuum was applied to the boiler, the contact surface became uneven due to "bunching" of the added wick pad. The contact surface was then improved by placing a thin aluminum plate inside the bag between the felt pad and the bag (Configuration 3). This produced a smooth contact surface under vacuum, simulating an ideal situation where the human skin would conform perfectly to the irregular surface of the boiler. Results still indicated that boiler performance was less than predicted, but showed a significant improvement over the previous configurations tested.

During testing of Configuration 3, the temperature of the outside surface of the boiler opposite the heater was higher than the water boiling temperature. This indicated that backface boiling was occurring, which could impede vapor flow from the primary heated surface. This occurred when the boiler was first activated in reducing its temperature to the selected water boiling temperature. The boiling temperature being below the ambient temperature of the water (70°F) meant that boiling occurred throughout the wicks, possibly restricting the flow of vapor from the wicks during the initial stages of each test. However, all the tests were continued until a steady-state condition existed, and most were continued until the wicks were nearly dry.

Configurations 4, 5 and 6 were attempts to solve the contact and backface boiling problems. Alternate wicks were removed for additional vapor flow passages. Tri-Lock was also added to the back side for insulation and reduction of backface boiling and boiler pressure was raised to increase the boiling temperature above room ambient temperature. The results showed no particular improvement. Configuration 6 from which the aluminum plate was removed was noticeably poor in contact area due to "bunching" of the heavy wick pad.

Lack of contact area appeared to be the major barrier to heat flow. It was apparent that contact of the boiler with the relatively softer human skin compared to the copper plate would improve the situation. However, results of tests with the thin aluminum plate, showed this was not the only problem, and that heat flow was limited by some feature of this configuration which was not readily identified. Furthermore, the pressure required to approach 100 percent surface contact with this irregular surface would cause extreme discomfort to the person wearing it. A new design approach was therefore instituted.

SECOND BOILER DESIGN (SMALL TEST MODEL)

Information obtained from previous tests was utilized to develop a new boiler consisting of the following elements:

1. An outer gas-tight wall of neoprene-coated Nylon supported by small aluminum boxes (outside dimensions: 1.75" x 1.75" x 0.50") flexibly connected by stainless steel extension springs (0.438" o.d.).
2. A water storage section in each box filled with polypropylene wicking in contact with the inner surface of the aluminum box and surrounding the central vapor duct.
3. A vapor passage axially through the continuous helical extension spring which connects the individual boxes.

The wick test chamber (Figure 1) was used to evaluate the basic configuration before fabrication of a larger model for testing on the human analog test fixture. The test boiler consisted of ten aluminum boxes assembled around a continuous extension spring (for vapor passage) elongated within each box. The elongation permitted water vapor to enter the passage from the polypropylene wick filling the portion of each box surrounding the spring. The spring was left in its original pre-loaded condition between the boxes for structural support of the vapor passage and flexibility. An example of this basic configuration is shown in Figure 8. A sufficient length of spring projected from the group of boxes for structural support of the neoprene tubing used for ducting to the vacuum sink. The group of boxes was encapsulated in a Nylon-neoprene bag, which was then bonded to the tubing, making a gas-tight water boiler. Due to the high thermal conductivity of aluminum, its use in this configuration did not change the theoretical U value of 54 for the wick-neoprene combination.

TEST PROCEDURE

In the first configuration tested (Configuration 8, Table III, Appendix), a layer of Tri-Lock had been installed inside the boiler between the wall of the

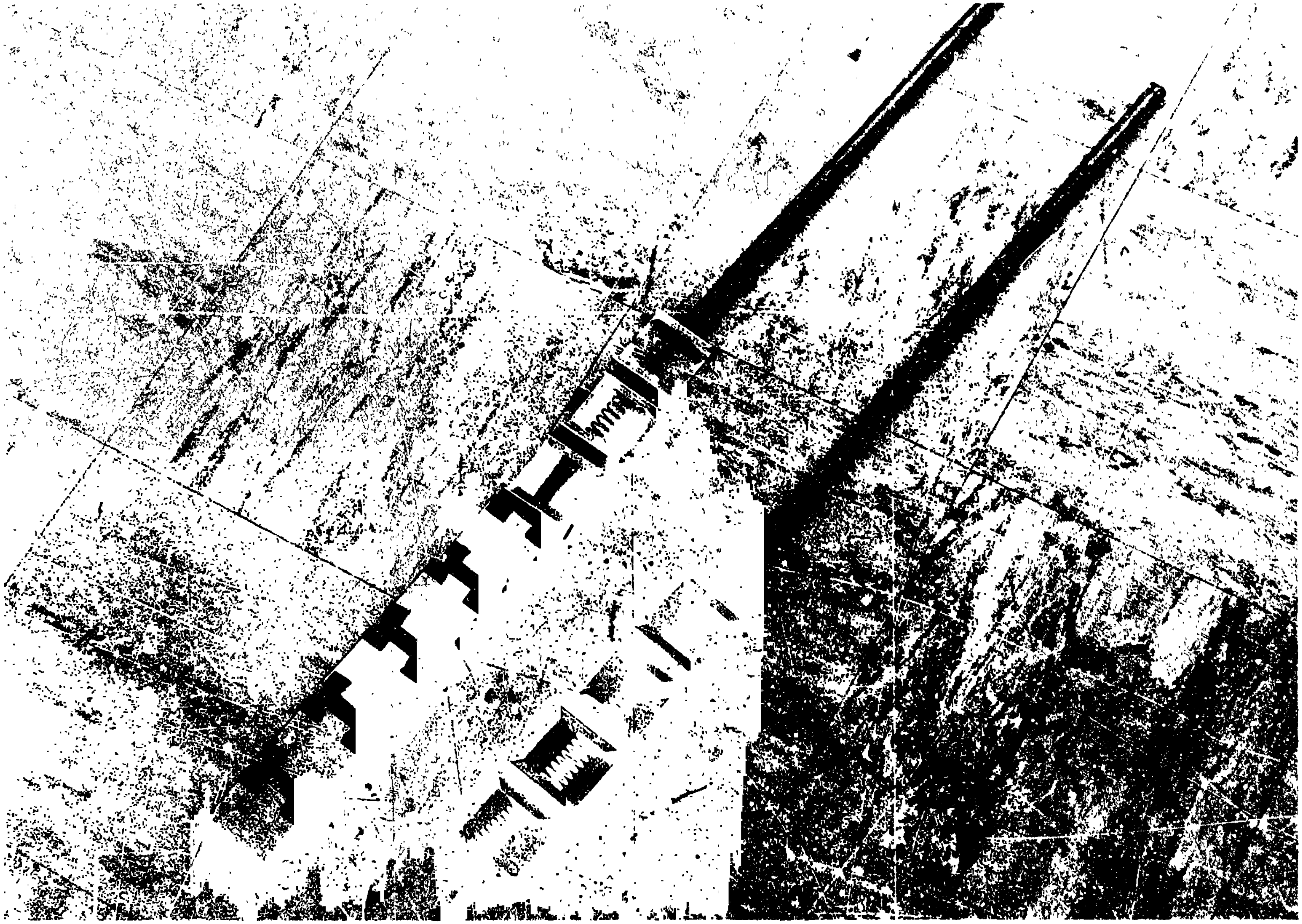


FIGURE 8 ALUMINUM BOX BOILER CONFIGURATION

aluminum box and the wicking, on the side opposite the heat source, to reduce heat input from that side and to prevent back-face boiling. The test boiler was filled with water and allowed to soak. Unabsorbed water was poured out before placing the boiler in the test chamber. To assure good contact, the test boiler was clamped against the copper plate. The test chamber was placed inside the tubular Plexiglass chamber, which was evacuated to 3.5 psia to simulate the pressure of spacesuit environment during the test. Tests were performed at a fixed heat input and boiler pressure to determine at which temperature the copper plate could be maintained under steady state conditions.

TEST RESULTS

Marked improvement in boiler performance resulted in U values of 45 and 64 (see Table III). The configuration was modified by replacing the Tri-Lock with additional wick (Configuration 9); test showed equally good results. Using the same configuration (9), the test was repeated with the pressure in the outer cylindrical chamber at ambient. This simulated the conditions for demonstration testing of the laboratory model and resulted in a significant decrease in performance. Two other wick configurations (10 and 11) were also tested under this condition, with no apparent improvement.

Configuration 12 included a support in the center of each box to prevent panel deflections when the surrounding pressure was held at ambient during testing. This was to determine if the additional pressure was causing poor performance due to panel deformation materially reducing the contact area. The results indicated this to be true. Averaging these values with those obtained previously under the reduced surrounding pressure yields a U value of 54, which is the theoretical value predicted. On the basis of these test results, this basic boiler design was considered satisfactory to demonstrate the feasibility of the cooling system in a laboratory model. A support in the design of the boilers for the laboratory model was not considered necessary because the panel deflections which occurred in the unsupported configurations did not exceed 0.010 inch, and this would present no problem in contact with human skin.

SECOND BOILER DESIGN (HUMAN ANALOG TEST MODEL)

Concurrently, a large boiler consisting of 66 boxes arranged in eleven rows of six each had been fabricated and was being tested on the human analog test fixture.

The same general procedure was used in these tests as that followed for testing the first boiler design. However, to improve contact during these tests, atmospheric pressure was applied uniformly across the outer surface of the test boiler by placing a heavy plastic bag around the test fixture, and evacuating it with a separate vacuum source (see Figure 9). These test results are shown in Table IV of the Appendix.

TEST RESULTS

Initially, Configurations 13, 14 and 15 were tested with the 11 rows of boxes connected in series. Because of the curvature of the test fixture, the flat boxes used in Configurations 13 and 14 could not achieve good contact. The boxes were modified for Configuration 15 by removing a portion of the two sides of each box parallel with the axis of its connecting spring, allowing the contact face of each box to deflect inward for better conformation to the test fixture curvature. The resulting improvement is reflected in the U values shown in Table IV (Appendix) for Configuration 15. During these tests, heat losses were minimized by maintaining the plate temperature close to ambient (not done for Configurations 13 and 14), which indicates the improvement is greater than that shown by a direct comparison of U values.

Configuration 16 was identical to Configuration 15 except that the six rows of boxes were vented in parallel rather than in series, and more effective insulating techniques were employed. This resulted in a significant increase in the U value as shown in Table IV (Appendix). No pressure drop was observed across the parallel arrangement, but a pressure drop of 2 mm Hg occurred across the series arrangement. This was a three-degree difference in boiling temperature across the series arrangement, which contributed to the lower U value. This provided additional guidance for the design of the laboratory model.

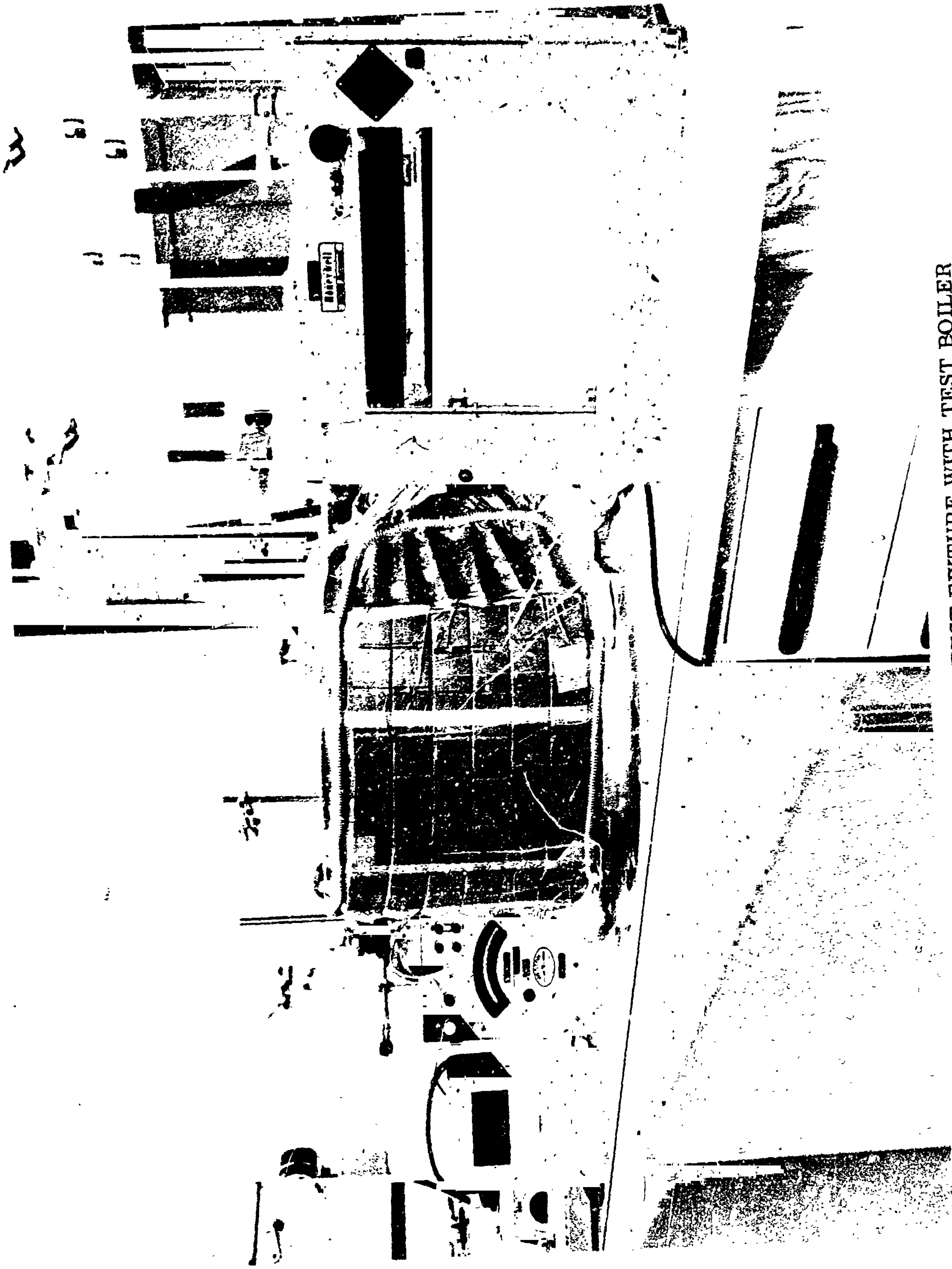


FIGURE 9 HUMAN ANALOG TEST FIXTURE WITH TEST BOILER IN PLACE WITHOUT INSULATION

IV. DESIGN, DEMONSTRATION TESTING AND EVALUATION OF THE LABORATORY MODEL

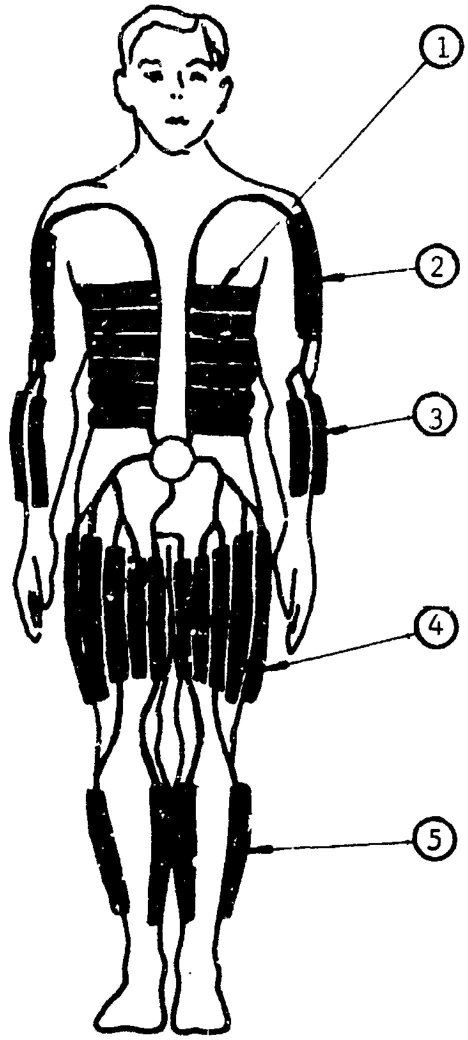
DESIGN

The laboratory model consists of a hermetically sealed system of water boilers, ducted and manifolded to an adjustable relief valve and supported in place by an elastic garment covering the arms, legs and torso. The design was based upon the following constraints:

1. The wick boilers must be held in close contact with the skin of the wearer under high activity levels.
2. The thickness of the wick boilers must be limited to one-half inch to be comfortably worn inside a spacesuit (by mutual agreement of NSL and NASA.
3. Skin coverage by the boilers to be limited to the chest area, arms, and legs, with sufficient contact area to remove 2500 Btu/hr peak with minimum interference to normal activity.
4. The differential relief valve to be adjustable for pressure differentials of 0.2 to 0.6 psi, with the pressure at a given setting to vary no more than ±0.02 psi, and capable of discharging 2.3 lb/hr of water vapor at 0.2 psia into a space environment without icing.

An elastic garment was fabricated of Spandex, with Velcro fasteners to hold the boilers in place, to maintain a constant pressure on the boilers and thereby attain close contact and the resultant thermal conductivity required for optimum performance. One-inch strips of Velcro were bonded to the backs of the wick boilers and two-inch strips of the mating Velcro were sewn into the corresponding areas of the garment, allowing a broad range of adjustment for boiler positioning. The garment was tailored to fit a test subject 5 feet 8 inches tall and weighing 155 pounds.

The general boiler locations, with the specific number and arrangement of boxes in each boiler, are shown by Figure 10. The total body area covered by the boilers is between five and six square feet. The total effective area of the boilers available for conductive heat transfer, assuming perfect contact, is 3.8 square feet. The total water capacity of the system is approximately eight and one-half pounds, of which 90 percent should be available for effective cooling at a capacity of 2000 Btu/hr for a period of four hours.



① (2) chest boilers, each consisting of (5) rows of (8) boxes and (1) row of (7) boxes
② (2) upper arm boilers, (4) boxes each
③ (4) forearm boilers, (3) boxes each
④ (10) thigh boilers, (4) with (6) boxes; (4) with (4) boxes; (2) with (5) boxes
⑤ (4) calf boilers, (4) boxes each

FIGURE 10 WICK BOILER SIZES & LOCATIONS

DEMONSTRATION TEST

The feasibility demonstration of this conductive cooling concept was conducted in the Northrop Space Environmental Laboratory, Hawthorne, California. In the test, the test subject wore the cooling system (plus boots, gloves, helmet and thermal outer garment to minimize convective heat losses), and walked on a treadmill at a rate of four miles per hour for a period of one hour.

TEST EQUIPMENT AND PROCEDURE

Standard monitoring equipment was used continuously to measure and record skin temperatures, core temperature, exhaled gases (for determination of metabolic rate), the heart rate, and the operating pressure of the cooling system. Based on baseline data available on the subject, this activity level was specified to produce a metabolic rate of approximately 2000 Btu/hr. As shown in Figure 11, the relief valve was exposed to a simulated space environment (pressure did not exceel 1 mm during test) inside the twelve-foot vacuum chamber. It was mounted inside the chamber on the end of a length of rigid copper tubing projecting through a viewing port to a supported position outside. A length of flexible stainless steel tubing was attached to the outside end. This completed the connection to the system manifold at the subject's waist line and allowed him sufficient freedom of movement to walk on the treadmill. The pressure setting of the relief valve was adjusted by an arm which also protruded from the viewing port of the vacuum chamber.

Cooling System Preparation. The cooling system wick was approximately 75 percent saturated before the test. The cooling system boilers attached to the Spandex garment were weighed before being donned by the subject, as were the boots, gloves, helmet, and thermal outer garment.

Subject Preparation. The subject, wearing swimming trunks, was instrumented for the demonstration. Three skin thermistors were applied directly to the skin at points which would place one under each of three wick boilers (trunk, thigh, arm - Figure 12). In areas adjacent to these but not under the boilers, three additional thermistors were placed. A colonic thermistor probe was inserted for use in monitoring core temperature, and EKG leads were attached to the chest for continuous observation of heart action throughout the test. The subject

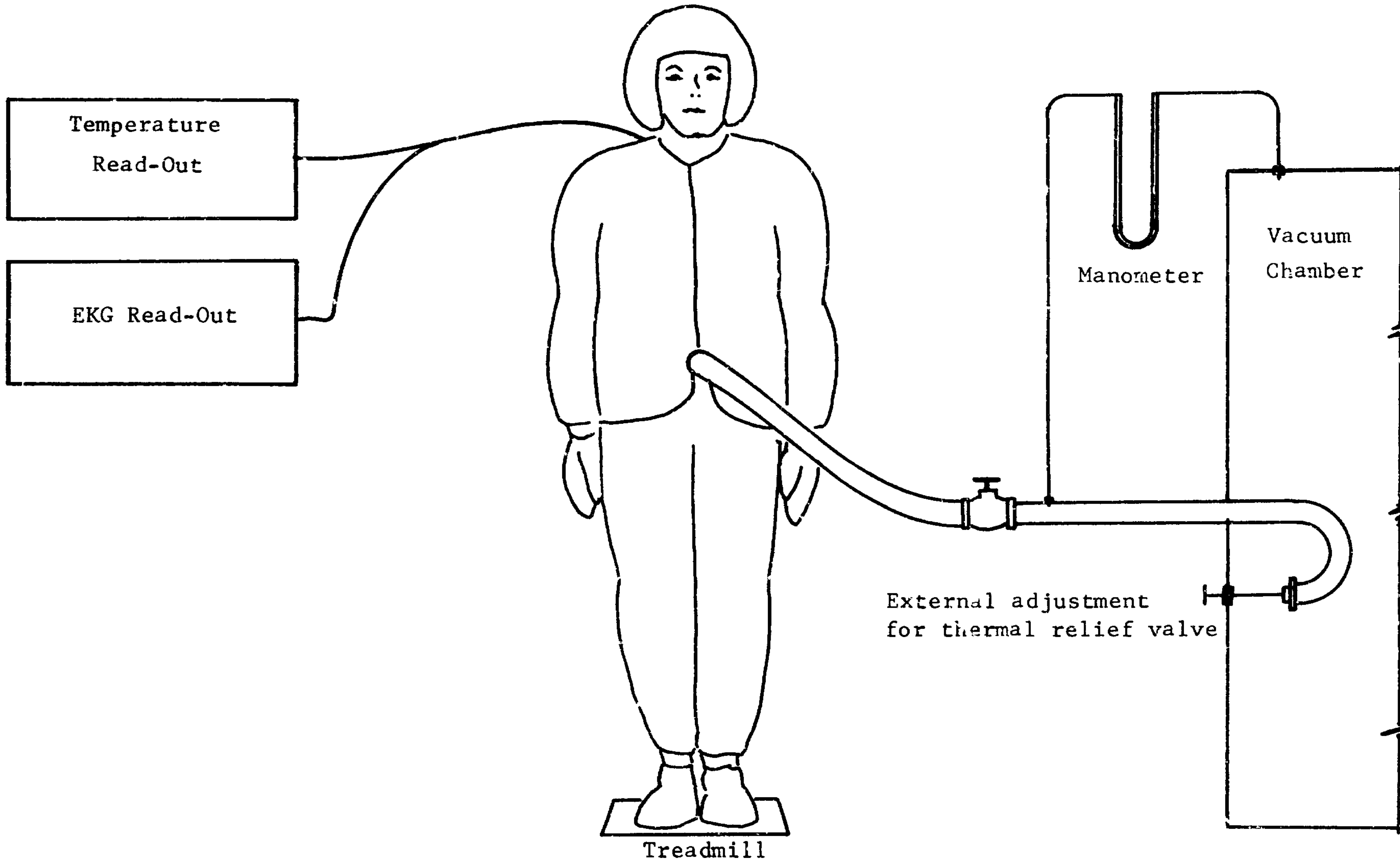
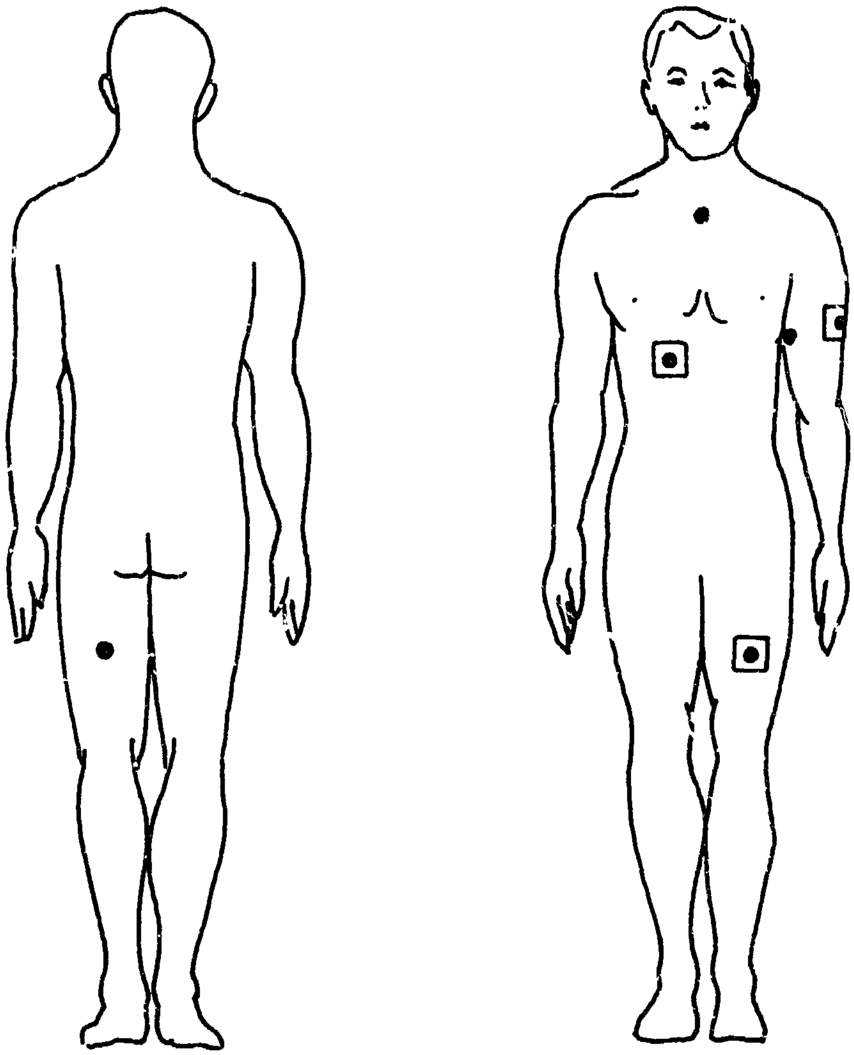


FIGURE 11 DEMONSTRATION TEST



Indicates thermistor under boiler
Indicates thermistor not under boiler

FIGURE 12 SKIN THERMISTOR LOCATIONS

was then weighed and donned the cooling system. The boiler ducting was then connected to the manifold, which had previously been attached to the flexible tubing leading to the vacuum chamber (see Figure 13). The instrumentation was connected and checked, and the pressure was quickly adjusted to one-half inch of mercury and a simultaneous adjustment of the treadmill rate of four miles per hour was made as the test began (see Figure 14).

TEST RESULTS

The skin and core temperatures with the corresponding heart rates are presented in Figure 15. The data and analysis regarding the weight loss of the subject during the test, and the data and calculations used to derive an energy balance are presented and discussed in succeeding paragraphs.

Subject Weight Loss. The weight lost by the subject during the test was 2.01 lb., and was the net result of the following elements:

1. Difference in weight between O_2 consumed and CO_2 eliminated
2. Evaporation of water from cooling system boilers
3. Evaporation of water via lungs
4. Evaporation of sweat from body surface.

In steady state excercise, at the level employed in this experiment, work physiologists recognize an RQ value of 1.0. This means that one molecule of carbon dioxide is given off for each molecule of oxygen used. The difference in weight per mole of gas exchange (22.4 liters) is the change in molecular weight (44-32), or twelve grams per mole. From test data, it was determined that 108 liters of oxygen were used. Therefore, the total weight loss resulting from the difference between the O_2 used and the CO_2 eliminated is calculated from the relationship:

$$12 \frac{\text{grams}}{\text{mole}} \times \frac{108 \text{ liters}}{22.4 \text{ liters/mole}} \begin{array}{l} = 58 \text{ grams} \\ = 0.127 \text{ lb.} \end{array}$$

The weight lost by evaporation of water from the cooling system boilers is calculated below:

Weight of Spandex garment and boilers before test	17.70 lb.
Weight of Spandex garment and boilers after test	16.92 lb.
Weight lost by evaporation of water from boilers	0.78 lb.

FIGURE 13 LABORATORY MODEL OF CONDUCTIVE COOLING SYSTEM SHOWING DUCTING OF WATER BOILERS TO MANIFOLD FOR DEMONSTRATION TEST

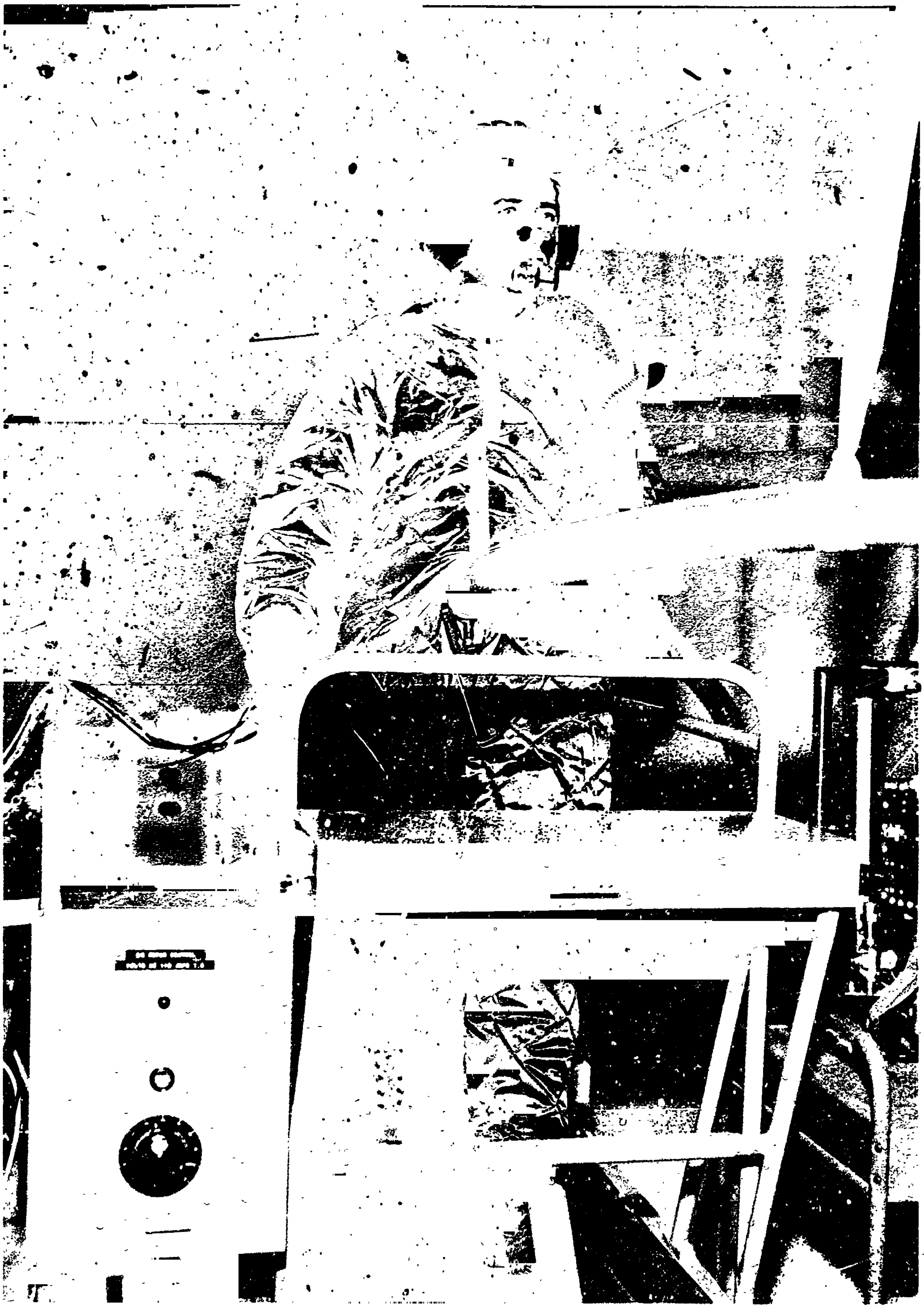


FIGURE 1. VIEW OF SUBJECT PERFORMING DEMONSTRATION TEST OF CONDUCTIVE COOLING SYSTEM

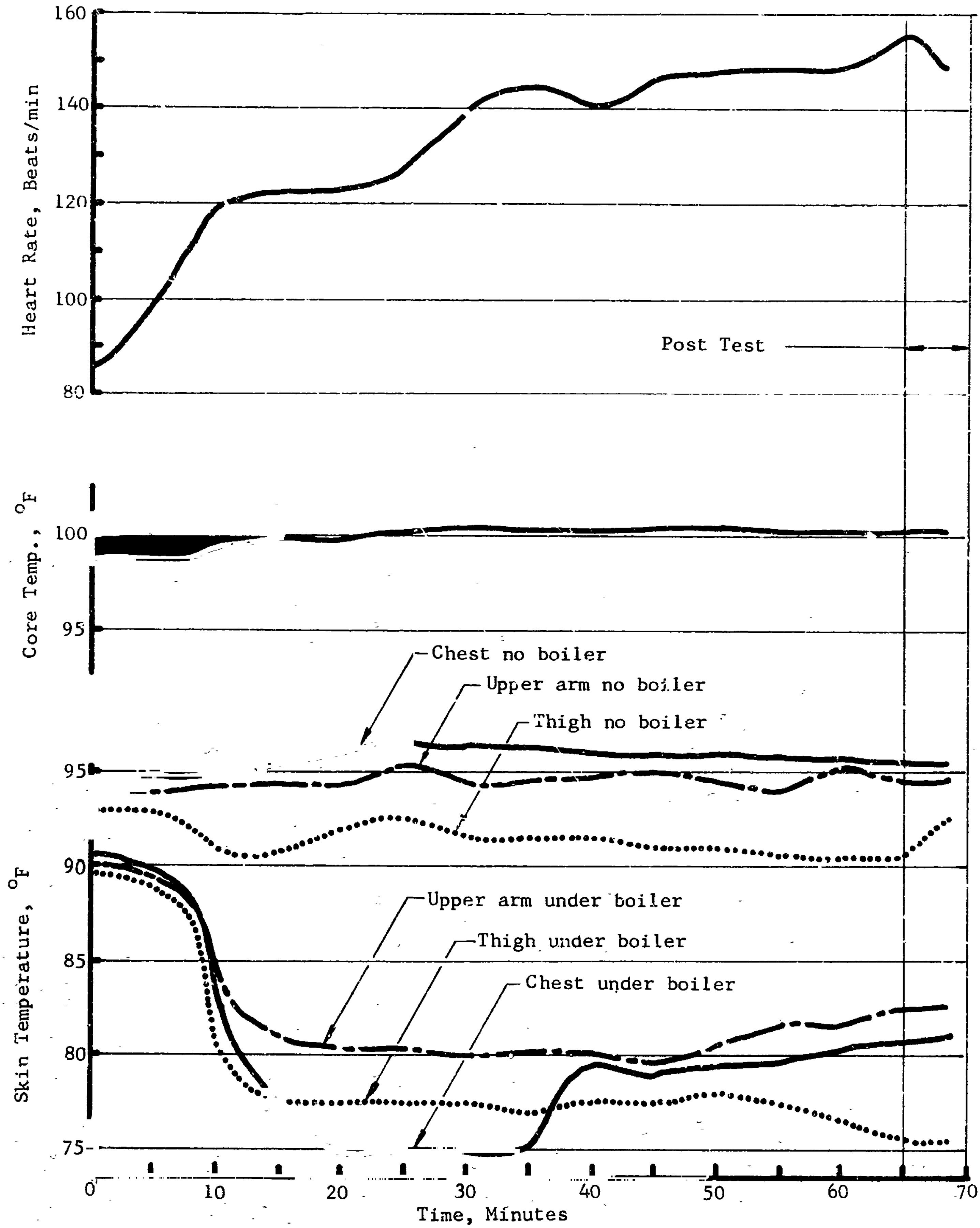


FIGURE 15 DEMONSTRATION TEST (Metabolic Rate, 2162 Btu/hr)

The foregoing analysis assumes that the garment did not pick up any weight from sweat. This factor has been neglected here because the weight of the garment before the test was essentially unchanged from the previous day after a trial run, even though it had been placed on a table to allow evaporation overnight. However, if the garment did pick up some sweat, this would offset some of the water evaporated from the boilers, so actual evaporation from the boilers could have been greater than shown above.

At the pressure one-half inch of mercury which was maintained in the cooling system boilers during the test, the heat of vaporization of water is approximately 1060 Btu/lb. The total heat removed by the cooling system is calculated as follows:

0.78 lb x 1060 Btu/lb = 827 Btu removed by cooling system

The total body evaporative loss (from lungs and body surface) is then 2.01 lb - 0.127 lb - 0.78 lb = 1.103 lb.

Since evaporative cooling of the body is approximately 1080 Btu/lb of water, cooling by evaporation of 1.103 lb of water equals 1191 Btu. It is known that less cooling by evaporation was accomplished during the test because some sweat was not evaporated, remaining on the body after completion of the test.

Evaporation of water into air breathed is estimated as follows:

a - Water vapor content of air (from psychrometric data) = 0.0075 lb water/lb dry air

b - Total lung ventilation (from Mueller-Franz meter) was 3154 liters (111.4 cu ft) in 60 minutes

c - Exhaled air at 90°F saturated, has a specific volume of 14.6 cu ft/lb

d - Weight of air breathed = 111.4/14.6 = 7.64 lb

e - Water to saturate air (from 50% dew point to 95°F) = 0.037-0.008 = 0.029 lb/lb dry air

f - Water evaporated in lungs = 0.029 (7.64) = 0.222 lb.

The remainder of the weight loss may be attributed to sweating, and this amounted to 1.103 lb-0.222 lb = 0.881 lb. Sweat, when present, could evaporate freely from the exposed face and neck, and from the body via clothing. Though a relatively good thermal insulation, the clothing was porous enough to permit outward diffusion of water vapor, especially during exercise.

The total accountable heat removed is the sum of the total body evaporative loss, 1191 Btu, and the evaporative loss through the cooling system, 827 Btu, which is 2018 Btu.

Energy Balance. The subject's heat production, from the Mueller-Franz respiratory data was 2162 Btu. Evaporative cooling (both body and cooling system) was estimated above at a maximum of 2018 Btu, and probably was somewhat less. Other possible avenues of heat loss were convective cooling (warming of air coming in contact with the body), and heat storage in the body, which would show up as increased body temperature.

The body temperature (rectal) rose 0.8°F at most, during the first 30 minutes, and not more than an additional 0.2°F in the second 30 minutes of the test. Heat storage based on 0.83 as the specific heat of the body, and subject weight of 155 lb was therefore approximately 125 Btu. Deducting 125 Btu from the estimated heat production of 2162 Btu leaves 2037 Btu.

DISCUSSION OF TEST RESULTS

Cooling System Components. The differential pressure relief valve required no further attention after its initial adjustment, maintaining a stable, constant pressure of one-half inch of mercury in the cooling system throughout the test. This established the boiling temperature of the water in the boilers at approximately 60°F. There was no evidence of ice formation on any portion of the valve during the test.

With the proven conductance of this boiler configuration, the fact that the average skin temperature under the boilers was approximately 80°F after a steady state condition was achieved indicates poor contact existed between the boilers and the skin. Had ideal conditions existed during this test, in which constant skin contact was maintained with all the available contact surface of the boilers, the skin temperature under the boilers would have been approximately 70°F. It was the opinion of the test subject when interviewed immediately after the test that approximately 20 percent of the available boiler contact surface was lost from contact shortly after the test began and was not regained throughout the remainder of the test. He stated that the loss occurred in the forearms, the middle boilers on the thighs (particularly the lower halves), and the chest boilers in the lower back area, and that it was apparently due to sagging of the garment as the test progressed. This loss in contact area, coupled with intermittent contact resulting from the flexing of muscles at this high level of activity, can easily account for the reduced effectivity exhibited by the cooling system in this initial test.

Upon examination of the boilers after the test, it was found that several minute leaks had developed at points where they had rubbed against each other and abraded the outer covering. All the boiler covers were removed to check individual containers for sharp edges, and the boilers re-covered with heavier (0.013 inch thick) neoprene-nylon material to improve their durability in future tests. This added thickness will result in a reduction in the theoretical U value from 54 to approximately 41, making it necessary to operate at a slightly lower boiling temperature inside the boilers. Specifically, the reduction in U of approximately 24 percent requires an offsetting increase in ΔT of approximately 30 percent for equivalent operation. This means that to duplicate the demonstration test, it would be necessary to operate the cooling system with a water boiling temperature of 57°F instead of 60°F.

To improve skin contact of the boilers on the extremities, two-inch Spandex belts with Velcro fasteners were attached to the outside of the Spandex garment at the calves, the thighs, and the forearms. This will make it possible to "cinch up" these areas locally and possibly eliminate sagging during subsequent tests.

Physiology. The total accountable heat removed from the body was calculated, as shown in the results, as 2018 Btu for the one-hour test. The corrected heat production, as calculated from the respiratory data, was 2037 Btu, which is close agreement for these types of physiological measurements.

As shown in Figure 15, the heart rate rose from 85 at the start of the test to about 140 at the end of the first half hour. During the second half hour, it rose slowly and approached 150 at the end of the test. One reading of 156 at 65 minutes is not considered significant since another three minutes later was 148. From this, and also from the very slight change in core temperature after the usual initial rise, it can be concluded that the subject was not unduly stressed, and was in relatively good thermal balance. This was substantiated by the subject's statement made after the test that he experienced little discomfort, and actually felt refreshed until the last 10 or 15 minutes of the test.

V. CONCLUSIONS

Bench tests proved the feasibility of conductive cooling with pressure-controlled, wick-filled water boilers, using the water as the heat sink and the vacuum of space as the system actuator. The ease of controlling the internal temperature of a water boiler by pressure regulation with a relief valve designed specifically for this system, and its immediate response to pressure changes, are graphically illustrated in Figure 2.

The one-hour test with a human subject effectively demonstrated that the total concept is a practical method of cooling a man in a space environment, although it attained a lower efficiency than expected. The demonstration model lacked the necessary support or flexibility to maintain the intimate contact required between skin and boiler. Performance of the relief valve during the manned test was stable throughout the test, and no evidence of icing was apparent.

The cooling concept demonstrated in this feasibility study shows great potential for the development of an advanced cooling system for a space worker's garment. A garment with such a system, because of the system's simplicity, would be less costly to produce and maintain. Again, because of its simplicity, a higher reliability could be achieved over systems currently in use. The additional advantages in mass and bulk reduction present further evidence of the desirability in refining the concept to final design.

VI. RECOMMENDATIONS

Many design improvements became apparent, particularly during the development and testing phases of the laboratory model. Schedule requirements and funding restrictions of this limited feasibility study precluded taking advantage of these opportunities.

Additional development is required to improve contact, either through contouring or varying the sizes and shapes of the boilers, increasing their flexibility, and refining the method of holding them against the worker's body. The possibility of increasing durability, flexibility and conductivity by sealing of the individual containers instead of encapsulating the whole boiler also merits investigation.

Refinements such as the addition of a simple water-replenishment system, and provisions for maintaining different skin temperatures for different body areas should also be included in further efforts. The incorporation of adequate fail-safe features within the system would necessarily be a prime objective of the final design.

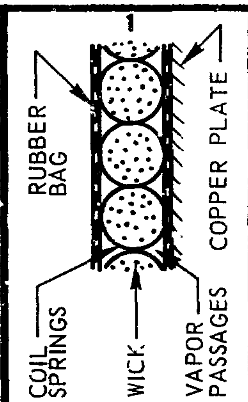
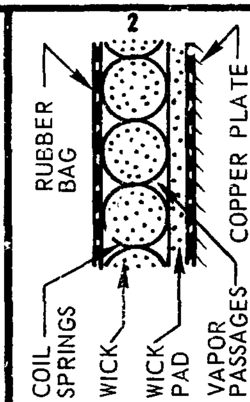
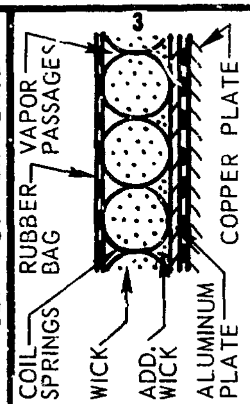
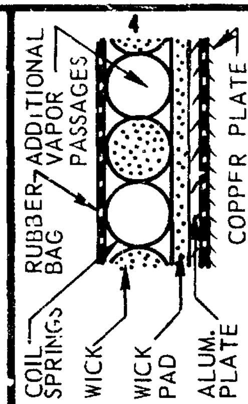
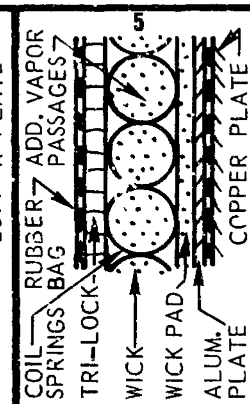
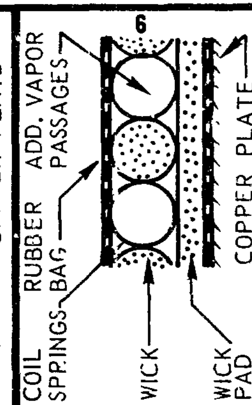
An integral part of such a development program would necessarily require a comprehensive test program in continuous support of the development effort.

VII. APPENDIX

TABLE I WICK MATERIALS TESTED FOR WATER STORAGE CAPABILITY

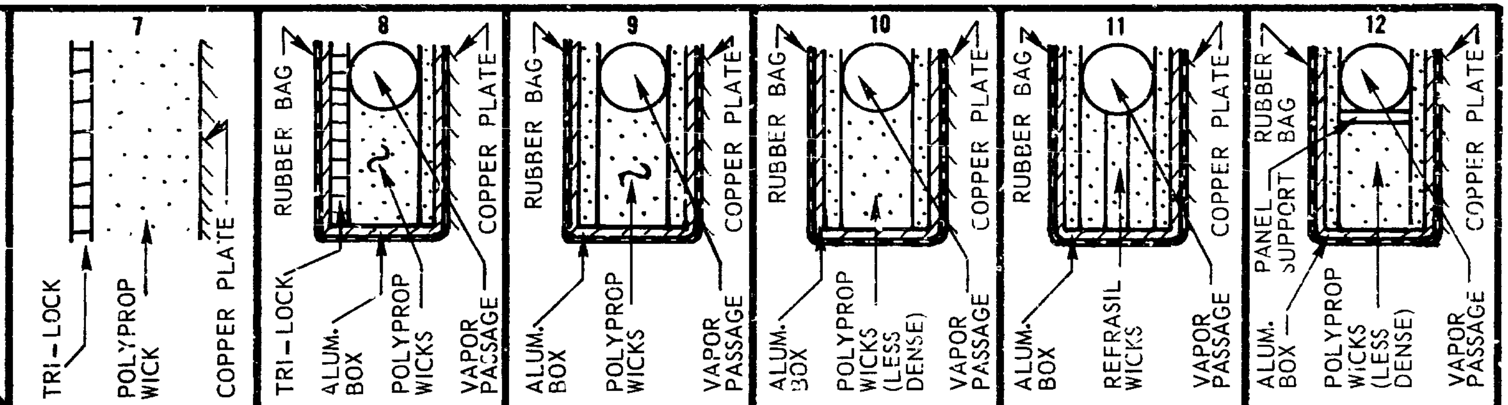
	Wick Description		As Received Condition				Soaked Condition In Distilled H_2O	
	Source	Designation	Cross-Section Dims. Cm.	Length Cm.	Weight Gms.	Density Gms/cm^3	Weight Gms.	Weight Increase %
1	Hitco, Gardena, Calif.	Refrasil series N 954 cm sleeving	1.143 x .102	25.40	2.360	0.800	3.930	66
2	" " "	Refrasil series N 635 cm sleeving	.762 x .114	25.40	1.550	0.702	2.690	74
3	" " "	Refrasil UB-100 batt	10.150 x .635	10.15	2.724	0.042	27.200	900
4	Atlas Asbestos N. Wales, Penna.	1.27 cm glassweb Tape style 2021	1.22 x .508	15.25	8.040	0.852	12.910	61
5	Taylor Instruments Rochester, New York	Cotton 97P15	.711 x .178	10.15	0.449	0.351	1.785	297
6	H. K. Porter Charlotte, N. Carolina	Asbestos #160 2.54 cm woven tape	2.540 x .159	12.70	4.786	0.933	10.477	120
7	American Felt Co. Glenville, Conn.	Data sheet #6 felt Mdse 51018	.953 x .635	7.62	1.094	0.237	5.853	436
8	" "	Dacron 62 DA11	1.270 x .635	16.50	0.885	0.066	7.408	736
9	" "	Polypropylene 62 PO38	1.270 x .635	16.80	2.383	0.[illegible]76	1[illegible].459	464
10	" "	Nylon 62 NY13	1.270 x .635	16.50	1.347	0.101	9.585	610
11	Western Felt Works Chicago, Illinois	Arnel 4.8 WAR-250-1	1.270 x .635	5.08	0.544	0.133	4.367	702
12	" "	Orlon 9.5 WO-130-1	1.590 x .476	5.08	0.496	0.128	[illegible].595	862
13	" "	Fortrel 6WF-250-1	1.270 x .635	5.08	0.604	0.148	4.522	648
14	" "	Rayon 8.6 WR-125-3	1.270 x .238	5.08	0.190	0.124	2.546	1240

TABLE II BOILER TESTS ON HUMAN ANALOG TEST FIXTURE (Spring Configuration)

CONFIGURATION / TEST CONDITIONS	1 			2 			3 			4 			5 			6 		
Heat Input BTU/Hr – Ft^2	Plate Temp °F	Water Boiling Temp °F	Result Calc U, BTU/hr ft^2 °F	Plate Temp °F	Water Boiling Temp °F	Result Calc U, BTU/hr ft^2 °F	Plate Temp °F	Water Boiling Temp °F	Result Calc U, BTU/hr ft^2 °F	Plate Temp °F	Water Boiling Temp °F	Result Calc U, BTU/hr ft^2 °F	Plate Temp °F	Water Boiling Temp °F	Result Calc U, BTU/hr ft^2 °F	Plate Temp °F	Water Boiling Temp °F	Result Calc U, BTU/hr ft^2 °F
103	99	85	7				89	85	25	89	85	25						
170	116	85	4				98	85	13							35 (1)	57	6
53				110	60	5							113	85	13			
366										118	35	11	100	73	13	117 (1)	57	6

(1) Very poor contact between boiler and copper plate. Numerous air gaps created by "bunching" of wick pad, creating a stucco surface contour under vacuum.

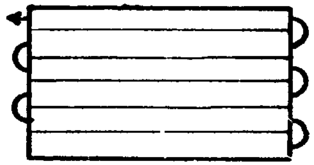
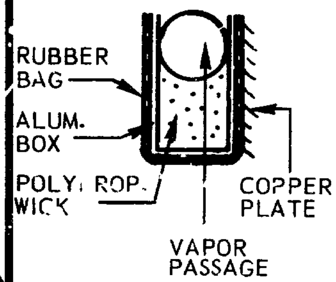
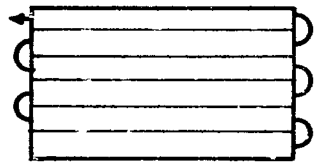
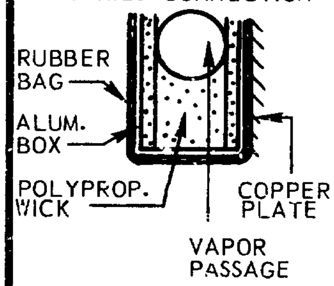
TABLE III BOX BOILER TESTS AND WICK TESTS IN WICK TEST CHAMBER



CONFIGURATION / TEST CONDITIONS	7			8			9			10			11			12		
Heat Input BTU/Hr – Ft²	Plate Temp °F	Water Boiling Temp °F	Result Calc U	Plate Temp °F	Water Boiling Temp °F	Result Calc U	Plate Temp °F	Water Boiling Temp °F	Result Calc U	Plate Temp °F	Water Boiling Temp °F	Result Calc U	Plate Temp °F	Water Boiling Temp °F	Result Calc U	Plate Temp °F	Water Boiling Temp °F	Result Calc U
425 (3)	89 80 78 80 70 80	85 74 73 75 65 75	106 71 85 85 85 85															
256				73 (1) 83 (1)	67 79	45 64	72 (1) 83 (1) 83 (2)	67 79 67	51 64 16	71 (1) 82 (1) 74 (1) 80 (1)	67 79 67 67	64 84 38 20	74 (1) 86 (1)	67 79	36 38	71 (2)	67	55
400							71 (1) 75 (2)	63 63	51 [illegible]	74 (2) 72 (1)	64 64	40 50	72 (1) 76 (2)	64 64	51 22	71 (2)	64	58

(1) Volume surrounding test boxes evacuated to 3.5 psia.
(2) Volume surrounding test boxes at ambient pressure.
(3) Volume surrounding test chamber evacuated to almost a complete vacuum.

TABLE IV BOILER TESTS ON HUMAN ANALOG TEST FIXTURE (Box Configuration)

CONFIGURATION / TEST CONDITIONS	13  6 ROWS – 11 BOXES/ROW SERIES CONNECTION 			14  6 ROWS – 11 BOXES/ROW SERIES CONNECTION 			15 SAME AS CONFIGURATION 14 EXCEPT SIDES OF BOXES RELIEVED TO BETTER CONFORM TO SURFACE OF HUMAN ANALOG TEST FIXTURE			16  6 ROWS – 11 BOXES/ROW PARALLEL CONNECTIONS SAME BOXES AS CONFIGURATION 15		
Heat Input BTU/Hr – Ft^2	Plate Temp °F	Water Boiling Temp °F	Result Calc U	Plate Temp °F	Water Boiling Temp °F	Result Calc U	Plate Temp °F	Water Boiling Temp °F	Result Calc U	Plate Temp °F	Water Boiling Temp °F	Result Calc U
253	79	67	21 (1)	79	67	21 (1)	75	67	32 (1)	70	64	42
415	83	64	22 (1)	90	64	16 (1)	79	64	28 (1)	73	64	46

NOTE: (1) Specimen was not adequately insulared. Some edge losses occured which makes data look optimistic. A quick check was made during Configuration 14 runs and indicated a U of 10. The test was continued with the lesser insulation to get comparative results of added wicking.