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GRUMMAN

DESIGN, FABRICATION AND TESTING OF A THERMAL DIODE

Final Report

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94

FOREWORD

This report was prepared by Grumman Aerospace Corporation for the Ames Research Center of the National Aeronautics and Space Administration. The work was performed under Contract NAS 2-6493, with Mr. J. P. Kirkpatrick serving as Technical Monitor.

The work described herein was performed from July 1, 1971 to November 15, 1972. The work was conducted under the direction of Mr. M. Tawil as project manager and Mr. B. Swerdling as project engineer. Contributions were also made by Mr. M. Urkowitz and Dr. R. Kosson in thermal analysis, and by Mr. J. Fiorello in structural design.

TABLE OF CONTENTS

1. Summary	1
2. Introduction	2
3. Review of Types of Diodes	5
3.1 Non-condensable Gas Blockage	5
3.2 Freezing of the Working Fluid	6
3.3 Liquid Trap for Wick Dryout	8
3.4 Excess Liquid Blockage	14
4. Diode Design and Fabrication	26
4.1 Selection of the ATFE Diode Design	26
4.2 Design of Engineering Model	26
4.3 Diode Fabrication	29
5. Mechanical Tests	34
6. Thermal Performance Tests	37
6.1 Engineering Model Tests Without Saddles	37
6.2 Engineering Model Direct Mode Tests with Saddles	38
6.3 Engineering Model Reverse Mode Tests	41
7. Thermal Tests - Qual. and Flight Diodes	48
7.1 Direct Mode Test Results	49
7.2 Reverse Mode Test Results	49
8. References	55
Appendix A - Tunnel Wick Analysis	A-1
Appendix B - Liquid Blockage Diode-Tunnel Wick Equations	B-1
Appendix C - Reverse Heat Leakage Calculation	C-1
Appendix D - DPCS-1, Charging of ATFE Thermal Diode	D-1
Appendix E - DPM-3A, Thermal Performance Test Plan	E-1

LIST OF FIGURES

1	Advanced Thermal Control Flight Experiment	3
2	Non-condensable Gas Diode - Reservoir Size Variation	7
3	Diode Liquid Trap Schematic	9
4	Liquid Trap Diode Heat Pipe Photo	10
5	Liquid Trap Development Diode Temperature Profile ~ Direct Mode	11
6	Liquid Trap Diode Reverse Mode Temperature Profile	11
7	Liquid Trap Diode ~ Ammonia and Methanol Parametrics	12
8	Freon-21 Liquid Trap Diode Parametric	15
9	Liquid Blockage of Vapor Space	16
10	Development Liquid Blockage Diode Ammonia Heat Pipe	17
11	Liquid Blockage Diode Pipe, Feasibility Test Model Direct Mode Temperature Distribution	19
12	Liquid Blockage Diode Pipe Shutoff Mode	20
13	Ammonia Liquid Blockage Diode Parametric Study	23
14	Reservoir Requirements for Thermal Diode Heat Pipes	27
15	Liquid Blockage Diode ~ Capacity vs. Artery Diameter	28
16	Liquid Blockage Diode ~ Capacity vs. Condenser Diameter	29
17	Diode Heat Pipe ~ ATFE	30
18	ATFE Diode Design Drawing	31
19	Diode Engineering Model ~ Q_{max} vs. Tilt	38
20	Diode Attached to Saddles	39
21	Engineering Model Diode ~ Thermocouple Layout	39
22	Engineering Model ΔT vs. Q	40
23	Engineering Model Direct Mode ΔT vs. Q	41
24	Insulated Diode showing Absorber Plate ~ Reverse Mode	42
25	Insulated Diode showing Back Side of Radiator ~ Reverse Mode	43

LIST OF FIGURES (Cont.)

26	Diode installed in Vacuum Chamber	44
27	Engineering Model ~ Direct to Reverse Mode Transient	46
28	Engineering Model Diode Transition Section	47
29	Direct Mode Test Results Summary	50
30	Reverse Mode Insulation Scheme	51
31	Qualification Model Reverse Mode Transient	52
32	Flight Model Reverse Mode Transient	53
33	Reverse Mode Temperature Distribution, Qual and Flight Models	54

Appendices

A-1	Tunnel Wick
C-1	Transition Section
D-1	Charge Bottle and Diode Evacuation Schematic
D-2	Diode Charging Schematic
D-3	Pinch Off Schemes
E-1	Diode Heat Pipe Thermocouple and Heater Locations

Symbols

A - cross-sectional area

C - viscous loss coefficient

D - diameter

DH - hydraulic diameter

g - gravitational acceleration

g_c - gravitational constant

ΔP - pressure drop

Q - heat flux

T - temperature

t - vapor space thickness

λ - latent heat

μ - absolute viscosity

ρ - density

σ - surface tension

Subscripts

A - artery

C - capillary

L - liquid

GR - thread or groove

V - vapor

W - retainer web

1.0 SUMMARY

This report reviews heat pipe diode types, and describes the design, fabrication and test of a flight qualified diode for the Advanced Thermal Control Flight Experiment (ATFE). The review covers the use of non-condensable gas, freezing, liquid trap, and liquid blockage techniques. Test data and parametric performance are presented for the liquid trap and liquid blockage techniques. The liquid blockage technique was selected for the ATFE diode on the basis of small reservoir size, low reverse mode heat transfer, and apparent rapid shut-off.

The design, fabrication and test of an engineering model, a qualification pipe and a flight pipe are described. The diode pipes were made of stainless steel and had nominal condenser and evaporator diameters of 0.450 inch and 0.375 inch, respectively. The working fluid was ammonia and the capillary system was a spiral artery tunnel wick. The diodes had a nominal capacity of 85 watts. Tests were conducted in both direct (heat pipe mode) and reverse (shutoff) mode and exceeded the specification by a factor of 2. Mechanical pressure tests were also conducted on each pipe. The report discusses in detail the fabrication, test procedures and results.

2.0 INTRODUCTION

One of the most useful of the recent developments in heat pipe technology is the capability to vary heat pipe thermal conductance in response to varying heat rejection requirements and/or changing thermal boundary conditions. Although studies have been made of both passive and active techniques for varying conductance (generally using noncondensable gases) with the object of minimizing heat-source temperature variations, many applications exist in which limiting the heat flow to one direction is of greater importance than minimizing variations in heat source temperature. Heat pipes designed for such unidirectional applications are described as thermal diodes since they transfer heat very efficiently in one direction, but very inefficiently in the other. Since heat pipes are inherently efficient heat transfer devices, the diode effect is achieved by interfering with or shutting off the heat pipe operation for heat transfer in one direction, while permitting normal operation in the other direction.

Task I of the work performed under this contract consists of a review of various heat pipe shut-off techniques, including use of noncondensable gas, liquid flow control, and freezing. The liquid flow control schemes were found to be most attractive, particularly for applications such as the Advanced Thermal Control Flight Experiment (ATFE), and are given more emphasis in this review than the other types. Two types of liquid flow control are considered: the liquid trap concept which shuts the pipe off by starving the wick, and the liquid blockage technique, which uses excess liquid to block the vapor space to achieve shut-off. These types were studied with several working fluids (ammonia, Freon-21, and methanol), pipe sizes, and wick designs. The studies led to selection of an ammonia, stainless steel, liquid blockage type of diode for the ATFE.

Tasks II and III of this contract were concerned with the development of such a diode for the ATFE. The ATFE (Fig. 1) for the ATS-F satellite consists of solar absorber, a thermal diode (or one-way heat pipe), a simulated equipment shelf containing a fusible material thermal accumulator, an active feedback-controlled variable conductance heat pipe, and a space radiator. The experiment is designed to demonstrate successful flight operation of a heat pipe thermal control system for electronic equipment. In lieu of electronic power dissipation, the solar absorber and thermal diode are used to supply heat to the equipment shelf. The feedback-controlled heat pipe transfers heat from the shelf to the radiator. Through the alternate freezing and thawing of its fusible material, the thermal accumulator is designed to assist the feedback-controlled pipe in holding the shelf temperature to 82 $\pm$ 2^{O}F. The thermal diode is designed to minimize the flow of heat from the shelf to the solar absorber during the dark portion of the orbit.

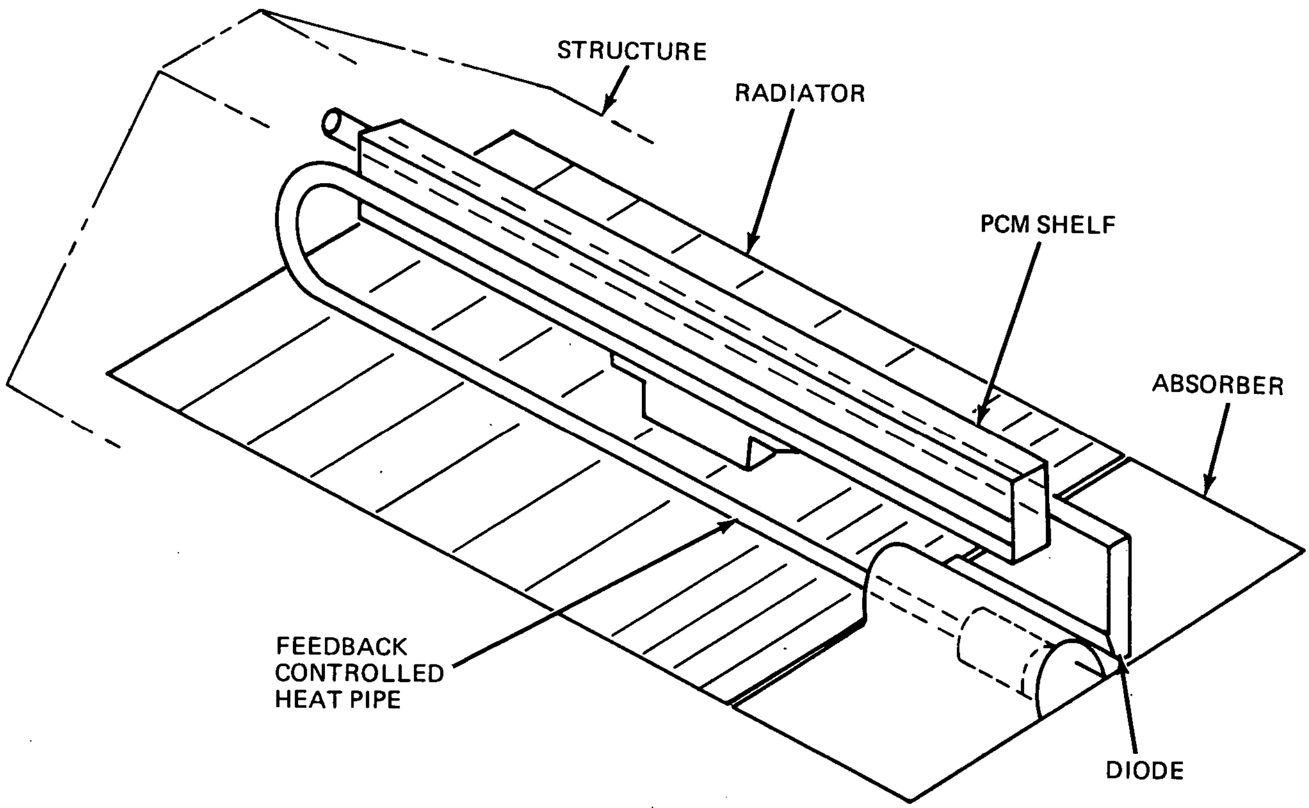


Fig. 1 Advanced Thermal Control Flight Experiment

The thermal diode, interposed between the solar absorber and the simulated equipment shelf of the ATFE, is required to transmit heat at its maximum efficiency from the absorber to the shelf whenever the absorber temperature exceeds the shelf temperature. This is the normal mode of operation. In the reverse or shutoff mode, where the shelf temperature is greater than the absorber temperature, the thermal diode is required to hold the reverse heat flow rate to the lowest practicable minimum.

In the normal mode, the diode must transmit a nominal 20 watts from the solar absorber to the equipment shelf when the maximum temperature of the absorber saddle is $105^{o}F (314^{o}K)$ and the temperature of the shelf saddle is $89^{o}F$ ($305^{o}K$). During that portion of the orbit when the solar absorber is in the earth's shadow, the thermal diode must transmit heat from the equipment shelf to the absorber at a design rate not exceeding 1.4 watts under steady-state conditions(reverse or shut-off mode). The heat required to shutoff the pipe has to be minimized. During the orbital phase, the maximum design temperature of the shelf saddle is $82 \pm 2^{o}F$ ($301 \pm 1^{o}K$), and the minimum temperature of the absorber saddle is $-180^{o}F$ ($155^{o}K$).

3.0 REVIEW OF TYPES OF DIODES

The techniques for interfering with normal heat pipe operation may be categorized as:

- o Noncondensable gas blockage of the vapor space
- o Freezing of the working fluid
- o Liquid trap to dry out all or part of the wick
- o Excess working fluid to block the vapor space
- o Mechanical variations

The first four items are of primary interest; the mechanical devices, being inherently more complex were not considered in this study since one or more of the others appeared suitable for the various boundary conditions envisioned.

3.1 Noncondensable Gas Blockage

This may be regarded as an application of the cold reservoir type of variable-conductance heat pipe.(1) The gas reservoir at the condenser end contains a wick, which communicates with the wick in the operating portion of the pipe. During normal operation, the reservoir must be colder than the vapor temperature to minimize reservoir size because the gas partial pressure is simply the difference in vapor pressures between the condenser and reservoir. This can be accomplished in two ways: 1) maintain the reservoir in thermal equilibrium with the heat sink during normal operation while designing for a relatively high temperature drop between the vapor and the outside wall of the condenser; 2) thermally isolate the reservoir radiator to cool the reservoir.

The thermal diode condenser must be fully operative for a reasonably large range of positive heat flows. Hence, the gas-vapor interface is located at the reservoir end of the condenser for the lowest positive heat flux for which full condenser operation is desired. As the heat flux goes to zero, the vapor velocity ceases and the gas tends to diffuse (albeit, slowly) throughout the pipe. When the original source temperature drops below that of the original condenser, a mixture of gas and vapor flows towards the original evaporator. The gas accumulates at the absorber end, eventually completely blocking it.

For the ATFE, the gas reservoir must be sized to hold an amount of gas sufficient to block both the transport and absorber sections under turned-off conditions to minimize conductance. Some calculations for this gas blockage technique, applied to the ATFE with the gas reservoir in thermal equilibrium with the simulated equipment rack, are presented in Table 1. The pipe is assumed to be made of stainless steel, 0.420 in. OD, 0.371 in. ID, with lengths for absorber, transport section, and condenser of 3.34, 6.50, and 18 in., respectively, and charged with Freon-21 working fluid. The longitudinal fluid pumping is effected with self-filling spiral artery wick having a diameter of 0.290 in. In the absorber section, fine internal circumferential grooves (approximately 100 per/in. of length) provide a low evaporator Δ T. This permits a design with a relatively large condenser Δ T, which, in turn, reduces the reservoir size. The condenser wall is lined with a tight-fitting stainless steel screen sufficient to provide a mean liquid layer thickness of approximately 0.0085 in. Predicted temperatures and pressures within the diode are shown in the normal mode at a heat flow of 33.3 watts, and in the shutoff mode at an absorber temperature of -125°F in Table 1.

Table 1 Predicted Temperature & Pressures ~ Gas Shut-off

	HOT CASE			COLD CASE		
	Temp. °F	Pressure, PSIA Vapor	Gas	Temp. °F	Pressure, PSIA Vapor	Gas
Absorber Wall	83.0	-	-	-125	-	-
Absorber Vapor Space	76.7	26.2	0		0.1	21.7
Transport Section	76.7	26.2	0	-29	2.0	19.8
Condenser Vapor Space	76.7	26.2	0	67	21.8	0
Condenser Wall	67.0	-	-	67	-	-
Reservoir	67.0	21.8	4.4	67	21.8	0

For these values, the reservoir volume would have to be 6.3 times the vapor space volume of the absorber and transport sections, or about 2.6 cu. in. A thermally isolated reservoir with a radiator surface to reject some heat could be significantly smaller, as shown in figure 2 for a range of values of reservoir temperature. This would require some changes in other portions of the flight experiment, however.

3.2 Freezing of the Working Fluid

The concept of freezing as a primary shut-off mechanism has been considered as a variable conductance technique [2]. It is also a candidate technique for thermal diode use where the end of the pipe at which freezing occurs is also the

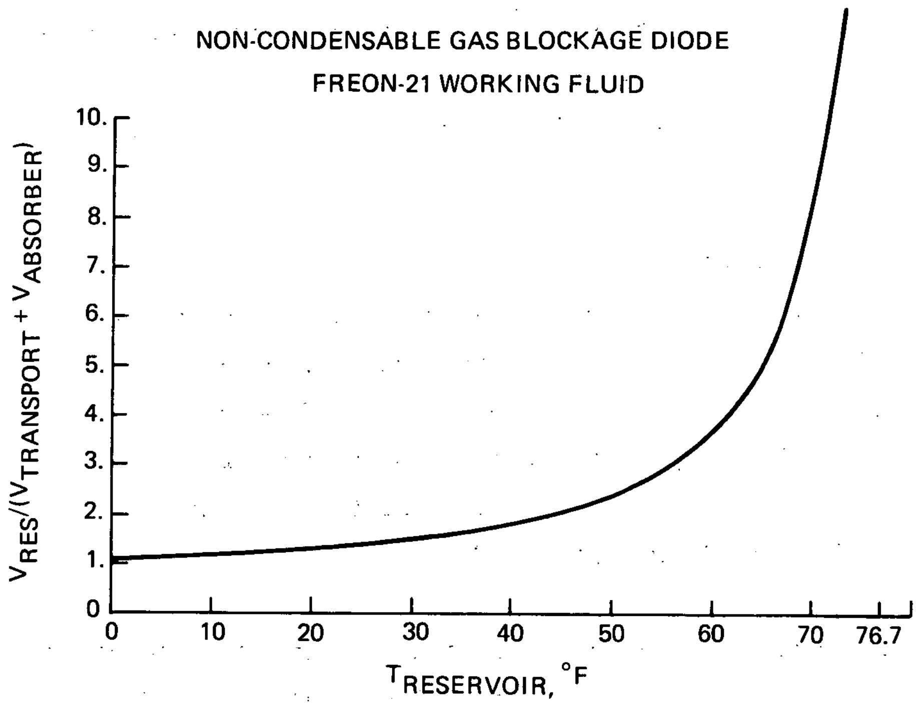


Fig. 2 Variation of Reservoir Size with Reservoir Temperature

same end which becomes hot in the normal mode. The main concern in designing a diode based on the freezing concept is that the pipe envelope may conduct so much heat in the reverse mode of operation that the cold end never gets cold enough to cause freezing. For example, in an early version of the ATFE the pipe was required, in the normal mode of operation, to conduct 33.3 watts with a maximum ΔT of 16°F between absorber and equipment shelf, giving a minimum effective heat pipe conductance of 2.08 watts/°F. Assuming that the evaporator and condenser wall wicks are of similar design and that the condenser film coefficient is twice the value of the evaporator film coefficient (a typical ratio), the conductance in the reverse mode of operation rises to 3.32 watts/°F. If, in the reverse mode of operation, the heat is fed from a 63°F shelf to a 40-square-inch radiator surface having an emittance fin effectiveness product of 0.8, the radiator root temperature will be 60.4°F. The working fluid would have to freeze at a temperature higher than 60.4°F for the pipe to shut off. This sets a difficult condition for a working fluid to meet that of freezing above 60°F and providing design performance at a 67°F evaporator temperature.

It is apparent that a freezing thermal diode must be tailored quite carefully to the application. The use of special working fluids presents problems for the designer because data may not be available on film coefficients and yet be critically important to the success of the design. Melting considerations on restart will influence wick design. All portions of the wick should melt readily, and the slug of frozen condensate should not extend beyond the absorber section.

3.3 Liquid Trap for Wick Dry-out

This technique is based on the tendency of liquid to accumulate at the coldest portion of the pipe, except as displaced by surface tension and gravity forces. The liquid trap is a volume made up of small passages capable of holding liquid against the action of gravity, placed at the end of the pipe which is hot during normal pipe operation. The trap is separate from, and does not communicate with, the wick in the operating portion of the pipe.

In the normal mode of operation, the trap is dry, and the diode operates as an ordinary heat pipe, with the correct amount of working fluid for the wick design employed. When the liquid-trap end becomes the cold end of the pipe, condensation begins to occur on the liquid trap surfaces, as well as on the absorber end internal surfaces. As liquid accumulates in the trap, the main heat pipe wick becomes underfilled causing a fairly rapid reduction in transport capacity. The reduction in pumping capacity with undercharge can be quite significant with only a few percent reduction in charge below the 100% fill requirement. For reduction in transport capacity to the order of 1% or less of the original value, however, it may be necessary for the main wick to dry out completely, with all the liquid in the trap.

When the trap end again becomes the warm end, the trap acts as an evaporator until all the liquid is expelled. The trap volume requirement is based on the amount of liquid in the main heat pipe wick and would appear to be most attractive for wicks having a relatively small volume. In contrast with the liquid blockage technique, it has very little dependence on vapor-space volume. The transient response on heating of the liquid trap involves the same considerations for boiling heat transfer as the liquid blockage concept. There is considerable latitude in the trap design, however, since the trap is not the main evaporator. The transient response on filling the trap for shut-off will depend on the ratio of trap condensation rate to absorber section condensation rate and on the main wick liquid fill requirements.

3.3.1 Liquid Trap Feasibility Tests

In order to verify the principle, a liquid trap diode was fabricated and tested as part of an in-house funded project. A schematic and photo of the pipe is shown in figures 3 and 4, respectively. Details of the pipe are listed below.

o Pipe Material	Aluminum
o Working Fluid	Ammonia
o Evaporator Length	4.0 in.
o Condenser Length	12.00
o Transport Length	17.62 in.
o Pipe O.D.	.580 in.
o Trap	.980 I.D. x 6.5 in.
o Wick	100 mesh .290 O.D. tunnel spiral artery

The pipe was instrumented with 18 copper-constantan thermocouples as seen in figure 3. Nichrome ribbon heaters were attached to the evaporator, trap and condenser sections. Condenser cooling was accomplished by both water and methanol spray baths.

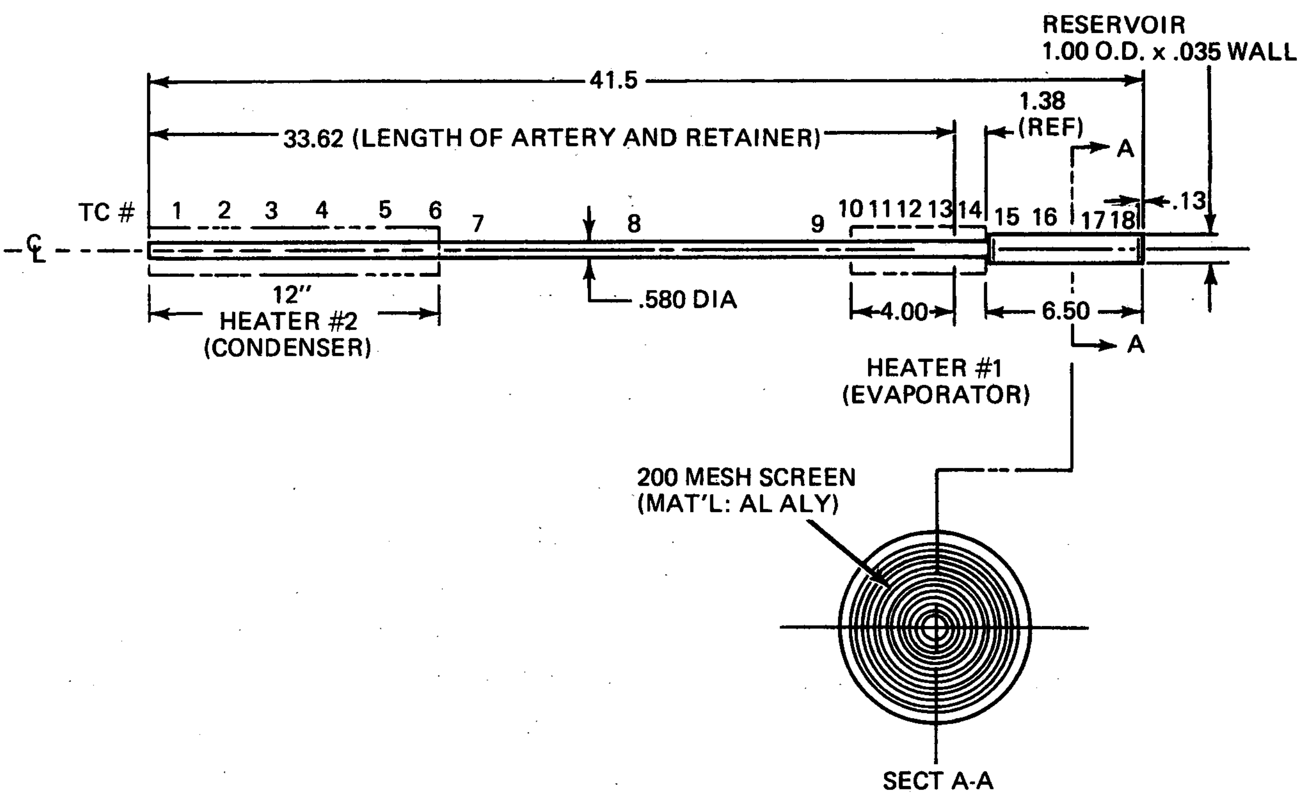


Fig. 3 Diode Liquid Trap Schematic

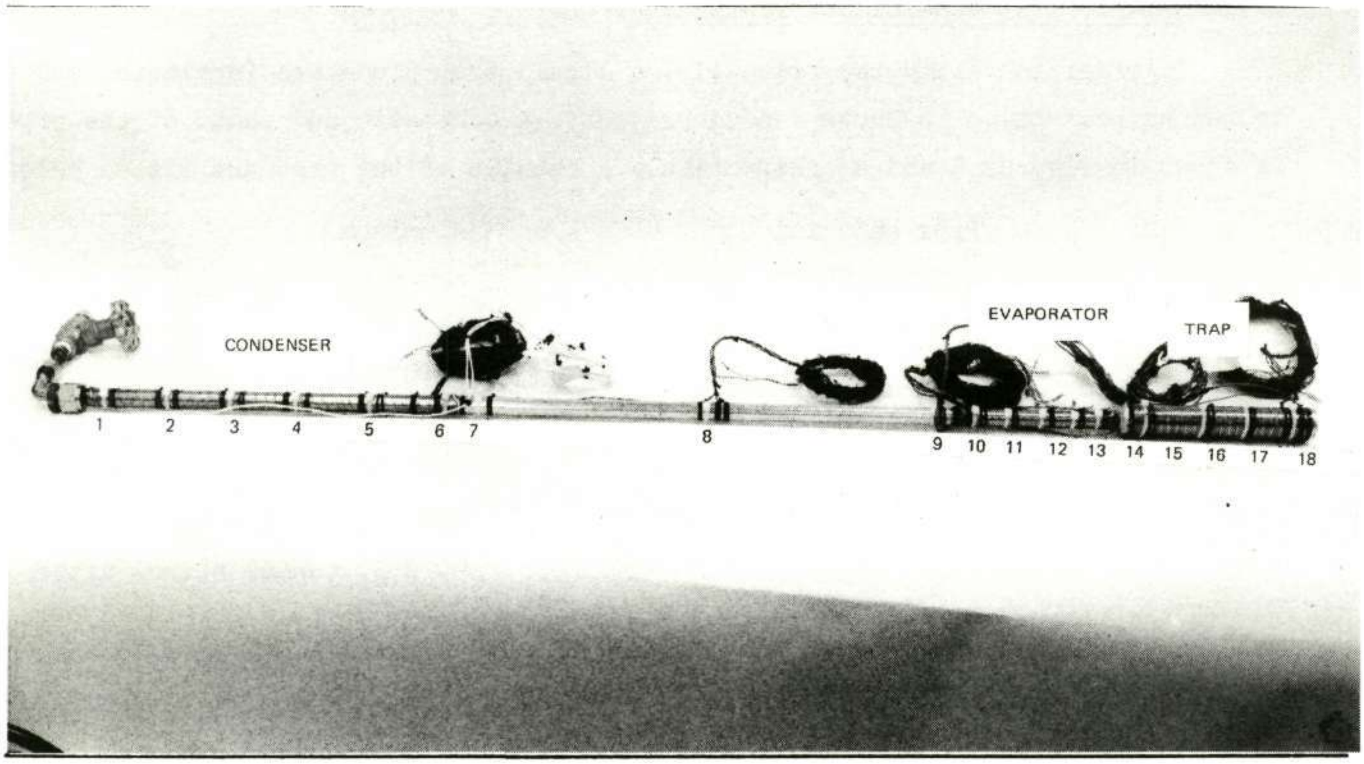


Fig. 4 Liquid Trap Diode Heat Pipe

Both direct and reverse mode tests were conducted. Unfortunately, the heaters on the evaporator and trap were connected in series and were different resistances. Therefore, at a given current the trap temperature was higher than the evaporator temperature. This can be noticed in figure 5 where some direct mode test data is plotted. In an actual application, the trap would be at the same temperature as the evaporator. The important point to note is that the direct mode conductance was 6 to 8 watts/$^{\circ}$F.

The reverse mode steady state data is shown in Figure 6. Shutoff of the pipe is evident by the large temperature difference between the condenser and evaporator. Reversal was obtained in 6 minutes with 60 watts of power applied to the condenser (20.6 Btu). As stated earlier, the shut off time and associated heat transport are functions of the condensation rate in the trap as compared with the condensation in the pipe itself. The data is thus a function of the external coupling of trap and pipe to the reverse mode heat sink as well as the specifics of the design itself.

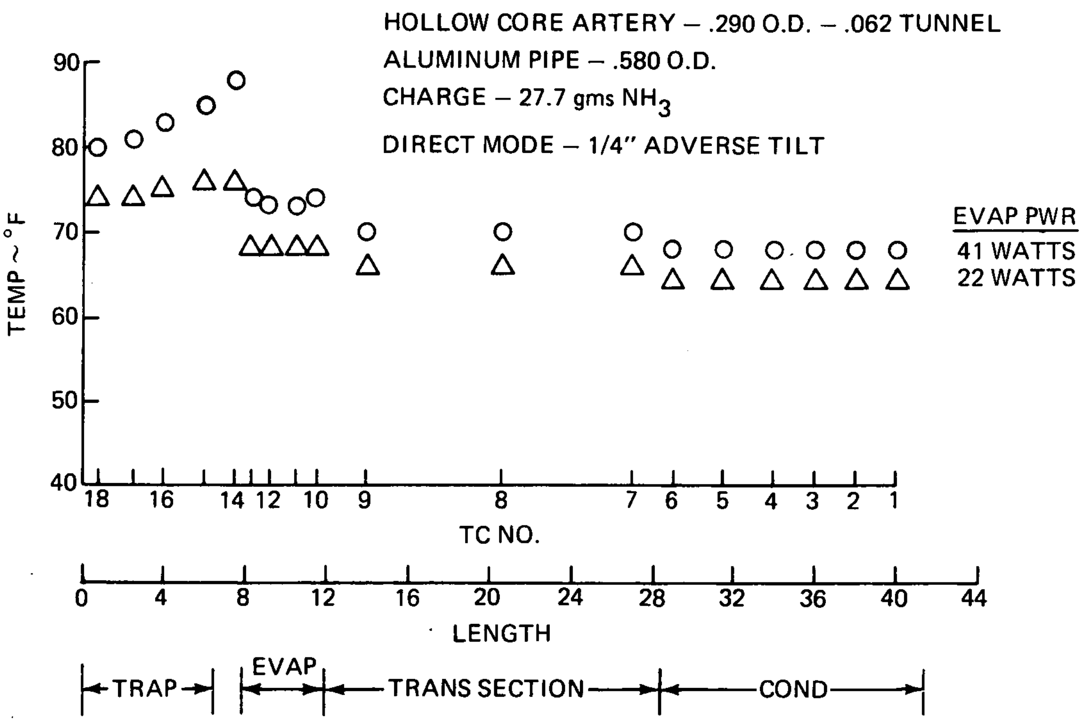


Fig. 5 Liquid Trap Development Diode Temp. Profile — Direct Mode

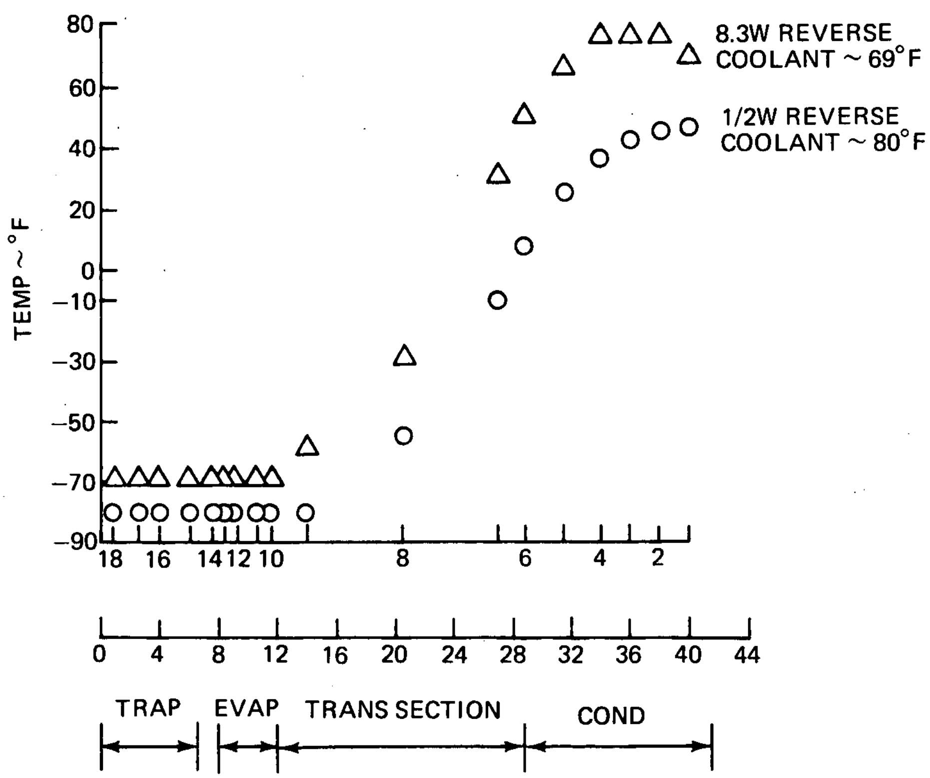


Fig. 6 Liquid Trap Diode Steady State Low Temp. Reverse Mode Profile

3.3.2 Liquid Trap Parametric Studies

The parametric studies conducted for the liquid trap design are based on use of the spiral artery tunnel wick. This wick is self-priming and combines high capacity with high conductance in the normal operating mode. With this wick, the transport capacity is a function of tunnel diameter and artery overall diameter, as well as pipe inside diameter when the artery is large enough to severely constrict the remaining vapor space. The principal item of interest is the reservoir volume required to hold all the liquid in the pipe in the reverse mode of operation.

The method of analysis for the tunnel wick is presented in Appendix A and is essentially the same as outlined in Reference 3. The calculations were made for a pipe similar to an early version of the ATFE diode, with lengths of 3.34" for the evaporator, 4.62" for the transport section and 18.0" for the condenser. Charge and transport capacity calculations are based on the mean of evaporator and condenser temperatures in the normal mode of operation (taken to be 93°F and 83°F, respectively). For the reverse mode, the evaporator was assumed to drop to -125°F with the condenser held at 83°F. The reservoir was assumed to be at the evaporator temperature of -125°F.

Calculated values of maximum transport capacity and reservoir volume are shown in Figure 7 using ammonia as working fluid. Results are shown as a function of artery diameter for three values of pipe inside diameter. In these calculations the artery consists of a hollow core or tunnel surrounded by a spiral artery annulus .070" thick.

Results for artery diameters smaller than that corresponding to peak transport capacity are of most interest. In these cases, liquid pressure drop is dominant and Q_{max} depends primarily on tunnel diameter. With artery diameters larger than those for peak capacity, vapor pressure drop becomes excessive. causing transport capacity to decrease.

Note that reservoir volume depends primarily on artery diameter. The small differences with pipe diameter are primarily due to variations in liquid volume in the webs which connect the artery to the wall. For a transport

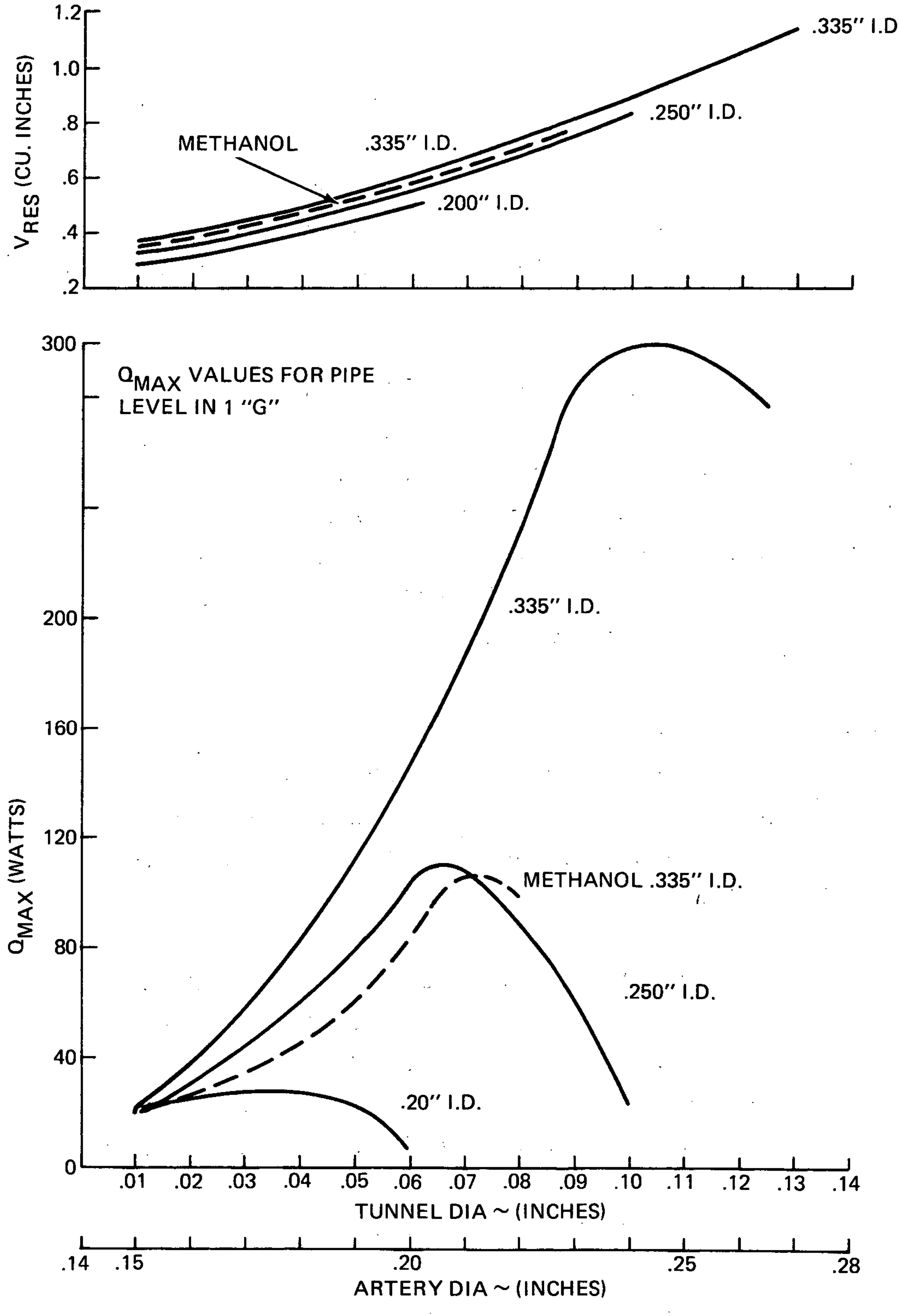


Fig. 7 Liquid Trap Diode Ammonia and Methanol

capacity in the 100 watt range (1500 watt-inches), a reservoir volume of approximately 0.5 cubic inches is required.

Results with Freon-21 as working fluid are shown in Figure 8. Trends are similar to those obtained with ammonia, though Q_{max} values are lower for Freon-21 because of the lower zero "g" liquid figure of merit (surface tension time latent heat divided by kinematic viscosity). A 100 watt pipe using Freon-21 would require a liquid trap volume of approximately 0.75 cubic inches, and a pipe diameter of at least 0.335".

Reverse mode steady state heat conduction values would simply be that due to solid conduction in the pipe wall augmented somewhat by the dried-out wick. For the assumed transport length of 4.62" and temperature difference of 208°F, a stainless steel diode with .020" thick wall should have a conduction heat transfer below 1 watt, even allowing for some wall thickening for mitered corners. The transient heat transfer during pipe shut-off is much harder to predict, but should be proportional to liquid trap volume.

3.4 Excess Liquid Blockage

If a heat pipe is charged with excess fluid, that fluid tends to accumulate as a slug in the colder portion of the pipe, except where displaced by surface tension and gravity forces. Because of its low conductivity, the liquid very effectively limits the heat transfer.

For a thermal diode, the excess liquid would shift naturally from one end to the other as hot and cold ends were interchanged. Under reverse-mode operation, the excess liquid must have a volume sufficient to block the vapor space of the cold end and a large part of the transport section (to minimize conduction heat transfer). A reservoir would be provided at the other end to contain the excess liquid under normal-mode conditions. The reservoir size must be a little larger than the absorber and transport section vapor space volumes, to allow for changes in liquid density with temperature. For Freon-21 working fluid, the ratio would be approximately 1.1:1, as compared with approximately 6.3:1 for the gas-reservoir concept.

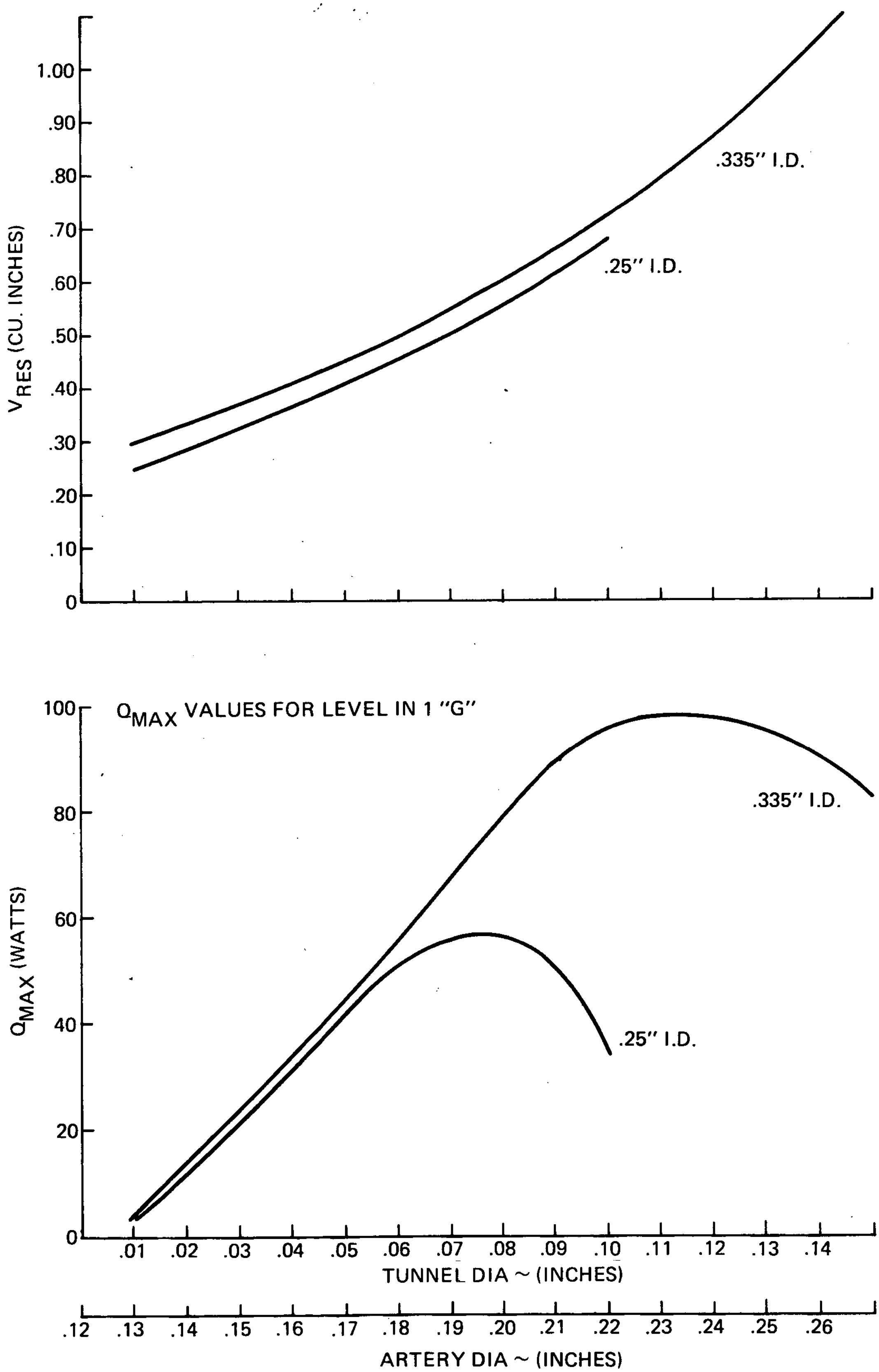


Fig. 8 Freon-21 Liquid Trap Diode

For the transient response in emptying the reservoir for shut-off, the total amount of heat transported depends on the ratio of reservoir evaporation rate to the evaporation rate from what is normally considered the condenser portion of the pipe. In going from the reverse to the normal mode of operation no startup time is required because evaporation of the excess liquid serves to carry heat to the equipment shelf in much the same manner as ordinary evaporation.

A limitation on this technique is the ground test requirement. In a gravity environment the vapor space in the blocked sections of the shutoff diode must be thin enough to insure that the capillary force, ΔP_{CAP}, will support the pressure head of the liquid slug (Fig. 9). This is necessary if the vapor space is to self-fill with liquid, and remain filled in the reverse mode. This requirement results in extremely thin vapor spaces, and consequently large vapor pressure drops during normal heat pipe operation. This limits the heat pipe capacity, restricting this type of diode to smaller heat transport applications.

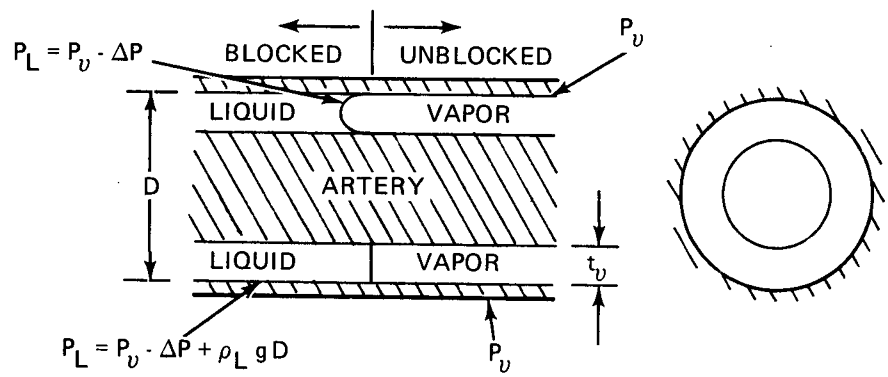
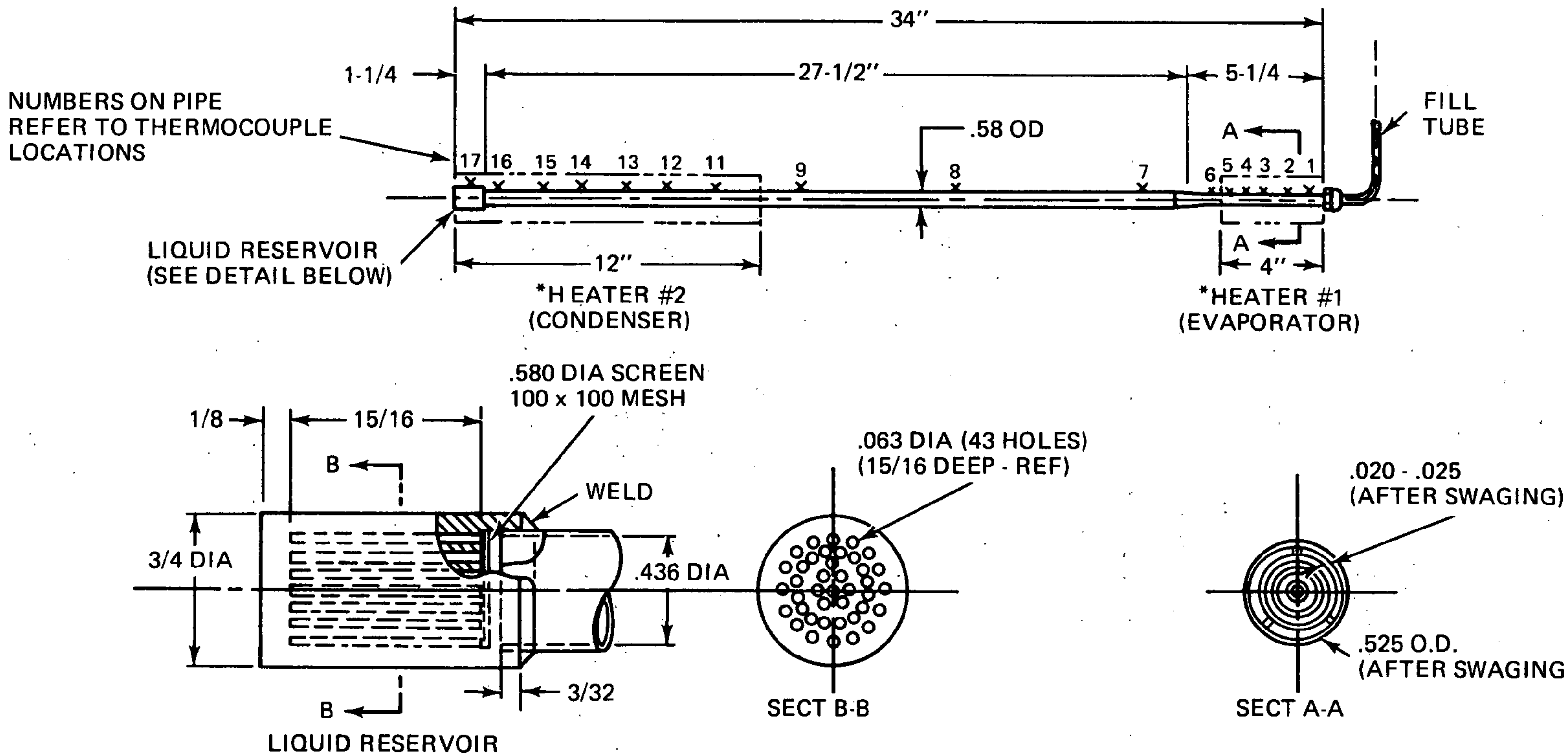


Fig. 9 Liquid Blockage of Vapor Space

3.4.1 Liquid Blockage Feasibility Tests

In order to demonstrate feasibility, a liquid blockage thermal diode was fabricated and tested as part of an in-house funded project. To expedite feasibility testing, an existing aluminum pipe was used. The artery was a stainless steel spiral artery/tunnel wick with an .069 inch diameter tunnel. The pipe length was 34 inches. Figure 10 shows a sketch of the pipe along with some of the pertinent details.



*HEATER #1 - 7.32Ω
HEATER #2 - 19.82Ω

Fig. 10 Development Liquid Blockage Diode Ammonia Heat Pipe

The basic pipe had an outside diameter of 0.580 inch , after the initial swaging operation required for good retainer contact. A second swaging operation was performed over 6 inches of the evaporator end of the pipe to reduce the vapor space to about 0.020 inches. This narrow gap permits self-priming of the vapor space in the shutoff mode and minimizes the amount of excess fluid required for blockage. The O.D. in this region was 0.525 inches.

A liquid reservoir was added to the condenser end of the pipe to trap the excess fluid added to the charge in order to obtain liquid blockage in the evaporator during the shutoff mode operation. The reservoir was made by drilling 43 - .062 x 1.00 inch holes in an aluminum cylinder. The reservoir was then welded on the condenser end of the pipe.

The pipe was charged with 28 grams of UHP (ultra high purity, 10 ppm H_2O max) ammonia. This is equivalent to an 8% artery overcharge at 75°F. Both the 4 inch evaporator and 12 inch condenser were equipped with heaters and cooling systems in order that both modes of operation could be tested.

Tests were conducted in both the normal and shutoff modes of operation. Figure 11 shows some results of the normal mode tests. It can be noticed that the evaporator did not run at a uniform temperature during normal operation. This is attributed to the extremely small vapor space that was created during the .525 inch swaging operation. After the latter operation was completed it was noticed that the retainer section was very close to the tube wall. Shims of .020 inch thickness were inserted into the evaporator in order to obtain the required vapor space, but the geometry remained somewhat irregular. Very narrow portions of the vapor space could retain liquid and locally raise the wall temperature.

Figure 12 shows some results in the shutoff mode of operation. Shutoff of the pipe is evident from the sharp gradient, characteristic of conduction heat transfer, in the swaged portion of the pipe (thermocouples 1 - 6). The fact that the pipe was aluminum resulted in much higher heat conduction than would occur with a stainless steel pipe. As shown in Figure 12 the evaporator temperature decreased as the heat flux was increased. This was because the spray coolant bath was colder during the high load cases.

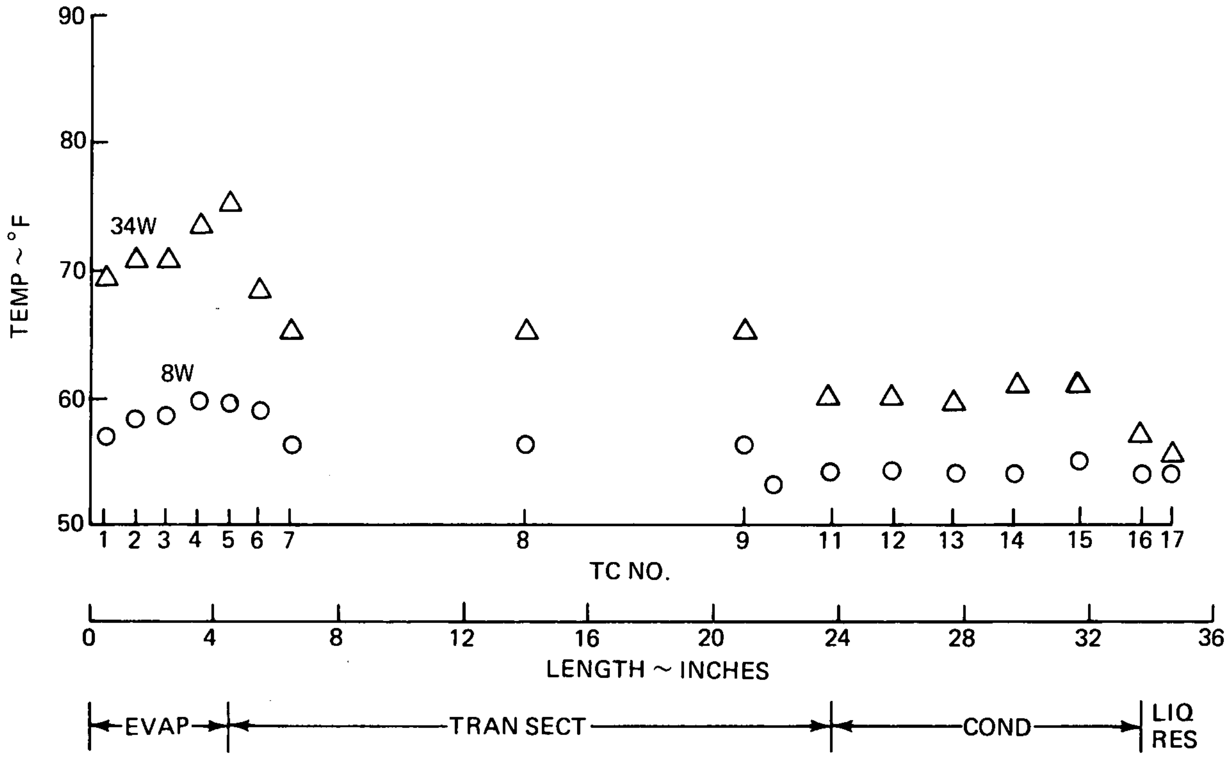


Fig. 11 Liquid Blockage Diode Pipe - Normal Mode Feasibility Test Model

The concept of using liquid blockage as a means of heat pipe shutoff was demonstrated. The very large shutoff gradients ($> 5^{o}F/watt$) clearly show the disruption of heat pipe operation when compared to the normal mode gradient of $0.3^{o}F/watt$.

3.4.2 Liquid Blockage Parametric Studies

The parametric studies conducted for the liquid blockage design are based (as were the liquid trap studies) on use of the spiral artery tunnel wick. The low pressure loss of this wick is particularly desirable for a liquid blockage diode to off-set the high vapor pressure loss associated with the use of narrow vapor passages. For the normal mode of operation, the calculations for transport capacity follow the method of analysis presented in Appendix A except that allowance is made for the use of a different pipe diameter in the condenser and unblocked portion of the transport section than is used in the evaporator and the portion of the transport section which is to be blocked. The artery itself is assumed to be the same throughout the pipe. These changes are given in Appendix B.

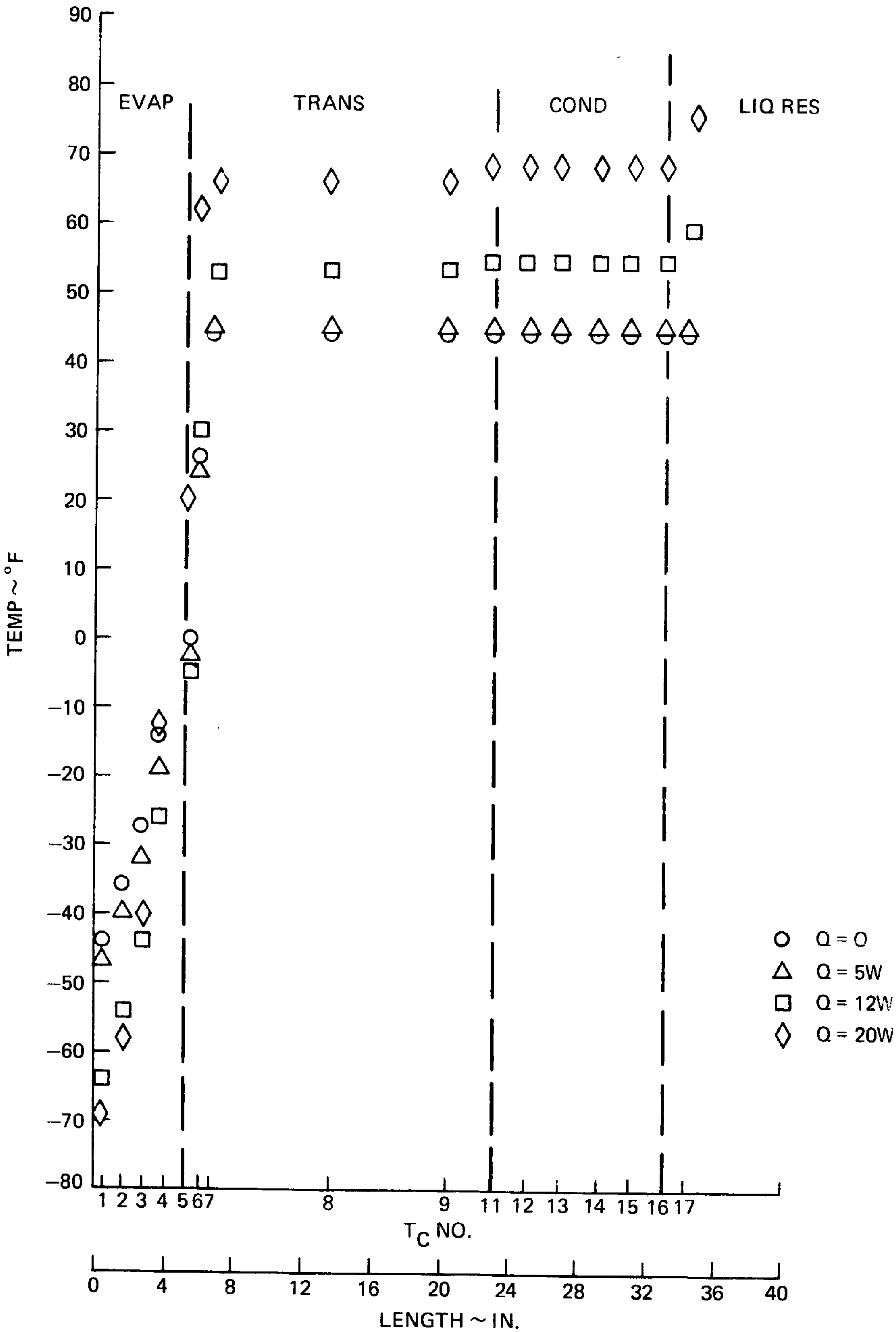


Fig. 12 Liquid Blockage Diode Pipe Shutoff Mode

The selection of the diode diameter and working fluid is governed by the thin vapor space requirements of the liquid blockage diode. As seen in Fig. 9,

$$t_v \sim \frac{\sigma}{\rho_L \quad D_i} \tag{1}$$

in the forward mode, when the diode operates as an ordinary heat pipe, the capacity of the pipe with no gravity head losses can be written as

$$Q = \frac{\Delta P_C}{C_A + C_V + C_W + C_{GR}}$$

where, for example, $(C)_A\ Q = \Delta P_A$, the artery pressure drop. For liquid blockage diodes of the size of the ATFE diode, the dominant pressure drop contribution is the pressure drop in the vapor space, $\Delta P_V = (C_V)Q$. Therefore, if

$$C_V \gg (C_A + C_W + C_{GR})$$

$$Q \approx \frac{\Delta P_C}{C_V}$$

Also:

$$\Delta P_C \sim \sigma$$

$$C_V \sim \frac{\mu_v}{\lambda \rho_v A_v (D_v)^2} \sim \frac{}{\rho_v \lambda t_v^3 D_i}$$

Then

$$Q \sim \frac{\sigma \rho_v \lambda t_v^3 D_i}{\mu_v} \tag{2}$$

or substituting equation (1)

$$Q \sim \frac{\sigma^4 \rho_v \lambda}{\mu_v \rho_L^3 D_i^2} \tag{3}$$

Equation 2 illustrates the importance (for small values of t_v) of the vapor space thickness on capacity. Equation 3 indicates that the most desirable fluid would have the largest value of

$$I = \frac{\sigma^4 \rho_v \lambda}{\mu_v \rho_L^3}$$

Of the three fluids considered for the ATFE design, ammonia, Freon-21, and methanol, ammonia has significantly the largest value of I (Table 2) and was therefore selected as the working fluid.

Table 2 Fluid Comparison

Fluid	$I = \frac{\sigma^4 \rho_v \lambda}{\mu_v \rho_L^3}$ $\frac{ft^8 - lb}{sec^7}$
Ammonia	1.59
Freon-21	0.02
Methanol	0.06

Equations (1) and (3) also indicate that for a diode for which $\Delta P_v \gg \Delta P_{ART}$, increasing the internal diameter D_i, decreases the vapor space and the capacity. The optimum diameter for maximum heat transport is therefore some small value where ΔP_v approaches in magnitude ΔP_A (recognizing that for this condition, equations (2) and (3) do not hold).

Calculations of liquid blockage diode performance with ammonia working fluid are presented in figure 13 for a diode similar to the ATFE with normal mode lengths of 4.56" for the evaporator, 5.70" for the transport section, and 18.0" for the condenser.

Reservoir volume requirements and maximum transport capacity are shown as a function of artery core and overall diameter for evaporator inside diameters of .25", .30" and .335". The condenser inside diameter was .335" in all cases. In the transport section, the unblocked portion has the same I.D. as the condenser, and the blocked portion (in the reverse mode) has the same I.D. as the evaporator. The artery consists of a hollow core surrounded by a .070" thick spiral artery annulus.

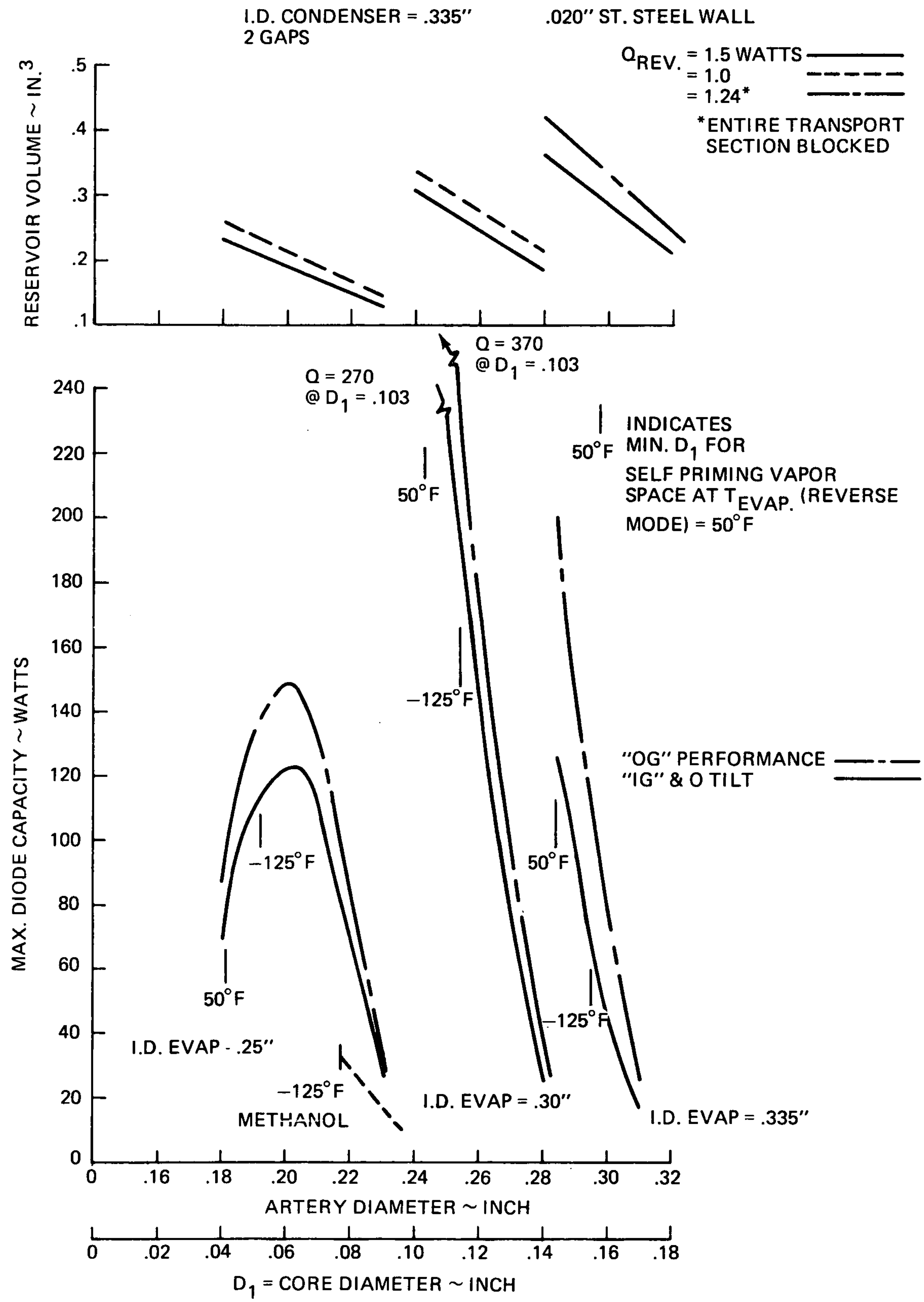


Fig. 13 NH_3 Liquid Blockage Diode Parametric Study

Values of maximum transport capacity are shown based on equation (A-10) with the diode level (h = 0) in one "g" and with the diode in zero "g" ($\Delta P_B = 0$).

For each evaporator I.D., there is a minimum artery diameter required to keep the vapor space thin enough to hold liquid in ground tests. This is calculated for the reverse mode of operation evaluating the meniscus surface tension at the condenser temperature and evaluating the liquid density at the evaporator temperature. When the evaporator is below freezing, liquid density is evaluated at the triple point temperature. Minimum artery diameters are shown in figure 13 for evaporator temperatures of 50°F and -125°F, and condenser temperature of +83°F in the reverse mode.

The reservoir volume required for each evaporator I.D. varies with the length of transport section which must be blocked. For a steady state reverse mode heat transfer of 1.5 watts and condenser and evaporator temperatures of 83°F and -125°F, respectively, the blocked portion of the transport section ranges from less than 4" in length at .25" I.D. to more than 5" at .335" I.D.. The lengths were calculated for one-dimensional heat conduction assuming = .020" thick wall with a thermal conductivity of 12 BTU/hr-ft-°F, and also taking into account the screen and fluid conductance. The corresponding reservoir volumes range from .13 to .36 cubic inches. Slightly larger reservoir volumes are also shown for longer blocked transport section lengths to obtain a reverse mode heat conduction of only 1 watt for .25" and .30" diameters. At .335" diameter, blocking the entire transport section only reduces the reverse mode heat conduction to 1.24 watts.

Note that the highest values of transport capacity are obtained with the .30" I.D. evaporator and the minimum permissible artery diameter. At a cold end temperature of -125°F the artery can be .254" overall diameter, providing a maximum heat transport of 192 watts (3000 watt-inches), and still retain liquid level in a one "g" field. This is an order of magnitude larger than the ATFE requirements.

Also shown in figure 13 is a single curve of maximum capacity of a diode with methanol working fluid with a .25" I.D. evaporator. The minimum artery diameter is .217" to retain liquid in ground test with -125°F evaporator and the corresponding maximum transport is 33 watts. These results are in line with the figure of merit values given in Table I. Clearly, methanol is marginal for the ATFE application. No results are presented for Freon-21 since they were below the ATFE requirement.

4.0 DIODE - DESIGN AND FABRICATION

4.1 Selection of the ATFE Diode Type

The requirements for the ATFE diode made either the liquid trap or the liquid blockage technique the most suitable for shutting off heat pipe operation. The temperature at which shutoff is required is 82°F, making impractical a design based on freezing of the working fluid. The relatively large reservoir volume required for the noncondensable gas blockage technique was inconsistent with the weight and dimension restrictions placed upon the flight diode.

After limiting the potential designs to either a liquid trap or an excess liquid blockage type diode, a parametric study was undertaken to select the most suitable design. The study was restricted to diode designs utilizing self-priming, axisymmetric, spiral arteries in order to obtain large film coefficients, in the case of liquid blockage diodes, these designs provide a relatively large vapor cross-sectional area considering the small vapor space hydraulic radius required to support the blocking liquid slug.

In figure 14, the trends indicated by the parametric study are presented. Feasibility models of both the liquid trap and liquid blockage pipes were built and successfully tested as described earlier, thus providing proof-of-principle of both designs. In the range of capacities less than 200 watts, the liquid blockage diode required a significantly smaller reservoir volume than a liquid trap diode of equal capacity. The liquid blockage diode therefore has an advantage in spacecraft applications, such as ATFE, where weight and size are important limitations. As previously mentioned, the vapor space restriction limits liquid blockage diodes to small capacity applications. Since the 200 watt limit far exceeds the 20-watt ATFE minimum requirement, the liquid blockage design was selected.

4.2 Design of Engineering Model

The objectives of Task II were to design, fabricate and performance test an engineering model of a thermal diode of a type, configuration, and capacity suitable for its inclusion as a component of the Advanced Thermal Control Flight Experiment (ATFE). Satisfaction of the objectives were to

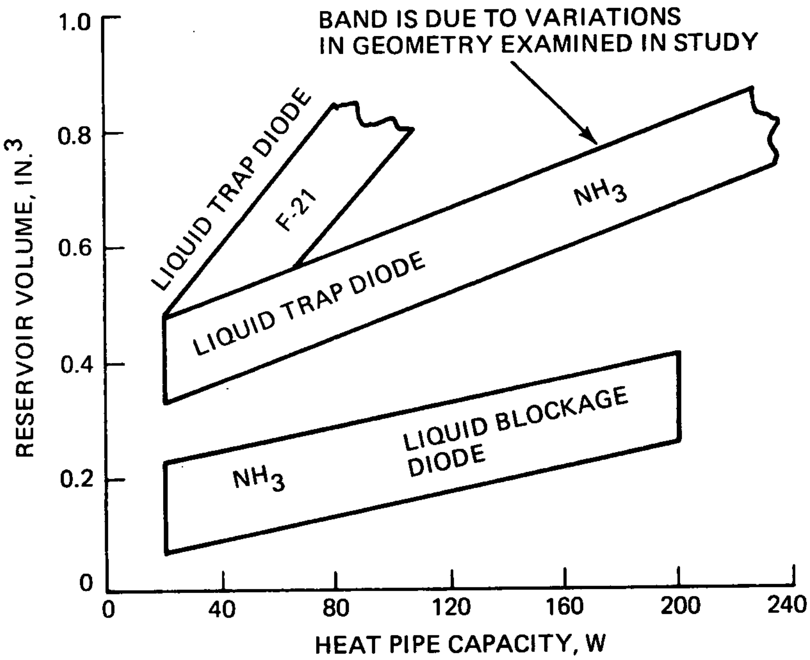


Fig. 14 Reservoir Requirements for Thermal Diode Heat Pipes

be based on the results of Task I. As stated in the previous section a liquid blockage type of diode with ammonia working fluid was selected. The thermal specifications which the diode had to meet are given below.

Mode	Q (Watts)	$T_{Abs.Saddle}$ (max) (°F)	$T_{Cond.Saddle}$ (°F)	T_{Max} (°F)
Direct	20 ± 2	105	89	16
Reverse	1.4	-180	82 ± 2	260

Mechanically, the diode had to be capable of withstanding without rupture the internal pressure resulting from a temperature of 260°F. In order to minimize the reverse conduction losses, stainless steel envelope was selected.

The spiral artery tunnel wick was selected for the parametric studies based on high transport capacity, high thermal conductance, and its self filling characteristic which provides proper operation in ground tests. From the parametric results presented in figure 13, an evaporator inside diameter of approximately 0.30" seems desirable, since it offers the potential of meeting transport capacity requirements an order of magnitude larger than the ATFE, and weight savings achievable with smaller diameters are relatively modest. For the ATFE, since transport capacity requirements are so modest, the artery was made with a smaller core diameter and a thicker annulus. This reduces the core volume and hence the amount of liquid which is in the vapor space prior to pressure priming the core (during start-up from an adiabatic condition in ground testing). The predicted capacity as a function of artery diameter with an annulus 0.112" thick is shown in figure 15. The condenser diameter also affects capacity, as shown in figure 16, particularly at small diameters where vapor pressure drop is large.

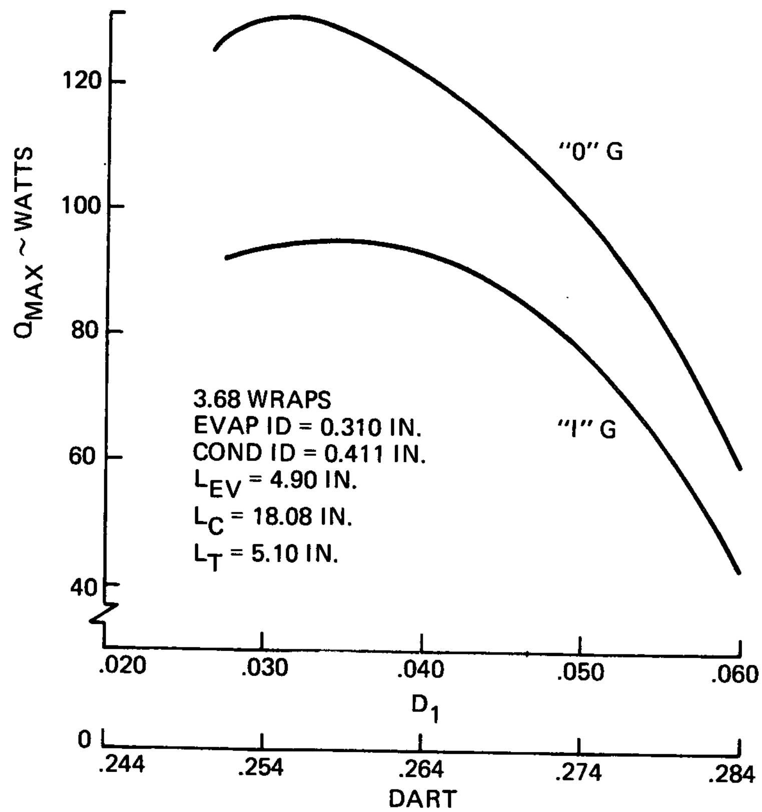


Fig. 15 Capacity vs Artery Diameter Liquid Blockage Diode - NH_3

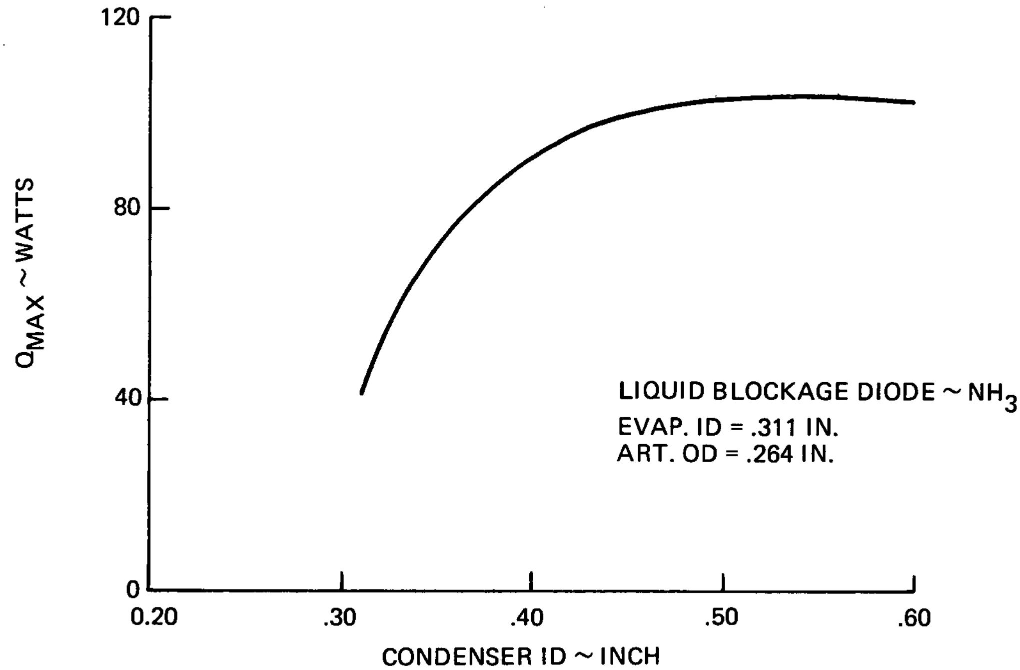


Fig. 16 Transport Capacity vs Condenser Diameter

While the 0.31" I.D. condenser meets more than twice the ATFE requirements, a large condenser diameter is desirable in order to reduce the internal pressure during a potential 260°F failure mode condition (if the feedback controlled VCHP should fail). With a 0.259" artery, if the complete diode was made with the .309 I.D., the specific volume that would exist (V = 41.5 cc/gm-mole) would cause a pressure in the pipe at 260°F of approximately 1800 psia. Also, maintaining the very narrow vapor space throughout the pipe would be difficult. It was therefore decided to increase the diameter of the condenser to an ID = .411. This increases the specific volume to 53.6 cc/gm-mole and results in a considerable reduction in pressure (~ 1490 psia at 260°F).

4.3 Diode Fabrication

Three liquid blockage diode heat pipes were fabricated during the program. The first one that was made was an engineering model followed by a qualification and flight model. The diodes consisted of four sections, namely, an evaporator (absorber), low conductance transport section, condenser and reservoir as shown in figure 17. Ammonia was the working fluid. The diode envelopes were made from Type 304 stainless steel tubing. The latter material was used to minimize thermal conduction in the reverse or shutoff mode. Capillary pumping in the heat pipes was accomplished with a 100 mesh self-priming spiral artery. The artery is centrally supported in the pipe by a three-legged mesh retainer assembly that also serves as a communication link between the circumferential wall grooves and the artery. The artery extends the full length of the pipe but is isolated from the reservoir. Details of the diode construction can be seen in figure 18 (AD 1411-1000-J) and Table III.

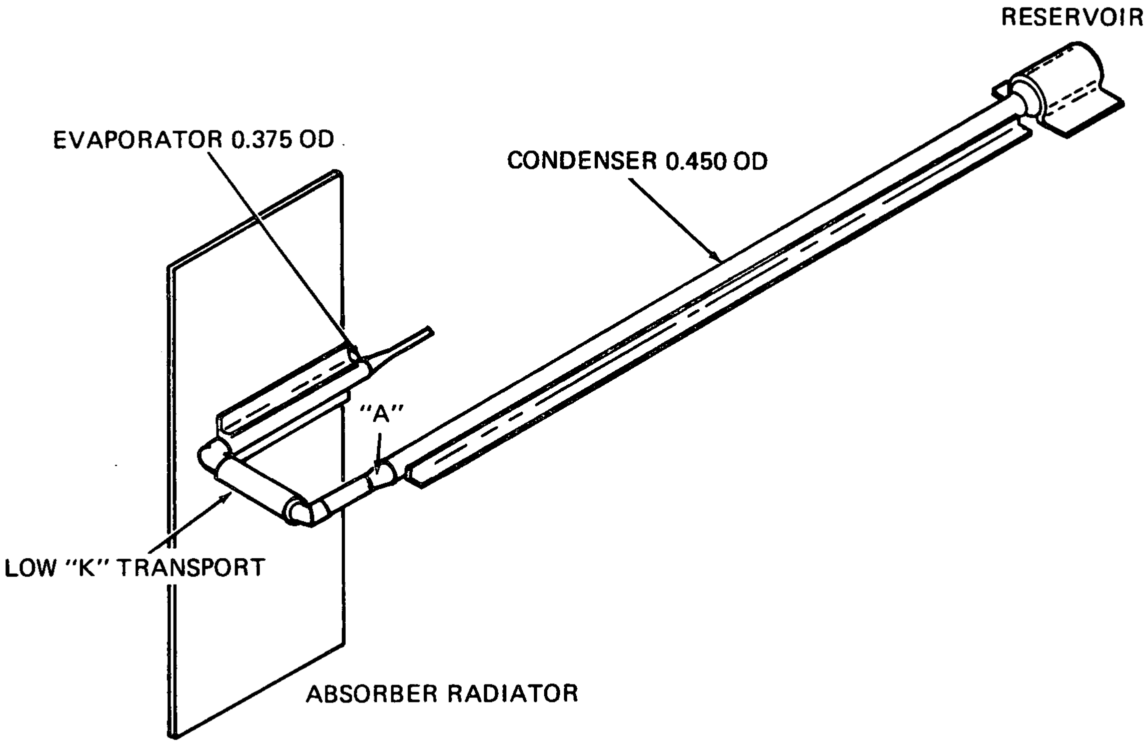


Fig. 17 Diode Heat Pipe - ATFE

In the reverse or shutoff mode, the vapor space in the evaporator, low "k" and transition sections are filled with NH_3. Thus, the only mode of heat transfer from the condenser to the evaporator or absorber is conduction. In order to minimize the conduction, a low conductance section was inserted between the evaporator and transition section. The low "k" section had a nominal ID = .309 with a wall thickness of 0.010 in. The length of the thin wall section was 1.880 in. The thin wall presented a potential handling problem therefore this section was reinforced with a fiberglass wrap. The latter also increased the burst pressure of the section from 7500 psi to 16,000 psi.

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The reservoirs of the diodes were made by drilling 86 - .063 in. holes in an aluminum cylinder 1.44 inches long. The reservoir was then encased in a stainless steel shell (figure 18). Aluminum was used in order to increase the heat transfer rates during the direct to reverse mode transport.

In order to attach the diode in the ATFE experiment package, the diode was attached to an aluminum saddle (manufactured by Dynatherm Corp.) and absorber plate. Initially, the attachment was made by a conductive adhesive but was later changed to a soft solder attachment. This will be discussed in more detail in the test section.

A summary of the flight diode dimensions and parameters is given in Table III.

Table III- Flight Diodes Dimensions

Section	Length(in.)	O.D.(in.)	I.D.	Vapor Space Thickness (in.)
Evaporator(Absorber)	4.90*	.377	.309	.025
Low "K"	1.88	.329**	.309	.025
Transition	1.42	.375	.309	.025
Condenser	18.08	.452	.411	.074
Reservoir	1.44	1.00	.884	-

*Engineering Model Evaporator Length was 3.90 in.
**Tube without fiberglass reinforcement.

- Envelope Material - 304 S.S.
- Wick - 100 Mesh S.S. Tunnel Spiral Artery
- Working Fluid - UHP Ammonia, 17.5 gms
- Reservoir Vol. = 0.369 in^3
- Weight (Diode only) = 0.63 pounds
- Burst Pressure 7500 psi

5.0 MECHANICAL TESTS

The major mechanical requirement imposed on the diode design was that the diode shall not rupture from the pressure resulting from a temperature of 260°F (Ref. 4). This temperature could occur if there is a failure of the Feedback Controlled VCHP and the diode absorber plate is absorbing solar radiation. At a temperature of 260°F, the diode pressure is approximately 1500 psia. The diode was designed to withstand at least 4 times this pressure. In order to verify the integrity of the diode design, proof and burst pressure tests were conducted on the components of the diode. Table IV summarizes the results of the pressure tests.

The major concern was a handling problem of the 0.010 in. thick low "k" section. Burst tests were conducted on this section using N_2 gas at room temperature. The section began to yield at 7200 psi and burst at 7500 psi. Although the burst was at a higher pressure than required, a fiberglass wrap reinforcement was applied to the section. The burst was then increased to approximately 16,000 psi. It should be noted that the .375" O.D. tube sections used in conjunction with the low "k" section did not have circumferential grooves. However, a .375 O.D. grooved section with a welded charged tube was proofed to 5000 psi with no anomolies.

During the proof pressure test of the engineering model diode, the reservoir end cap bulged slightly at 3200 psi. A test was later conducted on an equivalent reservoir with bursting occuring at 7500 psi. In order to eliminate bulging, the design of the end cap was changed to that shown in figure 18. The calculated burst of the reservoir was then increased to about 12,000 psi with a corresponding increase in yield. It should be noted that reservoir burst test was conducted using a typical .450 O.D. condenser tube. At a pressure of 7500 psi no anomolies were noted on the condenser. No further tests were therefore made on the condenser sections.

As requested by the NASA Technical Monitor, proof pressure tests were conducted on the completed flight pipes. Prior to charging the diodes with their working fluid, they were pressure tested with dry N_2 to 3000 psi at a

TABLE IV PRESSURE TEST RESULTS

Component	P[1], Calculated Burst (psi)	Actual Burst (psi)	Proof Pressure (psi)
1. Low "K" Section	6,300[4]	7,500	
2. Low "K" Section with fiber-glass reinforcement	-	16,000	
3. .375 O.D. EVAP.	11,200[4]	-	5,000
4. .450 O.D. COND.	9,400[4]		7,500
5. Reservoir	7,500[2] 12,000[3]	7,500[2]	
6. Charge Tube	30,000		5,000
7. Complete Pipe	7,500 Eng. Model 9,400 Flight Models		3,000 @ 260°F prior to pinch off 2,300 @ 285°F after pinch off

(1) $P = 2\frac{st}{D}$

(2) 304 Annealed SS End Cap - Engin. Model

(3) 301 - $\frac{1}{2}$ Hard SS End Cap - Flight Models

(4) 304 - 1/8 Hard SS

temperature of 260°F. After charging the pipes with NH_3 and welding of the pinched off charged tube, the pipes were placed in an oven at 280 - 285°F for 1 hour. The pressure in the pipe was approximately 2300 psi. After the test, the diodes were given a dimensional and NH_3 leak check. Both flight pipes were satisfactory.

6.0 THERMAL PERFORMANCE TESTS

Thermal performance tests were conducted on the engineering model, qualification and flight diodes. Tests were performed with two different saddle attachment techniques. The engineering model saddles were bonded to the diode with Hysol silver-filled epoxy. The qualification model was also tested with bonded saddles but due to a possible premature high temperature condition, adhesive bonding was eliminated and the qualification pipe was soldered to the saddles. The flight pipe was also soldered. Test results will be presented for both bonded and soldered configurations.

The thermal requirements that the diode had to meet are given in Table V below:

Table V - Thermal Requirements (Ref. 3)

Mode	Q (Watts)	$T_{Abs\text{-}Saddle}$ Max ($^{\circ}F$)	$T_{Cond\text{-}Saddle}$ ($^{\circ}F$)	ΔT_{Max} ($^{\circ}F$)
Direct	20 $\pm$ 2	105	89	16
Reverse	1.4	-180	82 $\pm$ 2	260

6.1 Engineering Model Tests Without Saddles

The engineering model was tested with and without saddles. The latter condition was tested in order to determine maximum capacity (Q_{Max}) versus tilt. For this test, a nichrome ribbon heater was attached to the evaporator portion of the pipe in such a way as to simulate the single-sided heat input from the saddles. The pipe was instrumented with copper-constantan thermocouples and mounted in an adjustable test fixture. Condenser cooling was accomplished with a variable temperature water spray bath impinging on one side.

Power was applied to the evaporator heater in 10-watt increments until dryout occurred at a condenser temperature of 80°F. Dryout or Q_{Max} levels were obtained at three tilts. Tilts were defined as the vertical distance between the evaporator and condenser planes. Figure 19 shows the results of the tests. Extrapolating the data curve to a zero tilt or level conditions gives a Q_{Max} = 85 watts.

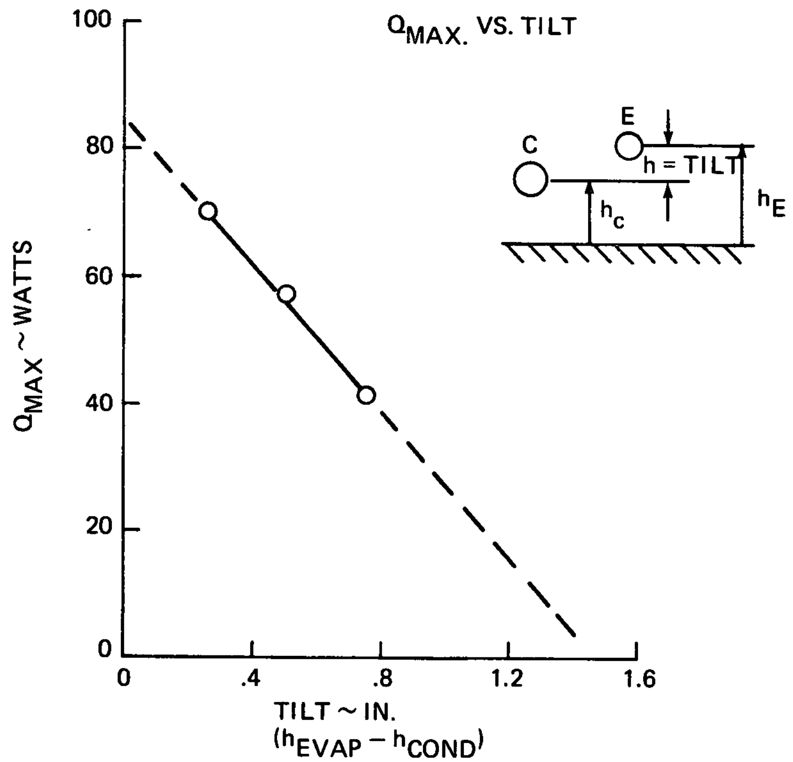


Fig. 19 Diode Engineering Model Heat Pipe

6.2 Engineering Model Direct Mode Tests With Saddles

Direct mode tests were performed with saddles attached to the evaporator and condenser portions of the pipe. The saddles were made of aluminum and were fabricated by Dynatherm Corporation. The condenser saddle was 18.08 inches long and the evaporator saddle was 3.90 inches in length. An absorber plate approximately 5 x 12 inches was attached to the evaporator saddle. The pipe was bonded to the saddles with silver filled Hysol epoxy. The pipe with saddles is shown in figure 20.

The pipe, saddles, reservoir and radiator plate were instrumented with thermocouples and heater ribbons were attached to the radiator plate. The thermocouple locations are shown in figure 21. The condenser saddle was cooled by a water spray bath located below the saddle. The absorber plate was insulated on both sides to insure minimum heat loss during the direct mode tests.

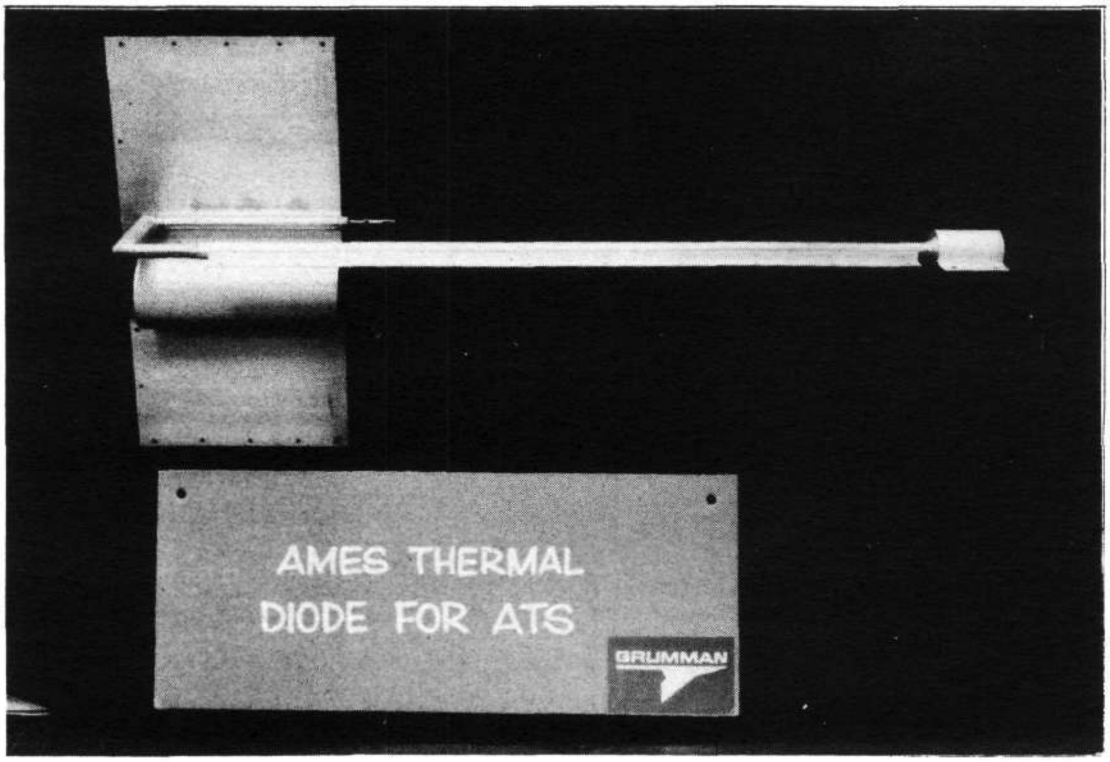


Fig. 20 Diode Attached to Saddles

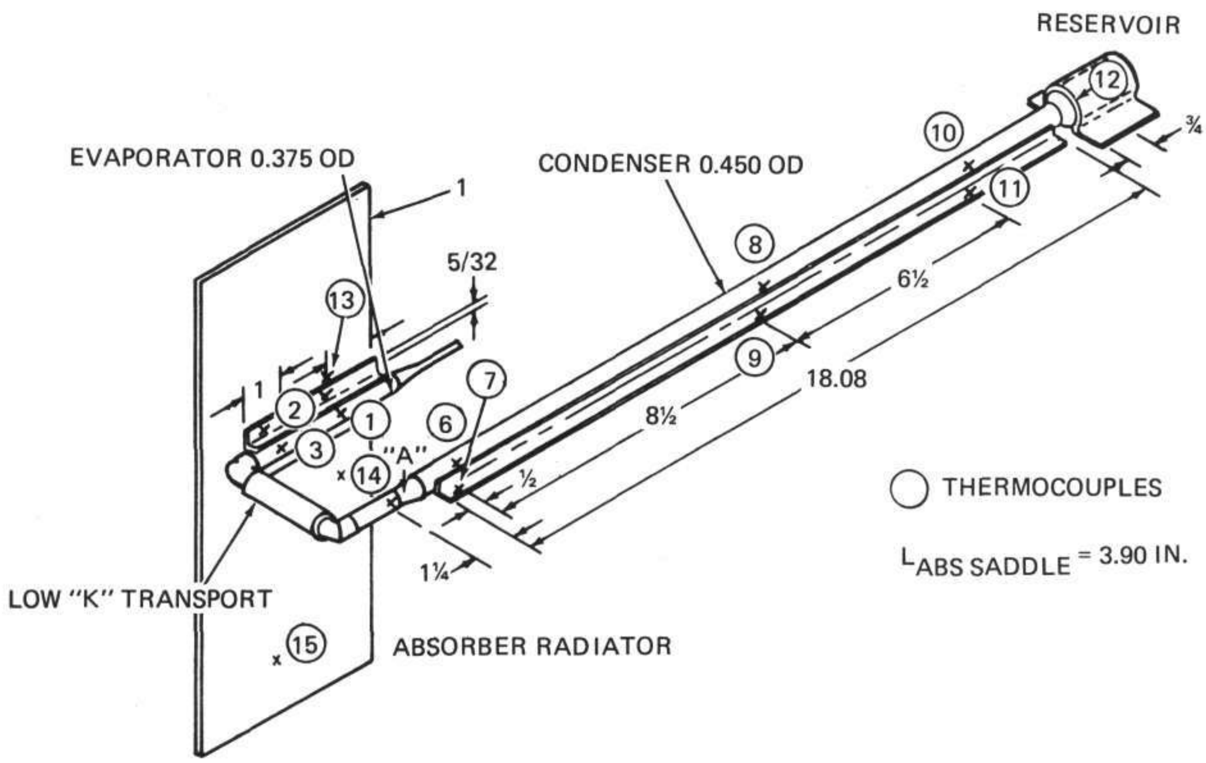


Fig. 21 Diode Heat Pipe, Thermocouple Layout - Engineering Model

The first direct mode tests were performed in early October, 1971. During the tests it became evident that there was a high thermal resistance between the absorber saddle. In order to investigate this, a small heater was placed on the absorber plate directly on the back of the saddle. Various heat inputs were imposed and the temperature difference across the plate-saddle interface was obtained. Figure 22 is a plot of the results. Also shown in the figure is the absorber saddle to condenser saddle ΔT. Due to the high plate-saddle ΔT, the NASA Technical Monitor instructed Grumman to remove the absorber saddle.

The joining of the plate to the saddle was accomplished by resistance welding and riveting. It was observed that fusion between the two surfaces was not accomplished thereby causing the high ΔT. A new configuration was fabricated by Dynatherm and installed on the pipe. In this configuration, the flanges of the saddle were butt welded to the radiator plate eleminating the plate to saddle ΔT. The pipe was retested and showed essentially the same evaporator saddle to condenser saddle ΔT, and as shown in figure 23.

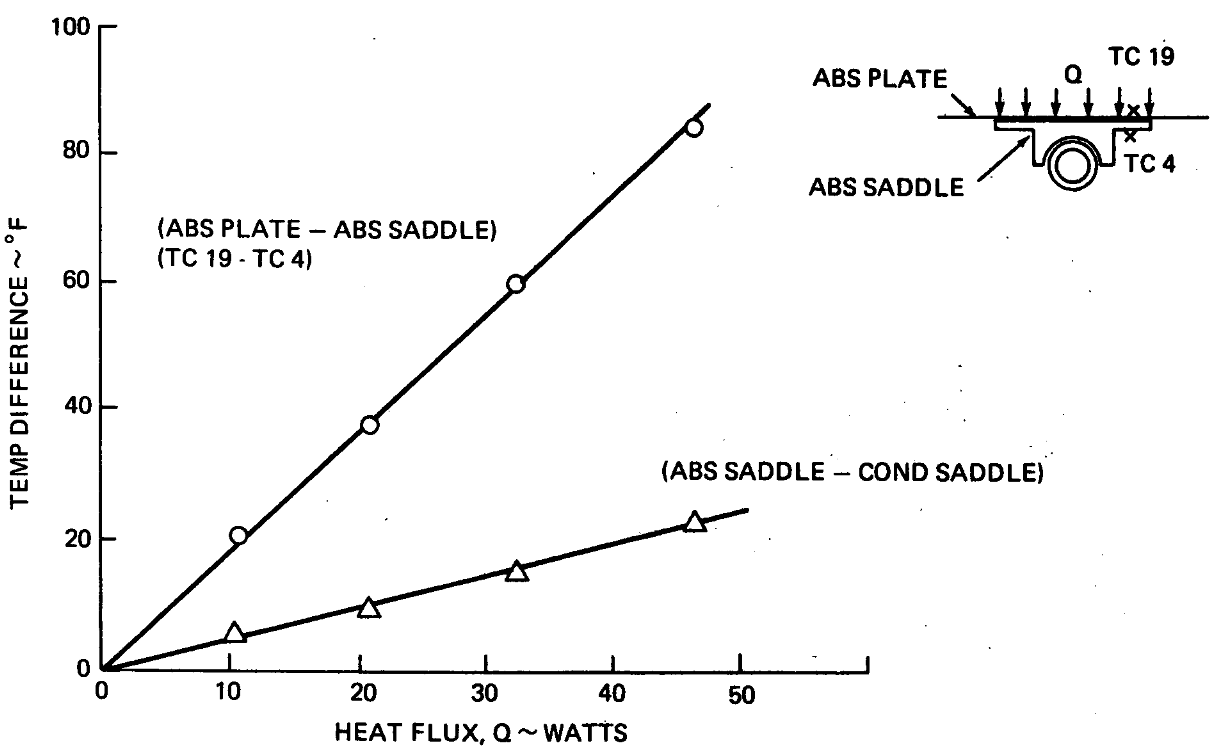


Fig. 22 ΔT vs Q Absorber Plate to Saddle - Initial Design

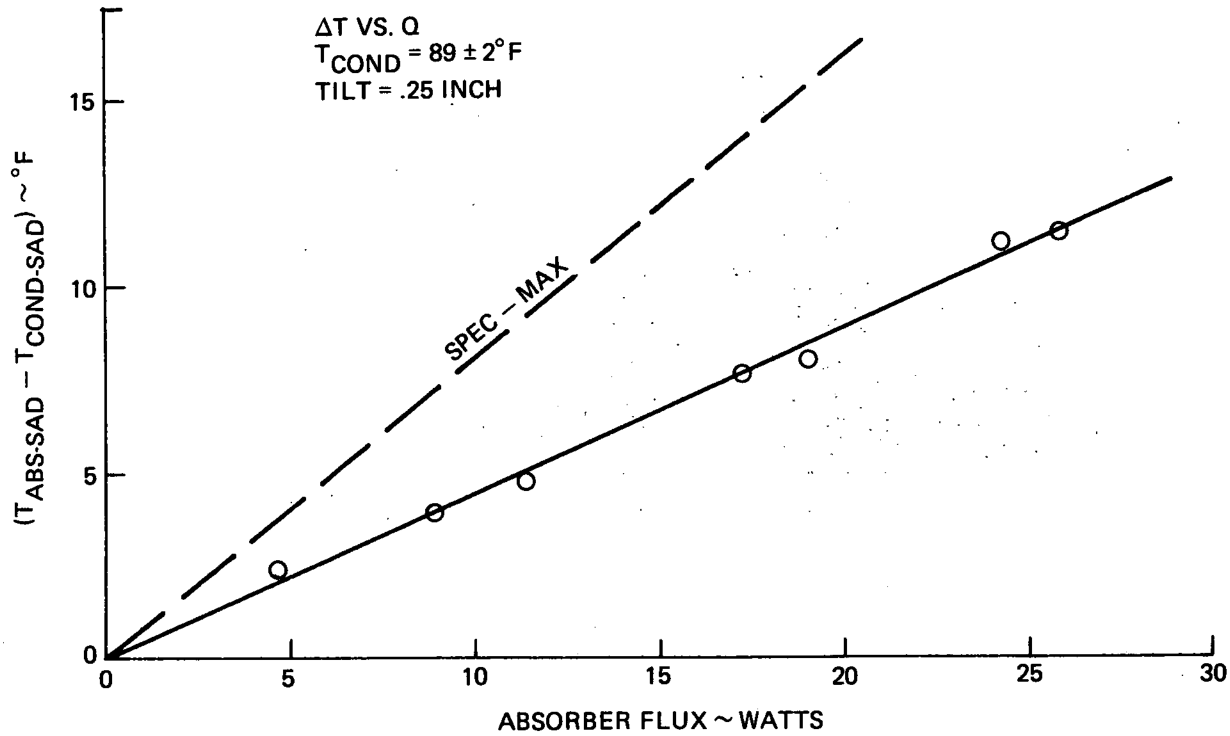


Fig. 23 Engineering Model Direct Mode Test Results

6.3 Engineering Model Reverse Mode Tests

The requirement for the reverse mode condition when the condenser saddle is at 82°F and the absorber saddle is -180°F is a conduction heat leak from condenser to absorber no greater than 1.4 watts. Based on this requirement the overall conductance of the pipe in the reverse or blocked mode must be 0.00538 watt/°F. In order to demonstrate this extremely low conductance, the diode heat pipe was insulated with a perforated multilayer insulation blanket, which had 15 denier nylon netting spacers. The insulation was applied in a tapered fashion to minimize any radiation tunneling from the warm condenser to the cold absorber. The back side of the absorber plate and a portion of the front side was insulated with 30 layers of insulation. The insulated front portion was the curved section which houses the reservoir of the Feedback Control Heat Pipe. Figures 24 and 25 are photos of the insulated pipe. It should be noted that the absorber plate was painted and had an emittance of .88. Prior to insulating, a heater was placed on the condenser saddle and reservoir flange to simulate the heat input from the phase change material. The insulated pipe and its test stand were installed in a vacuum chamber (equipped with a cold wall) and is shown in figure 26.

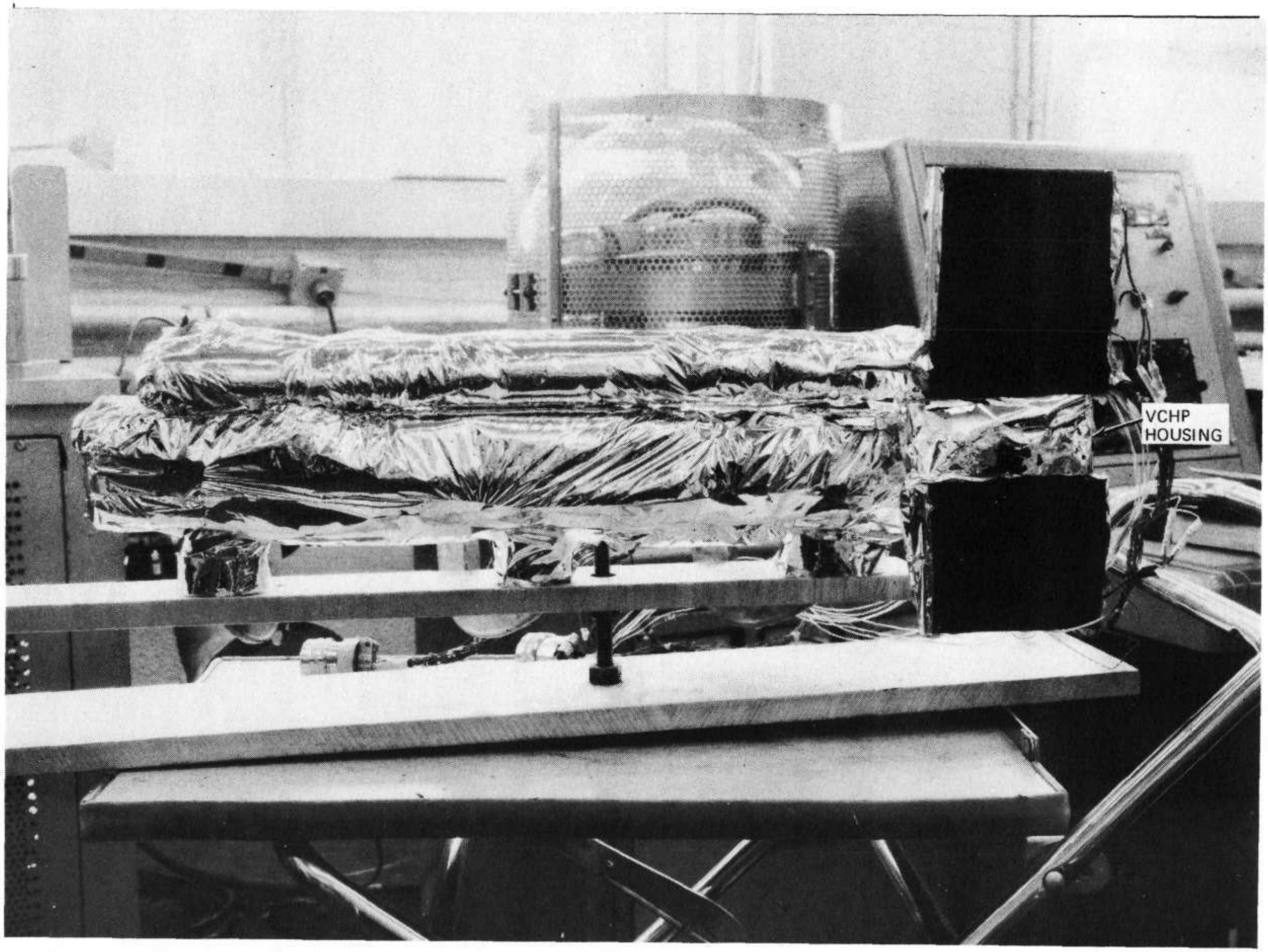


Fig. 24 Insulated Diode Showing Absorber Plate - Reverse Mode

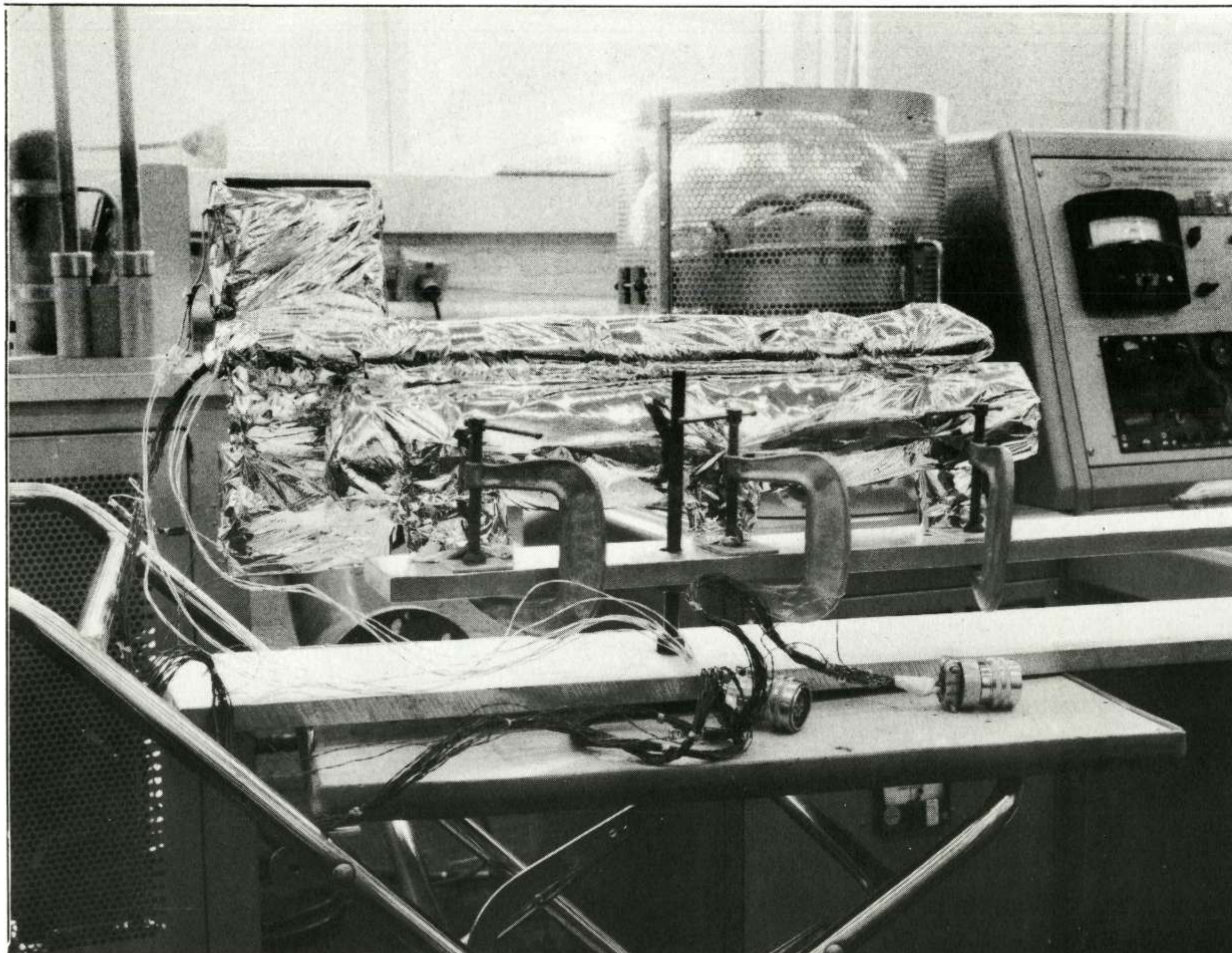


Fig. 25 Insulated Diode Showing Back Side of Radiator - Reverse Mode

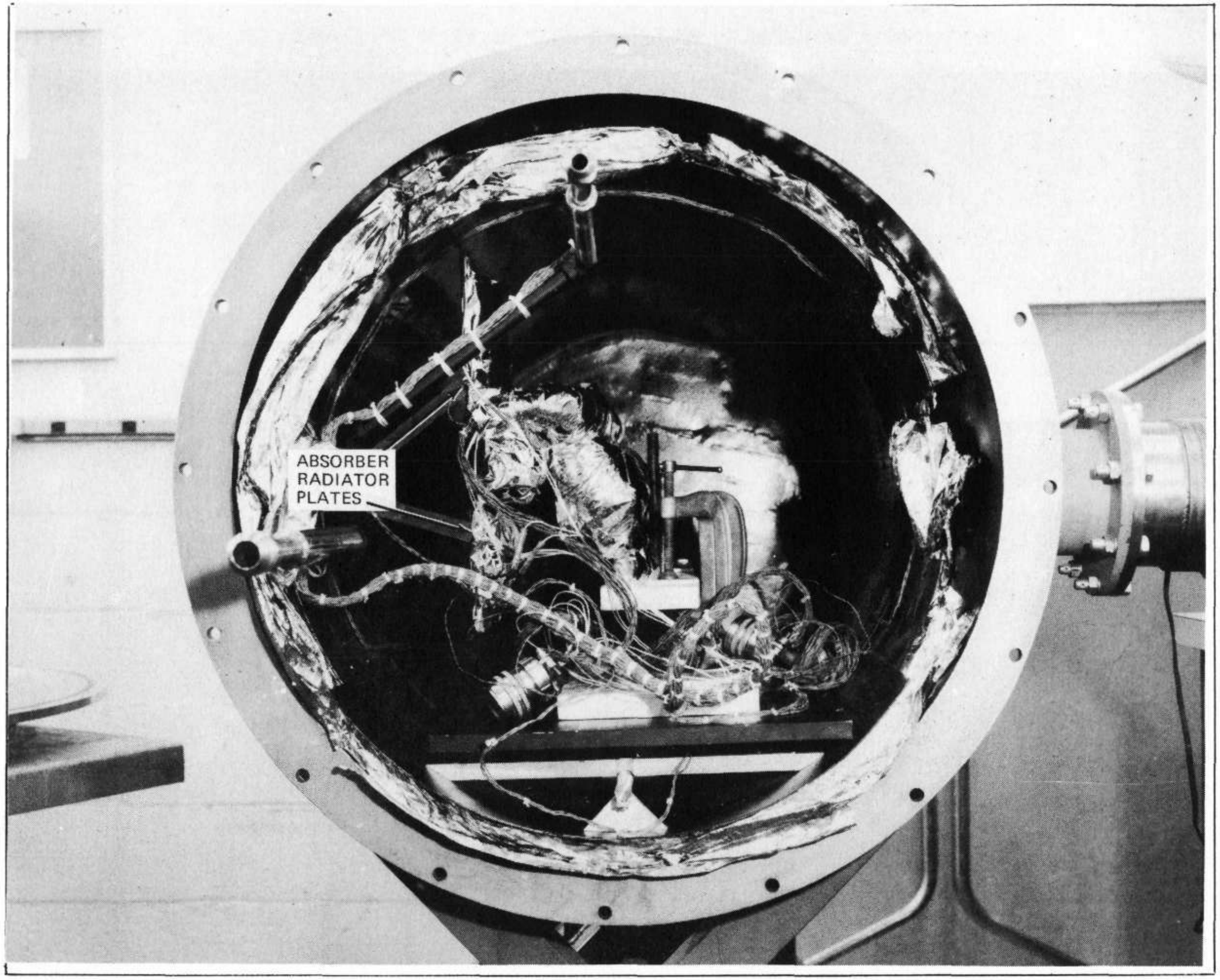


Fig. 26 Diode Installed in Vacuum Chamber

The chamber was evacuated to at least 10^{-6} mm Hg and a direct mode condition was simulated to insure that the reservoir was completely filled. After approximately one hour, electrical power to the absorber was turned off, and filling of the cold wall began. Reversal from direct to reverse mode occurred as soon as the absorber temperature was lower than the condenser temperature. No power to the condenser or reservoir heater was required to cause reversal. Figure 27 is a plot of $T_{condenser}-T_{absorber}$ versus time and demonstrates the rapid reversal.

Due to the chamber cold wall construction, the absorber minimum temperature obtained was on the order of -100°F. Thus, the maximum condenser-absorber temperature differential that could be maintained was about 180°F when the condenser was maintained at 82°F. The predicted reverse heat leak at a ΔT = 180°F is 1.01 watt.

From temperature measurements between the condenser and transition sections, the heat leak back to the absorber was determined to be less than 1 watt for a ΔT = 180°F. From a steady state test point when the condenser to absorber ΔT was 180°F, thermocouple (TC) 6 on the condenser was 80° and TC #5 on the transition section was 56°F (see figure 28). Based on the diode design, section A in figure 28 is also 80°F. The distance between section A and TC #5 is 0.55 inch. Fluid blockage must occur at least up to point A based on the geometry of the pipe. Taking into account the steel tube, artery and ammonia, the conductance in this section is 0.0230 watts/°F. The ΔT between TC #5 and (A) was 24°F, therefore, the conducted heat is 0.55 watts, which is approximately 1/2 of the predicted value.

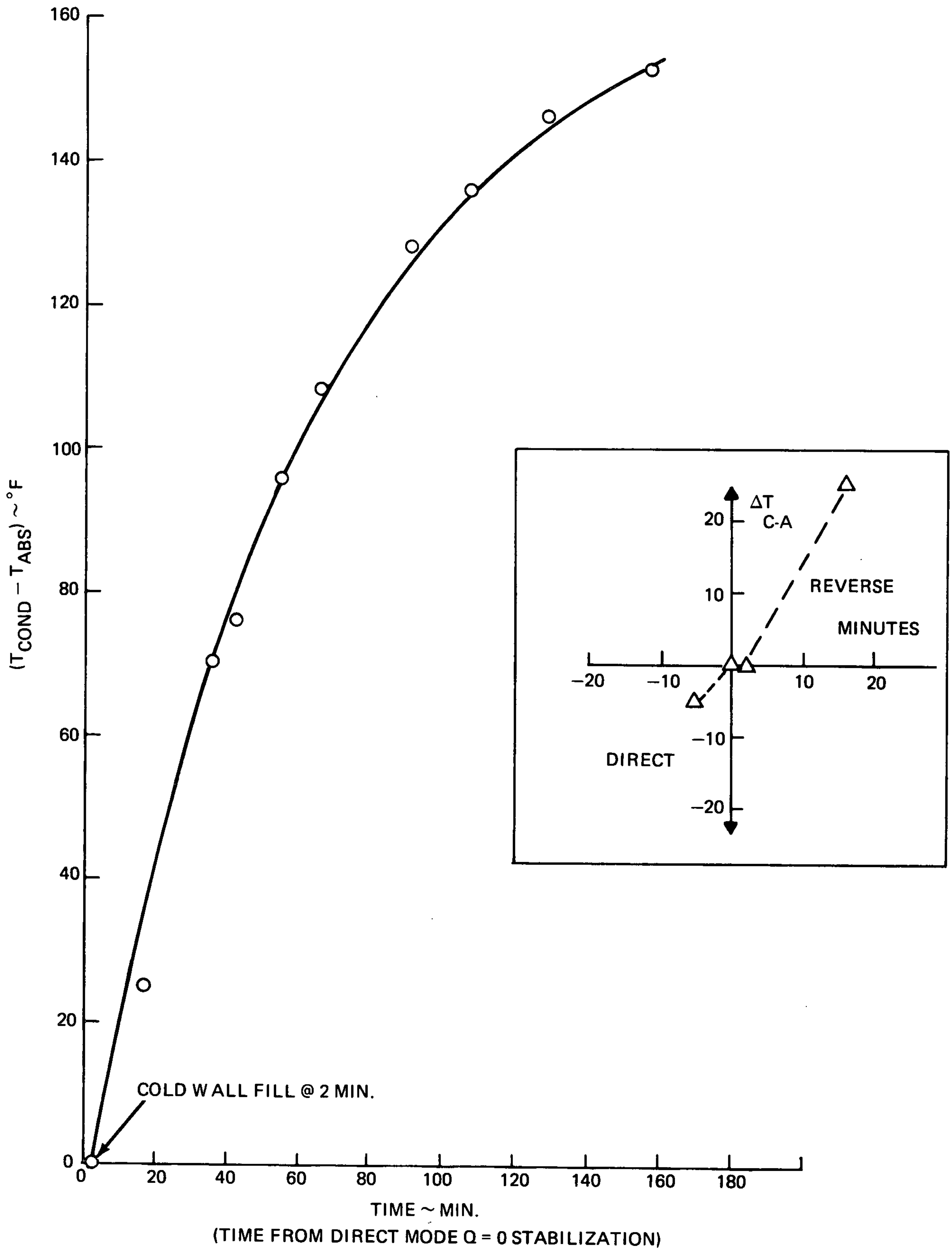


Fig. 27 Diode Engineering Model Thermal Vacuum Test Direct to Reverse Mode Transient

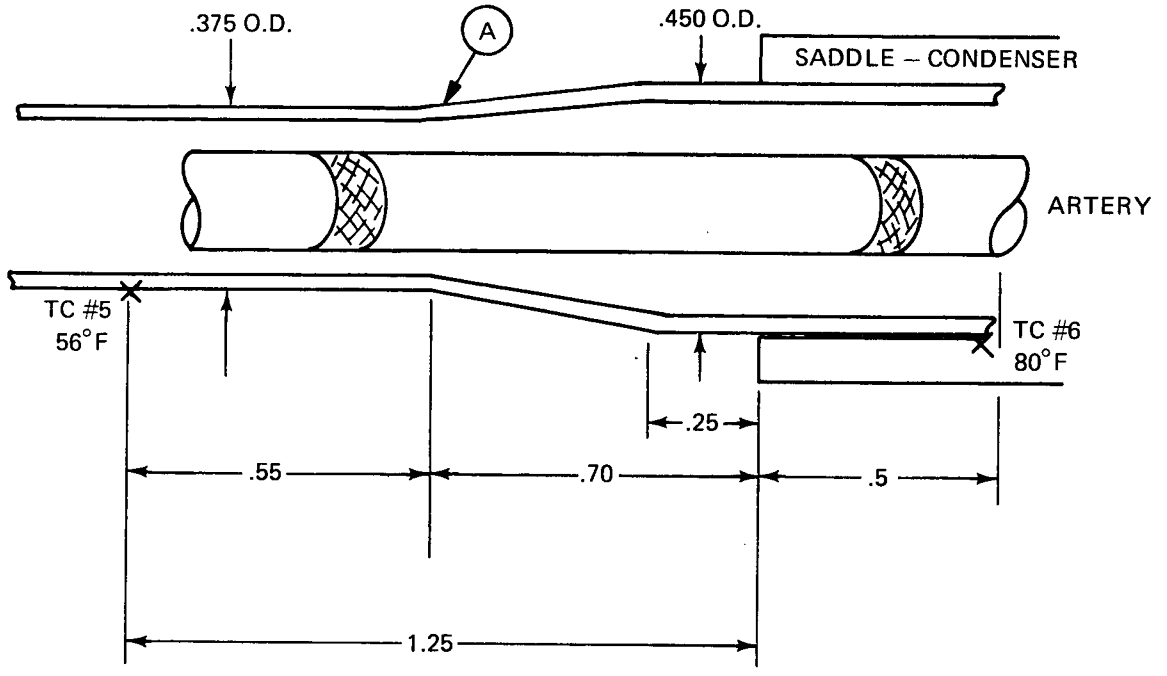


Fig. 28 Engineering Model - Diode Transition Section

7.0 THERMAL TESTS - QUAL AND FLIGHT DIODES

Based on the results of the ATFE engineering model tests, NASA determined that more absorber area was required. Grumman was therefore instructed to increase the length of the qualification and flight diode evaporators by 1.0 inch to 4.90 inches. The increase in pipe length required a minor redesign of the reservoir, i.e., the diameter of the holes in the reservoir were increased a few thousands of an inch in order to accommodate more fluid.

In April 1972, tests were conducted on diode #2, the qualification or prototype model. The diode was attached to the saddles by Hysol epoxy. The diode was charged with 17.8 grams of ultra high purity ammonia in accordance with Appendix D. The tests were conducted as per Appendix E and witnessed by both Grumman and NASA quality control. Thermocouples were attached to the absorber and condenser saddles, transition section, and reservoir. Thermocouples were not attached to the pipe directly in the evaporator and condensers. The reason was that due to the poor conductivity of the steel the portions of the pipe not attached to the saddles would be at an adiabatic temperature. This was noticed during the engineering model tests. The instrumentation and heater locations for the qualification and flight models are shown in Appendix E. The direct mode test was conducted in a similar manner as the engineering model. At the specification level of 20 watts input to the absorber, the absorber condenser saddle temperature difference was 9^{O}F, 7^{O}F below the maximum allowable.

The reverse mode test was conducted in a vacuum chamber at a pressure of 2 x 10^{-7} torr. A direct mode condition was setup at ambient temperatures to insure that the reservoir was filled at which time the cold wall of the chamber was filled. After approximately 24 hours, the absorber temperature was -145^{O}F and the condenser temperature 82^{O}F. The reverse heat leak was calculated to be 0.29 watts. For the 217^{O}F temperature difference, the maximum allowable leak was 1.2 watts. This calculation is shown in Appendix C.

At the conclusion of the thermal tests on Diode #2, Grumman was notified by the NASA Technical Monitor that a possible premature dryout of the Feedback Controlled Heat Pipe on the ATFE could occur. If this happened, the diode temperature could reach as high as 260^{O}F. Once the premature dryout was corrected, the diode would have to operate normally again. This possible condition was not part of the original specification. The impact was that the Hysol epoxy which bonds the diode to its saddles loses its structural strength at high temperatures and the thermal interface between the diode and its saddles could be damaged. Grumman was therefore instructed to do the following: (a) eliminate the Hysol epoxy, (b) ship Diode #3, the original flight pipe, to Dynatherm Corp. for a solder attachment to the saddles, and designate Diode #3 as the qualification unit, and (c) remove the epoxy from Diode #2, the original qualification pipe, and solder the saddles. Diode #2 would become the flight unit.

After the diode heat pipes were soldered to the saddles, the pipes were charged with ammonia and pinched off according to Appendix D. Prior to NH_3 charging, the diodes were proof pressured with N_2 at 3000 psi for one hour at a temperature of 285^{O}F. After pinch off the diodes were then subjected to a temperature of 285^{O}F for 1 hour. The resulting pressure was 2300 psi. Direct and reverse mode tests were then performed on both the qualification and flight units as per Appendix E. In addition, burnout levels in the direct mode were obtained at the test tilt of $\frac{1}{4}$ inch. Both pipes performed well within its specification.

7.1 Direct Mode Results

The direct mode test results for the Qualification and Flight diode are shown in figure 29. Also shown for comparison purposes, are the Engineering Model results and Diode #2 with Hysol attachment saddles. It can be noted that Flight model had a higher Δ T than the Qualification model. At 20 watts, the Δ T between the absorber and condenser saddles was 2.3^{O}F for the Qualification unit and 5.5^{O}F for the Flight unit. The difference could be attributed to a poorer saddle solder attachment noticed on the flight unit.

7.2 Reverse Mode Test Results

As indicated earlier, the reverse mode tests were conducted in a thermal vacuum chamber equipped with a LN_2 cold wall. Since the expected heat leakage in the reverse or shut off mode was so small, the diode had to be insulated in a special manner in order to minimize radiation tunneling. It was determined that with temperature difference of 220^{O}F between the condenser and absorber, approximately 1 watt of radiation could be transferred from the condenser to the absorber. Therefore, the pipe was insulated in a tapered fashion with superinsulation as shown in figure 30. Both pipes were installed in the vacuum chamber in a level position. The test chamber was evacuated to at least 10^{-6} torr at ambient temperature at which time the evaporator heater was energized to insure

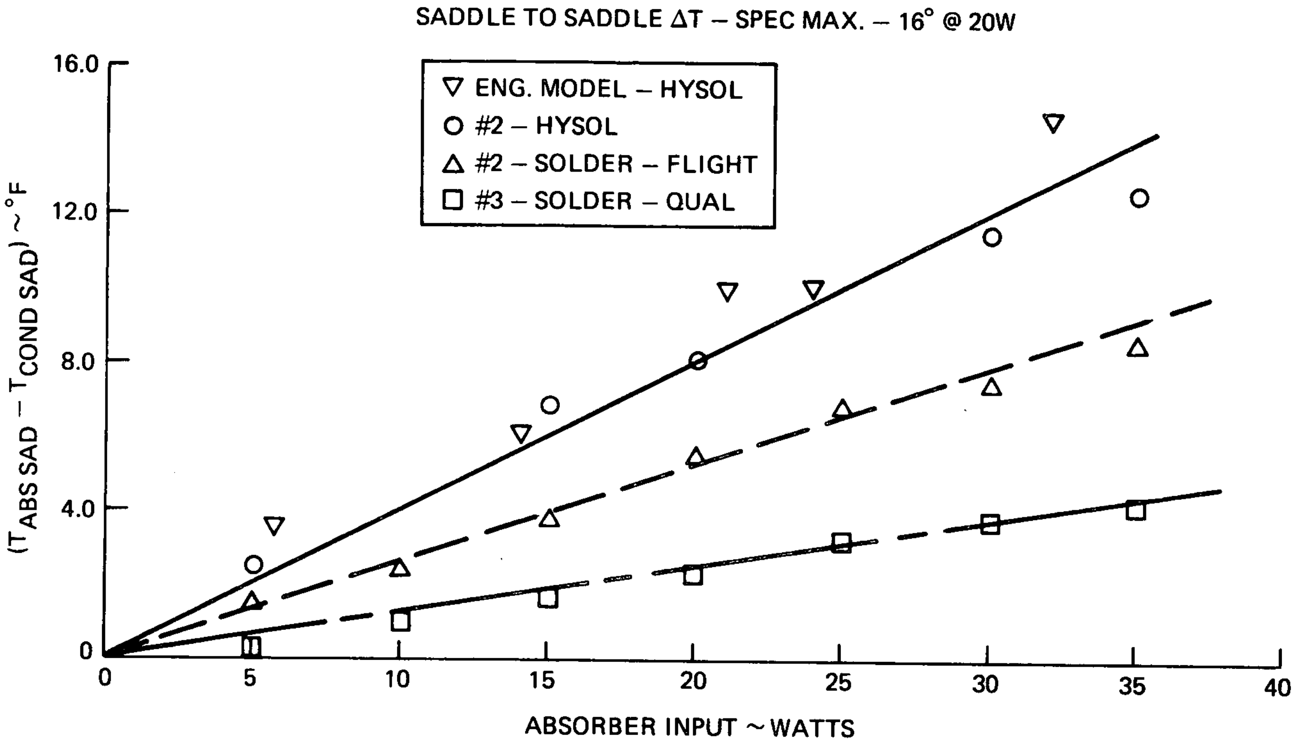
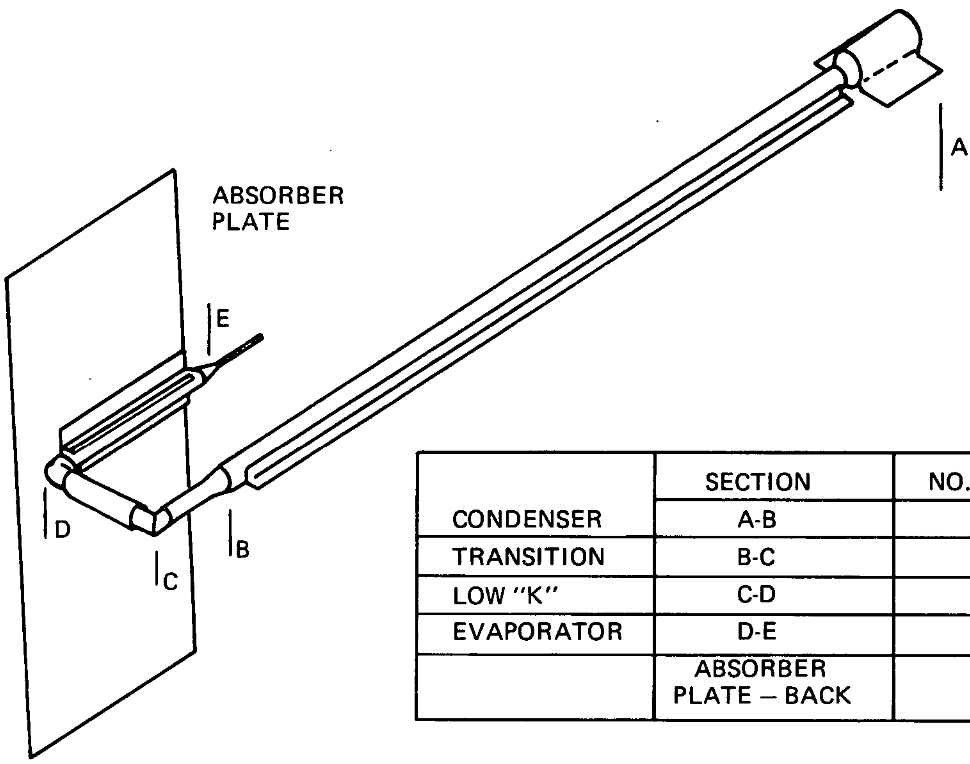


Fig. 29 NASA/Ames Diode Heat Pipe Direct Mode Test Results

complete filling of the reservoir, i.e., a direct mode condition. The evaporator heater was then turned off and after the pipe temperature reached about 89°F, filling of the cold wall began. Reversal or shut off of the diode began as soon as the absorber (normal evaporator) temperature fell below the condenser temperature. Figures 31 and 32 show transient data during the first 160 minutes of the reverse mode tests. Cessation of heat pipe operation between condenser and absorber is evident by the increasing ΔT between the latter two sections of the pipe. Once the average absorber saddle temperature stabilized at -145°F, the test was conducted. Figure 33 shows the final steady state temperature distributions for both Qualification and Flight Diodes.

The reverse heat leak was determined from $Q_R = (0.0107) \times (T_5 - T_4)$ where $(T_5 - T_4)$ is the temperature difference between thermocouples 5 and 4 and Q_R is in watts. The conductance value of 0.0107 includes the steel tube, artery and ammonia conductance values. The calculation is shown in Appendix C. The reverse heat leak was 0.33 watt for the Qualification Diode and 0.40 watt for the Flight pipe.



	SECTION	NO. LAYERS
CONDENSER	A-B	30
TRANSITION	B-C	20
LOW "K"	C-D	10
EVAPORATOR	D-E	10
	ABSORBER PLATE – BACK	10

Fig. 30 Reverse Mode Insulation Scheme

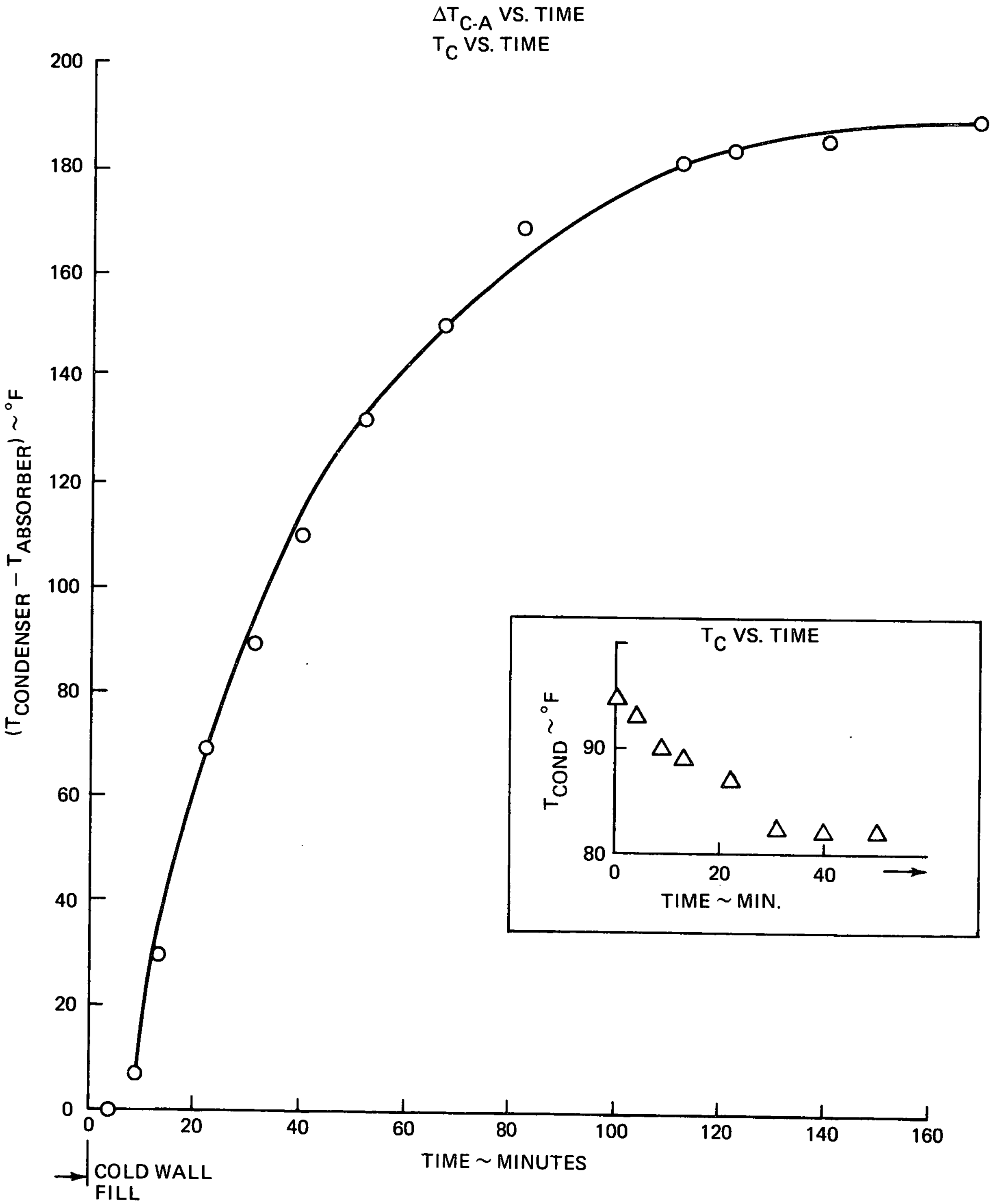


Fig. 31 Diode #3 - Qual Model Reverse Mode Transient

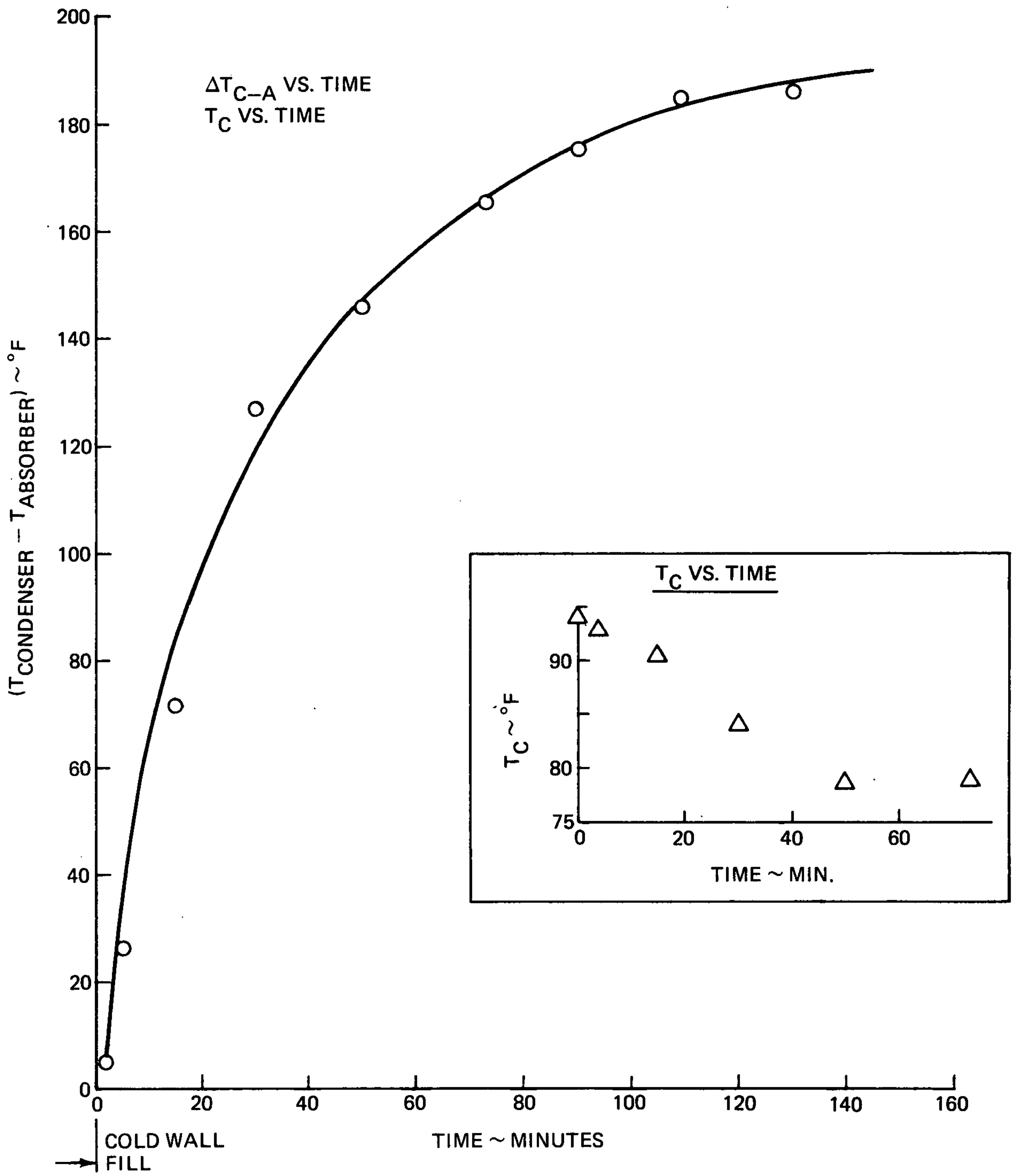


Fig. 32 Diode #2 - Flight Model Reverse Mode Transient

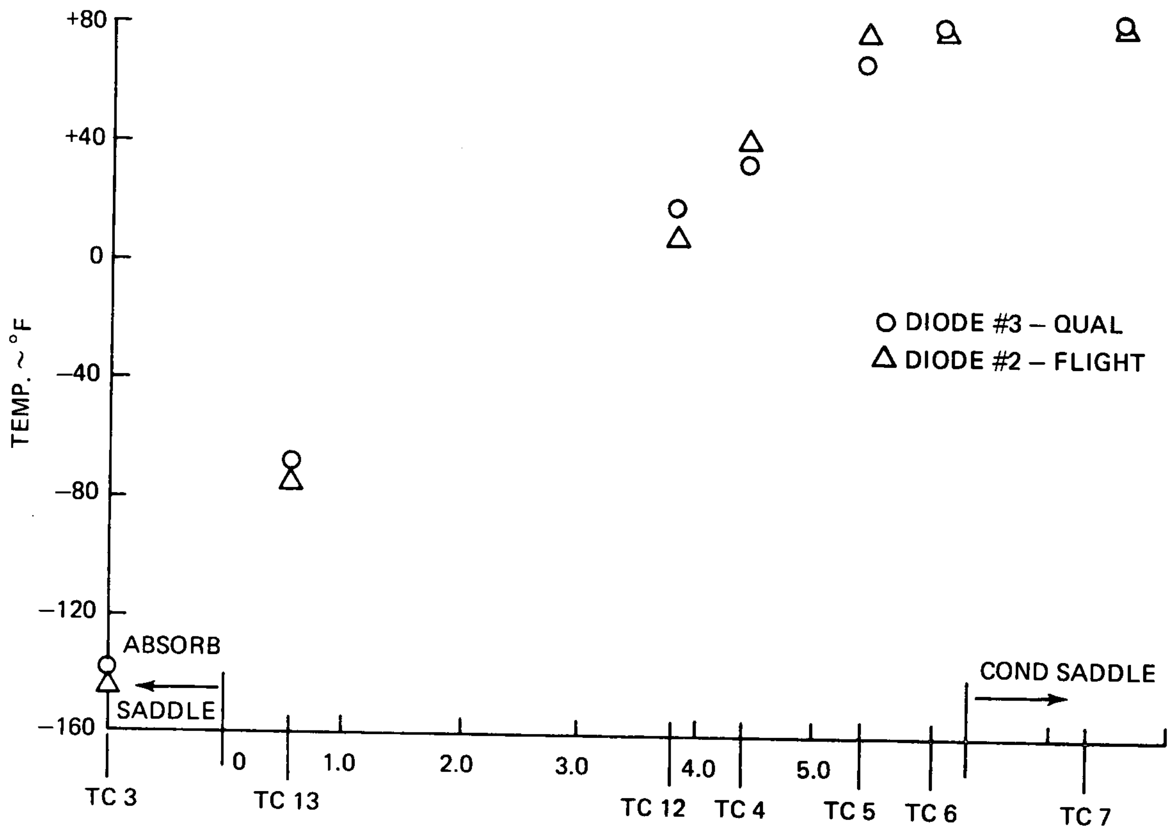


Fig. 33 Steady State Reverse Mode Temperature Distribution

8. REFERENCES

(1) F. Edelstein and R. J. Hembach, "Design, Fabrication and Testing of a Variable Conductance Heat Pipe for Equipment Thermal Control," AIAA Paper 71-422, April, 1971.

(2) J. P. Kirkpatrick and B. D. Marcus, "A Variable Conductance Heat Pipe/ Radiator for the Lunar Surface Magnetometer," AIAA Paper 72-271, April, 1972.

(3) R. Kosson, R. Hembach, F. Edelstein and M. Tawil; "A Tunnel Wick 100,000 Watt-Inch Heat Pipe," AIAA Paper 72-273, April 1972.

(4) "ATFE/Thermal Diode Interface Specification," NASA/Ames PES-ATS-1-A.

(5) Los Alamos Scientific Laboratory, "Theory of Heat Pipes", T. P. Cotter, LA-3246-MS, Los Alamos, New Mexico, February 23, 1965.

APPENDIX A - TUNNEL ~~WICK~~ ANALYSIS

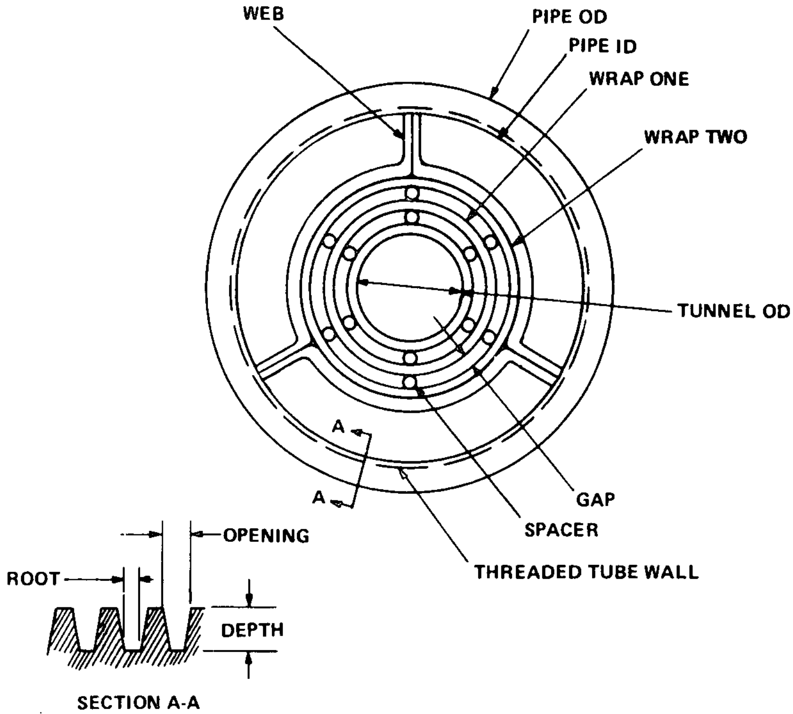


Fig. A-1 Tunnel Wick

For the spiral artery configuration, the liquid flow path consists of the condenser grooves, condenser webs, artery evaporator webs, and evaporator grooves. The liquid pressure drops continuously along this flow path. In ground tests, the liquid pressure is assumed to equal the vapor pressure at the lowest point of the condenser, which is taken to be at the far end of the condenser at the bottom of the pipe. The liquid pressure then drops with increasing elevation in a gravity or body force field in addition to viscous losses in the direction of flow. Compressibility effects are negligible for the cases considered.

The equation for the difference in pressure between liquid and vapor which must be sustained by the meniscus or capillary forces is

$$\Delta P_c = \Delta P_L + \Delta P_V + \Delta P_B \qquad \text{A-1}$$

which ΔP_L and ΔP_V refer to viscous losses in the liquid and vapor and ΔP_B refers to the body force pressure drop.

The circumferential grooves are assumed to have a symmetric trapezoid cross-section, as shown in Fig. A-1. For this shape, the maximum capillary force is

$$\Delta P_{c_{Max}} = \frac{2\sigma \cos(\theta + \alpha)}{w} \qquad \text{A-2}$$

The body force pressure drop is

$$\Delta P_B = \rho_L \frac{g}{g_c} (D_i + h) \qquad \text{A-3}$$

For laminar flow of a fluid in a smooth passage, the pressure gradient may be written:

$$\frac{dp}{dz} = \frac{32 \mu \dot{m}}{\rho g_c A D_h^2} \qquad \text{A-4}$$

where $\dot{m} = Q/\lambda$, neglecting liquid and vapor sensible temperature changes.

For the vapor, the mass flow is assumed to vary linearly with distance between zero and Q/λ within the evaporator and condenser, hence

$$\frac{\Delta P_V}{Q} = C_V = \frac{32 \mu_V}{g_c \rho_V \lambda} \; \frac{\frac{1}{2}(L_C + L_{EV}) + L_{TR}}{A_V D_V^2} \qquad \text{A-5}$$

For the liquid, the pressure drop consists of five terms

$$\Delta P_L = \Delta P_{L,GR,C} + \Delta P_{L,W,C} + \Delta P_{L,A} + \Delta P_{L,W,EV} + \Delta P_{L,GR,EV} \qquad \text{A-6}$$

For the condenser grooves, the mass flow is assumed to vary linearly from zero at the midpoint between webs to $Q/(2\, n_W \lambda\, n'_{GR}\, L_C)$ entering each side of each web. The effective groove length is then 1/4 the distance between webs, or $\pi D_i/4 n_W$.

For the evaporator grooves, the expression is the same except for the use of L_{EV} in place of L_C. Combining the two terms,

$$\Delta P_{L,GR} \equiv \Delta P_{L,GR,C} + \Delta P_{L,GR,EV}$$

$$\frac{\Delta P_{L,GR}}{Q} \equiv C_{GR} =$$

$$\frac{32\mu_L}{g_c \rho_L \lambda} \left(\frac{\pi D_i}{n'_{GR} A_{GR} D^2_{GR} \; 8n^2_w} \right) \left(\frac{1}{L_C} + \frac{1}{L_{EV}} \right) \qquad \text{A-7}$$

The webs are assumed to be made of screening with porosity ϵ, thickness t_w, and nominal pore diameter D_p. The mass flow is $Q/n_w\lambda$, the area $\epsilon t_w L_C$ or $\epsilon t_w L_{EV}$, and the path length $(D_i - D_A)/2$. Hence the pressure drop for the condenser and evaporator combined is

$$\Delta P_{L,W} \equiv \Delta P_{L,W,C} + \Delta P_{L,W,EV}$$

$$\frac{\Delta P_{L,W}}{Q} \equiv C_W = \frac{32\mu_L}{g_c \rho_L \lambda} \; \frac{(D_i - D_A)\;(b/8)}{2n_w \; t_w \epsilon D_p^2} \left(\frac{1}{L_{EV}} + \frac{1}{L_C} \right) \qquad \text{A-8}$$

where (b/8), following Cotter,(4) is a factor (generally between 1.2 and 2.5) accounting for the tortuosity of flow within the screening as compared with smooth passages.

The artery represents the major viscous loss in most applications, and is assumed to have parallel flow paths within the screening, the gap regions, and the tunnel. As with the vapor, the mass flow is assumed to vary linearly in evaporator and condenser. The pressure drop is then given by

$$\frac{\Delta P_{L,A}}{Q} \equiv C_A = \frac{32\mu_L}{g_c \rho_L \lambda} \; \frac{\frac{1}{2}(L_C + L_{EV}) + L_{TR}}{\left(A_G D_G^2 + \frac{\epsilon}{b} A_P D_P^2 + \frac{\pi}{4} D_T^2 \right)} \qquad \text{A-9}$$

where subscripts P, G and T refer to the screen, gap regions & tunnel respectively.

Substituting these expressions into equation 1 and rearranging to solve for Q_{Max} corresponding to $\Delta P_{c,Max}$ gives

$$Q_{Max} = \frac{\Delta P_{c,Max} - \Delta P_B}{C_v + C_{GR} + C_w + C_A} \qquad \text{A-10}$$

APPENDIX B

Liquid Blockage Diode - Tunnel Wick Equations

The tunnel wick equations of Appendix A must be modified for the liquid blockage diode to account for different pipe inside diameters in the condenser, evaporator, transport section portion which is to be blocked in the reverse mode, and transport section portion which is left unblocked.

Specifically, Equations A-3, A-5, A-7 and A-8 are replaced by

$$\Delta P_B = \rho_l \frac{g}{g_c} (D_{i,EV} + h) \quad \text{(B-1)}$$

$$\frac{\Delta P_V}{Q} = C_V = \frac{32 \mu_V}{g_c \rho_V \lambda} \left[\frac{L_C}{2 A_{V,C} D_{V,C}^2} + \frac{L_{TRU}}{A_{V,TRU} D_{V,TRU}^2} + \frac{L_{TRB}}{A_{V,TRB} D_{V,TRB}^2} + \frac{L_{EV}}{2 A_{V,EV} D_{V,EV}^2} \right] \quad \text{(B-2)}$$

$$\frac{\Delta P_{L,GR}}{Q} = C_{GR} = \frac{32 \mu_L}{g_c \rho_L \lambda} \left(\frac{\pi}{n_{GR}' A_{GR} D_{GR}^2 \; 8 n_w^2} \right) \left(\frac{D_{i,C}}{L_C} + \frac{D_{i,EV}}{L_{EV}} \right) \quad \text{(B-3)}$$

$$\frac{\Delta P_{L,W}}{Q} = C_W = \frac{32 \mu_L}{g_c \rho_L \lambda} \left(\frac{6/8}{2 n_w t_w \epsilon D_p^2} \right) \left[\frac{(D_{i,C} - D_A)}{L_C} + \frac{(D_{i,EV} - D_A)}{L_{EV}} \right] \quad \text{.... (B-4)}$$

where subscripts C, TRU, TRB, EV refer to condenser, transport section unblocked, transport section blocked, and evaporator, respectively.

These quantities are then substituted in equation A-10 to obtain Q_{Max}.

Appendix C

Reverse Heat Leakage Calculation for Qualification and Flight Diodes

The reverse heat leakage in the reverse mode was determined from temperature measurements made on a portion of the transition section. Two thermocouples (TC 4 and TC5 in figure C-1 were located 1.0 inch apart on the pipe. In the reverse mode, the vapor space in this area is filled with ammonia, thus there will be a conduction gradient from TC5 to TC4 as shown below.

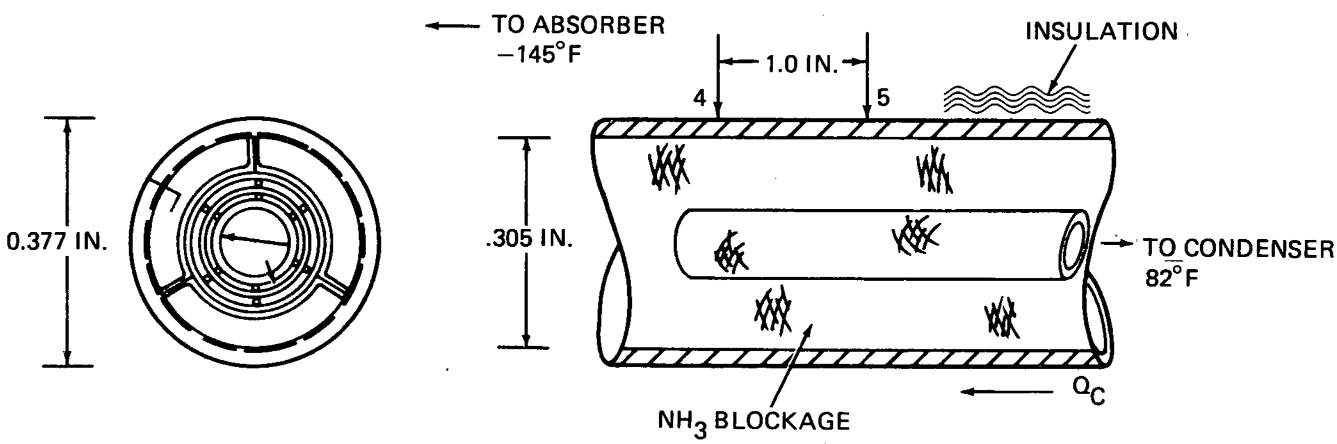


Fig. C-1 Transition Section

When blockage occurs, there is conduction heat transfer through the tube, artery and ammonia which is given by

$$Q_c = (C_1 + C_2 + C_3)(T_5 - T_4) \qquad \text{C-1}$$

where C_1 = tube conductance

C_2 = ammonia conductance

C_3 = artery conductance

(T_5-T_4) = temperature difference between thermocouples 5 and 4.

From the tube cross section area, $A_T = T/4\ (\bar{OD}^2 - \bar{ID}^2)$ and steel conductivity, k_{ST} = $0.228\ \frac{W}{in\text{-}^oF}$

$$C_1 = \frac{kA}{L} = \frac{(0.228)(0.0345)}{1.00} = 0.00787 \quad \text{Watt}/{}^oF. \qquad \text{C-2}$$

where A = tube cross sectional area in in^2

L = distance from TC4 to 5 in inches.

The conductance of the steel artery and retainer was determined in a similar manner as above. The cross sectional area was determined from the mass per unit length and density as follows:

M/L = 1.53 grams/inch

$$A = \frac{M}{L\rho_{ST}} = \frac{1.53 \text{ gm/in.}}{131.5 \text{ gm/in}^3} = 0.0116 \text{ in}^2$$

The conductance C_2 is

$$C_2 = \frac{kA}{L} = \frac{0.228\ (0.0116)}{1.0} = 0.00265 \ \frac{W}{{}^oF} \qquad \text{C-3}$$

The cross sectional are of the ammonia in the blocked vapor space is determined as follows:

$$A_{VS} = A_P - A_A \qquad \text{C-4}$$

$$A_{VS} = \pi/4 \left[(.305)^2 - (.255)^2\right] = 0.022 \text{ in}^2$$

Where A_P = internal pipe area in in^2

A_A = cross sectional area of artery and retainer.

The conductivity of ammonia at 60^oF is 0.00733 $\frac{W}{in^2\ {}^oF}$, therefore,

$$C_3 - \frac{k_{NH_3} A_{VS}}{L} = \frac{(0.00733)(0.022)}{1.0} \qquad \text{C-5}$$

C_3 = 0.00016 $W/{}^oF$.

The conductance of the ammonia in the artery was neglected. The total conductance C is just the sum of C_1, C_2 and C_3 which is 0.0107 W/°F. Thus, from (C-1), the leakage conducted through the diode is

$$Q_c = (0.0107\ \mathrm{W/^{o}F})\ (T_5 - T_4) \qquad \text{C-6}$$

CONTRACT REQUIREMENTS	CONTRACT ITEM	MODEL	CONTRACT NO.
			NAS 2-6493

APPENDIX D

REPORT

NO. DPCS-1 DATE: 3-8-72

CHARGING OF ATFE THERMAL DIODE HEAT PIPE WITH AMMONIA INSTRUCTIONS FOR FLIGHT PIPE

CODE 26512

PREPARED BY: B.Swerdling B.S. 3-22-72 TECHNICAL APPROVAL:

CHECKED BY: J. McNamara, Q.E. JMc 3-23-72 APPROVED BY:

DEPARTMENT: APPROVED BY:

SECTION: APPROVED BY:

REVISIONS

DATE	REV. BY	REVISIONS & ADDED PAGES	REMARKS
5-1-72	B.S.	Sect. 3.1.2, Page 2	Changed Welding Fixture to Test Fixture
5-1-72	B.S.	Sect. 4.3 Page 7	Added Note on Weights

GAC 324A REV 2
8-69 20M

CHARGING OF ATFE THERMAL DIODE HEAT PIPE WITH AMMONIA INSTRUCTIONS FOR

1. SCOPE

1.1 General - These instructions establish the procedure for the charging of the Thermal Diode Heat Pipes using ammonia prior to their installation on the Advanced Thermal Control Flight Experiment (ATFE).

1.2 Applicability - These instructions are applicable to the Diode Heat Pipes designated by the following drawing:

AD-1411-1000-1 Heat Pipe & Saddle Assembly

2. APPLICABLE DOCUMENTS

2.1 Reference Documents

Memorandum TIM 69-15	Ammonia Heat Pipe Handling Recommendations
Specifications A-17176	Specifications for Thermal Diode (NASA-Ames)
Test Plan DPM-3A	Thermal Performance Test Plan for Diode Heat Pipes

3. REQUIREMENTS

3.1 General -

3.1.1 Equipment and Material Required -

	Equipment	Manufacturer	Model Number
*	(a) Vacuum Station	Veeco	VS400(or equivalent)
	(b) Ionization Gauge Leak Detector	Varian Assoc.	975-0016
*	(c) Gram Scale	Ohaus Scale Corp.	2610 gm capacity (Calibrated in 0.1 gm increments)
	(d) Pinch-off Tools	GAC	MPOT-01 MPOT-02
	(e) Ammonia	Matheson Co. Rutherford, N.J.	Ultra High Purity
	(f) Freon TF	DuPont	-
	(g) V-clamp	-	-

*These items shall be calibrated in accordance with established calibration procedures. The equipment shall bear an approved calibration certificate dated not more than 6 months prior to date of use with the exception of the scale, which shall be calibrated immediately prior to its use.

3.1.2 Pipe Support - The heat pipe assembly shall be supported in a manner that restrains the ends from being opened from their free position. (During bake out and charging the diode shall be supported in its test fixture.)

CAUTION: Extreme care should be used at all times in the handling of the heat pipes so as not to bend or otherwise physically damage them. During storage or shipping, the pipes should not be exposed to a thermal environment in excess of 150°F.

3.1.3 Weight of Charge - The weight of the fluid charge shall be as specified below. The weighing shall be performed using a gram scale calibrated in 0.1 gram increments.

Pipe	Part No.	Charge Mass
Flight Pipe / Prototype	AD-1411-1000-1	17.5 grams

3.1.4 Ammonia - Ultra High Purity Ammonia shall be used as the final charging fluid. This material shall have a maximum water content of ten parts per million. A vendor analysis of the ammonia is required upon receipt.

3.1.5 Safety - Safety Engineering shall be notified prior to charging the heat pipe.

3.2 Charging Area - This operation shall be conducted at the Grumman test facility in Bethpage.

3.3 Data Retention - All pertinent data shall be recorded, signed and retained for record purposes for 2 years after completion of all stages of manufacture. Copies of these instructions may be obtained from Grumman Aerospace Corporation, Bethpage, Long Island, New York 11714, Attention: Thermodynamics Section

4. CHARGING PROCEDURES

4.1 Charging Procedure - Flush Charge (Anhydrous Ammonia) -

(a) Connect the heat pipe, charge bottle and storage cylinder to the vacuum station as shown in Figure 1. Open Valve D and reduce the heat pipe pressure to 10^{-6} Torr while heating to 170/250°F (See Note 1). Maintain at 10^{-6} Torr and 170/250°F for 18 hours (min). Check the system for leaks by spraying the valves and fittings with helium gas and check for helium at the vacuum station outlet using an ionization gauge leak detector. ________

(b) If the system is leak-tight, close Valve D. ________

(c) Measure and record the weight of the empty charging bottle with its fittings and valve within ± 0.1 gram. Prior to weighing the the charging bottle, it shall be carefully cleaned with Freon TF and heated externally using a hot air gun to drive out all Freon. ________

(d) Connect the charging bottle and ammonia storage cylinder to the vacuum system as shown in Figure 1. The system with Valves A and B open are then subjected to a pressure of approximately 10^{-6} Torr. During pumpdown when the pressure has been reduced to 10^{-4} Torr, heat Valves A and B, piping and fittings to a temperature of 125 to 200°F for 1/2 hour. The system shall be checked for leaks as detailed in step (a) above. ________

(e) Valve B to the vacuum station is then closed, the Valve C to ammonia storage cylinder opened, and the ammonia permitted to enter the ammonia charging bottle. It is filled with a mixture of liquid and gaseous ammonia by cooling (see Note 2) the bottle below 0°F while holding in an upright position with the charging valve on top. As an alternate, the charging bottle may be charged utilizing a second charging station. ________

WARNING: Heating gun shall not be used on charge bottle.

4.1 (Continued)

(e) (Continued)

NOTE: 1. The elevated temperature shall be maintained by suitable means such as strip heaters, hot air, etc. and monitored using three thermocouples strapped to the heat pipe.

2. The lower temperatures shall be maintained by use of liquid nitrogen, ice bath, etc., as required and monitored as in Note 1.

(f) Close Valves A and C, remove the ammonia charging bottle and storage cylinder and weigh the charged ammonia charging bottle. Ammonia is discharged from the bottle, until 19 gms of ammonia $\pm$ 3 percent is reached.

(g) Reassemble the charging bottle to the vacuum station as in figure 2, open Valve B and pumpdown to 10^{-6} Torr for 1/2 hour. Close Valve B and open Valves A and D permitting ammonia to enter the heat pipe. The end of the heat pipe opposite the charging end shall be lower than the inlet and cooled below room temperature, while the charging bottle is heated slowly to 120 to 200°F. Heat the fittings between the vacuum stations and heat pipe inlet to approximately 100°F. Then close Valve D on heat pipe and Valve A. (Note: Temperature not to exceed 100°F.)

(h) Remove heat pipe from the charging station and operate for 12 hours with a low heat flux. Then discharge ammonia and close Valve D on heat pipe.

4.2 Charging Procedure - Final Charge (UHP Ammonia) -

(a) While 4.1(h) is being performed, install a plug on the charge manifold at the point where the heat pipe was removed, and also install Ultra High Purity (UHP) Ammonia cylinder as in Figure 1. Open Valves A and B and pump to 10^{-6} Torr. Check for leaks at plug as installed in 4.1(a) above and then repeat 4.1(e).

4.2 (Continued)

(b) Close Valves A and C and remove the ammonia charging bottle. Ammonia is discharged from the bottle until 19 grams ± .5 grams is reached.

(c) Reassemble the charging bottle to the vacuum station, open Valve B, and pump down to 10^{-6} Torr. Using a Dewar flask of LN_2, immerse bottle in the LN_2 and freeze the Ammonia. Then open Valve A until vacuum station pressure is 10^{-4} Torr. Close Valve A and remove LN_2 Dewar. After temperature of bottle has returned to ambient temperature, repeat all of 4.2(c), one more time.

(d) Close Valve B, remove plug and reinstall heat pipe on vacuum station. Also remove storage cylinder, plug line and reinstall charge bottle as in Figure 2. Open Valves B and D and pump down to 10^{-6} Torr. Close Valves B and D and remove heat pipe from station and weigh heat pipe with its fittings, valve, etc. Record dry weight. Reinstall heat pipe and open Valves B and D and pump down to 10^{-6} Torr for 1/2 hour.

(e) Close Valve B and open Valve A, permitting ammonia to enter the heat pipe. The end of the heat pipe opposite the charging end shall be lower than the inlet and cooled below room temperature, while the charging bottle is heated slowly to 150°F. Heat the fittings between the vacuum station and the heat pipe inlet to about 100°F, then close Valve D on heat pipe and Valve A.

(f) Remove heat pipe from station and weigh at ambient temperature. Remove ammonia until specified weight is reached. (per 3.13)

(g) The Test Engineer will decide on one of the following:

(1) To pinch off the charge tube and remove Valve D on the heat pipe, or

(2) Not to pinch off the charge tube and maintain Valve D through a pre-saddle test after which pinch off of the charge tube will be made. Pinch off procedure is given in section 4.3.

Note: The Test Engineer will determine the pre-saddle test conditions.

4.3 Completion of Charging Procedure: - Upon satisfactory completion of all work, record on the Route Card.

DATA SHEET

Heat Pipe Serial No.			
Weight of empty Heat Pipe*			
Final Weight of Heat Pipe*			
Charge Weight (grams)			
Charge Weight as specified in 3.1.3 (grams)			

*Note: Weight of pipe includes saddles.

4.4 Final Pinch-off of Diode: - The pinch-off procedure is outlined below:

(a) Chill end of diode opposite charge tube below room temperature.

(b) Using Tool No. MPOT-01, pinch charge tube approximately $\frac{1}{4}$ inch from end of diode.

(c) Then using Tool No. MPOT-02, flatten charge tube another $\frac{1}{4}$ inch from pinch performed in (b) (see Figure 3).

(d) Install "V" clamp on pinch area performed in (b) and tighten. Do not remove "V" clamp until charge tube is welded.

(e) Allow diode to reach room temperature, open Valve D and check for ammonia leakage (per (g)).

(f) If after at least 5 minutes from the time Valve D was opened, there is no evidence of ammonia leakage, cut charge tube in flattened portion and weld while maintaining pipe temperature below 70°F.

(g) Allow pipe to reach room temperature and check weld with water soaked pink Litmus paper. If the Litmus paper turns blue, the Test Engineer will determine the course of action to be taken.

(h) If Litmus paper does not turn blue, perform leak test outlined in 4.5.

4.5 Leak Test -

4.5.1 General - This procedure outlines the method to be followed in leak checking heat pipes filled with ammonia.

4.5.2 Applicability - These instructions are applicable to any tube filled with ammonia and are therefore valid for all of the Diode heat pipes.

4.5.3 Requirements -

4.5.3.1 Acceptability - In order for the leak check to be acceptable it must comply with the requirements of this document as outlined in Paragraph 4.5.4 below with a leak rate of less than 1×10^{-7} std.cc.sec^{-1}.

4.5.3.2 Material Required - The material required to perform the ammonia leak test is listed below:

(a) Filter paper - Wattman No. 120 or equivalent.

(b) Reagent solution - 3% (by weight) copper sulfate ($CuSO_4 . 5H_2O$) and 10% (by weight) ethylene glycol in distilled water.

(c) Small plastic foil bags to cover ends of pipe after filter paper has been laid down.

(d) Rubberband (or adhesive-backed tape) to hold plastic bags in place.

(e) Nessler's reagent in dropping bottle.

4.5.4 Procedure - The following procedure shall be followed in leak checking heat pipes containing ammonia.

(a) Prepare filter paper as follows:

(1) Soak one (1) sheet of filter paper in copper sulphate solution (See (b) above). __________

(2) Blot wet filter paper between two sheets of dry filter paper. __________

4.5.4 Procedure - (Cont'd.)

(3) Place wet filter paper in airtight container (to prevent evaporation) until ready for use.

(b) Cut filter paper into sheets approximately 1-1/2 inches by 2 inches.

(c) Wrap filter paper from (b) above around ends of pipes.

(d) Cover ends of pipe and filter paper with small plastic bag and secure with rubberband or adhesive-backed tape.

(e) Leave ends of pipe covered for at least four hours. This should provide a leak sensitivity of approximately 3.3×10^{-7} std.cc.sec^{-1}.

(f) After at least four hours, remove plastic bag and filter paper and observe filter paper for dark blue spots. If these spots are visible, a leak rate of $\cong$ 3.3×10^{-7} std.cc. sec^{-1} has been exceeded.

(g) If no dark blue spots are visible, drop a few drops of Nessler's reagent on filter paper. If dark brown spots from the reagent appear, then a leak rate of 3×10^{-8} std. cc. sec^{-1} was exceeded.

Completion of Test - Upon satisfactory completion of the test, record in log book.

4.6 Certification or Evidence of Satisfactory Equipment: - After charging is completed, mark each successfully charged Heat Pipe in accordance with applicable Grumman Quality Control Procedures.

5. INSPECTION REQUIREMENTS

5.1 Inspection:- Compliance with the applicable engineering drawing and with all procedures of Section 4 shall be verified by a Grumman Quality Control representative, who shall witness the charging of each diode.

FIGURE 1

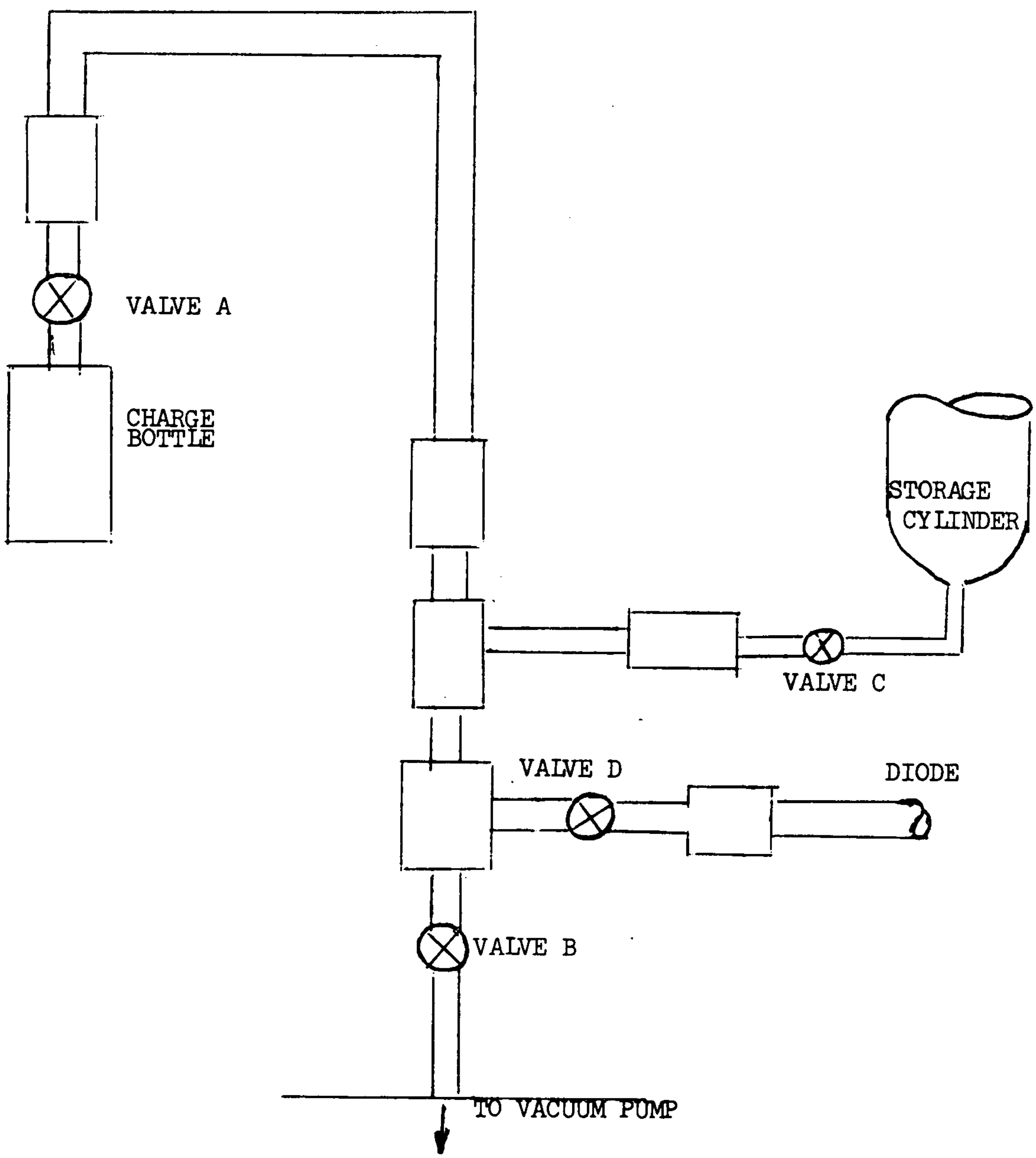
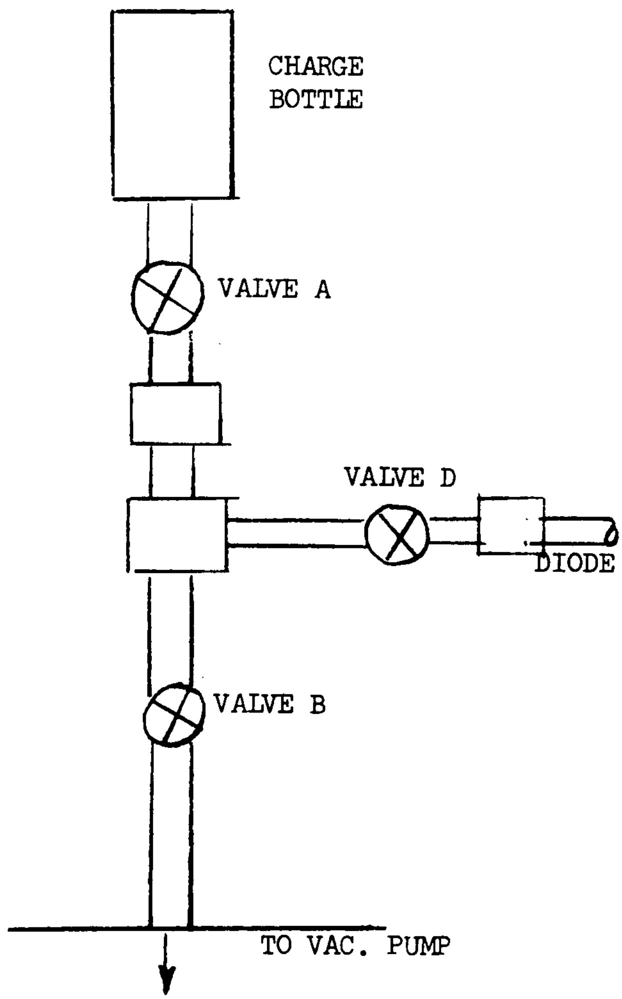

VALVE A
CHARGE BOTTLE
STORAGE CYLINDER
VALVE C
VALVE D
DIODE
VALVE B
TO VACUUM PUMP

FIGURE 2



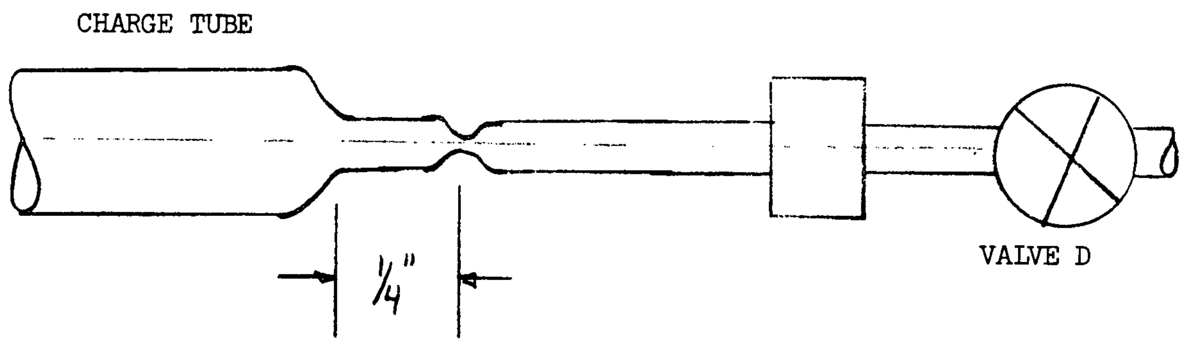


FIGURE 3(a)

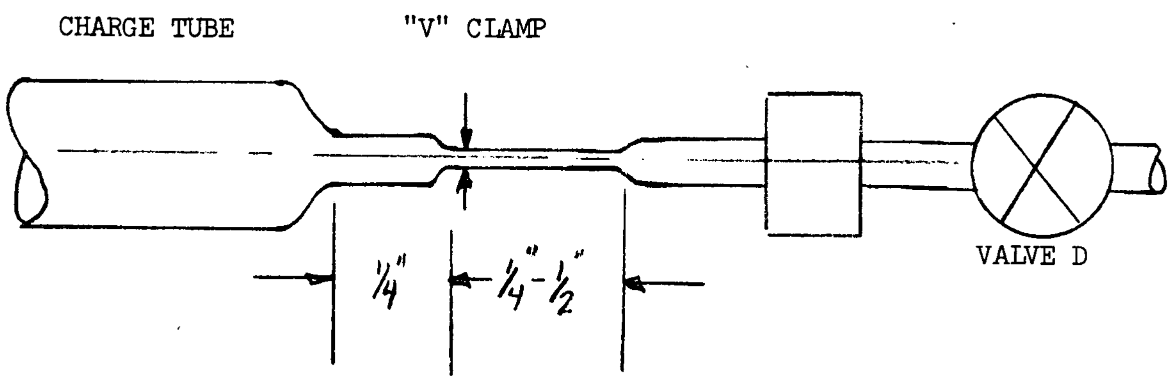


FIGURE 3(b)

CONTRACT REQUIREMENTS	CONTRACT ITEM	MODEL	CONTRACT NO.
Par. 4.3, SOW			NAS 2-6493

APPENDIX E

REPORT

NO. DPM-3A DATE: 3-21-72

THERMAL PERFORMANCE TEST PLAN AND PROCEDURE FOR THE ATFE THERMAL DIODE HEAT PIPE

CODE 26512

PREPARED BY: B. Swerdling BS 3-22-72

TECHNICAL APPROVAL:

CHECKED BY: J.McNamara, Q.E. JMC 3/23/72

APPROVED BY: M.Tawil

DEPARTMENT:

APPROVED BY:

SECTION:

APPROVED BY:

REVISIONS

DATE	REV. BY	REVISIONS & ADDED PAGES	REMARKS
5-1-72	B.S.	4.2(b) and 4.2(c) - added tolerance	
"	B.S.	4.3(b) omitted "as detailed in Fig. 3"	
"	B.S.	4.4(e) added tolerance comments	
"	B.S.	4.4(f) changed recording time	
"	B.S.	to at least every 30 minutes	
"	B.S.	Also changed -180°F to -145°F	
"	B.S.	Table I - changed Q_{REV} to 1.2±0.1	
		and -180°F to -145°F	

GAC 324A REV 2
8-69 20M

1.0 SCOPE

1.1 General: - This test plan and procedure define the test procedure and data requirements for the thermal performance testing of the ATFE Thermal Diode Heat Pipes.

1.2 Applicability: - This test plan and procedure is applicable to the Prototype and Flight Diode Heat Pipes defined by Drawing AD-1411-1000H. The Diode will be part of the Advanced Thermal Control Flight Experiment on the ATS-F Satellite.

1.3 Diode Description: - The Diode to be tested is made from stainless steel tubing and has outside diameters of 0.450 inch and 0.375 inch. The shape of the Diode is a modified "L" shape. The longest dimension is approximately 23 inches. The pipe is charged with Ammonia working fluid and has GFE saddles attached to the evaporator and condenser.

1.4 Objective: - The objective of this test is to demonstrate compliance with the performance of PES-ATS-1-A. The Diode Heat Pipe shall be tested under two thermal load conditions as follows:

Condition A: Direct Mode (Level $^{+ .250}_{- .000}$ inch)

Condition B: Reverse Mode (Level $^{+ .250}_{- .000}$ inch)

2.0 APPLICABLE DOCUMENTS

2.1 Government Documents

Specifications

PES-ATS-1-A ATFE/Thermal Diode Interface Specification

2.2 Grumman Documents

Drawing

AD-1411-1000-H Diode Heat Pipe Liquid Blockage Configuration

ICD AD-1411-1001-A Interface Control Drawing

3.0 REQUIREMENTS

3.1 General: - The Diode shall be tested in accordance with the requirements specified in Section 4.

3.2 Test Environment: - The Diode shall be tested in two environments. Condition A shall be tested in standard atmospheric conditions and Condition B shall be tested in a vacuum chamber of at least 10^{-5} mm of mercury.

3.3 Test Conditions: - The Diode shall be subjected to thermal load conditions as specified in Table I.

3.4 Acceptance Criteria: - Two conditions shall determine compliance to the test conditions as specified in 3.3. These conditions are:

(a) Temperature Difference (ΔT): Compliance to the Δ T requirement of Condition A of Table I shall be based on average absorber saddle temperature to average shelf saddle temperature.

(b) Reverse Heat Flow: Compliance to the Reverse Heat Flow requirement of Condition B of Table I shall be based on an average rate under steady state conditions. This rate shall be calculated from temperature measurements on the diode.

3.5 Test Equipment Required: - The following test equipment or equivalent shall be used for the performance of the tests specified herein. Test equipment marked * shall be calibrated in accordance with current established calibration procedures. The equipment shall bear an approved calibration certificate dated not more than six months prior to date of use. The equipment marked ** shall mean "or equivalent".

Test Equipment Nomenclature	Manufacturer and Model No.
*Thermocouple Readout	Bristol Strip Chart Recorder ($-200^{\circ}F + 100^{\circ}F$)
*Ammeter - AC	Weston Instrument Div.**
*Voltmeter - AC	Weston Instrument Div.**
Heater Wire	Driver Harris Ribbon
Test Fixture	
Thermocouples ( )	Copper Constantan
Vernier Height Gage	L. S. Starrett Co.
Vacuum Chamber with LN_2 Cold Wall	

3.6 Test Facilities: - All testing shall be performed in the Grumman Bethpage facilities.

3.7 Data Recording: - The results of the test shall be recorded in the appropriate documentary and check-off spaces provided, as called for in the text. Documentary and check-off sheets shall be signed and retained for record purposes for two years after the equipment delivery. Copies of this test plan and procedure may be obtained from Grumman Aerospace Corporation, Bethpage, New York 11714, Attention: Thermodynamics Section. All recorded data shall be sufficiently legible such that copies can be submitted with the test report. The following is a listing of the data to be recorded during the thermal performance test of the Diode Heat Pipe.

(a) Date

(b) Time

(c) Power Input

(d) Temperatures

(e) Test Condition

Prior to recording data, the Diode temperatures shall reach steady state as achieved not sooner than 10 minutes after a power set point change. A second set of readings shall be taken within 5 minutes to establish the relative stability of the Diode. In the event steady state conditions cannot be achieved, recording of data shall be determined by the GAC Test Engineer and Quality Control Engineer.

3.8 Test Summary: - Within five (5) days after completion of the performance test, a test summary shall be prepared which will contain test results as well as test conclusions.

3.9 Test Reports: - Within thirty (30) days after completion of performance testing, a test report shall be prepared which will contain the following:

(a) Test Objectives

(b) Test Description

(c) Test Assessment Criteria

(d) Test Results

(e) Conclusions

4.0 METHOD OF TESTING

WARNING: The Diode Heat Pipe contains ammonia working fluid under high pressure. Handling of the Heat Pipe shall be in accordance with the recommendations contained in Thermal Laboratory Memo TLM #69-15.

4.1 Test Setup for Condition A:

(a) Instrument Diode with thermocouples and heater as shown in Figure 1. ____________

(b) Mount Diode to test fixture. ____________

(c) Insulate radiator plate, **absorber**, low "k" section and transition section with proper thermal insulation as determined by Test Engineer. ____________

(d) Provide condenser saddle cooling by water via spray bath. ____________

(e) Connect ammeter in series with heater & voltmeter across heater.

4.2 Test Procedure for Condition A:

(a) Adjust test fixture such that evaporator is .25 inch higher than condenser. ____________

(b) Adjust water spray temperature to maintain condenser saddle temperature of $89^{\circ}F \pm 1^{\circ}F$ ____________

(c) Apply 5 watts to absorber heater & readjust water temperature to maintain $89^{\circ}F \pm 1^{\circ}F$ saddle temperature. ____________

(d) Record temperature, current and voltage. ____________

(e) Repeat steps (c) and (d) at 5 watt increments up to 35 watts. ____________

4.3 Test Setup for Condition B:

(a) Install heater on condenser saddle & reservoir strap. ____________

(b) Insulate complete diode (except front radiator faces) with superinsulation, after diode is mounted in test fixture. ____________

(c) Install in vacuum chamber equipped with LN_2 cold wall. ____________

Note: At the discretion of the Test Engineer, cooling may be accomplished by other means.

(d) Adjust test fixtures to level pipe. ____________

4.4 Test Procedure for Condition B:

(a) Evacuate chamber to a pressure lower than 10^{-5} mm Hg. ____________

(b) After chamber pressure stabilization, apply power to absorber heater (approximately 5 - 10 watts) to insure reservoir filling. Record temperature and power. ____________

Note: When absorber saddle is 90°F and condenser & reservoir saddle temperatures are lower, and approximately steady, reservoir is filled.

(c) Reduce absorber heater power to zero. ____________

(d) Begin LN_2 filling of cold wall. ____________

(e) Apply power to condenser & reservoir heater if required to maintain condenser saddle temperature of 82°F $\pm$ 2°F during steady state condition. During transients, tolerance may be $\pm$ 10°F. ____________

(f) Record temperature, voltage, & current at least every 30 minutes until absorber saddle temperature is 145°F.

(g) From temperature measurements on the diode, the Test Engineer shall calculate the reverse heat flux using the equation given below.

$$Q_R = (0.0107)x(T_5-T_4)$$ ______________

where:

Q_R = reverse heat flux in watts

(T_5-T_4) = temperature difference between thermocouples 5 and4 in ^{0}F.

Completion of Test - Upon satisfactory completion of the test, record in log book.

Test Performed by:______________________________ Date____________

Witness by Q.A.
Representative ______________________________ Date ____________

TABLE I

Test Requirements *

Condition	Mode	Q(watts)	$T_{Abs-Saddle(Max)}$	$T_{Cond-Saddle}$
A	Direct	20 ± 2	105°F	89°F
B	Reverse	1.2 ± 0.1	-145°F	82 ± 2°F(max)

Shutoff - 5 BTU

*PES-ATS-1-A, ATFE/Thermal Diode Interface Specification, 1 September 1971

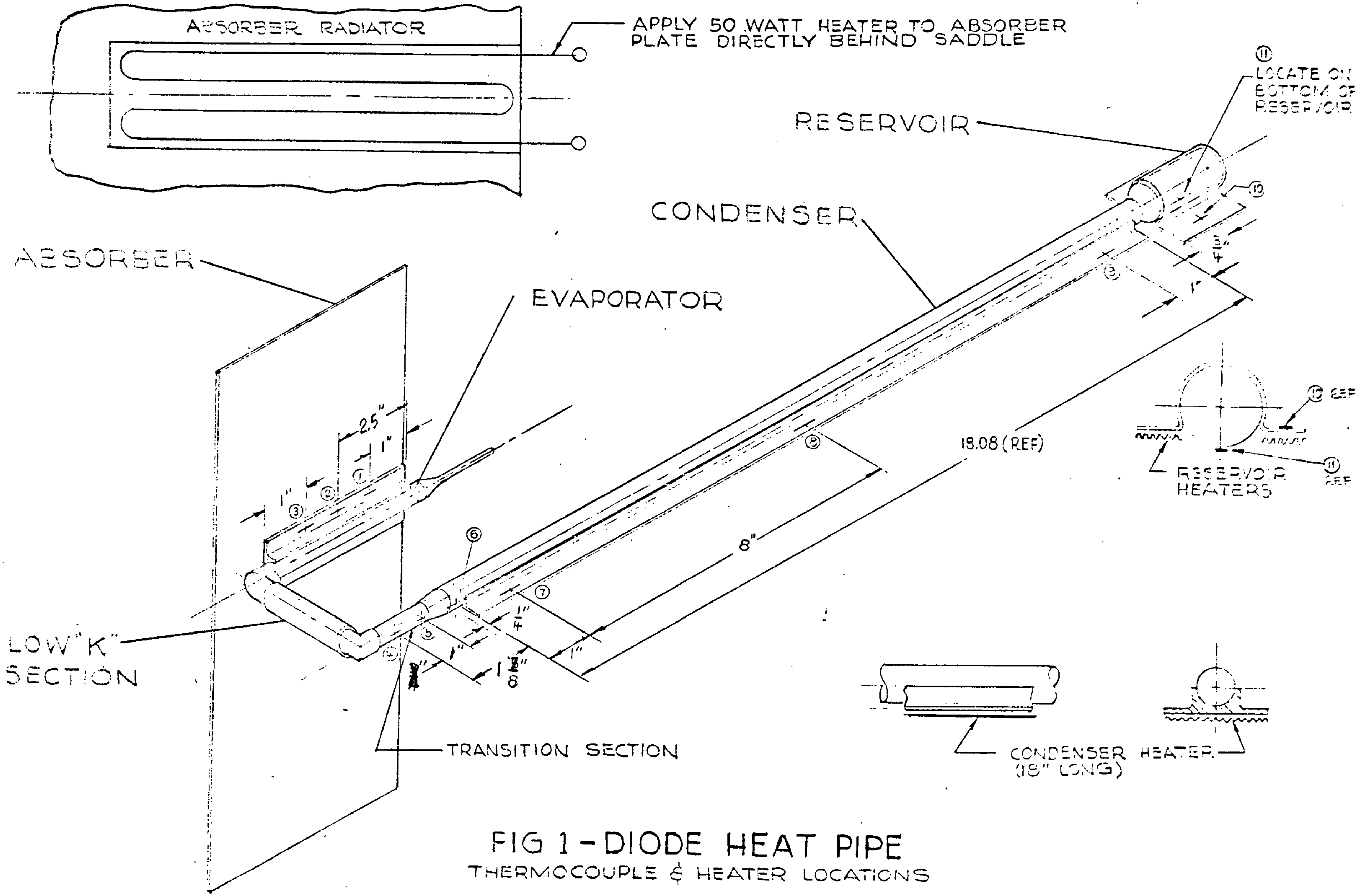


FIG 1 - DIODE HEAT PIPE
THERMOCOUPLE & HEATER LOCATIONS

THERMAL PERFORMANCE TEST
NASA - ATFE DIODE HEAT PIPE

MODEL__________ TEST CONDITION__________

TIME														
Location	TC No.													
Absorber Saddle	1													
" "	2													
" "	3													
Transition Sect.	4													
" "	5													
" "	6													
Condenser Saddle	7													
" "	8													
" "	9													
Reservoir Strap	10													
Reservoir	11													
$T_{ABS(AVE)}$ °F														
$T_{COND(AVE)}$ °F														
$\Delta T = T_{ABS} - T_{COND}$														
Heater Current I(Amps)														
" Voltage V(Volts)														
Power = I x V = Watts														

G316 REV.
8-70 2000F

Recorded by:__________

Date__________

GRUMMAN

Date Sheet __________