CR 171970

ALTERNATE HIGH CAPACITY HEAT PIPE FINAL REPORT

CONTRACT NAS9-17327

31 OCTOBER 1986

REPORT NO.
3-14000/6R-45

SUBMITTED TO: NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
JOHNSON SPACE CENTER

BY: LTV AEROSPACE AND DEFENSE COMPANY
DALLAS, TEXAS

(NASA-CR-171970) ALTERNATE HIGH CAPACITY HEAT PIPE Final Report (LTV Aerospace and Defense Co.) 168 p CSCL 20D

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LTV Missiles and Electronics Group
Missiles Division

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DALLAS, TEXAS

PREPARED BY:	REVIEWED BY:	APPROVED BY:
F E Voss	J. A. Oren	R L Cox
F. E. VOSS	J. A. OREN	R. L. COX

TABLE OF CONTENTS

APPENDICES

1.0 SUMMARY AND INTRODUCTION

This report describes the effort put forth to design and test an alternate high capacity heat pipe. The period of performance was between June 1985 and March 1986.

The program reviews for all the presentations on the alternate high capacity heat pipe portion are attached as Appendices B through D. These reviews with the facing page words are presented as the Task reports required in the contract. These reviews provide the background information necessary to lead into this wrap-up report on the progress and final status of the Alternate High Capacity Heat Pipe program. Appendix E provides detailed technical progress and status of the program between final program review of 15 November 1985 and 24 February 1986. A brief synopsis of the program is still considered viable for this report in addition to the attached reviews.

Under task 1.1 Heat Pipe Concept Studies were conducted. These concepts started with the LTV capillary pumped heat pipe, Figure 1, which used the modified Cat's Eye for a condenser and a capillary pumped evaporator using Porex[1], a high density, small pore size 20 micron polyethylene material as the wicking material. As shown in Figure 1 the evaporator section of the heat pipe is round which provides an effective interface for a contact heat exchanger and is required by the contract Statement of Work.

In conjunction with the testing of the Figure 1 capillary heat pipe priming element, a consultant, Thermacore, of Lancaster, Pennsylvania, was contracted to help analyze the LTV heat pipe. Based upon the testing, with results shown in Table 1, and the analysis by LTV and Thermacore it was concluded that: (1) the heat pipe was not primed; (2) the fluid flow from the condenser to the evaporator was by puddle flow which severely limited the heat load of the heat pipe to 330 watts maximum; (3) the Porex inserts in the cat's eye artery did not insure condenser priming; and (4) if the artery prime is ever lost, the shape of the cat's eye will prevent self or re-priming of the artery. In conclusion to the analysis for the priming element under task 1.1 it was determined that a method that would ensure complete artery priming must be found.

Also under task 1.1 several concepts were proposed by LTV and Thermacore. Six concepts were presented in the 23 August 1985 Program Review, Appendix B. Between 23 August and 20 September 1985 a variety of additional

[1] Registered trademark of Porex Technologies Corp.

FIGURE 1
LTV CAPILLARY PUMPED HEAT PIPE

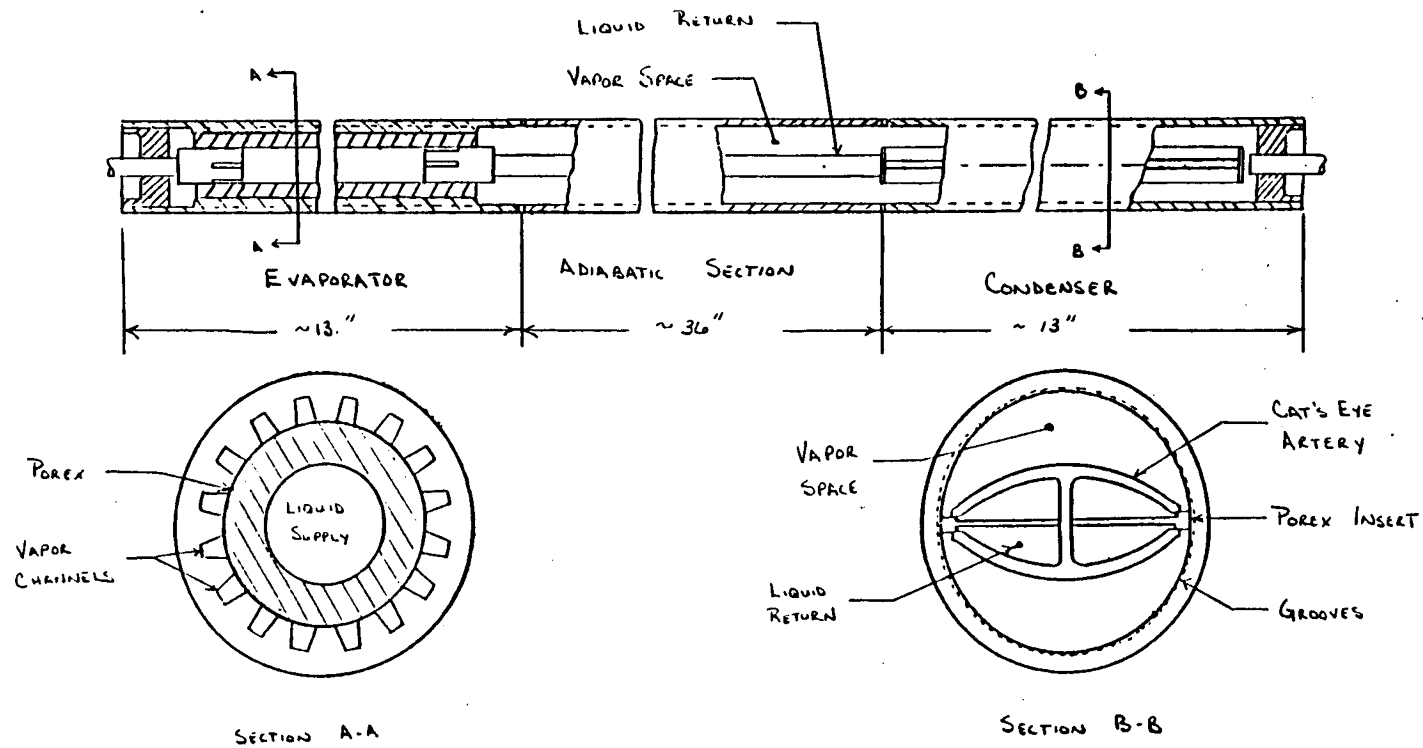


TABLE 1

TYPICAL TEST RESULTS

PIPE CONFIGURATION [1] INCLINATION	ARTERY - HORIZONTAL HEAT LOAD	VERTICAL HEAT LOAD
HORIZONTAL	330W	330
$0^{o}15'$ ADVERSE TILT	290W	285
$0^{o}30'$ ADVERSE TILT	232W	245
$0^{o}45'$ ADVERSE TILT	114W	--- [2]
$1^{o}0'$ ADVERSE TILT	66W	---
$1^{o}15'$ ADVERSE TILT	24W	---

1 BY-PASS LINE OPEN, CHARGE BOTTLE AS RESERVOIR

2 DRY OUT - DID NOT RECOVER

concepts shown in Appendix C were considered and analyzed with our "Heat Pipe Performance Analyzer" computer routine listed in Appendix F. From the Program Review of 20 September 1985, Appendix C, it was recommended that the optimized capillary pumped (porous wick) evaporator mated with the Lockheed tapered artery condenser (Figure 2) be used as the heat pipe for further study and testing. The capillary pumped evaporator/tapered artery heat pipe was predicted to be a moderate risk approach to achieve advantages in weight and performance and to provide a round interface.

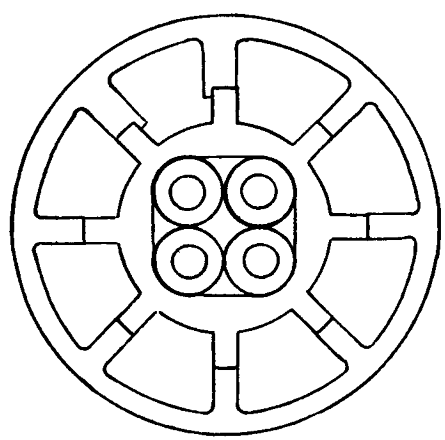
Under task 1.2, Element and Breadboard Tests, the initial intent of this program was to develop a heat pipe from the cat's eye condenser design. Because the initial element testing of the Cat's Eye demonstrated a failure to prime, task 1.2 was re-oriented to evolve the optimized capillary pumped evaporator/tapered artery condenser design selected from concepts of task 1.1. The O.D. was changed to 1.75 inches to be compatible with the proposed Space Erectable Radiator System (SERS) design. The new evaporator design is shown in Figure 3. This design was based upon the optimization studies for vapor spaces, liquid channels and lug sizes as well as the temperature drop from the outside of the pipe to the evaporative interface. This temperature drop was calculated to be 4°F. The liquid artery in the evaporator was changed to multiple (25) self-priming arteries of 3/32" in diameter. These arteries depicted in Figure 3 were to be drilled in Porex (porous polyethylene) 120 micron pore size, used as the evaporator wick. The final version of this design is given in Figure 4. An intermediate evolution, presented at the 15 November 1985 Program Review, is described in Appendix D. Ammonia was selected as the heat pipe fluid.

Another heat pipe test element for task 1.2 was developed and tested by Thermacore under contract to LTV. The test element was a four (4) foot heat pipe with a sintered wick external artery condensor and a sintered grooved evaporator. The conceptual round evaporator was modified for ground (1-G) testing by making it a flat surface with grooves. Description and test results of the Thermacore heat pipe test element are presented in Appendix A.

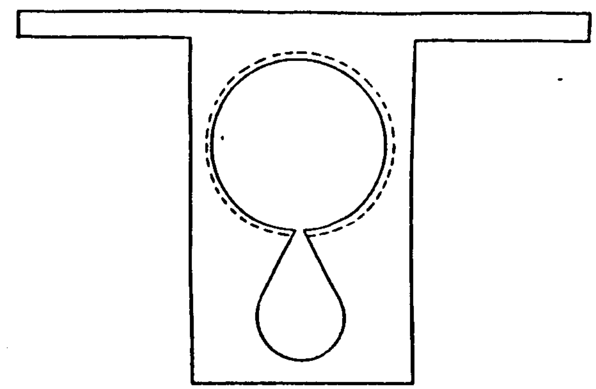
Due to the evolving heat pipe requirements necessary for the Space Erectable Radiator System, the 2kW design goal for a 50' heat pipe appeared to be insufficient. Therefore LTV performed an additional analysis on a condenser that would not limit the capability of the LTV evaporator. The results of this analysis is described in Appendix E and tabulated in Table E-1.

FIGJRE 2

CAPILLARY PUMPED EVAPORATOR/TAPERED ARTERY



OPTIMIZED EVAPORATOR
CAPILLARY PUMPED

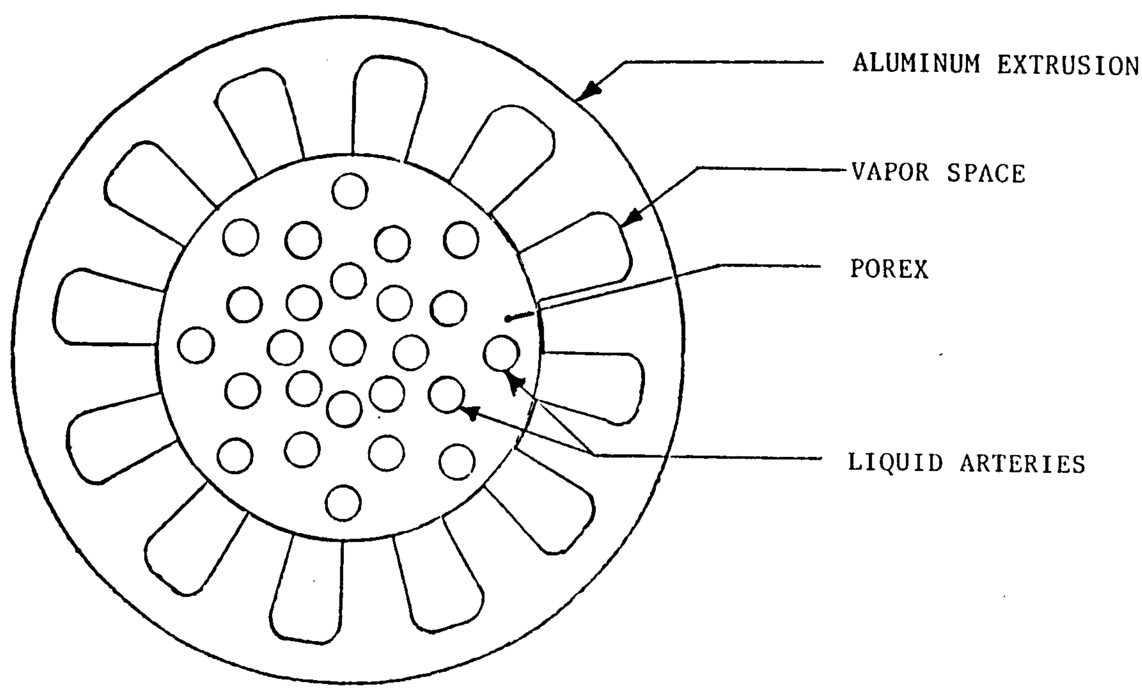


LOCKHEED TAPERED ARTERY
CONDENSER

LTV Aerospace and Defense
Vought Missiles anc
Advanced Program; Division

FIGURE 3

HEAT PIPE EVAPORATOR SECTION - 1 3/4" DESIGN



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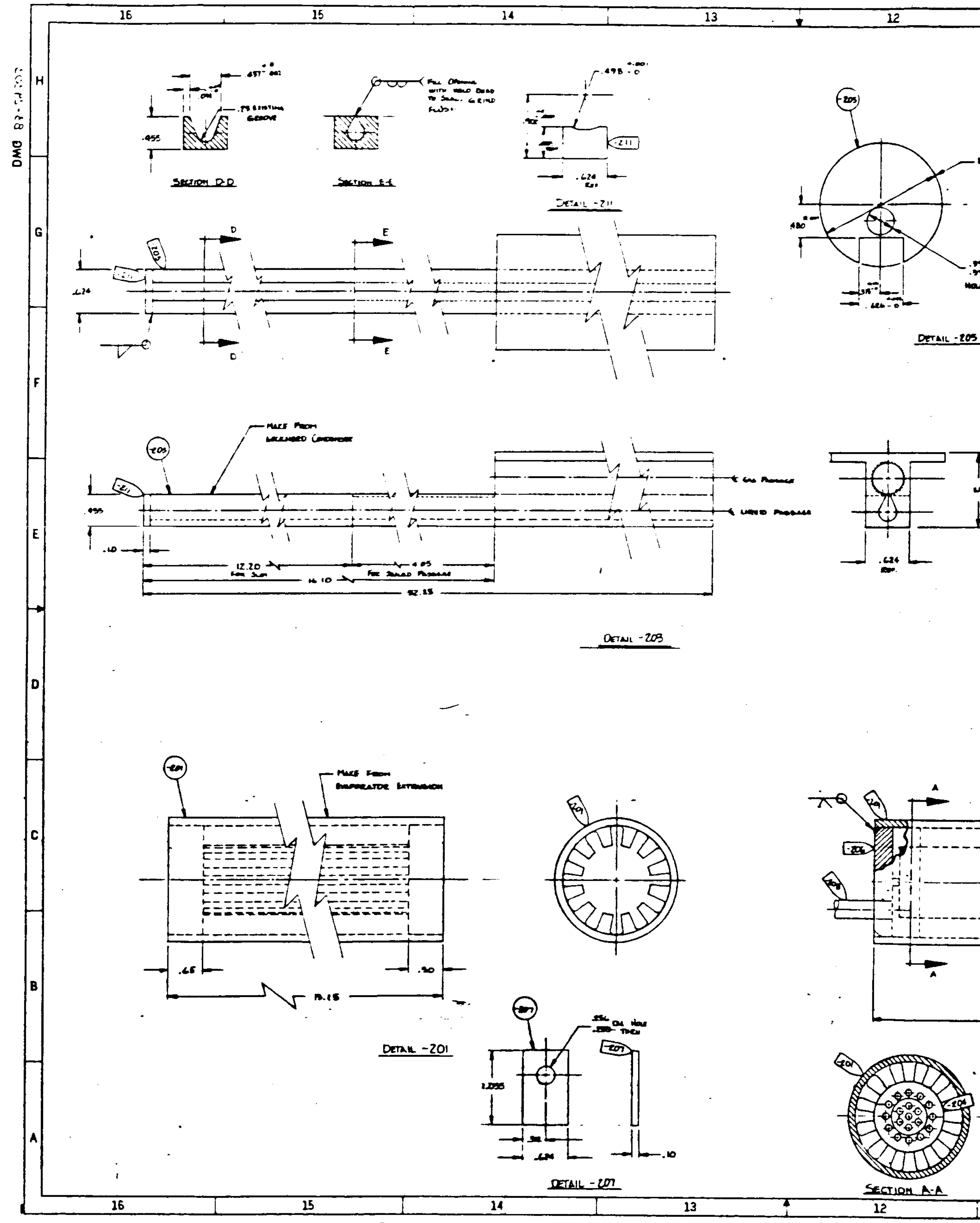

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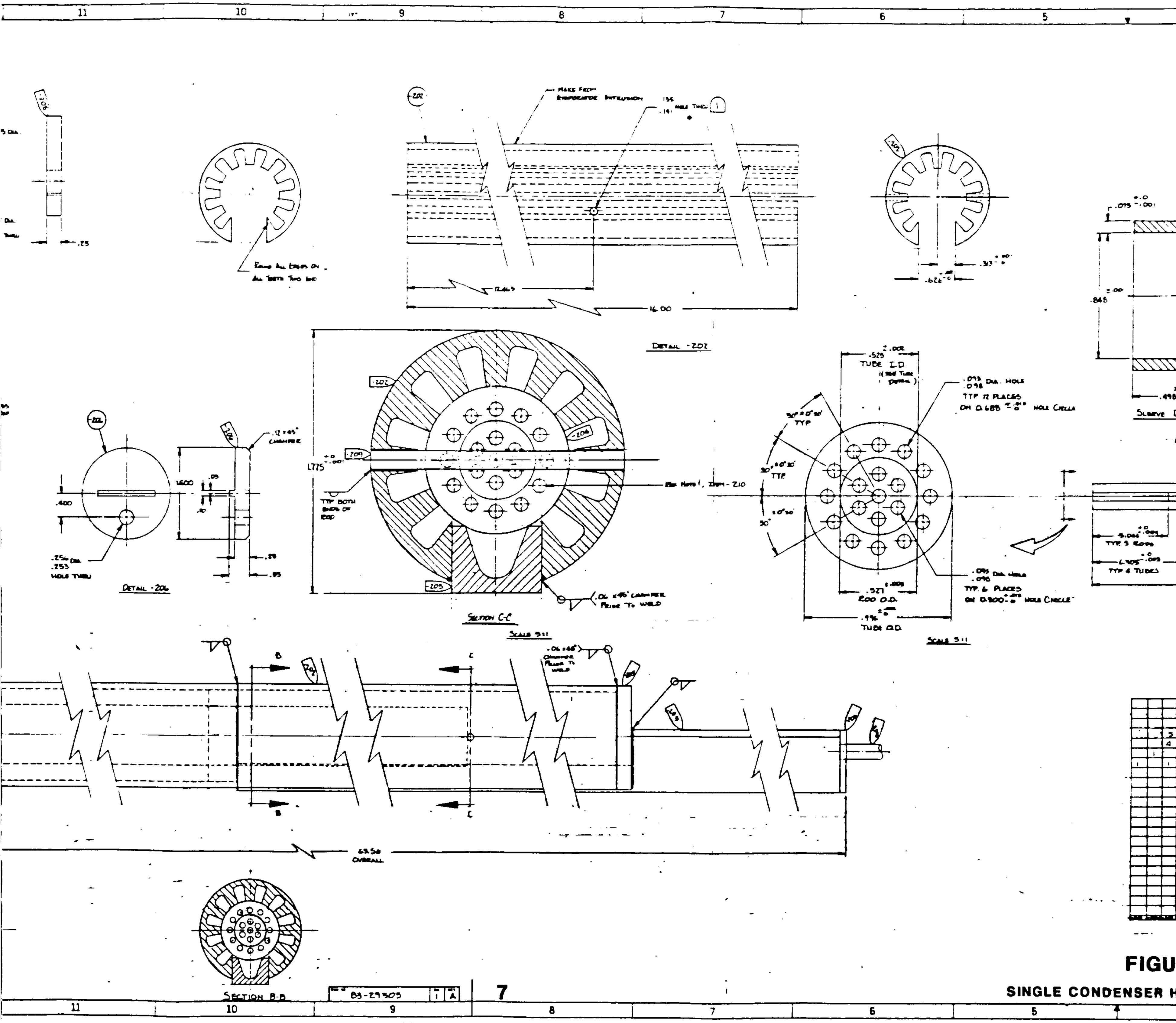

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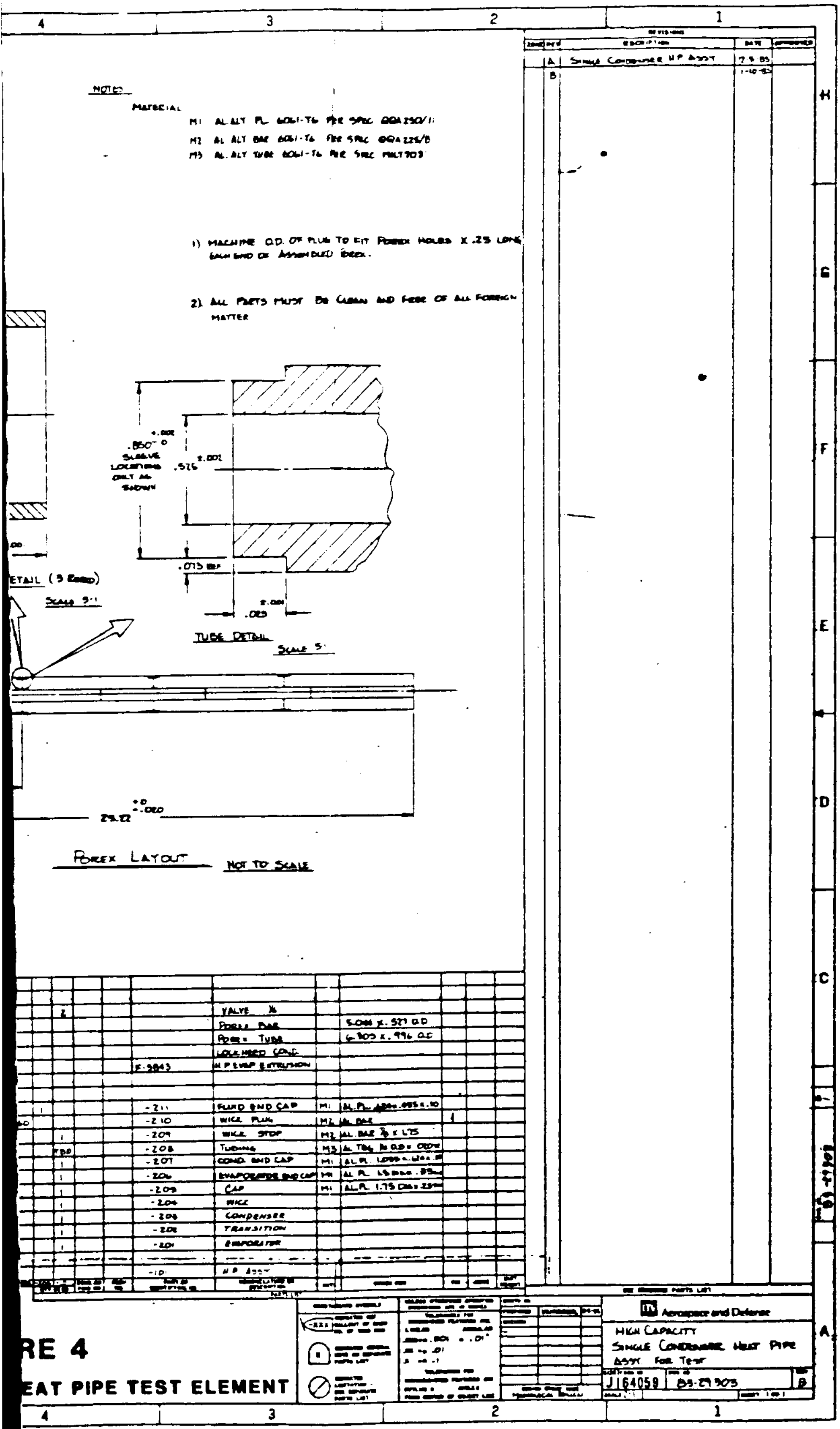

RE 4

EAT PIPE TEST ELEMENT

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Fabrication for breadboard tests under task 1.2 for the single and dual leg heat pipe test elements was started. Due to problems in the fabrication techniques for the Porex wick evaporator, work was halted to assess alternatives to drilling the arteries in the Porex. Several approaches were considered, the most promising of which used sintered aluminum powder metal in place of the Porex wick.

Under task 1.3 the design of the 25 ft. pre-prototype heat pipe with a dual leg condenser was completed utilizing the Porex wick evaporator, and long lead time items were placed on order.

Work on heat pipes for both tasks 1.2 and 1.3 was stopped due to the fabrication problems of the porous wick and budget constraints. A presentation on 24 February 1986 to NASA-JSC described the final status of the heat pipe effort.

2.0 CONCLUSIONS AND RECOMMENDATIONS

LTV has evolved a design concept for a round porous wick evaporator with an external artery condenser that shows promise through performance analysis. This round evaporator interface design allows uniform heat flux (constant temperature) to be provided to the thermal bus condenser. LTV predicts a temperature drop of 4°F from the outer surface of the evaporator extrusion to the evaporating interface. Matched with a complimentary condenser element the LTV evaporator design is predicted to give superior performance (up to 7340 watts) to existing high capacity heat pipes now available. The predicted performance exceeded by 2 times the SERS requirement with 100% margin.

Until future developments of porous plastic material become available to make a suitable evaporator wick, it is recommended that a sintered aluminum porous wick evaporator be used in a pre-prototype test article. It is further recommended that the Lockheed tapered artery condenser be coupled with the LTV evaporator in the pre-prototype article. This test article would demonstrate through testing that LTV's evaporator design offers improvement over other round evaporator designs.

To demonstrate the full performance potential of the LTV design, the porous wick evaporator should be matched with a porous wick condenser. A prototype unit of this design should be built following successful completion of the testing of the pre-prototype article.

APPENDIX A

THERMACORE REPORTS
&
TEST ELEMENT DESCRIPTION

APPENDIX A

The following documents were received from Thermacore in response to the fixed price contract issued to them as a consultant to LTV as required by the NASA contract.

Letter No. LET269.1-85 describes the analysis requested for task 1.1, Heat Pipe Concepts.

Letters LET269.2-86, 269.3-86 and 269.4-86 provide a description, predictions and test data for the four (4) foot test element for task 1.2.

THERMACORE, INC. HEAT TRANSFER SPECIALISTS / ENGINEERING – MANUFACTURING
780 EDEN ROAD / LANCASTER, PENNSYLVANIA 17601 / 717-569-6551

In reply refer to LET269.1-85

Ms. Beth Sauer
LTV Aerospace & Defense Co.
1902 W. Freeway
Grand Prairie, TX 75057

Dear Ms. Sauer:

SUBJECT: LTV High Capacity Ambient Temperature Heat Pipes

During our September 6, 1985 meeting at Thermacore, LTV (John Oren, Beth Sauer) requested us to optimize and analyze the performance for several high capacity ambient temperature (HCAT) heat pipe configurations. The intent of the analyses was to select and recommend a fifty foot long heat pipe configuration capable of transporting 4 kW. The selection was based on minimum mass, minimum ΔT and ease/cost of fabrication. This letter summarizes the results of our evaluations.

Our evaluations included the configurations presented during the September 6, meeting. These configuration are:

- o Capillary pumped evaporator/external artery condenser.
- o Capillary pumped evaporator/tunnel artery condenser.
- o Tunnel artery evaporator/external artery condenser.
- o Tunnel artery full length.

The results of these evaluations are summarized in Table 1.

From Table 1 it is apparent that the best performing design based on mass, ΔT and ease/cost of fabrication is the tunnel artery evaporator/ external artery condenser. Figure 1 is a conceptual drawing of this configuration. It has a mass of 7.4 kg for a 50 foot length. The next best performing alternative is the capillary pumped evaporator/external artery condenser. Figure 2 shows this concept. It has a mass of 8.2 kg for a 50 foot length. A conceptual drawing of the capillary pumped evaporator/tunnel artery condenser is included as Figure 3 to aid in visualizing this configuration. However, it appears to be a less desirable alternative since it has a mass of 16.2 kg.

The data for the Grumman Monogroove is included in Table 2. The monogroove is capable of only 2100 watts over 50 feet and has a mass of 11.1 kg.

Thermacore has fabrication and test experience for tunnel artery and external artery heat pipes. These are the primary elements in the best performing 4 kW-50 foot (HCAT) heat pipe configuration shown in Figure 1. These heat pipes were made in nominal 3 foot lengths. The preliminary test results show power levels of 1000 watts with temperature drops on the order of 5°C. Additional data will be provided as it becomes available in the next few days.

If you have any questions on this letter or the enclosures, please feel free to call me.

Sincerely,

Michael D. Keddy

Michael D. Keddy
Engineer

MDK/mln
Enclosures

P.S. Also included is a rough sketch showing the tunnel artery positions for a 4 kW-50 foot ground test prototype.

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TABLE 1. COMPARISON OF OPTIMIZED HIGH CAPACITY AMBIENT TEMPERATURE HEAT PIPE ALTERNATIVES

(Ø.Øg Environment)

$K = 1.5^{-7} cm^2 \quad R_c = .004\ cm^2$

	TUNNEL ARTERY EVAP. EXTERNAL ARTERY COND.	CAPILLARY PUMPED EVAP. EXTERNAL ARTERY COND.	CAPILLARY PUMPED EVAP. TUNNEL ARTERY COND.	TUNNEL ARTERY FULL LENGTH (Sintered Arteries)	TUNNEL ARTERY FULL LENGTH (Mesh Screen Arteries)
EVAPORATOR PARAMETERS					
o length	48"	48"	48"	48"	48"
o OD	1.5"	1.5"	1.5"	1.875"	1.750
o wall thickness	.065"	.065	.065	.070	.070
o No. vapor space	1	4	4	1	1
o Vapor Space Hydraulic Rad.	.207	.113"	.119	.310	.274
o No. arteries	2	8	15	2	2
o artery diameter	5/32	1/8	3/32	7/32	7/32
o wick thickness	.045	.045	.030	.045	.045
CONDENSER PARAMETERS					
o vapor space I.D.	.410	.420	1.737	1.735	1.610
o wall thickness	.065	.065	.075	.070	.070
o wall wick thickness	.045	.040	.045	.045	.045
o slot wick thickness	.090	.080	----	-----	------
o No. arteries	1	1	2	2	2
o artery diameter	1/4	5/16	3/32	7/32	7/32
PERFORMANCE PARAMETERS					
o ΔT	6°C	6°C	6°C	6°C	6°C
o mass	7.4 kg	8.2 kg	16.2 kg	14.6 kg	14.0 kg
o working fluid temp.	20°C	20°C	20°C	20°C	20°C
o power transport	4000 W	4 kW	4 kW	4 kW	4 kW
COMMENTS	light weight w/ a simple wick structure.	light weight w/ a complex wick structure.	heavy difficult to fabricate in 50' lengths.	heavy difficult to fabricate in 50' length	heavy/easier to make

TABLE 2

KEY DESIGN PARAMETERS FOR A HIGH CAPACITY MONOGROOVE HEAT PIPE[1]

Evaporator Length	=	48"
O.D.	=	Non-circular evaporator
Wall Thickness.	=	.063"
No. Vapor Spaces	=	1
Hydraulic Radius	=	.295"
No. Arteries	=	1
Artery Diameter	=	.393"
Slot Width	=	.009" - .016"
o ΔT	=	> 20°C
o Mass	=	.73 kg/m = 11.1 kg
o Working Fluid Temp.	=	20°C
o Qmax (tested)	=	1200 W
o Qmax (theory)	=	~2100 W

1. Alario, J., Brown, R and Kosson, R; "Monogroove Heat Pipe Development for the Space Constructible Radiator System"; AIAA 18th Thermophysics Conference; June 1-3, 1983, Montreal, Canada.

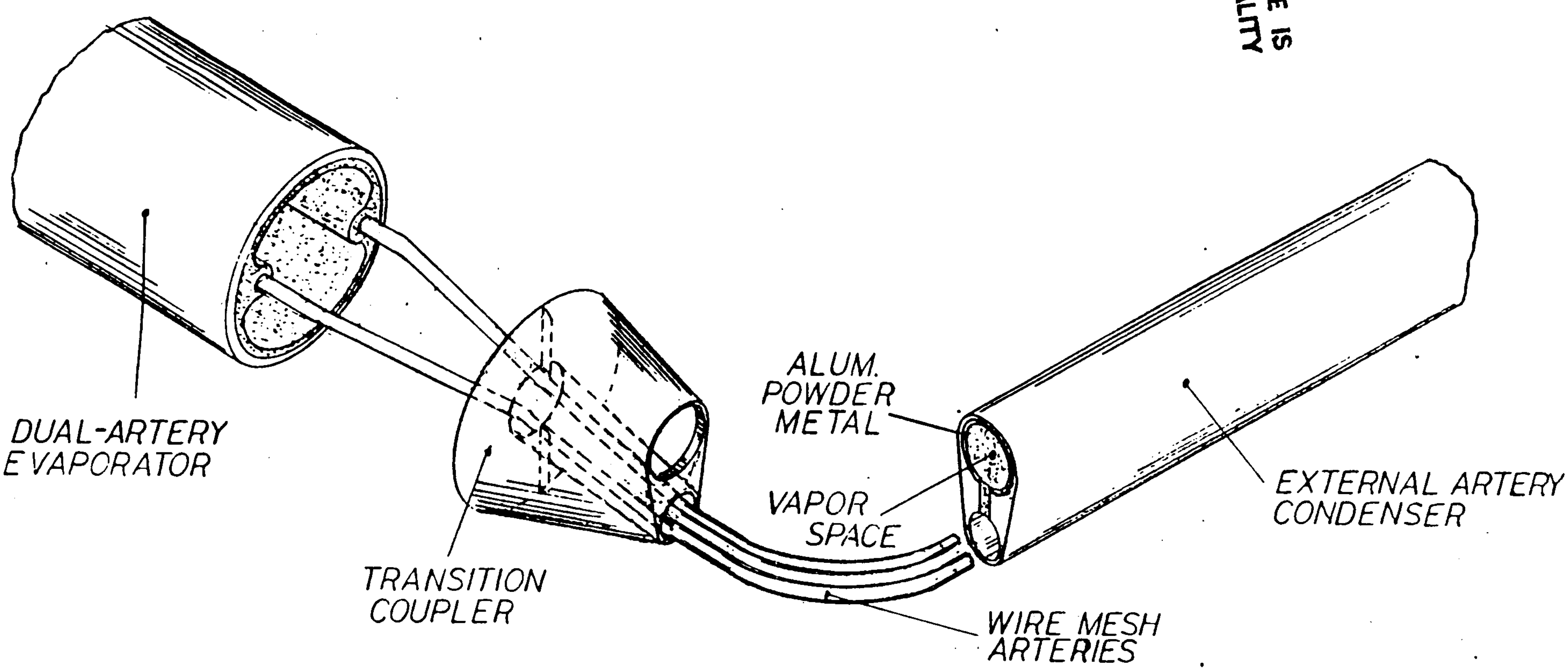


FIGURE 1

DUAL-ARTERY EVAPORATOR EXTERNAL ARTERY CONDENSER

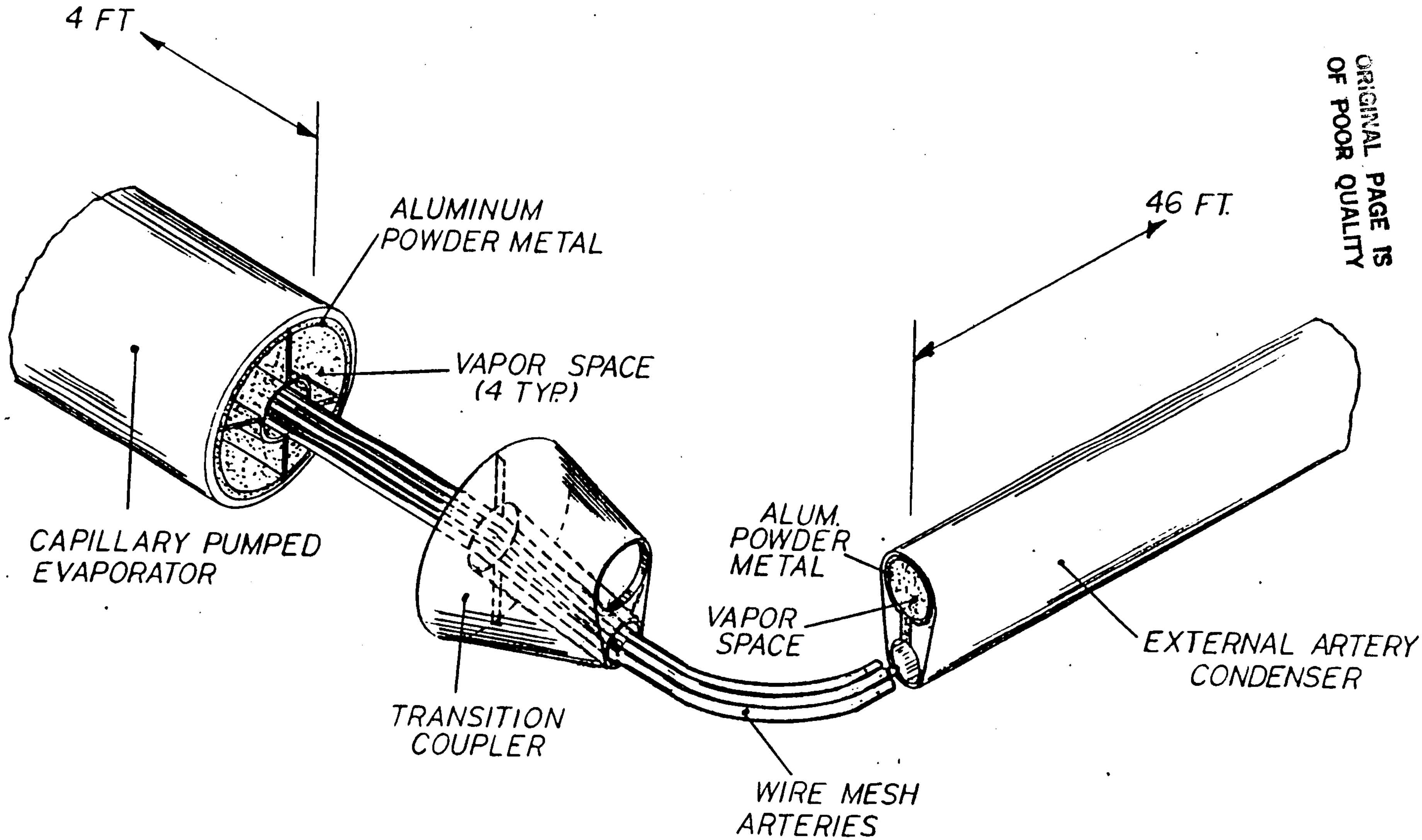


FIGURE 2

CAPILLARY PUMPED EVAPORATOR EXTERNAL ARTERY CONDENSER

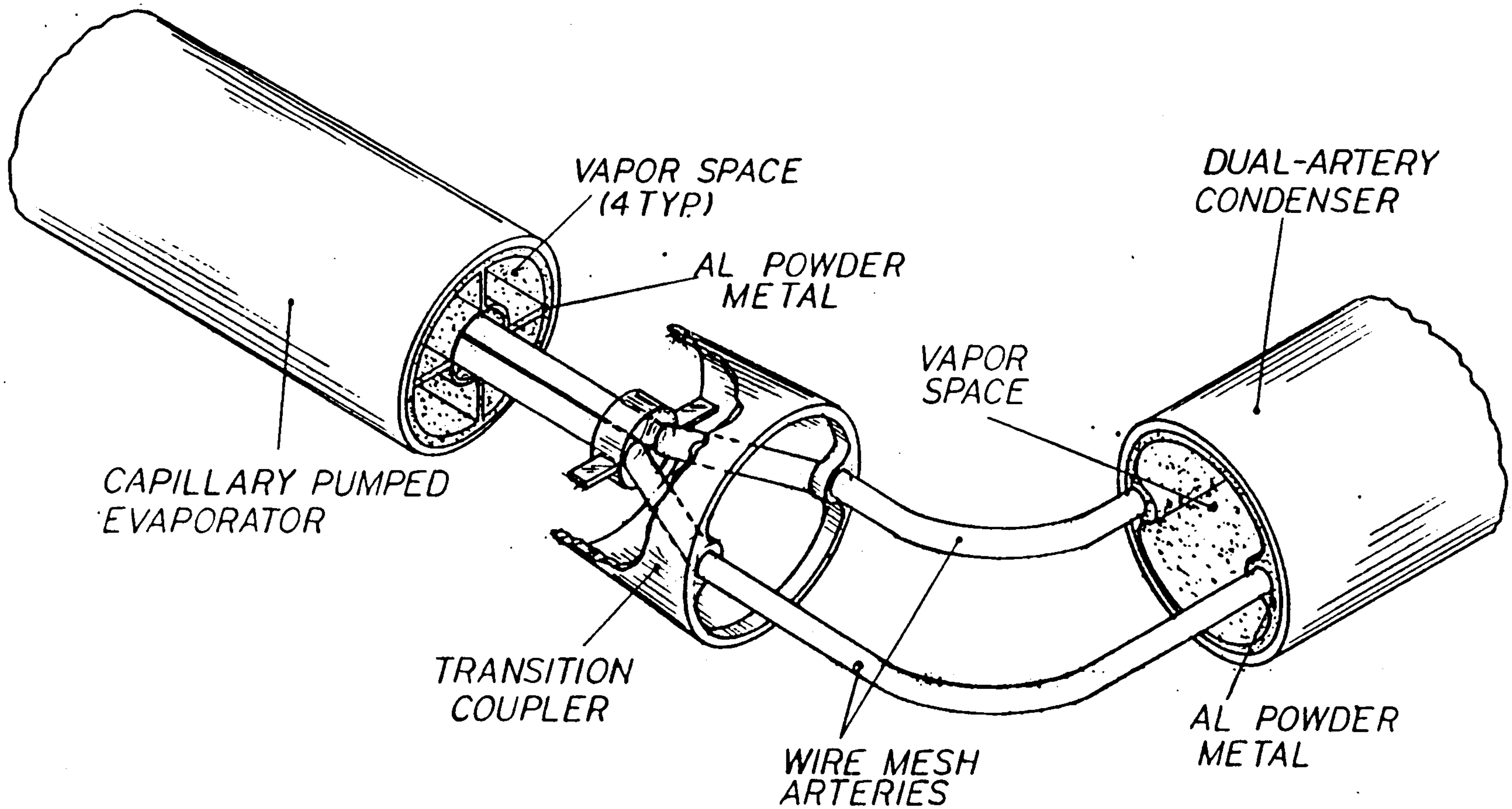
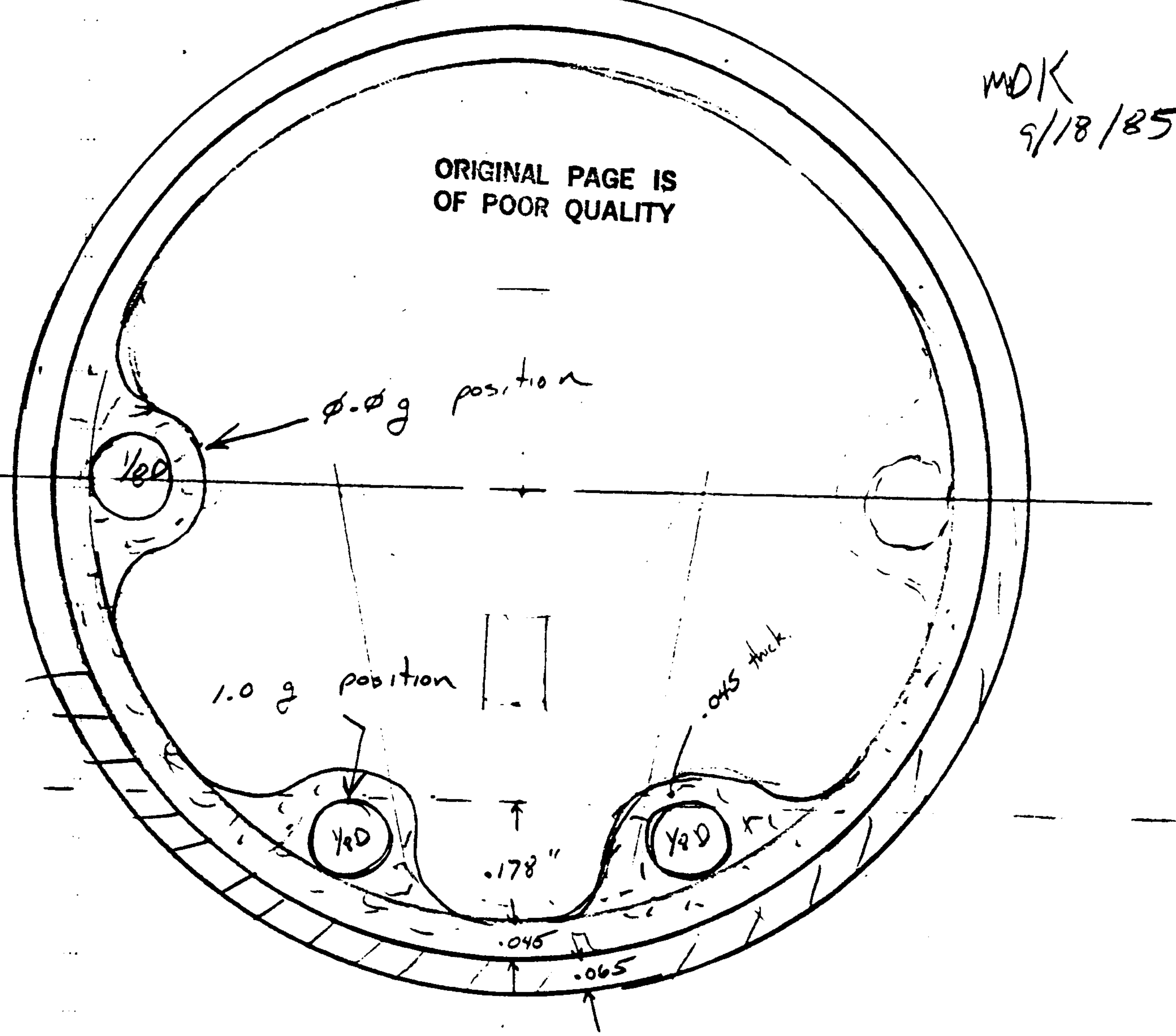


FIGURE 3
CAPILLARY PUMPED EVAPORATOR DUAL ARTERY CONDENSER

scale 4:1

MDK
9/18/85



4KW – 50 foot ground test prototype cross sectional view.
the light lines are superimposed over the tunnel artery cross section to show how the external artery evaporator would match up with the tunnel artery.

at 4KW the maximum adverse tilt is .05" for a 50 foot pipe.
at 1 kW the adverse tilt is ~ 4.6 "

THERMACORE, INC.

HEAT TRANSFER SPECIALISTS / ENGINEERING - MANUFACTURING

780 EDEN ROAD / LANCASTER, PENNSYLVANIA 17601 / 717-569-6551

Rec'd 2/12/86

In reply refer to LET269.2-86

February 7, 1986

Mr. Fred Voss, EM-53
LTV Aerospace and Defense Company
1902 West Freeway
Grand Prairie, TX 75051

Dear Mr. Voss:

This letter is intended to bring you up to date on the work being conducted at Thermacore to develop a four (4) foot aluminum/ammonia heat pipe with a powder metal wick structure. The heat pipe to be built and tested under this work effort should have the following characteristics:

- Total length of 4 feet (nominal).
- Evaporator length of 1 foot (nominal).
- Condenser length of 3 feet (nominal).
- Heat transport capability to be a scaler of at least 2 kW for a fifty foot design (4 foot evaporator - 46 foot condenser).
- An evaporator with a circular cross section.
- A condenser wick system using an external artery similar to that shown in Figure 1.

The specific tasks taken in developing the four (4) foot pipe are outlined below:

- Initially two (2) evaporator designs were considered (tunnel artery and spoke). Sketches of these designs are shown in Figures 2 and 3, respectfully. Both evaporator designs require transition pieces to couple them with external artery condensers. The design of the transition for the tunnel artery was less complex than for the spoke and was therefore the preferred design.

- A three foot long aluminum/ammonia heat pipe was built and tested under a Thermacore Internal Research and Development Program. This heat pipe used tunnel arteries in the evaporator and condenser. This was done as a first step toward fabricating the evaporator for the four foot heat pipe outlined above.

- The measured performance of the tunnel artery heat pipe was less than expected indicating: (1) the arteries were never fully primed or, (2) vapor and/or noncondensable gas in the wick structure was inhibiting the flow of liquid to the evaporator.

- Several additional tests were attempted to determine the mechanism(s) causing the pipe not to perform as predicted. The tests were inconclusive.

Since the primary objective of this program was to build, test and have deliverable by mid-January a four (4) foot aluminum/ammonia heat pipe, Thermacore decided to pursue alternative evaporator designs for this program and resolve the problems with the tunnel artery and spoke artery on our own funds.

Axial grooves were chosen for the alternative evaporator design. An evaporator of this type would be capable of achieving the operating characteristics described earlier and would require a minimal amount of development and fabrication time.

A sketch of an axial groove/external artery heat pipe for waste heat rejection on the Space Station is shown in Figure 4. One of the drawbacks with this design is that the 1.5" diameter round evaporator cannot be tested on earth. The grooves cannot lift the 1.5" diameter under 1.0 g.

An earth version of the axial groove/external artery heat pipe was designed built and tested for LTV under Purchase Order No. 808364. The earth version of the axial groove evaporator is made by laying the circumference of the evaporator out flat as shown in the fabrication drawings included as enclosures. In this way the grooves do not have to overcome the gravitational force.

The test results for the four (4) foot heat pipe and predicted performance for a fifty foot design are summarized below. Detailed results and performance predictions are included as enclosures.

The ground test axial groove/external artery heat pipe carried 340 watts at a static lift height of 0.05 inch. This value compares favorably with the predicted value of 350 watts at 0.05 inch. The predicted performance for a fifty foot axial groove/external artery heat pipe having a 1.5 inch diameter four foot long evaporator is 2 kW and for a 2 inch diameter evaporator is 2.4 kW. Achieving power levels on the order of 3 kW is feasible based on the following argument.

A key assumption made in predicting these performances was that the groove depth was twice the groove width, (assumed to be a fabricating limitation). An increase in the groove aspect ratio, depth to width ratio, increases the peformance of axial groove heat pipes substantially. Axial grooves in heat pipes have been made with aspect ratios of 3.

As stated in our telephone conversation on February 4, 1986 a test outline and drawing depicting experimental set-up will be forwarded in a few days.

Enclosed with this letter are:

- Fabrication drawings for the four (4) foot axial groove/external artery ground test heat pipe (1 foot evaporator - 3 foot condenser).
- Performance predictions for a fifty (50) foot axial groove/external artery heat pipe (4 foot evaporator, 46 foot condenser).
- Test results for the four (4) foot ground test heat pipe.

The ground test axial groove/external artery heat pipe is available upon request to LTV for further testing. Please advise. Upon forwarding the experimented test procedures and test set-up, Thermacore's obligation on LTV's PO# 803864 will be completed.

If you have any questions on the enclosures or need additional information, please feel free to call me.

Sincerely,

Michael D. Keddy
Engineer

MDK/mln
Enclosures

ENCLOSURE

DISCUSSION OF TEST RESULTS

The following discussion and supporting figures pertain to the performance predictions for a fifty (50) foot heat pipe (4 foot evaporator - 46 foot condenser). These performance predictions are supported by experimental data for a four (4) foot heat pipe.

Both heat pipes have evaporators with axial groove wick structures and condensers with powder metal external artery wick structures. The predicted performance of a rectangular axial groove/external artery heat pipe operating in space is shown in Figure A. Heat transport versus groove width is plotted for 100, 200 and 300 grooves in the evaporator.

The curves show that maximum power is achieved for groove widths from 0.040 to 0.053 as the number of grooves varies from 300 to 100. The corresponding range of maximum power is 3150 to 2400 watts.

Figure B shows the relationship between groove width and heat pipe evaporator diameter for 100, 200 and 300 grooves in the evaporator.

From Figure B it is apparent that a 1.5 inch diameter evaporator (based on the diameter at the base of the grooves) having 100 grooves 0.038 inches in width is capable of transporting 2 kW when coupled with a 46 foot condenser (external artery).

The predicted results in Figures A and B are tied to two major assumptions concerning the fabrication of rectangular axial grooves: (1) that the maximum groove depth is twice the groove width (i.e, the aspect ratio is 2), and (2) that the minimum land thickness is 0.010 inches. An increase in the aspect ratio would increase the heat transport capability of an axial groove heat pipe markedly.

Some aluminum extruders have fabricated heat pipe envelopes with axial grooves having aspect ratios of 3 and possibly more.

The predicted performance curves in Figure A are conservative. Figures A and B show that a fifty (50) foot heat pipe with a 1.5" diameter evaporator having axial rectangular grooves is capable of at least 2 kW.

A four foot heat pipe having a three (3) foot condenser and one (1) foot evaporator was built and tested. The evaporator wick structure used axial grooves with rectangular cross sections, and the condenser wick structure used powder metal with an external artery configuration. Fabrication drawings are enclosed.

Figure C shows the predicted and measured performance for this heat pipes. The agreement between predicted and measured performance is good and therefore substantiates the predicted performance for a fifty foot heat pipe.

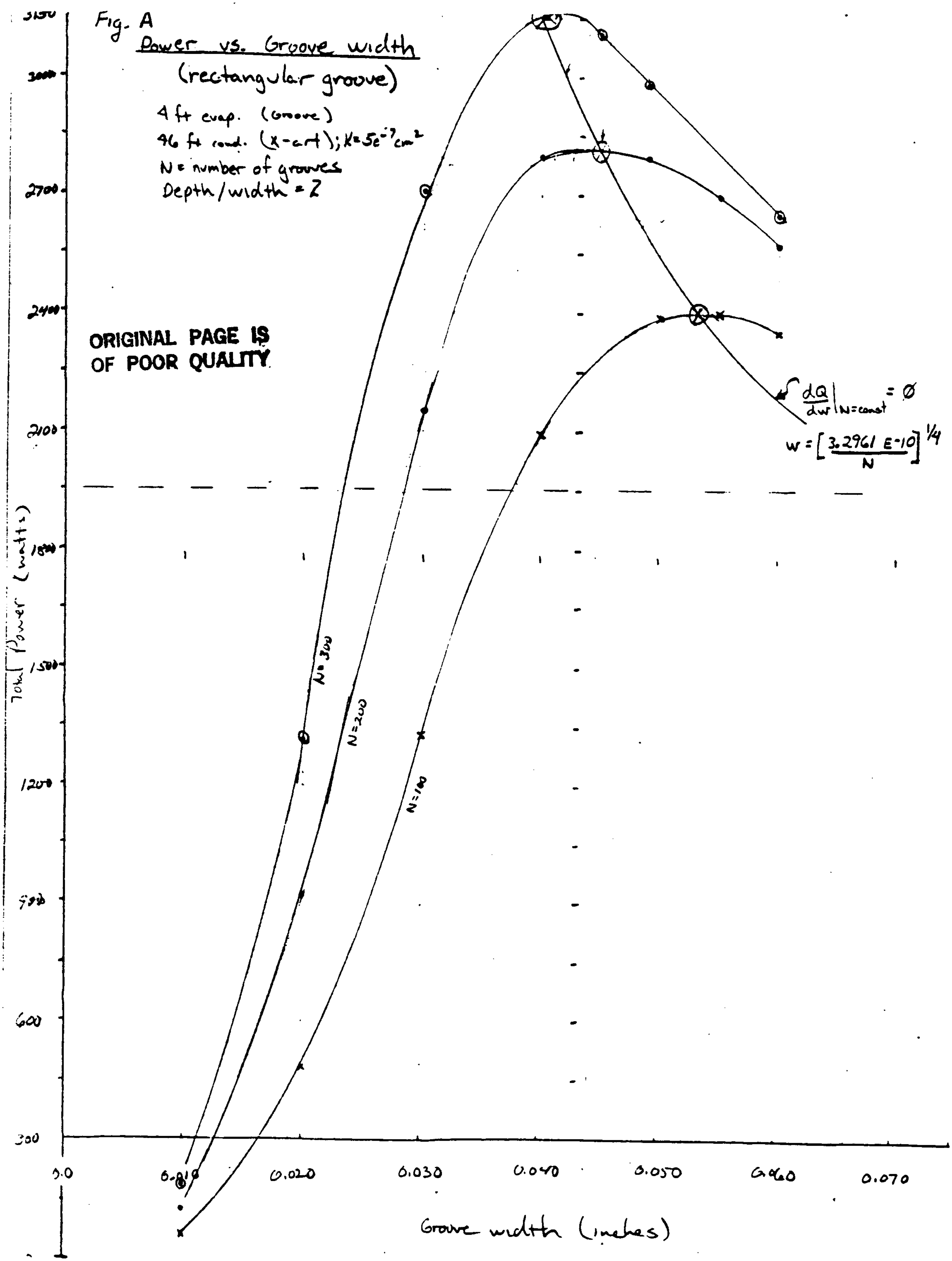
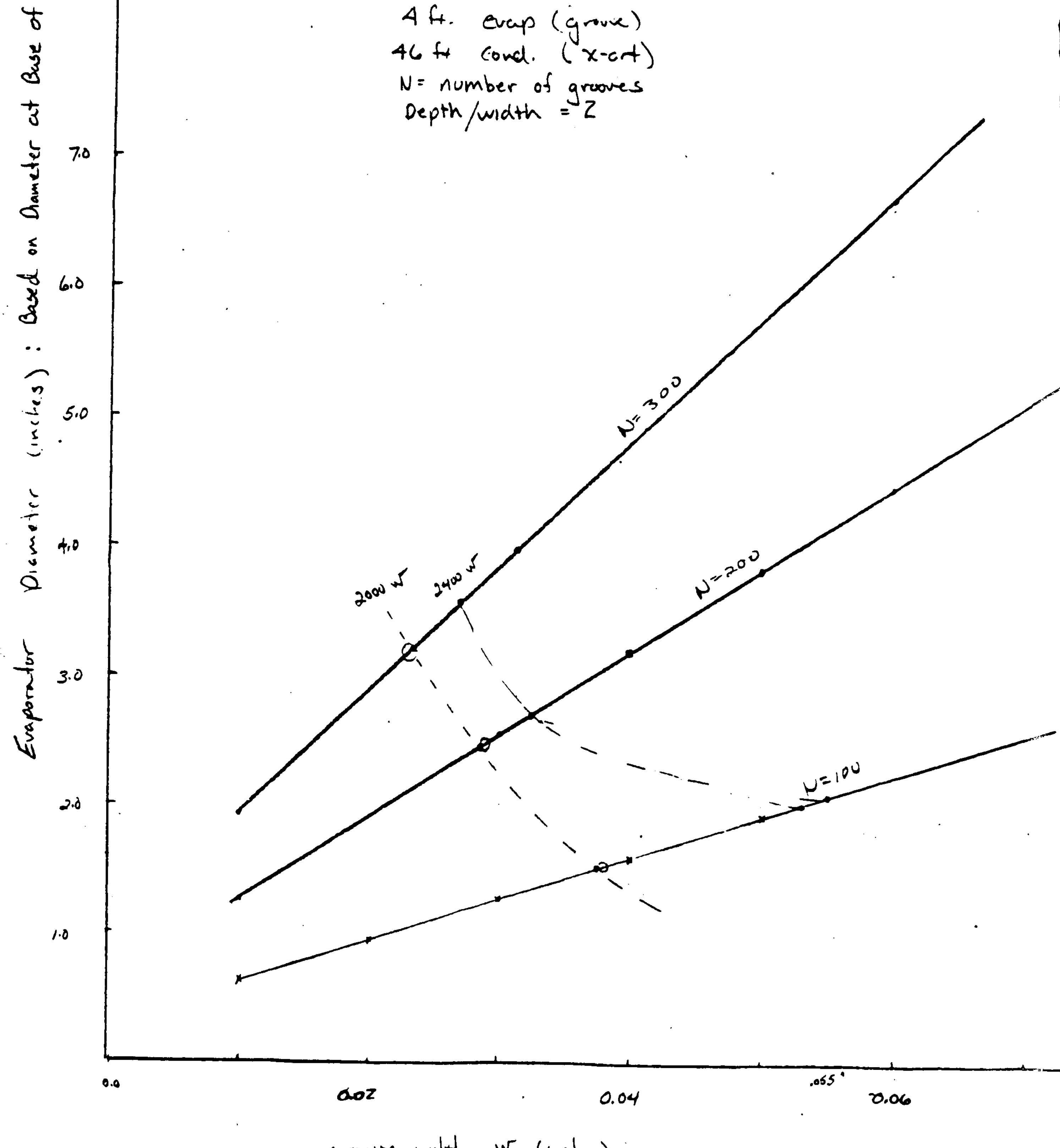


Fig. A
Power vs. Groove width
(rectangular groove)
4 ft evap. (Groove)
46 ft cond. (x-art); K=5e-7 cm²
N = number of grooves
Depth/width = 2
ORIGINAL PAGE IS OF POOR QUALITY
N=300
N=200
N=100
dQ/dw |N=const = Ø
w = [3.2961 E-10 / N]^1/4
Total Power (watts)
Groove width (inches)
3150
3000
2700
2400
2100
1800
1500
1200
900
600
300
0.0
0.010
0.020
0.030
0.040
0.050
0.060
0.070

Fig. B

Groove width vs. Evaporator Diameter
(rectangular grooves)



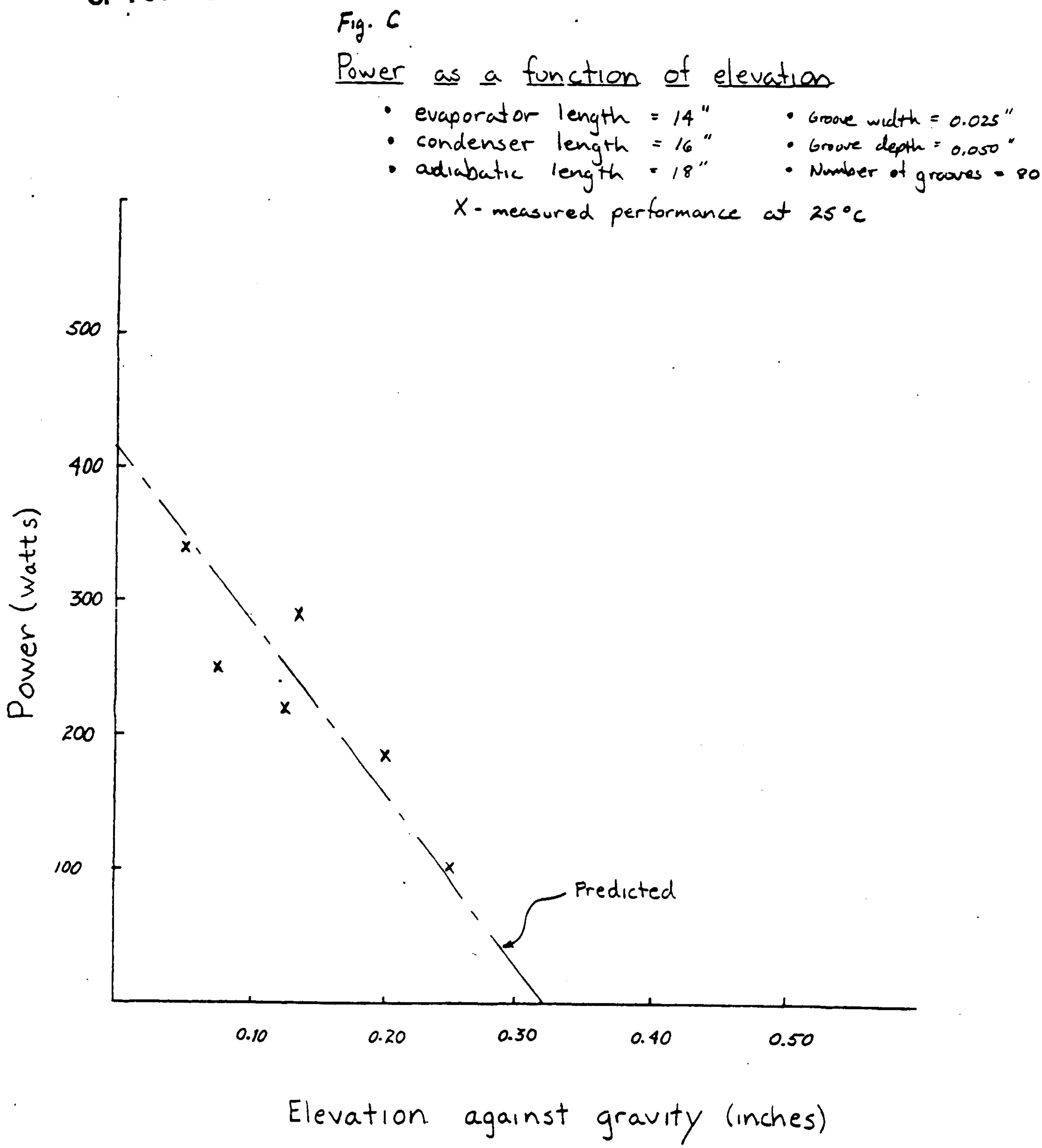


Fig. C
Power as a function of elevation
• evaporator length = 14"
• condenser length = 16"
• adiabatic length = 18"
• Groove width = 0.025"
• Groove depth = 0.050"
• Number of grooves = 80
X - measured performance at 25°C
Power (watts)
500
400
300
200
100
Predicted
0.10
0.20
0.30
0.40
0.50
Elevation against gravity (inches)

FABRICATION DRAWINGS

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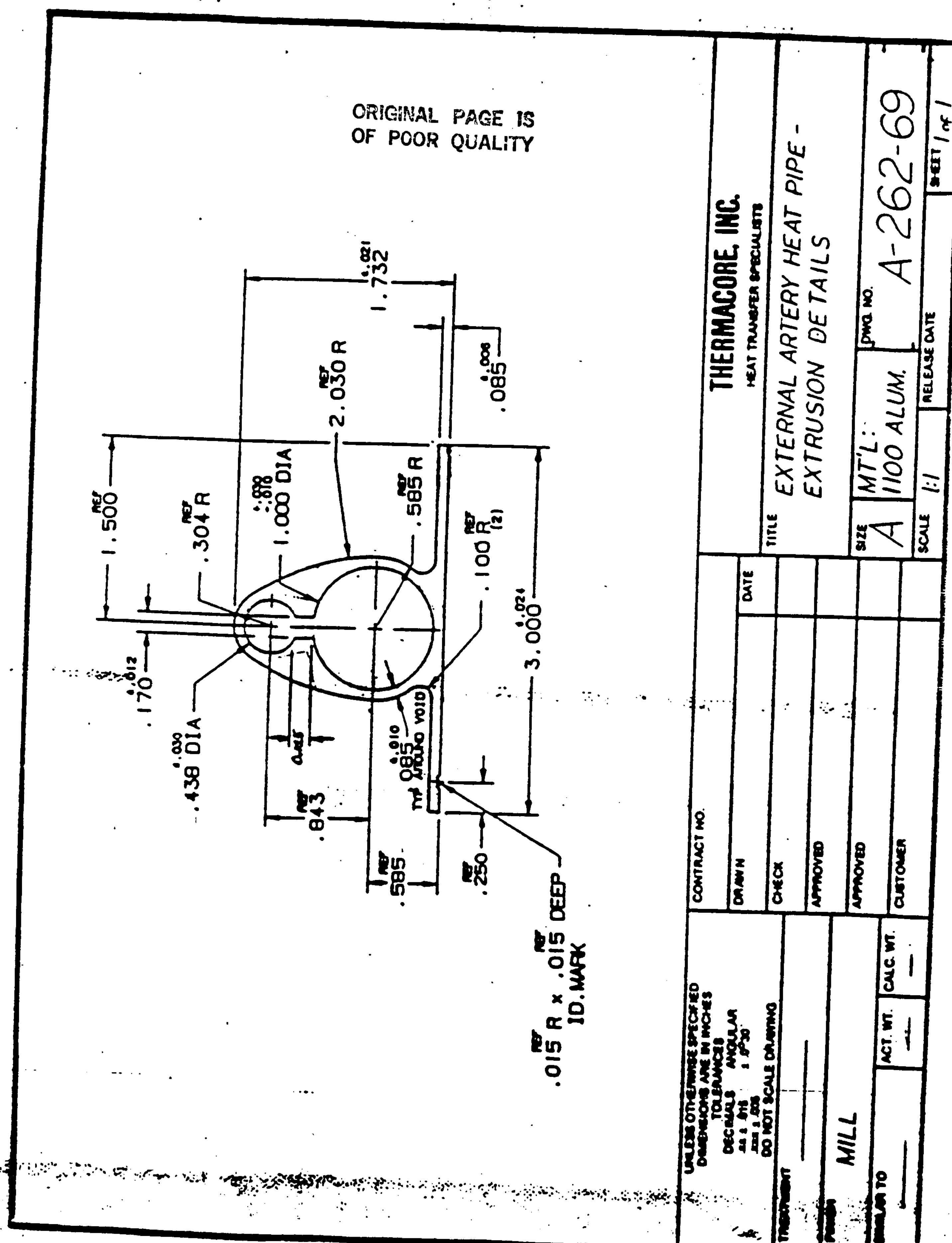

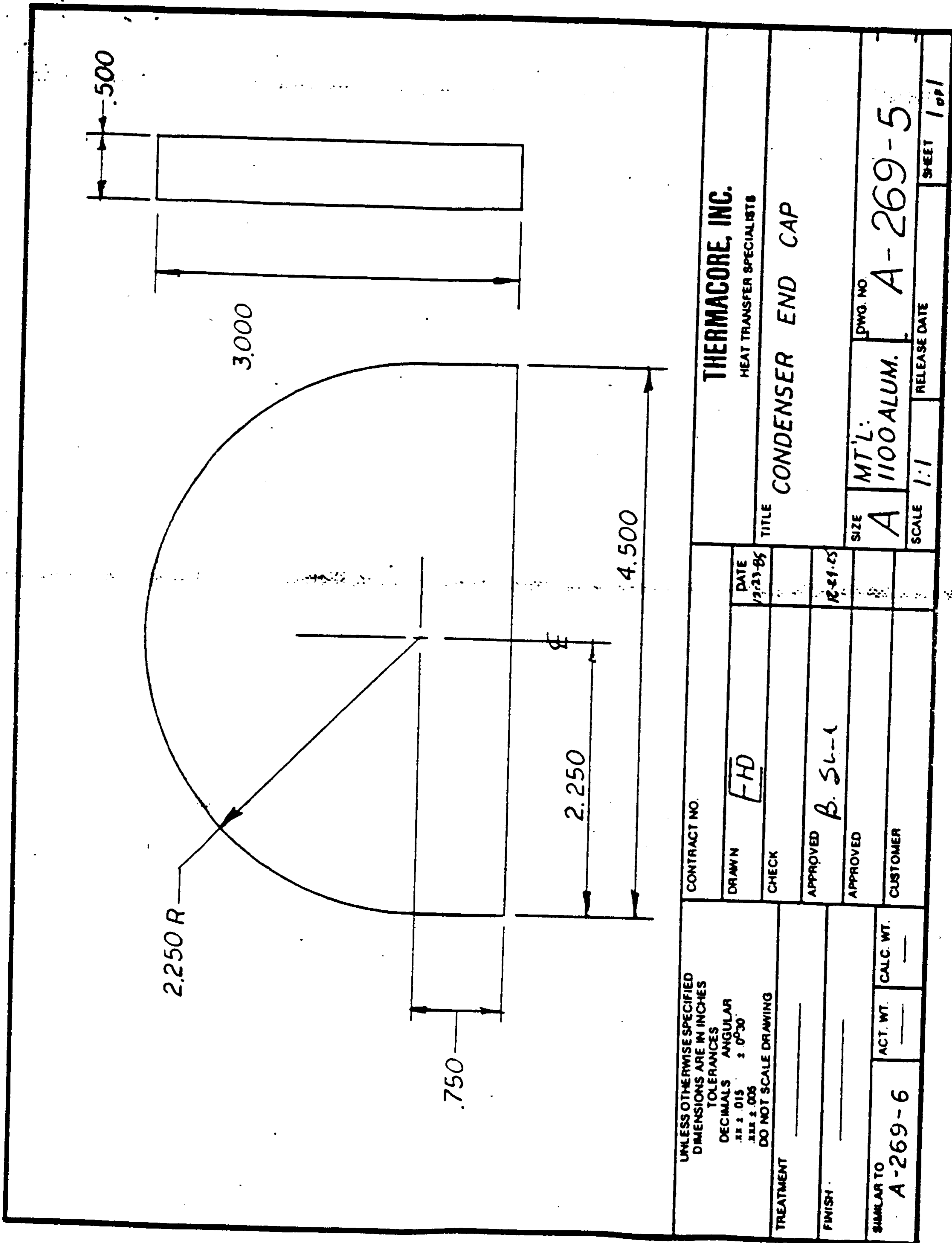
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3.000
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THERMACORE, INC.
HEAT TRANSFER SPECIALISTS
TITLE
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SCALE
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UNLESS OTHERWISE SPECIFIED
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DECIMALS ANGULAR
.xx ± .015 ± 0°30'
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DO NOT SCALE DRAWING
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lancaster blueprint company

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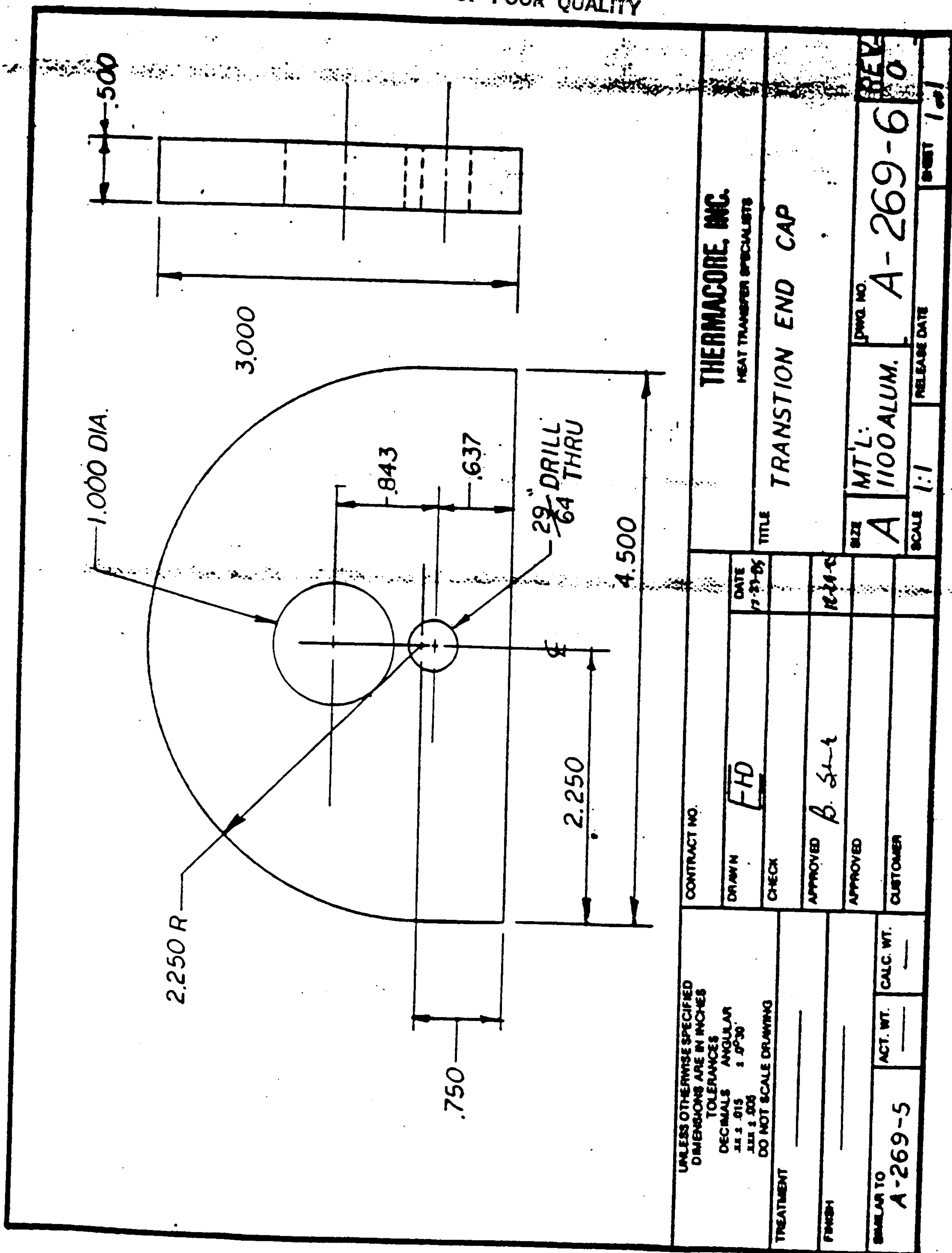

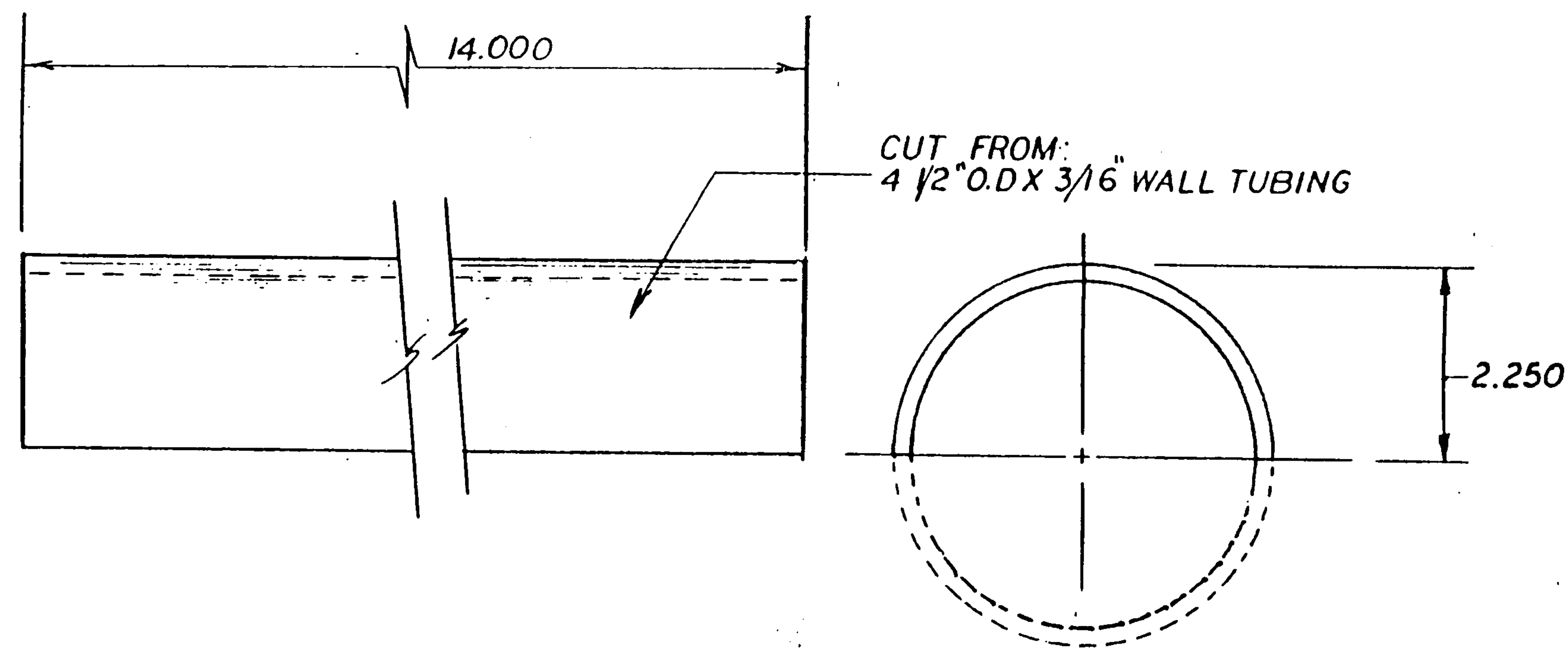

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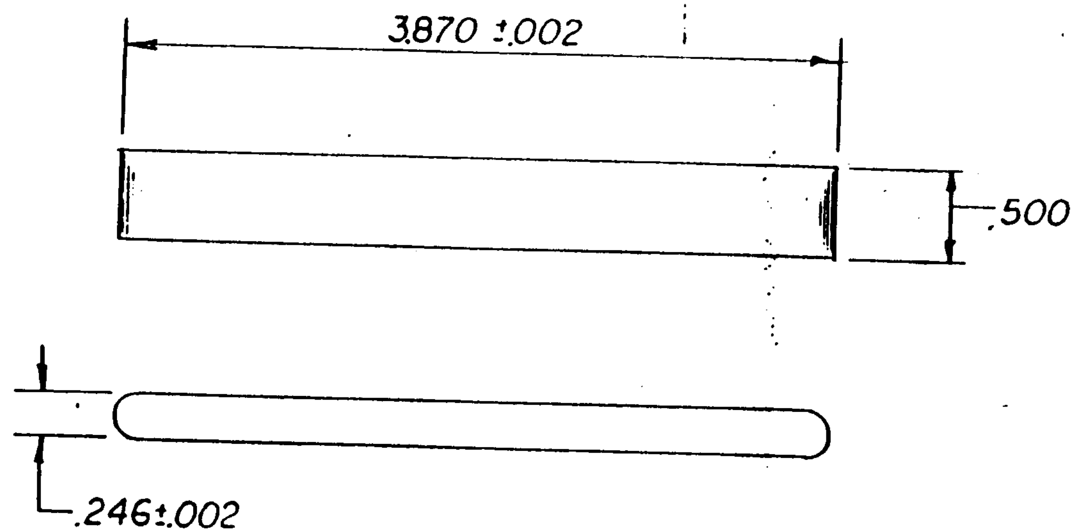

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SIMILAR TO

ACT. WT.

CALC. WT.

CONTRACT NO.

DRAWN EHD DATE 12-23-85

CHECK

APPROVED B. Shuk 12-24-85

APPROVED

CUSTOMER

THERMACORE, INC.
HEAT TRANSFER SPECIALISTS

TITLE RETURN PLUG

SIZE A

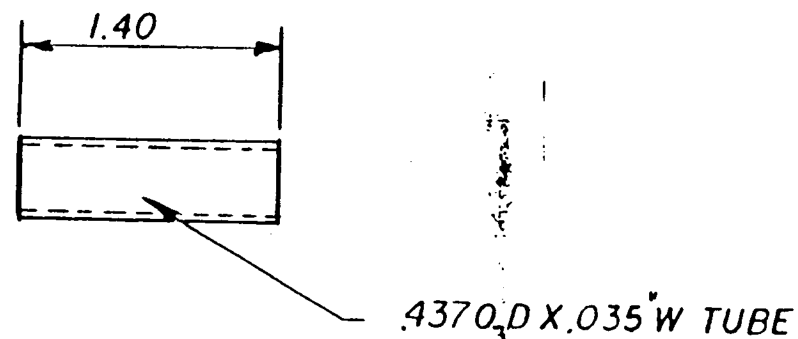
MT'L: 1100 ALUM.

DWG. NO. A-269-8

SCALE 1:1

RELEASE DATE

SHEET 1 of 1



UNLESS OTHERWISE SPECIFIED
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TOLERANCES
DECIMALS .xx ± .015 .xxx ± .005
ANGULAR ± 0°30'
DO NOT SCALE DRAWING

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FINISH	DRAWN EHD	DATE 12-23-85	
SIMILAR TO	CHECK		
ACT. WT.	APPROVED B. Shr	12-21-85	
CALC. WT.	APPROVED		
	CUSTOMER		

THERMACORE, INC.
HEAT TRANSFER SPECIALISTS

TITLE TRANSITION TUBE

SIZE	MTL	DWG. NO.
A	1100 ALUM.	A-269-9

SCALE 1:1 | RELEASE DATE | SHEET 1 of 1

FIGURE 1
EXTERNAL ARTERY CONDENSER

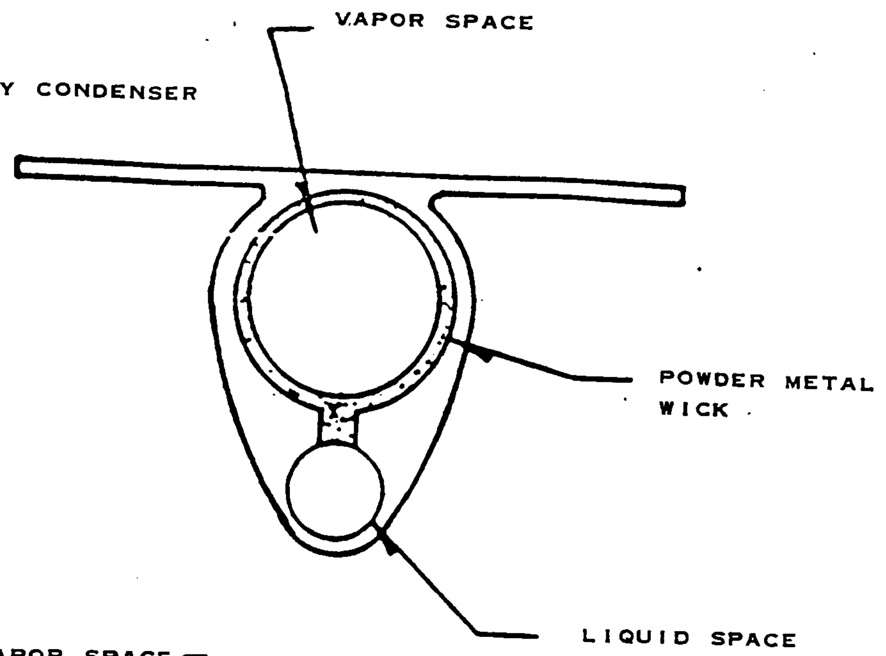


FIGURE 2
TUNNEL ARTERY
EVAPORATOR

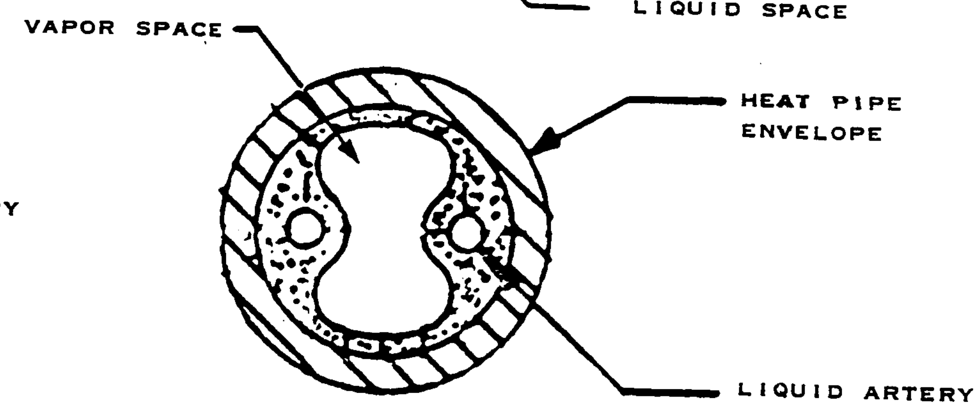
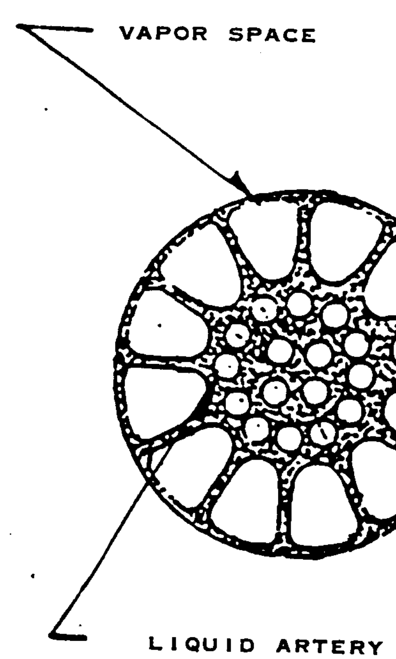


FIGURE 3.
SPOKE EVAPORATOR



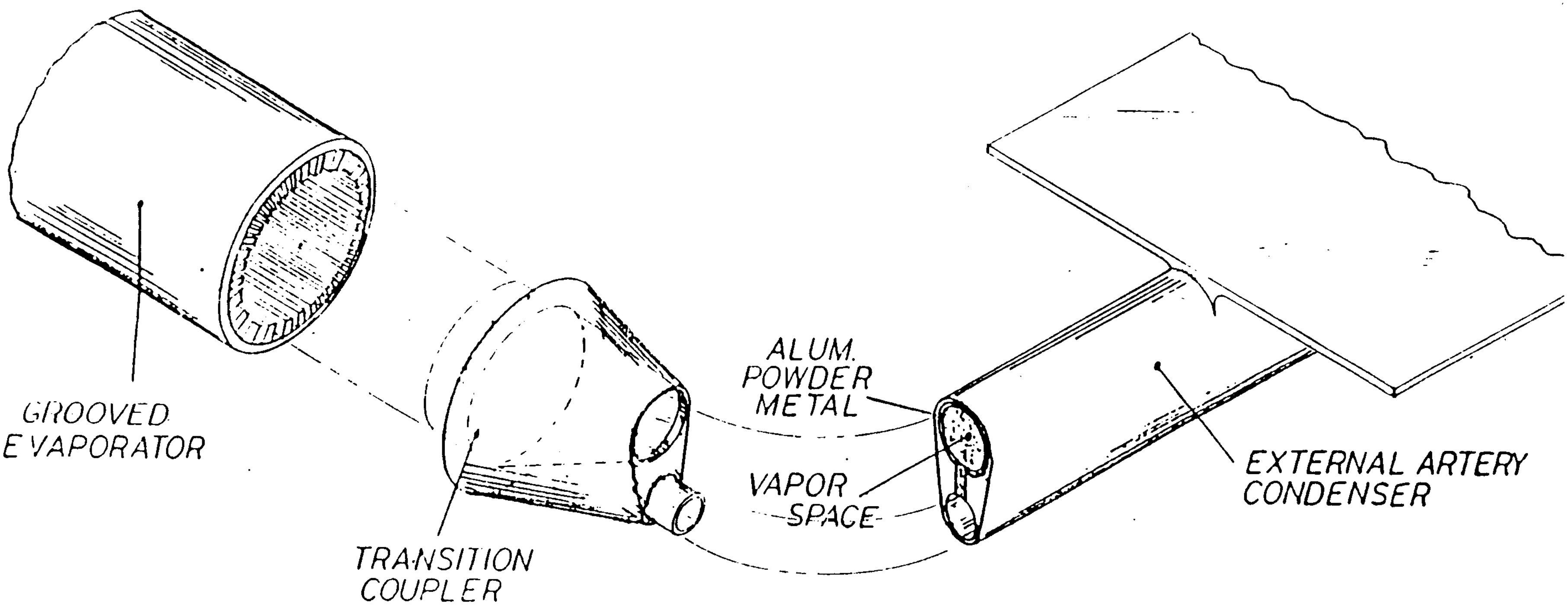


FIGURE 4. AXIAL GROOVE EVAPORATOR/EXTERNAL ARTERY CONDENSER HEAT PIPE RADIATOR FOR SPACE APPLICATIONS.

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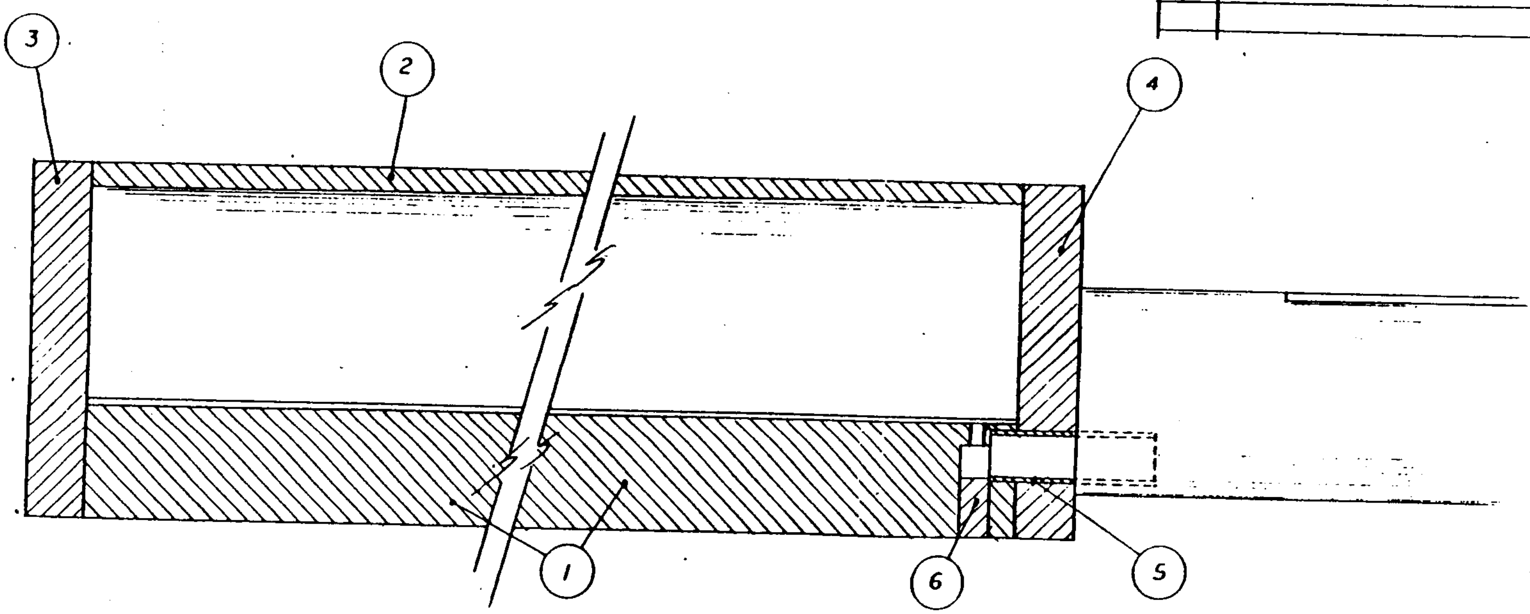
NO	DESCRIPTION	DWG. NO.
1	CONDENSER PLATE	B-269-4
2	CONDENSER SHELL	B-269-7
3	CONDENSER END CAP	A-269-5
4	TRANSITION END CAP	A-269-6
5	TRANSITION TUBE	A-269-9
6	RETURN PLUG	A-269-8



UNLESS OTHERWISE SPECIFIED
DIMENSIONS ARE IN INCHES
TOLERANCES
DECIMALS ANGULAR
.XX ± .015 ± 0°30'
.XXX ± .005
DO NOT SCALE DRAWING

TREATMENT —
FINISH —
SIMILAR TO — ACT. WT. — CALC. WT. —

CONTRACT NO.
DRAWN EHD DATE 12-23-85
CHECK
APPROVED B SL.E 12-24-85
APPROVED
CUSTOMER

THERMACORE, INC.
HEAT TRANSFER SPECIALISTS

TITLE EVAPORATOR
CONDENSER ASSEMBLY

SIZE B
DWG. NO. B-269-10
SCALE —
RELEASE DATE
SHEET 1 of 1

REVISIONS			
LTR.	DESCRIPTION	DATE	APPROVED

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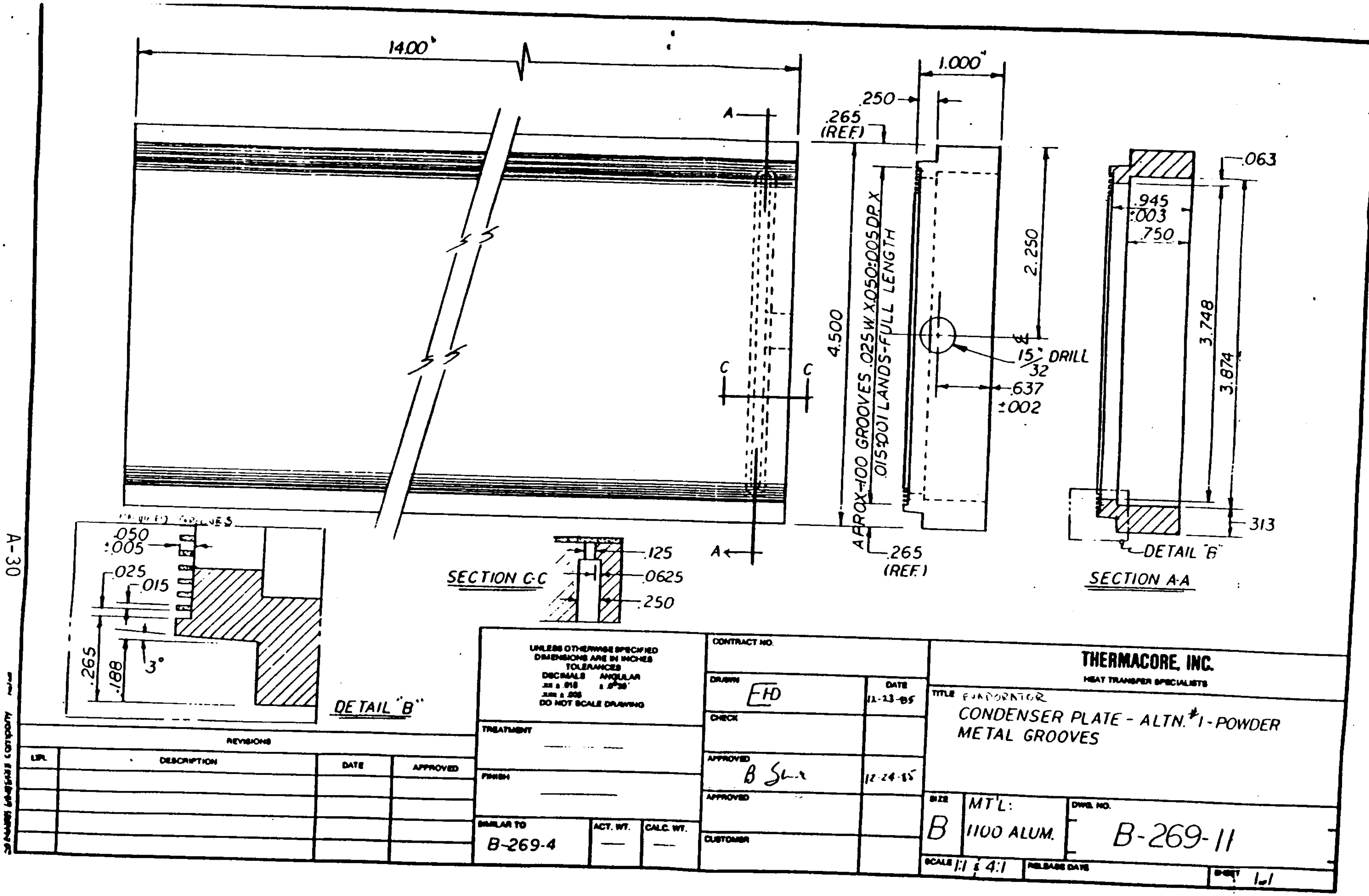


Rec'd 2-20-86
FEV

THERMACORE, INC.

HEAT TRANSFER SPECIALISTS / ENGINEERING – MANUFACTURING

780 EDEN ROAD / LANCASTER, PENNSYLVANIA 17601 / 717-569-6551

In reply refer to Let269.3-86

February 17, 1986

Mr. Fred Voss, E-53
LTV Aerospace and Defense Co.
P. O. Box 65003
Dallas, TX 75265-003

Dear Mr. Voss:

Enclosed please find a test procedure document and a sketch of the test set-up used by Thermacore for testing the four (4) foot heat pipe described in a previous letter (LET269.2-86). As mentioned in the preceeding letter, receipt of this document completes Thermacore's obligation on LTV's Purchase Order No. 803864.

If you have any questions concerning either the document or the sketch or need additional information, please feel free to call me.

Sincerely,

Michael D. Keddy

Michael D. Keddy
Engineer

MDK/mln
Enclosure

Enclosure 1
February 14, 1986

TEST PROCEDURE

Four Foot Axial Groove/External Artery Heat Pipe

PURPOSE:

This procedure documents the steps used to test the four (4) foot heat pipe designed and built for LTV under Purchase Order No. 803864.

DESCRIPTION:

This test heat pipe is shown in the fabrication drawings enclosed in the preceeding letter LET269.2-86 dated February 7, 1986, and has the following characteristics:

- o Evaporator (14 inches long)
  - axial groove wick structure
  - 80 rectangular cross-section grooves (0.025 inch wide, .050" deep)
- o Adiabatic Section (18 inches long)
  - powder metal wick structure
  - Thermacore's external artery configuration
  - 0.850 inch diameter vapor space
  - 7/16 inch diameter liquid space
- o Condenser (16 inches long)
  - same wick structure and configuration as the adiabatic section

APPARATUS:

The testing of this heat pipe utilized the equipment shown in Figure 1 and listed below:

- single pass water calorimeter clamped to the condenser of the heat pipe.
- pump or water tap capable of 0 to 8 gpm.
- 1/2 inch diameter copper water lines to and from the condenser calorimeter.
- ice bath for cooling incoming water to around $0^{o}C$.
- scissors jack for raising and lowering the condenser end of the heat pipe about $\pm$ 3 cm.
- dial indicator for measuring static lift height.
- copper heater block and electrical resistance heaters for applying heat loads to the evaporator. Maximum total heat load $\sim$ 2000 watts.
- Type K thermocouples for measuring heat pipe temperatures and water inlet and outlet temperatures.

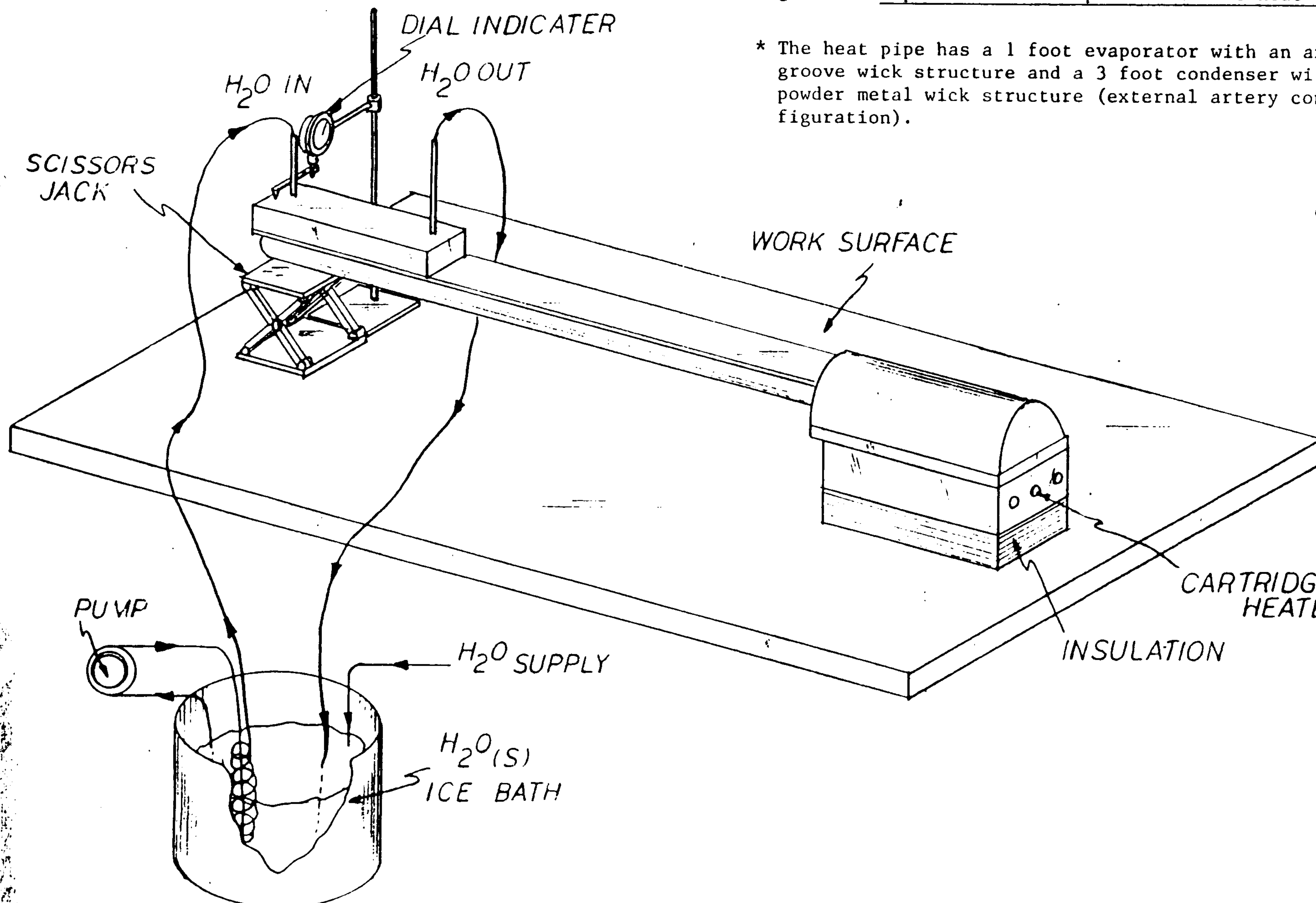
PROCEDURE:

The procedure used for testing this heat pipe is as follows.

1) Set up the heat pipe and instrumentation as shown in Figure 1.
2) With a slight gravity advantage (i.e., condenser higher than evaporator) and with cold water flowing through the calorimeter operate the pipe for a series of minutes at a power of about 100 watts until the pipe is isothermal.

Figure 1. Experimental Set-up for a 4 Foot Heat Pipe.

* The heat pipe has a 1 foot evaporator with an axial groove wick structure and a 3 foot condenser with a powder metal wick structure (external artery configuration).



3) Adjust the flow of water through the calorimeter until the heat pipe is maintaining a constant operating temperature. ($\pm$ 0.2^{o}C change in temperature over five minutes is practical).

4) Take readings of heat pipe temperature profile, temperatures of water in and water out of the calorimeter, volumetric flowrate of the water through the calorimeter, and heat input to the evaporator.

5) Lower the condenser end of the heat pipe by about 0.025 inch. The temperature in the evaporator will rise a few degrees and then begin to fall. Once the pipe has reached equilibrium repeat the measurements in step (4).

6) Repeat step (5) lowering the condenser by ~ 0.025 inch increments. Dryout of the evaporator is reached when the temperature at the furthest end of the evaporator rises but does not fall after a period of five to ten minutes.

7) Once dryout is reached raise the condenser and repeat steps 2 through 6 for successfully higher powers.

It is important to note that axial groove wick structures are sensitive to gravitational effects. They deprime very easy when in operation against gravity. Care must be taken to ensure that the pipe isn't subjected to vibrations or jolting while under test. When the pipe is operating near its static lift height limit, the condenser should be lowered by a series of small increments (~.010 inch). The pipe should be allowed to come to equilibrium, and the condenser lowered again until the point is reached at which data is to be collected. A plot of test data and predicted performance for this heat pipe is included as Figure 2. This will aid the tester in knowing when he or she is near the operating limit for the pipe.

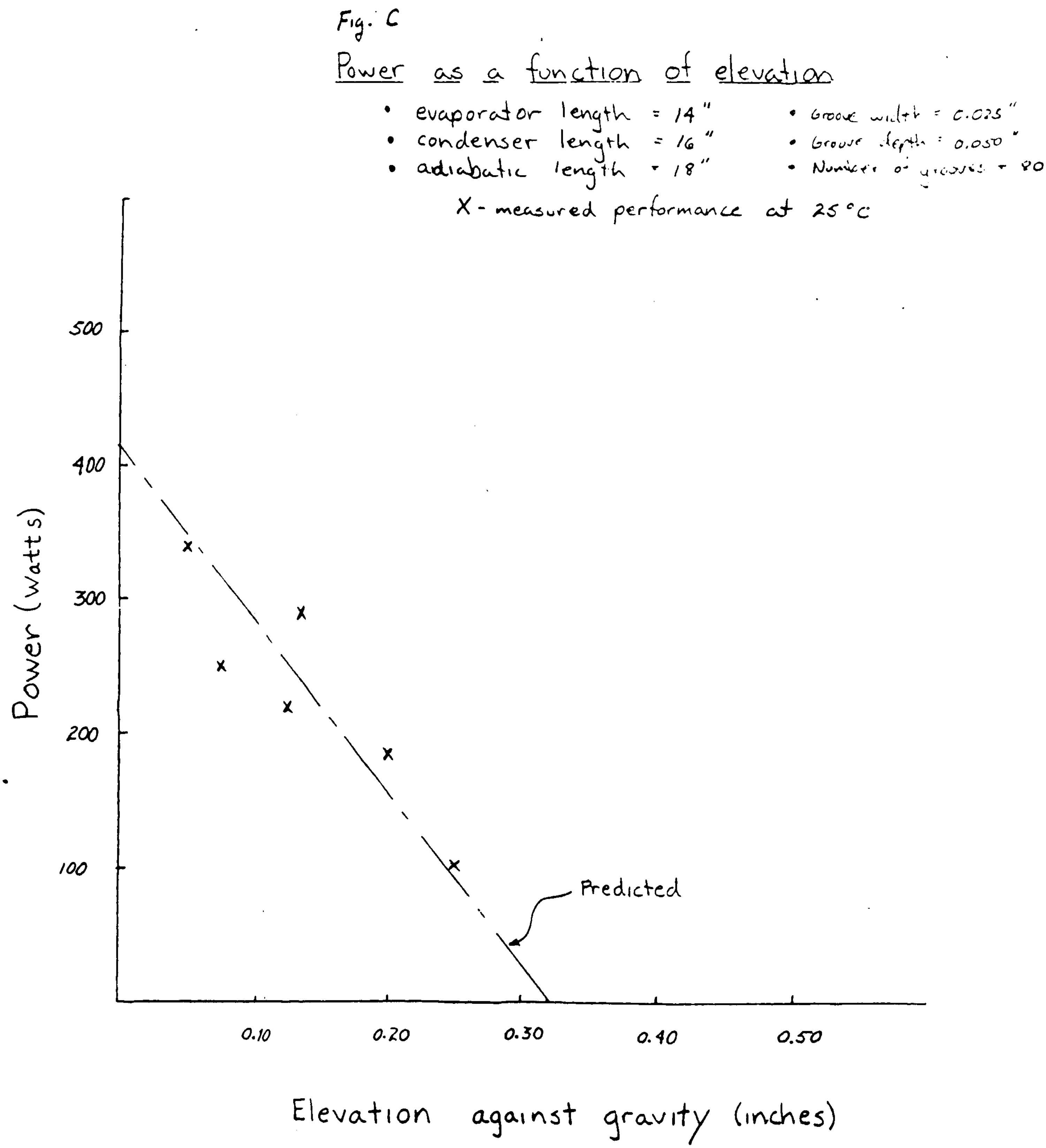


Fig. C
Power as a function of elevation
• evaporator length = 14"
• condenser length = 16"
• adiabatic length = 18"
• Groove width = 0.025"
• Groove depth = 0.050"
• Number of grooves = 80
X - measured performance at 25 °C
Power (watts)
500
400
300
200
100
Predicted
0.10
0.20
0.30
0.40
0.50
Elevation against gravity (inches)

Figure 2

THERMACORE, INC.

HEAT TRANSFER SPECIALISTS / ENGINEERING – MANUFACTURING

780 EDEN ROAD / LANCASTER, PENNSYLVANIA 17601 / 717-569-6551

In reply refer to let269.4-86

March 6, 1986

Mr. Fred Voss, EM 53 - 69460
LTV Aerospace and Defense Co.
P. O. Box 650003
Dallas, TX 75265-0003

Dear Mr. Voss:

Enclosed is the data you requested in our phone conversation on March 4, 1986. This data was collected in January, 1986, during the testing of the aluminum/ammonia heat pipe developed by Thermacore for LTV under P.O. #803864.

If you have any questions or need additional information, please feel free to call me.

Sincerely,

Michael D. Keddy

MDK/sle

Enclosures

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PROJECT 269 LTV

Notebook No. 1

Continued From Page

			ml/sec.	watts		T.C.		
Qin	Tin	Tout	Flow	Qout	ΔH ('')	13	14	15
300	4.5	12.0	100/14	225	-0.1	26.8	28.9	31.5
300	4.3	9.1	375/30	253	-0.1	23.8	25.8	27.6
300	5.3	9.8	375/30	236	-0.05	22.4	23.8	25.1
300	5.1	~~9.7~~ 9.9	375/30	252	-0.05	24.0	25.5	26.0
300	6.0	10.1	375/30	215	-0.075	24.6	26.3	28.0
300	6.0	10.7	375/30	247	-0.075	25.2	27.4	29.6
300	6.0	10.3	375/30	226	-0.100	25.3	27.4	29.6
300	6.0	10.6	375/30	242	-0.100	25.5	27.5	29.6
250	6.8	12.7	100/10	248	-0.05	25.8	27.2	28.8
250	6.4	12.0	100/10	235	-0.05	25.4	26.9	28.3
250	2.3	8.5	100/10	260	-0.075	24.2	25.8	27.8
250	2.9	10.2	100/14	219	-0.075	23.9	25.5	26.9
250	3.1	10.5	100/15	207	-0.075	24.3	25.7	27.0
250	3.6	10.9	100/15	204	-0.10	24.6	26.2	28.0
250	4.1	11.9	100/15	218	-.125	25.9	27.5	29.4
150	4.1	9.9	100/15	162	-.150	19.6	20.7	21.6
150	4.4	12.0	100/39	110	-.150	19.9	20.8	21.4
150	3.9	~~12.0~~ 11.9	100/29	116	-.200	19.7	20.6	21.4
150	4.1	12.5	100/29	122	-.225	19.6	20.6	21.7
150	4.3	11.4	100/29	103	-.250	19.9	20.8	21.6
150	4.2	11.5	100/29	106	-.250	19.9	21.0	22.0
150	4.7	12.6	100/29	114	-.275	20.1	21.4	22.6
75	6.2	14.7	100/55	65	-.250	19.0	20.2	20.9
200	3.3	11.1	100/15	218	-.10	24.1	25.3	26.7
200	4.0	11.1	100/15	199	-.10	22.8	24.0	25.2
200	4.0	10.0	100/15	168	-.15	21.6	23.1	24.4
200	4.2	11.2	100/15	196	-.175	21.2	22.2	23.7
200	4.0	10.7	100/15	188	-.20	21.1	22.4	23.8
200	4.1	10.1	100/15	~~[illegible]~~ 168	-.225	20.8	22.1	23.6

Continued on Page

Read and Understood By

Signed ____ Date ____ Signed ____ Date ____

PROJECT

Notebook No. 3

Continued From Page

Comments: Continuation of tests for LTV 26?
heatpipe.

Grooved evap.
external artery condens.

Qin	Tin	Tout	Flow (ml/sec)	Qout (watts)	ΔH	13 (Thermocouples)	14	15
300	5.7	8.8	1000/42	310	-0.[illegible]	23.2	24.9	26.6
300	5.9	8.6	1000/43	264	-0.030	23.0	24.6	26.0
300	5.6	8.6	1000/43	293	-.040	22.9	24.5	25.9
300	5.6	8.6	1000/43	293	-.085	22.8	24.6	26.1
300	5.6	8.6	1000/43	293	-.110	23.0	24.8	26.6
300	5.6	8.6	1000/43	29.3	-.135	22.9	24.8	26.6

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On 3/5 1986
the heatpipe was
readied for shipping
to LTV
wet wt. = 7620 gm
dry wt. = 7520 gm
NH_3 wt. = 100 gm

3/5/86 MK

Continued on Page

Read and Understood By

Signed: David G. Saaf Date: 2/4/86

Signed: Date:

Notebook No. 4

PROJECT

Continued From Page

16	17	18	19	20	3	4	5	6	Time
20.8	20.5	20.1	18.6	16.0	20.9	21.2	21.3	21.5	16:55
20.8	20.4	20.0	~~18.5~~	15.9 ~~15.5~~	20.8	21.0	21.1	21.2	17:15
20.7	20.3	20.0	18.4	15.8	20.7	20.8	20.9	21.0	17:25
20.5	20.2	19.8	18.2	15.6	20.6	21.0	21.2	21.4	17:30
20.4	20.1	19.8	18.3	15.8	20.7	21.3	21.5	21.6	17:40
20.2	19.9	19.6	18.0	15.6	20.6	22.2	22.6	23.1	17:55

FINAL SETUP, PICTURED AT LEFT, CONSISTS OF:

H.P. ON ALUMINUM I-BEAM. HINGED 1 END, JACK AT OTHER. VARIAC & WATTMETER TO 3 - 240V 1500W HEATERS IN CU BLOCK. SPACER, AL, 1/8" TK BETWEEN BLOCK & H.P., HAD Tc GROOVES IN IT. EVAPORATOR HAD Tc HOLES 1/2 - 3/4" DP IN SIDES. LEVEL, DIAL IND. FOR Δh. CALORIMETER FASTENED USING BOLTS, BLUE RTV, BACKUP STRIPS. 1/2" INLET, OUTLET.

WATER SOURCE: OVER 400W - PUMP UNDER 400W - TAP WATER THRU 1/2" ⌀ CU COIL IN ICEBATH - 12" ⌀ 12" HIGH.

CHANGES IN FUTURE: PUT JACK AT OPP. END. - LESS WEIGHT INCREASING Δh WOULD LOWER JACK, IT WOULD MOVE SMOOTHER.

MILL CU BLOCK SMALLER (THINNER) FOR FASTER RESPONSE TO A CHANGE IN Q IN.

Continued on Page

Read and Understood By

David B. Sarraf 2/4/86

Signed Date Signed Date

APPENDIX B

HIGH CAPACITY HEAT PIPE PORTION

PROGRAM REVIEW

23 AUGUST 1985

HIGH CAPACITY HEAT PIPE

AND THERMAL SYSTEM INTERFACE HEAT EXCHANGERS

PROGRAM REVIEW

NAS9 - 17327

23 AUGUST 1985

HIGH CAPACITY HEAT PIPE

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OBJECTIVES OF THIS CONTRACT TASK

The overall objective of the High Capacity Heat Pipe Task, Task 1.0, is to evolve and demonstrate the feasibility of a heat pipe design which would ultimately meet the requirements of being lightweight, having no restrictions on circumferential heat addition/removal, have a 2 kW design goal and be self-priming in 0-G, with priming demonstration in 1-G. The heat pipe selection and demonstration will be accomplished by concept studies and element and breadboard testing. Deliverable items at contract end are two, 4 - 5 foot breadboard test articles and a 25 foot pre-prototype article of the final selected design. If determined to be feasible/beneficial to the program 0-G visualization elements for testing on board a KC 135 will also be delivered.

OBJECTIVES OF THIS CONTRACT TASK

- DEVELOPMENT OF AN ALTERNATE TECHNOLOGY HIGH CAPACITY HEAT PIPE
  - LIGHTWEIGHT
  - CIRCULAR IN CROSS SECTION / UNRESTRICTED HEAT ADDITION
  - 2 kW DESIGN GOAL
  - SELF PRIMING IN 0-G, WITH 1-G DEMONSTRATION
- ACCOMPLISHED BY
  - CONCEPT STUDIES
  - ELEMENT AND BREADBOARD TESTS
- DELIVERING AT CONTRACT END
  - 2 - 4' TEST ARTICLES
  - 0-G VISUALIZATION ELEMENTS
  - 25' PRE-PROTOTYPE ARTICLE

HIGH CAPACITY HEAT PIPE TECHNOLOGY DEVELOPMENT PROGRAM SCHEDULE

The program schedule for the High Capacity Heat Pipe Alternate Technology Development is shown. This program task consists of three subtasks:

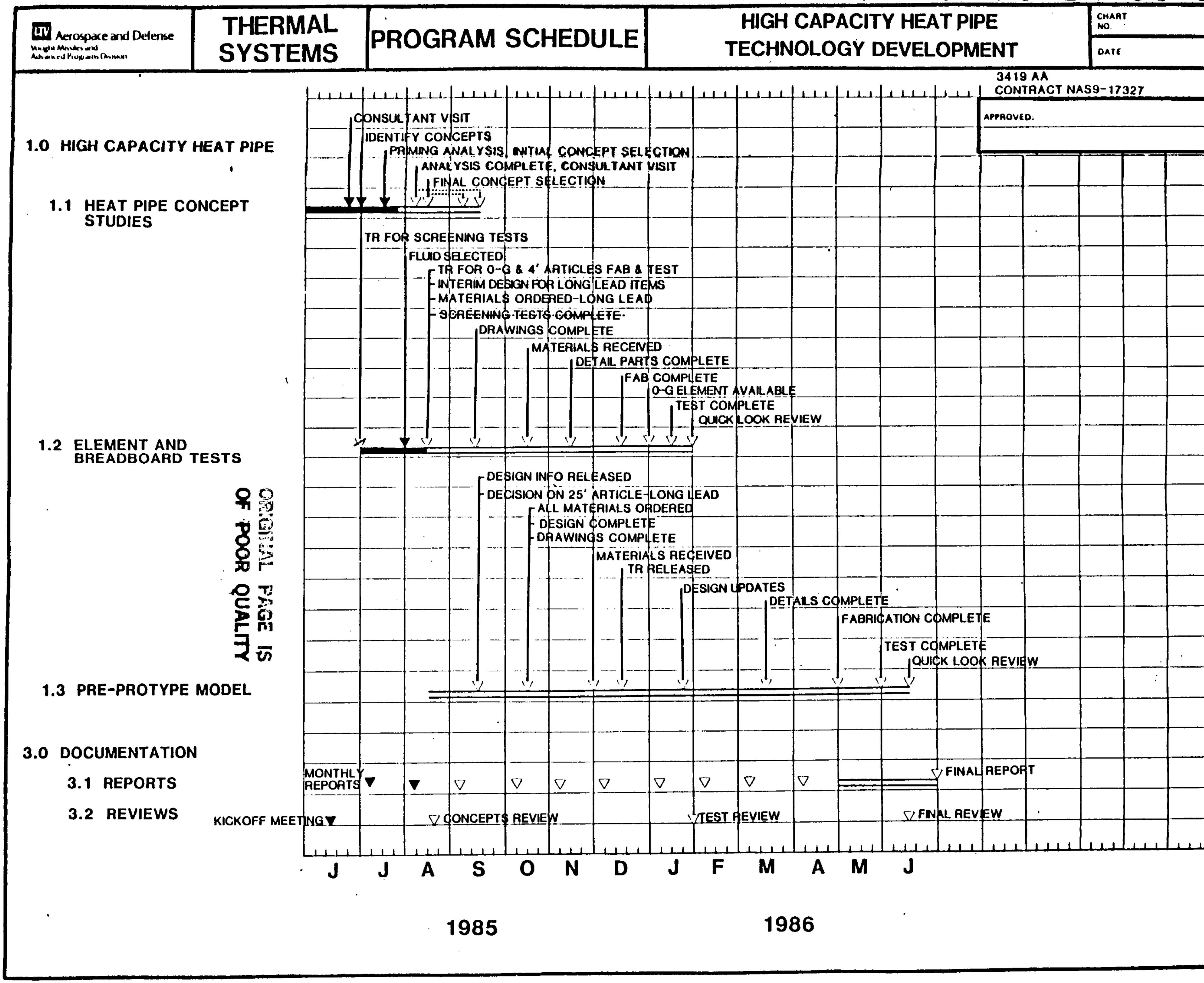
(1) Heat Pipe Concept Studies

(2) Element and Breadboard Tests

(3) 25-Foot Pre-Prototype Model Buildup and Testing

This program is a 13 month study.

The Program Schedule reflects the current status of the tasks. Task 1.1, Concept Studies, is approximately 3 weeks behind schedule due to completion and problems with the testing of the LTV Capillary Pumped Heat Pipe. Task 1.2, Element and Breadboard Testing, is on schedule. Testing of the LTV Capillary Pumped Heat Pipe has been completed. The LTV Capillary Pumped Heat Pipe was initially begun with LTV IR&D funds but was taken over by this contract once it was begun. Task 1.3, Development of the 25-Foot Pre-Prototype Model, has not yet been started.



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HEAT PIPE TEST RESULTS

The LTV Capillary Pumped Heat Pipe was developed under company IR&D funds. Upon contract award, testing of this pipe was taken over by the contract and completed.

The testing performed included: (1) the cat's eye condenser being oriented both vertically and horizontally, (2) the pipe's inclination being horizontal and at an adverse tilt, (3) both fixed and variable ammonia charge amounts, and (4) the heat pipe was configured to allow bypass operation; i.e., the condenser and evaporator ends were connected via external tubing.

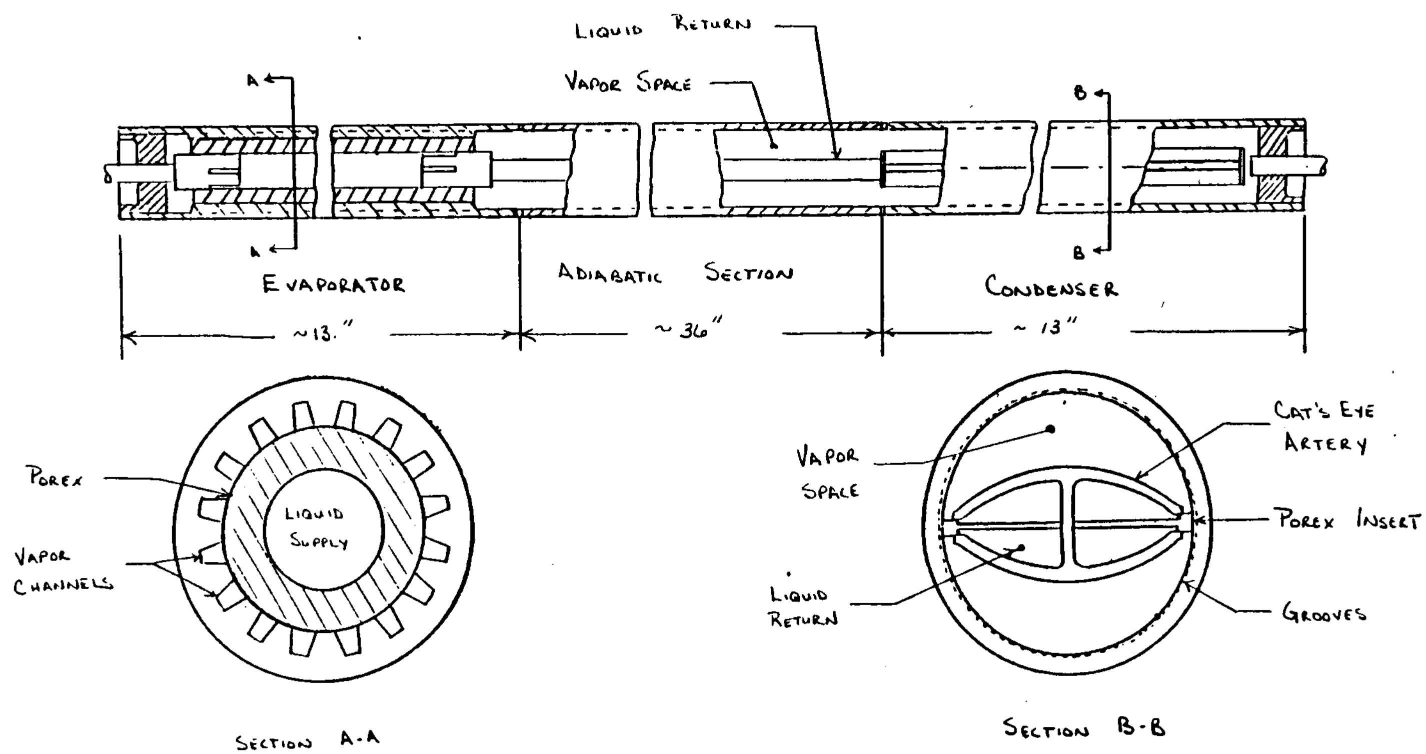
HEAT PIPE TEST RESULTS

- LTV CAPILLARY PUMPED HEAT PIPE
  - DEVELOPED UNDER IR&D FUNDS
  - TESTING COMPLETED UNDER CONTRACT
- TESTING PERFORMED
  - CAT'S EYE POSITION - HORIZONTAL, VERTICAL
  - PIPE INCLINATION - HORIZONTAL, ADVERSE TILT
  - CHARGE - FIXED, VARIABLE
  - BYPASS OPERATION

CAPILLARY PUMPED HEAT PIPE

This chart shows the LTV Capillary Pumped Heat Pipe configuration. The evaporator is capillary pumped using Porex, a high density, small pore size (20μ) polyethylene material as the wicking medium. The condenser is constructed of a cat's eye artery with Porex inserts. The Porex in the condenser is to provide a good interface with the condenser wall grooves and to facilitate artery filling. The condenser and evaporator liquid flow are connected via the adiabatic liquid return line. Liquid is wicked to the evaporator and supplied to the evaporating surfaces. Vapor flows through the longitudinal vapor channels into the adiabatic section and then into the condenser where it condenses in the wall grooves which then wick the liquid to the artery interface.

LTV CAPILLARY PUMPED HEAT PIPE



TYPICAL TEST RESULTS

This chart shows typical test results obtained during heat pipe testing. The cat's eye artery in the condenser was tested in both a horizontal and vertical position. The maximum heat load supported for either orientation was 330W.

TYPICAL TEST RESULTS

PIPE CONFIGURATION [1] INCLINATION	ARTERY - HORIZONTAL HEAT LOAD	VERTICAL HEAT LOAD
HORIZONTAL	330W	330
$0^{o}15'$ ADVERSE TILT	290W	285
$0^{o}30'$ ADVERSE TILT	232W	245
$0^{o}45'$ ADVERSE TILT	114W	--- [2]
$1^{o}0'$ ADVERSE TILT	66W	---
$1^{o}15'$ ADVERSE TILT	24W	---

1 BY-PASS LINE OPEN, CHARGE BOTTLE AS RESERVOIR

2 DRY OUT - DID NOT RECOVER

CONCLUSIONS

From both testing performed at LTV and analysis performed by Thermacore, it was concluded that:

(1) The heat pipe was not primed.

(2) Fluid return from the condenser to the evaporator is by puddle flow along the bottom of the heat pipe.

(3) Puddle flow limits the heat load the heat pipe can support in several ways:

   a. evaporator vapor transport is reduced by fluid blocking the evaporator vapor grooves

   b. available condensing surface area is reduced

   c. the 20 micron Porex permeability is low and so limits the liquid supply to the evaporating surface.

(4) The Porex inserts in the cat's eye artery do not insure condenser priming.

(5) A method that ensures complete artery priming must be found for dependable heat pipe operation.

(6) If the artery prime is ever lost, the shape of the cat's eye will prevent self/re-priming of the artery; even in 0-g.

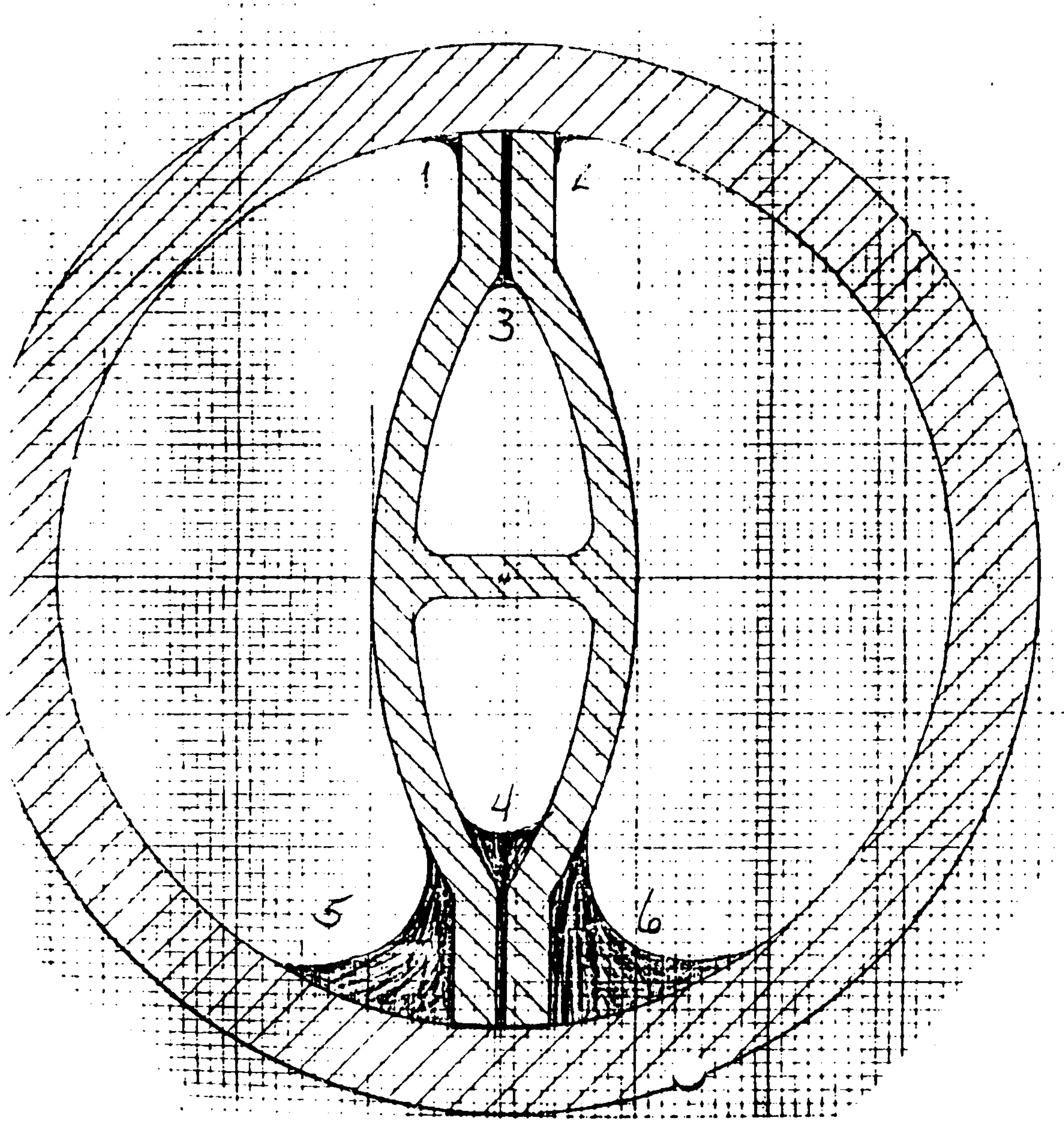
CONCLUSIONS

- O PIPE IS NOT PRIMED
- O FLUID RETURN FROM CONDENSER TO EVAPORATOR IS BY PUDDLE FLOW
  - o HEAT LOAD IS LIMITED
    - EVAPORATOR VAPOR TRANSPORT IS REDUCED BY FLUID BLOCKED VAPOR GROOVES
    - CONDENSER SURFACE IS REDUCED
    - POREX PERMEABILITY IS LOW AND LIMITS LIQUID SUPPLY
- O POREX INSERTS ALONE DO NOT INSURE PRIMING
- O ANALYSIS INDICATES THAT A MEANS OF COMPLETE ARTERY PRIMING MUST BE DEVELOPED TO ENSURE H.P. OPERATION
- O IF PRIME IS EVER LOST, ARTERY CONFIGURATION PREVENTS SELF PRIMING

FILLING OF THE CAT'S EYE ARTERY

This chart shows how the cat's eye artery is believed to fill in 1-G tests. Note that radii 4, 5 and 6 are similar in size and that the radius of 4 would tend to get larger the higher the liquid level rises. Once the radii become equal in size there will be no further tendency for the interior of the artery to fill.

FILLING OF THE CAT'S EYE ARTERY



46

DEVELOPMENT/FUTURE TESTING

This chart shows the recommendations as how to proceed with the contract's heat pipe task. Heat pipe analysis should be continued. Priming/visualization testing should be considered to help verify analysis. Once promising concepts are identified heat pipe elements will be built and tested.

DEVELOPMENT/FUTURE TESTING

0 CONTINUED HEAT PIPE ANALYSIS

0 PRIMING/VISUALIZATION TESTING

0 3' - 4' HEAT PIPE ELEMENTS

VISUALIZATION PRIMING TEST

If a visual priming test is deemed beneficial the test fluid used will be ethanol. Ethanol has similar properties to ammonia and is currently used at LTV when determining the capillary pressure of the wick. Ethanol can be used under ambient lab conditions with no special precautions or difficulties as long as ignition sources are kept from the area. It is also compatible with the available Lexan flanges which are to be used for the test.

The visualization test is expected to provide insight into the self-priming characteristics of the proposed artery designs. Because the proposed test element is small/compact it can also be used for zero-g element testing in a KC 135. Multiple elements can be constructed/tested.

VISUALIZATION PRIMING TEST

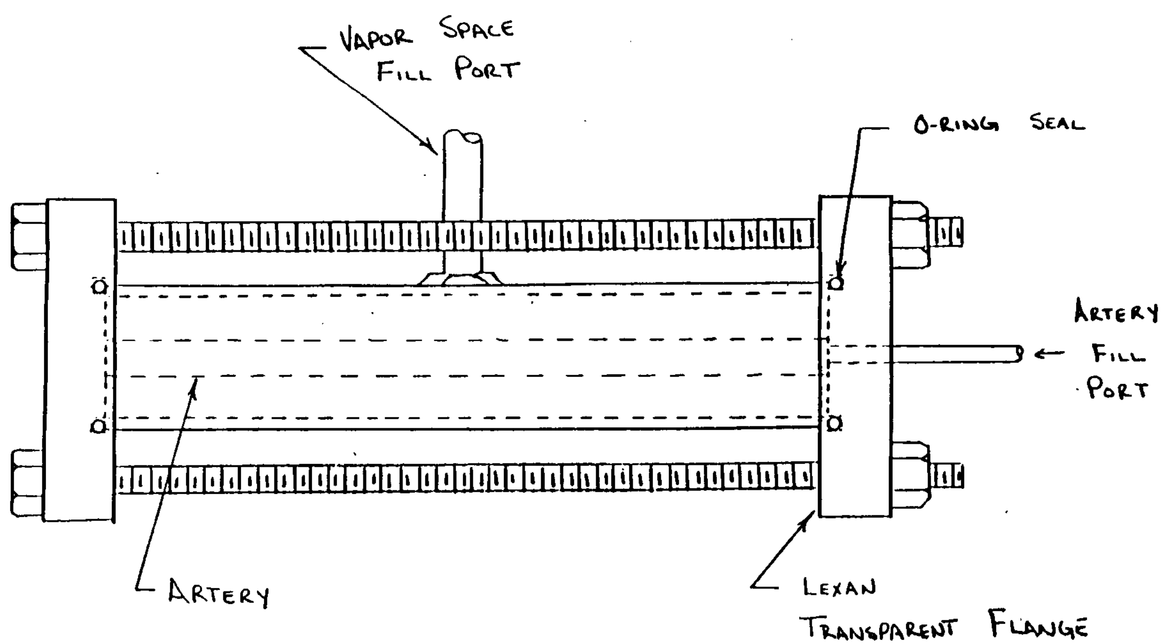
- O TEST FLUID WILL BE ETHANOL
  - o SIMILAR PROPERTIES TO AMMONIA
  - o CURRENTLY USED IN CAPILLARY PRESSURE DETERMINATION
  - o AMBIENT LAB CONDITIONS - NO SPECIAL PRECAUTION OR DIFFICULTIES
  - o COMPATIBLE WITH LEXAN TRANSPARENT FLANGES
- O WILL PROVIDE INSIGHT INTO SELF-PRIMING CHARACTERISTICS OF ARTERIES
- O CAN BE USED FOR ZERO-G ELEMENTS
- O MULTIPLE ELEMENTS CAN BE CONSTRUCTED/TESTED

PRIMING VISUALIZATION TEST ARTICLE

This chart shows the proposed visualization test article. This test article will be used if a priming test appears to be beneficial. This test article allows for filling through either the vapor space or the artery. The Lexan flanges provide viewing to the interior of the heat pipe section.

Because this test article is small and compact it can also be used, once again if deemed beneficial to the program, as a 0-G flight article on a KC 135 0-G simulation flight.

PRIMING VISUALIZATION TEST ARTICLE



HEAT PIPE ELEMENTS

Additional conceptual heat pipe designs are being proposed for program continuation. Four concepts are proposed by LTV. Two concepts are proposed by Thermacore. These designs will be analyzed by both LTV and Thermacore. Performance predictions will be made for the designs.

HEAT PIPE ELEMENTS

- O CONFIGURATIONS
  - o 4 CONCEPTS PROPOSED BY LTV
  - o 2 CONCEPTS PROPOSED BY THERMACORE
- O ANALYSIS/PERFORMANCE PREDICTION OF CONFIGURATIONS
  - o LTV
  - o THERMACORE

CONCEPTUAL DESIGNS FOR THE HIGH CAPACITY HEAT PIPE

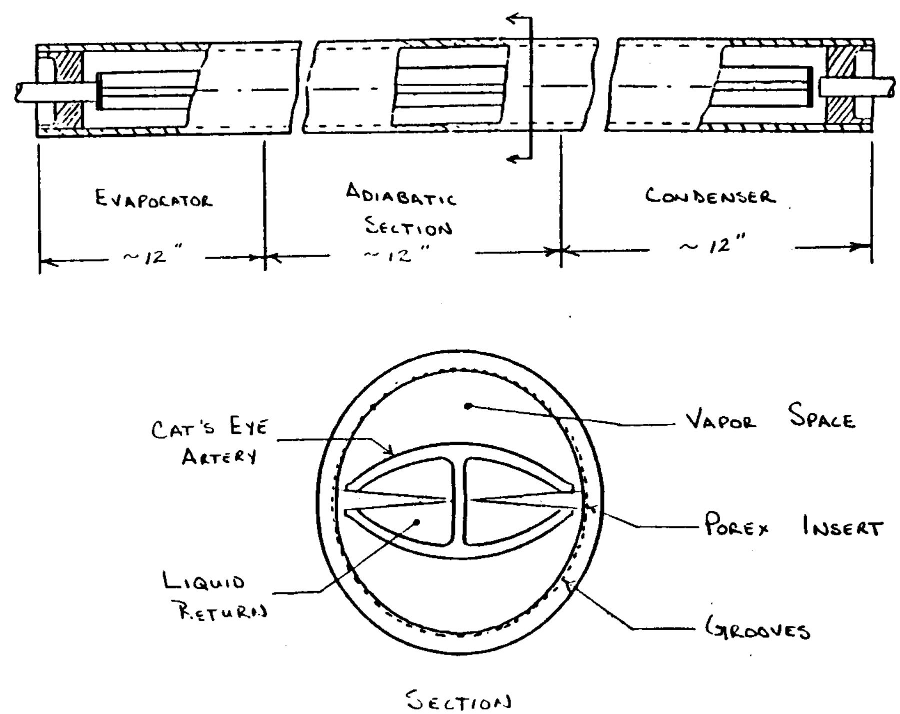
The following 6 charts present the conceptual designs proposed by LTV and Thermacore for further study. The four LTV designs are shown first.

CONCEPTIAL DESIGNS FOR THE
HIGH CAPACITY HEAT PIPE

MODIFIED CAT'S EYE ARTERY HEAT PIPE

This heat pipe design uses the cat's eye for the entire artery structure. The walls of the evaporator and condenser are grooved to aide fluid distribution and collection, respectively. A Porex wedge is inserted into the artery slot to enhance communication with the wall grooves. Fill tubes are provided into the condenser vapor space and directly into the evaporator end artery.

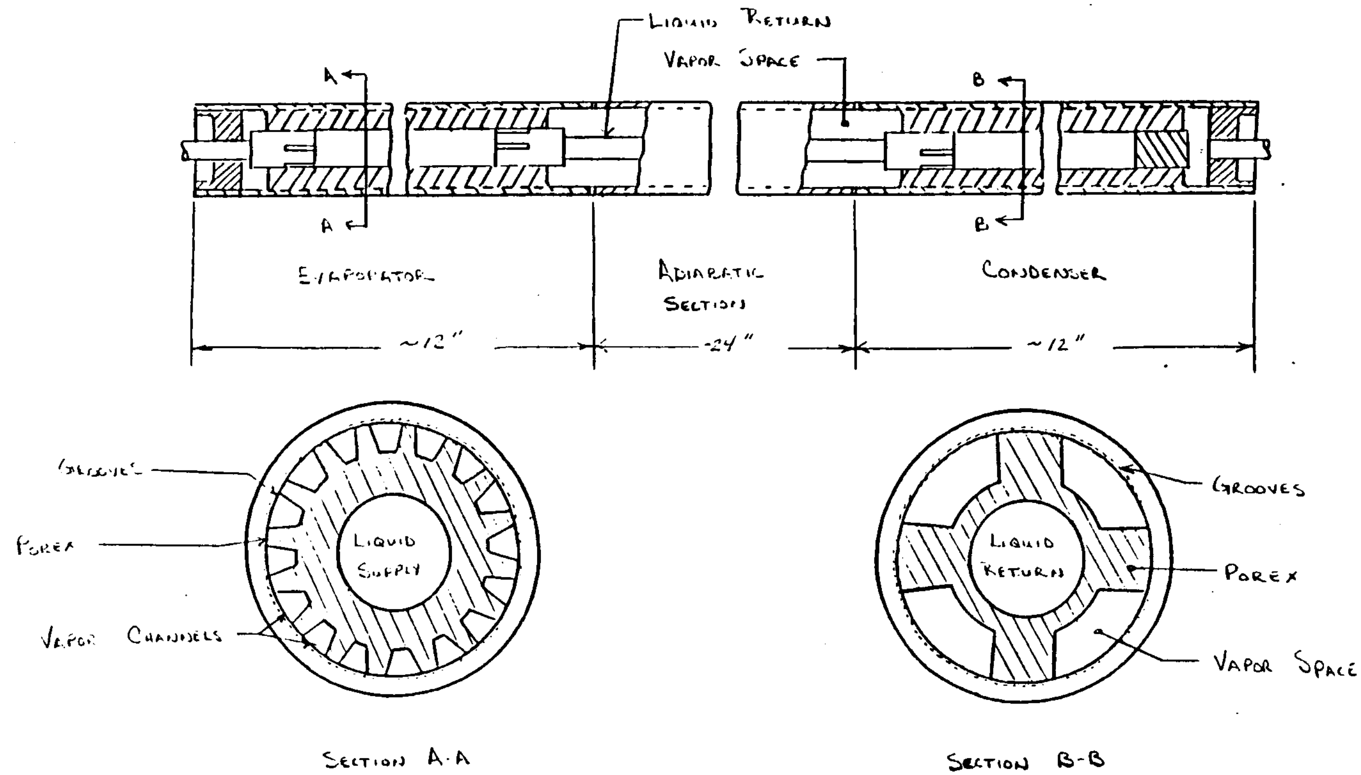
MODIFIED CAT'S EYE ARTERY HEAT PIPE



CAPILLARY PUMPED POROUS WICK ARTERY HEAT PIPE

This heat pipe uses a porous artery design in both the evaporator and the condenser ends. The walls of these areas are grooved. A tube connects the liquid channels of the evaporator and condenser sections through the adiabatic section of the pipe. In the evaporator, the Porex wick is spoked as opposed to the aluminum tube being slotted as with the previous LTV Capillary Pumped Heat Pipe design. This spoked wick design is expected to provide uniform liquid coverage to the evaporator grooves. The condenser artery is a pedestal design also constructed of Porex. Fill tubes are provided at both ends of the heat pipe. On the evaporator end the fill tube is connected directly to the liquid artery. On the condenser end the fill tube is connected to the vapor space.

CAPILLARY PUMPED POROUS WICK ARTERY HEAT PIPE



CAPILLARY PUMPED EXTERNAL ARTERY HEAT PIPE

This heat pipe is similar to the previously tested LTV Capillary Pumped Heat Pipe. The evaporator design has been modified and uses the spoked Porex configuration. This evaporator design is expected to be more efficient in that the evaporating surface is larger and closer to the outside of the pipe, the contact heat transfer surface. The condenser design uses the cat's eye artery. The major difference with this design is that the liquid return flow is external to the heat pipe. Flow in the heat pipe is one-way. Liquid flows into the evaporator liquid artery from the external artery. The liquid is wicked through the Porex to the evaporative surface, the evaporator grooves. The vapor flows from the vapor channels in the evaporator through the adiabatic section into the condenser. The vapor is condensed in the wall grooves from which it is wicked into the interior of the cat's eye, the condenser liquid artery. From the condenser liquid artery, the liquid flows out of the heat pipe through the external artery and then into the heat pipe's evaporator liquid artery.

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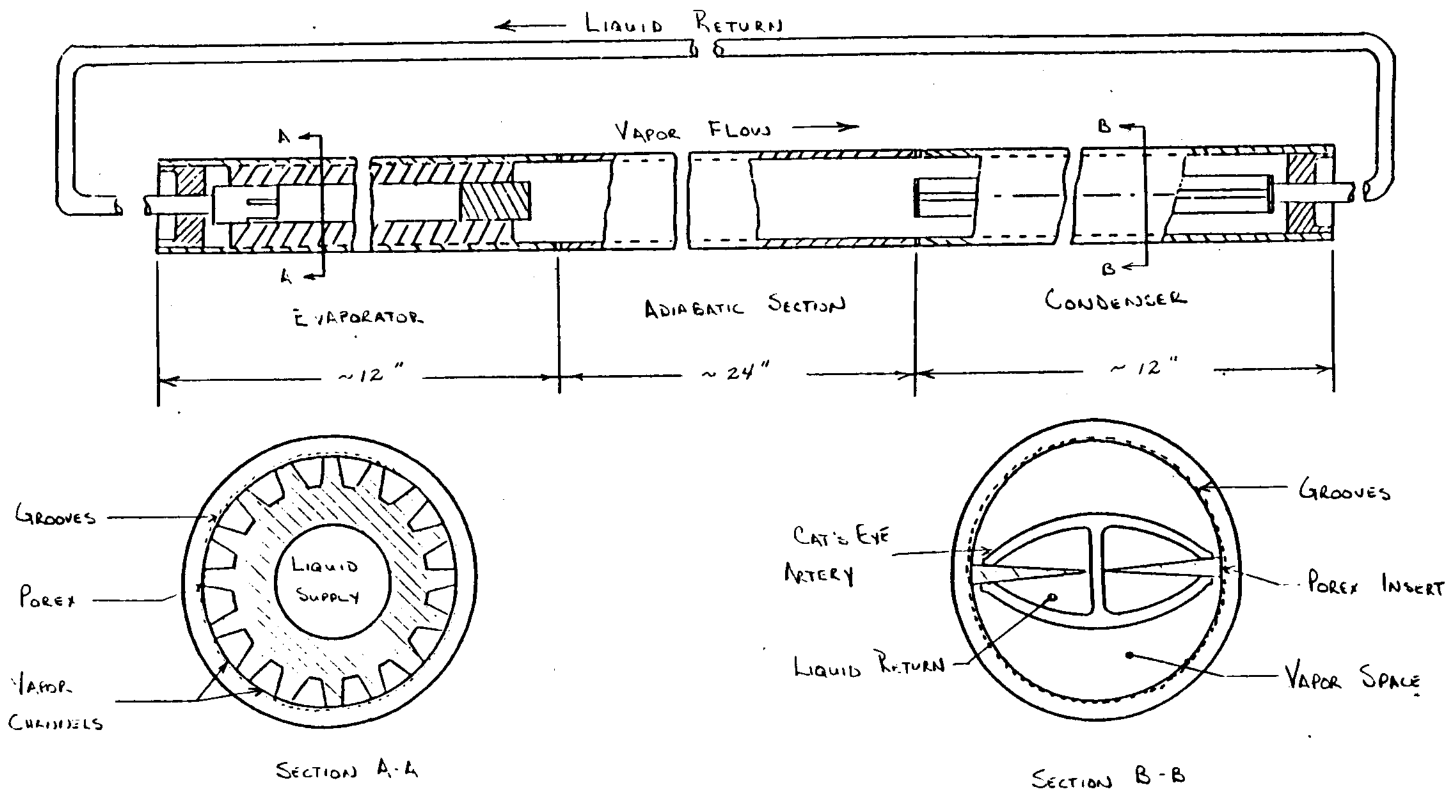
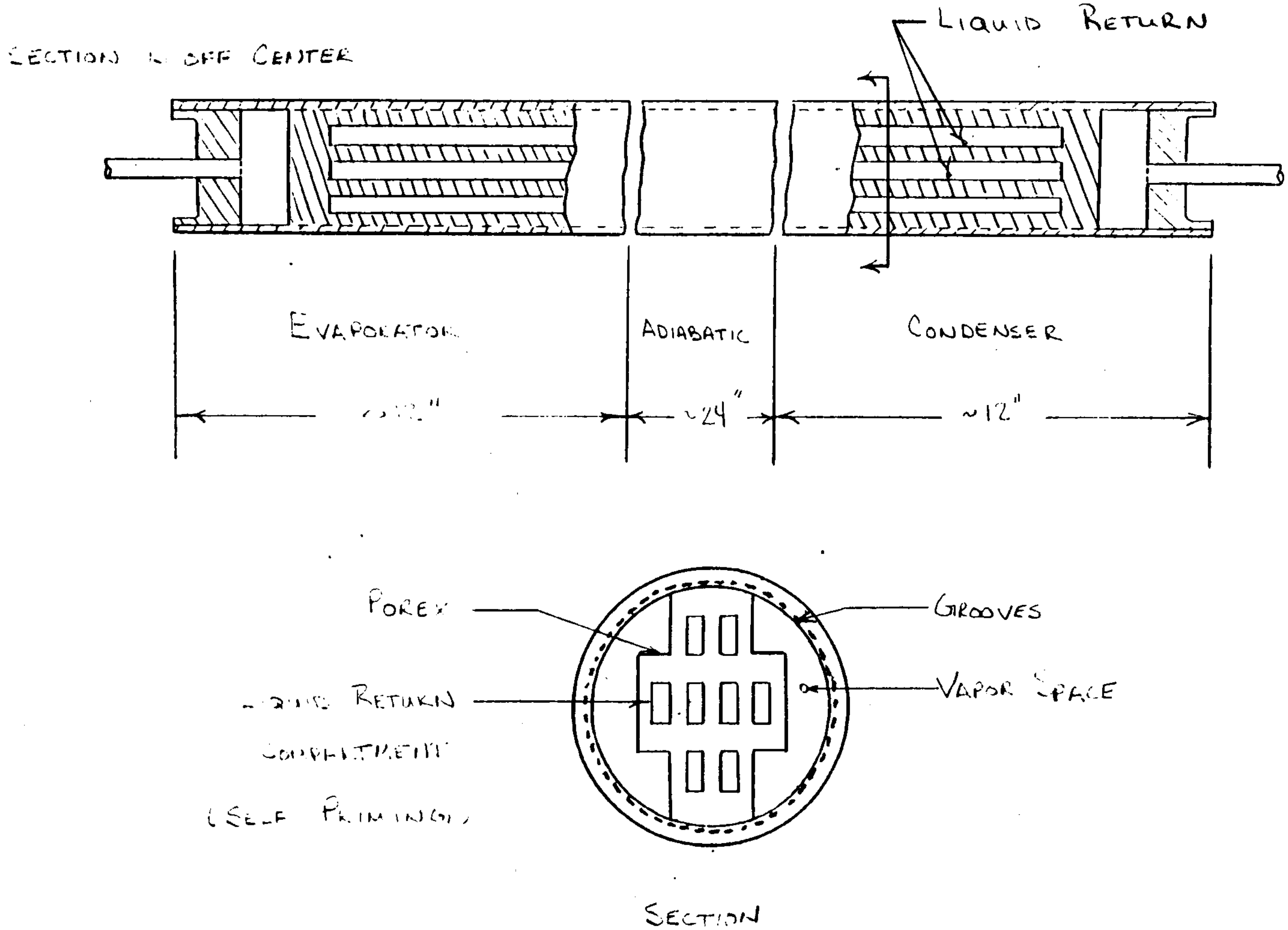
CAPILLARY PUMPED EXTERNAL ARTERY HEAT PIPE



POROUS ARTERY WITH SLOTS (PAWS) HEAT PIPE

This heat pipe is designed to be self-priming. The entire artery is constructed from Porex. Slots or holes are machined into the Porex wick or are grooved into layers of Porex which are then assembled into the desired configuration. The slots/holes are sized to be self-priming. The outer heat pipe tube is grooved to facilitate liquid distribution around the walls in the evaporator and liquid collection in the condenser.

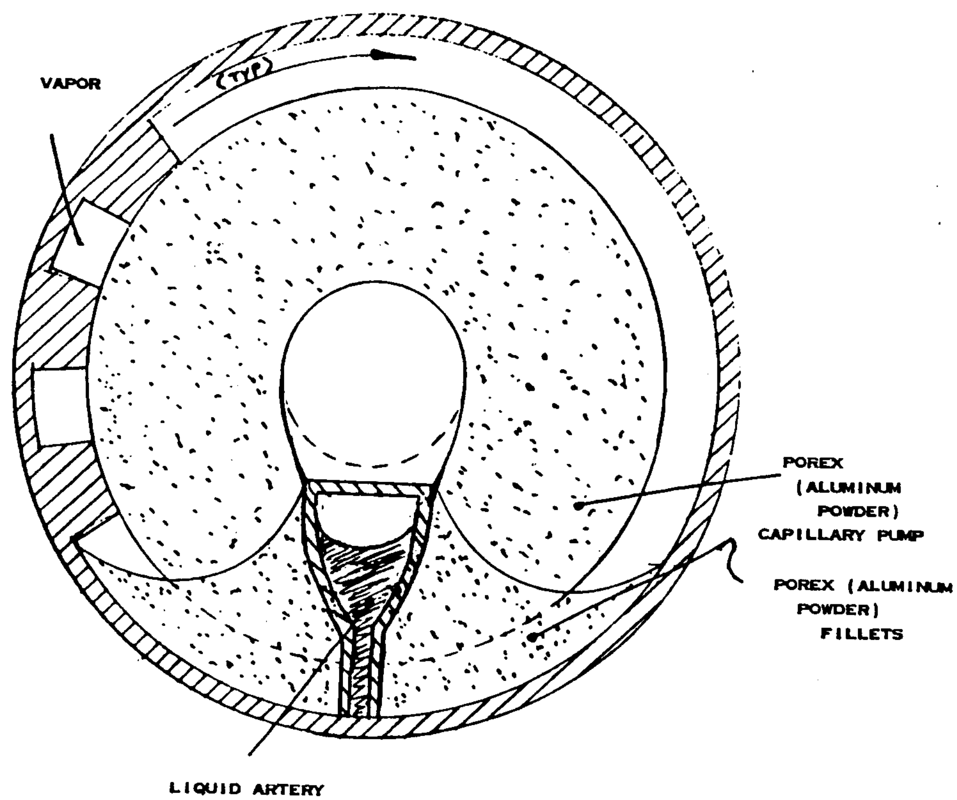
POROUS ARTERY WITH SLOTS HEAT PIPE



HIGH CAPACITY HEAT PIPE (GROUND TEST MODEL)

This heat pipe design was proposed by Thermacore as a ground test model for the LTV Capillary Pumped heat pipe. The view into the heat pipe is from the condenser end looking towards the evaporator. The condenser and adiabatic sections consist of a half cat's eye shaped liquid artery which is shorter than the standard cat's eye extrusion. Lowering the artery reduces the static heat losses that the artery has to prime and fill against. The Porex or Powdered Aluminum (sintered metal) fillets shown on either side of the liquid artery will help to force the artery to prime as they artificially keep these radii larger than the radius on the interior of the artery. They are of low permeability or solid material and will fill the space puddles might otherwise occupy as well as help ensure fluid return is via artery flow rather than puddle flow. The evaporator design is the same as the LTV Capillary Pumped heat pipe.

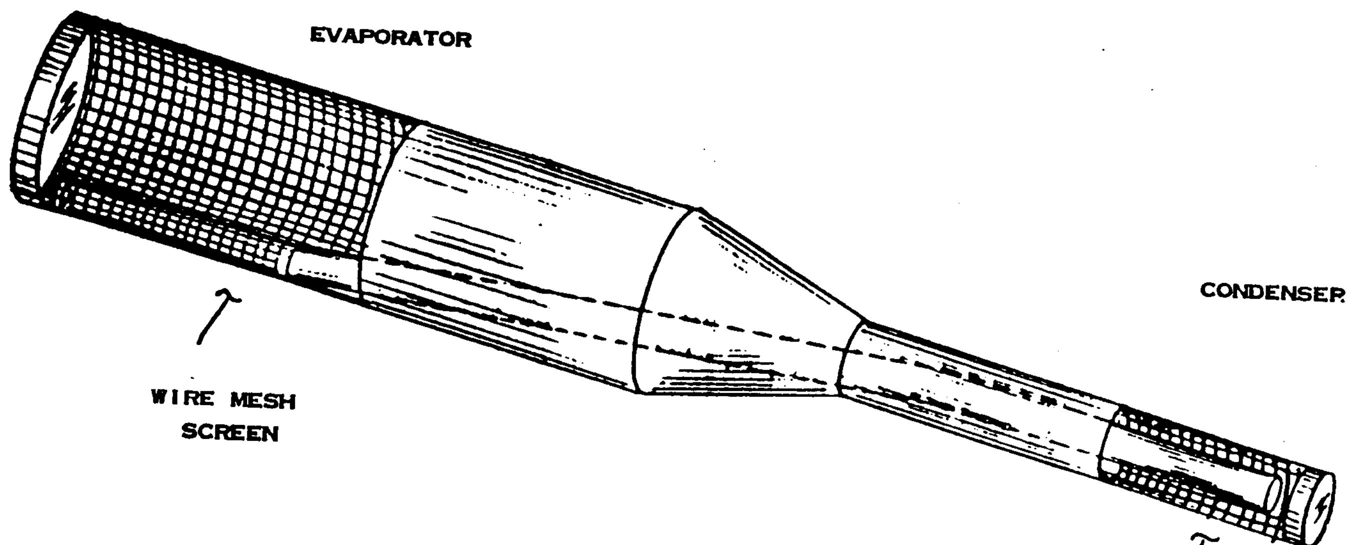
HIGH CAPACITY HEAT PIPE
(GROUND TEST MODEL)



VAPOR PRESSURE PUMPED HEAT PIPE

This Thermacore heat pipe design is a vapor pressure pumped heat pipe. The basic principle behind this design is that the high velocity vapor will sweep the fluid charge to the end of the pipe forming a slug of fluid. The fluid is then pushed into the artery tube and returned to the evaporator. A heat pipe of this sort is currently being fabricated. Thermacore will test it and if the results prove encouraging, extend the technology to the high capacity ambient temperature heat pipe.

VAPOR PRESSURE PUMPED HEAT PIPE



APPENDIX C

PROGRAM REVIEW

20 SEPTEMBER 1985

HIGH CAPACITY HEAT PIPE TECHNOLOGY DEVELOPMENT

CONCEPTS REVIEW

NAS9-17327

20 September 1985

LTV Aerospace and Defense
Vought Missiles and
Advanced Programs Division

OBJECTIVES OF THIS CONTRACT TASK

The overall objective of the High Capacity Heat Pipe Task, Task 1.0, is to evolve and demonstrate the feasibility of a heat pipe design which would ultimately meet the requirements of being lightweight, having no restrictions on circumferential heat addition/removal, have a 2 kW design goal and be self-priming in 0-G, with priming demonstration in 1-G. The heat pipe selection and demonstration will be accomplished by concept studies and element and breadboard testing. Deliverable items at contract end are two, 4 - 5 foot breadboard test articles and a 25 foot pre-prototype article of the final selected design. If determined to be feasible/beneficial to the program 0-G visualization elements for testing on board a KC 135 will also be delivered.

OBJECTIVES OF THIS CONTRACT TASK

- DEVELOPMENT OF AN ALTERNATE TECHNOLOGY HIGH CAPACITY HEAT PIPE
  - LIGHTWEIGHT
  - CIRCULAR IN CROSSECTION/UNRESTRICTED HEAT ADDITION
  - 2 kW DESIGN GOAL OVER A 50 FT LENGTH
  - SELF PRIMING IN 0-G WITH 1-G DEMONSTRATION
- ACCOMPLISHED BY
  - CONCEPT STUDIES
  - ELEMENT AND BREADBOARD TESTS
- DELIVERING AT CONTRACT END
  - 2 - 4 FT TEST ARTICLES
  - 0-G VISUALIZATION ELEMENTS
  - 25 FT PRE-PROTOTYPE ARTICLE

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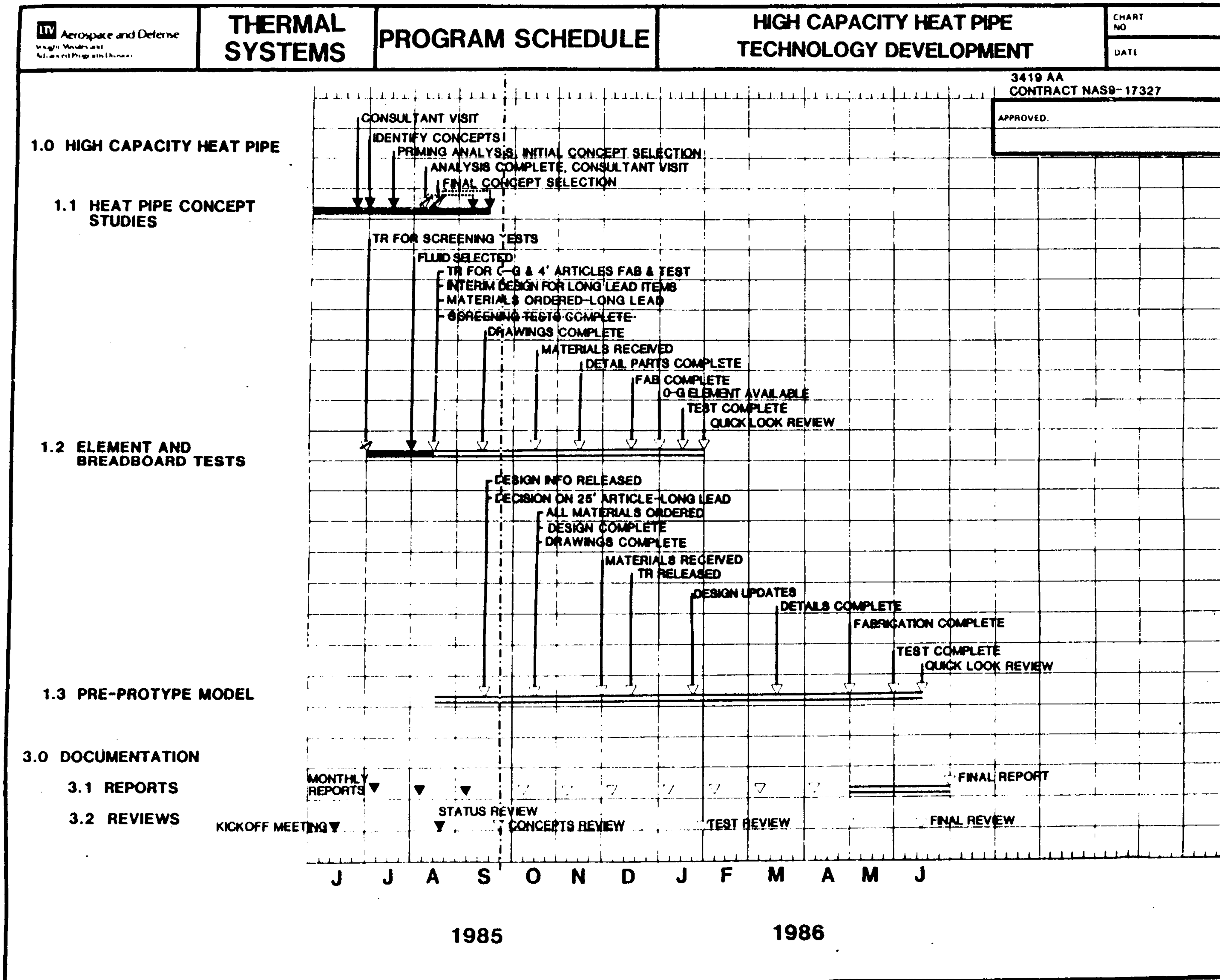
HIGH CAPACITY HEAT PIPE TECHNOLOGY DEVELOPMENT PROGRAM SCHEDULE

This chart shows the schedule for the High Capacity Heat Pipe Alternate Technology Development Program. This program consists of three subtasks:

1.1 Heat Pipe Concept Studies
1.2 Element and Breadboard Tests
1.3 25-Foot Pre-Prototype Model Buildup and Testing

This program is a 13-month study.

The Program Schedule reflects the current status of the tasks. Task 1.1, Concept Studies, was re-opened at the end of August. This was done to evaluate/analyze the designs proposed at the Status Review on 23 August 1985. Tasks 1.2 and 1.3 were put on hold until a decision could be reached as to which heat pipe designs should be carried forward into development and testing.



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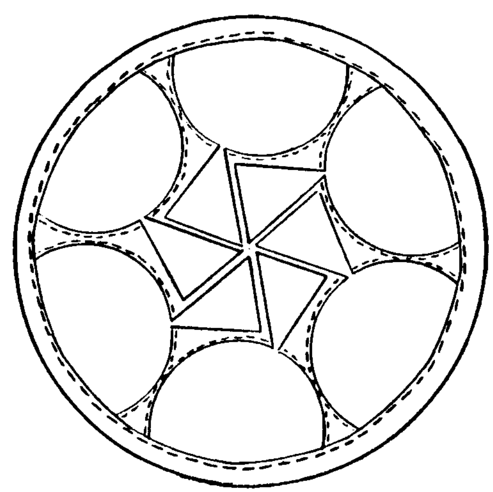
TESTING - LTV CAPILLARY PUMPED HIGH CAPACITY HEAT PIPE

Testing was performed on the LTV Capillary Pumped High Capacity Heat Pipe. This heat pipe was initially developed with IR&D funds. Testing was taken over upon contract award.

The performance of the heat pipe was less than expected, only 330W, maximum were transported at horizontal; i.e., no adverse tilt. As the heat pipe's evaporator end was raised performance fell off even further. It was concluded from analysis and testing that the heat pipe was not primed and that heat transport was therefore limited. Because the pipe was not primed, the liquid ammonia would puddle in the bottom of the pipe, thus liquid return from the condenser to the evaporator was by puddle flow only. Also, it was determined that the cat's eye artery is not a self-priming design and that even in zero-g, should the artery be primed and then deprime, that the cat's eye shape will keep it from repriming.

It was recommended that the heat pipe design be re-evaluated.

SPIROGRAPH ARTERY HEAT PIPE



LATE CONCEPT:

Believed to offer promise

Not Currently Analyzed

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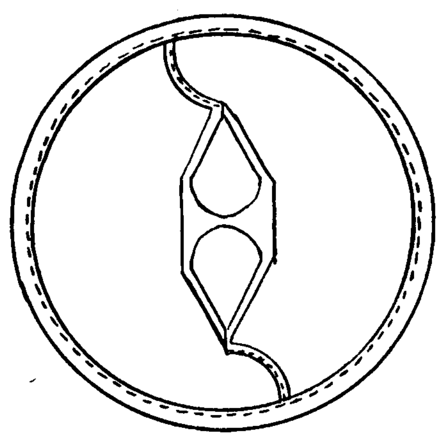
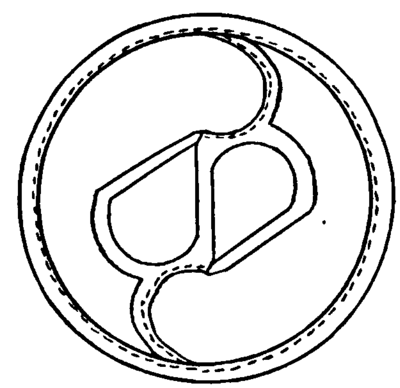
DOUBLE HOOK ARTERY HEAT PIPE

Two configurations of this design were evaluated. An end-to-end configuration was analyzed in a 1.0" and a 1.5" O.D. size. The side-by-side configuration was analyzed in a 1.0" O.D. Pipe performance will be discussed on a later chart.

DOUBLE HOOK ARTERY HEAT PIPES



END-TO-END CONFIGURATION
ANALYZED: 1" , 1.5"



SIDE-BY-SIDE CONFIGURATION
ANALYZED: 1"

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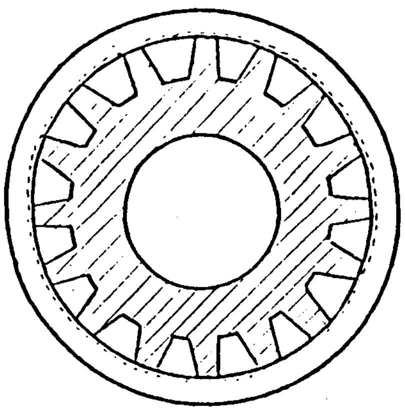
9

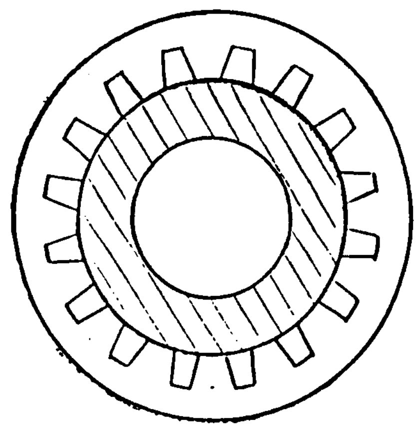
CAPILLARY PUMPED HYBRID HEAT PIPE

This heat pipe design mates either of the two 1.5" O.D. capillary pumped evaporator designs shown to a Lockheed Tapered Artery Condenser. The pipe's performance will be discussed on a later chart.

CAPILLARY PUMPED HYBRID HEAT PIPE

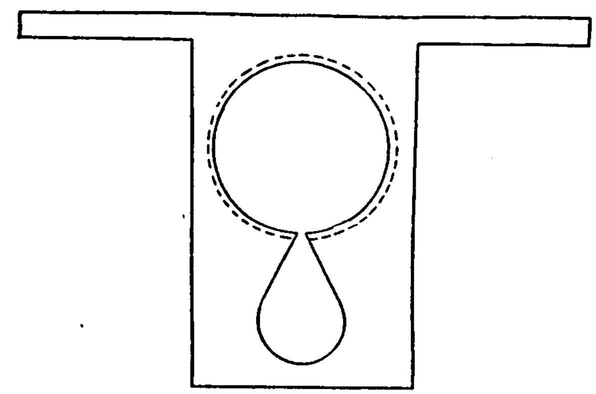


Gear Design



Lug Design

Capillary Pumped Evaporator Artery



Lockheed Tapered Artery Condenser

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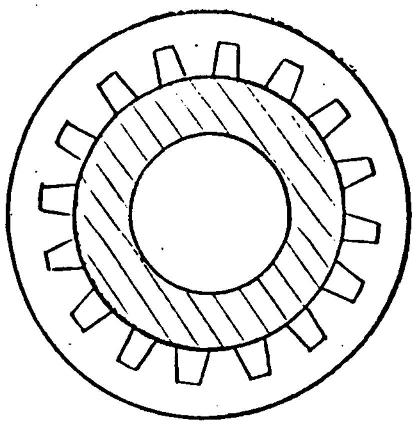
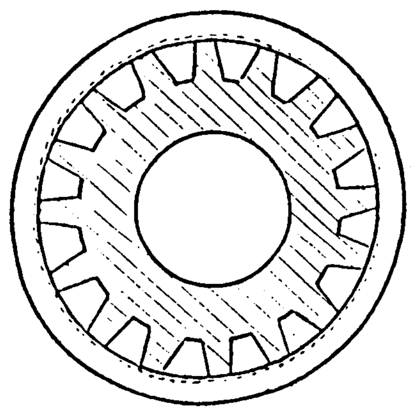
CAPILLARY PUMPED HYBRID HEAT PIPE

This heat pipe design mates either of the two 1.5" O.D. capillary pumped evaporator designs shown to a Thermacore Sintered Artery Condenser. The pipe's performance will be discussed on the following chart.

CAPILLARY PUMPED HYBRID HEAT PIPE

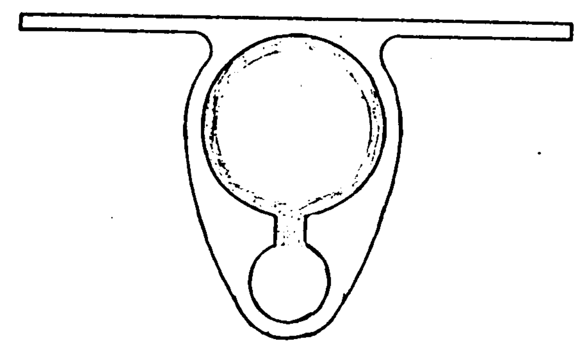


Lug Design



Gear Design

Capillary Pumped Evaporator Artery



Thermacore Sintered Artery Condenser

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HEAT PIPE EVALUATION MATRIX

This chart compares the performance of the six heat pipe configurations listed and previously shown. Predicted values of 1-G and 0-G performance, 1-G performance degradation with adverse tilt, and heat pipe dry weight are given. Also given are subjective weightings of these predicted values in addition to those of volume (envelope taken up by pipe), manufacturing, and priming. Giving all weighting factors equal importance or weight, results in the totals shown in the rightmost column (0 = worst, 10 = best).

The tapered artery and sintered artery heat pipe designs appear to be the best overall designs having the highest totals after summing the weighting factors. Further evaluations including optimization of the evaporator design will be performed on each of these designs.

HEAT PIPE EVALUATION MATRIX

EVAP/CONDENSER	PERFORMANCE 1G	PERFORMANCE 0-G	TILT 3/4" 1-g	WEIGHT (DRY) LB/FT	VOLUME	MANUFACTURING	PRIMING	TOTAL
LUG/TA	2300W	3000W (6)	70% (7)	.22 (9)	9	6	4*	41
GEAR/TA	2000W	3000W (5)	65% (7)	.21 (9)	9	6	4*	40
HOOK (S-1")	2000W	2900W (5)	65% (7)	.39 (4)	5	1	2	24
HOOK (E-1")	2200W	2900W (5)	68% (7)	.31 (6)	5	2	2	27
HOOK (E-1.5")	4400W	4860W[1] (10)	57% (6)	.49 (1)	1	2	2	22
LUG/S.A.	4860W[1]	4860W[1] (10)	94% (9)	.38 (4)	9	4	4*	40

*Need to address Evaporator Artery

[1]Heat Flux Limited

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12

HEAT PIPE ANALYZER ROUTINE

This routine was developed to predict heat pipe performance. It was used for predicting the performance of the heat pipe designs shown on the previous chart.

The routine predicts performance based on the pressure losses through the heat pipe. It accounts for the gravity head which the pipe has to overcome in 1-G performance as well as predicting 0-G performance. It also lists pressure drops and pumping pressures of the various heat pipe components; i.e., evaporator vapor losses, condenser groove wicking pressure, etc.

HEAT PIPE ANALYZER ROUTINE

- DETERMINES PERFORMANCE BASED ON PRESSURE DROPS
- 0 AND 1-G ANALYSIS
- UP TO 3/4" ADVERSE TILT ANALYSIS
- WIDE RANGE OF HEAT PIPE CONFIGURATIONS ACCEPTABLE
- LISTS INDIVIDUAL PRESSURE DROPS AND PUMPING PRESSURES

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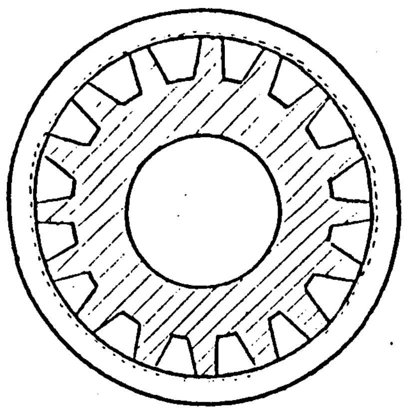
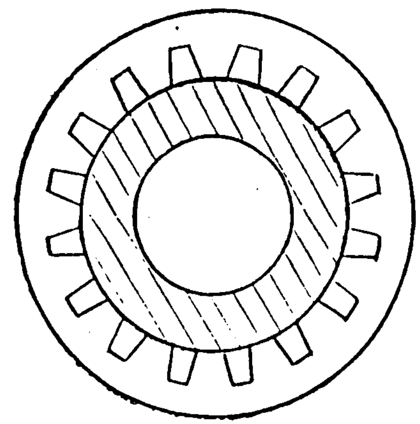
LTV CAPILLARY PUMPED EVAPORATOR

Both designs proposed for the capillary pumped evaporator; i.e., lug or gear, utilize a central, large liquid artery, surrounded by a Porex tube, surrounded by vapor passages. The gear design has the vapor spaces cut out of the Porex, with circumferential grooves in the aluminum shell to deliver liquid to a larger evaporating surface. The lug design has vapor spaces extruded out of the aluminum pipe, placing the evaporating surface at the lug tips.

LTV CAPILLARY PUMPED EVAPORATOR



GEAR DESIGN



LUG DESIGN

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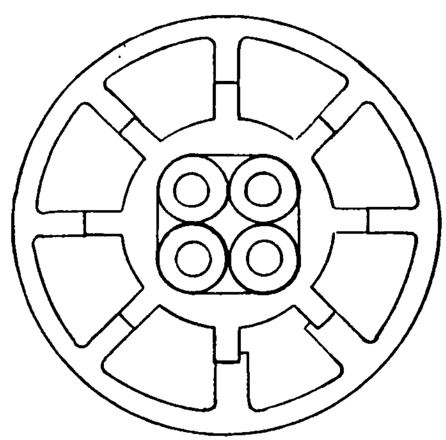
14

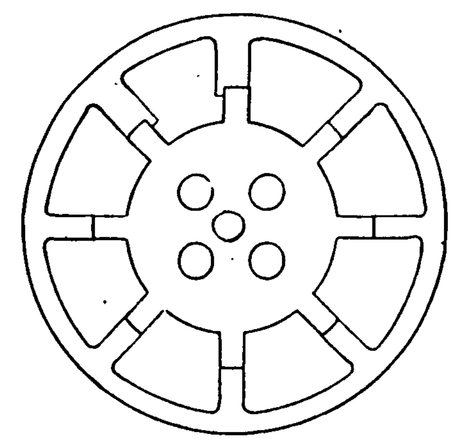
OPTIMIZED LTV CAPILLARY PUMPED EVAPORATOR

These designs originated from the lug and gear evaporator designs shown on the previous chart. They are based on optimization studies for vapor spaces, liquid channels and lug sizes. Both use an aluminum outer extrusion and a Porex center; one uses off-the-shelf stainless steel porous pipe for liquid arteries. The other has the liquid arteries machined (drilled) directly into the Porex. Tabs are included on two of the aluminum lugs to secure the Porex. The preferred design has the Porex core as this design introduces one less material type and is believed to be simpler from a construction standpoint.

OPTIMIZED LTV CAPILLARY PUMPED EVAPORATOR



S S PIPE CORE



POREX CORE

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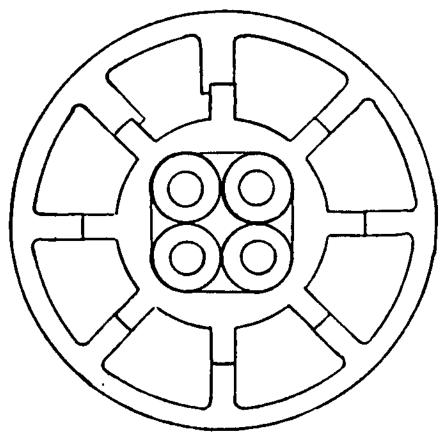
15

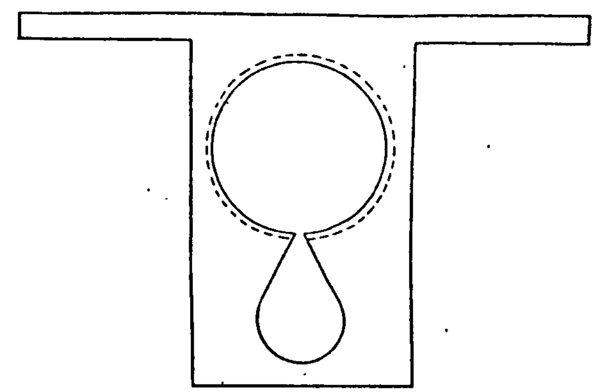
CAPILLARY PUMPED EVAPORATOR/TAPERED ARTERY

This chart shows the evaporator and condenser cross-sections for the LTV/Lockheed hybrid heat pipe. The design will use the optimized capillary pumped evaporator design, either the SS core as shown or the Porex core, and a Lockheed tapered artery condenser.

CAPILLARY PUMPED EVAPORATOR/TAPERED ARTERY



OPTIMIZED EVAPORATOR
CAPILLARY PUMPED



LOCKHEED TAPERED ARTERY
CONDENSER

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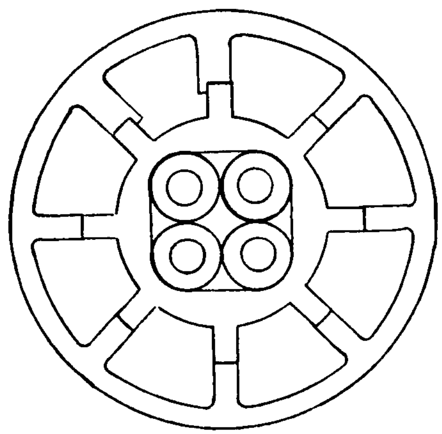
16

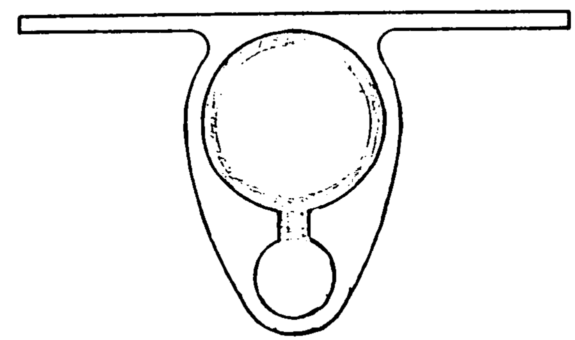
CAPILLARY PUMPED EVAPORATOR/SINTERED ARTERY CONDENSER HYBRID HEAT PIPE

This chart shows the evaporator and condenser cross-section for the LTV/Thermacore hybrid heat pipe. The design will use the optimized capillary pumped evaporator design, either with the SS core as shown or the Porex core and a Thermacore sintered external artery condenser.

CAPILLARY PUMPED EVAPORATOR/SINTERED EXTERNAL ARTERY CONDENSER HYBRID HEAT PIPE



OPTIMIZED EVAPORATOR CAPILLARY PUMPED



THERMACORE SINTERED EXTERNAL ARTERY CONDENSER

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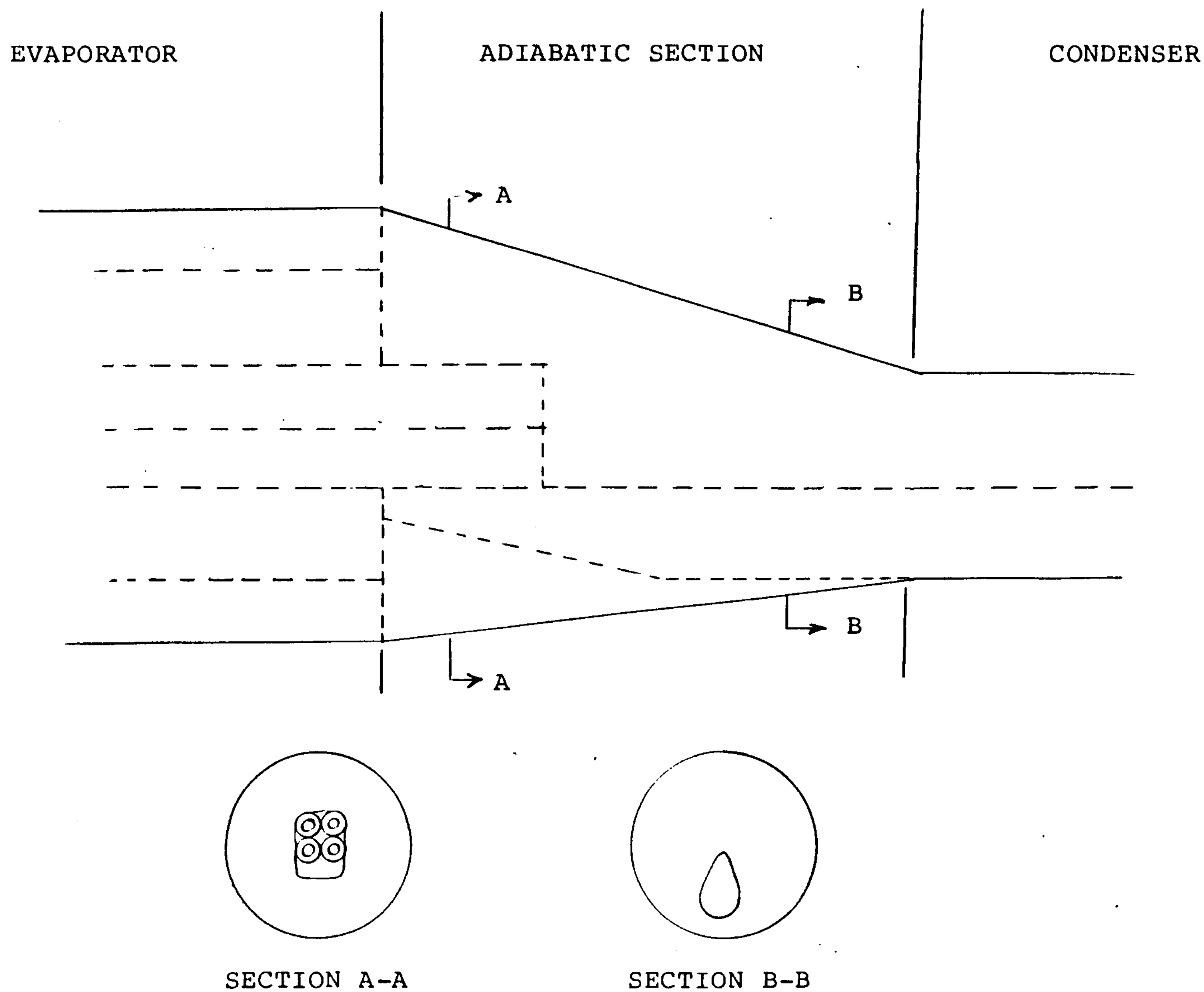
LTV TRANSITION SECTION CONCEPT

This diagram depicts the transition section developed to make the optimized LTV capillary pumped evaporator with the S.S. core and the Lockheed tapered artery condenser. Section A-A shows the stainless steel porous tubes extending into the transition section, in contact with the liquid artery for drawing liquid. Around this structure is the transition vapor space. Section B-B shows the liquid artery surrounded by the vapor space.

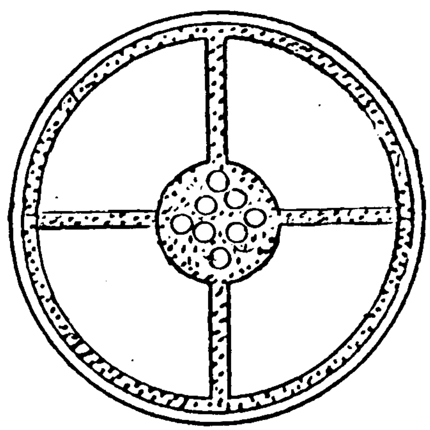
LTV TRANSITION SECTION CONCEPT



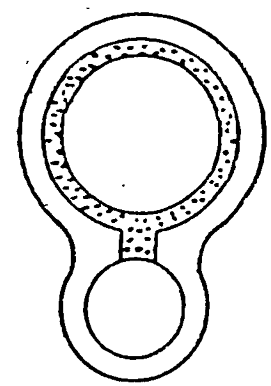
THERMACORE CAPILLARY PUMPED HYBRID HEAT PIPE

This chart shows the evaporator and condenser sections of a Thermacore proposed capillary pumped hybrid heat pipe. The evaporator design is capillary pumped and uses sintered metal for the wick structure. The liquid artery is comprised of many small tubes in the center wick structure. Sintered metal spokes connect the central wick structure to the wall wick, also made of sintered metal. The condenser is an external artery design. Sintered metal is used for the wall wick in the condenser vapor space as well as to fill the groove between the liquid and vapor arteries.

THERMACORE CAPLLARY PUMPED HYBRID HEAT PIPE



CAPILLARY PUMPED EVAPORATOR



EXTERNAL ARTERY CONDENSER

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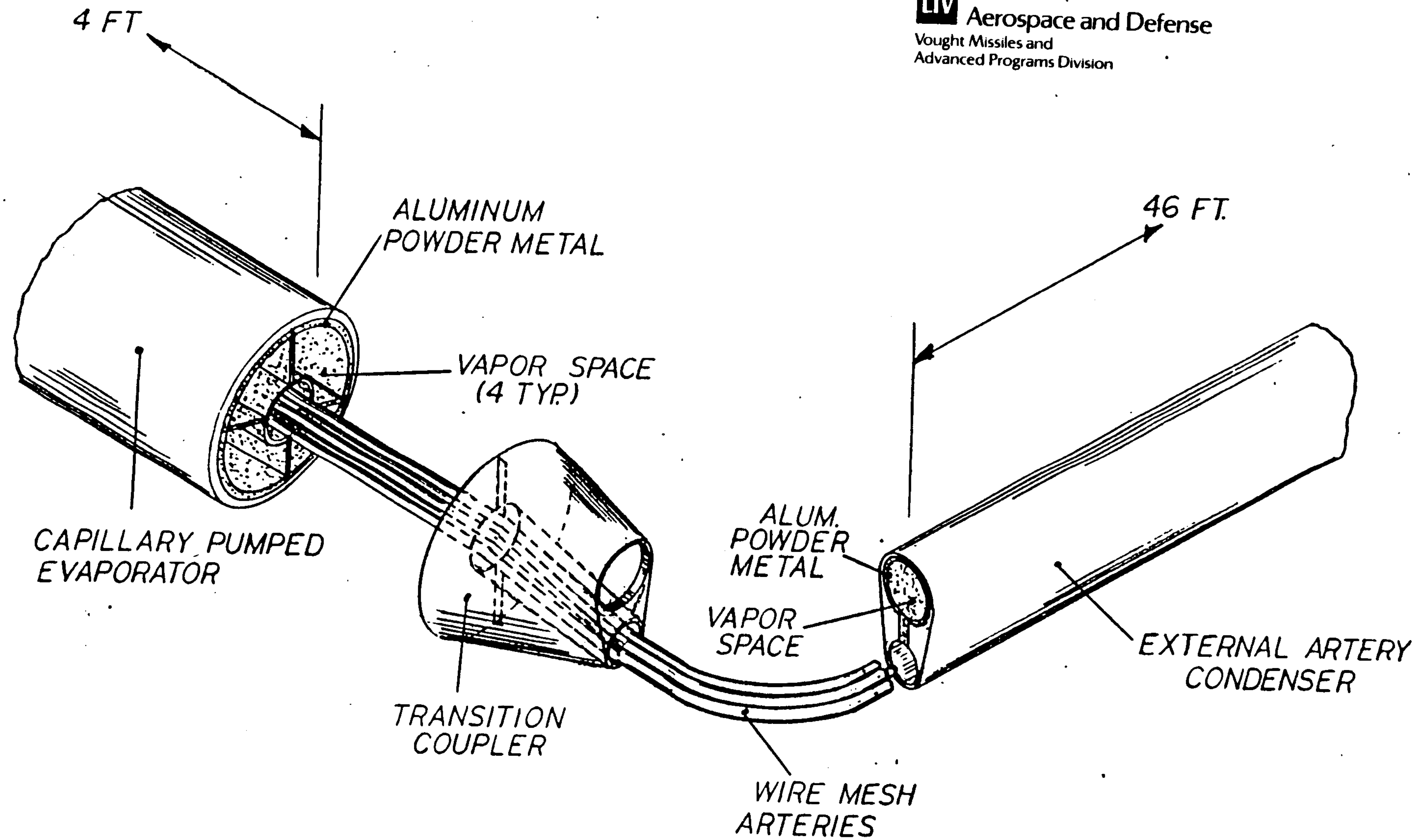
19

THERMACORE CAPILLARY PUMPED EVAPORATOR EXTERNAL ARTERY CONDENSER

This chart depicts the transition section proposed by Thermacore to mate its capillary pumped evaporator to its external artery condenser. The design uses wire mesh arteries to interface between the evaporator liquid arteries and the condenser liquid artery. The manufacturing process would allow the wire mesh arteries to be sintered into place.



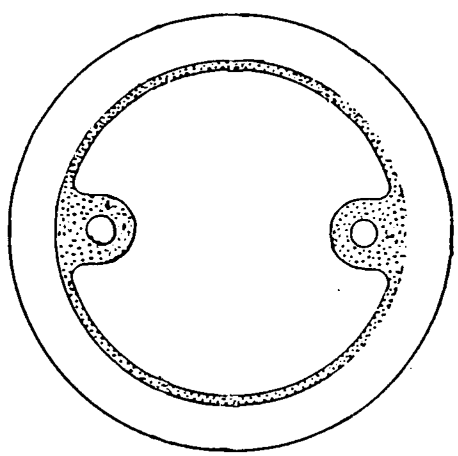
CAPILLARY PUMPED EVAPORATOR EXTERNAL ARTERY CONDENSER

THERMACORE

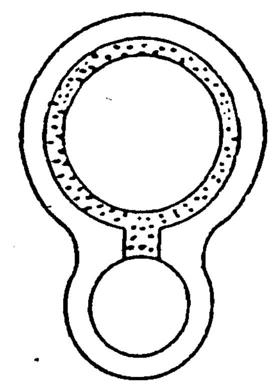
THERMACORE HYBRID HEAT PIPE

This chart shows the evaporator and condenser sections of a second Thermacore proposed hybrid heat pipe design. The evaporator is a Thermacore developed design. It is a tunnel artery design. Two liquid arteries are shown although more can be used if necessary. These liquid arteries supply the sintered wall wick with liquid in the evaporator. The condenser proposed for this heat pipe is the external artery design. Sintered metal is used for the wall wick in the condenser vapor space. Sintered metal is also used to fill the groove between the liquid and vapor arteries.

THERMACORE HYBRID HEAT PIPE



TUNNEL ARTERY EVAPORATOR



EXTERNAL ARTERY CONDENSER

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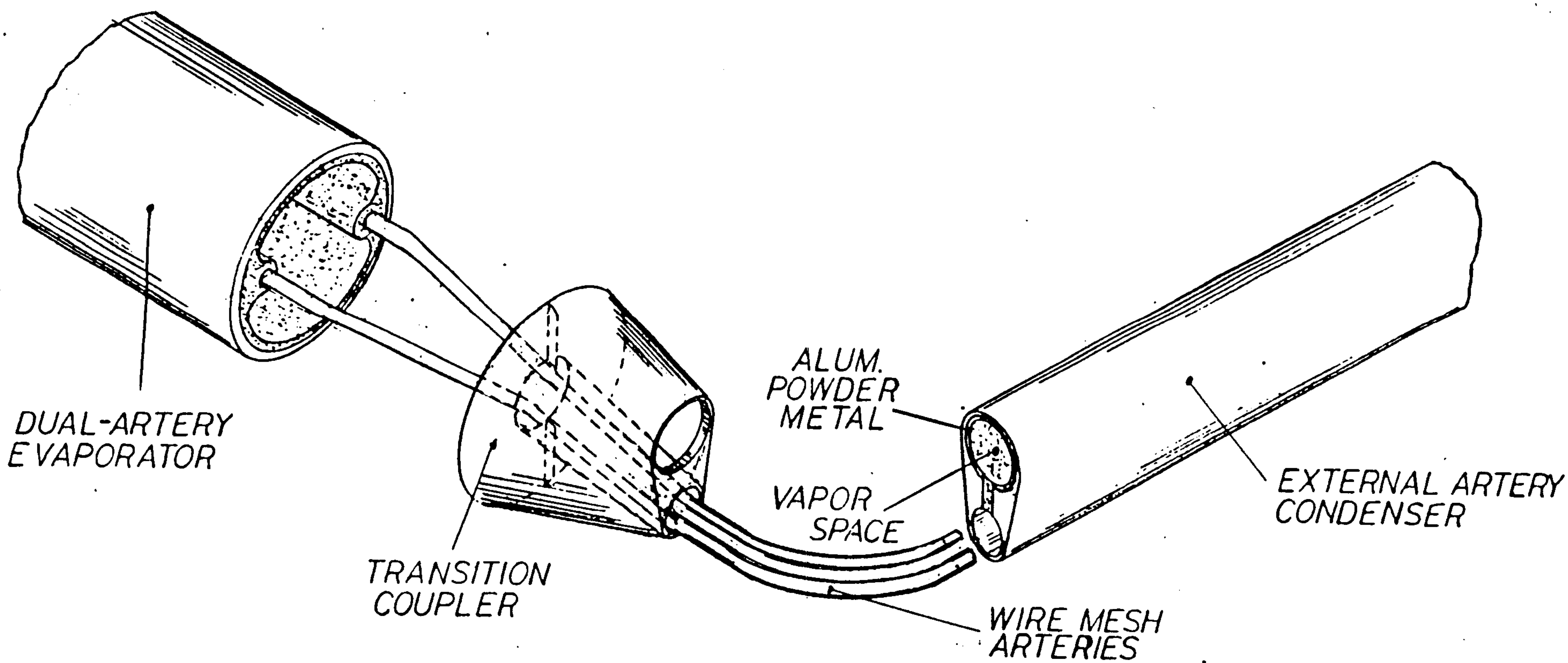
21

THERMACORE DUAL-ARTERY EVAPORATOR EXTERNAL ARTERY CONDENSER

This chart shows the transition section proposed by Thermacore to mate its dual-artery evaporator to its external artery condenser. This transition section uses wire mesh arteries inserted into its evaporator liquid arteries to transition into the liquid passage of the external artery condenser. Vapor from the evaporator flows around the wire mesh liquid arteries and is then channeled into the condenser vapor space.



DUAL-ARTERY EVAPORATOR EXTERNAL ARTERY CONDENSER

THERMACORE

FINAL HEAT PIPE CONFIGURATIONS

This chart gives the predicted performance of the four final heat pipe configurations under evaluation. A heat pipe configured entirely of the tapered artery is also listed for comparison. These predictions are for 50 ft heat pipes with 4 ft evaporators, 1 ft transition sections and 45 ft condensers. Predicted values of 1-G and 0-G performance, 1-G performance degradation with adverse tilt and heat pipe dry weight are given. The heat pipe configuration using the optimized capillary pumped evaporator and the tapered-artery condenser (OCPE/TA) lists performance predictions for both 100% recovery and 70% recovery. Recovery is defined as the amount of evaporator inertial losses which are regained in the condenser. The other heat pipe configurations were evaluated at 100% recovery.

FINAL HEAT PIPE CONFIGURATIONS

EVAP/COND	PERFORMANCE 1-G	PERFORMANCE 0-G	TILT 3/4" 1-G	WEIGHT DRY LB/FT
TA	2530	2860	77%	0.22
OCPE/TA				
100% Rec	2270	3030	71%	0.28 (w/ss)
70% Rec	2190	2910	71%	0.25 (w/Porex)
OCPE/SA	4860[1]	4860[1]	95%	0.42 (approx.)
CPE/SA	3280	3600	95%	0.36
TUNNEL/SA	3780	4120	95%	0.33

[1]Heat Flux Limited

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HIGH CAPACITY HEAT PIPE CANDIDATE EVALUATION

This chart summarizes the characteristics of the four final heat pipe candidates under evaluation, as well as the Lockheed Tapered Artery heat pipe for comparison. The characteristics listed are: 1) the heat pipe's evaporator interface shape - the contract's objective was to develop a heat pipe with unrestricted heat addition; 2) 1-G test sensitivity - heat pipe operation and performance must be demonstrateable in ground testing; 3) self-priming and restart capability; 4) liquid boiling sensitivity - how well insulated the liquid artery is from the heat addition surface; 5) non-condensible gas sensitivity - the effect that any non-condensible gas buildup would have on pipe performance, some designs tend to be self venting; 6) development status; 7) fabrication - expected ease or difficulty of construction.

HIGH CAPACITY HEAT PIPE CANDIDATE EVALUATION

CONFIGURATION	EVAPORATOR INTERFACE	1-G TEST SENSITIVITY	OPERATIONAL CHARACTERISTICS: SELF-PRIMING RESTART	OPERATIONAL CHARACTERISTICS: LIQUID BOILING SENSITIVITY	OPERATIONAL CHARACTERISTICS: NON-CONDENSIBLE GAS SENSITIVITY	DEVELOPMENT STATUS	FABRICATION
TA (LMSC)	RECT.	MODERATE	DEMONSTRATED START-UP OF MODERATE LOADS	LOW	LOW	6 TEST ARTICLES FABRICATED AND SUCCESSFULLY TESTED	SIMPLE
OCPE/TA LTV/(LMSC)	ROUND	MODERATE	SELF-PRIMING	LOW	LOW	LTV CAPILLARY PUMP CURRENTLY UNDER TEST DEMONSTRATED CON-DENSOR	MODERATE
OCPE/SA LTV/TC	ROUND	LOW	SELF-PRIMING	BELIEVED MODERATE	BELIEVED MODERATE	LTV C.P. CURRENTLY UNDER TEST. SINTERED EXTERNAL ARTERY CURRENTLY UNDER TEST.	MODERATE
CPE/SA (THERMACORE)	ROUND	LOW	SELF-PRIMING	BELIEVED MODERATE	BELIEVED MODERATE	CPE UNPROVEN/FABRI-CATION. SINTERED EXTERNAL ARTERY CURRENTLY UNDER TEST.	DIFFICULT
TUNNEL/SA (THERMACORE)	ROUND	LOW	SELF-PRIMING	MODERATE HIGH	BELIEVED MODERATE	BOTH CONDENSER AND EVAPORATOR CURRENTLY UNDER DEVELOPMENT AND TEST.	MODERATE

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CONCLUSIONS

This chart is self explanatory.

CONCLUSIONS

- Capillary Pumped Evaporator provides round interface and slight performance increases
- Computer analyses support Lockheed and Thermacore data
- Thermacore designs appear promising
- Capillary Pumped Evaporator/Tapered Artery Heat Pipe is a moderate risk approach to achieve advantages in weight, performance and interface

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RECOMMENDATIONS

- PURSUE TAPERED ARTERY/CAPILLARY PUMPED EVAPORATOR DESIGN

  o PROVEN CONDENSER
  o ROUND INTERFACE
  o 2KW + PERFORMANCE
  o LIGHT WEIGHT
  o RELATIVELY SMALL DEVELOPMENT EFFORT
  o EXISTING, WORKING LTV CAPILLARY PUMP

- FOR THE SECOND TEST ARTICLE, PURSUE A DUAL CONDENSER TAPERED ARTERY/CAPILLARY PUMPED EVAPORATOR

  o SAME ADVANTAGES AS MONO-CONDENSER OPTIMIZED CAPILLARY PUMPED EVAPORATOR/TAPERED ARTERY
  o APPLICABLE TO SPACE STATION

- PURSUE INDEPENDENTLY THERMACORE DESIGNS

  o PROMISING DESIGNS, SOME CONFIGURATIONS UNDER TEST
  o THERMACORE INDEPENDENTLY PURSUING TRANSITION SECTIONS

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2.6

APPENDIX D

HIGH CAPACITY HEAT PIPE PORTION

PROGRAM REVIEW

15 NOVEMBER 1985

HIGH CAPACITY HEAT PIPE

&

CONNECTABLE / DISCONNECTABLE

THERMAL INTERFACES

PROGRAM REVIEW

NAS9-17327

15 NOVEMBER 1985

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HIGH CAPACITY HEAT PIPE

TASK 1.0

PROGRAM STATUS

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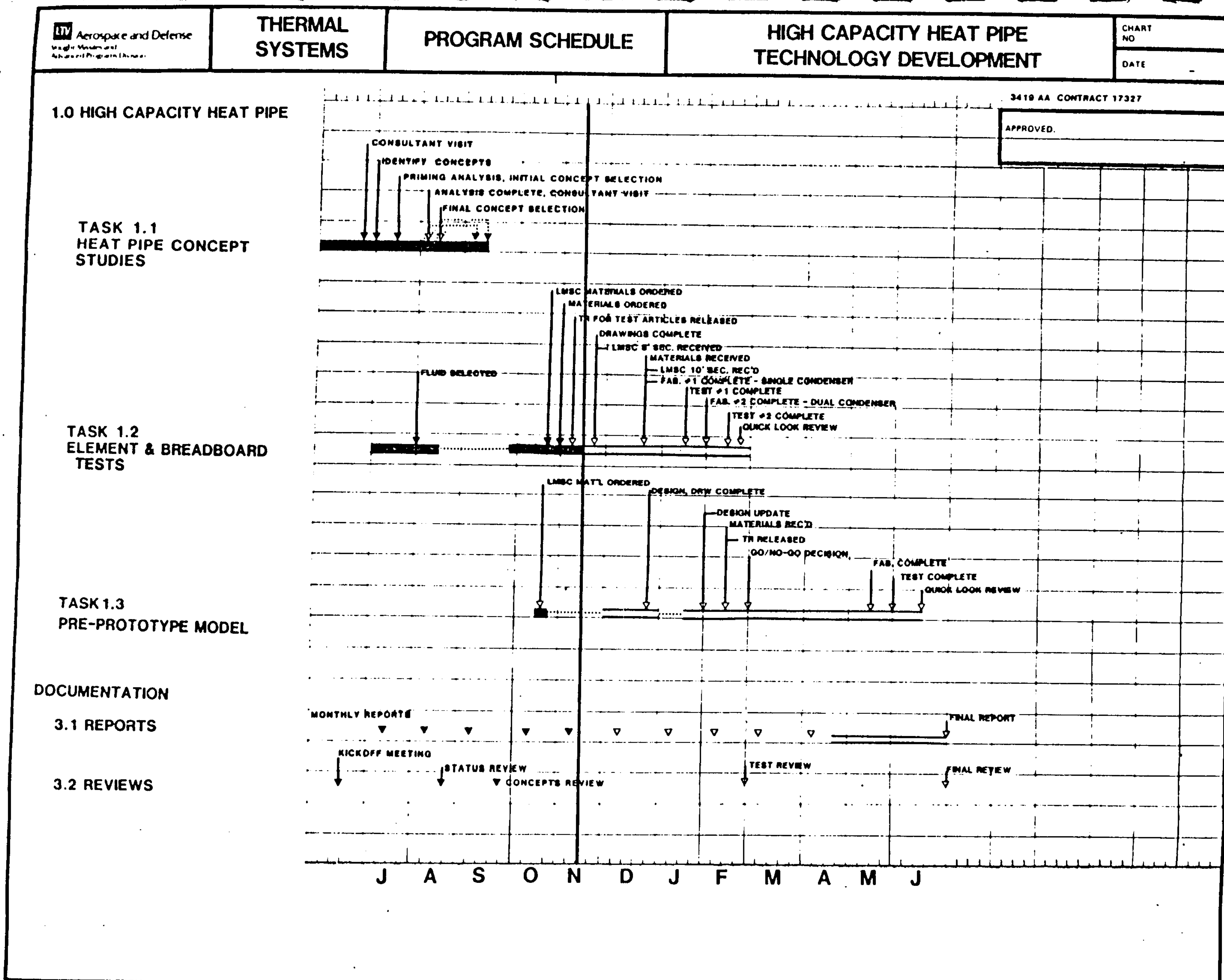
HIGH CAPACITY HEAT PIPE TECHNOLOGY DEVELOPMENT PROGRAM SCHEDULE

This chart shows the schedule for the High Capacity Heat Pipe Alternate Technology Development Program This program consists of three subtasks:

1.1 Heat Pipe Concept Studies
1.2 Element and Breadboard Tests
1.3 25-Foot Pre-Prototype Model Buildup and Testing

This program is a 13 month study.

The Program Schedule reflects the current status of the tasks. Task 1.1, Concept Studies, has been completed. The selected concept for developmental testing in Tasks 1.2 and 1.3 is an optimized capillary pumped evaporator of LTV design mated to a Lockheed tapered artery condenser. Two configurations of this design were proposed; a single leg condenser and a dual leg condenser. Work on Tasks 1.2 and 1.3 has been resumed. Materials for Task 1.2 have been ordered. The Test Request for the Task 1.2 Test Articles is in write-up. The material request for the Lockheed tapered artery extrusion has been made Task 1.3. Placement of the order is in work.



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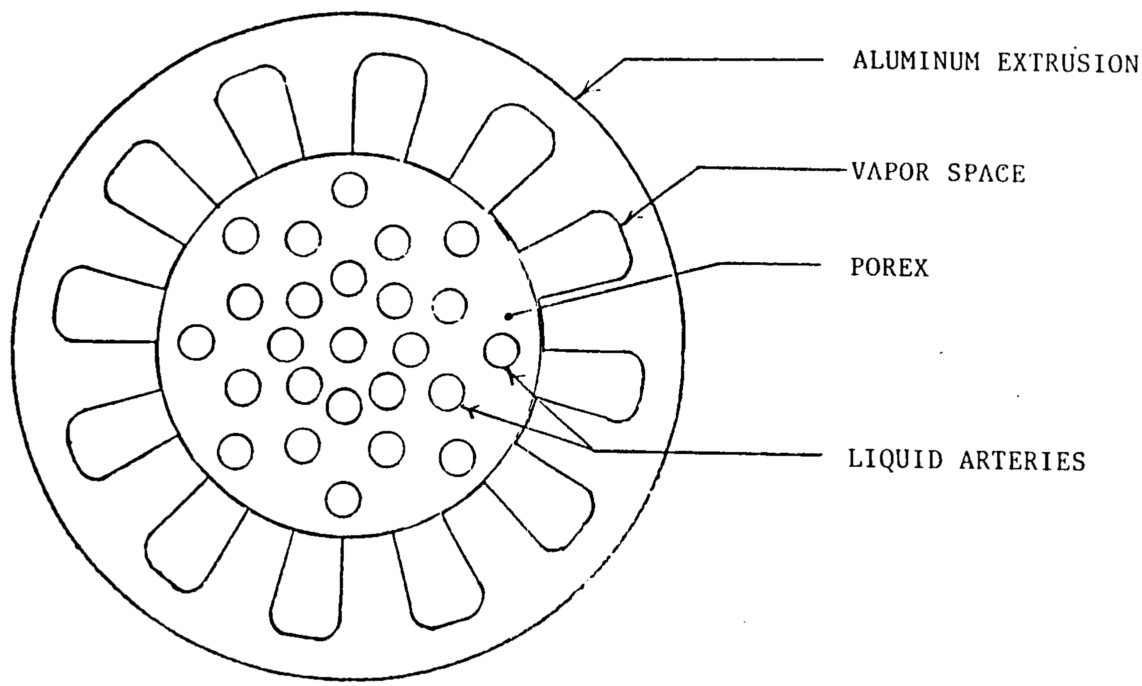
HEAT PIPE EVAPORATOR SECTION - 1-3/4" DESIGN

This chart shows the cross section of the optimized capillary pumped evaporator. The O.D. has been enlarged to 1.75". This will make the test article compatible with the proposed SERS design. The design is based on optimization studies for vapor spaces, liquid channels and lug sizes as well as the temperature drop from the outside of the pipe, the contact surface, to the evaporative interface. The multiple liquid arteries were sized to be self-priming, 3/32" diameter. Porex, 120 micron pore size, is used for the evaporator wick.

HEAT PIPE EVAPORATOR SECTION - 1 3/4" DESIGN

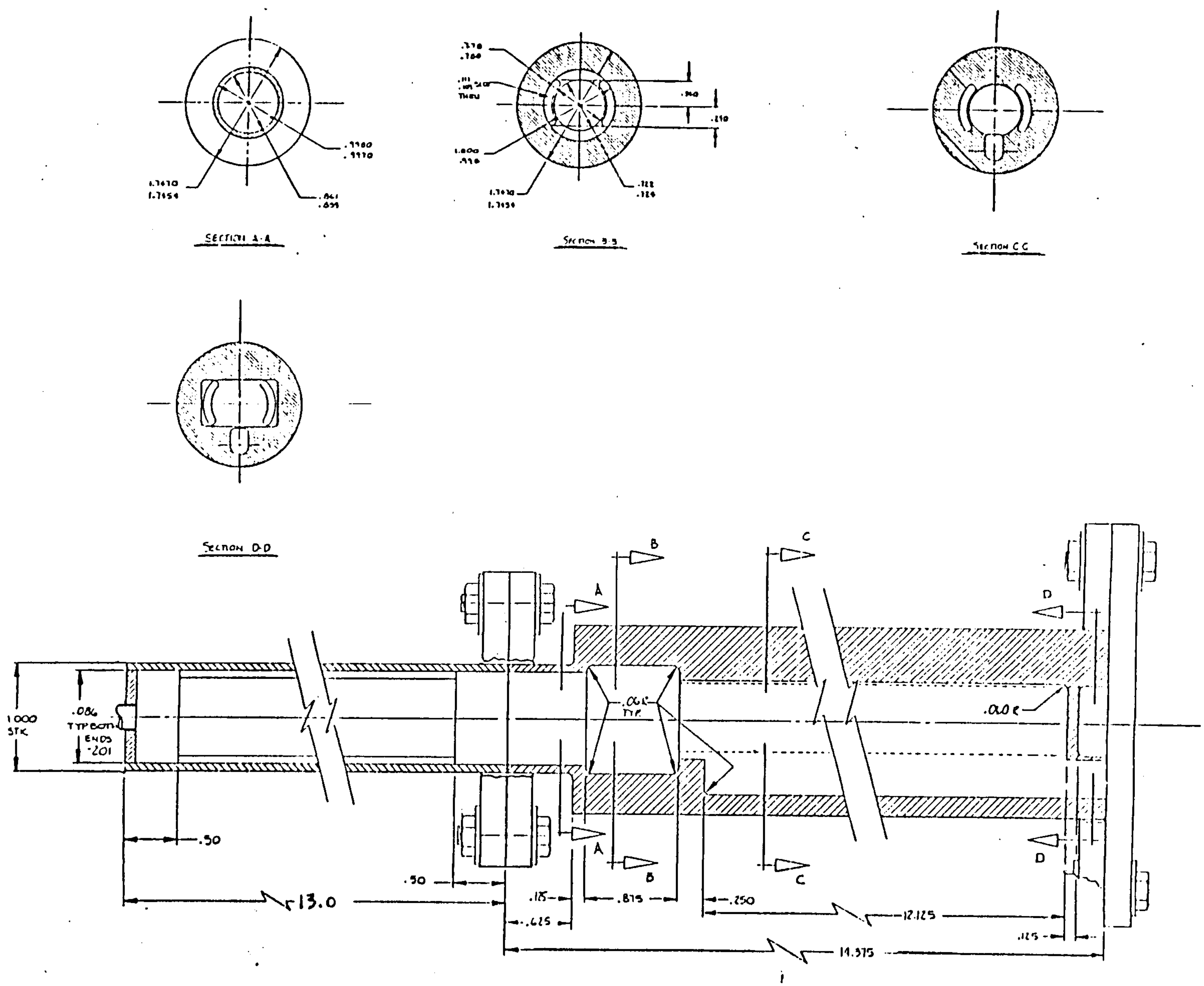


HEAT PIPE EVAPORATOR AND TRANSITION SECTIONS

This chart shows the evaporator and transition section proposed for the single leg condenser heat pipe test article. This article utilizes the available 1" evaporator extrusion which was used for the LTV High Capacity Heat Pipe test article and the LTV Capillary Pumped Loop test article. Using the available in-house extrusion will allow testing to begin at an earlier date. The first test article will primarily demonstrate the workability of the transition section design. The second test article will be the dual condenser design and will utilize the optimized 1-3/4" evaporator extrusion.

The transition section is used to channel the vapor and liquid flows between the evaporator and the condenser. The transition section collects the vapor flowing out of the evaporator (Section A-A) into an annular section (Section B-B) and channels it into two annular segments. These two segments run the balance of the transition section (Section C-C) and dump into the rectangular plenum shown in Section D-D. The Porex wick runs the length of the evaporator and transition sections although it is not shown in the sketches. Through the evaporator the liquid flows in the arteries located in the Porex. Once in the transition section (Section C-C) the Porex is in contact with a liquid full channel (the oval shaped lower channel of Sections C-C and D-D). It is through this interface that the liquid is wicked through the Porex and into the evaporator liquid arteries.

HEAT PIPE EVAPORATOR AND TRANSITION SECTIONS



APPENDICE E

DETAIL TECHNICAL PROGRESS AND STATUS

FOLLOWING 15 NOVEMBER ~~1986~~ 1985

This appendix presents the detailed technical program and status of heat pipe work subsequent to the 15 November 1985 program review. The transition design presented in the 15 November 1985 Program Review was modified for improved producibility, and is shown in LTV Drawings 83-29303 (Figure 4) and 83-29304 for the single and dual leg test article, respectively.

Since the desired evaporator wick was 1 inch in diameter, a fabricated wick arrangement was necessary because the Porex material cannot be produced in rods greater than 1/2 inch diameter or in lengths necessary to complete the evaporator wick. Therefore, LTV designed the wick to be a 1 inch Porex tube with a machined I.D. to have the 1/2 inch Porex rod press fitted within the tube. This design also necessitated a reduction of the drilled liquid arteries from 25 to 19 so that an artery would not be on the interface between the Porex tube and rod in order to reduce the potential that the evaporator would not prime. Any gaps between the two surfaces could cause a priming problem.

The reduction of evaporator liquid arteries to 19 was analyzed by our "Heat Pipe Performance Analyzer"of Appendix F. For our current 25 ft. test article for task 1.3 as well as the 50 ft. flight heat pipe at 0-G the reduction in the evaporator liquid arteries made no perceptible difference in performance. The reason that the performance did not decline is that the heat pipe is limited by the condenser performance.

A test request for the in-house element tests of task 1.2 was written and released. The initial scheduling for the element tests was to start in late January 1986 and be finished in February 1986 as shown on the program schedule of Figure E-1. The required materials were ordered for the testing of tasks 1.2 and 1.3. The 13 ft. condenser extrusion from LMSC for task 1.2 was received from their imperfect stock. This extrusion with improper threads would be suitable for the 1-G element testing scheduled at LTV. All materials were received for testing under tasks 1.2 and 1.3 except for the LMSC condenser extrusion required for the pre-prototype model testing of task 1.3.

The test build-up and fabrication for the 4-5 ft. test element under task 1.2 was begun in January 1986. A machining problem soon developed when trying to drill the liquid arteries within the Porex material for the evaporator wick. The liquid arteries needed to be placed in the Porex so that each artery would have continuity into the artery location of the next section of Porex. It was assumed that is was possible to drill the arteries six to

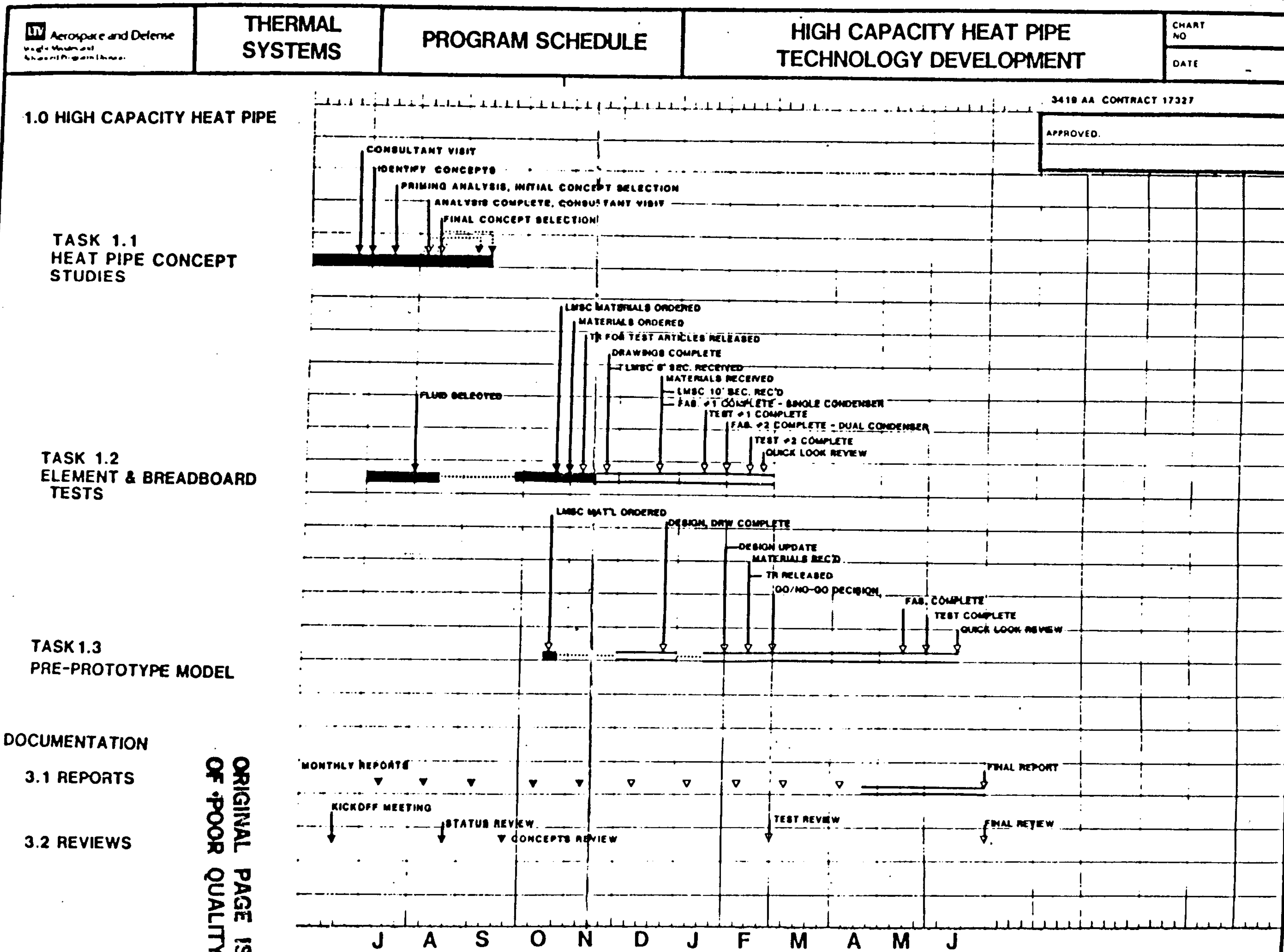


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FIGURE E-1

eight inches of length without having the drill bits sway. Through trying to drill the arteries it was learned that only 2-3 inches could be drilled in the 1 inch tube or the 1/2 inch rod without the arteries intersecting or protruding through the walls. Even the two to three inch length did not produce a truly parallel artery. Hence the next section was virtually impossible to produce since the outlet artery locations of the first wick section would have to be the beginning artery locations of the second section and so on.

With the problems encountered with machining the holes in Porex, new avenues of attack were considered. First, an attempt was made to cut the holes with a laser. The laser could easily be used to pinpoint the exact locations for the liquid arteries. However, when the attempt was made, the laser melted conical shapes in the Porex instead of round tubular holes. Even though never tested, it appeared that the areas around the resultant laser cones had fused together the porous material making it useless in the application intended. A second method of producing the holes which was considered was the use of a high pressure water drill. This system was not available within LTV and therefore abandoned because of schedule and potential cost. Another method was to redesign the evaporator wick to use either multiple Porex rods inside the 1 inch Porex tube or to use several porous (aluminum) metal tubes inside the 1 inch Porex tube similar to the evaporator in Figure 2. Upon analysis it was determined that these methods either would not prime or would not allow for liquid transport through the evaporator. Hence these methods were dropped from consideration.

All of the previous considerations dealt with using the Porex (porous polyethylene) material. The Porex was considered one of the best materials for this application because its thermal conductivity is much lower than metals so that it would not transfer heat as readily through the wick causing potential dryout. Porex has been successfully demonstrated in capillary pumped loop operation with ammonia as the fluid. However, the Porex material is not produced with sufficient dimensional tolerances that are necessary for a heat pipe wicking mechanism per LTV's design. The outer diameter of the tubes or rods is not uniform down the entire length of the pieces. Also the hole of the 1 inch Porex tubes was not on the centerline. The inner hole varied in location from tube to tube.

With the problems encountered with the Porex in machining and poor dimensional tolerances, alternative sources of evaporator wick materials were considered. Sintered aluminum powder metal with the evaporator liquid artery passages formed in place were deemed the most advantageous. An advantage with a sintered metal wick is that the pore size can be produced in a variety of diameters. For sintered aluminum powder metal filled with the working fluid, thermal conductivity was reported to us by Thermacore to be about 10% of the base aluminum thermal conductivity. Two fabrication techniques were considered. One was to have the evaporator wick sintered within the extrusion. The second was to have the evaporator wick sintered free standing to be inserted into the extrusion.

The first approach, "sintered in-place" evaporator wick provided some advantages and concerns. LTV along with Thermacore felt that the sintered-in-place approach provides a much higher confidence of producing the evaporator with the 25 liquid arteries in the proper locations and maintaining the wick material adjacent (without gaps) to the outer extrusion. The problems with the "sintered in-place" approach are mainly cost and leadtime concerns. The outer case extrusion (purchased from Mann-Made Inc. of Wylie, Texas) is made of Aluminum 6063-T6. Because of the sintering process an extrusion of either AL 1100 or AL 3003 that can handle the temperature range required for sintering would be required. Also the low strength extrusion alloy (AL 1100 or 3003) would increase the wall thickness required thus adding weight and reducing thermal performance. This extra wall thickness would also require design changes to be made. It was concluded the "sintered in-place" design would add six to eight weeks to the program schedule and incur significant additional material and tooling costs.

The second approach, "sintered free standing" evaporator wick required more effort to evaluate feasibility. The evaporator extrusions of AL 6063-T6 material could still be used. No redesign of the rest of the heat pipe would be necessary. The main concern is inserting the sintered wick material inside the aluminum extrusion. An effort to determine the best approach would be required. Two procedures had been identified, one was to press fit and the second was to shrink fit the wick inside the evaporator extrusion. The press fit and possibly the shrink fit method might require machining the outside diameter of the "sintered free standing" wick material. This machining procedure had been successfully performed by Thermacore on other than aluminum alloys. This machining procedure requires the use of a melt away wax. The shrink to fit procedure with sintered powder metal material to our knowledge has never been performed. Therefore, some investigative testing with free standing sintered elements in a shrink to fit procedure would be necessary. Based upon previous strength tests on other sintered powder metal materials, it is believed that the sintered aluminum powder metal has sufficient crush strength to be used in a shrink-to-fit procedure. The shrink-to-fit procedure should be less risk than the press fit procedure because there would be less chance of a gap between the wick and the extrusion to occur. As previously described a gap could cause the wick to de-prime.

At the point of cessation of heat pipe effort the sintered metal wick approach was recommended, with the selection of "sintered-in-place" vs. "sintered free standing" left for further investigation.

Based on evolving heat pipe requirements for the Space Erectable Radiator System (Contract NAS9-17495), the current 2kW design goal of this contract appeared to be insufficient. Analysis on the SERS contract showed a per panel requirement of 2500 to 3500 watts depending upon margins of 30 to 100%, respectively. With the 12 inch wide SERS panel and a 48 foot total length (45' condenser) the heat pipe requirement would be 1750 watts. The LTV designed evaporator with the Lockheed dual leg tapered artery condenser (0.48 vapor passage) is predicted to provide 2650 watts in zero-gravity and 0% recovery by out heat pipe analyzer, Appendix F. Recovery (pressure recovery) is the reclamation of the vapor momentum in the condenser that was lost in the evaporator. The 2650 watt prediction allows only a 34% margin. The LTV evaporator heat pipe design (1.75) inch diameter) would allow as much as 7500 watts performance when coupled with a comparable condenser. The use of a sintered evaporator wick would allow wick pore diameter adjustment for the best performance. Since the Lockheed tapered artery condenser has an effective pore diameter of 432 microns, analysis was conducted on another condenser design to provide the additional load to match evaporator capacity. The Thermacore 1 inch vapor passage external artery condenser extrusion (depicted in Appendix A) with a sintered wick around the vapor passage and between the vapor and liquid arteries was used for analysis with our evaporator. Table E-1 lists the results of the parametric analysis computed with LTV's Heat Pipe Performance Analyzer. By adjusting the pore size of both the evaporator and the condenser, a liquid transport limit for a dual legged condenser was determined to be 7340

TABLE E-1

HEAT PIPE PREDICTED PERFORMANCE

50 FOOT HEAT PIPE 0-G
LTV EVAPORATOR (25 liquid arteries) 4'
THERMACORE CONDENSER (1" vapor passage sintered wick) 45'

LIQUID TRANSPORT LIMIT - - - WATTS

EVAPORATOR PORE MICRONS	CONDENSER PORE MICRONS 100	120	150
	SINGLE CONDENSER		
40	3310	3320	3320
60	5550	5560	5570
80	7080	7100	7110
100	5800	5810	5820
120	-	5460	5470
150	-	-	4960
	DUAL CONDENSER		
40	3340	3340	3350
60	5680	5690	5690
80	7310	7330	7340
100	5980	6000	6010
120	-	5650	5670
150	-	-	5150

Analysis conducted with LTV Heat Pipe Performance Analyzer, Appendix F watts at 80 microns pore size for the evaporator and 150 microns for the condenser. This predicted performance is well above (more than twice) the SERS requirements even with 100% margin. This design was not weight optimized.

The fabrication problems of the Porex evaporator wick caused LTV to halt work on task 1.2 to formulate a new plan. After forming a plan to continue including using the sintered powder metal approach as discussed previously, LTV made a presentation to NASA-JSC on 24 February 1986 describing the program status and recommendations for continuing the heat pipe work. Because of budget restraints, NASA-JSC directed LTV to stop work on the heat pipe portion of the contract except to produce a final wrap-up report.

Task 1.3 was to develop a 25 ft. pre-prototype heat pipe test article. The design of a dual legged condenser heat pipe utilizing the Porex wick evaporator was completed. The design is shown in drawing number 83-29306. The Porex was the same 120 micron pore size as procurred under task 1.2. The long lead time items were placed on order. In fact, the evaporator extrusion and Porex were already received. The Lockheed condenser extrusion was the only major material requirement that was not in-house. Lockheed had received the extrusion but it had not been threaded. This condenser section was placed on hold pending the NASA-JSC decision requested by LTV on 24 February 1986.

Limited thermal analysis of the 25 ft. pre-prototype heat pipe had been performed. Analysis with a dual legged Lockheed condenser and 50% recovery showed performance of 2880 watts in 0-G. All other analyses previously described were performed at 0% recovery.

APPENDIX F

HEAT PIPE PERFORMANCE ANALYZER

COMPUTER LISTING

```
      PROGRAM ELSIETC

C  THIS PROGRAM EVALUATES THE PRESSURE DROPS ASSOCIATED WITH
C  A HEAT PIPE OF LTV EVAP/ADIABATIC, LOCKHEED COND DESIGN.
C  ASSUMES LAMINAR LIQUID, TURBULENT VAPOR FLOWS.

      IMPLICIT REAL (K-M)
      DIMENSION DP(4),DPT(4),MEM(20,4)
      CHARACTER TITLE*75, NAME*10, ACOND(2)*8
      DATA PI/3.14159/QMAX/10000./ACOND/' (Single',' (Dual'/
      GC = 32.173*3600**2
      CONST = 0.317/8/4.**.25/144/GC
      CONL = 2.*144/GC
      CONW = 1./144/GC

      WRITE(6,*) ' WHAT INPUT FILE?'
      READ (5,1001) NAME
      OPEN(3,FILE=NAME,STATUS='OLD')
      OPEN(9,FILE='ELSIETC.RES',STATUS='NEW')

C  A word about the inputs:
C
C  LE: length of evaporator
C   (ft)
C  DE: ID of evaporator; used in heat flux calc, head calc.
C   (ft)
C  LA, LC: length of adia sec, cond
C   (ft)
C  DA, DC: ID of adia sec, cond
C   (ft)
C  DPE,DPC: effective pore diameter of wick in evap/cond;  used
C   (microns)   in pumping pressure calc
C  KE,KC: permeability of wick in evap/cond;  used for pressure
C   (ft-ft)     drops in wicks
C  WTE,WTC: wick thickness in evap/cond;  is the average radial
C   (ft)        distance the fluid must travel to/from the artery
C               from/to the evap/cond-ing surface
C  FWE,FWC: average flow width for the fluid as described in
C   (ft)        WTE,WTC ... fluid traveling radially
C  VISL,VISV: dynamic viscosity of liquid, vapor
C   (#/ft-h)
C  RHOL, RHOV: density of liquid, vapor
C   (#/cu ft)
C  LAM: latent heat of vaporization
C   (BTU/#)
C  SIG: surface tension
C   (#/ft)
C  WETANGL: fluid wetting angle
C   (degree)
C  CGEW, CGCW: circumferential groove width, 1 groove
C   (in)
C  CGEBTA, CGCBTA: circ groove half included angle
C   (degree)
C  CGETPI, CGCTPI: circ groove threads per inch
C  GEVL, GCVL: total length (not greater than DE, DC) of
C   (ft)        groove/vapor interface;  used in calc of
C               pressure drops in grooves
C  RCVRYI: amount of inertial pressure drop is to be
C               recovered in the cond
C  MAXTLT: maximum tilt desired in 1/4 inch increments
```

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C    (in)
C   WPEL, WPAL, WPCL: wetted perimeter of liquid passages
C    (in/passage)
C   AFL, AAL, ACL: flow area of liquid passages
C    (in-in/passage)
C   NEL, NAL, NCL: number of liquid passages
C   WPEV..., AEV..., NEV...: as above but for vapor passages
C   WLA: length of Porex wick in the transition section
C    (ft)
C   WTA: wick thickness in transition section; i.e., average
C    (ft)         distance radially from reservoir into wick
C   FWA: flow width, adiabatic section; the width of the Porex/
C    (ft)         liquid interface
C   FLA: flow length, adiabatic section; length of Porex/liquid
C    (ft)         interface
C   NCOND: number of condensers
C    (1,2)
C
   10 CONTINUE
        READ (8,*,ERR=999,END=999) LE, DE, LA, DA, LC, DC
        READ (8,*) DPE, DPC, KE, KC, WTE, WTC, FWE, FWC
        READ (8,*) VISL, RHOL, LAM, SIG, VISV, RHOV, WETNGL
        READ (8,*) CGEW, CGEBTA, CGETPI, CGCW, CGCBTA, CGCTPI
        READ (8,*) GEVL, GCVL, RCVRYI, MAXTLT
        READ (8,*) WPEL, AEL, WPAL, AAL, WPCL, ACL
        READ (8,*) WPEV, AEV, WPAV, AAV, WPCV, ACV
        READ (8,*) NEL, NAL, NCL, NEV, NAV, NCV
        READ (8,*) WLA, WTA, FWA, FLA, NCOND

        IF (NCOND.NE.2) NCOND=1
C   THE FOLLOWING VALUES ARE FOR THE TRANSITION SECTION
C   USED IN DUAL CONDENSER CONFIGURATIONS.  IT IS A V SHAPED
C   SECTION WITH A 68 DEG HALF INCLUDED ANGLE.  THE V LEGS ARE
C   5.6 INCHES AND EACH LEG HAS ONE VAPOR AND ONE LIQUID PATH,
C   EACH BEING CIRCULAR AND SEPARATE.  THE VAPOR DIAMETER IS
C   0.48 INCHES AND THE LIQUID 0.25.
        WPTV=1.5080
        LT=0.46666
        ATV=0.1810
        NTV=1
        WPTL=0.7854
        ATL=0.0491
        NTL=1

        READ (8,1001) TITLE
        WRITE(9,1002) TITLE
        READ (8,1001) TITLE
        WRITE(9,1001) TITLE
        READ (8,1001) TITLE
        WRITE(9,1001) TITLE

        WRITE(9,1000)
        WRITE(9,1100) VISL, RHOL
        WRITE(9,1300) LAM, SIG, WETNGL
        WRITE(9,2000)
        WRITE(9,1100) VISV, RHOV
        WRITE(9,3000)
        WRITE(9,3500) LE, DE*12
        WRITE(9,3300) DPE, KE*144, WTE*12, FWE*12
        WRITE(9,3600) CGEW, CGEBTA, CGETPI
```

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```
      WRITE(9,3100) WPEV, AEV, NEV
      WRITE(9,3200) WPEL, AEL, NEL
      WRITE(9,4000)
      WRITE(9,3500) LA, DA*12
      WRITE(9,3700) WLA, WTA*12, FWA*12, FLA
      WRITE(9,3100) WPAV, AAV, NAV
      WRITE(9,3200) WPAL, AAL, NAL
      WRITE(9,5000) ACOND(NCOND)
      WRITE(9,3500) LC, DC*12
      WRITE(9,3300) DPC, KC*144, WTC*12, FWC*12
      WRITE(9,3600) CGCW, CGCBTA, CGCTPI
      WRITE(9,3100) WPCV, ACV, NCV
      WRITE(9,3200) WPCL, ACL, NCL

      VRV = VISV**0.25/RHOV
      VRL = VISL/RHOL
      DPE = DPE*3.28E-6
      DPC = DPC*3.28E-6
C
C  Calculate pumping pressures:
C
      DPWKE = 2*SIG*COSD(WETNGL)/DPE*2/144
      DPWKC = 2*SIG*COSD(WETNGL)/DPC*2/144
      DPCGE = 2*SIG*COSD(WETNGL)/12*COSD(CGEBTA)/CGEW
      DPCGC = 2*SIG*COSD(WETNGL)/12*COSD(CGCBTA)/CGCW

      DP(1) = DPWKC
      DP(2) = DPWKE
      DP(3) = DPCGE
      DP(4) = DPCGC

C Convert vapor data to feet dimensions; leave liquids in inches:
      WPEV = WPEV/12
      AEV  = AEV/144
      WPAV = WPAV/12
      AAV  = AAV/144
      WPTV = WPTV/12
      ATV  = ATV/144
      WPCV = WPCV/12
      ACV  = ACV/144

C  0 and 1 gee:
      DO 600 IGRAV = 0,1
         ELEV2 = MAXTLT*IGRAV

         DO 500 ELEV = 0.0,ELEV2,0.25
            IF (IGRAV.NE.0) WRITE(9,5500) ELEV

            DO 450 INDEX = 1, 4
               IF (DP(INDEX) .LE. 0) GO TO 450

C  input increasingly higher heats (Watts)
            DO 400 IQP = 200,QMAX,100
               QP = IQP
               QFLAG = 0.0
  350          Q = QP*3.413

C  calculate system pressure drops:
C  (individual pressure drop variables may be cross referenced
C  in the write and format statements below.)
```

```
                    MDOT = Q/LAM
                    MDOTD= MDOT/NCOND
                    DPEVI = CONW*RHOV*(MDOT/NEV/RHOV/PI/
     1                 (AEV/WPEV)**2)**2
                    DPEVV = CONST/2.75*WPEV**1.25*LE/AEV**3*VRV
     1                   *(MDOT/NEV)**1.75
                    DPEV = DPEVI + DPEVV
                    DPAV = CONST      *WPAV**1.25*LA/AAV**3*VRV
     1                   *(MDOT/NAV)**1.75
                    DPTV =(CONST      *WPTV**1.25*LT/ATV**3*VRV
     1                   *(MDOTD/NTV)**1.75)*(NCOND-1)
                    DPCVV = CONST/2.75*WPCV**1.25*LC/ACV**3*VRV
     1                   *(MDOTD/NCV)**1.75
                    DPCVI = -(DPEVI*RCVRYI)
                    DPCV = DPCVV + DPCVI
                    DPCW = CONW*VRL*WTC/KC/FWC/LC *MDOT/2
                    DPAW = CONW*VRL*WTA/KE/FWA/FLA*MDOT/2
                    DPEW = CONW*VRL*WTE/KE/FWE/LE *MDOT/2
                    DPTL =(CONL   *WPTL**2* LT/ATL**3*VRL*MDOTD/NTL)*
     1                                                           (NCOND-1)
                    DPCL = CONL/2*WPCL**2* LC/ACL**3*VRL*MDOTD/NCL
                    DPAL1= CONL/2*WPAL**2*FLA/AAL**3*VRL*MDOT /NAL
                    DPAL2= CONL/2*WPEL**2*WLA/AEL**3*VRL*MDOT /NEL
                    DPEL = CONL/2*WPEL**2* LE/AEL**3*VRL*MDOT /NEL
                    DPEG = 8/PI*VRL*MDOT/NEV*GEVL/NEV/4*DE/
     1                               CGEW**4/CGETPI/LE*2/GC*12
                    IF (CGEBTA .EQ. 90.0) DPEG = 0.0
                    DPCG = CONW*VRL*MDOT/NCV*PI*DC/KC/CGCW/LC/8
                    DPH = RHOL*(DE+ELEV/12)/144*IGRAV
                    DPT(1) = DPCV+DPCL+DPCG+DPCW
                    DPT(2) = DPT(1)+DPEL+DPH+DPEW+DPEG+DPEV+DPAV+DPTL+
     1                              DPAW+DPAL2+DPTV+DPAL1
                    DPT(3) = 0
                    DPT(4) = DPCG

C   when system drop exceeds total current pumping, back off
C   by 10 watt increments until equality is found:
                    IF (DPT(INDEX) .GT. DP(INDEX) .AND.
     1                 QP .GT. 0. .AND. QP .LT. QMAX)THEN
                       QFLAG = 1.0
                       QP = QP - 10
                       GO TO 350

C   when equality is found, save data and print results later:
                    ELSE IF (QP .EQ. QMAX .OR. QP .EQ. 0. .OR.
     1           (DPT(INDEX).LE.DP(INDEX) .AND. QFLAG.EQ.1.))THEN
                       QL = QP*(LE/2+LA+LC/(2*NCOND))*12
                       MEM(1,INDEX) = DPEVV
                       MEM(2,INDEX) = DPEVI
                       MEM(3,INDEX) = DPAV
                       MEM(4,INDEX) = DPTV
                       MEM(5,INDEX) = DPCVV
                       MEM(6,INDEX) = DPCVI
                       MEM(7,INDEX) = DPCG
                       MEM(8,INDEX) = DPCW
                       MEM(9,INDEX) = DPCL
                       MEM(10,INDEX) = DPTL
                       MEM(11,INDEX) = DPAL1
                       MEM(12,INDEX) = DPAW
                       MEM(13,INDEX) = DPAL2
```

```
                    MEM(14,INDEX) = DPEL
                    MEM(15,INDEX) = DPH
                    MEM(16,INDEX) = DPEW
                    MEM(17,INDEX) = DPEG
                    MEM(18,INDEX) = QP
                    MEM(19,INDEX) = QL
                    MEM(20,INDEX) = DPT(INDEX)
                    GO TO 450

                 END IF
  400          CONTINUE
  450          CONTINUE
               J1 = 1
               DO 475 J=2,4
                  IF(MEM(18,J).LT.MEM(18,J1).AND.DP(J).GT.0.) J1=J
  475          CONTINUE
               TOTDP = 0.
               DO 480 J=1,17
  480             TOTDP = TOTDP+MEM(J,J1)
               WRITE(9,6000) IGRAV,MEM(18,J1),MEM(19,J1),ELEV
               WRITE(9,6300)
               WRITE(9,6310) (MEM(I,J1),I=1,17)
               WRITE(9,6400) TOTDP
               IF (J1.EQ.1) WRITE(9,6550) DPWKC, DPWKC-MEM(20,1)
               IF (J1.EQ.2) WRITE(9,6500) DPWKE, DPWKE-MEM(20,2)
               IF (J1.EQ.3) WRITE(9,6600) DPCGE, DPCGE-MEM(20,3)
               IF (J1.EQ.4) WRITE(9,6650) DPCGC, DPCGC-MEM(20,4)
  500       CONTINUE
  600 CONTINUE

C  calc various, possible limits:
      QENT = ACV/3.413*NCV*LAM*(GC*SIG*RHOV/DPC/2)**0.5
      WRITE(9,7000) QENT
      ASMAL = AEV*NEV
      IF (AAV*NAV .LT. ASMAL) ASMAL = AAV*NAV
      IF (ACV*NCV .LT. ASMAL) ASMAL = ACV*NCV
      QSON = ASMAL*RHOV*LAM*660*3600/3.413
      WRITE(9,7100) QSON
      QHF = 5*929*PI*DE*LE
      WRITE(9,7200) QHF
      GO TO 10

  999 STOP

 1000 FORMAT(/1X,'LIQUID PROPERTIES:')
 1001 FORMAT(A)
 1002 FORMAT(1H1,A)
 1100 FORMAT(6X,'Viscosity (#/ft-h) =',4X,F7.4/
     1 6X,'Density (#/cu ft) =',3X,F9.4)
 1300 FORMAT(6X,'Latent Heat (BTU/#) =',1X,F7.2/
     1 6X,'Surface Tension (#/ft) =',1X,F8.6/
     2 6X,'Wetting Angle (deg) =',2X,F6.2)
 2000 FORMAT(/1X,'VAPOR PROPERTIES:')
 3000 FORMAT(/1X,'EVAPORATOR GEOMETRY:')
 3100 FORMAT(6X,'Vapor Wetted Perimeter/Channel (in) =',1X,F9.5/
     1 6X,'Vapor Flow Area/Channel (sq in) =',1X,F9.5/
     2 6X,'Number of Vapor Channels =',1X,I4)
 3200 FORMAT(6X,'Liquid WP/Channel (in) =',1X,F9.5/
     1 6X,'Liquid Flow Area/Channel (sq in) =',1X,F9.5/
     2 6X,'Number of Liquid Channels =',1X,I4)
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3300 FORMAT(6X,'Wick Pore Diameter (micron) =',1X,F5.1/
    1 6X,'Wick Permeability (sq in) =',1X,F15.13/
    2 6X,'Wick Thickness (in) =',1X,F9.5/
    3 6X,'Wick Radial Flow Width (in) =',1X,F9.5)
3500 FORMAT(6X,'Section Length (ft) =',1X,F6.3/
    1 6X,'Section Diameter (in) =',1X,F6.3)
3600 FORMAT(6X,'Circumferential Groove Width (in) =',1X,F9.5/
    1 6X,'C Groove Half Included Angle (deg) =',1X,F5.2/
    2 6X,'C Groove Threads per Inch =',1X,F4.0)
3700 FORMAT(6X,'Wick Length (ft) =',1X,F9.5/
    1 6X,'Wick Thickness (in) =',1X,F9.5/
    2 6X,'Wick Flow Width (in) =',1X,F9.5/
    3 6X,'Liquid Flow Length (ft) =',1X,F9.5)
4000 FORMAT(/1X,'ADIABATIC GEOMETRY:')
5000 FORMAT(/1X,'CONDENSER GEOMETRY:',A,' Condenser)')
5500 FORMAT(/1X,'============  ',F4.2,' in  TILT   =============')
6000 FORMAT(/2X,'=============  ',I1,'G  GRAVITY  ============='/
    A 1X,'Liquid Transport Limit (w) =',1X,F8.1/
    1 1X,'Heat Pipe Transport QL (W-in) =',1X,F10.1/
    2 1X,'Heat Pipe Evaporator Elevation (in) =',1X,F4.2)
6300 FORMAT(1X,'HEAT PIPE PRESSURE DROPS (psi):')
6310 FORMAT(6X,'Evap Vapor Viscous =',2X,F9.6/
    A 6X,'Evap Vapor Inertial =',1X,F9.6/
    B 6X,'Adiabatic Vapor =',5X,F9.6/
    C 6X,'V Transition Vapor =',2X,F9.6/
    D 6X,'Cond Vapor Viscous =',2X,F9.6/
    E 6X,'Cond Vapor Inertial =',1X,F9.6/
    F 6X,'Cond Grooves =',3X,F9.6/
    G 6X,'Condenser Wick =',6X,F9.6/
    H 6X,'Condenser Liquid =',4X,F9.6/
    I 6X,'V Transition Liquid =',1X,F9.6/
    J 6X,'Adiabatic Liquid =',4X,F9.6/
    K 6X,'Adiabatic Wick =',6X,F9.6/
    L 6X,'Adiabatic Liquid =',4X,F9.6/
    M 6X,'Evaporator Liquid =',3X,F9.6/
    N 6X,'Elevation of Liquid =',1X,F9.6/
    O 6X,'Evaporator Wick =',5X,F9.6/
    P 6X,'Evap Grooves =',3X,F9.6)
6400 FORMAT(6X,'** TOTAL **',19X,F9.6/
    1 1X,'MAXIMUM WICKING PRESSURES (psi):')
6500 FORMAT(6X,'Evaporator ''Wick'' =',
    1 1X,F7.5,3X,'Difference: ',F8.5)
6550 FORMAT(6X,'Condenser ''Wick'' =',
    1 2X,F7.5,3X,'Difference: ',F8.5)
6600 FORMAT(6X,'Evaporator Groove =',
    1 1X,F7.5,3X,'Difference: ',F8.5)
6650 FORMAT(6X,'Condenser Groove =',
    1 2X,F7.5,3X,'Difference: ',F8.5)
7000 FORMAT(/1X,'ENTRAINMENT LIMIT (w) =',1X,F10.1)
7100 FORMAT(1X,'SONIC LIMIT (W) =',1X,F10.1)
7200 FORMAT(1X,'(ROUND EVAP) HEAT FLUX LIMIT (W) =',1X,F10.1)
     END
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