CR 73270
AVAILABLE TO THE PUBLIC

TRW SYSTEMS REPORT NO. 06462-6006-RO-00
NOV. 1968

FINAL SECOND PHASE REPORT
CONTRACT NO. NAS 2-3817

# STUDY OF PASSIVE TEMPERATURE AND HUMIDITY CONTROL SYSTEMS FOR ADVANCED SPACE SUITS


BY
A. P. SHLOSINGER


PREPARED BY

TRW
SYSTEMS GROUP



FOR THE

AMES RESEARCH CENTER

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

TRW SYSTEMS REPORT NO. 06462-6006-RO-00
NOV. 1968

FINAL SECOND PHASE REPORT
CONTRACT NO. NAS 2-3817

# STUDY OF PASSIVE TEMPERATURE AND HUMIDITY CONTROL SYSTEMS FOR ADVANCED SPACE SUITS

BY
A. P. SHLOSINGER



PREPARED BY

TRW
SYSTEMS GROUP

FOR THE

AMES RESEARCH CENTER

NATIONAL AERONAUTICS
AND SPACE ADMINISTRATION

# FOREWORD

This report covers research activities performed in a program with the title "Study of Passive Temperature and Humidity Control Systems for Advanced Space Suits." The program was performed in two phases. The results of the first phase are covered by a separate report, ref. 1, and briefly summarized in this report.

The program was sponsored by the Ames Research Center of the National Aeronautics and Space Administration at Moffett Field, California, under Contract No. NAS 2-3817. Research activities performed from 2 September 1967 to 1 September 1968 are covered. Mr. James Blackaby of the Environmental Control Research Branch directed this effort as Technical Monitor for the NASA/Ames Research Center.

The program was performed by the Environmental Sciences and Engineering (ESE) Department of the Systems Engineering and Integration Division of the TRW Systems Group. Mr. A. P. Shlosinger, Head of the ESE Research Section, was the Principal Investigator and Program Manager. Valuable contributions in the performance of the program were made by W. Woo and E. W. Bentilla, Members of the Technical Staff; G. Hwa, Engineer and Research Specialist; G. B. Patchell and J. G. Morgan, Laboratory Technicians.

TABLE OF CONTENTS

## LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS (Cont'd)

# FINAL SECOND PHASE REPORT

# STUDY OF PASSIVE TEMPERATURE AND HUMIDITY CONTROL SYSTEMS FOR ADVANCED SPACE SUITS

By A. P. Shlosinger

## SUMMARY

Investigations were performed to develop techniques for control of temperature in an extravehicular space suit by radiation of heat from the external space suit surface. Modified heat pipes, permitting control of heat flow were developed as means of heat transmission from the skin of an astronaut to the external suit surface. Flexible heat pipes were developed for heat removal by direct contact with the human skin. The techniques developed are intended to be eventually integrated with passive control of humidity in space suits, investigated previously under Contract NAS 2-2102.

This report briefly summarizes research activities performed in the first phase of the effort in the area of controllable two-chamber heat pipes. It describes research activities performed which resulted in the development of flexible heat pipes, which use water as working fluid and operate in a temperature range such that the internal pressure is significantly lower than the pressure of the external environment.

Design and fabrication of a space suit wall prototype panel, including rigid and flexible heat pipes and thermal switching capability are described.

## INTRODUCTION

### Objective

It is anticipated that future orbital and lunar missions will require fairly extensive extravehicular activities. Assembly of orbital and lunar surface research facilities, and exploration of the lunar surface will require groups of astronauts to perform extravehicular tasks for series of days. With present extravehicular space suit systems the weight penalty for water, used as evaporative coolant and for electric power, required for circulation of coolant fluids, may well become a serious problem.

The objective of this program is to develop techniques which will significantly reduce the penalties in expendable supplies required for extensive extravehicular space suit operation.

### Background

In order to attain the objective of reduced power requirements and reduction in the amount of water required for evaporative cooling, means are required for transport of heat in a space suit by devices other than forced circulation of a fluid, and the external suit surface must be made available as a thermal radiator for the emission of body heat.

A potential means to eliminate the requirement for a forced fluid heat transport loop was provided by the invention of the heat pipe. A heat pipe is a device, applying a closed evaporating-condensing cycle with condensate return by capillary action to heat transmission. Heat pipes have been extensively discussed in the literature. Refs. 1 and 2, which were generated as part of this program include discussions of heat pipes and their application to temperature control. Suffice to say that a closed container of any geometry, if internally lined with a capillary structure (wick), evacuated of air or other noncondensable gases, and the wick soaked with a suitable liquid working fluid, will transmit heat from areas of heat addition to areas of heat removal by the process of a heat pipe. This heat transmission process results from endothermic evaporation of working fluid liquid at the areas of heat addition, flow of vapor to the areas of lower temperature and pressure, and exothermic vapor condensation. The liquid condensate is returned by capillary pumping to the areas of the wick where heat addition has generated a deficiency of liquid. Depending on operating temperature, water, alcohols, ammonia and low melting point metals are potential working fluids for heat pipes. Heat pipes have shown high heat transmission capability with small temperature gradients.

A general concept for essentially passive temperature and humidity control in extravehicular space suits was generated. Research performed earlier under Contract NAS 2-2102 on "Passive Control of Humidity in Space Suits" (ref. 3) had demonstrated that it is feasible to control humidity within a space suit by condensation of evaporated perspiration on wicks, which are cooled below the desired internal dew point temperature. Further, that diffusion of water vapor is adequate for transfer of the vapor from the human skin to the chilled wicks, located at a distance in the order of an inch or less from the skin surface. Passive humidity control would eventually be integrated with temperature control techniques applying heat pipes for heat transmission and radiation from the external space suit surface for heat rejection.

Under many conditions of the external radiation environment, a man in space suit will require the protection of highly effective thermal insulation. Under conditions of low heat input into the external surface of a space suit, such as will occur in the absence of significant incident thermal radiation, the external suit surface may reach temperatures as low as -70° C to -80° C. The large temperature gradient between the skin, at approximately 33° C, and the external suit surface would cause excessive heat loss, unless an adequate thermal resistance in the form of thermal insulation is imposed between the body of the man and the external suit surface. This requirement exists for any type of extravehicular space suit. It is not too difficult to satisfy because of the ready availability of vacuum in space, which makes it easy to provide insulation by multiple reflective shields.

In order to use the external space suit surface as thermal radiator, it is, however, necessary to transmit heat from the body of the astronaut to the external space suit surface. The heat transmission rate must be adjusted to the rate of metabolic heat production and the net radiant heat rejection capability of the external space suit surface.

The thermal balance between metabolic heat production and space suit surface heat rejection is discussed in ref. 1. It is shown that significant savings in water weight required for evaporative cooling can be achieved even under the unfavorable conditions of lunar day operation, although auxiliary cooling by evaporation or sublimation will be required.

A concept was generated and investigated during the preceding phase of this contract, where an insulation layer is bypassed by heat pipe-type devices in which heat flow can be controlled and turned on or off in response to automatic or manual control signals.

The basic heat pipe configuration is modified to include two chambers, one of which will absorb heat from the human skin inside the space suit (evaporator chamber), while the other one will be located at the external suit surface and reject heat by radiation to space (condenser chamber). The two chambers are interconnected by separate passages for a wick and for flow of vapor. The assembly thereby becomes a two-chamber heat pipe with separate wick and vapor passages as schematically shown in fig. 1. Insertion of a control valve into the vapor passage provides control of heat flow in the device. The separation into separate evaporating and condensing chambers facilitates a geometry in which these chambers are flat panels, interconnected in only a limited number of points by wick and vapor passages. The number of penetrations causing a heat leak in the thermal insulation layer can thereby be kept to a minimum and the effectiveness of the thermal insulation can be maintained.

A schematic of a variable thermal conductance space suit shell is shown in fig. 2. This figure shows a two-chamber heat pipe integrated with a space suit pressure shell and a layer of reflective shield-type vacuum insulation.

The pressure shell shown is of a type which was considered for application to an advanced hard space suit under development at the NASA/Ames Research Center. It consisted of two sheets of fiberglass separated by a corrugated spacer, forming a lightweight, rigid fiberglass structure of a geometry similar to corrugated cardboard. A fiberglass panel of this configuration is not a good conductor of heat. In order to improve the effective thermal conductance of the pressure shell, the tubular cavities formed by the corrugated spacer were internally lined with wick and modified to function as heat pipes. Thereby, a much higher effective thermal conductance was achieved for the pressure shell. External to the shell, using the outer sheet of the pressure shell as one of its boundaries, a two-chamber heat pipe with vapor passage control is provided. The figure shows the evaporating and condensing chambers, the transfer wick and a bellows-operated vapor flow control valve. The two chambers are separated by reflective shield-type vacuum insulation. This figure was taken from ref. 1, which describes the development of the integrated hard space suit thermal control shell in detail.

The variable thermal conductance space suit shell is essentially a panel which, in response to an externally applied signal, will change from an effective thermal insulator to an effective heat conductor, as required by the metabolic heat production of the astronaut and the external radiation environment.

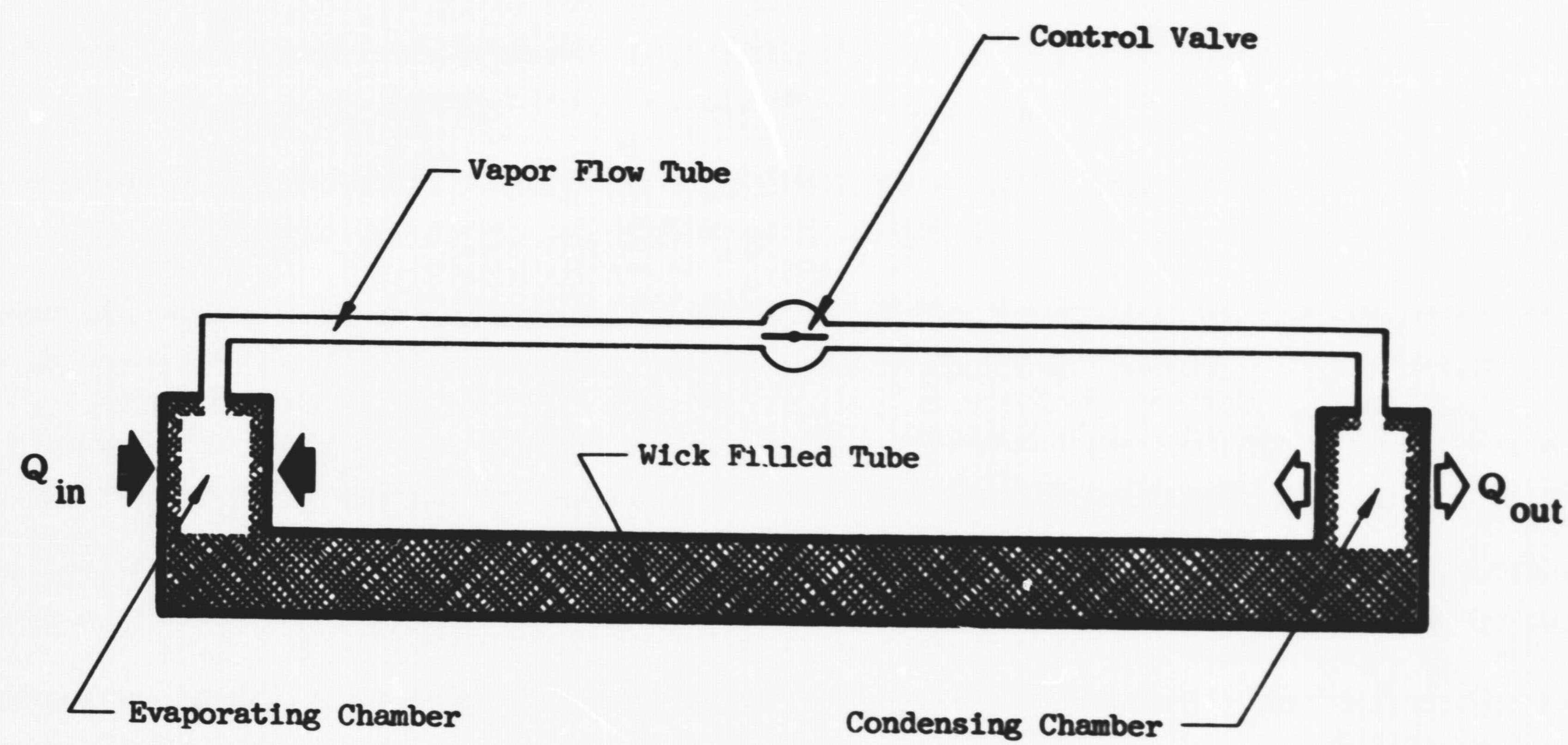



**FIG.1 VARIABLE HEAT PIPE (VAPOR FLOW CONTROL CONCEPT)**

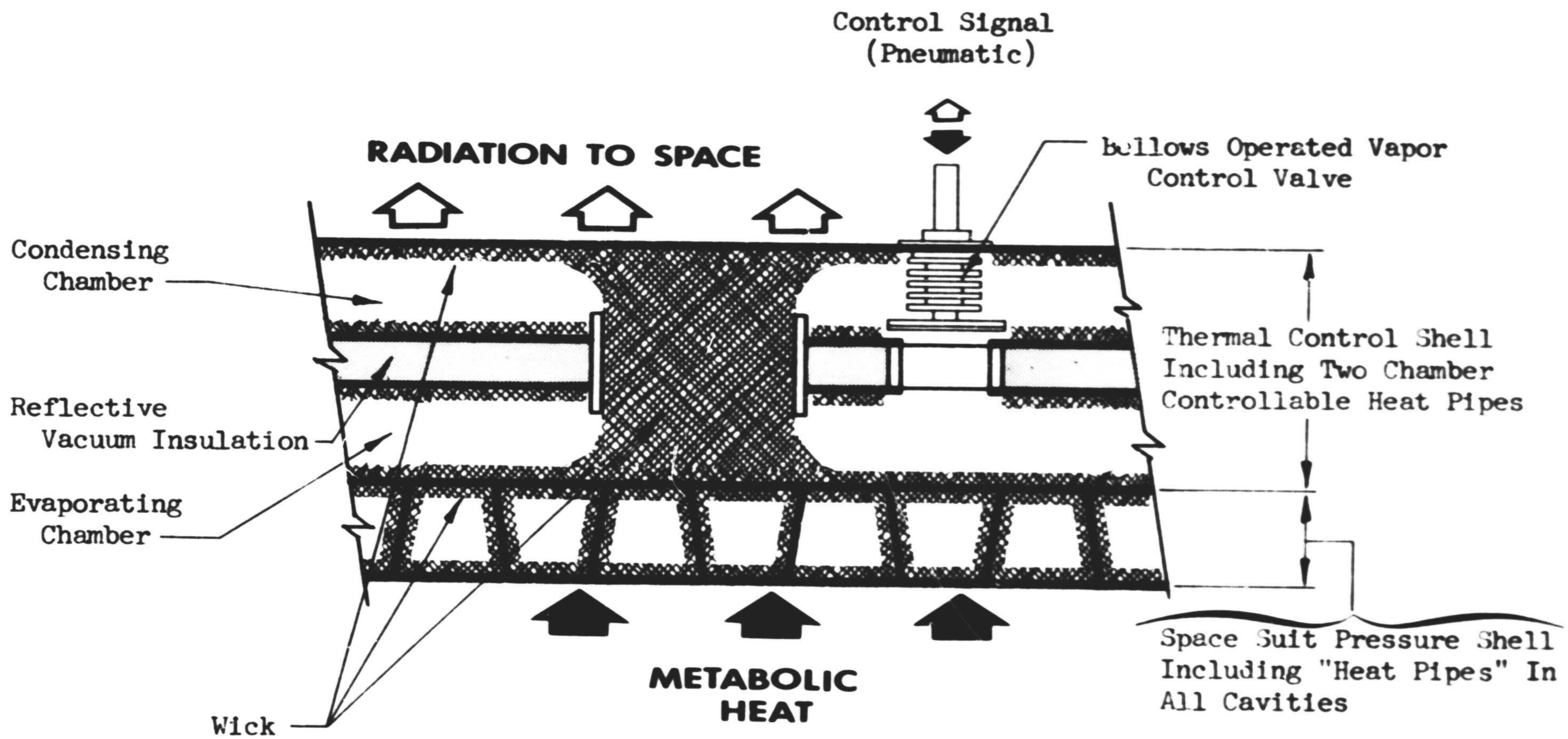



**FIG. 2 SCHEMATIC CROSS SECTION OF A VARIABLE CONDUCTANCE SPACE SUIT SHELL**

The development of the variable thermal conductance suit shell was an important step toward passive space suit temperature control. Together with demonstrated feasibility of passive control of humidity in space suits, the following development status had been established at the beginning of the phase of the program covered by this report:

- The feasibility of passive control of humidity in a space suit by condensation of water vapor on cooled wicks and absorption and retention of the liquid condensate in the wick by capillary action had been demonstrated under the earlier program, Contract NAS 2-2102.

- The feasibility of the variable thermal conductance space suit shell had been demonstrated and experimental devices had been developed and tested.

- The remaining problems and requirements for further research had been identified and evaluated.

## Space Suit System Concepts

At the initiation of the research activities under this program, the space suit temperature and humidity control system was defined in only general terms. It was felt that an overall system concept was required for the present only to the extent necessary to define the specific research tasks. As a technology was developed and feasibility of specific approaches established, it would then be possible to more realistically define the overall suit system.

It had however been stipulated that the temperature and humidity control should be applicable to an advanced hard shell fiberglass space suit under development at the NASA/Ames Research Center.

The selection of technology research tasks was therefore based on the overall concept of a hard shell space suit in which controllable heat pipe-type devices would provide heat transport from the skin of the astronaut to the external surface of a hard suit shell which would reject heat by radiation to space. Auxiliary devices, using water as an evaporant, would be integrated with the heat transport system in order to provide auxiliary cooling whenever required.

Loose as this concept may be, it provided essential problem definition. With heat pipes thermally connecting the skin of the astronaut and the external space suit surface, it was obvious that the heat pipes would have to be controllable and provide a variable means to thermally bypass an insulation layer, as discussed in the preceding paragraph. It was further apparent that a means was required to transmit heat from the skin to the internal face of the space suit shell.

Radiation between the human skin and the interior surface of the space suit shell could only provide a fraction of this heat transfer requirement. The possibility of transmitting heat by radiation from the human body to the cooled internal surface of a space suit has been investigated in ref. 4. This reference shows that with, for example, an internal suit surface temperature of 10° C (50° F), only approximately 195 joules/sec (665 Btu/hour) can be transmitted by radiation from 1.8 $m^2$ (19.5 $ft^2$) of human skin at 33° C (91° F). A more efficient means to transmit heat from the skin to the space suit wall is therefore required.

Heat pipes have the potential to satisfy this requirement, but the devices used for this purpose would have to be flexible. The shell of a hard space suit can not be brought into direct contact with the human skin. A gap between body surface and hard space suit shell is required to permit body expansion resulting from breathing and muscular activities. Flexible heat pipes could thermally bridge this gap.

A number of alternatives are apparent in arrangement of the subsystems. For example, the auxiliary system for water evaporation could be located in any portion of the heat transmitting system. The flexible heat pipes and the rigid portion could be internally connected such as to provide one single heat pipe system or could be separated such that the flexible portion would contact the skin and inner face of the external space suit shell and heat transfer between the flexible and the rigid heat pipes would be provided by thermal conduction.

The final selection of the overall system configuration will eventually be influenced by ease of donning of the suit, reliability, questions of safety, etc. Separation of the heat pipe system into a flexible internal system and a rigid external system, separated by the pressure shell of the suit, would permit the use of working fluids with different solidification temperatures in the two separate heat pipe systems. Water could be used in the internal system where temperatures below the freezing point would not be anticipated and where water would be desirable for reason of safety and absence of atmosphere contamination potential. A low freezing point working fluid, such as methyl alcohol or a refrigerant could find application in the rigid external part of the system.

Several tentative overall suit configuration concepts were generated. The evaluation of these concepts helped in the definition of the subsystem problems.

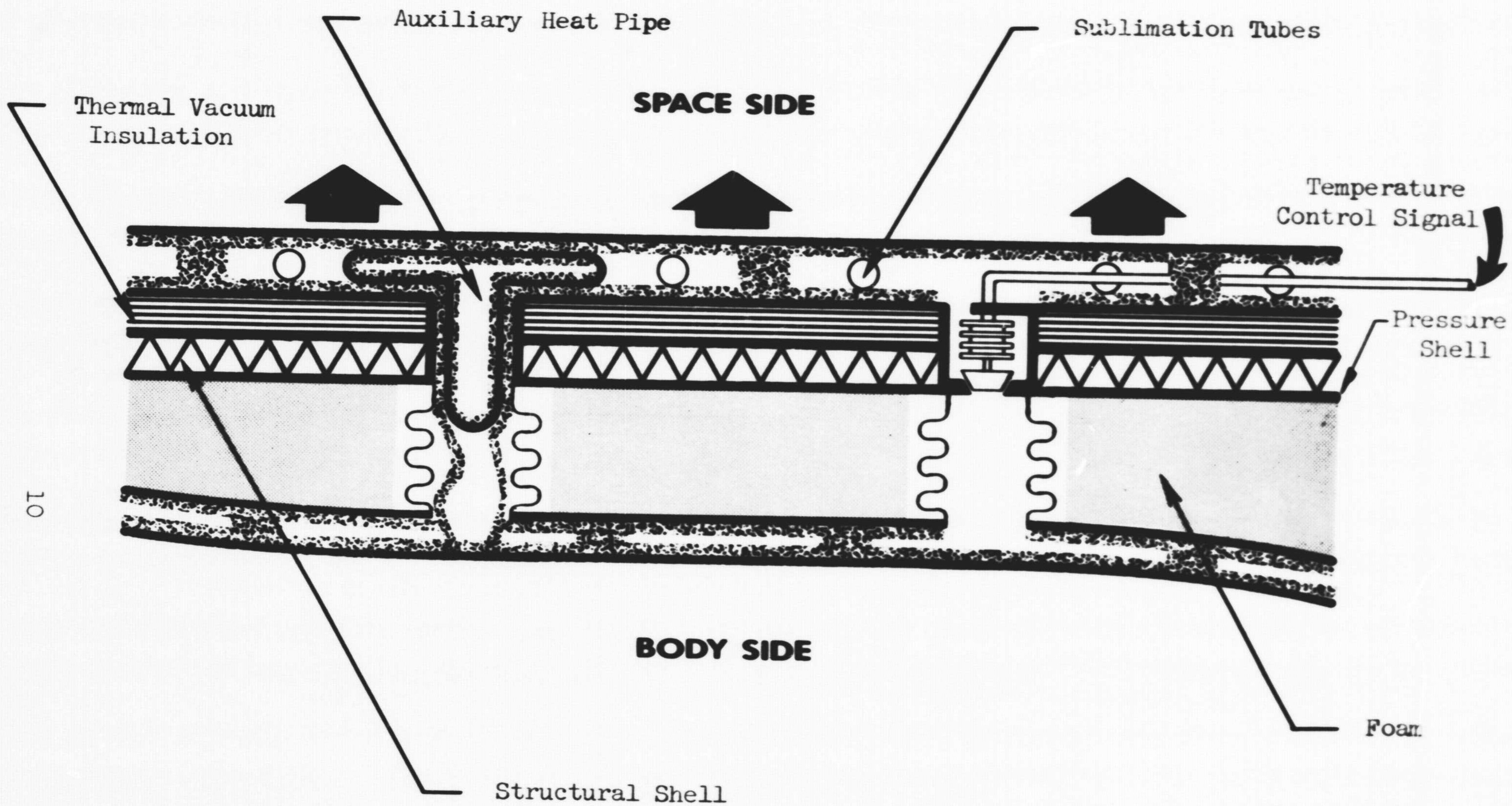
Figures 3 and 4 show two of these concepts. They have the use of a variable thermal conductance rigid suit shell, which incorporates a thermal insulation layer, in common. They may use water as working fluid in the external as well as the internal subsystem and apply an auxiliary heat pipe concept, which will be discussed later in this report, to either prevent freezing of the water or permit ready restart of the heat pipes, should freeze up occur under conditions of low load and high heat rejection. Contrary to the initial variable thermal conductance space suit shell shown in fig. 2, the pressure shell of the suit is not modified into a heat pipe, but bypassed by wick and vapor flow channels.

The gap between the body and the rigid shell is filled with an open-cell, soft flexible foam layer which provides padding and support for the flexible heat pipes contacting the skin of the astronaut.

Sublimation tubes for auxiliary cooling are located in the heat pipe panel at the external suit surface. This is an advantageous location for sublimation devices. Vapor rejection to space is facilitated by this location, the sublimation devices can be of rigid construction and they are external to the suit pressure shell. Heat transmission between the sublimation tube and the skin is provided by the heat pipe systems. Automatic temperature control is performed by a single heat pipe thermal control system for radiant, as well as evaporative heat rejection.

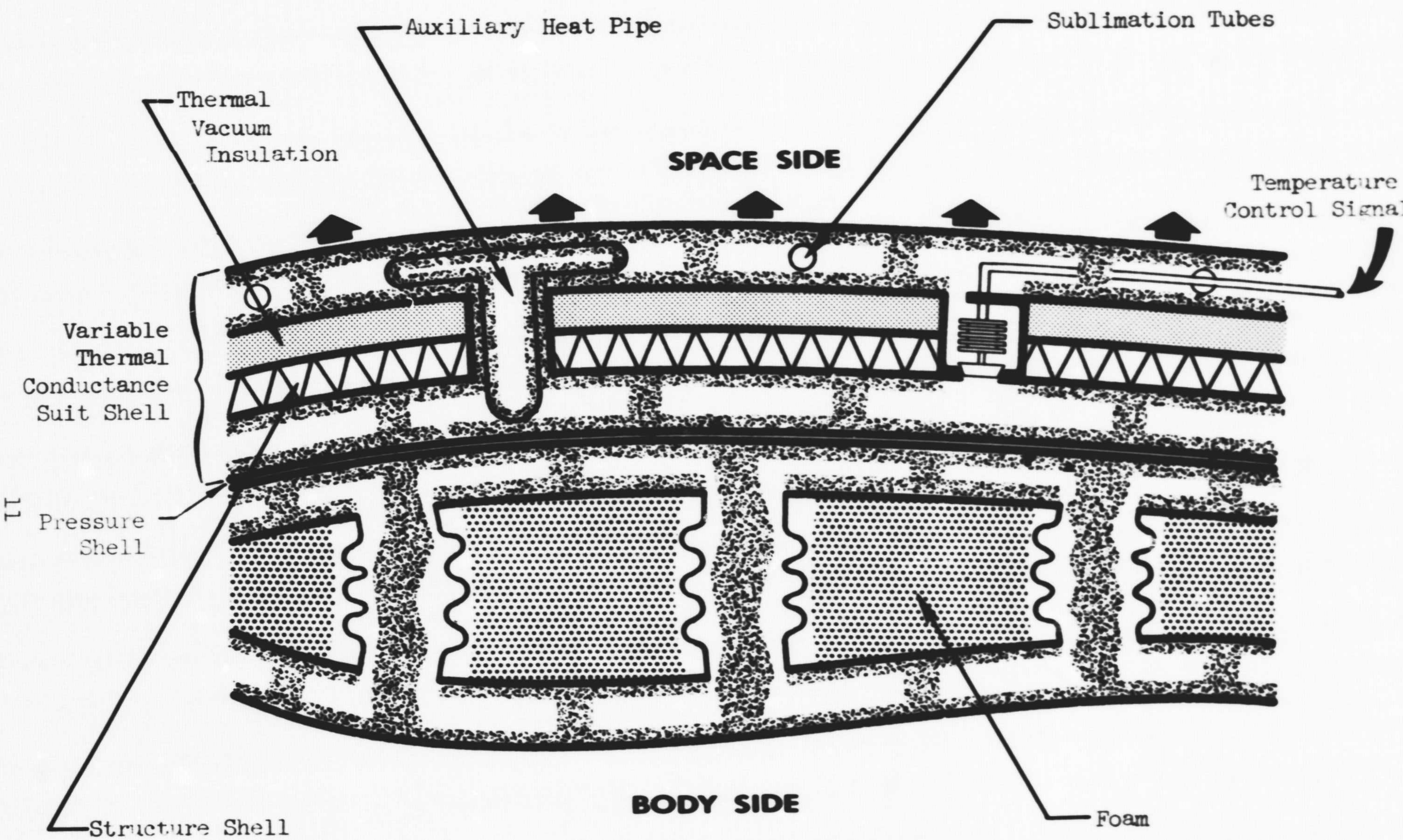
The concepts shown, while strictly preliminary, identify the basic elements of the suit temperature control system:

- A variable thermal conductance rigid space suit shell with integrated thermal insulation.
- Flexible heat pipes for heat transmission between the skin and the variable thermal conductance space suit shell.
- A technique for freeze prevention or ready restart of frozen heat pipes.
- Devices integrated into the variable thermal conductance space suit shell for auxiliary cooling by evaporation or sublimation of water.




SCHEMATIC CROSSECTION

**FIG. 3 - INTEGRATED SPACE SUIT SHELL WITH FLEXIBLE INTERNAL PADDING (HUMIDITY CONTROL WICKS NOT SHOWN)**




SCHEMATIC CROSSECTION

**FIG. 4 - INTEGRATED SPACE SUIT SHELL WITH SEPARATE UNDERGARMENT**

**(HUMIDITY CONTROL WICKS NOT SHOWN)**

The research activities in the first phase of the program were directed to development and performance demonstration of the variable thermal conductance space suit shell. The activities of the research phase covered by this report were predominantly devoted to the development of flexible heat pipe-type devices, with a lower effort level directed towards the freeze prevention/restart problem and conceptual work in the area of integration of heat pipes and auxiliary evaporative heat sinks.

Applying the level of technology development achieved towards the end of the research phase covered by this report, an experimental prototype of a suit panel, including flexible and rigid heat pipe panels and thermal switching capability was built, tested and delivered to the NASA/Ames Research Center.

## Material Problems

Heat pipes previously developed and discussed in the literature were essentially pipes or tubes, closed on both ends. A wire screen rolled into a cylinder was usually used for capillary pumping. Because these wire screens were of stainless steel, all that needed to be done to provide thermal contact with the tube wall was to roll them up tight enough to get them inside the tube and then let them expand by their own springiness.

The devices required for the space suit differ in geometry and materials drastically from these early heat pipes. They are built of nonmetallic materials. Quartz fiber fabrics were found to be more effective lightweight wicks. These fabrics required bonding to the internal surfaces in order to obtain satisfactory heat transfer between external heat pipe surface and the working fluid. Polymeric plastic materials were used for wick bonding, for internal support of flexible devices and for other purposes. It soon became apparent that the change in configuration required new techniques of fabrication and careful selection of materials, suitable to application in heat pipes.

A research approach was used which separated the material research from the studies of design configuration. Thereby, it was possible to verify functional integrity of a design, identify the material problem and pursue solution of material problems in a parallel effort. As better materials were identified, these materials were applied and tested in the designs which had demonstrated functional suitability.

This was possible because the difficulties caused by unresolved material problems effected predominantly the duration of satisfactory operation of the devices. For example, inadequate bonding techniques for wicks permitted satisfactory operation for several days before the wick separated from the substrate and permeability of enclosure materials of heat pipe devices permitted operation as long as noncondensable gases would be vented at periodic time intervals. The major shortcomings of materials included the following:

- Materials would introduce noncondensable gases into the cavity of the heat pipe. These noncondensable gases could be the result of simple outgassing of atmospheric gases which adhered to the material surfaces, could result from the vapor pressure of the material or could be the result of chemical processes. Such processes would potentially include interaction of materials and slow post curing processes resulting from operation at elevated temperatures.

- Strength of the materials would deteriorate as result of high or low temperature or material interaction, for example, with the working fluid. A typical example of this is the deterioration of some materials used for the bonding of wicks to the interior surfaces of the heat pipe cavity (ref. 5).

- The materials used for application to heat pipe-type devices would be permeable to the vapor of the working fluid, or to atmospheric gases. The devices, under exposure to external vacuum, must retain the working fluid, and at external pressure not permit entry of noncondensable atmosphere gases into the interior of the heat pipe.

The research activities directed towards finding solutions to material problems are, in accordance with contractual requirements, covered by separate Material Research Reports (refs. 5 and 6). The functional effects of material properties, achievements of material research to the time of this writing, remaining problems and suggested approaches to their solution are briefly summarized in the following and/or covered by the respective sections of this report.

It has been known for considerable time that the presence of gases, noncondensable at the temperatures at which the heat pipe operates, has a detrimental effect on heat pipe performance. During operation of a heat pipe, noncondensable gases will, by the flow of the working fluid vapor, be flushed towards the cooled (condenser) end of the heat pipe. There they will cause significant resistance to heat conduction from the condensing vapor-liquid interface to the heat pipe enclosure.

Presence of noncondensable gases was identified as a major cause of poor heat pipe performance. Normal performance could however be restored by venting from the condenser end of the devices to vacuum for a few seconds. This can be done repeatedly without significant loss of working fluid.

Depending on the type of material used, periods of satisfactory heat pipe operation between ventings varied from fractions of an hour to many weeks. For example, heat pipes made from heat-shrinkable, irradiated polyolefin required, for satisfactory operation, venting at intervals of only several minutes because of rapid inward leakage of atmosphere gases. On the other hand, experimental devices of stainless steel and all soldered construction would operate satisfactorily after periods of many months of exposure to a one atmosphere laboratory environment.

It was also observed that some of the devices which required venting to vacuum after short periods of operation when exposed to the one atmosphere laboratory environment, would operate for extensive periods of time without performance deterioration when operated and stored in an environment at a vacuum approximately equal to the internal vapor pressure of the heat pipe. This observation identified inward leakage of atmospheric gases as the source of the difficulty. In other experimentation, however, deterioration of performance would occur even when the devices were maintained in a vacuum environment and the conclusion was drawn, that gas emission from the construction materials of the device was responsible for the malfunctions.

Two major sources of noncondensable gases were thereby identified. The gases could be emitted from the materials used for the fabrication, and they could result from inward leakage of atmosphere gases. In the latter case, this inward leakage could be due to gas permeability of the materials themselves or it could have resulted from shortcomings of sealing and fabrication techniques. For convenience of experimentation, some devices had removable covers with "O" ring seals. Also feed-throughs into the interior of the devices for thermocouple wires, required for experimental purposes, were a potential source of leaks.

In order to identify materials suitable to application in space suit heat pipes, potential materials were exposed to hard vacuum in fused all glass containers, equipped with fused-in pressure measuring devices for extended time periods. The pressure rise vs time was recorded (refs. 5 and 6). The purpose of these tests was to eliminate materials from consideration for this application which showed gas emission over extended time periods. The results of these tests were, as far as polymers are concerned, quite discouraging. As refs. 5 and 6 show, too many of the potential materials would emit gases at a rate which could be detrimental to the operation of a heat pipe. The problem was reviewed on the basis of the results obtained and the question raised, whether the conditions imposed on the material were not unrealistically severe.

The interior environment of a heat pipe is not a hard vacuum. To the contrary, it is a vapor environment at a low, but significant vapor pressure. In the case of water as working fluid and the application to a space suit, the vapor pressure would cover the range of approximately 667 to 4800 N/m$^2$ (5 to 36 mm of mercury). A device was developed to test potential materials in this, more realistic, vapor environment. The tests and the results of these tests are reported in ref. 6. Suffice to say that as a result of this test it was found that only very few of the potential materials emitted gases at an objectionable rate.

The problem of gas permeability of heat pipe external enclosure materials was critical for the development of flexible heat pipes.

In experimentation with flexible heat pipe devices, inward leakage of atmosphere gases was extensively observed as reported in the chapter on flexible heat pipes and in refs. 2 and 6. A laminate of polyester, aluminum foil and a vendor proprietary heat-sealable layer was, up to the time of this writing, the least permeable external enclosure film for flexible heat pipes.

Within the scope of the effort covered by this report, no attempt could be made to develop new materials for the specific application and materials were selected from commercially available stock. These materials had been tailored by their manufacturers to applications other than the application to space suit heat pipes. For example, the aluminum-polymer laminate mentioned above is manufactured for purpose of food packaging, i.e. an application where impermeability to gases is of no importance. It is believed that laminates can be tailored for application to flexible heat pipes which will possess much improved properties. The approach suggested is to laminate polymers with low permeability to the specific gases contained in the atmosphere and possibly combine them with high grade aluminum film. This approach is discussed in detail in ref. 6.

## FLEXIBLE HEAT PIPES

The purpose of the de elopment of flexible heat pipes was to provide devices capable to thermally connect the human skin with the temperature-controlled shell of a hard space suit The man's skin can not be brought into direct contact with the hard space suit shell as has been explained in the introduction. The gap between the body surface and the internal surface of the space suit shell may be of the order of one to two inches. It is, therefore, required to provide devices which will contact the skin, not cause any discomfort, be capable to receive metabolic heat from the body by conduction and transmit it to the variable thermal conductance shell of the hard suit. The various approaches conceivable, such as for example padding, attached to the space suit shell which would contact the skin when the shell is closed, or an undergarment separately donned and either plugged into or in thermal contact with the space suit shell have one thing in common: They require flexible heat transmission devices and, if heat transmission shall be performed without power penalty by the use of heat pipes, they require flexible heat pipes.

These devices will be located within the pressurized space suit shell. They will be exposed to internal space suit pressure and be in contact with the space suit atmosphere. The flexible devices must, therefore, be capable to resist the internal suit pressure without collapsing and they furthermore must not contaminate the suit atmosphere during normal operation or as result of a localized failure.

In order to be flexible, the devices must be built of plastic or elastomeric films. Such films differ widely in their permeability to various gases and vapors, but it is safe to assume that even the most careful selection would not result in a film absolutely impermeable to the vapors of the working fluid.

Water was, therefore, selected as the working fluid for these heat pipes. Leakage of water vapor in small amounts into the space suit atmosphere would not be objectionable, as this water vapor could readily be handled by the humidity control system of the suit. Even breakage of a flexible heat pipe would have no consequences other than a small local performance degradation. None of the other potential working fluids would be as safe as water in this application.

Water is, aside from safety considerations, a very good working fluid. The temperature range at which the heat pipes in the space suit will operate obviously excludes the high temperature working fluids such as the liquid metals. Ammonia and methyl alcohol would be potential alternatives, but aside from their toxic properties, their performance in the temperature range of the human body would not provide any significant improvement relative to water. Ammonia has furthermore in the range of human body temperature a high saturation pressure, which would exclude it from application.

For the application to flexible heat pipes in the pressurized atmosphere of a space suit, the use of water does, however, cause one serious difficulty. In the range of human body skin temperature or below, the internal pressure of the flexible heat pipes would be significantly lower than the internal suit pressure. Internal pressure in present space suits using an oxygen atmosphere is in the order of $24 \times 10^3$ N/m$^2$ (3.5 psia). The space suit under development by the NASA/Ames Research Center will probably eventually operate with gas mixtures at higher pressures, maybe up to one atmosphere. The working fluid in a heat pipe is in a saturated condition due to the simultaneous presence of the liquid and the vapor phase of the fluid. At 33° C (average human skin temperature), the internal pressure in a heat pipe would be in the order of only $4.8 \times 10^3$ N/m$^2$ (0.7 psia).

This pressure relationship between the internal and external pressure requires that flexible heat pipes for this application be made noncollapsible under the effect of external pressure. Devices known to be flexible, yet noncollapsible, include convoluted bellows and hoses supported with wire spiral inserts. These devices are circular in cross section and usually quite heavy walled.

For application to the space suit, devices are required which can have relatively large surfaces in contact with the skin and, possibly, with the space suit shell. Flat, thin panels are desirable. These panels require internal support by structures which are capable to keep wick and vapor flow passages open, yet permit flexibility of the device. Such panels could also be assembled from small diameter tubular devices, arranged in parallel rows.

In the performance of the research activities directed towards development of flexible heat pipes, using water as a working fluid and suitable for operation under up to one atmosphere external pressure, both approaches were studied.

Panels were developed which used for internal support a woven structure, which can be described as a "three-dimensional fabric." This fabric is commercially available and is woven from plastic fibers of different material characteristics. Two different fibers are applied along the length of the fabric and another fiber across its width. When temperature processed, one of the longitudinal fibers shrinks more than the others. As a result of this contraction along its length, the fabric "puckers" and gets its third dimension. The result of this process looks like corrugated cardboard made of screen material. It has large pores in all directions and the corrugated core forms a multitude of parallel channels, like the channels in corrugated cardboard. The material is available in various dimensions, degrees of flexibility and resistance against collapsing under pressure, made from various polymeric materials. It has had previous use in space suits for internal support of ventilating gas channels.

In its application to flexible heat pipes, it was applied between layers of polymeric enclosure films for the purpose of providing an open cavity for vapor flow and wicks, when under internal vacuum and external pressure.

Two methods of internal support were used in connection with the concept of small, tubular flexible heat pipes. One method applied a spiral spring as internal support. Heat-shrinkable tubes were used as external enclosure and the wick was located between the supporting spring and the external tube.

The other approach to a tubular, flexible heat pipe applied an internal support consisting of a rod of hard, yet bendable plastic with a cross-shaped cross section. Wick and vapor passages were provided by the triangular channels formed by the arms of the cross. Heat-shrinkable tubing was used as external enclosure. These heat pipes, after being evacuated had a square cross section, with the enclosure film under tension between the arms of the cross-rod support.

Figure 5 shows a schematic of a heat pipe using a spiral spring for internal support. In this heat pipe a braided, tubular, quartz fiber wick was put over the spring and the wick and spring assembly then pushed inside a heat-shrinkable irradiated polyolefin tubing. A rigid tube for evacuation and filling of the device was fitted into one end of the polyolefin tube and the device heat treated.

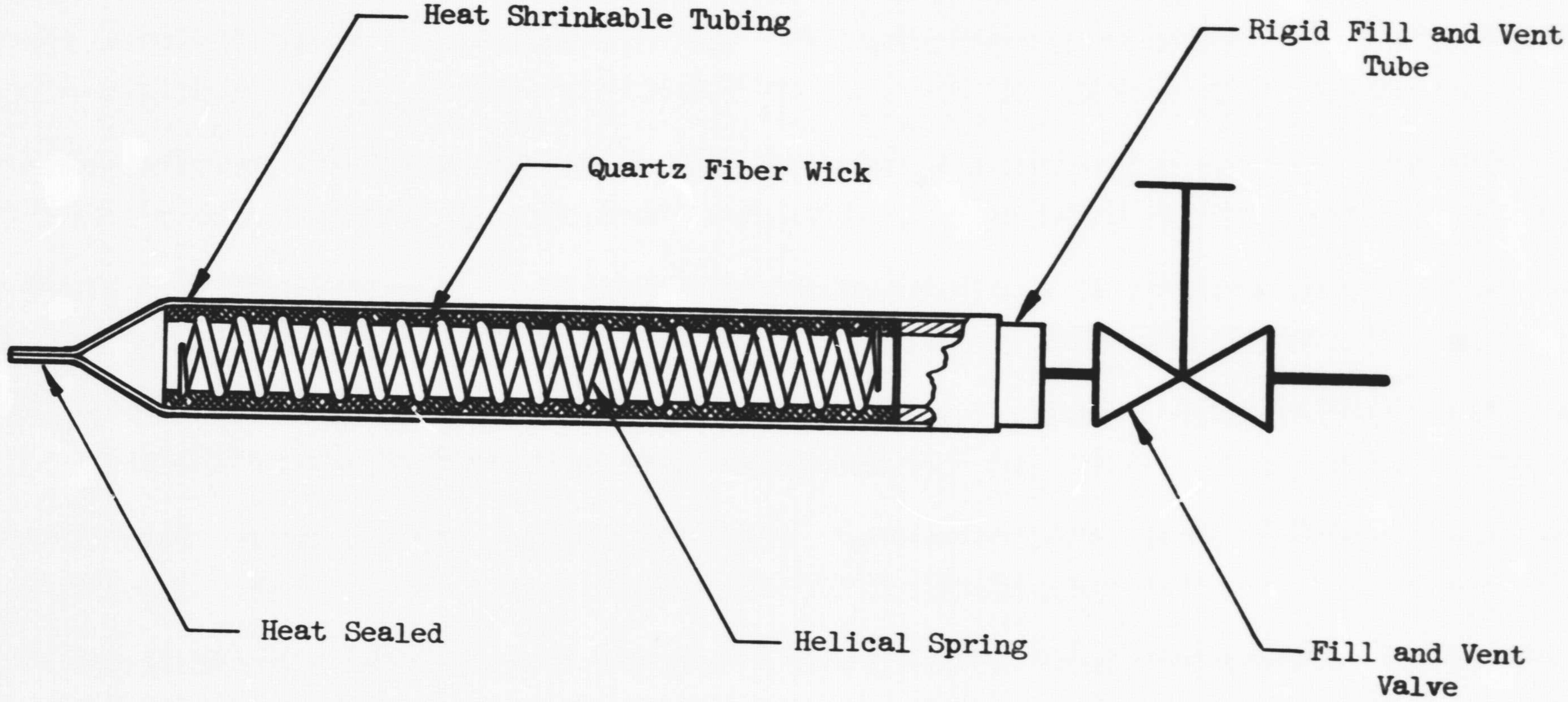



FIGURE 5 - FLEXIBLE HEAT PIPE - SPRING SUPPORTED

The heat-shrinkable polyolefin tubing was thereby shrunk tightly around the spring, wick and fill tube. The free end of the tube was flattened and heat-sealed.

This device did not perform satisfactorily as a heat pipe. One reason for the malfunction may have been that the wick along its contact with the spiral spring was "choked" due to the external pressure. A wick, when compressed, will not perform well and capillary pumping can be completely inhibited by mechanically applied pressure. The liquid in the wick had, therefore, to be capillary pumped in a spiral path along the gap between the spring wire. This path was excessively long and capillary pumping was greatly reduced.

It was demonstrated in further experimentation that the polyolefin tubing is highly permeable to atmospheric gases. Presence of noncondensable gases may have been another cause for the poor performance of the device. This approach was not further pursued, although it is quite possible that given a different arrangement of the wick it might have been successful.

The idea to use a spiral spring for support of a tubular, flexible heat pipe was borrowed from the spiral spring-supported vacuum hoses. Further thought resulted in a different approach which seemed more suitable to application in heat pipes.

A spiral spring-supported hose or flexible tube will, when evacuated, not collapse because the flexible enclosure material will be under tension between the wires of the spring.

The same effect of providing support points to a flexible polymer film, such that the film is under tension between support points, can be achieved by supports parallel to the axis of the tube. The concept of a rod with the cross section of a cross, star or gear, supporting a tube against collapsing resulted from these considerations. This rod would be made from a plastic which, when of small diameter, would readily bend. Such plastics include TFE (polytetrafluoroethylene) and nylon (polyamide).

It was initially attempted to find commercially available extruded rods, in the belief that gears used in toys and fishing reels are cut from such extrusions. When it appeared that such extrusions are not readily available, the necessary profiles were machined out of solid stock.

For simplicity of machining, the cross section of a cross was used. The actual dimensions were somewhat larger than those envisioned for final application of this concept and selected to fit readily available heat-shrinkable tubing. Several rods of approximately 30 cm length and 0.6 cm across the arms of the cross were machined from TFE and used in the experimentation.

The thought underlying this design was that a wick put between the cross-support rod and the enclosure film would be choked only along four longintudinal lines, rather than along a spiral line as was the case in the application of a spiral spring as support. The heat pipes so assembled had four parallel, longitudinal strips of effective wick and four open vapor flow channels of triangular cross section (fig. 6).

This approach showed limited success. The major difficulty experienced was that the external enclosure films used were fairly permeable to atmospheric gases and, therefore, rapid performance deterioration occurred as result of the penetration of these gases into the heat pipe cavity. The external enclosure films used included heat-shrinkable tubing of irradiated polyolefin and irradiated FEP.

Inward leakage of atmosphere gases was identified as the cause of unsatisfactory performance by the following observations: As long as the heat pipes were operated in the one atmosphere laboratory environment, heat pipe performance deteriorated with time. Venting of noncondensable gases from the condenser end of the heat pipes reestablished normal performance. When the same heat pipes were operated inside a vacuum chamber at an air pressure approximating the water vapor pressure inside the heat pipes, performance deterioration with time was nearly eliminated. It is worth noting that repeated venting did not result in loss of working fluid sufficient to cause noticeable performance degradation.

Figure 7 shows a comparison of performance deterioration as function of time between irradiated polyolefin and irradiated FEP. While the deterioration of the better performing FEP heat pipe still excludes it from practical application, it is demonstrated that the device did operate as a heat pipe and that the concept of cross-rod or star-rod supported flexible heat pipes would be practical, provided an enclosure material of sufficiently low gas permeability for use as external enclosure film would be developed. Parallel arrangements of such heat pipes of, maybe, 0.2 cm diameter, supported by an undergarment would provide excellent flexibility and good comfort when in contact with the human skin.

The heat-shrinkable tubing was used because it was convenient for assembly. Tubes with lower gas permeability which would permit

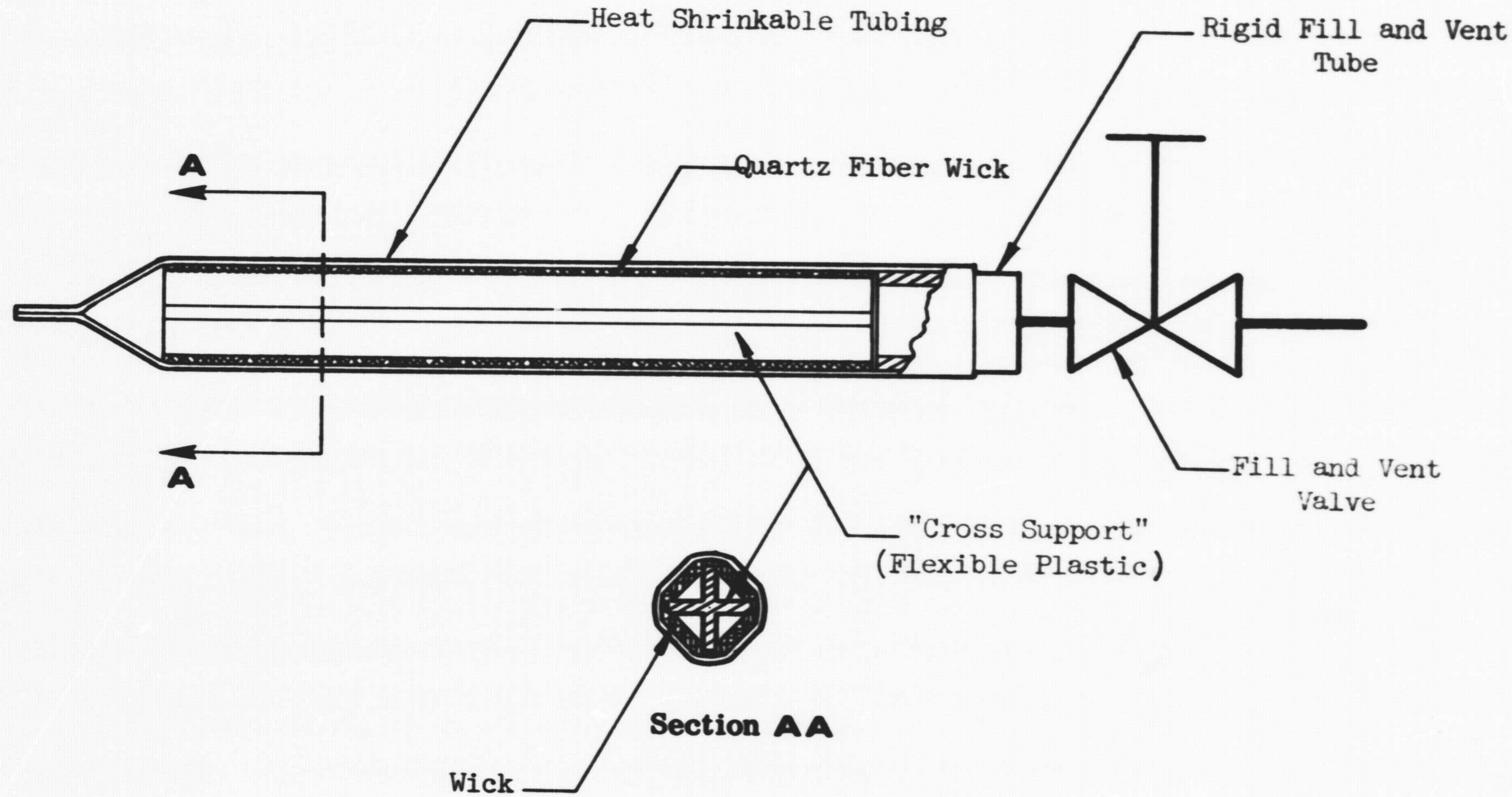



FIG. 6 - FLEXIBLE HEAT PIPE – CROSS-ROD SUPPORTED

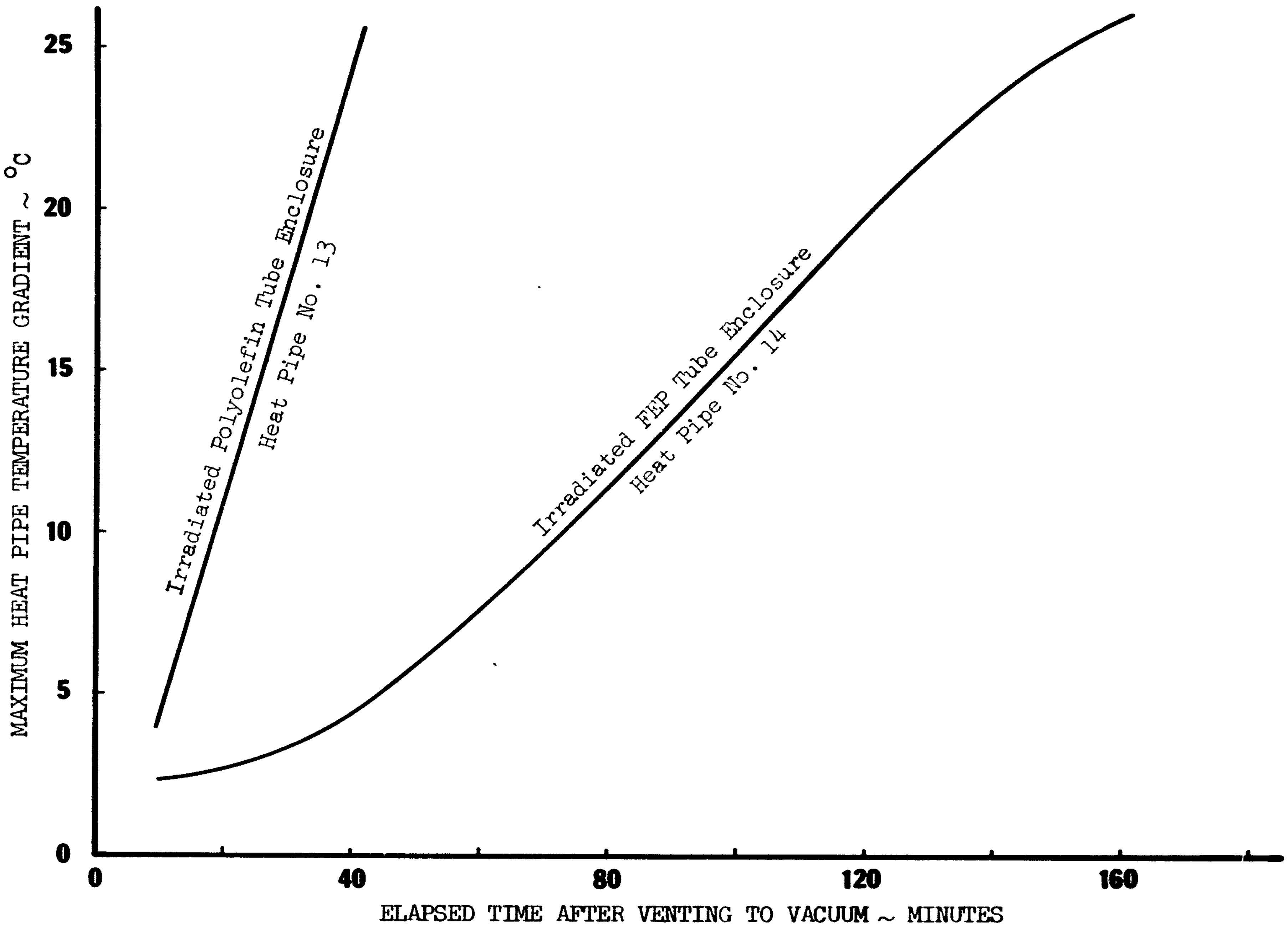



Figure 7 PERFORMANCE DETERIORATION OF FLEXIBLE HEAT PIPES RESULTING FROM INWARD LEAKAGE OF AIR

similar convenient assembly of heat pipes could not be readily identified.

In the parallel effort to develop flat heat pipe panels with three-dimensional fabric support, similar problems of inward leakage of atmosphere gases were encountered. It was, however, apparent that the available number of flat polymer films was much larger than that of polymer tubing. It was decided to concentrate on development of three-dimensional fabric supported flat panels and to abandon efforts for the development of cross-rod supported flexible, tubular heat pipes.

The flat panel heat pipes applied single or multiple layers of three-dimensional fabric, for internal support. In order to avoid wick choking, the wicks were located inside the channels formed by the corrugated layer of the three-dimensional fabric. The wicks were located in alternating channels, while other channels were left empty in order to provide adequate vapor flow passages. Figure 8 shows a schematic cross section through a layer of three-dimensional fabric with alternating wick filled and open vapor flow channels. The three-dimensional fabric and wick assembly was heat-sealed between two layers of a flat polymer film. A small flanged tube machined from polyethylene rod was heat-sealed to the enclosure film and served as evacuation and fill connection (fig. 9).

The polymer films applied included commercially available films of polyethylene-polyester, nylon-saran-polyester and laminates of aluminum foil and polymer films.

Table 1 provides a summary of the major characteristics of 18 flexible heat pipes of tubular or panel design which were fabricated for experimental purposes. Figure 10 shows a schematic of an experimental arrangement used for performance evaluation. As stated above, tests were performed with the flexible heat pipes either inside a bell jar, evacuated to approximately the average water vapor pressure existing inside the heat pipes or under exposure to the one atmosphere laboratory environment. Heat was supplied to the evaporator of the devices by electric resistance heaters and removed from the condenser by a block of copper, drilled for internal circulation of chilled water. Thermocouples were located along the heat pipe and the temperature distribution along the heat pipe surfaces was recorded. If after the initial evacuation and filling procedure, a temperature gradient along the heat pipe was observed which indicated improper functioning, the heat pipe was vented to vacuum for 10 to 15 seconds from the vent and fill connection, located at the condenser end of the device. Venting

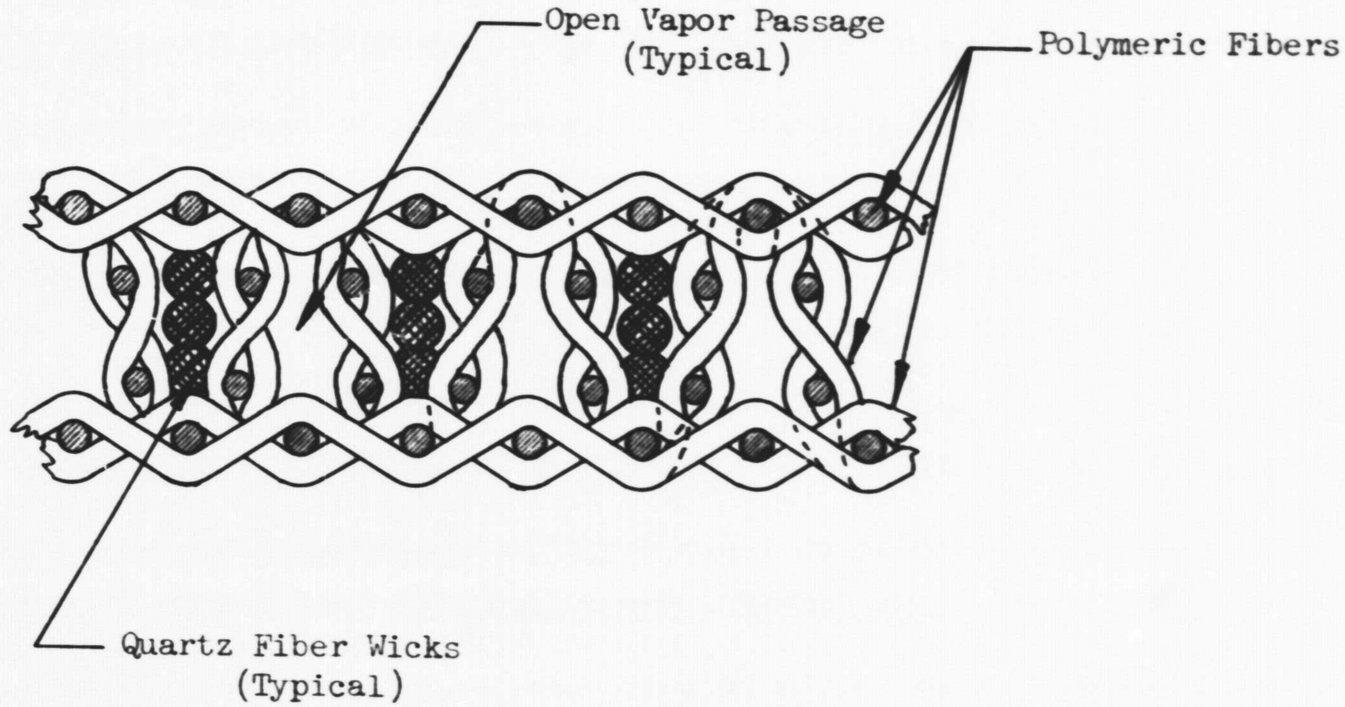



**FIGURE 8 - SCHEMATIC CROSS SECTION THROUGH TYPICAL THREE-DIMENSIONAL FABRIC WITH WICKS IN ALTERNATING CHANNELS**

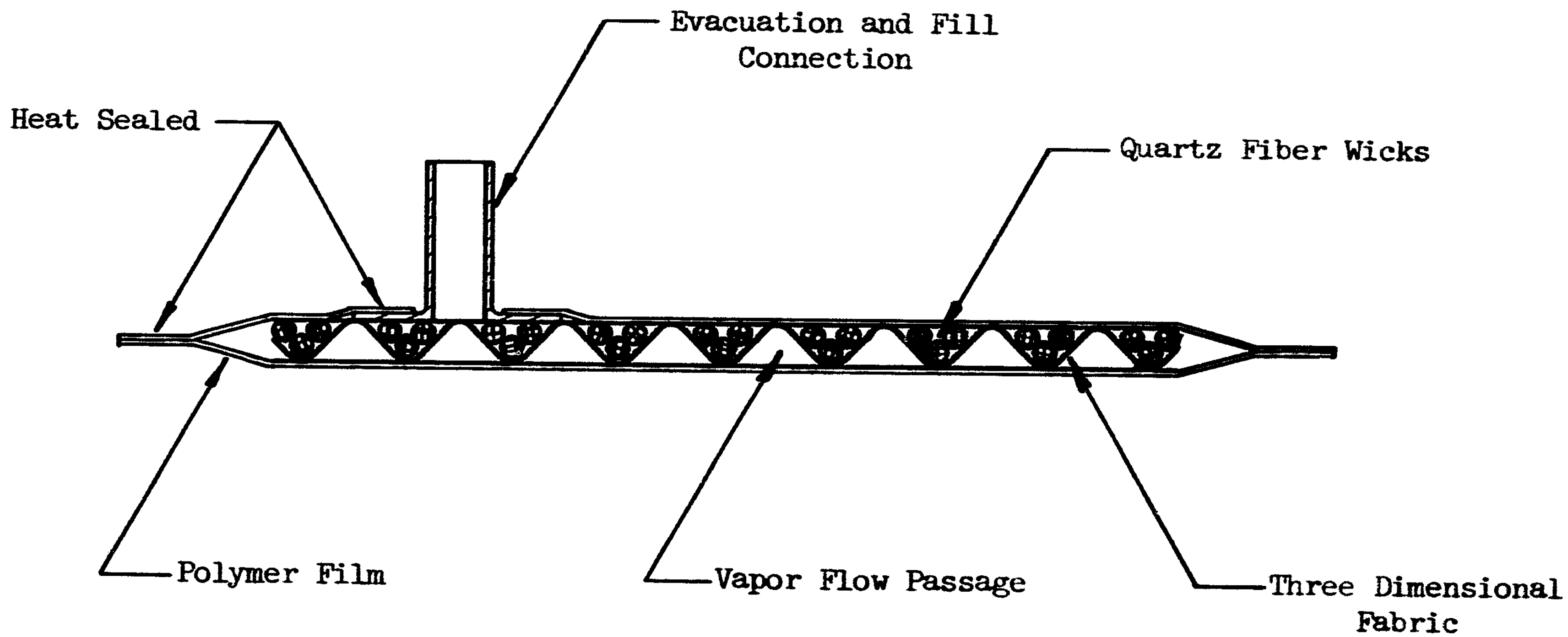



**FIG. 9 – FLEXIBLE HEAT PIPE PANEL, SCHEMATIC CROSSECTION**

Table I, Characteristics of Experimental Flexible Heat Pipes

| Heat Pipe No. | Internal Support | Enclosure | Wick | Overall Dimensions, mm |
|---|---|---|---|---|
| 1 | Three-dimensional fabric | polyethylene-polyester film, heat sealable 0.11 mm thick | quartz fiber thread, 4 threads per channel in every channel | 70 x 40.6 x 2.5 |
| 2 | Three-dimensional fabric | polyethylene-polyester film, heat sealable 0.11 mm thick | quartz fiber thread, 4 threads per channel, 2 out of every 3 channels filled | 72.5 x 34 x 2.5 |
| 3 | Three-dimensional fabric | nylon-saran-polyethylene film, 0.09 mm thick, heat sealable | quartz fiber thread, 4 threads per channel, every other channel filled | 68.5 x 37 x 2.5 |
| 4 | Three-dimensional fabric | polyethylene-polyester film, 0.11 mm thick, heat sealable | quartz fiber thread, 4 threads per channel in every other channel. Quartz fiber batt used to fill voids between support and enclosure film | 152 x 38 x 2.5 |
| 5 | Three-dimensional fabric | polyethylene-polyester film, 0.11 mm thick, heat sealable | quartz fiber thread, 2 threads per channel, 2 out of every 3 channels | 152 x 38 x 2.5 |

Table I, Characteristics of Experimental Flexible Heat Pipes (Cont'd)

| Heat Pipe No. | Internal Support | Enclosure | Wick | Overall Dimensions, mm |
|---|---|---|---|---|
| 6 | Triple layer of three-dimensional fabric of different pore sizes | polyethylene-polyester film, 0.11 mm thick, heat sealable | braided quartz fiber tubing, 0.7 mm o.d. One strand in every channel of outer support layers | 148 x 36.5 x 4.8 |
| 7 | Triple layer of three-dimensional fabric of different pore sizes | polyethylene-polyester film, 0.11 mm thick, heat sealable | braided quartz fiber tubing, 0.7 mm o.d. One strand in every channel of outer support layers | 148 x 36.5 x 4.8 |
| 8 | TFE rod with cross-shaped cross section | heat shrinkable irradiated polyolefin tubing | braided quartz fiber tubing, 9.5 mm o.d. | 203 x 8.7 x 8.7 |
| 9 | Helical spring | heat-shrinkable irradiated polyolefin tubing | braided quartz fiber tubing, 9.5 mm o.d. | 89 x 12 dia. |
| 10 | Helical spring inside stainless steel wire screen | heat-shrinkable irradiated polyolefin tubing | braided quartz fiber tubing, 9.5 mm o.d. | 114 x 8 dia. |
| 11 | Helical spring inside braided oxidized copper wire "shielding" sleeve | heat-shrinkable irradiated polyolefin tubing | braided quartz fiber tubing, 9.5 mm o.d. | 82.5 x 12 dia. |

Table I, Characteristics of Experimental Flexible Heat Pipes (Cont'd)

| Heat Pipe No. | Internal Support | Enclosure | Wick | Overall Dimensions, mm |
|---|---|---|---|---|
| 12 | Three-dimensional fabric | polyester-saran-polyester film, heat sealable | quartz fiber thread, 2 threads per channel, 2 out of every 3 channels filled | 152.5 x 38 x 2.5 |
| 13 | Stainless steel rod of cross-shaped cross section (not flexible, for performance evaluation only) | heat-shrinkable, irradiated polyolefin tubing | braided quartz fiber tubing, 9.5 mm o.d. | 203 x 8.9 x 8.9 |
| 14 | Stainless steel rod of cross-shaped cross section (not flexible, for performance evaluation only) | heat-shrinkable, irradiated FEP tubing | braided quartz fiber tubing, 9.5 mm o.d. | 203 x 9.6 x 9.6 |
| 15 | Stainless steel rod of cross-shaped cross section (not flexible, for performance evaluation only) | heat-shrinkable, irradiated FEP tubing | braided quartz fiber tubing, 9.5 mm o.d. | 241 x 9.6 x 9.6 |
| 16 | Three-dimensional fabric | polyethylene-saran-polyester film, heat sealable | braided quartz fiber tubing, 0.7 mm o.d. 2 strands per channel every other channel | 152 x 38.1 x 2.5 |

Table I, Characteristics of Experimental Flexible Heat Pipes (Cont'd)

| Heat Pipe No. | Internal Support | Enclosure | Wick | Overall Dimensions, mm |
|---|---|---|---|---|
| 17 | TFE rod with cross-shaped cross sections | heat-shrinkable, irradiated FEP tubing | braided quartz fiber tubing, 9.5 mm o.d. | 203 x 8.4 x 8.4 |
| 18 | Three-dimensional fabric | 0.012 mm polyester-0.012 mm aluminum-0.073 mm vendor proprietory heat sealing layer | braided quartz fiber tubing, 0.7 mm o.d. 2 strands per channel, every other channel | 152 x 38.1 x 2.5 |

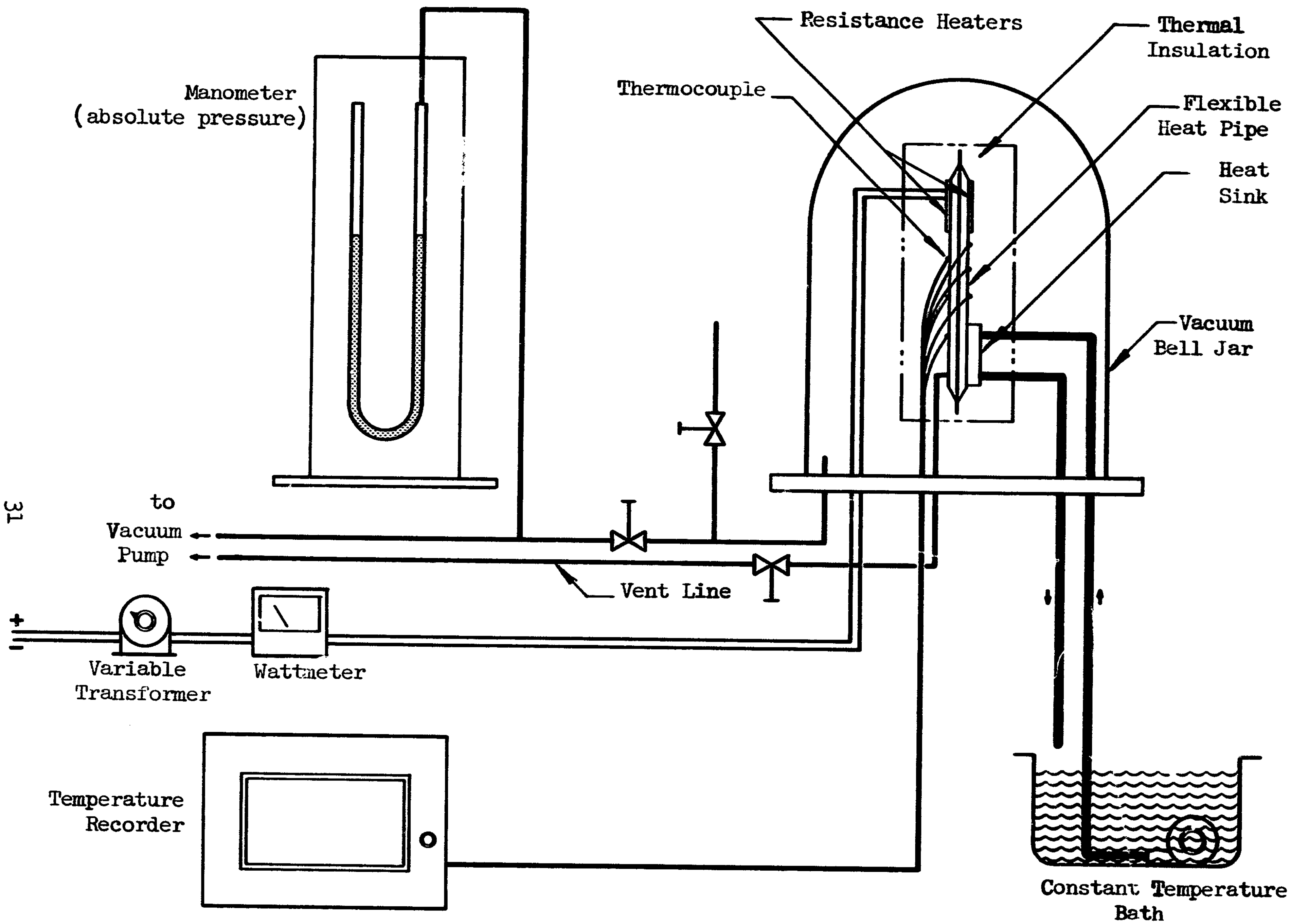



**FIG. 10 SCHEMATIC OF EXPERIMENTAL ARRANGEMENT FOR PERFORMANCE TESTING OF FLEXIBLE HEAT PIPES**

usually restored near isothermal operation of the device, indicating that improper function was caused by presence of noncondensable gases.

Performance of the devices was entirely dependent on gas permeability of the enclosure film. Practically all of the devices would show satisfactory performance immediately after venting of noncondensable gases to vacuum. In the tests performed in the one atmosphere environment, the time until performance degradation became apparent differed with the type of enclosure film. The best results were obtained with a commercially available aluminum-polymer laminate. This enclosure film was applied to heat pipe no. 18.

A maximum heat pipe temperature gradient of $5^{\circ}$ C was arbitrarily selected for comparative evaluation as the upper limit of what was considered "satisfactory performance." Figure 11 shows performance of heat pipe no. 18 as a function of time at three different power input levels. The drastic difference between performance after eight days for the different power input levels, is typical for the behavior of heat pipes when noncondensable gases are present in the heat pipe cavity.

The temperature gradient between the external surfaces of a heat pipe (at the condenser and evaporator) is almost entirely due to the thermal resistance between the external surface and the evaporating or condensing liquid-vapor interface. This temperature gradient will, for a given resistance, be a function of heat flow. The noncondensable gas layer represents an additional (and relatively large) resistance element, causing an increased temperature gradient, which is, however, still dependent on rate of heat flow.

The same heat pipe (no. 18) was operated in a vacuum environment approximately matching the internal vapor pressure in the heat pipe. Figure 12 shows performance, as expressed by temperature gradient, vs time in the reduced pressure environment. At the same power levels, performance remained satisfactory for the full duration of the test run of nine days. Only a very slight deterioration in performance could be observed over this time period. Comparison of the performance deterioration under exposure to the laboratory atmosphere and the controlled air pressure inside a vacuum bell jar confirms that it is inward leakage of atmosphere gases which is the major cause of performance deterioration of flexible heat pipe devices.

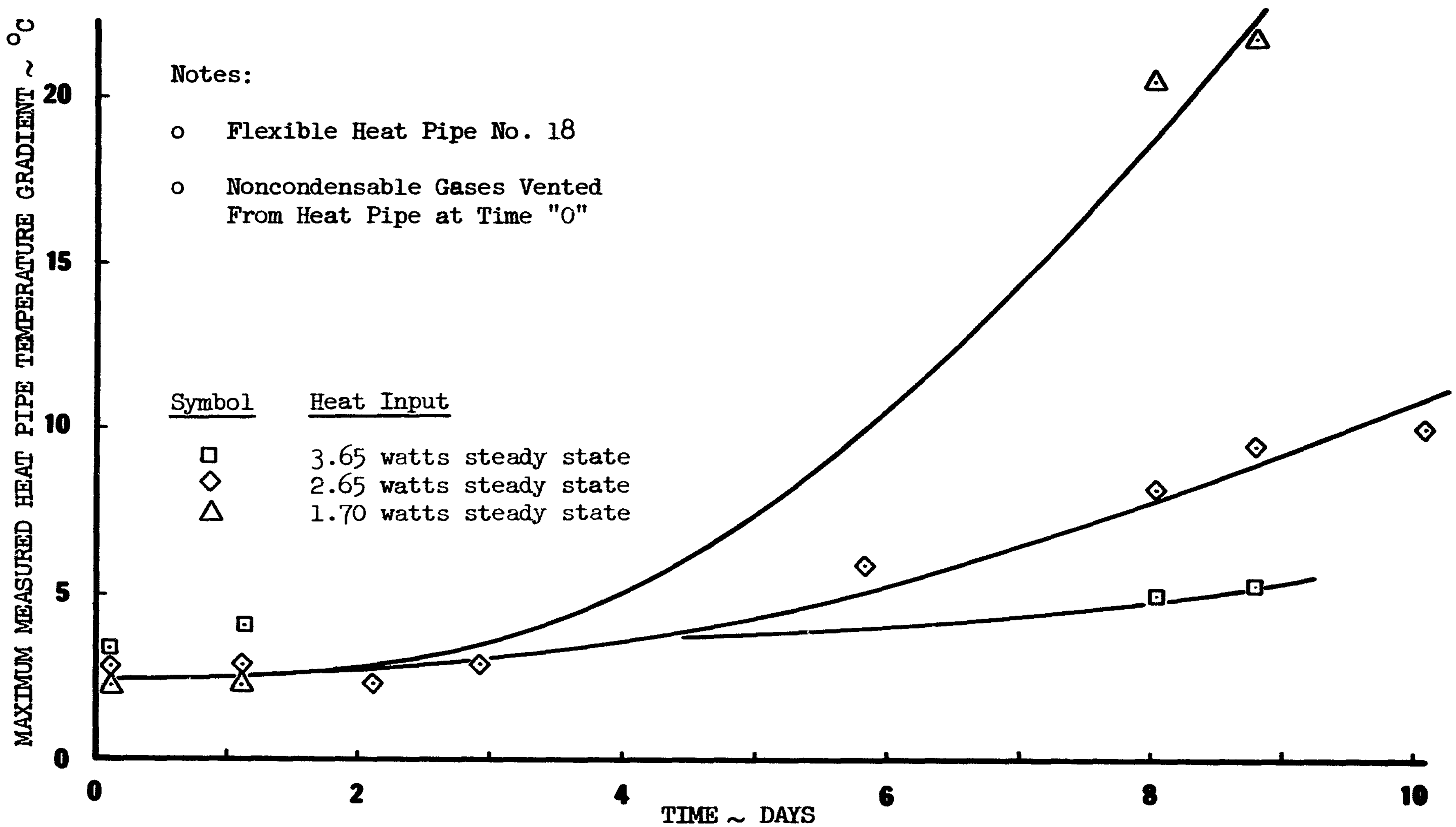



Figure 11 - FLEXIBLE HEAT PIPE PERFORMANCE vs TIME IN ONE ATMOSPHERE PRESSURE ENVIRONMENT

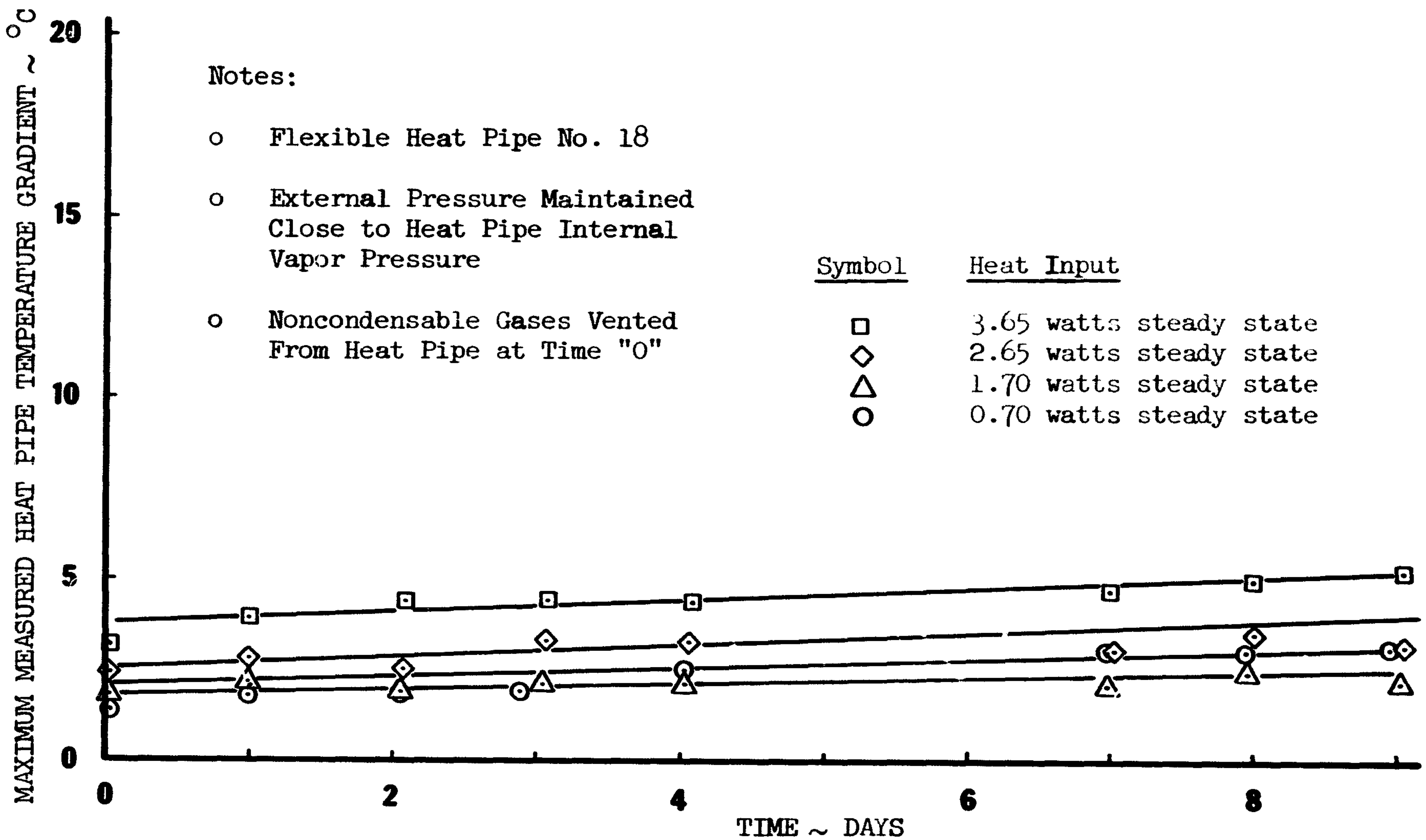



Figure 12 - FLEXIBLE HEAT PIPE PERFORMANCE vs TIME IN REDUCED PRESSURE ENVIRONMENT

The experimentation performed confirmed suitability of design configuration and feasibility of flexible heat pipes, which use water as a working fluid and operate under external atmosphere pressure. The remaining problem is one of material development.

The material used for heat pipe no. 18 is a laminate of polyester, a 0.012 mm aluminum foil and a heat sealing layer, proprietary to the manufacturer of this material. The material is produced for the purpose of food packaging and the manufacturer is in no way interested in making it impermeable to gas. The aluminum foil is of commercial quality and most probably contains tiny pinholes as a result of impurities. Such impurities will, when the material is rolled into a thin foil, penetrate through the thickness of the foil, allowing passage of gas molecules.

The scope of the present program did not permit development of new materials. It is, however, believed that flexible laminates of very low gas permeability can be developed.

Various polymer films have known permeability to specific gases. A laminate could be developed from polymers of low permeability to the specific gas molecules. Such laminates could, if necessary, include metal films rolled from high purity metals. Materials problems are more fully discussed in the Material Research Report, Second Year, ref. 6, prepared under the same contract.

## FREEZE PREVENTION OR RESTART TECHNIQUES FOR FROZEN HEAT PIPES

The advantage of the use of water as working fluid in space suit heat pipe systems has been discussed in preceding chapters of this report. It was stated that, aside from the absence of toxic properties and inflammability, water is also an efficient working fluid in regard to its heat transmission in a heat pipe. Water as heat pipe working fluid has, however, a serious shortcoming for application to space suits. The external surface of a space suit will, during extravehicular activities at times get far colder than the freezing point of water and water, in a heat pipe close to the external surface, would freeze.

The capability of the external surface of a hard space suit to reject heat by radiation to space has been evaluated in ref. 1. Using the model of a space suit, from ref. 1, i.e. an external area effective for thermal radiation of 1.7 $m^2$ (18.43 sq. ft.) and a thermal emissivity of 0.88, it can be calculated that approximately 1700 x $10^3$ J (1610 Btu) per hour will be emitted from the suit at $0^{\circ}$ C surface temperature. This amount of emitted heat will balance radiant heat inputs into the suit surface as well as metabolic heat. Assuming an attitude of the astronaut resulting in solar irradiation of the largest projected area of the suit, no other radiant heat inputs from planetary surfaces or nearby spacecraft, and again using the assumptions and suit model from ref. 1, the surface of the suit will cool down to $0^{\circ}$ C when the metabolic rate drops to approximately 913 x $10^3$ J (865 Btu) per hour.

In the case of an astronaut, operating on the moon during the lunar night, the warmest element of the external environment is the lunar surface at or below -160° C. There are, therefore, no significant radiant heat inputs from the external environment and the temperature of the external suit surface would reach the freezing point of water at a metabolic rate of approximately 1700 x $10^3$ J (1610 Btu) per hour. The above figures show that the external suit surface will be below the freezing point of water under conditions which are not at all extreme or improbable in regard to metabolic rate or the thermal radiation environment.

The astronaut in his space suit will be protected from excessive heat loss by the thermal insulation layer, which is a component of any type of extravehicular space suit. This insulation layer will maintain a large temperature gradient and it can be safely assumed that the temperature on the body side of this insulation layer will never be below the freezing point.

The application of water in the heat pipes on the body side of the insulation layer will, therefore, not present a problem. A suit system concept where separate heat pipes are used internal and external to the pressure shell as shown in fig. 4 appears, therefore, attractive. A low freezing point working fluid would be applied to the variable thermal conductance space suit shell and water used for the flexible heat pipes within the pressure shell. Heat transfer across a single pressure shell layer would be by thermal conduction. While the variable thermal conductance space suit shell heat pipes have one chamber on the body side of the thermal insulation layer, the vapor transfer valve would under low temperature conditions be closed or in a throttling position. A sufficiently high temperature would thereby be maintained in the chamber at the body side of the thermal insulation layer and low temperatures occur only in the chamber located at the external suit surface.

Concepts of space suit systems such as the one shown in fig. 3, where a heat pipe with a single cavity transmits heat from the skin of the astronaut to the external suit shell have, however, been considered. An arrangement of this type would, with the vapor transfer valve open, permit maximum heat rejection with a minimum temperature gradiant between the skin and the external space suit surface.

It can furthermore not be assumed that safety considerations can be disregarded in selecting a working fluid for the heat pipes external to the suit pressure shell. The limitations as to non-toxicity and nonflammability of the working fluid will undoubtedly, at least in part, apply to the heat pipes located external to the pressure shell of the suit. The extent to which they will be applicable will depend, for example, on the storage location of the suit in the spacecraft. If the suit is stored inside the manned cabin, essentially the same restrictions as for the space suit interior will apply. If the suit is stored in an air-lock section, which would be normally unmanned and be pressurized for astronaut transfer only, a relaxation of working fluid safety requirements could be considered.

These considerations led to recognition of the need for safe, noncombustible working fluids, or for techniques permitting application of water or predominantly aqueous solutions under low temperature conditions.

Two basic approaches were considered:

- Prevention of freezing of the working fluid. This approach would apply low freezing point fluids or fluid mixtures, applicable to heat pipe operation.

- Acceptance of freezing of the working fluid. This approach requires techniques for restart of heat pipes after freezing, when heat load and temperature at the evaporator (body side) increase. Without such provisions a heat pipe, after freezing of the working fluid, will not readily restart for reasons discussed in the following.

In order to prevent freezing of the working fluid in a heat pipe, the first approach would be to select a working fluid with a freezing point below the lowest temperature to which the condenser of the heat pipe would be exposed. This temperature, in the case of the space suit, is of the order of -80° C.

A brief review of potential fluids shows that the choice is rather limited and that none of these fluids has very desirable properties. A comparison of working fluids and a parametric expression for working fluid evaluation can be found in ref. 1. This reference shows, that working fluids should have high heat of vaporization, density and surface tension, and low viscosity. The parametric expression compares the working fluids on the basis of the ability of the wick to provide capillary pumping. The higher the heat of vaporization and density, the more heat can be transmitted per unit volume of liquid, pumped by the wick A given wick will further be capable to pump more liquid if the fluid surface tension is high and the resistance to flow, resulting from viscosity is low.

Reference 1 shows that on this basis, for the temperature range of space suit applications, ethyl and methyl alcohol, and ammonia have relatively good performance characteristics, although they fall far short of water. Obviously, ammonia can not be considered because of its high vapor pressure, toxicity and flammability. The alcohols, while less objectionable than ammonia, are also toxic and flammable. Other working fluids with low temperature characteristics include refrigerants of the halogenated hydrocarbon type. These refrigerants are nontoxic and nonflammable, although they may break down into toxic components in case of fire or when passing through a catalytic trace contaminant oxidizer. These refrigerants are not very good performers in heat pipes. They are difficult to pump by capillary action because of their low surface tension and their heats of vaporization are small. They may, however, be the most acceptable choice for application in heat pipes exposed to low temperatures, unless better techniques can be developed.

The above considerations stimulated a search for other approaches to a solution to the low temperature problem. The thought occurred whether it would be possible to prevent freezing of water at low temperatures by the use of freezing depressing additives. This required in the first place an evaluation of the behavior of fluid mixtures in heat pipes.

The performance of a mixture of two fluids in a heat pipe will depend on the vapor pressure relationship between the fluids. Mixtures of methyl alcohol and water have been used in many applications as low freezing point heat transport fluids. If, for example, such a mixture would be applied as heat pipe working fluid, the vapor in the heat pipe would be a mixture of water and methyl alcohol vapors at a volume ratio corresponding to the saturation vapor pressures of the two fluids. As methyl alcohol has a higher vapor pressure than water, the vapor would contain a large fraction of methyl alcohol vapors and a relatively small fraction of water vapor.

At 0° C the volume fraction of methyl alcohol in the vapor would be 36.6 percent. This large fraction of methyl alcohol in the vapor would deprive the water remaining in the wick of most of the anti-freeze protection for which the methyl alcohol addition was intended. Too large a fraction of methyl alcohol would be required in the working fluid mixture to provide freeze protection. The working fluid would consist predominantly of methyl alcohol and the small fraction of water present would not significantly reduce the flammability of the mixture, nor would the small percentage of water vapor taking part in the heat-mass transfer process contribute significantly to the performance of the heat pipe. The conclusion can be drawn that freezing point depressants should have a low vapor pressure.

The search for potential freezing point depressants resulted in the identification of normal propyl alcohol (propanol-1) as a potential freezing point depressant with a vapor pressure curve which, above 0° C, is almost identical to that of water. Propanol-1 has a freezing point of -127° C. Data available in the literature on the freezing points of mixtures of water and propanol-1 were inadequate. A series of tests to determine freezing points at a number of mixture ratios was performed in order to generate a complete curve of freezing point vs concentration.

These efforts and their results are presented in refs. 2 and 6. The freezing point depression obtainable by addition of propanol-1 to water at relatively small concentrations were insufficient. In order to obtain the required freezing point of -80° C, more than 90 percent propanol-1 concentration would be required. A limited search for other potential freezing point depressants with the desired vapor pressure vs temperature characteristics failed to identify any other obviously promising additives.

A possibility for prevention of heat pipe freeze up by the use of freezing point depressants would be the use of additives of a vapor pressure much lower than that of water. This approach has at the time of this writing not been experimentally or analytically investigated. On a qualitative basis it is, however, believed that the application of a mixture of water with a low vapor pressure additive as heat pipe working fluid would result in a situation inverse to that described for the water-methyl alcohol mixture.

Water with its higher vapor pressure would be the major component of the vapor phase of the working fluid mixture. The additive would remain predominantly as liquid in the wick, at a concentration higher than the initial mixture ratio. It could therefore effectively depress the freezing point. Glycols and glycerol may be suitable additives.

Potential problems of this approach are that the presence of a high concentration of the freezing point depressant in the wick could interfere with the capillary pumping of water or, that the additive will, by the flow of water in the wick, be flushed to the evaporator, resulting in an insufficient concentration at the condenser. The whole problem area of behavior of working fluid mixtures in heat pipes has, at this time, not been sufficiently explored to permit theoretical prediction of the performance of heat pipes with mixed working fluids at a sufficient level of confidence. So far, a theoretical evaluation of the behavior of mixtures in regard to their heat transmission capability and freezing point depression was performed as an initial step. Results of this evaluation are presented in the Materials Research Report, Second Year, prepared under the same contract (ref. 6).

An alternate approach to the problem of freezing of the heat pipe working fluid in the proximity of the external space suit surface will not try so much to prevent freezing, but rather promote quick recovery when increasing heat load requires full heat pipe operation. This approach is based on the consideration that freezing will occur only at times when heat rejection capability of the external space suit surface is well in excess of metabolic heat generation. When freeze up occurs a large temperature gradiant must exist between the skin of the astronaut and the external suit surface. With heat pipes providing heat transmission, such a large temperature gradiant is only possible if the vapor transfer valve of the variable thermal conductance space suit shell is partially or totally closed.

Assuming that under such a condition the working fluid in the proximity of the external suit surface has solidified, it could be assumed that, when a larger heat rejection rate is required, the increased heat load would result first in opening of the vapor transfer valve and that then the heat available from the body of the astronaut would initially melt the ice which had been formed, reestablishing thereby normal operation of the heat pipes. Unfortunately, heat pipes have a characteristic which prevents this.

When freezing occurs at the condenser of a heat pipe, the resulting drop in vapor pressure will cause continuing evaporation in the evaporator and flow of vapor to areas of lower pressure, i.e. the condenser. In the variable thermal conductance space suit shell, this flow of vapor would occur with the vapor transfer valve in an open or throttled condition, as long as the valve is not completely closed. The vapor at the condenser will condense and freeze or sublimate to ice. No liquid working fluid will therefore be pumped by the wick to the evaporator. As a result, wick dry out at the evaporator will occur.

Increasing heat input to the evaporator will then not result in heat transmission to the condenser because the wick is dry and no working fluid available for transmission of heat. Experimental data confirming this behavior of frozen heat pipes are presented in ref. 2.

A concept was generated to overcome this difficulty by the use of auxiliary heat pipes internal to the variable thermal conductance space suit shell. These auxiliary heat pipes would use a low freezing point working fluid such as, for example, a refrigerant or alcohol. They would be arranged to be in thermal contact with the wicks, lining the condenser of the heat pipe, at the external space suit surface. Using an inefficient working fluid, the heat transmission performance of the auxiliary heat pipes is expected to be low, but these heat pipes would be designed to be sufficient to transmit enough heat from the body of the astronaut to the frozen sections of the heat pipe to melt some of the working fluid in the wick. This would promote restart of normal heat pipe operation after freeze up, whenever heat input rate in the evaporator increases.

Preliminary experimental investigations as to the practicability of these concepts have had promising results. The experiments performed and results obtained are presented in the "Research Report, Heat Pipe Devices for Space Suit Temperature Control" (ref. 2) prepared under the same contract. Auxiliary heat pipe devices applied to a variable thermal conductance space suit shell are strictly schematically indicated in figs. 3 and 4 of this report.

## AUXILIARY COOLING

As stated in the introduction, radiation from the external suit surface will not under all conditions of operation be sufficient to reject the metabolic heat generated by a man. A total radiant heat emission from the external surface of a space suit of $2677 \times 10^3$ J (2536 Btu) per hour has been calculated in ref. 1 on the basis of assumptions for suit surface area and emissivity believed to be reasonable. The total radiant heat rejection will balance both, radiant energy received by the suit surface from external radiation sources and metabolic heat generated by the body. Ref. 1 shows that the suit surface when irradiated by the sun and not exposed to planetary radiation or significant radiant inputs from nearby spacecraft can reject between $1890 \times 10^3$ J (1790 Btu) per hour and $2317 \times 10^3$ J (2195 Btu) per hour net metabolic heat. This range covers attitudes relative to the sun, with the lower net heat rejection resulting from the largest projected area exposed to solar radiation, and the larger figure resulting from exposure of the smallest projected area.

While these heat rejection rates will provide significant savings of water used as evaporative coolant (in the order of 1 kg per EVA hour), they are not sufficient under conditions of very strenuous activity. Additional heat inputs into the external suit surface in the form of infrared radiation from planetary or spacecraft surfaces would further diminish the net metabolic heat which can be rejected by radiation.

An auxiliary means of heat rejection will be required for periods of high metabolic rates during extremes of physical activity and/or large heat inputs from the external environment. Of two potential means of additional heat rejection, i.e. evaporation of water or auxiliary radiator surfaces, evaporation of water appears to be practical for the type of missions and operations which can presently be foreseen.

A hard shell space suit provides the potential for integration of subsystems into the space suit shell. With the concept of the variable thermal conductance space suit shell, it appears that the logical location for evaporative heat rejection systems would be within the heat pipe cavities of the suit shell itself. Such an arrangement would take advantage of the already existing heat transport and vapor valve-temperature control system. It would maintain the external space suit surface at the required temperature level at times when radiant heat rejection is unable to do so.

The evaporation of water would take place within tubes located in the external heat pipe cavity and vented to space vacuum as schematically indicated in figs. 3 and 4. These tubes would be partially filled with a wick which would be soaked with water. An adequate fraction of the tube cross section would be left open as vapor passage. The tubes would be distributed over the suit surface to satisfy the heat rejection requirements. Water would be stored by capillary action in the wicks. A type of quartz fiber wick which has been tested and applied in experiments in connection with studies of passive humidity control can retain nearly 10 times its own weight in water (ref. 3). The concept described here has similarity to a concept described in ref. 7. Under this concept the evaporation tubes were, however, placed in direct contact with the human skin. Locating the tubes in contact with the skin required tube flexibility. The tubes, in order to be flexible, had to be made of polymers or elastomeric materials, introducing an element of risk, as the wall of these tubes became the barrier between internal suit pressurization and space vacuum.

Placing the evaporator tubes inside the heat pipe cavities of the external space suit shell eliminates the need for flexibility and related problems and risks. Leakage, much less likely in a rigid tube, would only result in venting of a section of heat pipe and not in loss of suit pressurization. Excellent heat transfer between the heat pipe-thermal transport system and the evaporator tubes would be provided by this arrangement.

## PROTOTYPE PANEL, DEVELOPMENT AND PERFORMANCE TEST

The concept of removal of heat from the human skin by flexible heat pipes as, for example, shown in fig. 4 and discussed in the introduction, requires assembly of flexible heat pipe panels with flexible vapor and wick interconnections into two-chamber heat pipes.

An experimental prototype of a suit panel, which includes flexible and rigid heat pipe panels, flexible interconnections and thermal switching capability was designed and fabricated.

This experimental prototype was designed to be suitable for performance testing under laboratory conditions. Electric resistance heaters, bonded to the evaporator chamber were used to simulate heat input from the skin. A solid plate heat exchanger with drilled internal passages for circulation of cooling water was used as heat sink.

In order to obtain good thermal contact with the heat exchanger, the condenser chamber is rigid and built from stainless steel. It has flat panel construction with internal support against collapsing by circular hollow studs, cut from thin-walled, stainless steel tubing. This design is similar to the design applied to heat pipe panels of fiberglass, reported on in ref. 1.

The use of a proven design and stainless steel construction eliminated such variables as inward leakage or material gas emission from the condenser chamber. The condenser was thereby made to be a reliable "sink" for the vapor and heat transmitted to it from the flexible components under test.

The evaporator chamber is of flexible design and very similar to flexible heat pipe no. 18, described earlier in this report (Table I). It has three-dimensional fabric internal support, braided quartz fiber tubing as wick and heat-sealable polyester-aluminum laminate as external enclosure. One vapor connection and three wick connections were provided between the evaporator and condenser chamber. They consist of flexible vinyl tubing. Glass fiber filtering wool, packed to 0.5 g per cc density was used in three vinyl tubes as transfer wick. The vapor transfer tube can be closed by an external pinch clamp, which provides thermal switching action by vapor passage control. The tests were performed with the evaporator chamber on top, therefore, at negative "g".

The condenser was clamped in close thermal contact to the heat exchanger plate, through which cooling water was circulated. A low vapor pressure silicon grease was used between the condenser surface and the heat exchanger to fill voids and promote heat transfer. Twenty-four thermocouples were provided, located on the upper and lower surfaces of the two chambers, at the heat exchanger and at the heater. The thermocouples were arranged such that temperature gradients between the two chambers, as well as lateral gradients over the surface of the chambers could be recorded. The assembly was insulated with fiberglass wool. In order to further reduce errors due to heat exchange with the room environment, operating temperatures were maintained as close as practical to room temperature.

Figure 13 shows a schematic drawing, and figs. 14 and 15 photographic views of the panel assembly.

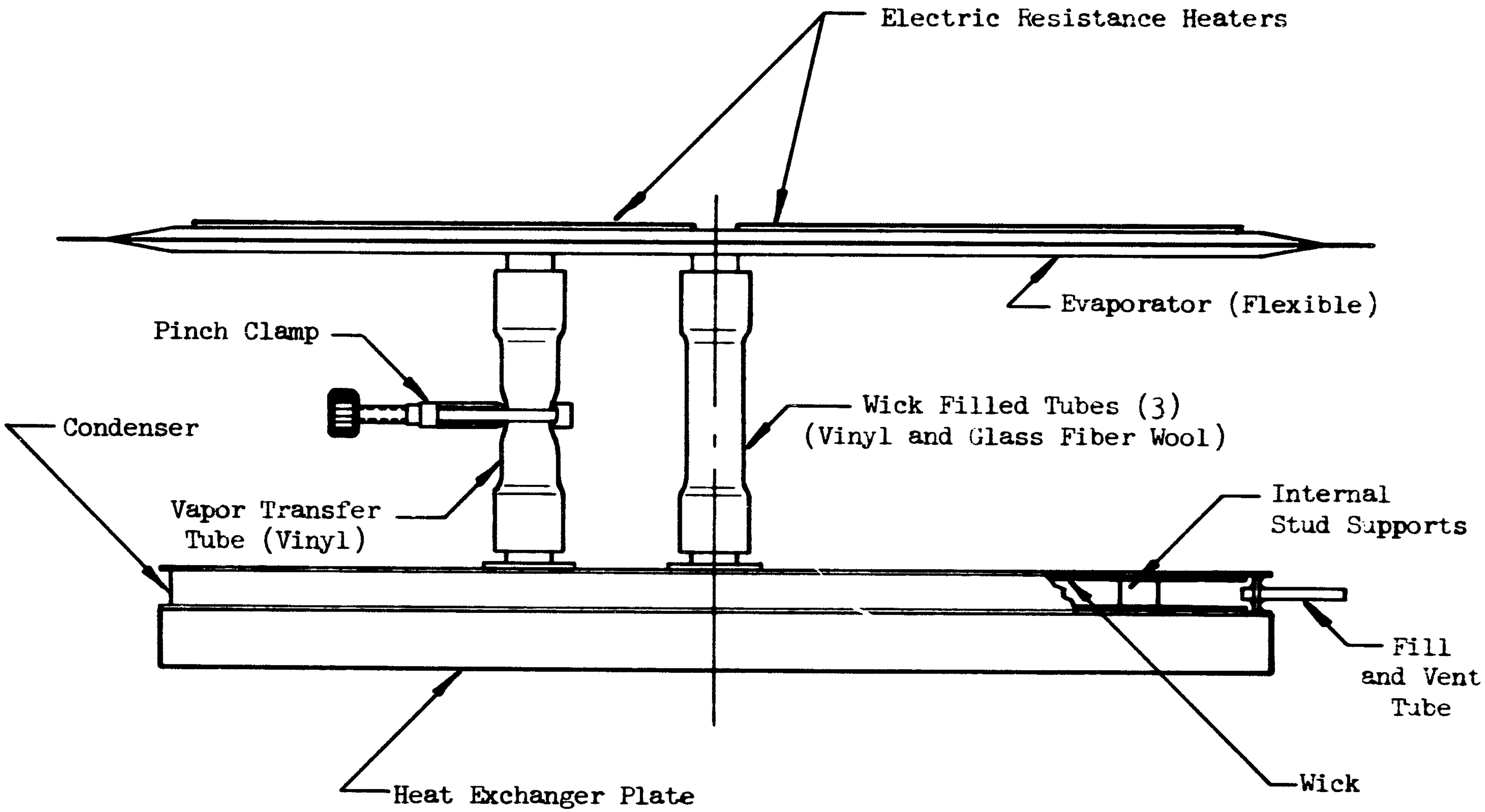



**FIGURE 13 - PROTOTYPE PANEL ASSEMBLY**

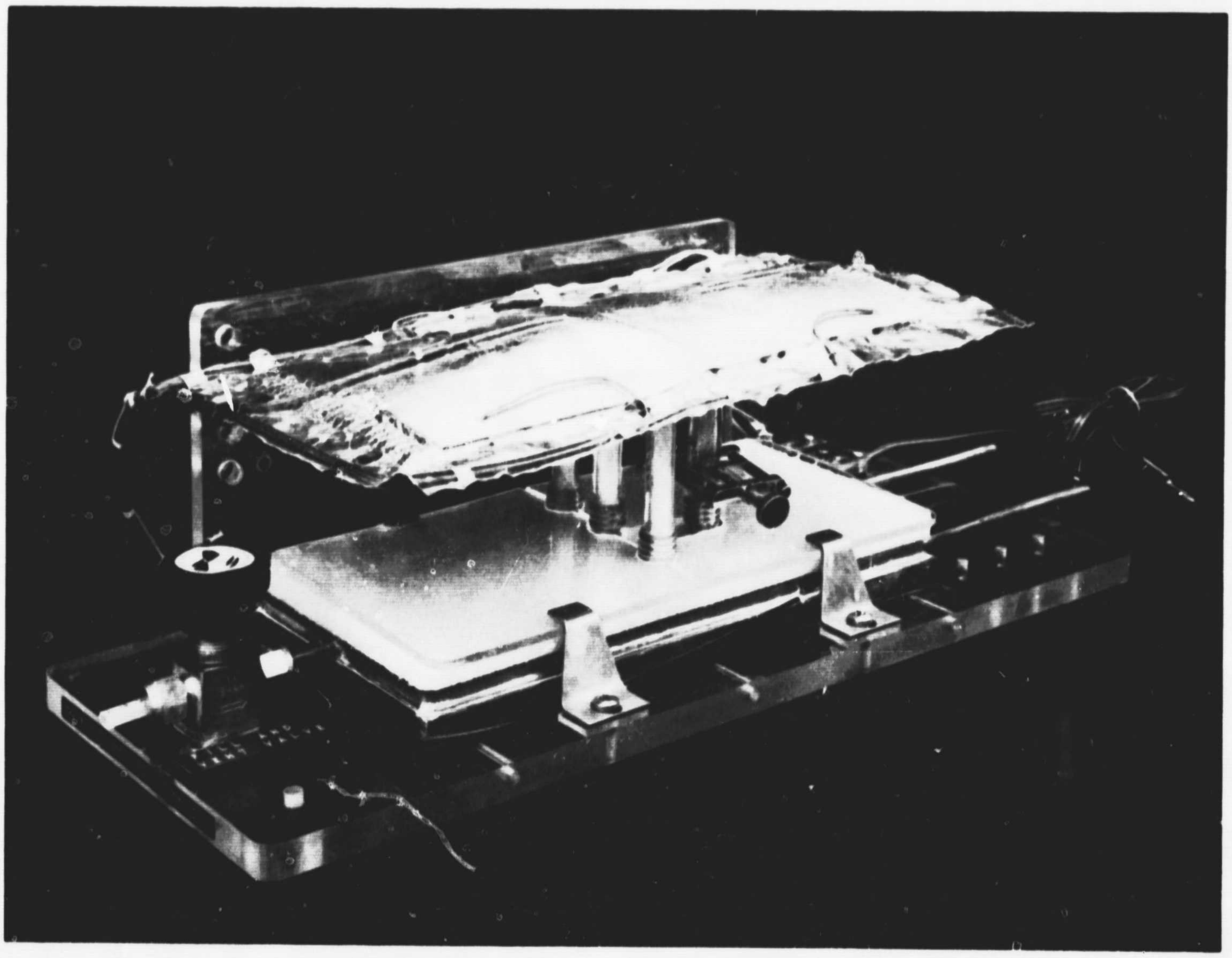


Figure 14 - PROTOTYPE PANEL ASSEMBLY

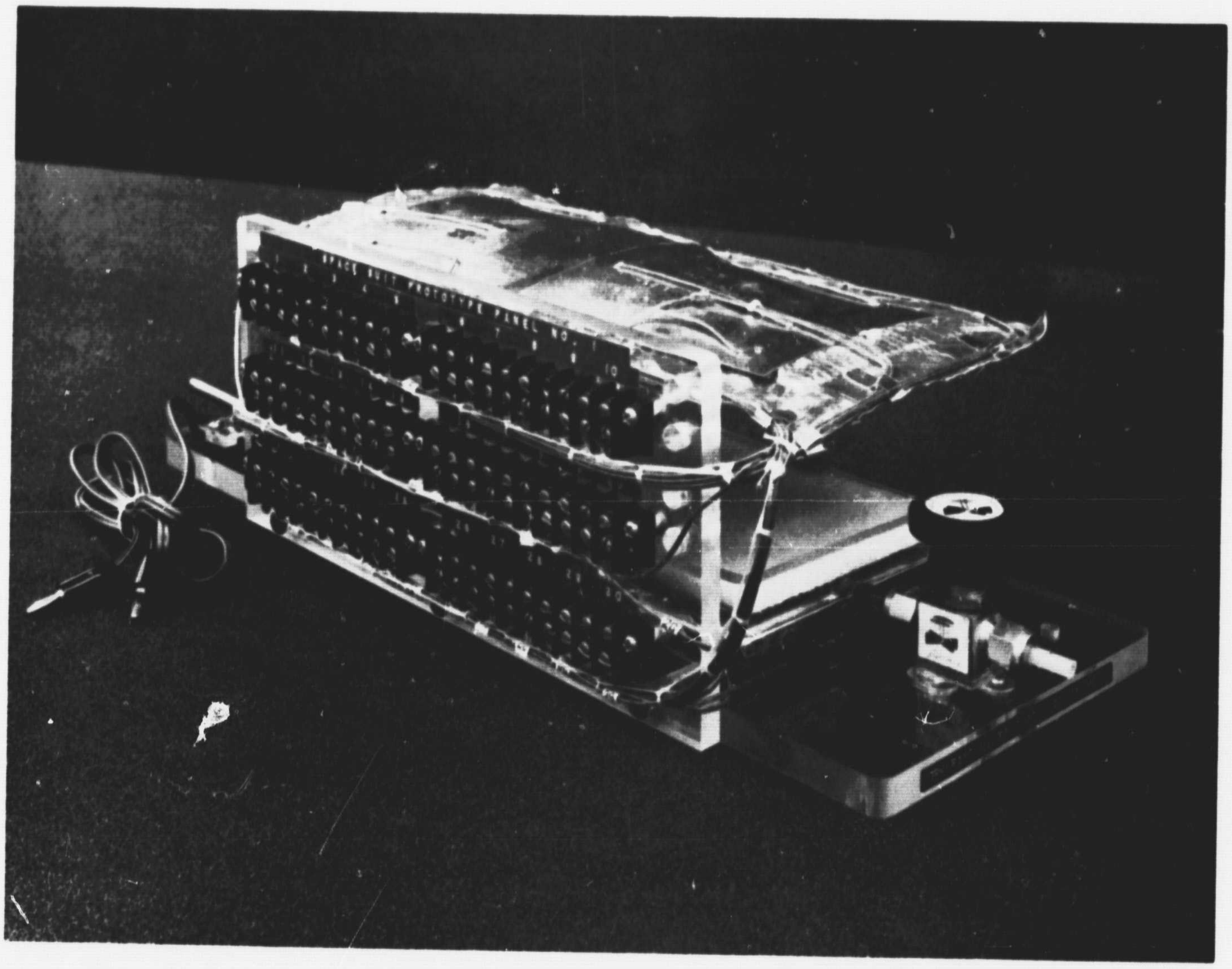



Figure 15 - PROTOTYPE PANEL ASSEMBLY

The objectives of the tests performed were:

- To demonstrate performance of the flexible chamber as a heat pipe, as would be demonstrated by nearly isothermal conditions lateral over the surface of the chamber.

- To demonstrate performance of the assembly as a two-chamber heat pipe, thereby demonstrating operation of flexible transfer wicks and vapor interconnections.

- To demonstrate performance of a flexible two-chamber heat pipe as a thermal switching device.

Figure 16 shows the lateral temperature distribution as a function of distance from the centrally located transfer wicks for the evaporator and condenser chamber. This lateral heat distribution was nearly isothermal, indicating adequacy of capillary pumping by the wicks in both chambers. This is particularly interesting because of the difference in the wicks used in the two chambers. The wick of the rigid condenser chamber is quartz fiber cloth, bonded to the stainless steel surfaces and providing continuous coverage of the internal surfaces. The wicks of the evaporator chamber are braided quartz fiber tube of 0.7 mm o.d., located in every other channel of the three-dimensional fabric as described for flexible heat pipe no. 18.

Figure 16 also shows that the temperature gradient between the evaporator and condenser chamber was in most locations less than 2° C, indicating very good heat transmission performance of the device. This test was performed at a power input into the heater of 16 W, corresponding to 2504 x $10^3$ J per hour per $m^2$ (220 Btu/hr - $ft^2$).

Figure 17 shows one curve for the highest temperature gradient observed between the two thermocouples showing the highest and lowest temperature on the evaporator chamber and a second curve for this on the condenser chamber, as a function of heater power input.

Figure 18 shows the temperature gradient between the average temperature of the thermocouples located on the evaporator chamber and the average temperature of the thermocouples located on the condenser chamber, as a function of heater power input.

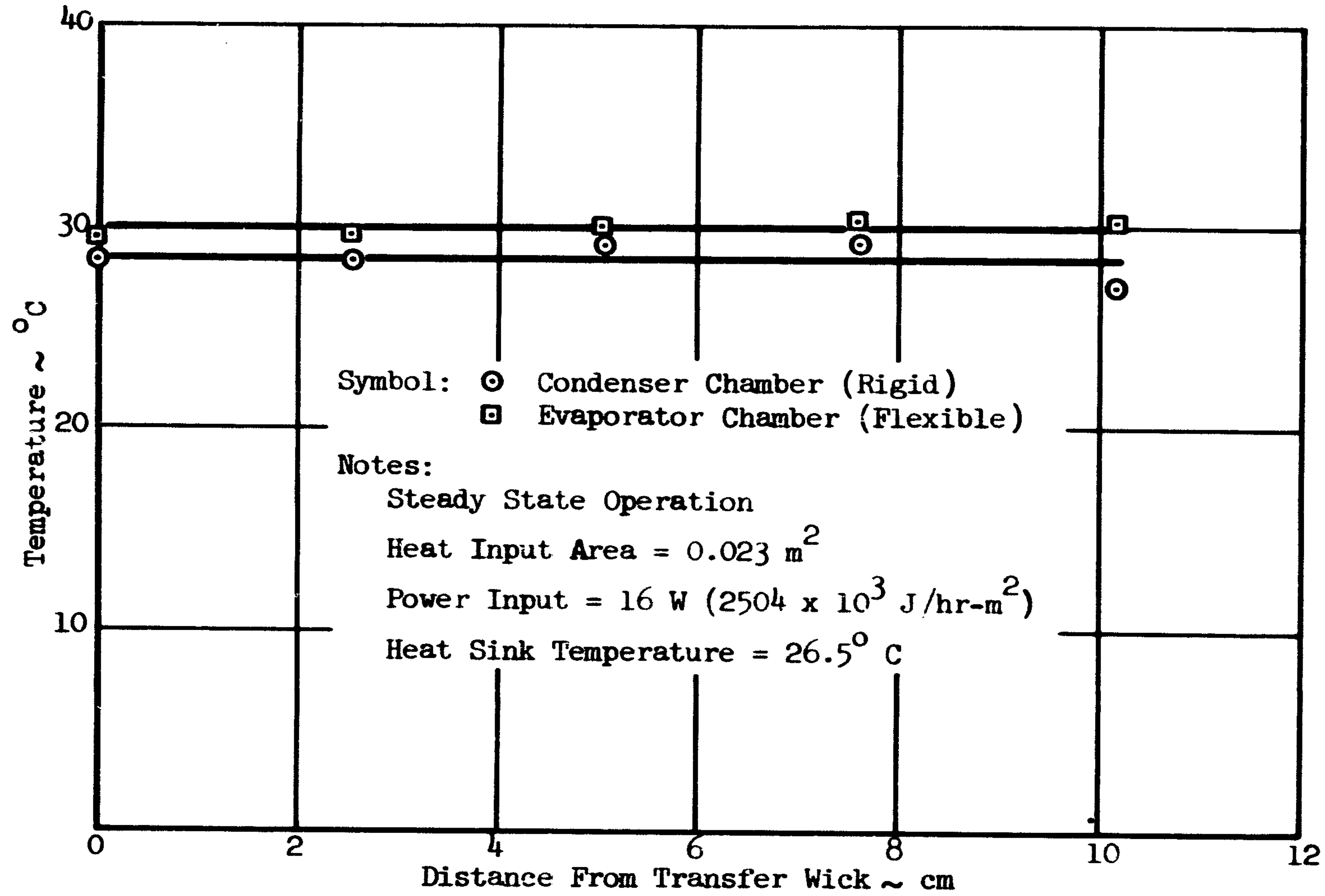



Figure 16 - LATERAL TEMPERATURE DISTRIBUTION AT SURFACE OF EVAPORATOR (FLEXIBLE) AND CONDENSER (RIGID) HEAT PIPE PANEL AS FUNCTION OF DISTANCE FROM TRANSFER WICKS

Symbol: ⊙ Condenser Chamber

⊡ Evaporator Chamber

Notes: Steady State Operation

Heat Sink Temperature = $25^{\circ}$ to $27.5^{\circ}$ C

Heat Input Area = 0.023 $m^2$

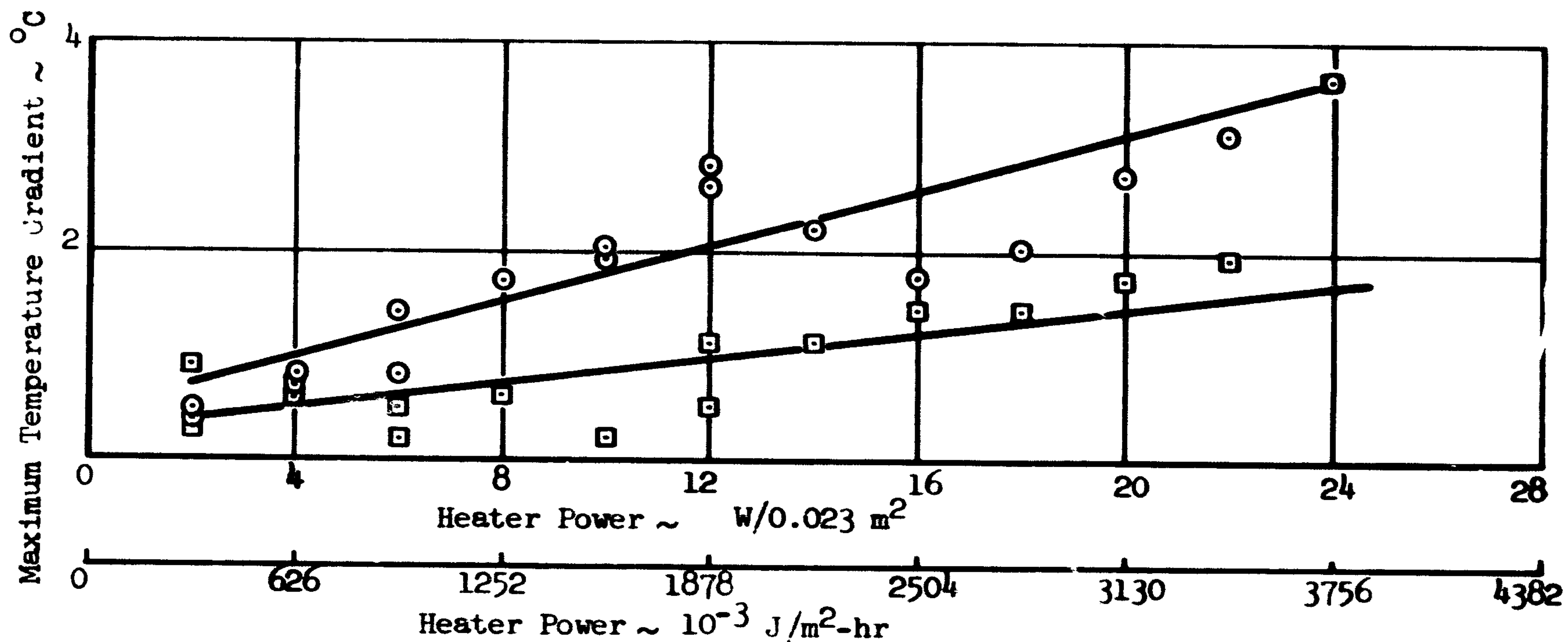



Figure 17 - MAXIMUM TEMPERATURE GRADIENT AS A FUNCTION OF HEATER POWER, OBSERVED BETWEEN THERMOCOUPLES ON CONDENSER AND ON EVAPORATOR CHAMBER

Notes: Steady State Operation

Heat Sink Temperature = $25^{\circ}$ to $27.3^{\circ}$ C

Heat Input Area = 0.023 $m^2$

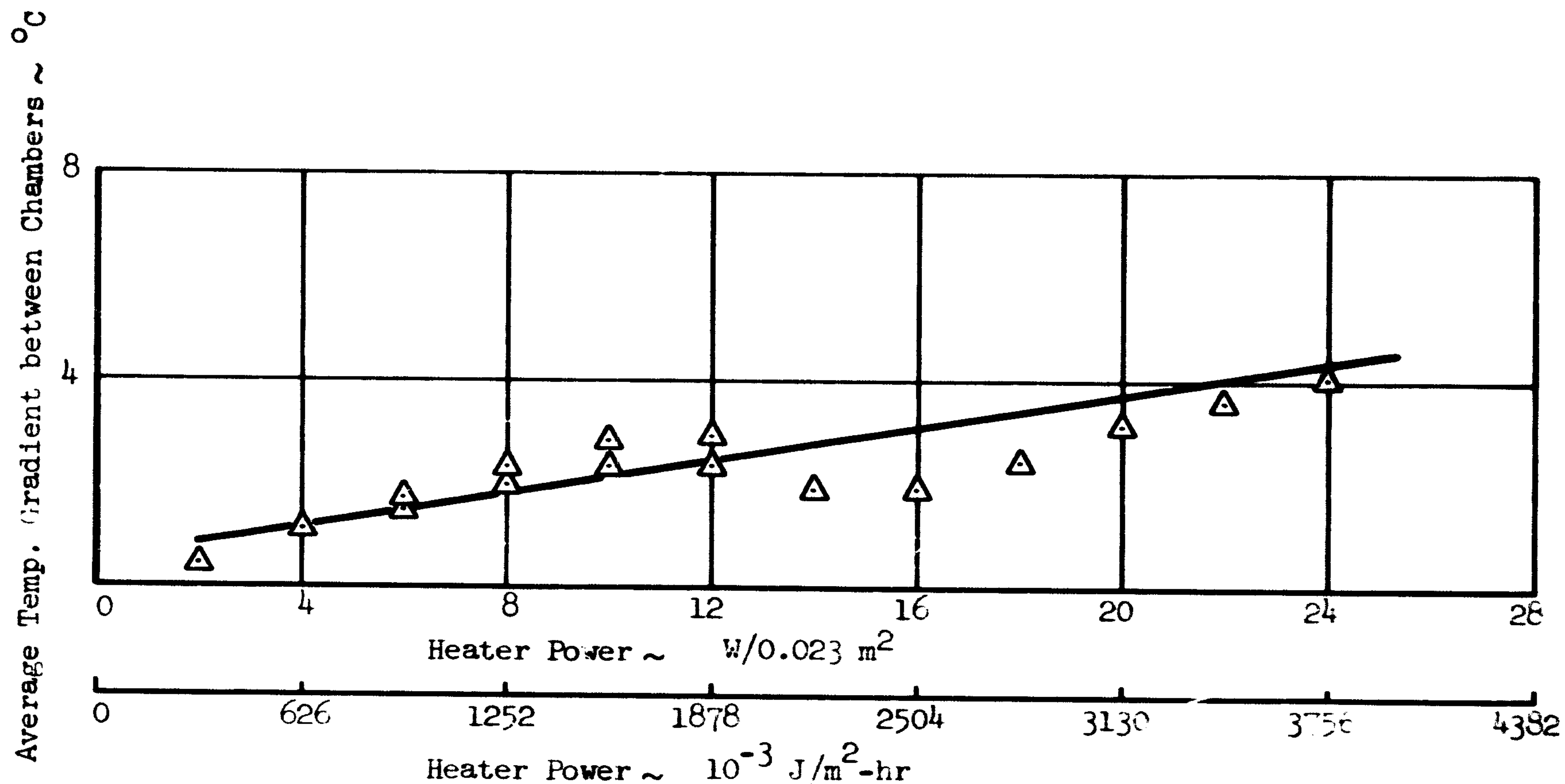



Figure 18 - GRADIENT BETWEEN THE AVERAGE TEMPERATURES OF THE EVAPORATOR AND CONDENSER CHAMBER

Figure 19 shows the largest temperature gradient observed as function of heater power input between the two thermocouples showing the highest and lowest temperature of the assembly. At 16 W heater input ($2504 \times 10^3$ J/hr-$m^2$) which is considered as the approximate design load, the maximum gradient on the line, averaging point scatter, is only slightly above 4°C (actual thermocouple readings were 3.0°C and 3.3°C).

The cross section applied to transmission of 16 W with the above gradient consists of four (4) tubes of 6.35 mm i.d. It could be stated that 16 W were transmitted over a distance of 75 mm with a temperature gradient of 4°C through this cross section. These assumptions are conservative, as 75 mm is the length of the wick and vapor transfer tubes between chambers, and any lateral distance of heat flow in the chambers to the location of the coldest and warmest thermocouple is disregarded.

From these assumptions, a heat transmission performance in terms of an equivalent or pseudo thermal conductance of 2800 J/sec-m-°C can be calculated.

It is interesting to compare this equivalent conductance shown by the assembly when operating as a heat pipe, with the calculated thermal conductance, which can be anticipated with the vapor transfer valve closed, and heat conduction only by the walls of the tubing and the wick.

A thermal conductance of vinyl of 0.1255 J/sec-m-°C ($3 \times 10^{-4}$ cal/sec-cm-°C) was used. For the water-soaked wick, the thermal conductivity of water was used for the calculation.

On the basis of these assumptions, the overall thermal conductance of the three (3) wick-filled tubes and of the vapor transfer tube was calculated as $2600 \times 10^{-4}$ J/sec-m-°C. A factor of over $10^4$ between heat transmission performance of the prototype with the vapor valve open and closed is thereby indicated.

Figure 20 shows the response of the assembly during operation as a thermal switching device. Attention is led to the fast response to closing and opening of the vapor transfer valve, believed to be the result of improved transfer wick design and the low thermal mass of the assembly.

Notes: Steady State Operation

Heat Sink Temperature = 25° to 27.3° C

Heat Input Area = 0.023 m²

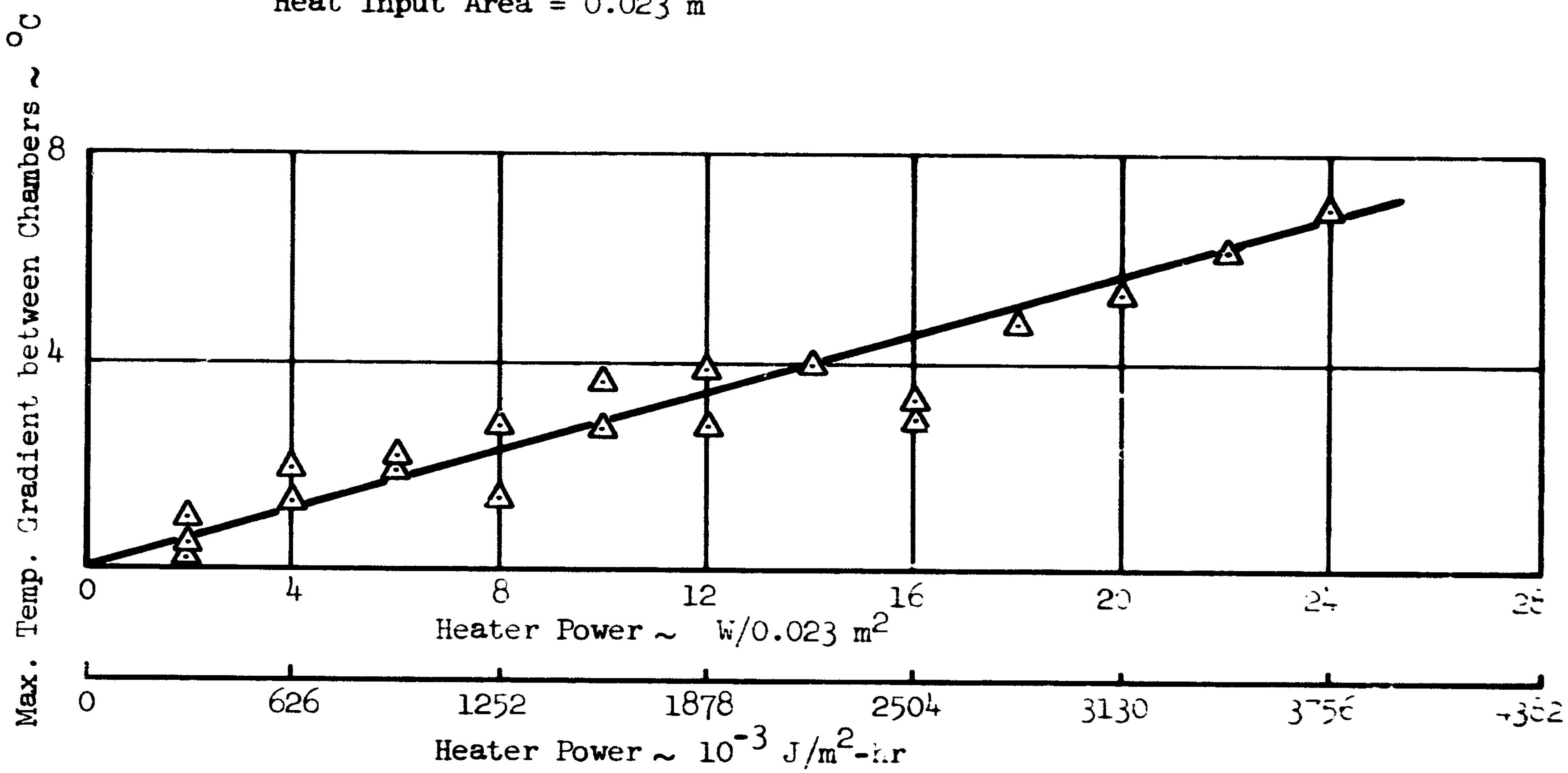



Figure 19 - MAXIMUM TEMPERATURE GRADIENTS OBSERVED ON THE ASSEMBLY AS A FUNCTION OF HEATER POWER

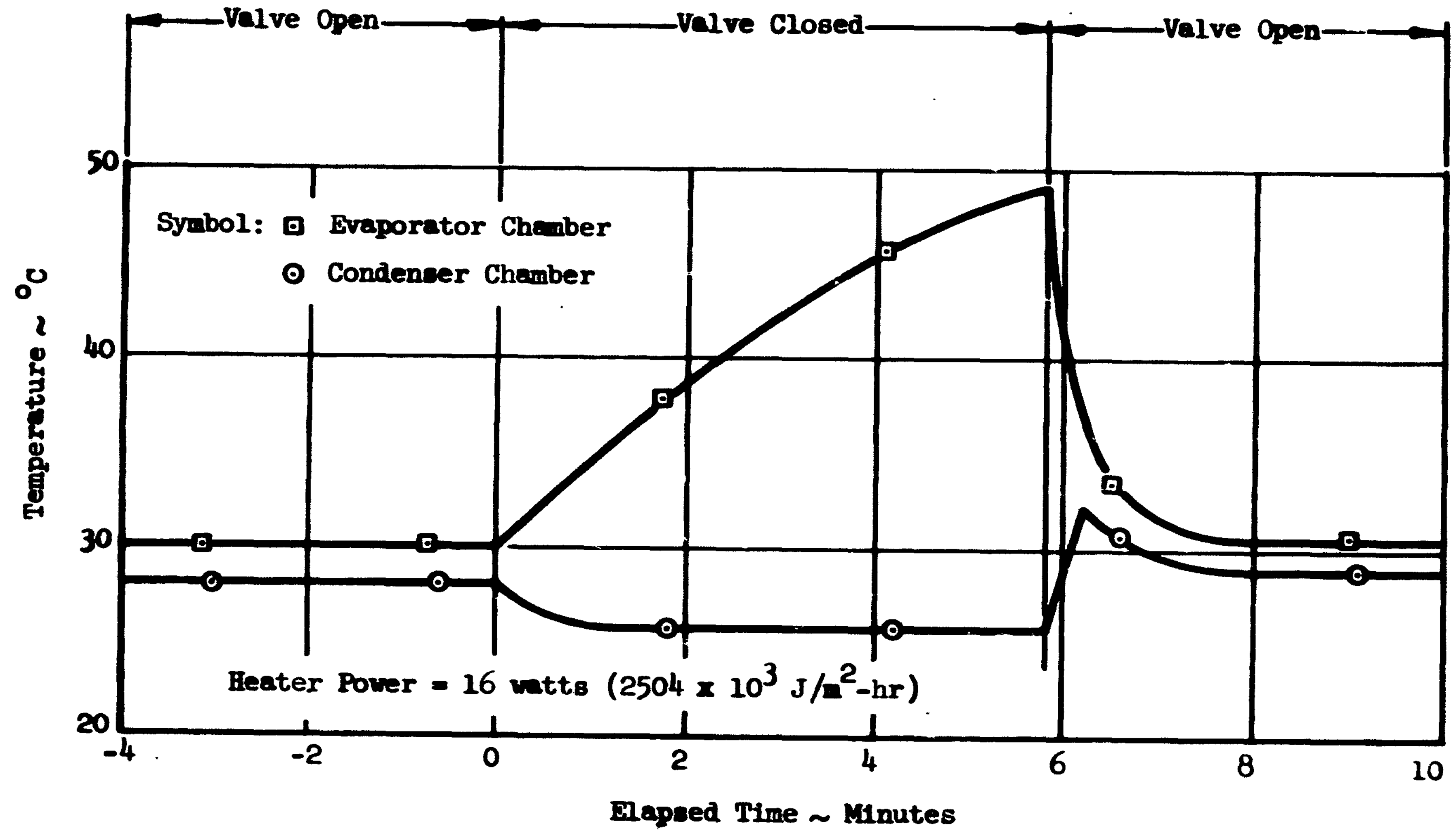



Figure 20 - RESPONSE OF PROTOTYPE PANEL AS THERMAL SWITCHING DEVICE

## CONCLUSIONS AND RECOMMENDATIONS

As stated in the Introduction (p. 9), technology in four areas is required for the improvements of space suit temperature and humidity control systems, which are the objective of this program. These four technology areas are:

- A variable thermal conductance space suit shell with integrated thermal insulation.
- Flexible heat pipes for heat transmission between the skin and the variable thermal conductance space suit shell.
- A technique for freeze prevention or ready restart of frozen heat pipes.
- Devices integrated into the variable thermal conductance space suit shell for auxiliary cooling by evaporation or sublimation of water.

Technological knowledge in these areas will permit various designs of advanced suit thermal control systems, tailored to specific suits and specific missions. In these areas, technologies have either been generated or further research requirements identified.

Techniques for design and fabrication of variable thermal conductance space suit shells, using two-chamber heat pipes with vapor flow control, have been generated.

Techniques for design and fabrication of flexible heat pipes have been developed. The feasibility of flexible heat pipes operating at internal pressures significantly lower than the pressure of the external environment has been demonstrated. The properties of materials required for flexible heat pipes, and the direction of future research in the materials area were defined.

In problem areas of freezing of heat pipe working fluids and auxiliary cooling, concepts have been generated, evaluated and, to a limited degree, feasibility demonstrated by experiment.

It is concluded that the objectives of the program, i.e. development of techniques which will significantly reduce the weight penalties for expendable evaporant and electric power for extravehicular space suit operation are attainable.

It is recommended that research be continued to solve remaining problems, which include:

- Development of better enclosure materials for application to flexible heat pipes.
- Improvement in material and fabrication technology for all system components.
- Research in the area of behavior of working fluid mixtures in heat pipes, with special emphasis on freeze-depressing additives for water of vapor pressures lower than water, and in other areas related to the heat pipe working fluid freezing problem.
- Development of integrated heat pipe-evaporative cooling systems in accordance with the concepts outlined in the respective chapter of this report.

## REFERENCES


1. Shlosinger, A. P.: "Study of Passive Temperature and Humidity Control Systems for Advanced Space Suits." NASA CR-73168, September 1967.

2. Shlosinger, A. P.: "Heat Pipe Devices for Space Suit Temperature Control." TRW Systems Report No. 06462-6005-R0-00, November 1968.

3. Shlosinger, A. P.; Woo, W.; Cafaro, C.; and Bentilla, E.W.: "Technology Study of Passive Control of Humidity in Space Suits." NASA CR-69098, September 1965.

4. Felder, J. W., Jr.; and Shlosinger, A. P.: "Research on Methods for Thermal Transport in a Space Worker's Garment." AMRL-TDR-63-90, November 1963.

5. Shlosinger, A. P.; and Jacobi, E. F.: "Study of Passive Temperature and Humidity Control Systems for Advanced Space Suits, Material Research Report - First Year." NASA CR-73169, September 1967.

6. Woo, W.: "Study of Passive Temperature and Humidity Control Systems for Advanced Space Suits, Material Research Report - Second Year." TRW Systems Report No. 06462-6007-R0-00, November 1968.

7. Olson, R. B.; Felder, J.; and Lombard, C. F.: "The Development of an Advanced System to Cool a Man in a Pressure Suit." NSL 66-73 (prepared under Contract NAS9-4925), 1966.