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TITLE: DEVELOPMENT AND TEST OF A SPACE-REACTOR-CORE HEAT PIPE

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DEVELOPMENT AND TEST OF A SPACE-REACTOR-CORE HEAT PIPE

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Abstract

A heat pipe designed to meet the heat transfer requirements of a 100-kW_e space nuclear power system has been developed and tested. General design requirements for the device included an operating temperature of 1500 K with an evaporator radial flux density of 100 W/cm². The total heat-pipe length of 2 m comprised an evaporator length of 0.3 m, a 1.2-m adiabatic section, and a condenser length of 0.5 m. A four-artery design employing screen arteries and distribution wicks was used with lithium serving as the working fluid. Molybdenum alloys were used for the screen materials and tube shell. Hafnium and zirconium gettering materials were used in connection with a pre-purified distilled lithium charge to ensure internal chemical compatibility.

After initial performance verification, the 14.1-mm i.d. heat pipe was operated at 15 kW throughput at 1500 K for 100 hours. No performance degradation was observed during the test. This demonstration of power-transport capability and material compatibility at temperature has provided an experimental basis for heat-pipe-cooled reactor design. Continued development will be directed to long-term material compatibility demonstration and to the determination of power limits for the design.

I. Introduction

The use of heat pipes to transfer thermal energy from a nuclear reactor core to electrical conversion devices provides a number of system characteristics that are particularly advantageous in space power system applications. These advantages include the capability for use of liquid metals in phase change application without the need for fluid pre-heat, programmed fluid injection or any preconditioning of the system, and without the need for a core pressure vessel. The resultant mechanical simplicity provides for a high degree of system reliability. This inherent reliability is amplified by the redundancy provided by the large number of independent heat transfer paths represented by the heat pipes. A heat pipe cooled reactor core may be designed to tolerate loss of a number of heat pipes with minimal degradation of system performance and so eliminate the possibility of a single point heat transfer system failure leading to loss of overall system capability.

Transient performance, particularly during system start-up and shut down, is another area in which heat pipes confer advantages over alternative means of high temperature heat transfer. As the heat pipe will, over a wide range, adjust its performance to the loads imposed on it, concerns for coordination of reactor power output and core cooling system capability during start up are minimized. This is also true in system shutdown where the ability of heat pipes to handle high heat inputs without the need for an external power source provides an inherent ability to dispose of decay heat from the core.

As a result of these evident benefits of heat pipes in space reactor heat transfer, such an application was suggested shortly after the development of the high temperature heat pipe at Los Alamos National Laboratory.¹ Design studies of similar applications were conducted in the same period, primarily for out-of-core thermionic power conversion systems.²⁻⁵ Thermionic emitter temperatures for these designs ranged from 1600 K to 1800 K with typical assumed heat pipe axial power densities of 10-20 kW/cm². Various refractory materials were proposed for use in the heat pipe envelopes with lithium generally considered as the working fluid. Lower temperature application of heat pipes in Brayton cycle space power systems has also been considered⁶ using sodium as a working fluid at temperatures to 1200 K.

More recently a design study for a 100 kW_e space power system led to the choice of a heat pipe cooled reactor design employing thermoelectric conversion at a nominal temperature of 1400 K.⁷ This recent space power system study has provided the impetus for the current Los Alamos heat pipe development effort. In most of the prior studies heat pipe performance, particularly axial and radial power capability, was estimated, based on theoretical models or on sub-scale and sub-temperature tests. Few experiments at design conditions have been conducted. Exceptions include a demonstrated performance of 9.5 kW/cm² at 1820 K for 4000 hours⁸ and a peak power density of 15.5 kW/cm² at 1225 K.⁹ The need for supplementation of this limited body of experimental data on heat pipe operation under reactor design conditions has led to the present investigation.

II. Design Requirements and Rationale

The SPAR space nuclear power system, a 100 kW_e, UO₂ fueled fast reactor design studied by Los Alamos National Laboratory, uses heat pipes for thermal transport from the reactor core to thermoelectric elements located behind a radiation shield.¹⁰ These core cooling heat pipes are 2-m in length, with an evaporator length of 0.3 m, a 1.2-m adiabatic section, and a condenser length of 0.5 m. Nominal heat transport requirement in the SPAR configuration is 12.4 kW_t per pipe at an operating temperature of 1400 K to 1475 K. Corresponding design values for axial and radial heat flux are 9.3 kW/cm² and 106 W/cm² for the 15.8 mm o.d. heat pipes. In order to avoid single point failure modes the reactor core is designed to operate with a number of failed heat pipes. This mode of operation entails an increase in local fuel temperature and transfer of thermal load to adjacent heat pipes. The maximum thermal transport requirement for the heat pipes under these conditions is approximately 12 kW/cm².

The heat pipe configuration used to achieve these goals is an outgrowth of development work conducted at Los Alamos on similar heat pipes using sodium as a working fluid at slightly lower temperatures.¹¹ The most pertinent of these

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earlier designs employed a dual artery configuration with wicks formed of screen materials. The performance of this prior design was limited by the coarse mesh of the refractory screen material available at that time, however the development served to prove the fabrication and assembly techniques required for the screen artery and distribution wick configuration. Since that time 400 mesh molybdenum alloy screen wick material has been developed for use on the program, making possible the present heat pipe design (Fig. 1). This design uses four screen arteries attached in pairs to a screen distribution wick by means of a screen wrap tube. Lithium is used as the working fluid. Fig. 2 presents the predicted power limits for the design with all arteries functional, with two opposing arteries functional, and with only a single artery operational. The redundancy of the design is evident in the small decrease in performance from the four artery to the two artery case. This redundancy was intended to provide performance margin against any damage of the artery structures during assembly or deterioration in operation. The use of a separate screen wrap to retain the arteries was also intended as a protection against loss of performance due to distortion of the screen wicks during fabrication and assembly, in particular during weld attachment of the arteries to the distribution wick.

Fig. 1. Screen wrap-compacted artery heat pipe.

Predicted performance limit for the heat pipe, assuming laminar vapor flow, is more than 25 kW at 1500 K, nearly double the design value for the reactor application. This design margin is provided to ensure successful operation under off-design conditions and to reduce performance sensitivity to wick pore size variation.

III. Fabrication and Process Development

A 2-m-long, 15.8-mm-diam, artery heat pipe was constructed in the configuration outlined above. Arteries and distribution wicks were fabricated from 400-mesh screen of 0.025-mm diameter molybdenum/41% rhodium alloy wire. The arteries and artery wrap were formed by winding the screen on a steel mandrel, inserting in a steel tube and drawing the assembly through a tubing draw die to slightly compress the screen layers. The steel mandrels were then removed by acid etching.

Fig. 2. Core heat pipe performance.

This screen-wrapping technique eliminates the need for a separate sintering operation and provides rigidizing of the multiple screen layers to allow handling.

A flow sheet of the steps involved in the fabrication is shown in Fig. 3. The dual arteries are contained in a screen wrap tube, with spot welds joining the assembly to the expanded distribution wick. The screen edges are secured as shown in Fig. 4 to provide alignment of the screen on the mandrel and prevent separation after dissolving the mandrel. The spot welds were made with a Unitek 500 welder using a series nandpiece to increase pressure sensitivity. The standard 20N minimum triggering force was reduced to 4N for welds on the 0.025-mm-diam wires.

The distribution screen mandrel was made from 15.88-mm-o.d. x 0.89-mm stock SAEC1015 Shelby steel tubing drawn to 13-mm o.d. Wrapping a 305-mm-width screen on this mandrel gave the required 6-3/4 wrap distribution wick thickness. Expansion of the bladder and wrap into the TZM container was accomplished by pressurizing to 73 MPa. Radiographs were taken of samples to evaluate the contact between wick and container. Expansion of the distribution wick was controlled to preclude tension fracture of the screen while providing clearance for assembly. The limit of the expansion was determined with a sample using an intentionally undersized mandrel of 12.65-mm o.d., wrapped with 400 mesh screen to a screen outside diameter of 13.36 mm. The sample was expanded to a container bore of 14.22 mm, for a diametral expansion of 0.86 mm. A longitudinal crack in the wick, resulting from the overexpansion, measured 0.13 mm circumferentially. Subtracting this amount from the diametral expansion gave the point at which the screen reached its expansion limit at an increase of 0.82 mm in diameter. This value was

Fig. 3. Artery heat pipe fabrication.

used as an upper bound in the process development. For the final heat pipe assembly the 2-m bladder was drawn to 13.0-mm outside diameter so that, when expanded, the screen was at 62% of the limit. Samples of the 400-mesh molybdenum-rhenium screen tested under tension showed a 5.9% elongation at failure, in fair agreement with the 6.3% of the hydraulic sample. After expanding the distribution wick the inner mandrel was removed by acid dissolution.

Fig. 4. Securing the edges of multiple-layered screen.

Samples of distribution wick were made up using 400 mesh molybdenum-rhenium screen and tested for permeability prior to fabrication of the complete assembly. Measured values were in the 10^{-12} to 10^{-11} m² range, which was within range of the heat pipe design requirements.

Artery development involved varying radial compression and number of screen layers to achieve the desired pore size and permeability. Table I gives the parameters used to produce a final effective pore size of 45 μ m in the artery and artery wrap.

The artery wrap provided a means of attaching the dual arteries to the distribution wick without the necessity of welding directly to the arteries. The central trough of the artery wrap also provided the location for a hafnium ribbon getter. The wrap was sized to capture the dual arteries tightly and was compressed to provide a pore size equal to the arteries to provide capillary pumping continuity. The pore size was controlled by compacting the screen tube by drawing through a die with screen compression as indicated in Table I.

TABLE I
ARTERY MANDREL AND SHEATH DIMENSIONS

	Artery			
	Mandrel		Sheath	
	o.d. (mm)	i.d.	o.d. (mm)	i.d.
Predraw	1.6	0.25	4.0	2.97
Postdraw	1.6	0.25	3.81	

	Artery Wrap			
	Mandrel		Sheath	
	o.d. (mm)	i.d.	o.d. (mm)	i.d.
Predraw	5.97	4.19	9.35	7.75
Postdraw			8.08	

After drawing the artery wrap to size and removing the sheath and mandrel by acid etching, the wrap was preformed to provide parallel lobes to locate the arteries. Preforming was accomplished in a half-shell fixture, which provided a cylindrical supporting surface the length of the wrap. A forming mandrel was used in the preforming operation and remained attached to the arteries for use in pulling them into the wrap. Final forming of the wrap with arteries in place was accomplished by pressing a blade tool into the trough of the artery wrap while it was supported in the half-shell fixture.

The artery wrap was attached to the inside of the distribution wick by spot welding. The welds were performed in an inert atmosphere to prevent embrittlement. The welding head pictured in Fig. 5 was developed for these welds. It incorporated a tungsten roller electrode with alumina-coated sides, which provided abrasion resistance and electrical insulation. Electrical isolation of the head allowed the sheathed copper wand, the plastic-coated brass head, the roller axle, and the roller to be used as conductors. The electrical resistance of the screen in the artery wrap and the distribution wick to the grounded container provides the necessary weld heat.

Fig. 5. Spot welder roller head.

Weld pressure is achieved by a cantilevered leaf-spring, with the force adjustable by a set screw at the midpoint of the spring. The free end of the spring houses a second axle with free-wheeling dielectric rollers to provide the force opposing the electrodes. These rollers bear on the distribution wick straddling the opposing artery wrap.

The container tube served to exclude air during the welding operation. A steady flow of argon provided an inert gas shroud for the weld. Following the welding of the artery wraps, the same welding head was used to attach the hafnium getter ribbons along the length of the wick structure.

Additional gettering was provided by hafnium and zirconium getter discs at the ends of the heat pipe. At the condenser end, the discs were captured between the fill plug and the end of the distribution wick. A hole in the center of each disc provided passage for fluid during the fill operation. At the evaporator end, a screw was used to attach the discs to the end plug. Shallow dimples in each disc provided spacing for fluid contact. A longitudinal cross section of the heat pipe assembly is given in Fig. 6.

IV. Heat Pipe Material Processing

The internal chemical environment of high temperature heat pipes is of concern in long term application because of potential effects on operation through changes in fluid surface tension,

wick pore size or permeability, surface wetting characteristics, noncondensable gas generation, or low volatility fluid accumulation. In addition, complete loss of performance through penetration of the heat pipe envelope is possible. Observation of some of these effects in prior high temperature heat pipes has led to an intensified effort to identify, predict, and control sources of chemical contamination within the heat pipes. Steps in the thermochemical control effort have included chemical characterization of heat pipe materials and processes throughout the fabrication and assembly cycle, material preprocessing for cleanup, in-situ cleaning during heat pipe filling by hot and cold trapping, and gettering during heat pipe operation. Each of these steps has been conducted to some extent in prior heat pipe efforts. Improvements in the control of these process steps in the present heat pipe are the result of additional understanding gained from prior post test analyses and from the development of detailed chemical models of heat pipes. These models permit the evaluation of alternative gettering materials and other changes in heat pipe chemistry without test operation, thereby accelerating the development process.

As a result of the chemical phenomena observed in prior heat pipes, particularly silicon and titanium deposits on the inner surface of the wick, chemical analysis of heat pipe materials at each stage of processing was undertaken in an attempt to identify the source of the contaminants.

Fig. 6. Cross section of the heat pipe assembly.

This chemical analysis was concentrated on the screen wick materials because prior analyses had shown that the tube material was of good quality and because the large surface area of fine-mesh wick materials can lead to high levels of heat pipe contamination from slight surface contamination. The chemical analyses conducted included quantitative spectrographic analysis for the metallic elements listed in Table II, plus wet chemistry for oxygen, carbon, and sulfur. The results to date are summarized in the table. The tests showed that no single process was the major source of contamination. A caustic cleaning agent used on the molybdenum screens was shown to be a source of silicon, but not a major one. The same cleaning process was shown to be effective in reducing carbon levels in the screens and was retained as a final process step for the screen materials.

TABLE II
CHEMICAL ANALYSIS OF 400 MESH SCREEN MATERIAL

Condition	Al	Si	Ca	Fe	Cu	O	C	S
As received	<15	30	<4.5	120	15	100	80	40
Caustic clean	20	45	<4.5	45	15	110	20	--

Review of the screen geometry showed that a monolayer of oxygen on the surface of a 0.025-mm-diam molybdenum wire wick corresponded to a bulk oxygen measurement of 16 ppm. Thus surface contamination of the molybdenum screen by oxygen could be responsible for high oxygen impurity levels. Because protection of the wire from atmospheric contamination throughout the assembly process is impractical, it was concluded that final cleanup of the heat pipe material should take place during the filling and sealing operation. This was accomplished by a hot and cold trapping operation that removed contaminants from the lithium pool during refluxing of the lithium vapor over the heat pipe interior surfaces. This technique is effective with lithium because of the high chemical affinity of lithium for oxygen, nitrogen, and carbon.

The selection of gettering materials to be used for continuous cleanup during heat pipe operation and during the hot trapping operation, and the selection of parameters for cold trapping were based on chemical modeling of the heat pipe as a function of temperature and the species present. This modeling was conducted through the use of a chemical equilibrium computer program that uses a free-energy-minimization method to calculate equilibrium compositions in systems containing gaseous and condensed phases.¹²

An attempt was made to include all species that would be significant for the objectives of the calculations, and for which thermodynamic data existed at temperatures of interest or could be extrapolated with reasonable confidence to such temperatures.

Calculations were made for lithium heat pipes with molybdenum or TZM walls. Table III shows the amounts of each element assumed in baseline calculations for the lithium/TZM system. The elemental composition was based on the composition of

TABLE III
ELEMENTAL COMPOSITION OF THE LITHIUM-TZM SYSTEM

Element	Amount, moles
Lithium	3.85
Molybdenum	9.65
Carbon	0.008 (0.1 wt% in Mo)
Nitrogen	0.002 (30 ppm in Mo)
Oxygen	0.006 (100 ppm in Mo)
Titanium	0.094 (0.5 wt% in Mo)
Zirconium	0.007 (0.07 wt% in Mo)
Hafnium	variable
Inert gas	variable

the TZM alloy, the measured major impurities, provision for hafnium and zirconium getters, and the inclusion of an inert gas for convenient adjustment of the relative amounts of gaseous and condensed-phase solutions.

Table IV lists the species for which thermodynamic data were included in the calculations of lithium systems.

TABLE IV
SPECIES INCLUDED IN LITHIUM SYSTEMS

Gas Phase		Liquid Lithium Solution	
Li	Li ₂ O	Li	
Li ₂	LiN	C (as in Li ₂ C ₂)	
O ₂	Li ₂ MoO ₄	N (as in Li ₃ N)	
LiO	N ₂	I (as Li ₂ O)	
MoO	CO		
MoO ₂	NO		
MoO ₃	Inert		
Other Solid/Liquid Phases			
Li ₂ MoO ₄	Li ₂ C ₂	Li ₃ N	Li ₂ O
Mo	Mo ₂ C	Mo ₂ N	MoO ₂
C			
Ti	TiC	TiN	TiO
Zr	ZrC	ZrN	ZrO ₂
Hf	HfC	HfN	HfO ₂

Table V is an abbreviated version of a typical output from a calculation in the lithium-TZM system at 1500 K and 1 atm total pressure.¹³

These results indicate that titanium, zirconium, and hafnium are effective getters for carbon and nitrogen (500 to 1500 K) in the lithium/TZM system. Molybdenum is a less effective getter for carbon and becomes worse with increasing temperature. Molybdenum does not getter nitrogen at any temperature. Hafnium is the only one of the metals showing any gettering of oxygen, and that is only partial at intermediate temperatures (~50% of oxygen in the calculation at 800 K).

TABLE V
SAMPLE OUTPUT FOR THE LITHIUM/TZM SYSTEM
(1500 K, 1 atm total pressure)

Gas Phase	Moles	Partial Pressure
Li	3.11 E-02	0.368
Li ₂	3.40 E-03	4.02 E-02
LiO	1.59 E-16	1.88 E-15
Li ₂ O	1.99 E-09	2.36 E-08
Co	9.43 E-15	1.11 E-13
N ₂	7.24 E-16	8.56 E-15
Inert gas	5.00 E-02	0.592
Liquid Li Solution	Moles	Partial Pressure
Li	3.80	0.0994
Li ₂ O	6.01 E-03	1.58 E-03
Li ₃ N	1.06 E-08	2.79 E-09
Li ₂ C ₂	8.19 E-17	2.15 E-17
Other Phases	Moles	
Mo	9.65	
Ti	9.10 E-02	
TiC	3.00 E-03	
ZrC	5.00 E-03	
ZrN	2.00 E-03	

Based on these analyses and considerations of metallurgical compatibility, hafnium and zirconium were selected as gettering materials to be sealed in the heat pipe. Oxygen reduction was accomplished by prepurification of the lithium working fluid and by cold trapping after lithium fill and before sealing the heat pipe.

Heat Pipe Fill and Processing

Filling of the heat pipe with lithium and in-situ processing before sealing were accomplished using the apparatus shown in Fig. 7. Primary components of the apparatus are a distillation pot containing pre-processed lithium and gettering materials; a loading pot, also containing gettering material; the heat pipe, and various heaters and water cooled lines used as valves. The lithium charge in the distillation pot is 2.5 to 3 times that required for the heat pipe. The net loading pot volume is equal to the intended final heat pipe lithium charge and is used to control the amount of lithium transferred into the heat pipe. The heat pipe is enclosed by a quartz envelope that is maintained under vacuum throughout the filling process. The heat pipe interior is connected to a second vacuum system via the fill lines, loading pot, and distillation pot. This interior vacuum system is also used in degassing the lithium during melting, warm-up, and distillation. The vacuum line is kept open during lithium distillation by means of a water cooled lithium trap on the pump line. The use of an open system during lithium distillation permits monitoring of outgases with a residual gas analyzer, providing a check on lithium quality during fill.

Fig. 7. Lithium fill apparatus.

Processing was started with the heat pipe in a vertical orientation and consisted of outgassing at 1500 K. Both inner and outer vacuum systems were active during this process. The heat pipe was brought to temperature using a full length induction coil coupled to a 125 kW, 350 kHz rf power supply. Rate of warmup was controlled to maintain vacuum levels at 10^{-4} mm Hg or less. The final vacuum level of $< 10^{-6}$ mm Hg for the heat pipe interior was attained after 16 hours. The loading pot was next outgassed at 1050 K using resistance heaters for a period of 2 hours. The distillation pot, previously charged with purified lithium was next heated to the melt point and further heated to approximately 1050 K while continuous vacuum was maintained. Partial pressures of noncondensable gases released during this process were monitored with a residual gas analyzer. Maximum partial pressures measured occurred during lithium melting and were in the 10^{-7} mm Hg range. The principal species detected was argon. Once melting of the lithium was complete partial pressures remained in the 10^{-8} mm Hg range throughout warmup. When the lithium temperature reached 1050 K the loading pot temperature was decreased to about 300 K and the water chill below the pot was activated. The distillation pot temperature was then increased to 1150 K and the purified lithium distilled into the loading pot. When the loading pot was full, the lower chill was deactivated and the contents of the loading pot forced into the heat pipe by the vapor pressure of the lithium in the distillation pot. The distillation process was then repeated and the loading pot refilled.

After filling was completed, the heat pipe was tilted horizontally and an rf coil used to heat the entire length at 1125 K. After the wetting-in for 23 hours the heat pipe was operated with a

short heating coil at one end and the liquid fill quantity verified. The distillation pot was then removed and a cover cap EB-welded over the fill tube in preparation for further testing.

Heat Performance Measurements

After sealing, the heat pipe was set up to operate in a vertical orientation with the evaporator at the top. The heat pipe was operated at 1500 K in this configuration with a heat throughput established by thermal radiation. Estimated power throughput was about 4 kW, based on an assumed surface emissivity of 0.2 for the TZM tube. The lithium pool length at the lower end of the heat pipe was measured at approximately 14 cm under these conditions. After the vertical test the heat pipe was installed in a gas-gap controlled calorimeter and vacuum chamber. The heat pipe was performance mapped to dryout as indicated in Fig. 8, where each data point represents an evaporator dryout. The results were below predicted limits.

The radiatively loaded inverted operation had established a maximum effective pore size of 105 μm for the heat pipe artery wick structure. The test performance data was analyzed assuming this limiting capillary size as the operational value. A best fit to the test data appeared to be consistent with a model that assumed only a single artery was functional as indicated in Fig. 8. The heat pipe was therefore removed from the test assembly and subjected to x-ray radiography. The radiographs showed some helical ripples in the unbonded distribution screen structure but did not indicate interior structural changes that would, of themselves, explain the degraded performance. The extent and location of the lithium charge could not be determined from these radiographs because of the low x-ray absorption of lithium. To establish the extent of the lithium fill, particularly the number of arteries filled, the heat pipe was taken to Sandia National Laboratory where neutron radiographs of the entire length were taken. These radiographs showed that none of the arteries were filled with lithium and that no pool of excess lithium was present in the heat pipe. Measurements taken from the neutron radiographs indicated that the distribution wick had separated from the inner tube wall an average distance of about 0.25 mm, and that filling of this annular space had depleted the lithium inventory available for filling the arteries. Performance analysis of this configuration indicated that the heat pipe would be capable of achieving the original design limits if the arteries were filled, so plans were made to add more lithium to the heat pipe. Measurements taken from the neutron radiographs were used to calculate the required additional lithium quantity. Provision for growth in the distribution wick-tube wall space was included.

Using the same procedures as originally used to fill the heat pipe, lithium was distilled into a 35-cc molybdenum loading pot. Using liquid metal plugs as seals to maintain the integrity of the heat pipe and loading pot, the heat pipe was cut under an argon gas blanket at the fill tube end and the molybdenum loading pot EB-welded to the heat pipe. The heat pipe and attached molybdenum loading pot were installed in the tilt-test stand, and the lithium was transferred to the heat pipe by induction heating the reservoir to force the

lithium into the heat pipe. In subsequent operations, a chill was used to keep the lithium solid at the reservoir end of the heat pipe and thus avoid transfer of the lithium back into the loading pot. The heat pipe was again shipped to Sandia National Laboratory for neutron radiography. The films showed all the arteries full and an excess pool length of approximately 15 cm. The heat pipe was returned and assembled in the gas-gap controlled calorimeter and installed in the vacuum test chamber. The heat pipe was operated at a power level of 1.0 kW at 1300 K for 12 h for wet-in before the start of performance tests. The calorimeter gas pressure and rf power input were then increased to bring the heat pipe operating point to 15 kW at 1500 K and a 100-h operating test was begun. Figure 9 is a power-temperature plot of this operation with the 100-h operating point and the predicted heat pipe performance limits indicated. The high-power, extended-operation test was interrupted three times during the 100-h run because of test equipment problems. The test history is summarized in Table VI.

TABLE VI
SPAR-6 HEAT PIPE EXTENDED OPERATING TEST
AT 15 kW and 1500 K

Accumulated Hours	Events
0	Heat pipe brought to test point 15 kW, 1500 K
26	System shutdown for calorimeter instability
26	Restart at 15 kW, 1500 K
49	System shutdown for rf generator burnout
49	Restart at 15 kW, 1500 K
66	System shutdown on water interlock
66	Restart at 15 kW, 1500 K
100	100-h operating period completed

The calorimeter instability at 26 h was caused by a weld crack in the flange region of the calorimeter, which allowed cooling water leakage into the gas gap. Repair involved removing the calorimeter from the heat pipe and repairing the weld. The rf generator burnout at 49 h was caused by an electrical short in the input transformer. The test was restarted by switching to a second generator, because repair of the 125-kw primary generator would require a period of weeks. The third shutdown was related to the use of the back-up generator with attendant increase in rf line losses. The problem was solved by changing to an open-loop water system and restarting the system. None of the interruptions appeared to affect the heat pipe operation. At 100+ h the test was completed per plan and the test system shut down.

V. Conclusions

The molybdenum-lithium artery heat pipe developed for space reactor application was operated successfully at an axial power level greater than 10 kW/cm² for 100 hrs at 1500 K. These tests have demonstrated both the adequacy of the design and the short-term compatibility of the materials used. Future testing will be directed to the demonstration of limits for the design and to long-term material compatibility investigations.

Fig. 8. Performance test before refill.

Fig. 9. 100 hour test operating point.

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