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Evaluation of Commercially Available Spacecraft-Type Heat Pipes

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As part of an effort to develop reliable, cost-effective spacecraft thermal control heat pipes, life tests are being conducted on 30 commercially available heat pipes in ten groups of different design and material combinations. Results for seven groups are reported herein. Materials are aluminum and stainless steel; working fluids are methanol and ammonia. The formation of noncondensible gas was observed for times exceeding 11,000 h. The heat transport capacities of the pipes were also determined. Considerable gas was found in two groups of methanol pipes; one group showed no gas. One group of ammonia pipes had no observable gas while another group had much gas. Manufacturers' processing schedules were examined for differences, explaining the presence of gas. Heat transport capacity was found to be severely reduced in some pipes containing gas.

Introduction

THERE has been an increasing interest in the development of reliable, cost-effective heat pipes for spacecraft thermal control. A program was therefore initiated to assess the reliability and performance of commercially available spacecraft thermal control pipes. The types and sources of pipes procured for the program reflect the variety of fabrication and processing techniques described in Ref. 1.

One of the main factors investigated was the evolution of noncondensible gas by corrosion reactions of working fluids with the heat pipe structure. This troublesome phenomenon can occur with working fluids that are compounds, degrading heat pipe performance and shortening useful life.[2-5] Life tests were conducted for a period exceeding 11,000 h with temperature evaluated to 60°C to accelerate the formation of gas. Another factor observed was the heat transport capacity in 1 *g*.

The purpose of this study was to supplement the survey of Ref. 1 with laboratory experience on spacecraft thermal control heat pipes. In conjunction with Ref. 1, the information herein may facilitate decisions as to processing procedures necessary for adequate life. An additional benefit may be improved knowledge of heat pipe characteristics among potential users.

Advances in technology since the pipes were manufactured in 1974 could result in any of the manufacturers proposing items differing from those reported herein both in construction and processing.

Apparatus and Test Procedure

Heat Pipes

Pipes of ten different types were purchased from four manufacturers. This paper is confined to those pipes for which the testing time exceeded 11,000 h on Jan. 1, 1978.

The fabrication and processing represented the then current procedures for each of the manufacturers and are reflected in the inputs to Ref. 1. Three pipes of each type were purchased to give a better sample. All pipes were approximately 92 cm in length and 1.27 cm in diameter.

Table 1 provides an index of the heat pipes tested, associating heat pipe groups with the internal configuration, working fluid, envelope material, and processing schedule. Tables 2-4 present the processing schedules provided by the manufacturers.

Figure 1 shows the internal configurations. All tubes were threaded the entire length with grooves. Configuration I consisted of a metal fiber slab wick and two screen arteries. A cap of thin foil at the evaporator end of the arteries was perforated with tiny holes to vent gas trapped in the arteries. Configuration II consisted of multiple screen arteries centered by a screen support. Configuration III had an artery of spiraled screen contained in a screen tube and supported by six screen pedestals. All internal parts were 304 stainless steel except for configuration II in which 316 stainless steel was used. All envelopes or tubes were made of either 6061-T6 aluminum or of 304 stainless steel.

Test Facilities

Each heat pipe is mounted on a support plate. The plate, in turn, is attached to a mounting flange. A vacuum housing, of about 15 cm diameter, is clamped to the flange. This housing is evacuated to about 8 N/m^2 (60 mTorr). The mounting flange pivots on an instrument rack and a jack screw on the end of the housing enables evaporator elevation to be adjusted.

Each pipe is fitted with an evaporator heater on one end and a condenser heat extractor on the other end. The heater is a stainless tube of 2.5 cm diam and 30.5 cm length sprayed with alumina, wound with resistance wire, and resprayed. A split annular aluminum sleeve is inserted between the heater tube and the heat pipe. Thermal conduction grease is applied liberally to the surfaces of contact. The first 5-cm section of the sleeve is spaced from the remainder by a plastic disk. The resulting partial thermal isolation of the thermocouple at the evaporator end makes response to dryout a little more sensitive. Radiation losses are reduced by several wraps of aluminum foil over the heater. The 30.5-cm heat extractor consists of a series of split brass blocks of about 2.5 cm length spaced slightly apart. The block halves are penetrated by two stainless tubes brazed to form half a heat extractor. The two halves are clamped on the pipe by two bolts through each block. The blocks are spaced off the condenser by shrink tubing of 0.03 cm thickness. Coolant circulates through the stainless tubes in such a manner that the average sink temperature is uniform along the condenser.

Temperatures are measured by 19 iron, constantan thermocouples – three in the evaporator, five in the adiabatic section, and one on top between the two halves of each condenser block pair. Couples in the condenser and adiabatic sections are spotwelded on stainless pipes and are glued down on aluminum pipes with thermal epoxy cement. The thermocouple installation on the evaporator is described elsewhere.[5] Figure 2 shows the locations of the thermocouples on the pipes. An additional thermocouple in the evaporator is connected to an overtemperature sensor, set to shut the heater off at about 75°C.

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Table 1 Index of heat pipes[a]

Heat pipe group	Heat pipe numbers	Internal configuration	Working fluid	Envelope material	Processing schedule
A	1,2,3	I	Methanol	Stainless	1
B	4,5,6	II	Methanol	Stainless	2
C	7,8,9	III	Methanol	Stainless	3
D	10,11,12	I	Ammonia	Aluminum	1
E	13,14,15	II	Ammonia	Aluminum	2
F	16,17,18	III	Ammonia	Aluminum	3
G	19,20,21	II	Ammonia	Stainless	2

[a] All wick and artery structures were stainless steel.

Table 2 Processing schedule no. 1

Artery or wick	Envelope
Cut, form wick	Machine end caps
Cut screen, clean[a]	Solvent clean caps
Vacuum fire screen 1000°C, 1h	Al caps, anneal
Form, weld artery	Stainless caps, weld fill tube
Attach artery cap	Caps, clean[a]
Clean artery[a]	Tubes, clean,[a] groove, cut to length
Bubble test artery	Tubes, clean[a]
Seal artery	
Spot arteries to wick	
Clean assembly[a]	
Vacuum fire, Al pipes only, 1000°C, 1 h	
Insert wick in pipe, weld end caps	
Stainless pipes, vacuum fire 1000°C, 1 h	
Stainless pipes, pressure test	
Helium leak check	
Process and fill[b,c]	
Functional test	
Closure and leak test	

[a] Ultrasonic clean in Freon, acetone, then hexane. Vacuum bake 15 min at 100°C after each clean, store.

[b] Vacuum bake heat pipe 160°C, 12 h. For Al pipes: vacuum bake transfer lines, reservoir 30 min at 70°C. Charge reservoir, rebake lines, transfer fluid to pipe. Reflux 125°C, 4 h, dump. Transfer final charge, reflex 80°C, 2 h, burp. Stainless pipes: bake transfer lines, reservoir 105°C, 13 h, final charge the pipe.

[c] Ammonia of 99.998 vol % purity, distilled into charge reservoir. Methanol, spectroscopic grade with less than 0.05% moisture.

Table 3 Processing schedule no. 2

Artery or wick	Envelope
Fabricate assembly	Machine in water soluble oil
30 min wash in 25% HNO_3	Anneal stainless end plugs only, 815°C
Rinse in cold tap water	Flush in tap water
Rinse in distilled water	Flush in distilled water
Outgas at 120-135°C, 8 h at 10^{-5} mm Hg	Al tubes, etch[a]
	Check residue, repeat flushes[b] if needed
	Outgas at 120-135°C, 8 h at 10^{-5} mm Hg
Pull wick into heat pipe using isopropanol lubricant	
Remove isopropanol, purge with argon	
TIG weld end plugs	
Charge working fluid,[c] agitate 5 min and dump, three times	
Charge to 50% free internal volume, reflux 5 days at 65°C, dump	
Charge with small overload, reflux 3 days at 65°C	
Purge noncondensible gas, adjust charge	
Pinch off, weld, leak test	

[a] Triacid etch solution (CrO_3, HNO_3, H_2SO_4) 5 min. Repeat water flush. Flush with 2-propanol.

[b] Stainless, water flush. Al, 2-propanol flush in addition.

[c] Ammonia processed after receipt to 99.99% purity, 7 ppm H_2O, 10 ppm nonvolatile. Methanol was 99.9% pure, with 0.02% H_2O, 0.0001% nonvolatile material.

A cooling system circulates water to the heat extractors, except when performance or noncondensible gas is being checked. The temperature of the water is adjusted to hold the adiabatic section temperature to 60 ± 1.5°C. For performance and gas checks, a temperature-controlled bath of ethylene-glycol water mixture with a small circulating pump is attached to individual pipes and is capable of providing temperatures from −10 to 60°C.

A data system controlled by a desktop computer was used to obtain data.[5] This system was also used to plot the data for evaluation from recordings on tape cassettes. A typical data plot is shown on Fig. 3.

Results and Discussion

Noncondensible Gas Accumulation

The noncondensible gas inventory was checked at the start of testing, at an intermediate time, and near the time of reporting. The latter times varied. For taking of the gas data the coolant bath was operated near 0°C. The relatively low adiabatic temperature and heat pipe internal pressure assured that the noncondensible gas occupied as much of the condenser as possible.

The moles of noncondensible gas were computed from the thermocouple readings by the ideal gas law. The vapor cross-sectional area of the pipe at any operating temperature was computed from the total working fluid inventory, the amount of working fluid in the vapor phase, and the total volume of the pipe available for liquid and gas. The vapor cross section area of the pipe was assumed constant with position. For best determinations of gas the evaporators were placed 0.3 cm below condensers. Puddles detected in some pipes were thereby moved out of the condenser.

Methanol Pipes

At the time of startup and also around 4300 h data were taken which were suitable for a visual, qualitative judgment as to the presence of gas. At about 12,000 h a better determination of gas was made. The results are shown in Table 5.

Heat pipes of Group A showed no gas even at the 12,000-h point. One of the heat pipes of Group B and one of Group C showed noncondensible gas at startup. This represents either gas introduced in processing or gas generated on the shelf during the interval between manufacture and startup. For the methanol pipes this was a span of 23-25 months. At the 4300-h point, all pipes of Group B and one of Group C had observable gas.

At the 12,000-h level, all pipes of Groups B and C had gas. On the average, Group B had about two and one-half times the gas of Group C. The gas in Group B was sufficient to shut off nearly all of the condenser at a typical gas check condition of 12 W heater power and adiabatic temperature of 27°C. This is shown in Fig. 3, a typical plot produced by the data system for data stored on tape.

Noncondensible gas evolution in methanol, stainless steel pipes had been previously studied.[3] Equations contained

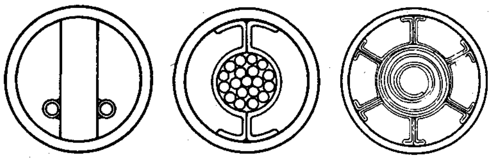
CONFIGURATION I CONFIGURATION II CONFIGURATION III

Fig. 1 Internal configurations.

Table 4 Processing schedule no. 3

Artery or wick	Envelope
Passivate screen[a]	Machine
Wrap screen	Passivate stainless[a]
Priming test	Deoxidize aluminum[b]
Fabricate retainers	
Weld assembly	
Repeat priming test	
Pull arteries into pipe	
Weld end caps and fill tube	
Water test to 1.4×10^7 N/m^2, 5 min	
Bake out in vacuum	
Al pipes, 175°C, 2 h	
Stainless pipes, 315°C, 4 h	
Charge with unprocessed charge, reflux 12 h, dump	
Evacuate final charge with processed ammonia or unprocessed methanol	
Check noncondensible gas, thermal test, pinch off	

[a] Passivation of stainless includes cleaning, immersion in nitric acid or a dichromate, rinse, dry.

[b] Deoxidation of aluminum pipes includes brush scrubbing with solvent, several dips in solvent, dip in alkaline cleaner, rinse in water, immersion in chromate deoxidizer, rinse in tap water, dry in filtered air, flush in isopropanol, dry in heated N_2, and bagging or capping.

[c] Ammonia, ultrahigh purity 99.999%, processed by several freeze-thaw cycles. Methanol, 99.9% pure.

therein, based upon experiment, enable a "theoretical" gas evolution to be computed. The variables are time, temperature, and total area exposed to the working fluid. For the methanol pipes in the present tests, the theoretical quantity of gas evolved at 60°C over 12,000 h is found to be in the range of 3×10^{-6} g moles. This amount of gas is undetectable in our facility. It is also 1-2 orders of magnitude less than that measured for pipes of Groups B and C.

Comparison of processing schedules for methanol, stainless steel pipes of Groups A, B, and C (Tables 2, 3, and 4, respectively) indicate one possible noteworthy variation. The pipes of Group A were vacuum fired to 1000°C for 1 h after assembly, and the pipes of Group C were fired to 315°C for 4 h. These groups had less gas than the pipes of Group B for which no such firing is indicated.

Ammonia Pipes

Table 6 presents noncondensible gas in ammonia-filled pipes. The pipes of Group D show by far the most gas. Indeed, considerable gas was present in pipes 10 and 11 at the start of testing. These pipes, with the rest of the ammonia pipes, except pipe 12, were on the shelf about 18 months before startup. Pipe 12 of Group D was accidently punctured at installation. After reprocessing and refilling by the manufacturer, it was placed on test within 2 weeks. This pipe showed no gas at startup, and less than half as much as its siblings after the 12,000- to 14,000-h points. The conclusion seems to be that the gas in pipes 10 and 11 was not introduced in processing, but accumulated on the shelf at room temperature.

The pipes of Group D represent a couple between aluminum and stainless steel. Electrochemistry cannot bear the entire blame for the amounts of gas formed relative to the other pipes since Groups E and F also produce couples. Moreover, all stainless steel pipe 21 of Group G showed as much gas as a pipe in Group E, processed in a manner similar to Group G. Reference to the processing schedules of Tables 2, 3, and 4 for insight as to the possible cause of gas in Group D is inconclusive. For instance, pipes of Groups D, E, and F received reflux charges which were dumped before final filling. Group F was refluxed with unprocessed ammonia and filled with processed ammonia. Group F was treated with dichromate deoxidizer. Therefore, the processing of Group E resembles that of Group D more than Group F, yet Group D formed much more gas than any pipes of Group E.

The pipes of Group D were cleaned and baked to an extent probably exceeding the others. The conjecture can be made that perhaps the cleaning was responsible for the gas. Indeed, recent work[2] has suggested that the deliberate introduction of contaminating water in the charge to be refluxed and dumped may greatly lessen gas formation.

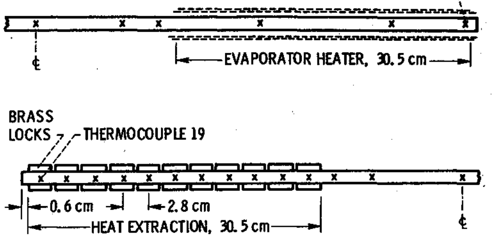

Fig. 2 Thermocouple locations.

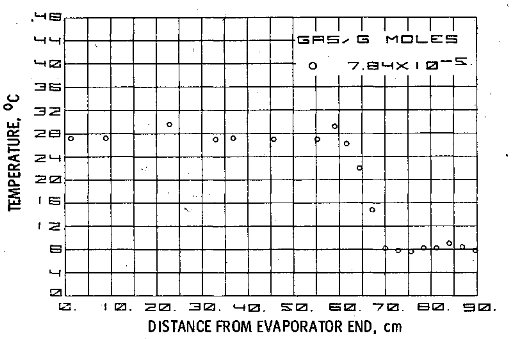

Fig. 3 Temperature profile for pipe 6 showing noncondensible gas.

Heat Transport Capability

The 1 g heat transport capability was determined for the pipes where feasible. The tests were conducted at about the same time as the most recent gas accumulation checks reported in Tables 5 and 6. Power to the evaporator heater was used as the heat input to the condenser. Very little was lost to the environment because of radiation shielding of the heater, low heater temperature, and enclosure in a vacuum. The procedure was to set an evaporator elevation by raising the upstream end of the evaporator a predetermined amount above the downstream end of the condenser. Power was increased in increments until dryout was detected. Usually thermocouple 1 (Fig. 4) would suddenly begin rising without apparent limit. In some instances one or more thermocouples of the evaporator would increase by several degrees after power was changed, but would stabilize. This was also interpreted as dryout, possibly of grooves only, and was usually followed by runaway dryout with a further small increase in power. No distinction has been made in these modes of dryout. About 10 min was allowed between power changes for equilibrium to be restored. Care was taken to reprime the liquid carrying structures after dryout by shutting off power and lowering the evaporator below the condenser for a period of time. The nominal adiabatic temperature was chosen as 50°C for the tests, and was maintained wherever the cooling system would allow.

Table 5 Noncondensible gas in methanol heat pipes at various times

Heat pipe group	Heat pipe no.	Gas at start of testing, g mol	Gas at time T_1		Gas at time T_2	
			g mol	T_1, h	g mol	T_2 h
A	1	0	0	4330	0	12290
	2	0	0	4330	0	11856
	3	0	0	4240	0	12420
B	4	0	a	4390	9.0×10^{-5}	12480
	5	a	a	4330	10.0×10^{-5}	12414
	6	0	a	4230	7.0×10^{-5}	12090
C	7	a	a	4370	3.6×10^{-5}	12680
	8	0	0	4260	5.2×10^{-5}	11040
	9	0	0	4230	1.6×10^{-5}	12290

[a] Gas present, amount not determined.

Table 6 Noncondensible gas in ammonia heat pipes at various times

Heat pipe group	Heat pipe no.	Gas at start of testing, g mol	Gas at time T_1		Gas at time T_2	
			g mol	T_1, h	g mol	T_2, h
D	10	3.8×10^{-4}	7.3×10^{-4}	4390	10.1×10^{-4}	14220
	11	6.0×10^{-4}	10.2×10^{-4}	10100	9.4×10^{-4}	14280
	12	0	...	...	4.4×10^{-4}	12158
E	13	0	1.7×10^{-4}	10046	1.3×10^{-4}	14405
	14	0	0	4592	0	13794
	15	0	0	4600	3.3×10^{-4}	14136
F	16	0	0	9880	0	14347
	17	0	0	9739	0	14360
	18	0	0	10808	0	14415
G	19	0	0	2598	0	13032
	20	0	0	7919	0	12587
	21	0	0	9686	1.5×10^{-4}	14398

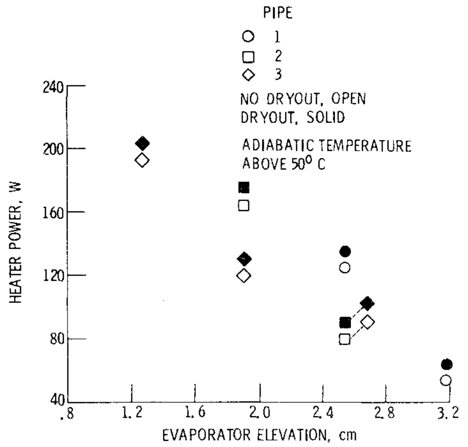

Fig. 4 Maximum heater power without dryout for methanol pipes of Group A.

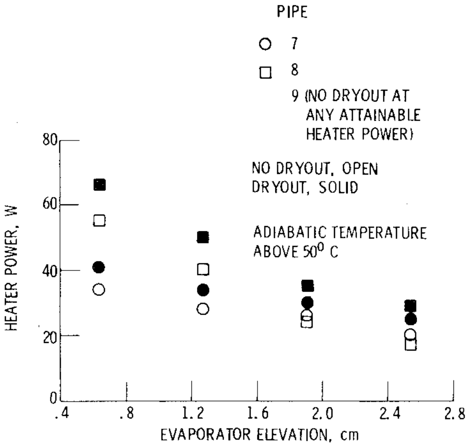

Fig. 5 Maximum heat power without dryout for methanol pipes of Group C.

Methanol Pipes

Figure 4 shows the maximum heater power before dryout against evaporator elevation for the methanol pipes of Group A. Below an evaporator elevation of 1.27 cm, a sufficiently low coolant temperature could not be obtained to hold the adiabatic temperature near 50°C because of the high power being transported. The heat capacity of this group of pipes at no evaporator elevation can be projected linearly to be about 290 W. A variable conductance pipe of similar internal design but twice the length, tested in a similar facility, gave results that extrapolate to about 230 W.

Because of the severe gas blockage, the pipes of Group B could not be tested for heat transport capability. The conductances of these pipes were reduced so much that excessive adiabatic temperatures would have been reached at any appreciable heat input. Data determined by the manufacturer at the time of shipment indicate that these pipes as a group should be capable of at least 150 W with no evaporator elevation.

Figure 5 shows maximum heater powers for dryout against evaporator elevation for pipes of Group C. Two pipes, 7 and 8, performed at a very low level which was substantiated by repetition on other occasions. Pipe 9, on the other hand, could not be dried out with 300 W at 2.5 cm or with 279 W at 3.8 cm. After the latter determination, pipe 9 was left unattended with 95 W at 0.63 cm over a lunch period and subsequently was found in the process of drying out. Gas inducted into the arteries of Group C possibly caused the low or erratic performance observed. The behavior of pipe 9 suggests that pipes of Group C design may offer very high

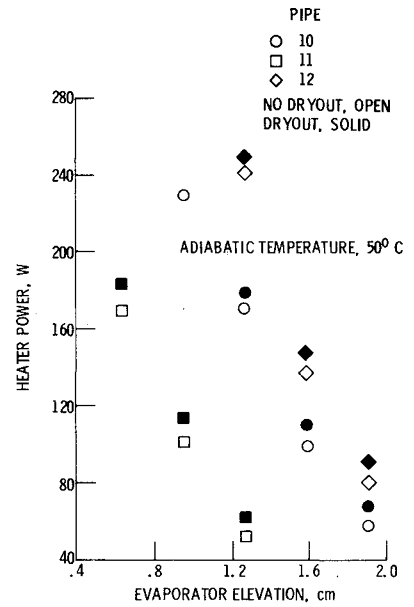

Fig. 6 Maximum heater power without dryout for ammonia pipes of Group D.

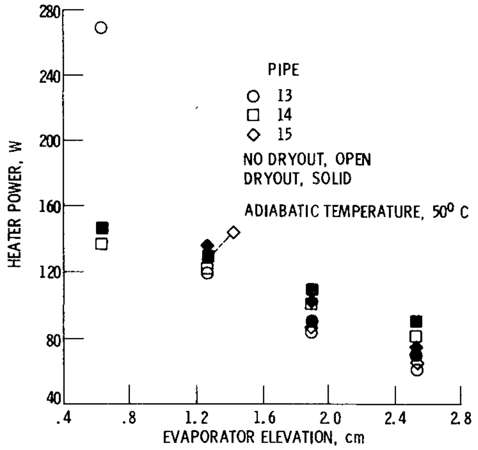

Fig. 7 Maximum heater power without dryout for ammonia pipes of Group E.

performance if problems due to the presence or generation of gas can be ameliorated.

Ammonia Pipes

Figures 6-9 show maximum heater power before dryout against evaporator elevation for the ammonia heat pipes of Groups D, E, F, and G, respectively. Most of the performance data for ammonia were obtained between about 12,000 and 15,500 h. Except as noted, the data were again taken at nominal adiabatic section temperatures of about 50°C.

The pipes of Group D show great sensitivity to change in evaporator elevation but promise high 0 *g* transport capacity. The best performers had three or four times the capacity of the poorest, pipe 11. Pipe 11 performance was checked at a later time and found to have worsened. These circumstances suggest the failure of an artery.

The pipes of Group E were less sensitive to change in elevation than those of Group D, but exhibited lower performance at low evaporator elevations. The anomalous behavior of pipe 13 will be discussed in the next subsection.

Two of the pipes of Group F exhibited very similar heat transport capacities over the range of elevations. Pipe 18, however, could not be dried out at any power attainable with the heater. Heat transport capacity otherwise resembled that of Group E.

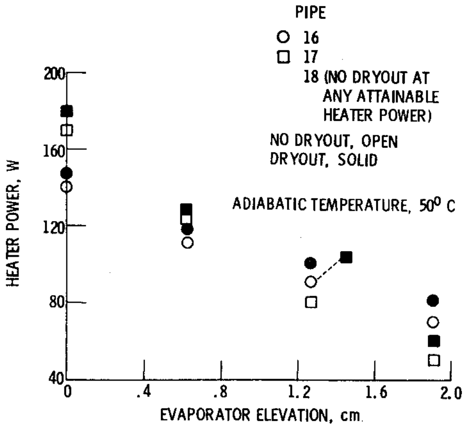

Fig. 8 Maximum heater power without dryout for ammonia pipes of Group F.

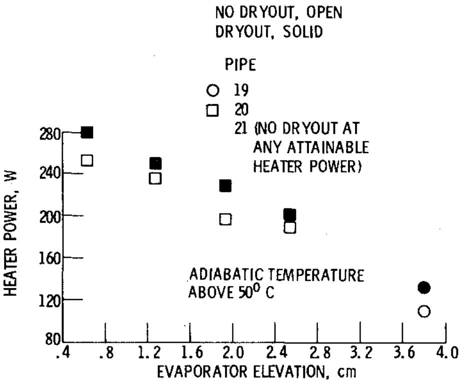

Fig. 9 Maximum heater power without dryout for ammonia pipes of Group G.

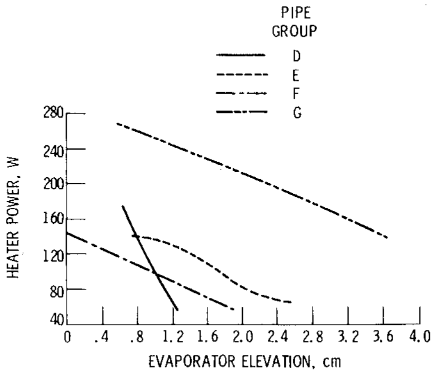

Fig. 10 Envelopes of maximum heater power without dryout for ammonia pipes of Groups D, E, F, and G.

Most heat transport data for the pipes of Group C could not be taken at the desired adiabatic section temperature of 50°C used for the other pipes. The temperature of the controlled bath could not be lowered sufficiently to maintain 50°C at the dryout power. This may have been due to increased thermal resistance between the heat pipe vapor and the coolant passages in the heat extractor. However, Group G exhibited higher transport capacity than any other group of ammonia pipes.

Group D promises performance similar to Group G at low elevation and therefore at 0 *g*. This can be seen on Fig. 10 where the envelopes of no dryout for the ammonia pipes from Figs. 6-9 are shown. An interesting feature is that all the aluminum-walled pipes, Groups D, E, and F, are clustered together, with the stainless pipes of Group G by themselves. However, the pipes of Group E and the pipes of Group G have the same internal configuration (Fig. 1).

Problem of Erratic Performance

Some pipes exhibited very erratic maximum heat transport capability. This is best exemplified by pipe 13 of Group E. At one point this pipe was found to dry out with 102 W at 0.63 cm evaporator elevation. Attempting to repeat this observation at a later time, the pipe was run to the 269 W point shown on Fig. 7 without dryout. The pipe was then returned to a lower power for a weekend. When an effort was made to continue the search for the dryout point the pipe dried out at less than 100 W. Possibly some arteries did not reprime despite considerable efforts to assure priming.

For this pipe and for others exhibiting erratic performance despite care, the possibility of partial blockage of arteries by gas must be reiterated. Whether noncondensible gas introduced to vary the thermal conductance becomes a problem may depend upon the pipe configuration with which it is used.

Conclusions

The studies described here of necessity represent the level of heat pipe design and processing technology that existed at the time of fabrication in 1974. While advances may have been made since then, the possibility exists that procedures leading to relatively gas-free pipes are not being uniformly observed. In methanol, stainless steel pipes, the inclusion of a very high-temperature vacuum bakeout after assembly may be desirable. In ammonia, aluminum-stainless steel pipes, the elimination of unwanted noncondensible gas still appears to be an art whose success may depend partly upon undocumented features in the processing schedule.

Acknowledgments

The skillful assembly and data-taking assistance of our technicians W. Frey and R. Schaal are gratefully acknowledged.

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