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VARIABLE THERMAL CONDUCTIVITY HEAT TRANSFER RESEARCH FOR PERSONAL PROTECTIVE ASSEMBLIES

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FOREWORD

The work reported was conducted by the Northrop Corporate Laboratories, Hawthorne, California, for the Aerospace Medical Research Laboratories, Wright-Patterson Air Force Base, Ohio 45433, in accordance with Contract AF 33(615)-5109, and in support of Project 7164, "Aerospace Protective Technology," and Task 716411, "Aerospace Pressure Outfits." Dr. C. F. Lombard was Program Manager for Northrop Corporate Laboratories. Mrs. Lee Rock, Altitude Protection Branch, Life Support Division, Biomedical Laboratory, succeeded Captain D. L. Haub, USAF, as contract monitor for the Aerospace Medical Research Laboratories. This study was accomplished between 1 June 1966 and 31 August 1967.

This technical report has been reviewed and is approved.

WAYNE H. McCANDLESS
Technical Director
Biomedical Laboratory
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ABSTRACT

A new concept in thermal control for a man in a space suit was investigated. Within the suit a variable thermal conductivity layer (pressure regulated) is placed between the heat source (human body) and the heat sink (sublimator). The two major components, a sublimator and a variable conductance layer were developed. However, the performance achieved was less than anticipated. In both cases material limitations resulted in inadequate performance. One sublimator performed satisfactorily, but the porous plate could not be duplicated. Heat removal rates up to 2100 Btu/hr ft^2 of plate surface were realized. The variable conductance layer did demonstrate a change in heat flux of approximately 3:1 but the available pressure (3.5 psi) was not sufficient to overcome contact resistance within the urethane foam. The results demonstrate the need for advances in technology and further development work to make this concept feasible.

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INTRODUCTION

The human body maintains a relatively stable temperature by transporting metabolic heat to the body surface where it is removed through radiation, conduction, convection, and evaporation. Naturally, external environmental conditions greatly influence the ratios and methods of heat transfer. When the body is enclosed within a full pressure suit, the amount of thermal transport by radiation, convection, and evaporation is limited by various practical factors. Thermal transport via conduction can be more readily accomplished with a circulating liquid, which transports the heat to an external heat sink. However, when the external heat sink is mounted in the most appropriate location, namely, on the back of the suited worker, bulk and mass problems are created that impose both operational and structural restrictions on the suit system. Therefore, it was deemed worthwhile to investigate a system that promises reduced size and mass while still rejecting the amount of heat required to maintain body temperature under various working conditions.

The amount of heat absorbed during the phase change of water as liquid to gas or water as ice to gas is considerable and several methods for mechanizing such a thermal control system for a full pressure suit appeared to be feasible. In principle, the system conducts the heat directly from the body surface to the heat sink, which can be either a boiler or a sublimator, depending upon the operating temperature (and construction). The internal boiler system has been investigated earlier by Olson (ref 1) and proven feasible, but the internal sublimator system appeared to offer a greater potential for control of heat transfer rate. By placing a variable thermal conductive layer between the surface of the body and the sublimator and by providing a method by which the surface temperature of the body controlled the thermal conduction to the sublimator, it should be possible to control the heat flux from the body to the vacuum of space. Using the heat lost through the phase change of water as ice or water to gas, a pressure regulator on the variable thermal conduction layer should control the heat transfer rate.

This study investigated the feasibility of using a pressure-regulated thermal conductivity layer between the heat source (man) and the heat sink (sublimator). The study was divided into two phases. Phase I involved study of a sublimator conductive cooling unit, which consisted of a porous plate sublimator with a bladder providing water on one of its surfaces with the low pressure vapor channel on the opposite side. Analyses and tests were conducted to obtain good sublimator plates and to measure quantitatively the thermal transfer in the temperature range pertinent to the body temperature control. Phase II centered on study of a pressure regulated thermal conduction layer. This layer consisted of an elastic plastic open cell foam in a flat plastic bag vented through a variable control valve to a vacuum. The bag matched the sublimator unit in size and was located between the sublimator and the heat source. Tests were conducted to measure the amount of thermal transport and its variation as the bag was compressed at various pressure levels within the range of 0 to 7.0 psi established by the spacesuit environment.

SECTION II

PHYSIOLOGICAL AND PHYSICAL CONSIDERATIONS

In order to establish the potential value of an advanced system to cool a man in a space suit using conduction as the principal avenue of heat transfer from the man to the heat sink, both physiological and physical principles were considered. The physiological mechanisms that modify the heat flux channels to maintain the internal body temperature within the range set by the thermoregulation centers in the hypothalamus may or may not properly adjust to a rapid change in heat transfer capacity of conductive cooling. Therefore, the mechanical design used in a conductive cooling system should permit adjustment of the transfer rate and of rates of change of heat transfer. The system developed should be optimal in terms of weight, volume, power requirements, reliability, ease of maintenance, fail-safe factors, comfort, ease of control, and be applicable to either hard or soft space suits in the pressurized or unpressurized condition.

PHYSIOLOGICAL CONSIDERATIONS

Man is capable of maintaining a relatively constant temperature in spite of wide variations in surrounding environmental temperatures. Man's core temperature refers to the temperature of tissues lying deep within the abdomen, thorax, and head, and varies from that of the superficial tissues, such as the skin and muscles of the limbs. The core temperature is controlled by thermoregulation centers in the hypothalamus and varies generally from 97° F while resting to 104° F during exercise. To remain within these limits, a balance is maintained between the heat production and heat loss mechanisms of the body. Heat production resulting from metabolic activities and exercise is lost by radiation, conduction, convection, and evaporation. The skin plays a major role in maintaining this balance and acts as a heat exchanger between the deep tissues of the body and the external environment.

Comfort during rest is usually associated with a skin temperature at approximately 84° F but during exercise comfort will be dependent upon the heat loss which is favored by a lowered skin temperature. Thus, skin temperatures need to be lowered by the conductive heat sink in proportion to the heat produced by exercise. After exercise ceases, the temperature gradient should be decreased as the body heat production is decreased; however, the gradient should permit depletion and return of the total body temperature to normal.

The concept under consideration involves heat transfer from the skin by direct conductance to a heat sink within a suit. This application is similar to that found with men in an aquatic environment. Therefore, examination of thermal data acquired from aquatic sports is useful.

Buskirk (ref 2) notes that for the short 50-yard dash, water temperatures between 84-94° F are best while for an endurance swim, water temperatures between 74-79° F are desirable. This shows the need for maintenance of optimal internal temperature by rapid warm up for the "dash" and the need for greater heat loss during endurance or lengthy exercising to prevent excessive rise of the core temperature above 104° F.

Contract requirements dictate a variable heat removal rate of 300 to 2500 Btu/hr. The average skin temperatures needed to maintain body thermal equilibrium within this metabolic range are 95° F and 75° F respectively.

PHYSICAL CONSIDERATIONS

The overall objective of this program was the development of an advanced thermal control system for a space suit. The system performance requirements as established by the contract were:

(a) Heat rejection ------- variable from 300-2500 Btu/hr
(b) Mission length ------- 4 hours
(c) Mission profile ------ 100-300 nautical mile earth orbit
(d) Minimum body area coverage by the system

Furthermore, the system was to consist of two major elements, a heat sink and a heat transfer control. These elements were identified as sublimator and variable thermal conductivity units, respectively.

Early in the program, analysis of the requirements permitted establishment of the interface conditions between man and system and system and external environment. As previously discussed under physiological considerations, the desired average skin temperature range is 75° to 95° F. These values are average and the desired temperatures may vary somewhat with the body area coverage. Few data exist on the amount of heat that may be removed from localized areas of the body or the resulting skin temperatures. Therefore, the established system design requirement called for the removal of 300 Btu/hr with a resultant skin temperature of 95° F, and 2500 Btu/hr at a skin temperature of 75° F. We anticipated that actual use test of the system would result in some adjustment of the required skin temperatures.

The conditions extant on the other side of the system were more readily established. Since the system utilizes a sublimator exposed to the vacuum of space, the operating temperature was assumed to be approximately 32° F. These values permitted establishment of the available gradients for heat transfer, namely 63° F for a 300 Btu/hr and 43° F for transfer of 2500 Btu/hr. Thus, the heat transfer control must be capable of adjusting to heat fluxes of 300 to 2500 Btu/hr with a variation in resulting skin temperatures of 20° F.

Other considerations which cannot be overlooked include: the thickness of the total system (must be contained between the space suit and occupant), compatibility with the environment (those portions exposed to vacuum must not undergo degradation, those in contact with the man must be nontoxic and stable in the presence of body excretions-perspiration), weight (must be as light as possible consistent with function), and utilize man's thermoregulatory mechanism to the greatest extent possible.

With these considerations established, the development of the two major components was initiated. The sublimator was undertaken first since the variable conductance unit was dependent on the available heat sink temperature at the interface of the two units.

SECTION III

SUBLIMATOR DEVELOPMENT

The development of sublimators has been in progress by various organizations for a period of several years (ref 3). Work to date has centered on units to be installed in spacecraft in which the heat is transported to the unit via a transport media, i.e., air, water, glycol, etc. This unit, on the other hand, receives the heat to be rejected by direct conduction from the heat producing mechanism with venting of the water vapor to the vacuum through ducts. Thus, the problems of ice formation on the outside of the sublimator plate and intermittent ejection of ice particles can present potential failure modes due to plugging of ducts and subsequent loss of vacuum, rather than a small loss in efficiency experienced in other systems. Therefore, some positive means must be incorporated to preclude this malfunction. After exploration of several avenues, the most reliable method of control was the use of sublimator plates having water breakthrough pressures greater than the operating pressure; this permitted only water vapor to be expelled through the plate. A second possible choice, which was not extensively investigated because of increased complexity, was an approach wherein the system was exposed to the total vacuum and then water would be admitted and the pressure gradually increased to operating pressure. This would require the suited man to enter the space lock, reduce to ambient, and then admit water to the system in a controlled manner.

BREADBOARD SUBLIMATOR UNIT DESIGN

A breadboard model of the sublimator unit (figure 1) was developed and consisted of a flexible Neoprene bladder (figure 2) approximately 3.75 inch in diameter, and 0.5 inch in height bonded to a stainless steel flange. The flange also served to mount the porous sublimator plate and connect the vapor channel. A water-fill port of 0.25 inch diameter was located on the bladder. A stainless steel vapor channel designed to fit over the flange and a glass fiber reinforced epoxy transition coupling were provided to connect the vapor channel to a wire reinforced Neoprene exhaust tube. The breadboard model was developed primarily for laboratory testing but was designed to fit inside a space suit and be flexible enough to contour to the wearer's body.

POROUS SUBLIMATOR PLATE SELECTION

An intensive survey of possible porous plates for use in this application was accomplished. The materials studied included stainless steel nickel, copper, bronze, monel, ceramics, and various polymers. Those materials that possessed the desired characteristics of strength, porosity, pore size, and vacuum stability were cut into sublimator-plate samples and tested. A discussion of the apparatus used for testing, the test procedure, and the results are presented in the following paragraphs.

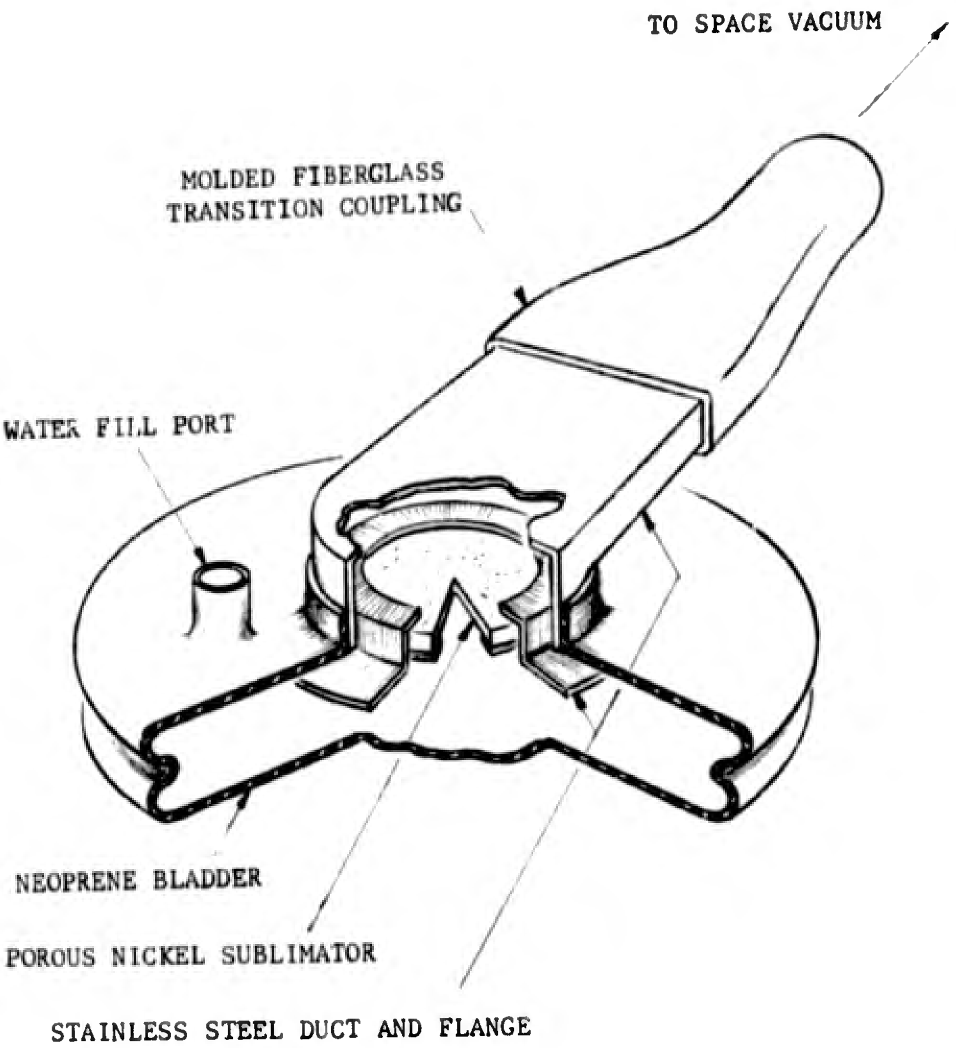

FIGURE 1 VAPOR CHANNEL, POROUS PLATE SUBLIMATOR, AND WATER BLADDER ASSEMBLY

FIGURE 2 BLADDER AND SUBLIMATOR PLATE

Apparatus

Test Fixture

The test fixture, as shown in figures 3 and 4 consisted of a 5-inch-diameter Plexiglas cylinder divided into two separate chambers by a Plexiglas divider containing a circular opening with provisions for mounting a 1.5-inch-diameter porous plate specimen. The lower chamber served as a water reservoir. Distilled water was supplied through a port in the side of the cylinder. The floor of the lower chamber consisted of a copper plate with a heating element bonded to its lower surface. Three thermocouples were located in the lower chamber. One was imbedded in the copper plate, the second centrally located in the chamber to sense the water temperature, and the third held in contact with the bottom surface of the porous plate being tested.

A space containing glass-fiber insulation was provided below the heating element to help reduce heat losses. Electrical leads from the power supply passed through ports in the side of the cylinder, and connected to the heating element binding posts.

During tests the upper chamber was evacuated to provide a simulated space vacuum for testing the porous plates. The top plate of the chamber which was provided with a vacuum port was clamped to the cylinder and sealed with an O-ring.

Laboratory Test Setup

The test fixture and associated equipment are shown diagramatically in figure 5. The test fixture rested on a vacuum plate which had ports for vacuum lines, water supply, and electrical and thermocouple leads. Located beside the test fixture was an open flask which was slightly elevated to provide gravity feed to the chamber in the test fixture. A line containing a shutoff valve connected the flask to the test fixture. The vacuum port in the top of the test fixture was connected to a vacuum console with a liquid nitrogen cold trap located between the vacuum console and the test fixture to prevent water from entering the vacuum pump. The vacuum console was equipped with instrumentation to measure pressures to 10^{-6} microns. A mercury manometer was utilized to measure gross pressures. A bell jar was utilized to enclose the test fixture and open flask on the vacuum plate. Pressure within the bell jar was controlled by a separate system consisting of two vacuum pumps manifolded with a bleed valve and equipped with a mercury manometer. A multichannel brown recorder connected to the thermocouples monitored and displayed the temperatures. The electrical input to the test fixture heating element was controlled by a variac and measured by a voltmeter and milliameter.

Test Procedure

Preparation of the porous plate for testing consisted of cutting the material to a 1.5-inch-diameter disc and cleaning with ethyl alcohol. The

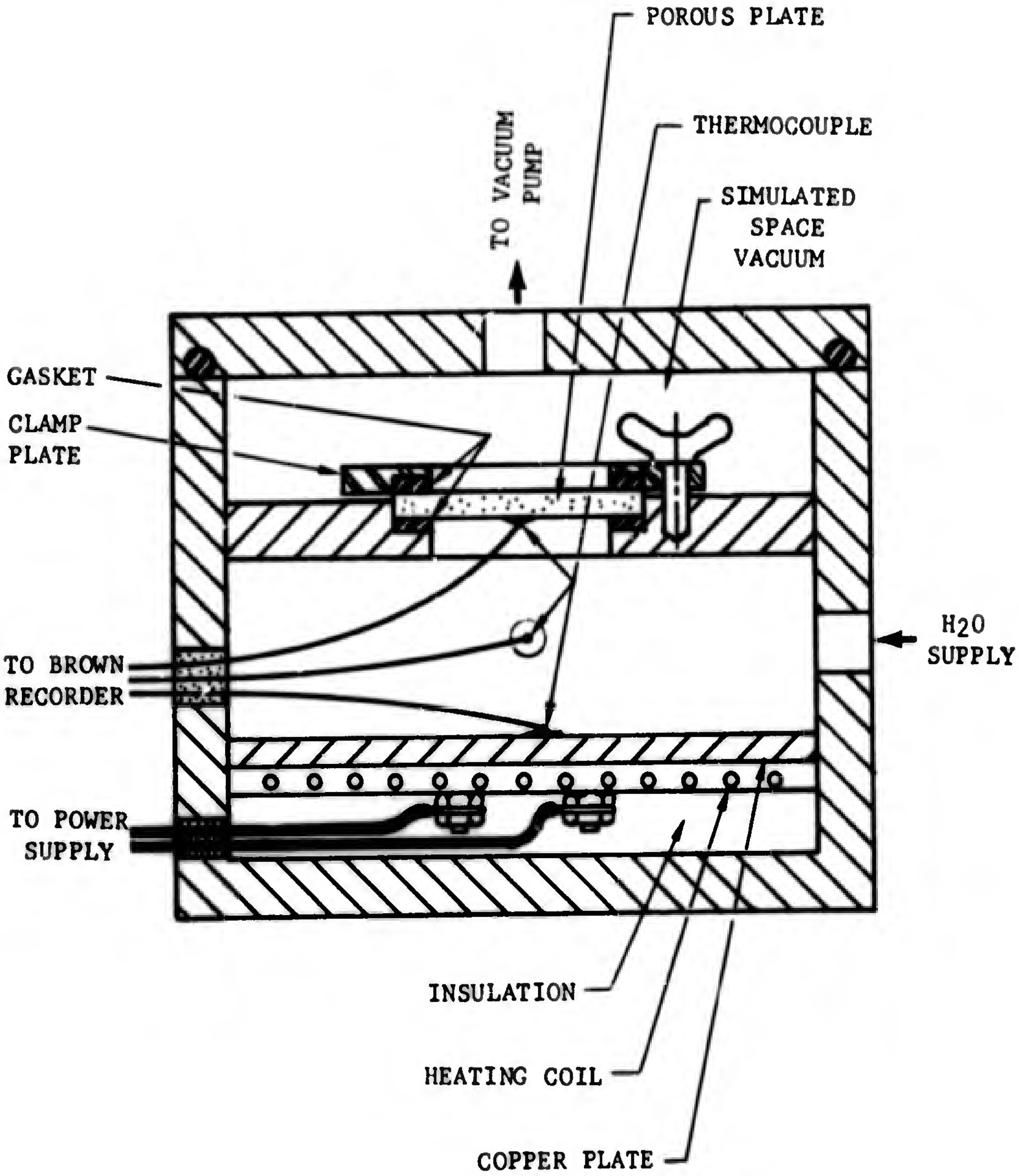

FIGURE 3 POROUS PLATE SUBLIMATOR TEST FIXTURE

FIGURE 4 TEST FIXTURE

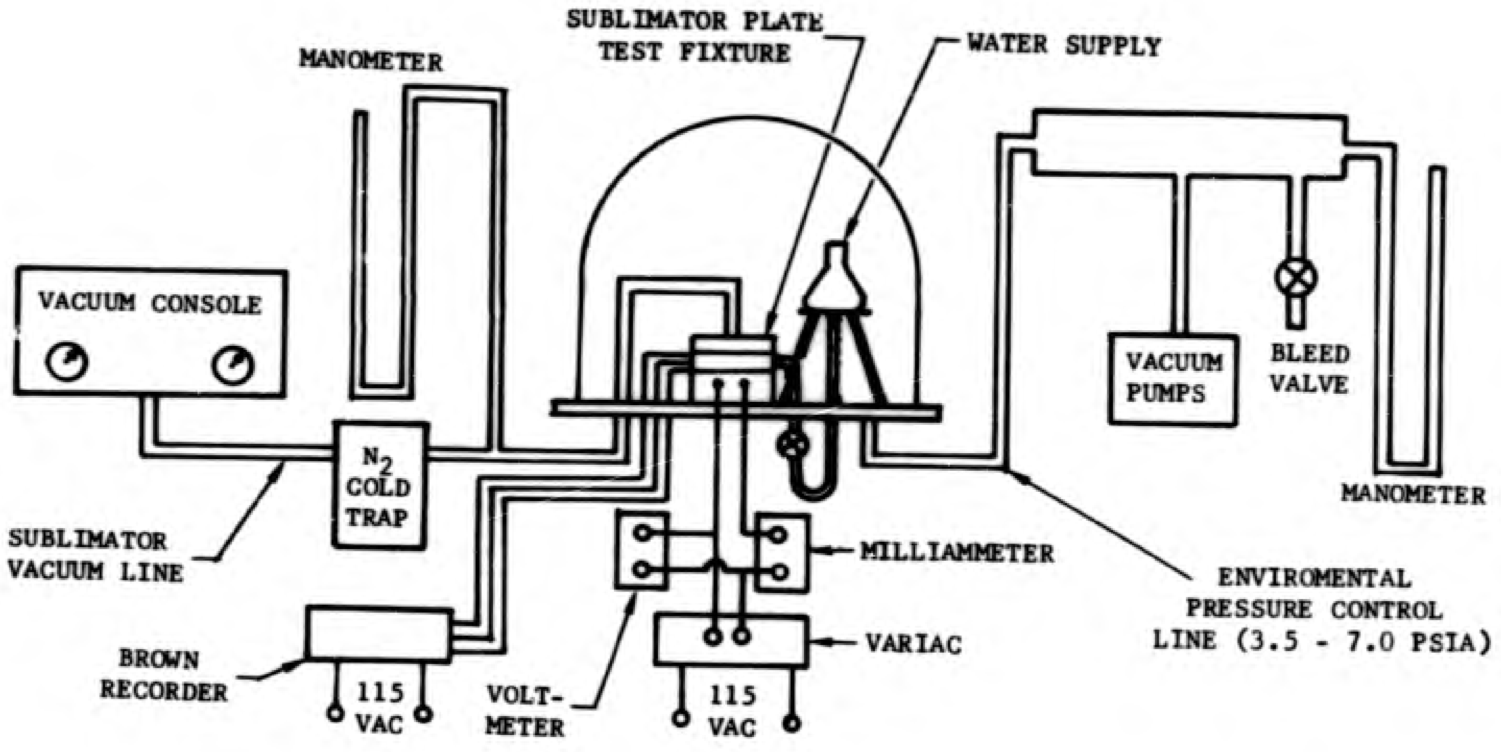

FIGURE 5 LABORATORY APPARATUS FOR TESTING POROUS SUBLIMATOR PLATES

porous plate was clamped into the recessed opening between the chambers of the test fixture with a gasketed flange held by three wing nuts. The top plate of the test fixture was installed and secured with a clamping device as shown in figure 6. Water from the flask was then allowed to flow into the lower chamber of the test fixture until the water level reached the porous plate. The bell jar was then positioned on the vacuum plate. The vacuum console for the test fixture and the vacuum system for the bell jar were then activated simultaneously and the pressures reduced at equal rates until the pressure in the bell jar reached and was stabilized at 3.5 psi or 7.0 psi, depending on test requirements. The temperature monitoring devices were activated to monitor temperature changes. The full vacuum capacity of the console was then applied to the upper chamber of the test fixture, creating a simulated space vacuum at the surface of the porous plate. Simultaneously the water shutoff valve was released, allowing the pressure exerted on the exposed water surface in the flask to be transmitted to the water in the lower chamber of the test fixture. Thus, the conditions in the lower chamber simulated the expected conditions in a water-filled bladder in a space suit. During this time, the surface of the porous plate was kept under constant surveillance. If excessive icing or slugging (i.e., combined ice and water flow) occurred, the porous plate was unacceptable and the test terminated. If little or no icing occurred, the test was continued and the temperatures recorded at five minute intervals to determine cooling effectiveness. The heater was activated and the thermal load gradually increased to determine maximum cooling capacity within the anticipated temperature operating range. The porous plates showing promise were identified for later testing to establish water breakthrough pressures, i.e., the pressure differential at which water begins to flow through porous plates.

To establish the water breakthrough pressure, the porous plate was mounted in the test fixture and the top of the upper chamber secured. The water shutoff valve was released and the vacuum console activated, gradually reducing the pressure in the upper chamber until water breakthrough occurred. During this test, the bell jar was not used and the pressure exerted on the water surface in the flask was the ambient air pressure.

Results

Tests were conducted using sublimator plate samples of various materials with average pore sizes in the 2.0 to 5.0 micron range. Water flow through the plates occurred at low differential pressures during these tests. Therefore, sintered-nickel porous plates having water breakthrough pressures greater than 7.0 psi were ordered. When received and tested, the water breakthrough pressures varied in supposedly identical parts from 1.5 psi to 11 psi with no effective cooling. This was apparently caused by extremely low porosity. Thereafter, numerous porous plates of sintered nickel and stainless steel with average pore sizes ranging from 0.5 to 5.0 microns were tested and found unacceptable. Nylon and Teflon filters sandwiched between porous metal plates were also tested. In

FIGURE 6   TEST FIXTURE SET-UP

these tests, either the water breakthrough pressures were too low or, in cases where it was acceptable, the cooling effect was inadequate. A porous sintered-nickel sheet was received from Union Carbide's Stellite Division which had a nominal pore size rating of 1.8 microns. A 1.5-inch-diameter disc was cut from this sheet and tested with excellent results. Water breakthrough occurred at approximately 7.0 psi and very effective cooling was demonstrated. Performance curves for this plate are shown in figures 7 and 8. Additional plates were cut from the same sheet and tested, but all permitted water flow at much lower pressures (0.1 psi to 2.0 psi). To increase their water breakthrough pressures, some of these plates were cold worked with a hydraulic press to reduce their pore sizes. Testing of these plates revealed increased water breakthrough pressures but a corresponding reduction in porosity as demonstrated by essentially complete loss of effective cooling.

BREADBOARD SUBLIMATOR UNIT TESTING

The one successful sublimator plate was mounted into the breadboard sublimator unit and tested to determine unit performance. Apparatus, test procedure, and results of these tests are presented in the following paragraphs.

Apparatus

The apparatus used in testing the breadboard model, as shown in figure 9, was similar to that described on page 9 with two exceptions. In place of the test fixture, an electrically heated 4-inch diameter copper plate was utilized. This plate was used to simulate a portion of the body surface of a man. A thermocouple was embedded in the plate to sense its temperature. No water flask was used during these tests because the capacity of the water bladder was adequate.

Test Procedure

Preparation of the breadboard model for testing included cleaning the porous plate sublimator and water bladder assembly with ethyl alcohol, then adding approximately 200 cc of distilled water to the bladder and clamping off the water-fill port. It was then placed on the copper heater plate and the vapor channel mounted on the flange and connected to the vacuum line from the vacuum console. The bell jar was installed and the temperature monitoring system turned on. From this point on, the procedure was similar to that described on page 13 in that the porous plate sublimator was exposed to a simulated space vacuum and the water bladder was in a simulated spacesuit pressure environment of 3.5 psia or 7.0 psia. The stainless steel vapor channel was used in a few tests, but in most cases a Plexiglas vapor duct shown in figure 10 was used to permit continuous observations of the surface of the porous plate.

In initial tests the heat load was changed periodically while observations were made of the surface condition of the porous plate

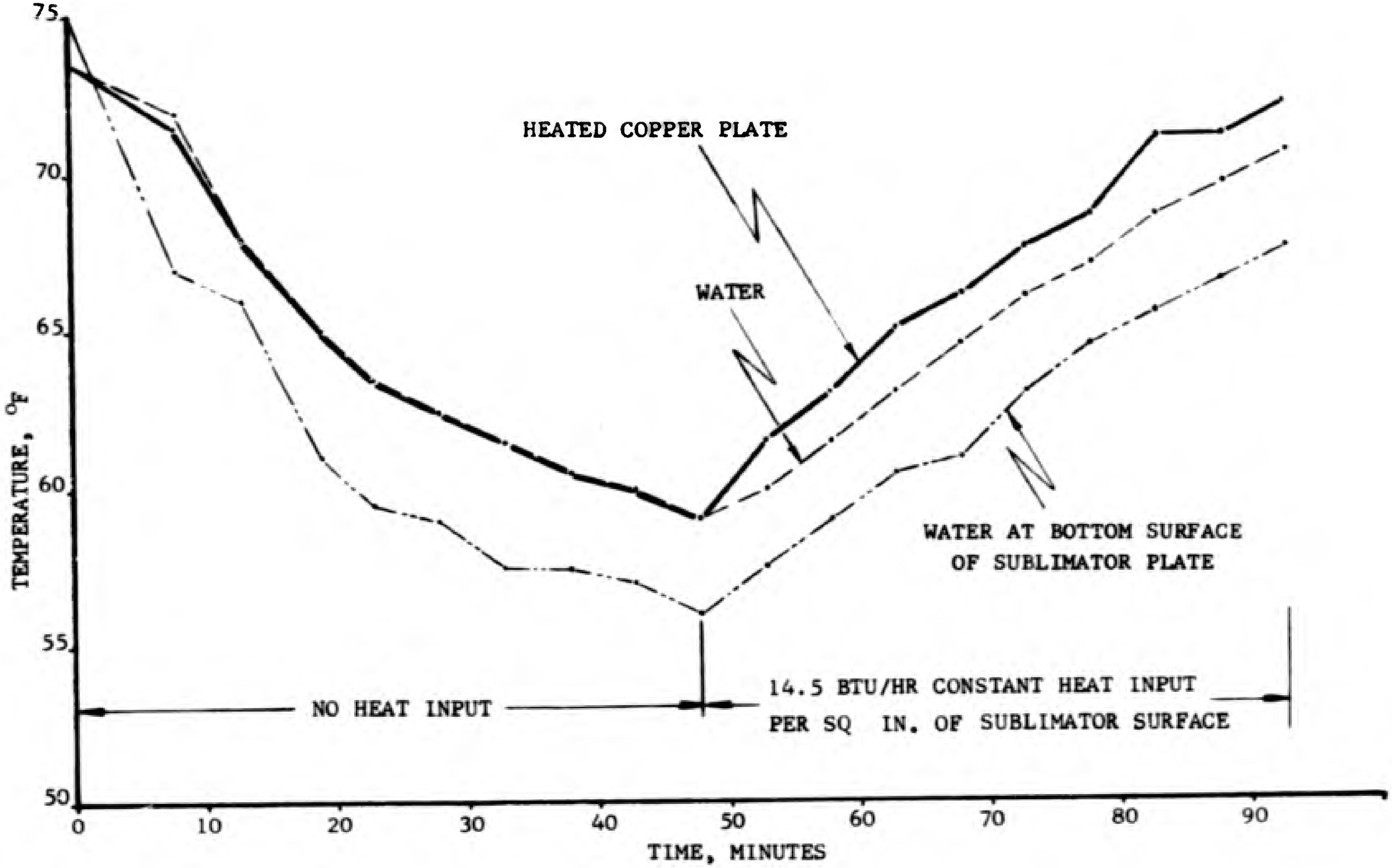

FIGURE 7 TEST OF SUBLIMATOR PLATE (3.5 PSI ENVIRONMENT)

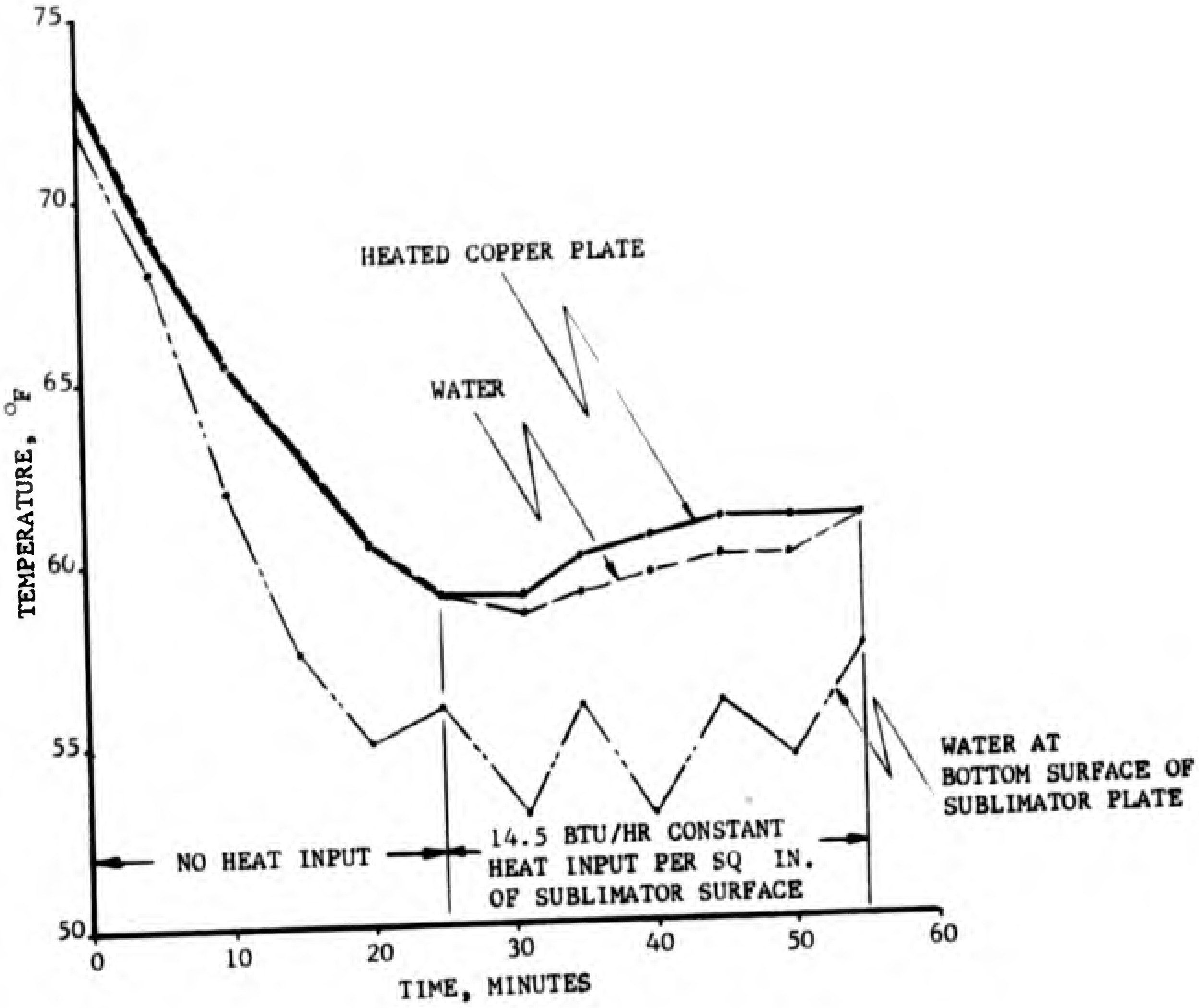

FIGURE 8 TEST OF SUBLIMATOR PLATE (7 PSI ENVIRONMENT)

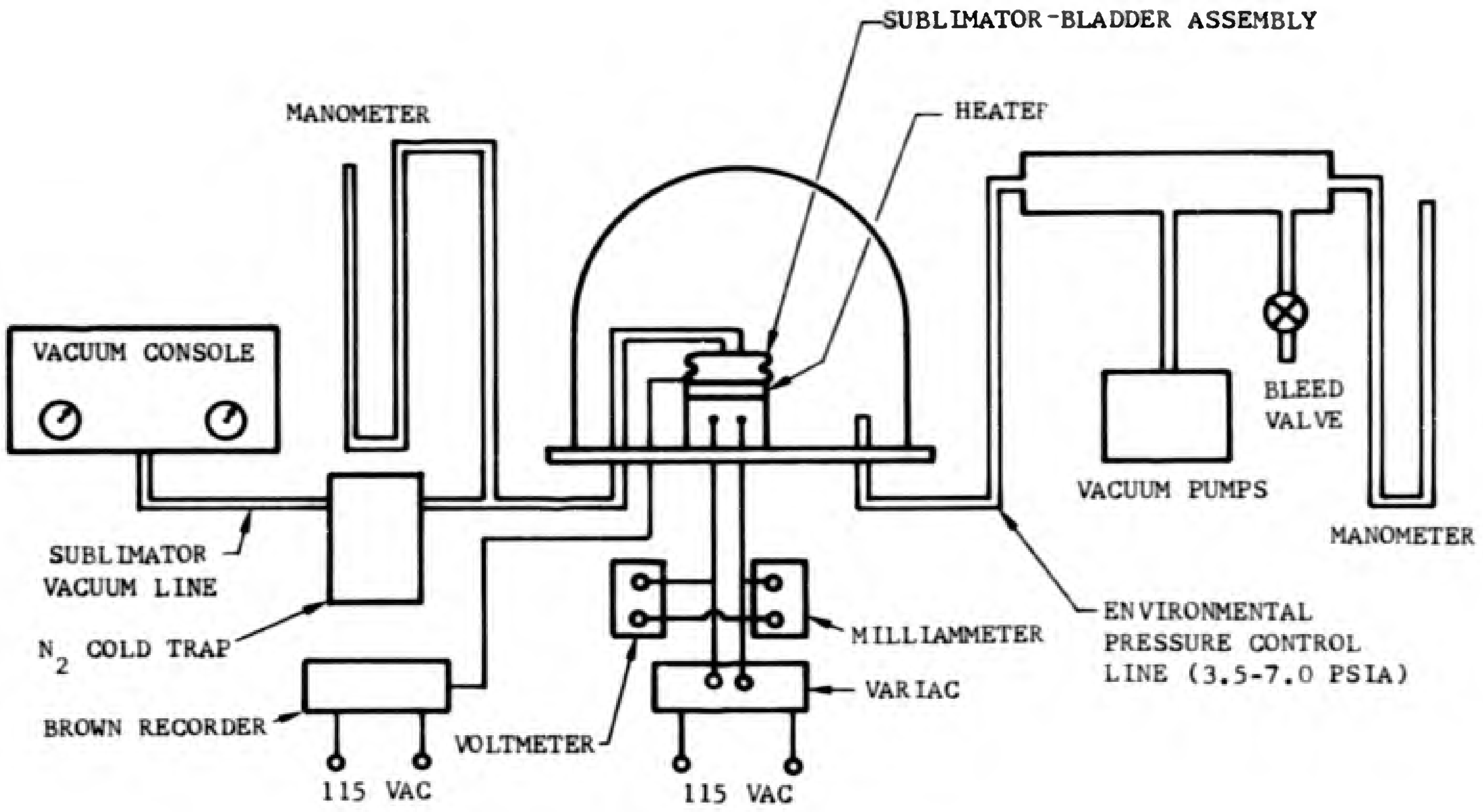

FIGURE 9 LABORATORY APPARATUS FOR TESTING SUBLIMATOR-BLADDER ASSEMBLY

FIGURE 10 TEST SET-UP USING PLEXIGLAS VAPOR DUCT

sublimator and of the temperature changes of the copper plate. Tests were then conducted to determine the cooling capability of the porous plate sublimator and water bladder assembly using a fixed heat input. Throughout each test, the bell jar was covered by a glass fiber and aluminized Mylar hood to minimize radiative transfer.

Results

The performance of the breadboard model using the Plexiglas vapor channel is presented in figures 11, 12, and 13,using the stainless steel duct in figure 14. Test 3 described in figure 11 was conducted to show response of the sublimator assembly to changes in heat loads under the applicable environmental pressures. Test results shown in figures 12, 13, and 14 demonstrate ability of the cooling unit to maintain a given plate temperature with a constant heat input. For comparative purposes an additional curve shows the time rate of change of plate temperature with the sublimator inoperative under otherwise identical conditions.

EFFECT OF REDUCED PRESSURE ON POROUS PLATE SUBLIMATOR PERFORMANCE

Current fabrication techniques did not permit duplication of the porous plate used in the one successful cooling unit. Therefore, the effort was redirected to investigate the effect of reduced pressure on the performance of commercially available porous plates used as sublimators as this appeared to offer a possible solution to acceptable sublimator performance. Tests were conducted at reduced pressures ranging between 0.5 and 3.5 psi on several test specimens. A modified cooling unit utilizing a rigid bladder (figure 15) was then developed and tested to verify performance.

Apparatus and Test Procedure

The apparatus used in testing the porous plates was the same as that described on page 9. The test procedure followed was essentially the same as previously described on page 9, with the exception of the bell-jar pressure. Each porous plate was tested for 2 hours with a constant heat input and bell-jar pressure. The bell-jar pressures were increased in 0.5 psi increments within the range of 0.5 psi to 3.5 psi or until unsatisfactory performance was observed. At 15-minute intervals throughout each test the temperatures were recorded. Between tests, the heater plate was allowed to cool to approximately 65° F. Cleaning of each porous plate with ethyl alcohol was performed before and after each series of tests.

Results

After a review of the many porous plates tested and evaluated during Phase I, two porous plates of sintered nickel and one of stainless steel were selected for this test series. They had water breakthrough pressures of less than 1.0 psi and were representative of commercially available

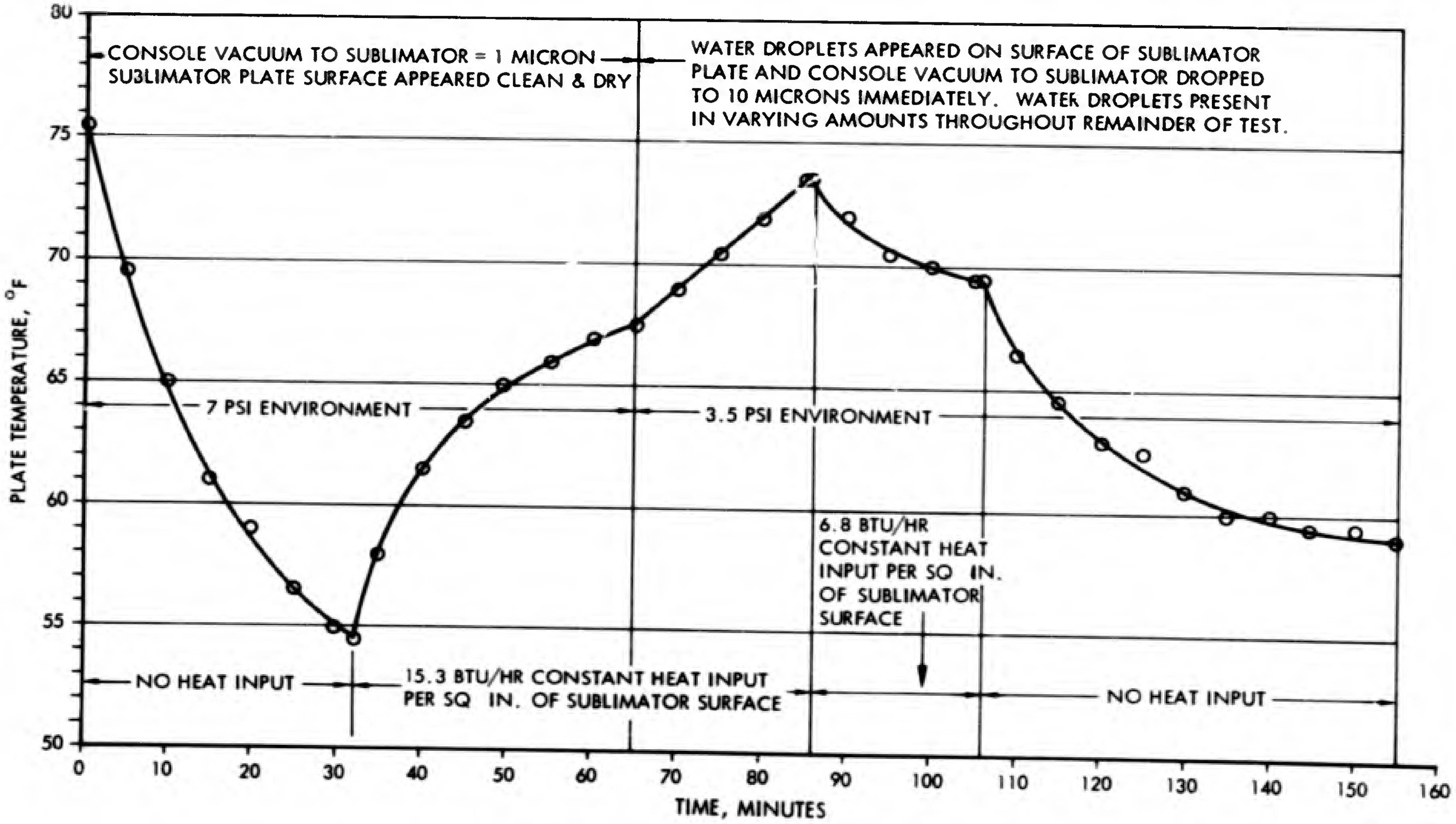

FIGURE 11 SUBLIMATOR MODEL TEST 3

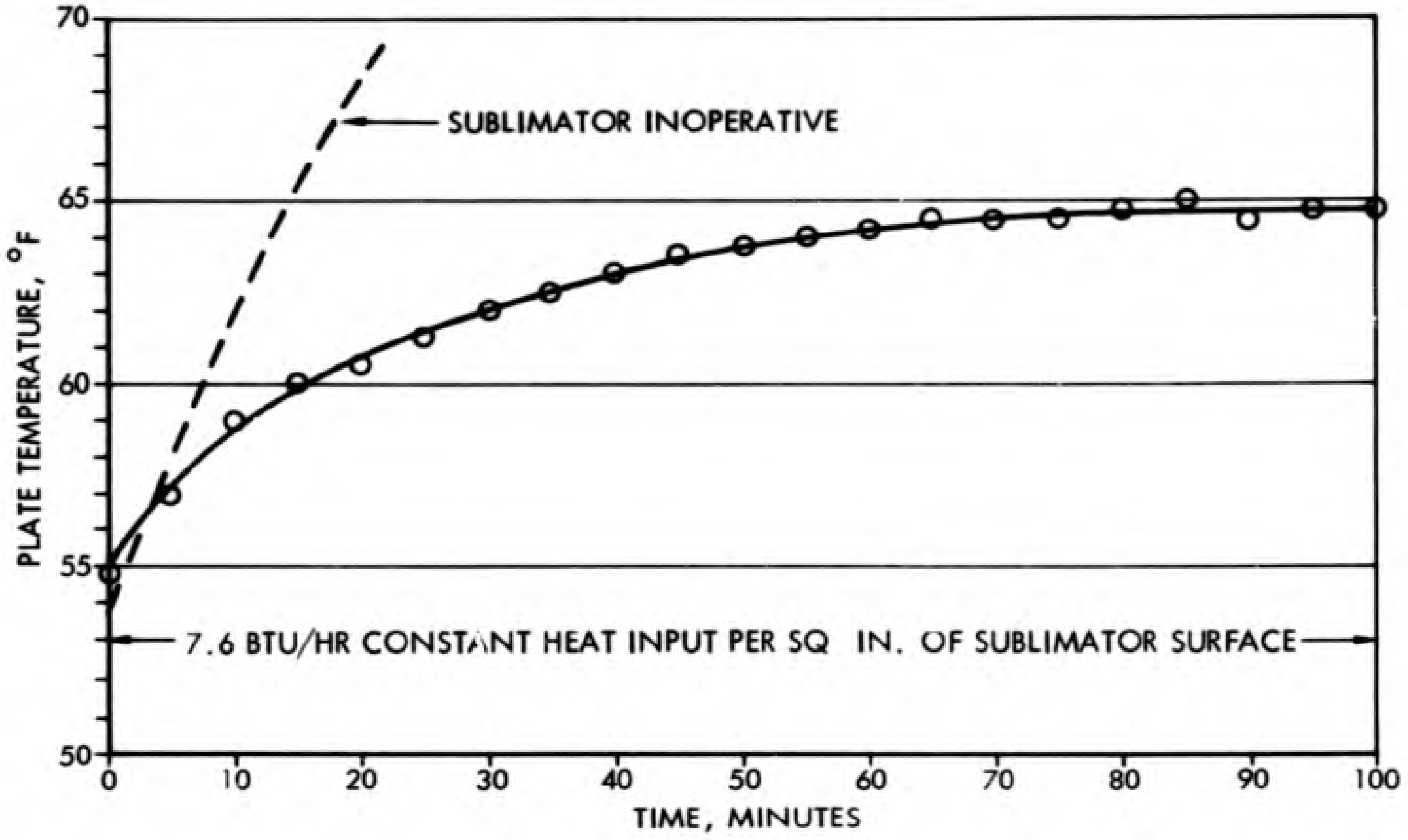

FIGURE 12 SUBLIMATOR MODEL TEST 7 (3.5 PSI ENVIRONMENT)

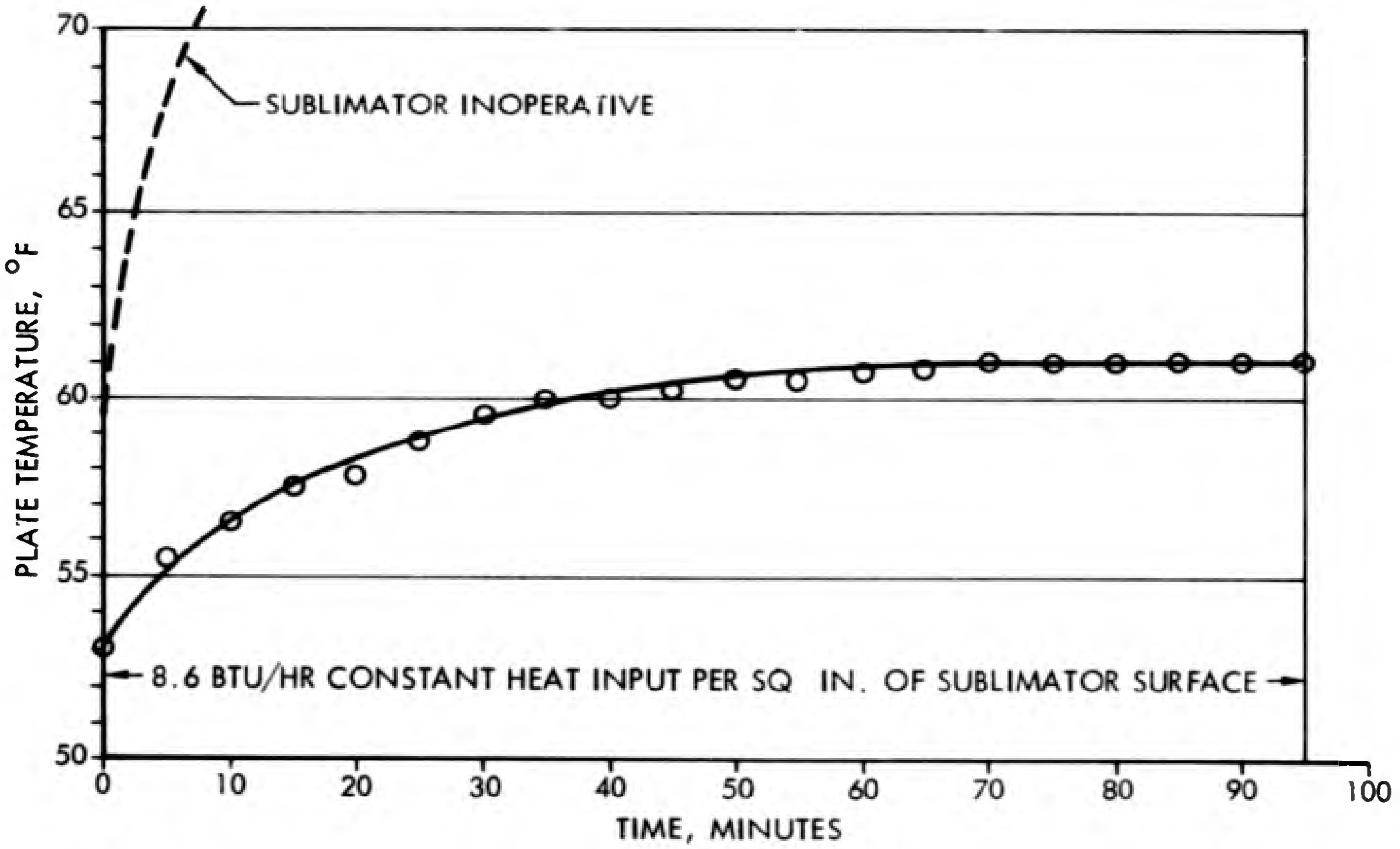

FIGURE 13 SUBLIMATOR MODEL TEST 8 (7 PSI ENVIRONMENT)

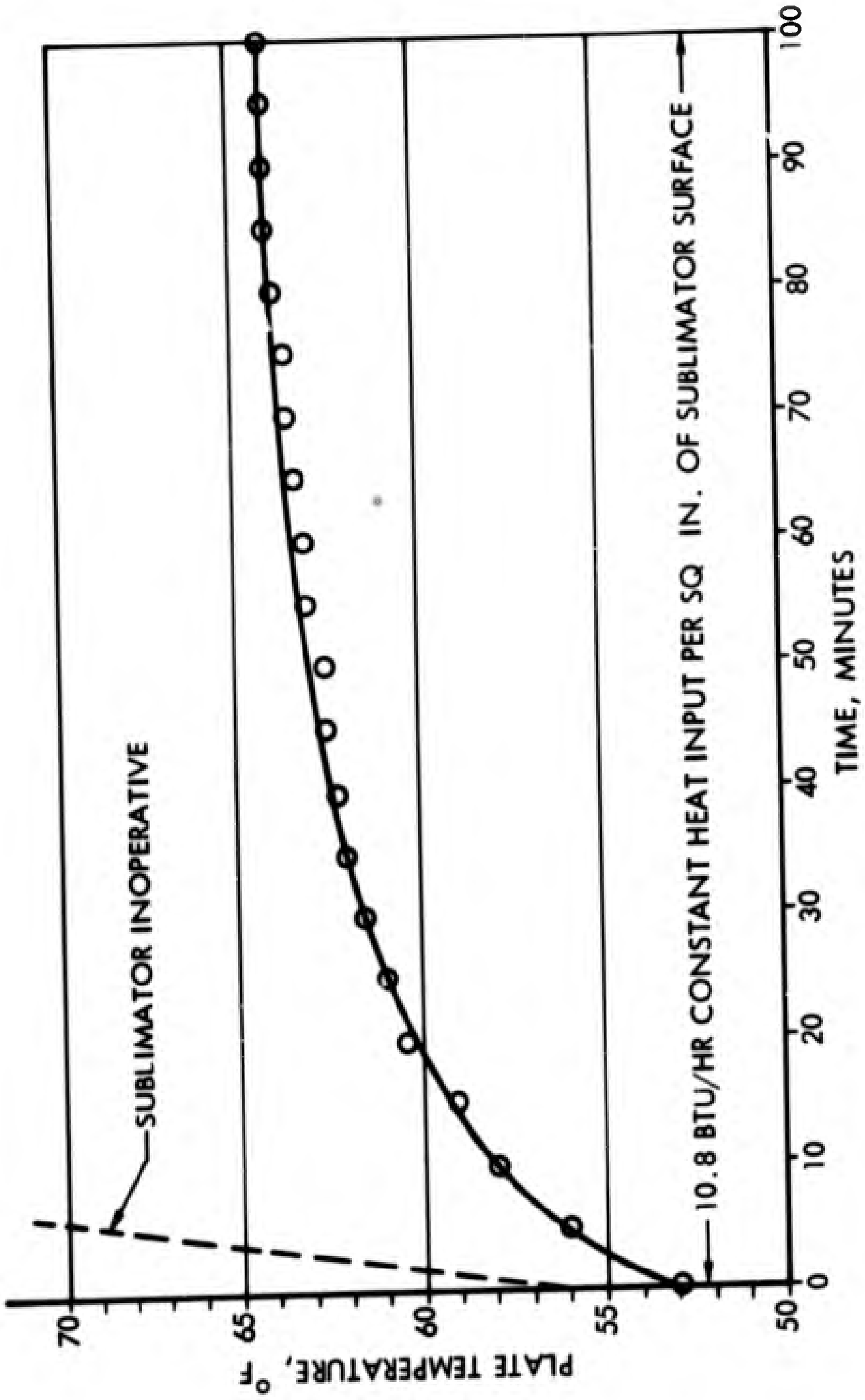

FIGURE 14 SUBLIMATOR MODEL TEST 10 (7 PSI ENVIRONMENT)

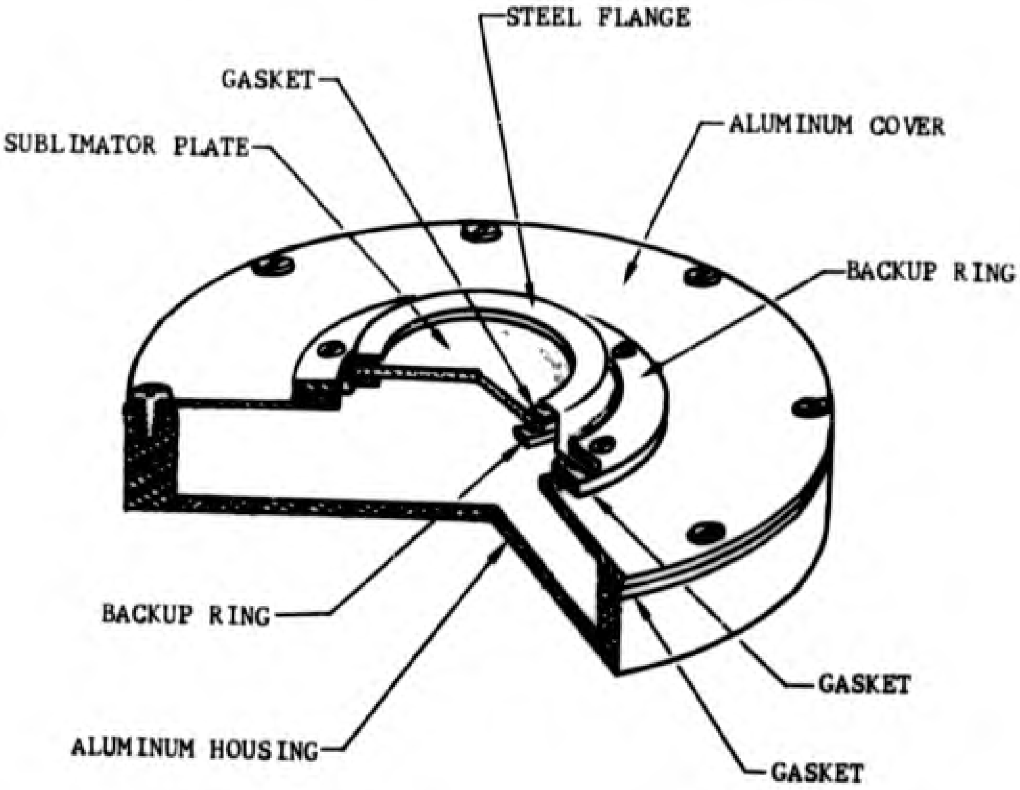

FIGURE 15 RIGID BLADDER SUBLIMATOR ASSEMBLY

materials. The results demonstrated that effective cooling can be accomplished at reduced water-feed pressures. With increasing pressure, the effective cooling generally improved. As shown in figures 16 and 17, porous plate No. 4R with an average pore size of 1.0 to 2.0 microns operated in the range of 0.5 to 3.5 psi without icing or slugging. The peak shown in the 3.0 psi curve may indicate contamination and self cleaning. Porous plate No. 6R (figure 18), with an average pore size of 2.0 to 5.0 microns operated in the range of 0.5 to 1.5 psi before icing and slugging occurred, and showed the most effective cooling performance. As shown in figure 19, porous plate No. 7R, with an average pore size of 1.0 to 2.0 microns operated in the range of 0.5 to 1.5 psi. No icing or slugging occurred, but the test was terminated because of its relatively poor cooling performance.

Porous plate No. 6R, which had shown the most effective cooling, was mounted into the rigid bladder test unit and tested to verify performance. Figure 20 presents the performance curve derived from this test.

Figure 21 shows the temperature variations within the test fixture at a pressure of 0.5 psi with a fixed heat input for porous plate No. 6R. This test was conducted to provide data for comparison with the earlier tests conducted under fixed environmental pressures of 3.5 and 7.0 psi.

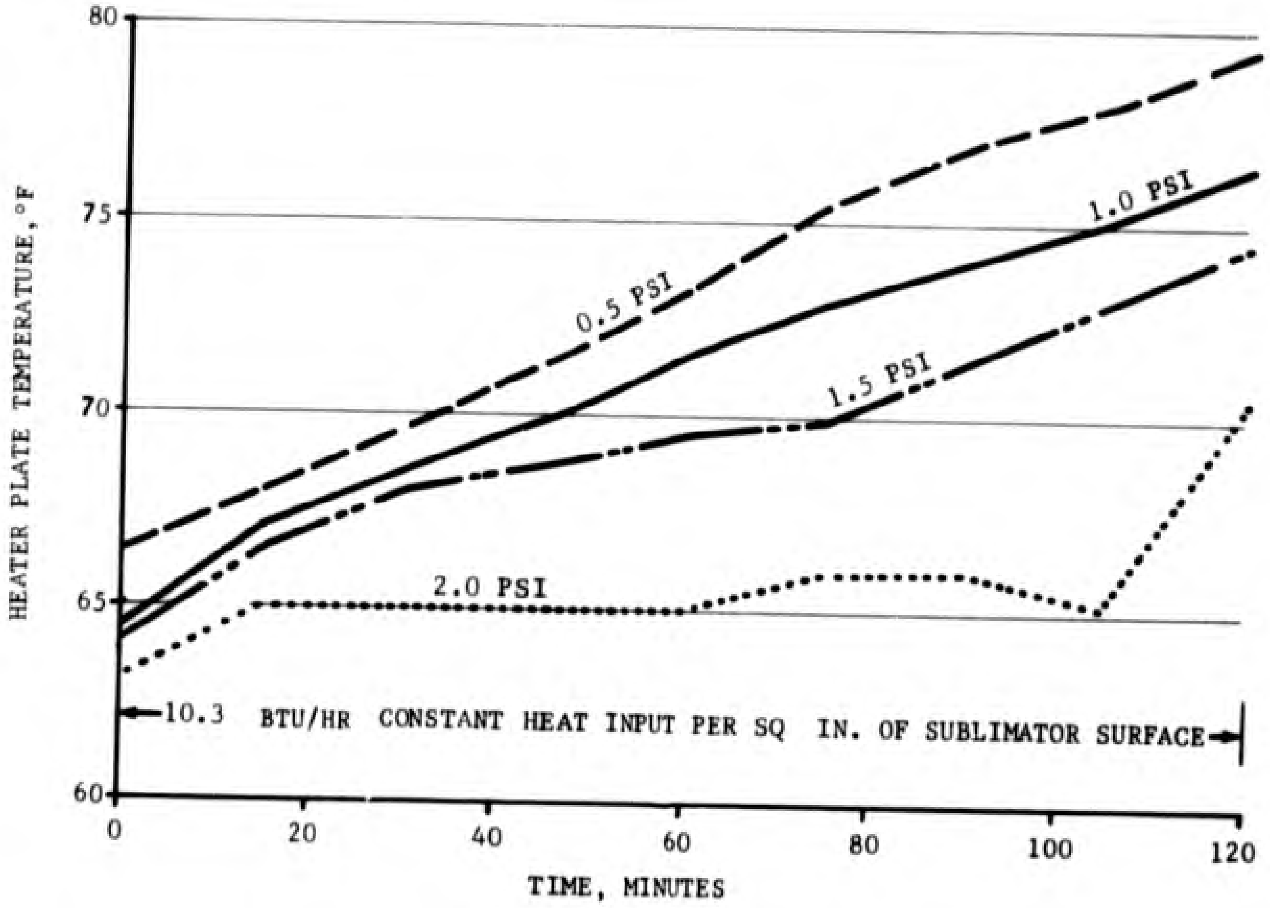

FIGURE 16 TEST OF PLATE NO. 4R POROUS SINTERED NICKEL (AV PORE SIZE 1.0-2.0 μ)

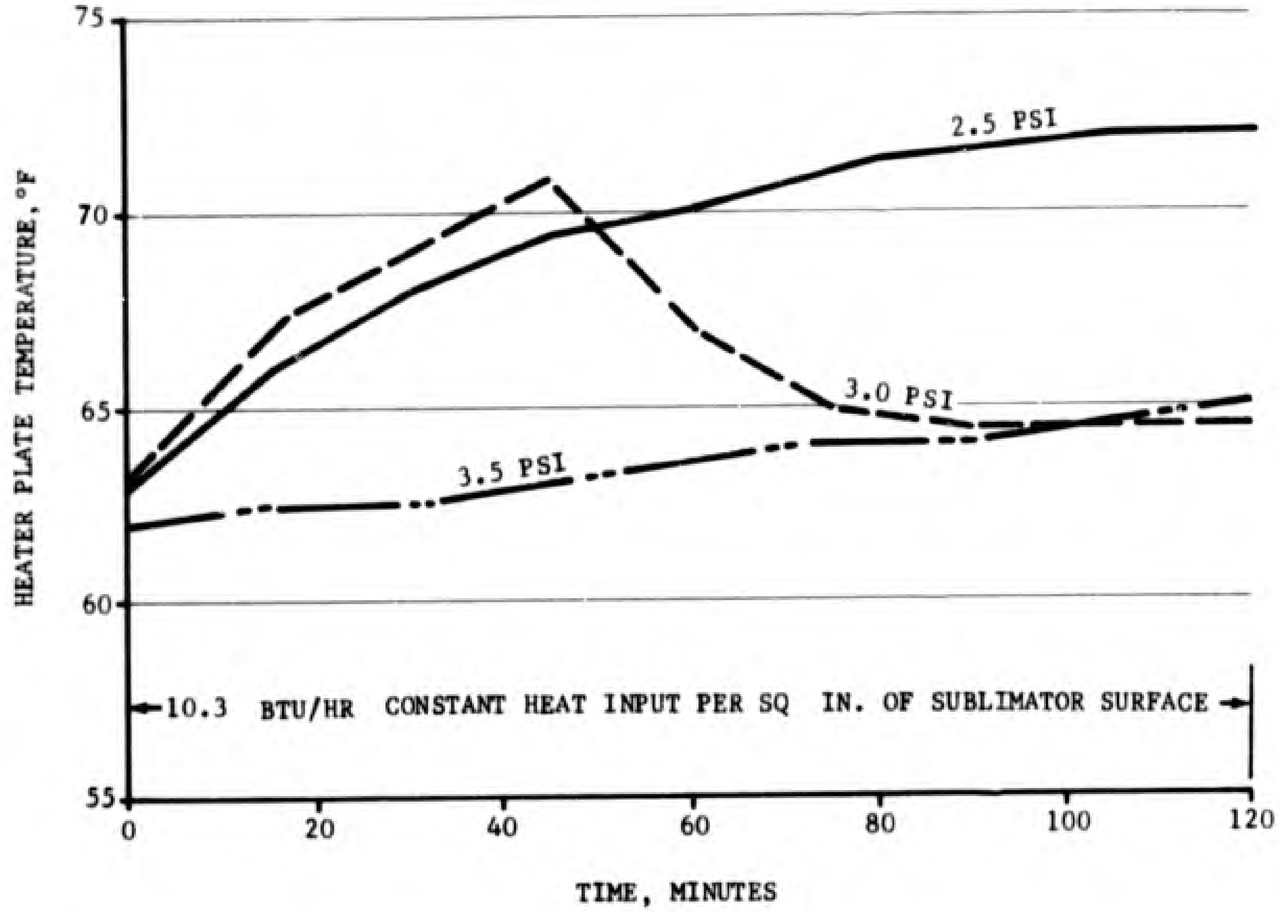

FIGURE 17 TEST OF PLATE NO. 4R POROUS SINTERED NICKEL (AV PORE SIZE 1.0-2.0 μ)

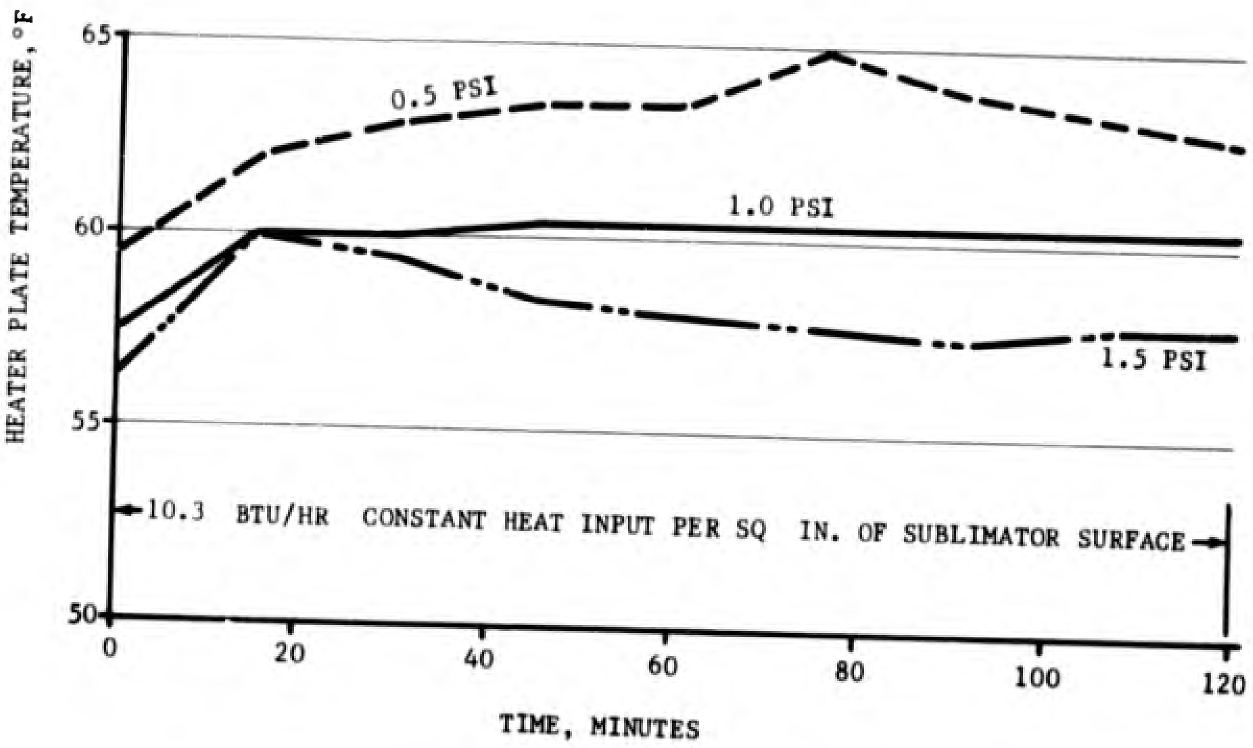

FIGURE 18 TEST OF PLATE NO. 6R POROUS SINTERED STAINLESS STEEL (AV PORE SIZE 2.0-5.0 μ)

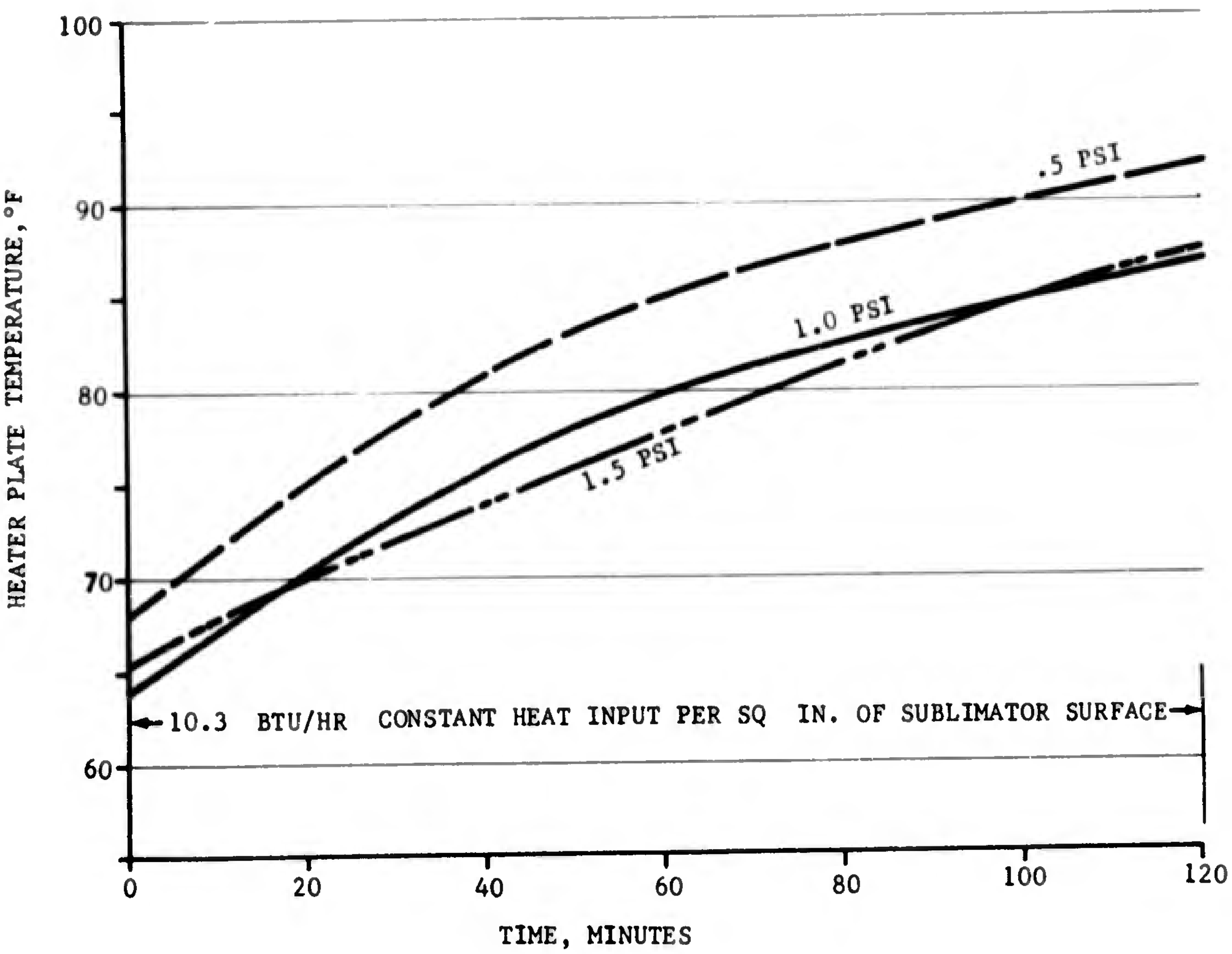

FIGURE 19 TEST OF PLATE NO. 7R POROUS SINTERED NICKEL (AV PORE SIZE 1.0-2.0 μ)

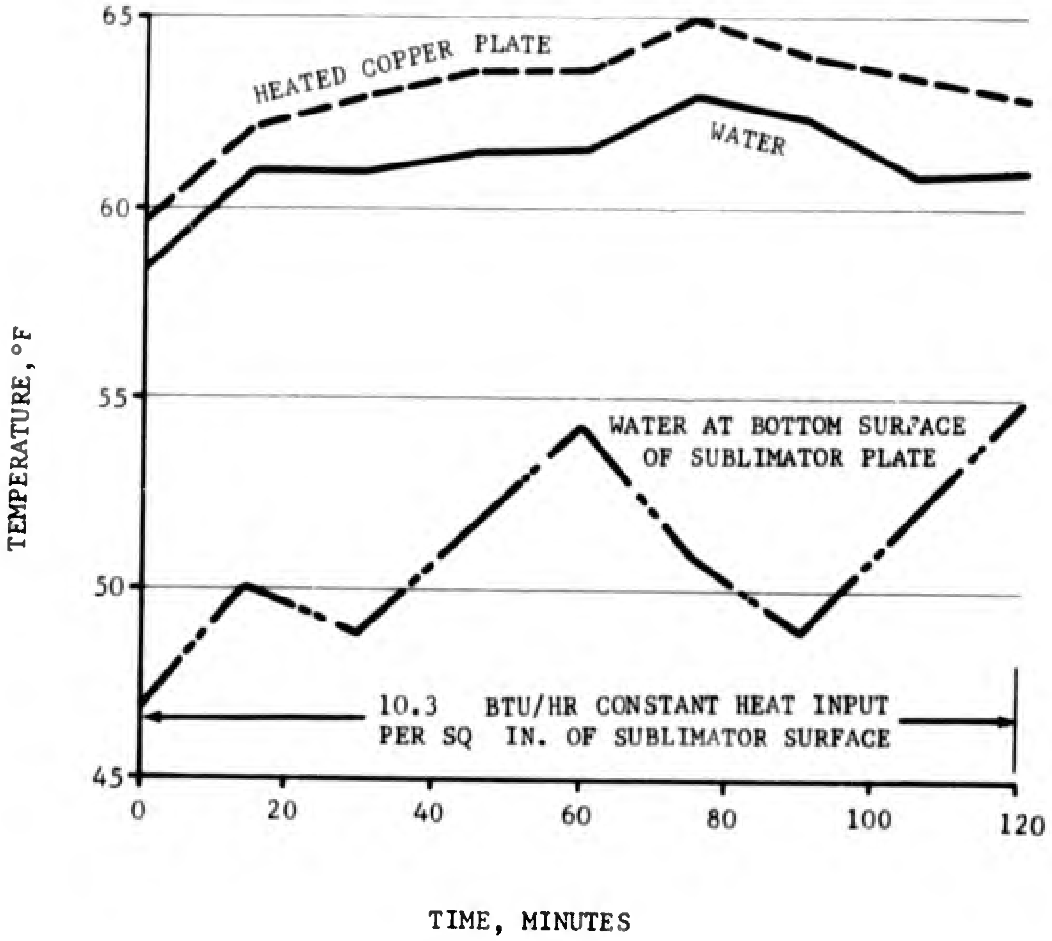

FIGURE 20 TEST OF PLATE NO. 6R (0.5 PSI FEED WATER PRESSURE)

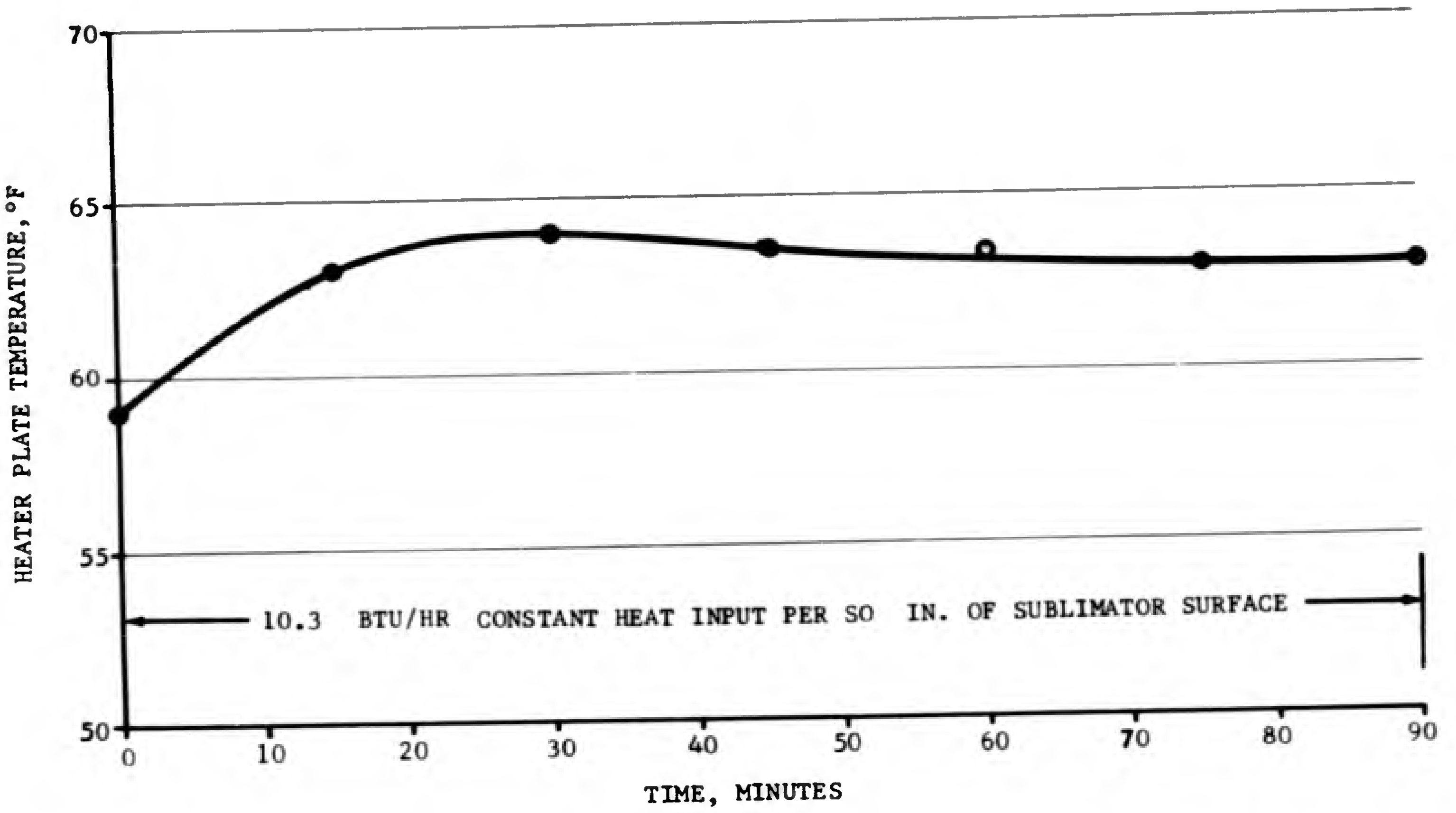

FIGURE 21 TEST OF PLATE NO. 6R MOUNTED IN RIGID BLADDER (0.5 PSI FEED WATER PRESSURE)

SECTION IV

VARIABLE CONDUCTIVITY LAYER DEVELOPMENT

The concept of a variable conductivity layer was based on the premise that compression of a resilient, compressible foam would not only shorten the length of the conductive heat flow paths, but would also considerably alter the effective density of the material and its corresponding effective thermal conductivity. Foam sealed within a bladder and compressed by controlled evacuation, would comprise the variable conductive layer. This layer, if provided with an adjustable differential pressure regulator (control valve), could be maintained at any selected thickness by utilizing the pressure differential between the suit and the vacuum of space.

LAYER DESIGN

Each variable conductivity layer specimen consisted of a layer of resilient, compressible material, 4.75 inches in diameter encased in a layer of 0.006-inch-thick polyvinyl chloride film. The thickness of the specimens ranged between 1/8 inch and 1/2 inch. A port was provided in the polyvinyl chloride film and was connected to the evacuation system. Variable conductivity layer specimens are shown in figures 22 and 23.

MATERIAL SELECTION

Open-cell foam was considered best suited for application in a variable-conductivity layer since it assured maximum compression with reduced pressure. Closed-cell foam was not considered because of its expansion characteristics in a reduced pressure environment. Additional considerations included (a) negligible losses in physical properties when exposed to a vacuum environment, (b) elastic compression in the pressure range of 0 to 7.0 psi, (c) negligible radiative intracellular heat transfer, and (d) increased effective thermal conductivity with increased compression.

Of the commercially available flexible foams considered, urethanes and Neoprene were found to be capable of satisfactorily withstanding the vacuum environment. However, Neoprene was not available in sufficiently compressible open-cell configurations and was eliminated. Samples of both ether and ester urethane foams were procured and tested. The urethane ether samples had densities of 1.0, 1.5, and 2.0 pounds per cubic foot.

BREADBOARD CONDUCTIVITY TESTS

A series of tests was conducted using specimens of different thicknesses and densities to study the effect of compression on thermal conductivity. Apparatus, test procedure, and results presented in the following paragraphs.

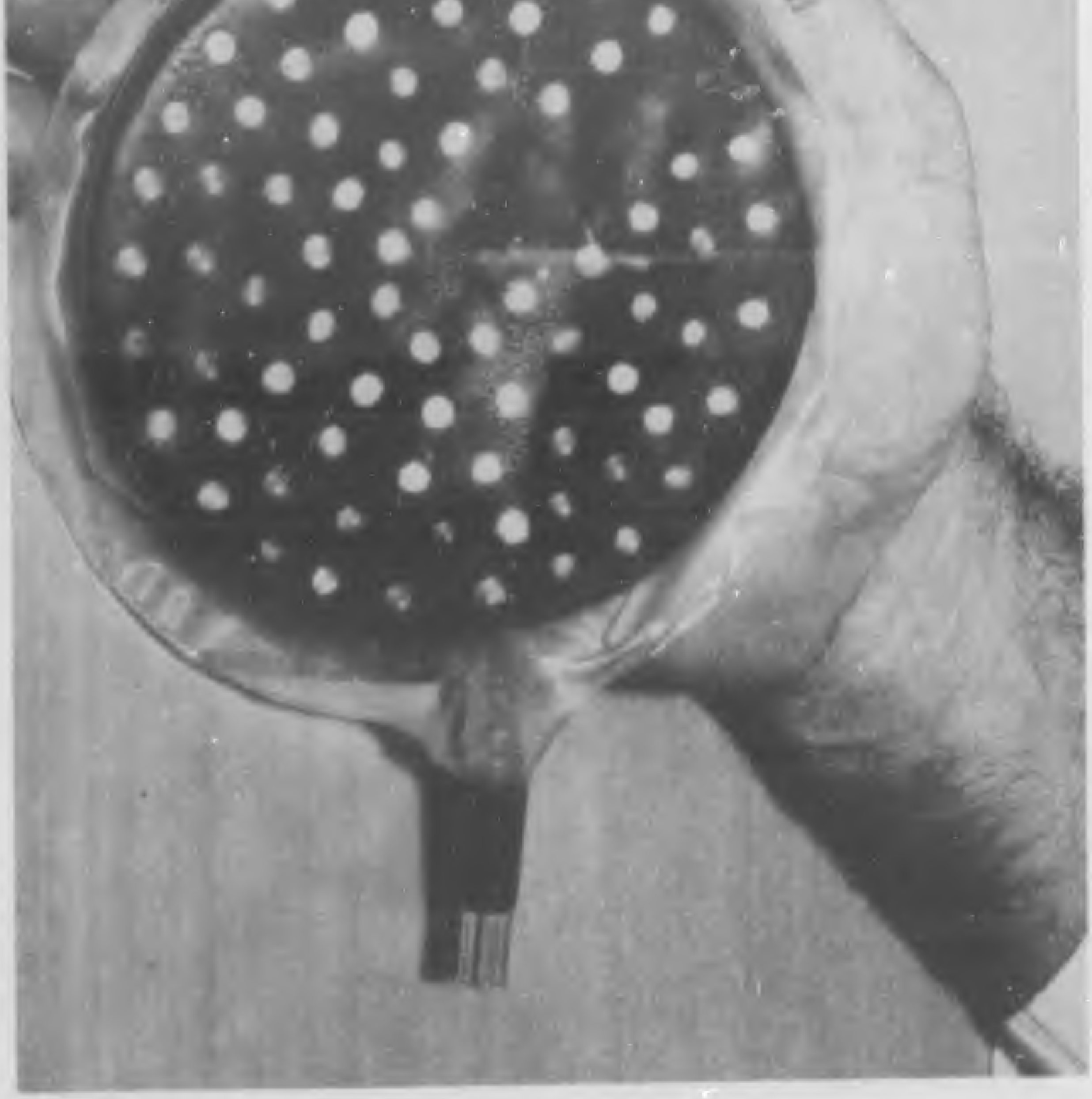

FIGURE 22 VARIABLE CONDUCTIVITY LAYER SPECIMEN

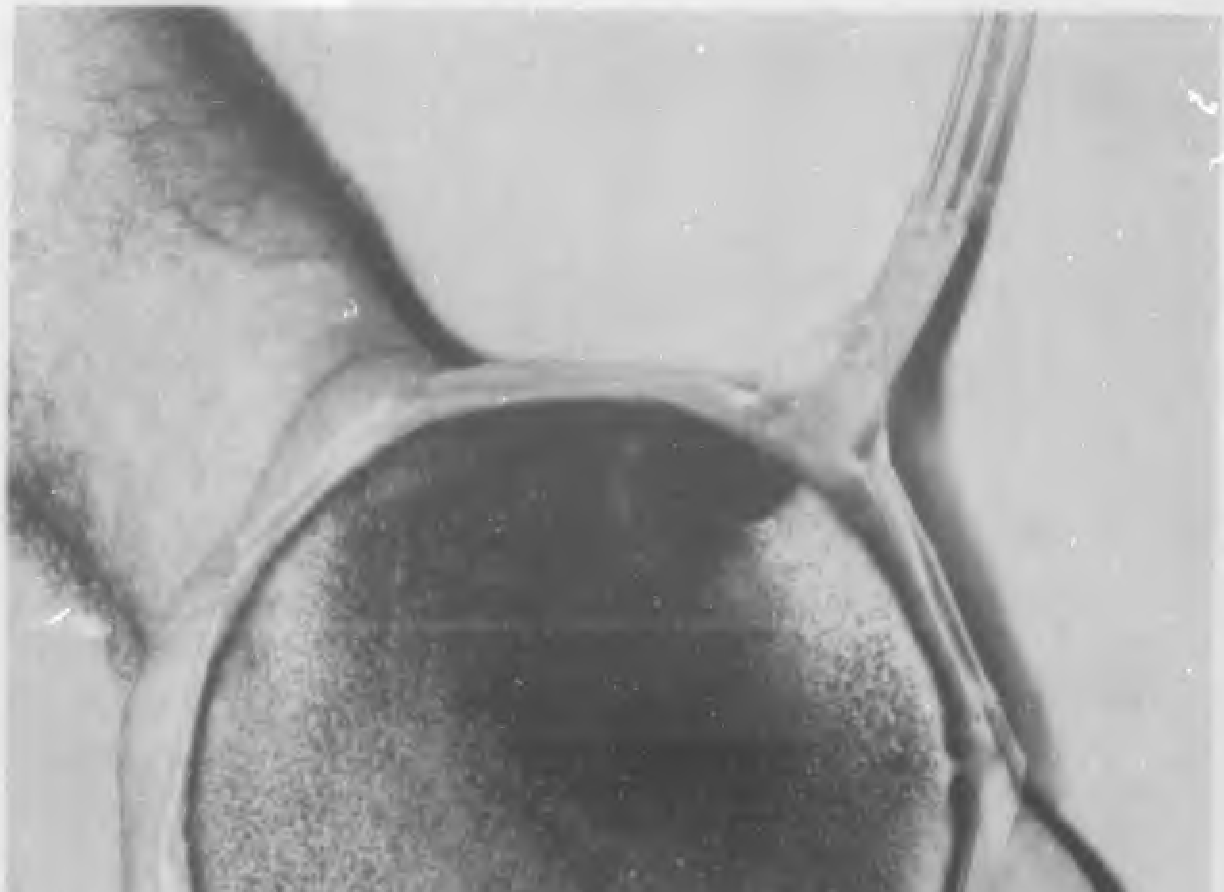

FIGURE 23 VARIABLE CONDUCTIVITY LAYER

Apparatus

The test equipment utilized for measuring the thermal conductivity of the urethane foam test specimens, as shown in figures 24 and 25, consisted of an electric heater, heat exchanger, vacuum system, and ice bath with electric pump. The electric heater and heat exchanger each had a copper surface plate with a thermocouple embedded for sensing plate temperature. Cooling water for the heat exchanger was circulated through Tygon tubing from the ice bath with continuous flow maintained by the pump. Both inlet and outlet water temperatures were sensed by thermocouples located at the corresponding ports of the heat exchanger. Thermocouple outputs were monitored and displayed by the Brown recorder. Input to the electrical heater was controlled by a Variac and monitored by a voltmeter and milliameter. The manifolded vacuum system (with bleed valve) controlled the thickness of the test specimen.

Test Procedure

The test specimen was placed on the copper surface of the heater and the heat exchanger placed on the specimen. The thickness of the specimen was measured for each compression load applied by controlled evacuation. Heat input was fixed at a preselected value and the temperatures of the heater and heat exchanger surfaces recorded. Thick glass fiber shielding was used to minimize thermal inputs from the environment. For each pressure setting approximately 2 hours was required to reach thermal equilibrium.

For two tests the foam was perforated and aluminum slugs of uniform length and diameter were placed in the perforations. The slugs were long enough to contact the film on both sides of the foam only when it was compressed. This was to provide a highly conductive heat path when compressed and an effective insulation when expanded.

Results

The thermal conductivity of the test specimens was calculated using the basic thermal conduction equation,

$$Q = \frac{k}{x} A(t_1 - t_2),$$

where Q = heat flow, Btu/hr

k = thermal conductivity, $\frac{\text{Btu}}{\text{hr - ft - °F}}$

x = thickness of panel, ft

A = area, ft^2

t_1 = temperature of heater plate

t_2 = temperature of cold plate

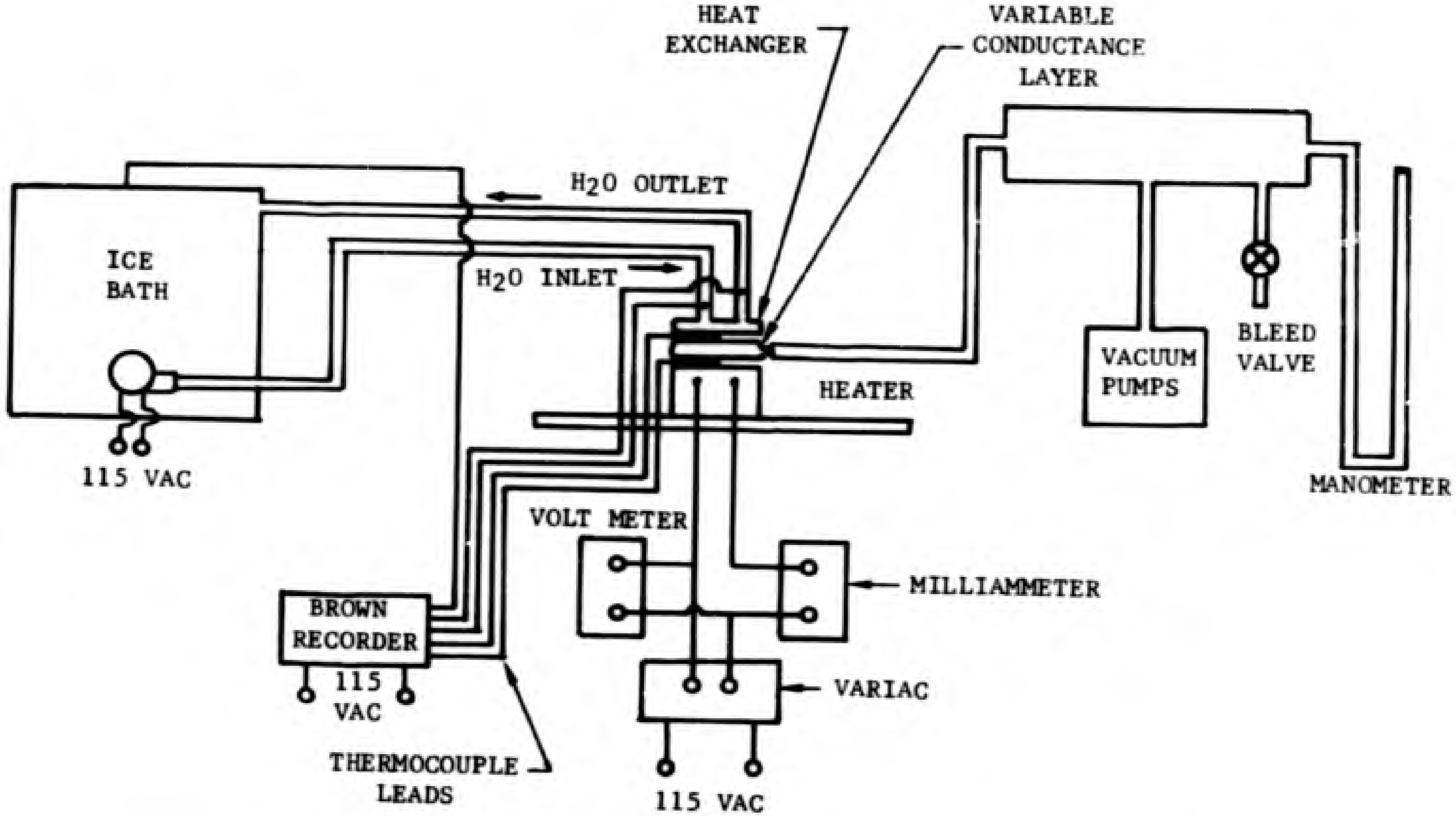

FIGURE 24 LABORATORY APPARATUS FOR TESTING VARIABLE CONDUCTANCE LAYER

FIGURE 25 THERMAL CONDUCTIVITY TEST FIXTURE

Many specimens of various thicknesses were tested and the results revealed little change in overall conductance throughout the compression range of 0 to 3.5 psi. The ratio of the maximum overall conductance to the minimum overall conductance $(k/x)_{max} / (k/x)_{min}$ varied from 1.5 to 2.0. In an effort to increase the ratio, silicone grease was applied to the inner surface of the film to reduce the contact resistance between the film and the foam. This resulted in a measurable improvement in overall conductance. A specimen containing aluminum slugs was tested with silicone grease and it too had improved overall conductance. The best performance achieved yielded $(k/x)_{max} / (k/x)_{min}$ approximately 3:1. This test specimen was a 5/32-inch-thick layer of urethane foam having a density of 4 pounds per cubic foot, impregnated with silicone grease, and encapsulated in 0.006-inch polyvinyl chloride film. The test data obtained with thie specimen are presented in table I.

TABLE I
Test Data*

Q, Btu/hr	t_1-t_2, °F	Press. Diff. psi	x, ft	k, $\frac{\text{Btu}}{\text{hr-ft-°F}}$
6.5	30	0	0.0154	0.0271
6.5	20	1.0	0.0083	0.0219
6.5	16	1.5	0.0075	0.0247
6.5	13.5	2.0	0.0065	0.0254
6.5	11	3.5	0.0058	0.0278

*Area of heater plate 0.123 ft^2

The results shown in table I indicate the effective conductivity remained essentially constant in the pressure range under consideration. The overall conductance varied inversely as the thickness only as shown by t_1-t_2. Therefore, this specimen is more properly referred to as a variable conductance layer rather than a variable-conductivity layer.

VARIABLE CONDUCTIVITY LAYER CONTROL VALVE

Some reliable means of controlling the pressure in the variable conductance layer was necessary. A simple on-off valve, while permitting adjustment of pressure by porting to vacuum or suit pressure, would not reliably maintain the desired pressure if any leakage occurred. Furthermore pressure adjustment would be difficult with resulting under or overshoot.

To obtain the desired performance an upstream pressure regulator was used. The regulator as shown in figure 26 was designed to be mounted in the suit wall with the adjusting knob on the outside surface. A fitting was provided on the inside surface for connection of the variable conductance layer. Ports to both the outside (vacuum) and inside

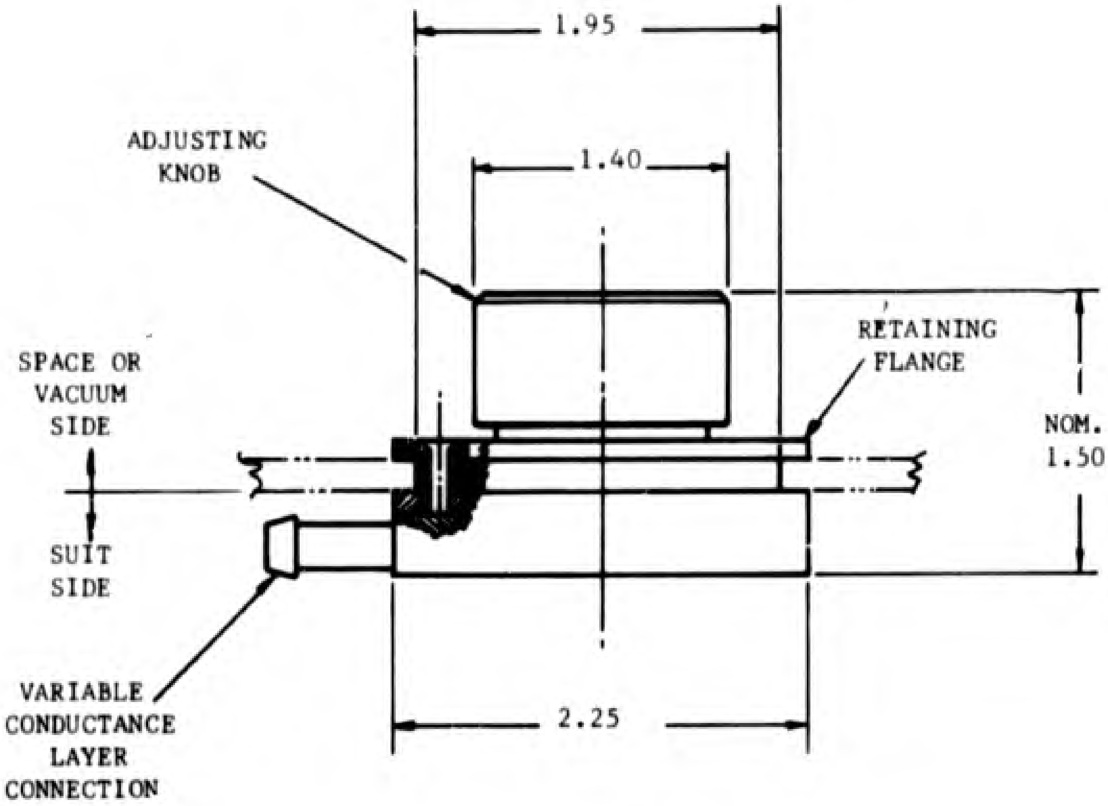

FIGURE 26 PRESSURE REGULATOR (DIMENSIONS ARE IN INCHES)

(suit pressure) provide control pressures. The regulator was designed to maintain an adjustable differential pressure in the conductivity layer of from 0 to 3.5 psi with a tolerance of ± 0.1 psi.

In operation the adjusting knob is set for the desired operating pressure. This displaces the diaphragm which in turn opens the vacuum port. As soon as pressure in the variable conductivity layer reaches the set pressure, the diaphragm returns to neutral and closes the vacuum port. If the pressure in the layer is too low, the diaphragm is driven in the opposite direction, thereby opening the suit pressure port and thereby increasing the pressure within the layer.

TESTS OF COMPOSITE BREADBOARD MODEL

The variable-conductance layer was integrated with the control valve and the breadboard model of the cooling unit as shown in figure 10. Testing was initiated and the cooling unit was found to be inoperable because the pores of the sublimator plate were clogged. Apparently contamination had occurred during the 3 months it was in storage after completion of Phase I testing. Several methods of cleaning utilizing alcohol and other common solvents were unsuccessful. The sublimator plate was then cleaned ultrasonically. Testing was resumed and the porous sublimator plate allowed slugging at low pressure differentials. Additional tests resulted in similar performance. A successful test was accomplished after the cooling unit had been left overnight with the water bladder filled and the porous plate exposed to the ambient conditions of the laboratory. This suggested that pore size and porosity were extremely sensitive to contamination and corrosion. It also emphasized how critical pore size and porosity were for adequate performance. Further testing was not conducted because of the unpredictable performance of the cooling unit.

SECTION V

CONCLUSIONS AND RECOMMENDATIONS

As a result of the investigations conducted it is concluded that:

1. Sublimator technology is not sufficiently advanced to permit use within full pressure suits since operation modes are unpredictable.

2. Variable conductance between the human body and the sublimator presently can not be controlled sufficiently by the use of variable thickness layers of resilient foam plastic.

3. Test results indicate the most successful performance obtained with these experimental sublimators occurred during mixed mode operation in which the evaporation mode was predominate. Many uncontrollable variables operated to prevent consistent duplication.

4. We recommend that no effort be made to incorporate this method of thermoregulation of man in a full pressure suit until the technologies of both the sublimator and the variable conductance components are more advanced.

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13. ABSTRACT

In this program a feasibility study was conducted of a conductive cooling system for cooling a man in space. In the concept studied the cooling was provided by a porous plate sublimator and controlled by a variable thermal conductance layer. The results of the tests performed demonstrate the need for advances in technology and further development work to make this concept feasible.

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14 KEY WORDS	LINK A		LINK B		LINK C	
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