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TITLE: HEAT PIPE TECHNOLOGY ISSUES

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HEAT PIPE TECHNOLOGY ISSUES

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ABSTRACT

Critical high temperature, high power applications in space nuclear power designs are near the current state of the art of heat pipe technology in terms of power density, operating temperature, and lifetime.

Recent heat pipe development work at Los Alamos National Laboratory has involved performance testing of typical space reactor heat pipe designs to power levels in excess of 19 kW/cm^2 axially and 300 W/cm^2 radially at temperatures in the 1400 to 1500 K range. Operation at conditions in the 10 kW/cm^2 range has been sustained for periods of up to 1000 hours without evidence of performance degradation. The effective length for heat transport in these heat pipes was from 1.0 to 1.5 M. Materials used were molybdenum alloys with lithium employed as the heat pipe operating fluid. Shorter, somewhat lower power, molybdenum heat pipes have been life tested at Los Alamos for periods of greater than 25,000 hours at 1700 K with lithium and 20,000 hours at 1500 K with sodium. These life test demonstrations and the attendant performance limit investigations provide an experimental basis for heat pipe application in space reactor design and represent the current state-of-the-art of high temperature heat pipe technology.

INTRODUCTION

As self-starting, self-regulating, high efficiency means of transferring heat under high vacuum and zero gravity conditions, heat pipes are a logical choice for incorporation into space nuclear power system designs. Many current design concepts employ heat pipes both for high temperature heat transport from the reactor to the power converters and in system primary heat rejection.

Additional uses for heat pipes at or near reactor temperatures may be found in applications such as electromagnetic pump cooling, radiation shield cooling, control drum and motor cooling, and in start-up and shut-down thermal conditioning of liquid metal pumped heat transfer loops. As detail designs are developed heat pipes will also be used in the control of power conditioning equipment, in control electronics cooling, and in low temperature waste heat radiators for these systems.

Figure 1 illustrates these potential applications schematically. Current attention is focused on the two direct heat transport applications shown in the figure; primary heat transport from the reactor to the power conversion system and reject heat transport from the power conversion system to a surface radiating to deep space. These applications have received most attention in recent experimental investigations and are the primary interest in current discussions of heat pipe technology.

In these applications the characteristics of heat pipes that are of most interest are those concerned with their passive operation and with their ability to function over an extreme range of temperature, starting from below the melting temperature of the working fluid, without the need for thermal preconditioning. The passive operation provides for automatic handling of reactor decay heat as well as for restart after extended periods of nonoperation without the need for stored power for pumps or controls. The fact that heat pipes operate with minimal temperature differences is of importance in radiation coupled systems and in radiant heat rejection systems. Added to these operational advantages is the fact that heat pipe heat transfer systems are, by their nature, highly redundant systems offering multiple, independant heat transfer paths.

PRIMARY HEAT TRANSPORT HEAT PIPES

The operating requirements imposed on heat pipes used as primary heat transport devices in space nuclear power systems are summarized in Table I. Perhaps the most difficult of these requirements to satisfy within the present state-of-the-art will be operation of radiantly coupled heat pipes at a fraction of their design power for extended periods, and the demonstration of stable operation of heat pipes under a wide range of transient conditions. Demonstration of other operational requirements such as low temperature cold start with radiation coupling and extended operation at high temperature without loss of performance, will require further work but should not involve severe development problems.

Critical high temperature, high power applications for primary heat transport will be near the current state of the art of heat pipe technology in terms of power density, operating temperature, and lifetime. Use of heat pipes as the primary nuclear reactor core heat transfer mechanism, coupling directly to the power conversion system will entail operation of the heat pipes at the reactor core temperature and at high power density. With space nuclear power systems constrained to high operating temperatures by low conversion efficiencies and the need for radiant heat rejection, reactor temperatures will be in the 1000 K to 1700 K range. For the reactor core heat pipes this implies the use of alkaline metal working fluids and refractory alloy structures. Performance characteristics necessary for the reactor core cooling applications will involve radial power densities in the 100 w/cm^2 range and axial power densities of > 10 kW/cm^2 over heat transport distances of 3 to 5 M (Koenig and Ranken, 1982). These power levels are necessitated by system weight constraints, which lead to compact reactor designs, and by the need to maintain subcriticality during water immersion in the interests of safety, which requires minimizing heat pipe volume within the reactor core.

Typical values of performance requirements for these primary heat transport applications are summarized in Table II. In applications where the heat pipes are coupled directly into the reactor core there may be an additional requirement for the heat pipes to bend around the radiation shield, incorporating two or more bends of nearly 90^o in their length.

In reviewing the status of heat pipe technology in the light of these requirements the heat pipe design may be considered in terms of the physical elements involved, specifically the enclosure, the capillary structure, and the working fluid. Consideration must also be given to the problems involved in assembling these elements into the desired configuration. The resulting heat pipe designs may be characterized in terms of the steady state performance limits implied by the working fluid and operating temperature, and by the transient characteristics.

ENCLOSURE MATERIALS

Over the temperature range of interest for primary heat transport the enclosure material used for the heat pipes will be a refractory material with the usable range for various alloys determined from creep strength considerations. Other criteria of concern in material selection will be the ductile-brittle-transition temperature, chemical compatibility with the heat pipe working fluid and external coolants and for cases where in-core use is entailed, compatibility with the fuel in the accompanying radiation environment. Another factor affecting the choice of alloys will be fabricability, particularly if secondary operations such as bending are entailed in the heat pipe manufacture. In general, heat pipe use will probably not be the criteria of concern in alloy selection for space power systems so long as the heat pipe working fluid does not have excessive vapor pressure at the operating temperature of the system.

WORKING FLUIDS

Candidate working fluids in the temperature range of interest for primary heat transport will be the alkaline metals and their alloys. Vapor pressure curves for potassium, sodium, and lithium are given in Fig. 2. Design values of operating pressures in heat pipe applications will usually be 0.1 Bar or greater in order to minimize effects of residual gases or radiation product gases on performance. Upper pressure limits will be determined by the creep strength characteristics of the heat pipe enclosure material.

The usable temperature range of the working fluids will be determined by the heat pipe heat transport capacity as well as the vapor pressure. Maximum demonstrated values of axial heat flux density for alkaline metal heat pipes are summarized in Fig. 3. Values in the range of interest for primary heat transport (> 10 kW/cm^2) have been achieved in sodium and lithium heat pipes over the range of 1000 K to 1500 K (Vinz and Busse, 1973; Merrigan et al. 1982). Demonstrated values for radial power density are in excess of 300 W/cm^2 over the entire range from 800 K to 1500 K and therefore not a severe design constraint for current heat pipe cooled reactor designs (Keddy and Martinez, 1982).

WICK MATERIALS

These experimentally confirmed radial and axial power density values were achieved in heat pipes designed for extreme performance. Duplication of these values will require the use of some form of arterial heat pipe design with a fine pore wick structure having good permeability. For the typical primary heat transport performance requirements wick structure requirements will be as given in Table III. Values of wick permeability required will depend on the wick configuration used. For the classic artery configuration shown in cross section in Fig. 4a the flow path length through the wick structure from the artery to the furthest point of the liquid-vapor interface will be equal to half the distance between adjacent arteries while for the configurations shown in 4b, c and d the corresponding flow path length will be approximately equal to the wick thickness. The required wick permeability for equivalent performance from these different configurations will therefore differ by approximately two orders of magnitude assuming isotropic properties (Merrigan et al., 1982).

A variety of methods of producing wick structures with the desired characteristics are available. The 50 μm pore size requirement will require multiple layer of screen material of approximately 400 mesh if conventional screen wick fabrication techniques are used. If coarser mesh wire screen is used it must be treated to reduce the pore size. Methods that have been used for pore size reduction of refractory screen wick include chemical vapor deposition (CVD) coating of the wires as shown in Fig. 5 and mechanical compaction of layers of screen. Either of these methods is capable of reducing the pore size of 150-200 mesh screen wicks to the required 30-50 μm range. Difficulties in producing practical wick structures are related to the reduction in permeability seen in compacted screen wicks; and the difficulties in scaling CVD process tc the lengths required. Given an adequate development program the CVD scaling problem may be overcome through the use of zone deposition processes that would allow fabrication of indefinite lengths of wick structure; however the reduced permeability of compacted screen wicks is inherent and will limit their use to annular or channel wick heat pipe designs.

Alternatives to screen wicks exist in powder metal or microsphere compacts, either of which may be used to form wick structures with integral artery passages as illustrated in Fig. 6. As with CVD structures the primary impediment to their use in long heat pipes lies in the fabrication facility requirements, particularly the need for large, high temperature, high pressure, furnaces for hot isostatic pressing. These facility requirements have led to the development and use of 400 mesh molybdenum-rhenium alloy screen wick materials for the high temperature, high power heat pipe development work conducted at Los Alamos National Laboratory for the SP-100 program (Ranken, 1982).

A cross section of one of these screen artery and distribution wick structures is shown in Fig. 7. A 2-m long, 1.58-cm diameter, molybdenum-lithium heat pipe of this construction has been tested to 22.6 kW throughput on the program. Peak power axial density achieved in test was greater than 19 kW/cm^2 without dryout (Merrigan et al., 1983).

WASTE HEAT RADIATOR HEAT PIPES

The second direct heat transport application of heat pipe technology to space nuclear power systems is in the area of primary power radiators. Performance requirements for radiator heat pipes under typical system operating conditions are summarized in Table IV. The operating temperature range will be approximately 500 K below that considered for the primary heat transport heat pipes with radial and axial power densities of 10% to 20% of those for the high temperature applications. Thermal transport performance limits of radiator heat pipes will not generally control their application, except in designs employing extreme lengths or complex geometry. Primary concerns in technology development for radiator heat pipes involve the reduction of weight per unit area of radiating surface while maintaining end-of-life heat transfer capability. In addition the normal heat pipe material concerns of strength at temperature and working fluid compatibility apply. For the radiating surfaces a high emissivity is necessary, either intrinsic to the heat pipe material or as a stable coating. Loss of radiating surface over the life of the system will occur primarily as a result of meteroid penetration of the heat pipes. The rate of loss may be calculated from meteroid velocity-density models if the behavior of the materials used is known to be ductile under hypervelocity impact (Lundberg et al., 1982). Cracking of heat pipe walls in brittle failure will increase the damage incurred over a given period of time and make prediction of loss rate difficult. These heat pipe material criteria favor the use of titanium-potassium systems to about 800 K, stainless steel-sodium from 800 K to $\sim$900 K and niobium alloy-sodium in the 900 K to 1100 K range.

Operational concerns for radiator heat pipes involve start-up of the system from below the freezing temperature of the heat pipe working fluid, operation with radiation coupling at a fraction of design power, and for deployable radiator configurations, the need to bend the heat pipe before or during operation. Capabilities in each of these areas have been demonstrated in heat pipe development programs at Los Alamos. Figure 8, reprinted from Girrens 1982, site changes. Demonstration of the required lifetimes at realistic values of temperature and mass flow is essential to the choice of heat pipes for system design concepts. A summary of relevant high temperature heat pipe life test data is given in Table V.

This summary, while not exhaustive, includes most available test data involving exposure of over 5000 hours for the material combinations and temperature ranges of interest. What is not shown in this or similar life test data summaries is that the directed heat flux for the majority of these tests was low. Most test capsules are radiation loaded without high emissivity surface treatment so that total power input is a few kilowatts and the directed power throughput to the condenser less than half of the input. Mass flow rate dependent corrosion mechanisms may not be disclosed by this type of testing. Recently Los Alamos has initiated a life test of a 2-m, radiation loaded, molybdenum-lithium heat pipe operated at 1500 K with a measured power throughput of 14 kW. This test has been operated for more than 1000 hours with a single interruption and without apparent deterioration of heat pipe performance. Continuation and extension of this type of testing is necessary to provide a reliability basis for space nuclear power system applications. Understanding of the life controlling phenomena is essential both to the development of accelerated test methods that will permit the accumulation of an adequate data base for reliability predictions in a reasonable length of time and to the control of the life limiting thermochemical degradation mechanisms. This understanding should come from the development of analytic models for equilibrium chemistry and reaction kinetics within the heat pipes. These models will have to be verified by tests involving close control of heat pipe internal chemistry. A first step to these goals has been taken with the development of shows temperature profiles along a 5.5 m, titanium-potassium heat pipe at successive intervals of one hour during a deliberately slow start-up transient. It may be observed that the condenser end of the heat pipe was held below the freezing temperature of the potassium working fluid for more than 4 hours without depletion of the working fluid supply in the evaporator region of the heat pipe. This is possible with alkaline metal working fluids because the extremely low value of vapor pressure at the triple point limits mass transfer to the frozen region of the condenser. The temperature profile of the same heat pipe operating at its design conditions of 3.1 kW and 775 K is given in Fig. 9. This steady-state temperature profile serves to illustrate the isothermal nature of heat pipe heat transfer, even over working lengths of 5.5 m. This characteristic is of particular advantage in radiation coupled systems. Operation of a radiator heat pipe during bending is demonstrated in the multiple exposures of Fig. 10. This sodium-stainless steel, flexible heat pipe has been repeatedly bent through a 180° arc while operating at approximately 900 K as well as with the sodium working fluid was frozen. When operating in the straight, deployed configuration the performance of this heat pipe is comparable to that of a conventional, rigid design.

LIFETIME DEMONSTRATION

In both primary heat transport and waste heat radiator applications for space nuclear power systems reliable operation of the heat pipes over multiyear periods is required. Internal thermochemical changes in high temperature heat pipes can affect their performance through alteration of fluid properties such as surface tension, through plugging or erosion of wick structures and through local accumulation of gas or liquid reaction products. Boiling limits may be altered by changes in wetting characteristics of the fluid or nucleation equilibrium thermochemical models for the molybdenum-sodium heat pipes tested at Los Alamos. These models have been successful in predicting vapor phase mass transport of molybdenum in sodium heat pipes under dryout conditions. Within the present state of knowledge recommendations pertaining to the achievement of long life in high temperature alkaline metal, heat pipes are quite general. First, it is observed both in chemical models and in practice that mass transport is primarily a function of containment levels in the tube and screen material and in the working fluid rather than being caused by basic solubility phenomena. Secondly, it is observed that maintaining a region of the heat pipe at temperature without a liquid phase present, as in evaporator dry out, leads to more severe corrosion than would otherwise be encountered, and finally it is observed that failures often occur at welds or areas where materials are not homogeneous. Quantification of these recommendations, as to allowable levels of containments, will require further research.

TRANSIENT BEHAVIOR OF HEAT PIPES

An area of concern for heat pipe applications in space reactor systems is the behavior of the devices under transient load conditions, both during start-up and shut down of the system and through operational variation of thermal loads. In laboratory testing of high power, radiation coupled heat pipes it has been observed that dry out during shutdown is possible if conditions are not properly controlled. An example is illustrated in Fig. 11 based on data taken during test of a 2-M molybdenum-lithium, annular wick heat pipe at Los Alamos. This heat pipe, which had been treated to obtain a surface emissivity of approximately 0.65, had been operated for an extended period with 14 kW throughput at 1500 K. During shutdown of the test for equipment maintenance the power coupled into the evaporator region of the heat pipe by RF induction was reduced in approximately 800 W increments. At a temperature of 1300 K and an input power level of about 7.2 kW, the heat pipe developed a hot spot in the evaporator region, triggering complete test shutdown. Subsequent examination of the heat pipe showed that lithium had been transferred from the evaporator region of the annulus to the condenser, apparently due to the continued high rate of radiation heat transfer from the condenser after the internal transfer of heat by the lithium vapor had become limited by sonic vapor velocity conditions at the evaporator exit. This test shut down was to some extent an artifact of the test method, caused by the constant power characteristics of RF induction heating, however if the evaporator reservoir of lithium were limited and the thermal capacitance of the structure surrounding the evaporator were high, a similar dryout situation could occur in a space power application. The determination of stable operating limits for heat pipes under the transient conditions to be expected in space nuclear power applications will be essential to their successful integration into such systems. Both analytic modeling and experimental verification under realistic conditions will be required.

SUMMARY

Recent heat pipe development work at Los Alamos National Laboratory has involved performance testing of typical space reactor heat pipe designs to power levels in excess of 19 kW/cm^2 axially and 300 W/cm^2 radially at temperatures in the 1400 to 1500 K range. Operation at conditions in the 10 kW/cm^2 range has been sustained for periods of up to 1000 hours without evidence of performance degradation The effective length for heat transport in these heat pipes was from 1.0 to 1.5 M. Materials used were molybdenum alloys with lithium employed as the heat pipe operating fluid. Shorter, somewhat lower power, molybdenum heat pipes have been life tested at Los Alamos for periods of greater than 25,000 hours at 1700 K with lithium and 20,000 hours at 1500 K with sodium. These life test demonstrations and the attendant performance limit investigations provide an experimental basis for heat pipe application in space reactor design.

Demonstrated performance for long heat pipes operating under space radiator conditions includes the transport of 2.6 kW and 920 K in a radiation loaded 4.4 m, sodium/stainless steel heat pipe developed by Thermacore Corporation for the Nuclear Electric Propulsion Program and the transport of 2.4 kW at 773 K in a radiation loaded, potassium/titanium heat pipe developed by Los Alamos National Laboratory. Flexible heat pipes intended for use in deployable space radiators have also been demonstrated at Los Alamos, with continuous operation achieved during bending of the pipe through 180°.

Technology development needs for space nuclear power heat pipe applications involve determination of the performance capabilities of specific heat pipe designs as a function of operating temperature, power density and local environmental conditions as well as the determination of the transient behavior of the devices during start-up, shut-down, and load variation. Finally an important concern in the application of heat pipes in a space nuclear power system is the lifetime to be expected and the type of performance degradation to be expected over the operating life. Prediction of operating lifetime of heat pipes will require the development of mass transport/corrosion chemistry models and their verification in controlled life tests.

TABLE I

PRIMARY HEAT TRANSPORT - OPERATING REQUIREMENTS

- Cold start from ∿ 200 K
- Stable operation during shutdown
- Restart after shutdown
- 7 - 10 yr operating life
- Fractional power operation

TABLE II

PRIMARY HEAT TRANSPORT - PERFORMANCE REQUIREMENTS

- Temperature: 1000 K to 1700 K
- Axial power density: 10 to 15 kW/cm^2
- Radial power density: 50 to 150 W/cm^2
- Transport distance: 3 to 5 m
- Temperature difference: < 10 K

TABLE III

PRIMARY HEAT TRANSPORT - WICKING REQUIREMENTS

- Pore diameter 30 - 50 μm
- Permeability 6×10^{-12} m^2 artery
  6×10^{-14} m^2 annular
- Bendable during fabrication

TABLE IV

WASTE HEAT RADIATOR PERFORMANCE REQUIREMENTS

o	Temperature	700 to 1000 K
o	Axial power density	0.5 to 1.0 kW/cm^2
o	Radial power density	2 to 20 W/cm^2
o	Transport distance	4 to 8 m
o	Temperature difference	< 20 k

TABLE V

HIGH TEMPERATURE HEAT PIPE LIFE TESTS

Fluid	Material	T(K)	Hrs	Failure
Lithium	Mo	1700	25,400	Evap. penetration
Lithium	TZM	1775	10,500	
			10,400	Weld failures
			9,800	
Lithium	W-26 Re	1875	10,000	
Lithium	Nb-1Zr	1776	9,000	
Sodium	Mo	1600	19,304	
Sodium	TZM	1500	19,304	
Sodium	Mo	1600	23,742	
Sodium	304 Stainless Steel	1073	12,760	
Sodium	Nb-1Zr	1120	16,000	
Potassium	Ti	900	5,000	
Potassium	347 Stainless Steel	780	6,500	

FIGURE CAPTIONS

1. Heat pipe applications in space power systems.
2. Liquid metal vapor pressure.
3. Demonstrated values of axial heat flux.
4. Heat-pipe wick structures.
5. Compacted screen wick.
6. Niobium porous metal artery wick inside 15.9-mm-o.d. molybdenum tube.
7. Screen wrap-compacted artery heat pipe configuration.
8. Axial temperature profiles of RAD-3 during start-up.
9. Comparison of analytical and measured temperature profile at maximum operating power.
10. Flexible heat pipe.
11. Transient performance of 2 M heat pipe.

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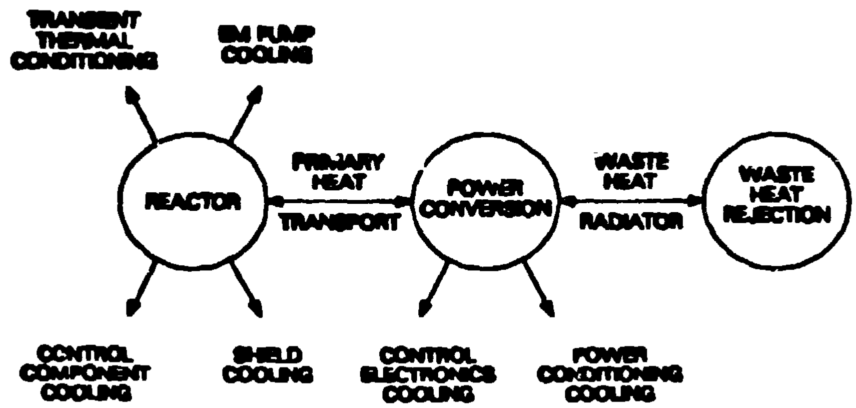

Fig. 1. Heat pipe applications in space power systems.

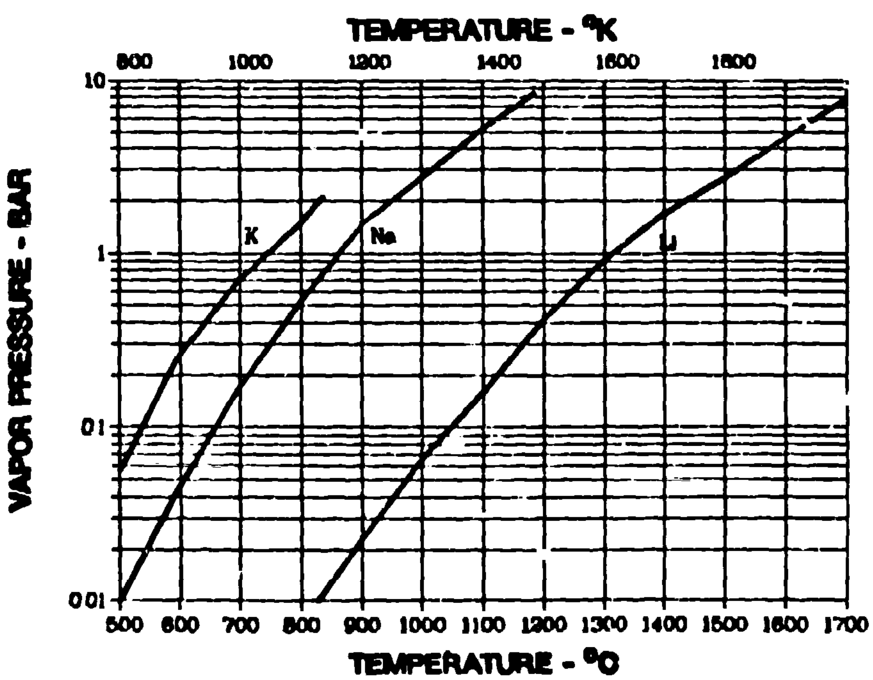

Fig. 2. Liquid metal vapor pressure.

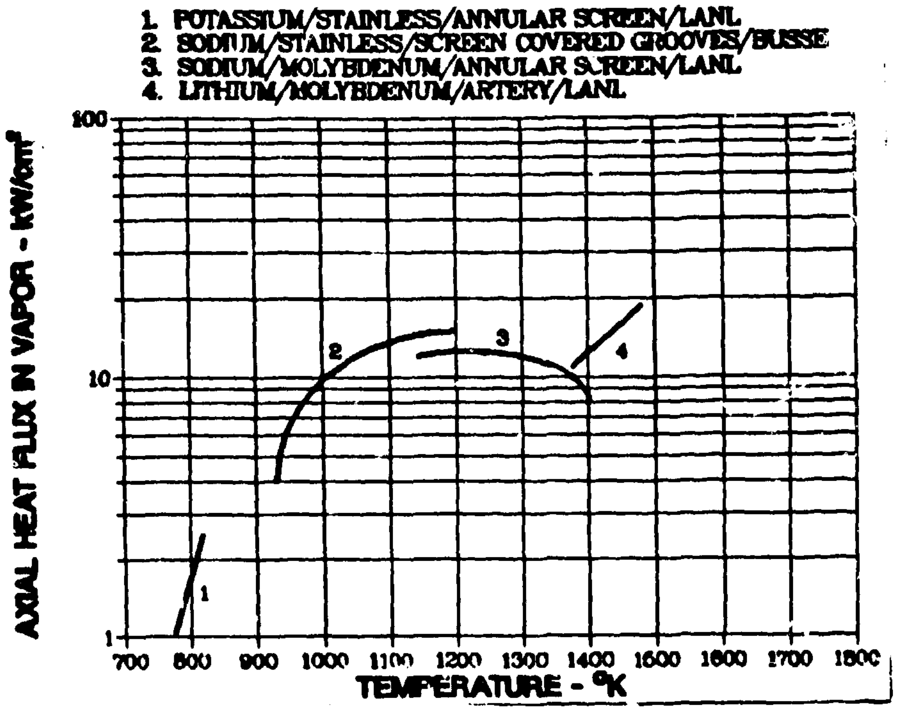

Fig. 3. Demonstrated values of axial heat flux.

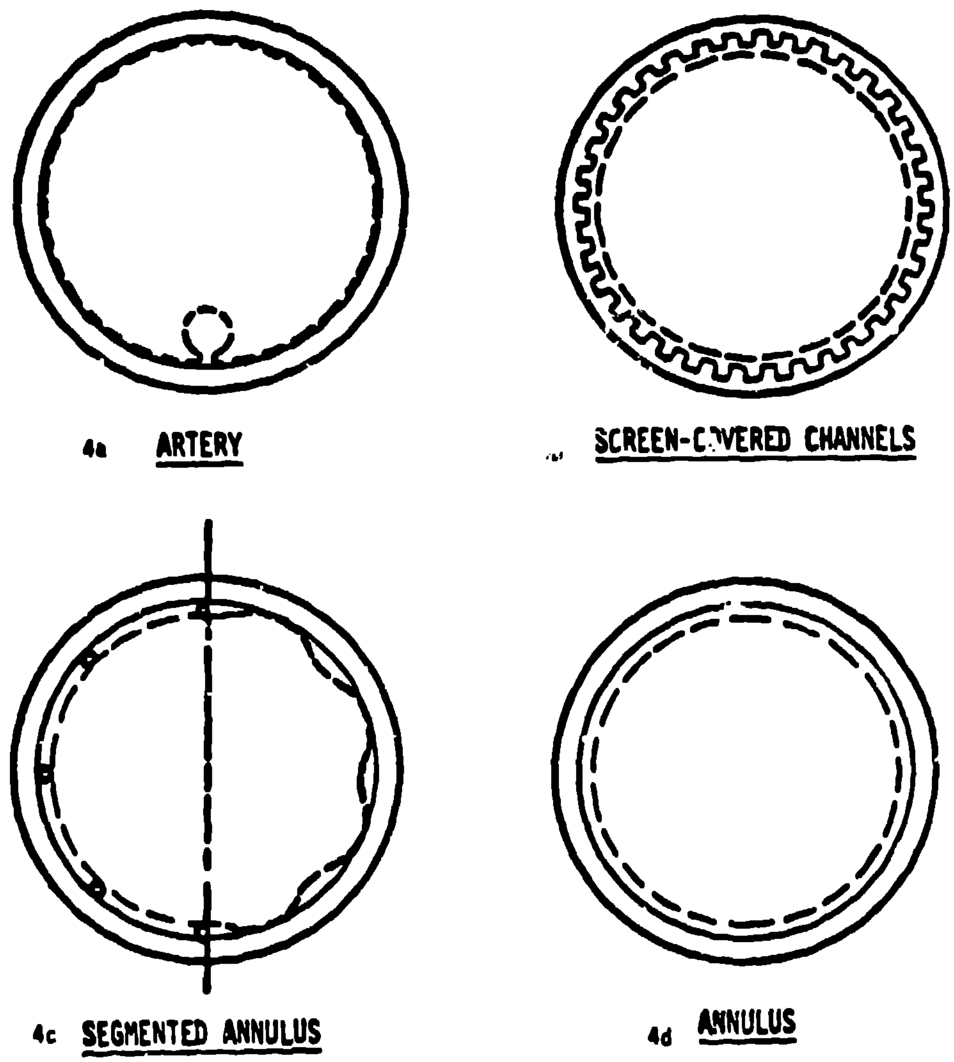

Fig. 4. Heat-pipe wick structures.

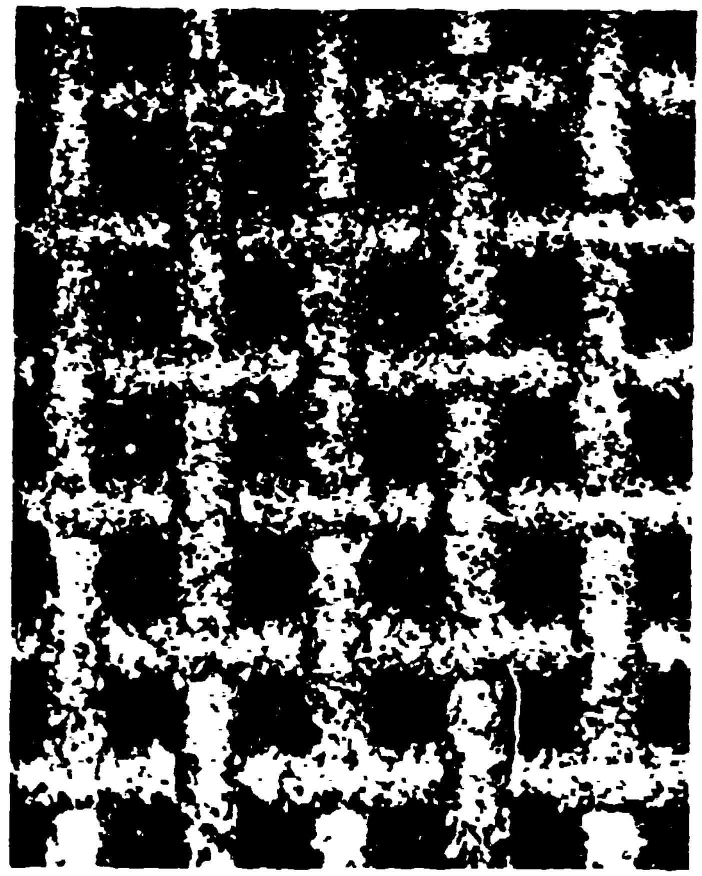

Fig. 5. Compacted screen wick.

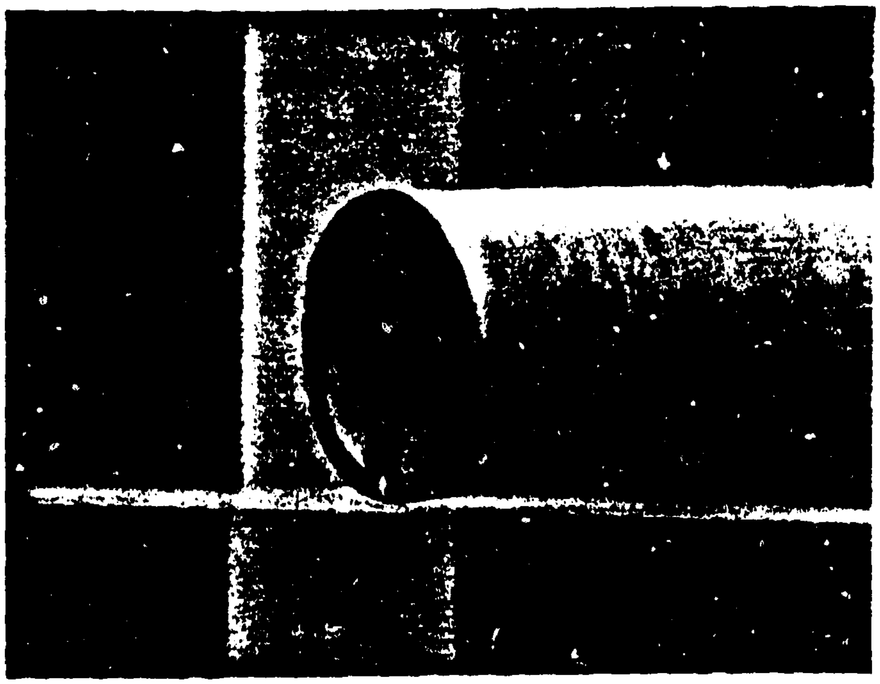

Fig. 6. Niobium porous metal artery wick inside 15.9-mm-o.d. molybdenum tube.

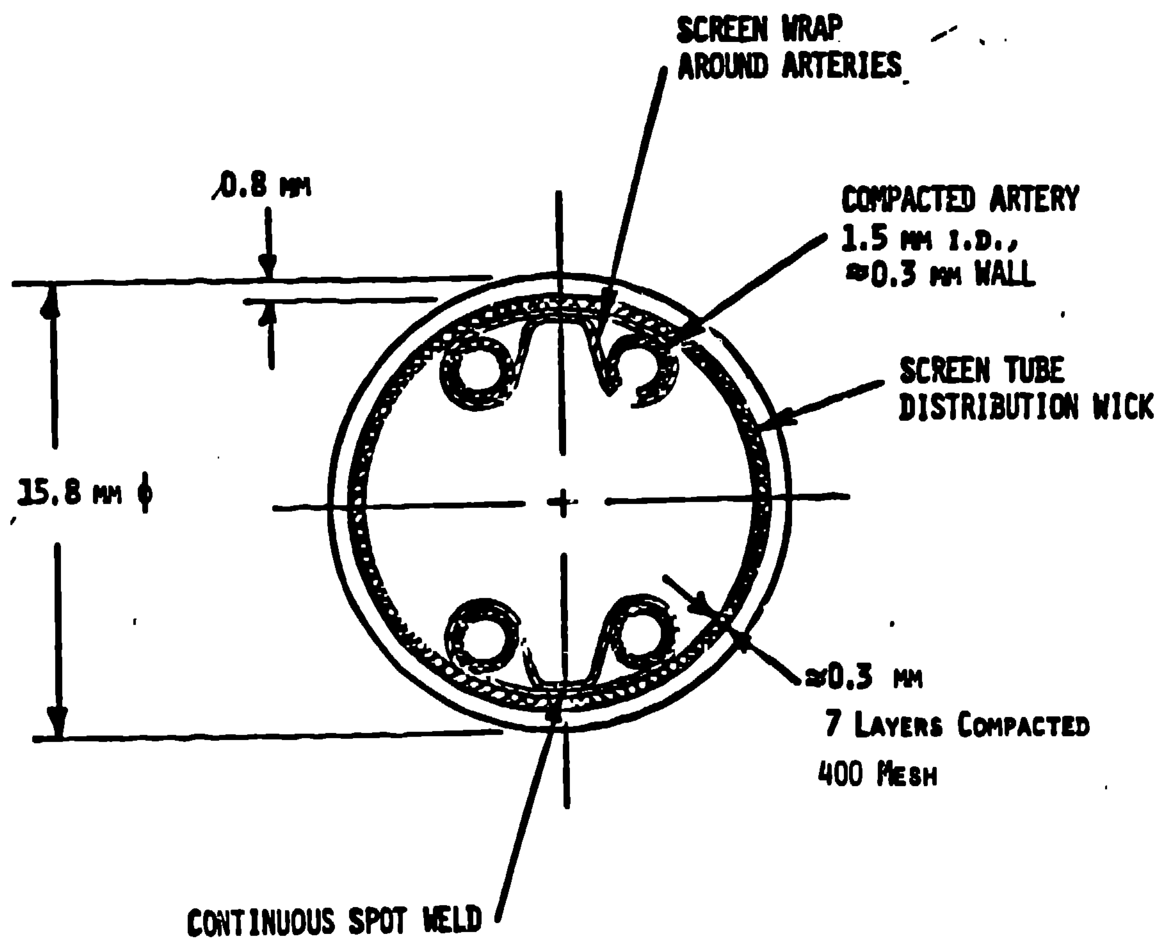

Fig. 7. Screen wrap-compacted artery heat pipe configuration.

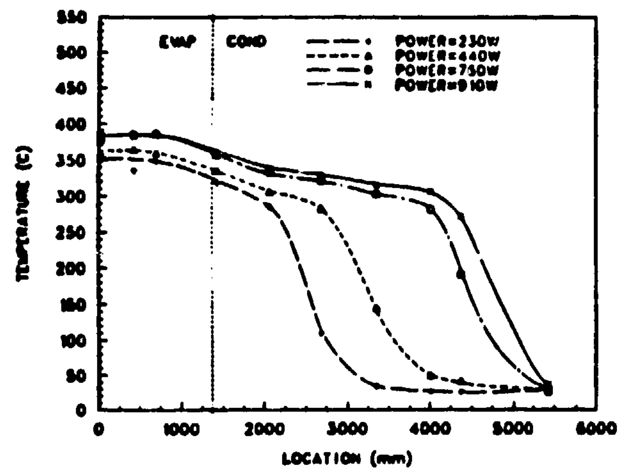

Fig. 8. Axial temperature profiles of RAD-3 during start-up.

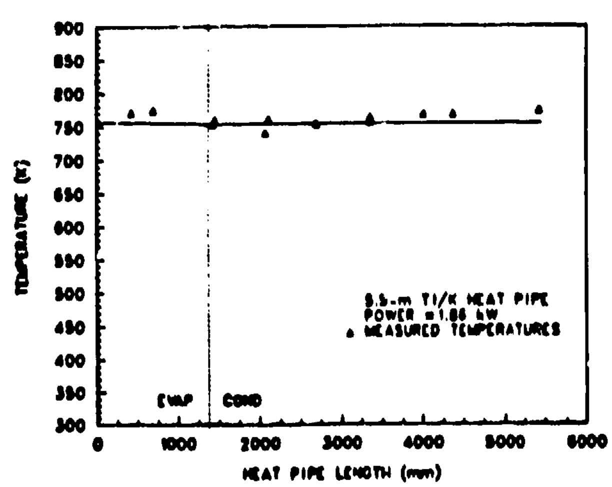

Fig. 9. Comparison of analytical and measured temperature profile at maximum operating power.

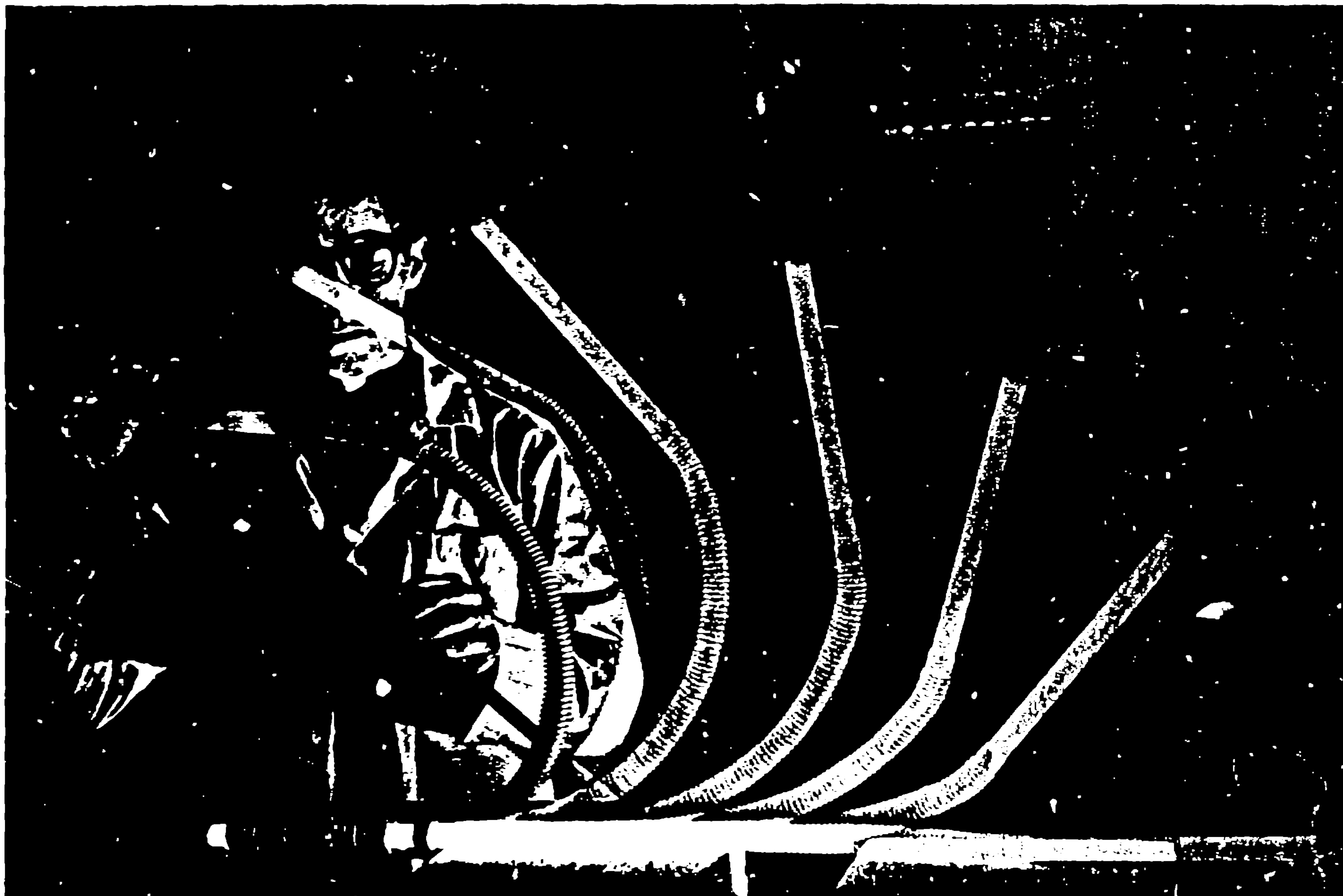

Fig. 10. Flexible heat pipe.

TRANSIENT PERFORMANCE

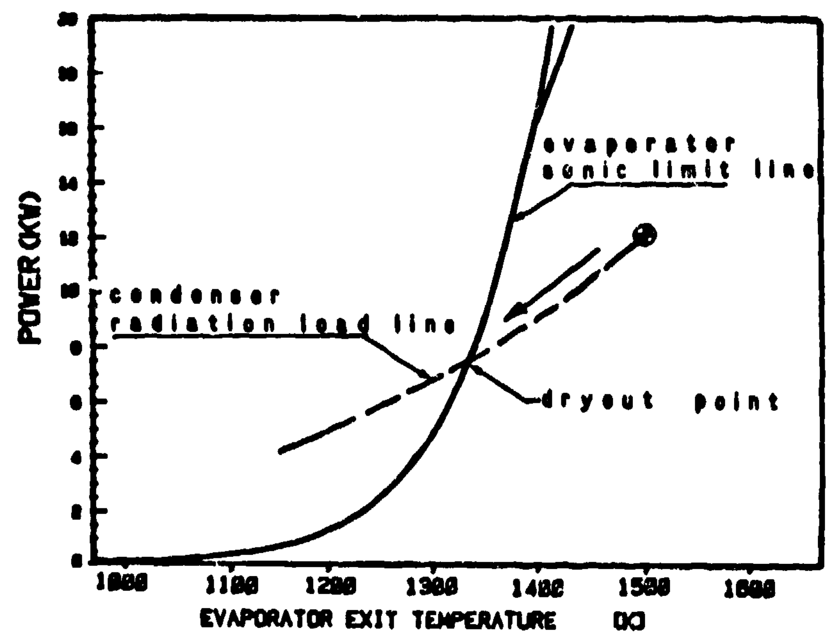

Fig. 11. Transient performance of 2 M heat pipe.

FIGURE CAPTIONS

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