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*Heat Pipe Development for
Advanced Energy Transport Concepts
Phase II Final Report Covering the Period
October 1, 1997, to September 30, 1998*

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by

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ABSTRACT

This report summarizes progress in the Heat Pipe Technology Development for Advanced Energy Transport Concepts (Phase II) program for the year October 1, 1997, to September 30, 1998. Significant accomplishments during the year include the processing and testing of a 1.8-m long Mo-Li heat pipe, development of a thermochemical model for the sodium-Haynes 230 material system, fabrication of a series of heat pipes to assess the compatibility of several materials with sodium, and the execution of a test measuring the response of a sodium heat pipe to the penetration of water.

1.0 Construction and Tests of 1.8-m Mo-Li Heat Pipe

The development of a molybdenum-lithium heat pipe was undertaken to demonstrate design, fabrication, and operational capability of refractory-metal heat pipes at temperatures to 1500 K, near the maximum contemplated temperature for thermo-photovoltaic conversion systems. The heat pipe design was based on the technology originally developed and demonstrated on the space reactor programs particularly SPAR and its successor, the SP-100 Program. Progress was expedited by the existence of test and fabrication facilities, experienced personnel, and some materials from the cited programs. For reference, see Merrigan et al. (1986). Nominal characteristics of the heat pipe are specified as follows:

1.90-cm (0.75-inch) outside diameter
180-cm overall length
30-cm (12-inch) induction heated evaporator section
150-cm radiation cooled condenser section

A cutaway drawing of this heat pipe showing the location of the end plug and getter pack is given in Figure 1. The heat pipe envelope consists of a low-carbon arc-cast molybdenum tube having a 1.91-cm (0.75-inch) outside diameter and a 1.52-mm (0.060-inch) thick wall. The tube was purchased from Thermoelectron, Tecomet Division in Wilmington, MA. The end plug material was identical in composition. The screen wick material was woven in Ireland from molybdenum/41% rhenium wire, drawn to 25- μ m diameter by Plansee Corporation in Austria. This material was originally developed for the SP-100 program. It is the finest-mesh molybdenum screen material available.

An annular wick configuration was chosen as the simplest design possible for a high-performance alkali metal heat pipe. This wick configuration is ideally suited for use with lithium. Liquid lithium wets well to refractory metal surfaces. Lithium also has high thermal conductivity and high heat of vaporization. These attributes result in a heat pipe that is insensitive to boiling. The annular wick also provides minimal liquid-side axial pressure drop. This configuration is essentially identical to that used in the Los Alamos SPAR-7 heat pipe.

Fabrication of the wick for the heat pipe was accomplished by wrapping seven layers of 400-mesh molybdenum/41% rhenium screen on a preformed mild-steel tube mandrel. The mandrel consisted of a length of 1.59-cm (0.625-inch) outside diameter, 3.18-cm (0.125-inch) thick wall, mild steel tubing pre-drawn to 1.51-cm (0.594-inch) outside diameter. The as-drawn diameter of the tube mandrel was chosen to result in vapor space diameter of 1.45 cm (0.570 inch) after fabrication. The screen was held in place on the mandrel by wire-to-wire spot welds at approximately 2-mm intervals along the trailing edge of the screen. The pre-drawn thickness of the screen wick assembly was 0.44 mm (0.0175 inch).

The mandrel-wire assembly was then inserted in a cover tube of 2.22-cm (0.875-inch) outside diameter, 1.59-mm (0.0625-inch) wall mild steel that had been pre-drawn to 1.98-cm (0.781-inch) outside diameter to give an internal diameter slightly larger than the screen

Figure 1. Cutaway view of annular 1.8-m Mo-Li heat pipe showing some detail of hafnium getter pack and evaporator end plug.

assembly outside diameter. The cover tube, screen, and mandrel assembly was then processed in a tube drawing machine to reduce the outer diameter of the cover tube to a final dimension of 1.83-cm (0.719-inch) outside diameter, compressing the screen assembly and reducing the diameter of the internal mandrel. The cover and mandrel tubes were then removed by hot acid etching to expose the compressed screen assembly. Final dimensions of the screen wick were 1.45-cm (0.570-inch) inside diameter and 1.53-cm (0.602-inch) outside diameter for a wick thickness of 0.41-mm (0.016-inch).

After cleaning in a water and alcohol bath, the screen wick was suspended inside a molybdenum susceptor within a vacuum enclosure. A full-length induction coil was used with a 100-kW radio frequency power supply to diffusion-bond the screen material. Sintering was conducted at 1670 K for 20 minutes at a vacuum level of approximately 10^{-5} -Torr. Following the sintering operation, the screen wick was checked for maximum pore size in an ethyl alcohol bath using helium as a pressurizing gas. Experiments verified that the pore diameter was less than 40 microns.

The evaporator end of the wick tube was then closed with a fitted molybdenum plug, mechanically retained with a molybdenum wire wrap and then brazed in place with zirconium wire filler material. Figure 2 shows the molybdenum wick and end plug being brazed with zirconium wire. The temperature of the surrounding susceptor was optically measured to be 1950 K. Approximately 20 disks of 0.125-mm thick hafnium foil were placed in the space between the end of the wick and the end plug. The disks were dimpled to provide fluid space and were strung together on a molybdenum wire for retention. Final closure of the heat pipe envelope was accomplished by electron beam welding an evaporator end plug to the pipe.

Processing of the 1.8-m long Mo-Li Heat Pipe

The assembled heat pipe was then vacuum-baked for cleanup and prepared for lithium filling. The heat pipe was charged with lithium by distillation. The charge quantity was calculated to provide filling of the wick void volume, getter voids, annulus volume, and surface cavities; and 25 percent excess for liquid expansion and dimensional uncertainty. The initial charge was approximately 43 g of lithium.

After charging, a chilled-water valve was used to establish a freeze plug in the fill stem. A plastic glove bag was then put in place around the heat pipe, filled with argon and, in the

Figure 2. Braze of Mo-Re wick to Mo plug with Zr wire.

argon atmosphere, the fill stem was cut and fitted with a mechanical-valve end cap in preparation for installation in the test stand. To wet the wick, the heat pipe was brought to 1123 K with a full-length induction coil. A picture of the lithium wetting operation is shown in Figure 3.

The heat pipe was then installed horizontally in a chamber attached to a cryopump. A 30-cm-long induction coil was placed around the heat pipe between 3 and 33 cm from the evaporator end. Water was allowed to flow through a chill block on the fill stem to keep the lithium plug solid during heat pipe operation isolating the heat pipe vapor space from the charge valve located further down the fill stem.

Operating History and Analysis of 1.8-m Long Mo-Li Heat Pipe

An initial diagnostic run was made. Starting from room temperature, power to the induction coil was increased until the thermocouple at the evaporator-exit measured 1160 K. Two problems were observed. A hot region (100°C to 200°C above the surrounding surface) along 10 cm of the heat pipe surface formed under the induction coil. A sharp decrease in surface temperature (300°C) began 70 cm from the end of the condenser. The hot region under the induction coil was attributed to blockage of the annular gap by trapped noncondensable gas. The condenser-region temperature gradient was likely from residual noncondensable gas in the vapor space and an excess lithium pool.

To remove noncondensable gas and excess lithium from the vapor space, a chill block, a known-volume cold trap, and a cryopump were connected to the fill stem. Power was increased to the induction coils until the thermocouple at the evaporator exit read 1400 K. Soon after, the cryopump connected to the fill stem was started. With no water flowing through the chill block, conduction along the fill stem was sufficient to melt and vaporize the lithium fill plug. Lithium from the fill stem condensed and solidified in the cold trap. After the fill stem was cleared of solid lithium, noncondensable gas and lithium vapor from the heat pipe moved down the fill stem and into the cold trap. The lithium condensed and solidified in the cold trap. Any noncondensable gas moved through the cold trap and toward the cryopump. This continued until the condensed and solidified lithium filled the cold trap and isolated the heat pipe from the cryopump. Water was then allowed to flow through the chill block to form a freeze plug in the fill stem. Measurements made later indicated that 14-g of lithium were transferred from the heat pipe to the cold trap during this operation.

Figure 3. Wet in of Mo-Li heat pipe with full-length radio frequency induction coil.

The heat pipe was then re-tested in the vacuum chamber. As before, the 30-cm induction coil was placed around the evaporator end of the heat pipe. Power was increased to the induction coil until the thermocouple at the evaporator exit read 1400 K. Noncondensable gas was removed from the condenser vapor space, but the temperature of the evaporator region appeared non-uniform.

Another series of adjustments were made to improve the heat pipe's operating characteristics. To remove the noncondensable gas trapped in the annular gap, the heat pipe was placed, with the condenser side up, inside a vertical quartz tube. An induction coil was placed around the quartz tube along the entire length of the heat pipe. Water was allowed to flow through a chill block attached to the fill stem. Power was increased to the induction coil until a pyrometer, focused on the heat pipe surface, read 1120 K. The pipe was kept at this temperature for 4 hours to allow buoyancy forces to push noncondensable gas out of the annulus and into the vapor space

The pipe was then restarted. When the thermocouple at the evaporator exit measured 1360 K, the condenser surface temperature was uniform to within a couple of centimeters from the fill stem. A pool of lithium remained at the condenser end. Another pool of smaller size formed at the part of the evaporator end not covered by the induction coil. A local hot spot covering 30° of pipe circumference and 0.7 cm of length developed under the induction coil about 6 cm from the evaporator end. This hot spot was much smaller than the one previously observed. Optical measurements made between the induction coils indicated that the spot was 100°C hotter than the surrounding surface. The hot spot may have been caused by local de-wetting of lithium either from the heat pipe's inner wall surface or in the wick as a residual effect of the gas seen previously.

In an effort to rewet the evaporator region, the heat pipe was inserted horizontally into a quartz tube. A full-length induction coil was placed over the quartz tube and was used to bring the pipe to 1100 K. The heat pipe was kept at this temperature for 4 hours.

The heat pipe and quartz tube assembly was then installed in a variable-angle-tilt fixture. A 30-cm induction coil was placed over the quartz tube with the coil's end 3 cm from the evaporator end of the heat pipe. The heat pipe was oriented with the condenser tilted 10° above the evaporator. The pipe was started from the frozen state and was brought to 1330

K in 4 hours. Figure 4 shows typical detail of the test fixture geometry. A picture of the heat pipe operating near 1330 K and with a 10° positive tilt is shown in Figure 5.

The thermocouple mounted nearest to the fill stem read 30°C cooler than the other six thermocouples. The remaining thermocouples read temperatures that were all uniform to within the $\pm 15^\circ\text{C}$ thermocouple error limit. At 1330 K no hot spots were observed under the induction coil. The power to the induction coil was then reduced to zero in a single step, and the heat pipe was cooled to room temperature. During this shutdown, all thermocouples read below 700 K within 20 minutes of shutting off the induction coil.

A 30-cm long induction coil with circular cross section was connected to a 60-kW induction generator and placed over a 5-cm diameter quartz tube enclosing the heat pipe. In that configuration, the 60-kW generator only had enough capacity to bring the heat pipe to 1330 K at the evaporator exit. The heat pipe was moved to a 100-kW generator, which brought the heat pipe to 1400 K at full capacity, still 100°C short of the goal. Generator adjustments to improve load matching produced only a modest increase in heat pipe temperature.

It became apparent that 1500-K operation would require better coupling between generator and heat pipe. A 30-cm long induction coil with a rectangular cross section and 1.3-cm inside radius was selected to enhance coupling and reduce $1/r^2$ attenuation. A quartz tube made to fit the coil and heat pipe was evacuated, and the heat pipe was restarted. Generator plate voltage was increased until the thermocouple nearest the evaporator exit read 1480 K. There, generator capacity, as indicated by plate voltage, was ample to bring the pipe well above 1500 K. This test was ended because of a vacuum leak in an improperly seated O-ring. After shutdown, plated MoO_2 , formed by the leak, was removed from the inside surface of the quartz tube.

Figure 4 . Schematic drawing of 1.8-m Mo-Li heat pipe in test fixture showing typical thermocouple placement. The hatched box gives the approximate position of the induction coil. Open boxes represent the location of the refractory brick supports.

Figure 5. Picture taken of 1.8-m Mo-Li heat pipe in variable angle test fixture while operating near 1330 K at the evaporator exit. The heat pipe is inclined with the condenser 10° above the horizon.

The heat pipe was brought to 1400 K to remove an oxide layer that had formed over a portion of the condenser. The pipe was then placed inside a clean quartz tube and restarted in the horizontal position. Power was increased until the thermocouple at the evaporator exit read 1500 K. A plot of surface temperature, at several axial locations, versus time from the beginning of startup is shown in Figure 6. The heat pipe was brought to an isothermal state in 90 minutes. The lower temperature reading at 179 cm resulted from a liquid pool that accumulated near the condenser end-cap. The pipe was then tilted with the condenser end 15° above the horizontal and operated in that orientation for 30 minutes. The tilt was then increased to 45° above the horizontal and operated there for 10 minutes. Figure 7 shows a plot of surface temperature during the maneuvers from 15° to 45° to 0°. The large swing in temperature at 179 cm from the evaporator end cap was caused by the shift in pool position. The pipe was then rapidly returned to the horizontal. Soon after, a dry out occurred in the heated zone, coinciding with the sudden movement of surplus working fluid to the condenser region

Power Calibration Test

A test was then performed to calibrate the 100-kW induction generator power settings to heat pipe power throughput. The power setting versus time profile for the calibration startup is shown in Figure 8. Power was gradually increased to the heat pipe evaporator over a 4-hour period. The temperature and generator setting versus time profiles enabled estimates of condenser power throughput versus generator setting in subsequent runs.

The wall temperature data in Figure 9 were used later to make a more detailed calculation of condenser power throughput. In this calculation, the spectral behavior of the heat pipe surface and the surrounding quartz tube is considered. The calculation also accounts for the insulation of the heat pipe surface from the refractory brick mounts and the ceramic thermocouple leads. Unsteady absorption of thermal energy by the heat pipe wall and wick is also calculated from transient temperature data. Working fluid distributions within the heat pipe found from measurements, observations, and calculations are used to estimate the energy absorbed by the solid and liquid lithium at a given operating condition. The thermal energy absorbed by the heat pipe wick, liquid, and wall between data measurement times can be estimated from the transient temperature data.

$$q_{wick,i} = m_{wick,i} c_{p,wick,i} 0.5(T_{i+1}^{n+1} + T_i^{n+1} - T_{i+1}^n - T_i^n) \quad , \quad (1)$$

$$q_{wall,i} = m_{wall,i} c_{p,wall,i} 0.5(T_{i+1}^{n+1} + T_i^{n+1} - T_{i+1}^n - T_i^n) \quad , \quad (2)$$

Figure 6. Surface temperatures on 1.8-m Mo-Li heat pipe during horizontal startup.
Distance in legend is measured from the evaporator end-cap.

Figure 7. Surface temperature on 1.8-m Mo-Li heat pipe with condenser tilted 15° , 45° , and horizontal. Distance in legend is measured from the evaporator end-cap.

Figure 8. 100 kW induction generator power setting versus time for calibration startup test of 1.8-m Mo-Li heat pipe.

Figure 9. Condenser surface temperatures measured during horizontal startup of 1.8-m Mo-Li heat pipe. This data was used to calibrate the generator power settings. The large circles track the temperature of the surrounding quartz tube.

$$q_{liq,i} = m_{liq,i} c_{p,liq,i} 0.5(T_{i+1}^{n+1} + T_i^{n+1} - T_{i+1}^n - T_i^n) \quad (3)$$

The thermal energy absorbed by the melting lithium requires knowledge of the change in melt-front location in the data collection interval. Melt-front movement is tracked by interpolation between thermocouple locations

$$z_m = \frac{T_m(a-b) - T_a b - T_b a}{T_a - T_b} \quad (4)$$

The location of the lithium melt front versus time during the calibration startup of the 1.8-m Mo-Li heat pipe is shown in Figure 10. The origin selected for this plot is the evaporator end cap. The apparent step change in melt front location from zero to 50-cm is an artifact of the use of only condenser temperature data in the calculation. The thermal energy absorbed by the melting lithium in any given time interval can be found with

$$q_{sf} = h_{sf} \frac{(z_{i+1} - z_i)}{L} \sum m_{liq,i} \quad (5)$$

The net radiant energy rate from a quartz-enclosed condenser surface to its surroundings can be written

$$\dot{Q}_c = \sum_{i=1}^{N_c} \sigma p_i \left\{ \varepsilon_m \int_a^b T^4 dz - (b-a) \left[\varepsilon'_q F'_q T_q^4 + \varepsilon''_q (1 - F'_q) T_q^4 + \tau'_q F_0 T_0^4 \right] \right\}_i, \quad (6)$$

where the condenser surface is divided into segments between temperature measurement locations. The boundaries of each segment are $[a,b]$; a is the left boundary, and b is the right boundary. Calculation of the net energy rate emitted from the heat pipe condenser requires integration of the temperature distribution along the heat pipe surface. The heat pipe surface temperature varies axially between points $[a,b]$ but can be normally assumed uniform about its circumference.

The emitted energy rate is proportional to the fourth power of absolute temperature, so for some arbitrary temperature distribution

$$J \propto \int_a^b T(z)^4 dz \quad (7)$$

Figure 10. Location of the lithium melt front during horizontal startup of the 1.8-m Mo-Li heat pipe.

Given two discrete temperature measurements at adjacent locations $[a, b]$ along the length of the heat pipe, a linear relation is assumed for all points between

$$T(z) = T_a \left(\frac{z-b}{a-b} \right) + T_b \left(\frac{z-a}{b-a} \right) \quad (8)$$

Integrating the linear temperature distribution between $[a, b]$ and using Equation (7) gives the emitted-energy-rate proportional result for each condenser segment.

$$\begin{aligned} \int_a^b \left[T_a \left(\frac{z-b}{a-b} \right) + T_b \left(\frac{z-a}{b-a} \right) \right]^4 dz = & \\ & (T_a^4 + T_b^4) \left[\frac{(b-a)}{5} \right] - \\ & \frac{4T_a^3 T_b}{(a-b)^4} \left[-\frac{b^5}{20} + \frac{b^4 a}{4} + \frac{a^5}{20} - \frac{ba^4}{4} + \frac{b^2 a^3}{2} - \frac{b^3 a^2}{2} \right] + \\ & \frac{6T_a^2 T_b^2}{(a-b)^4} \left[\frac{b^5}{15} - \frac{b^4 a}{6} + \frac{b^3 a^2}{3} - \frac{a^5}{15} + \frac{ba^4}{6} - \frac{b^2 a^3}{3} \right] - \\ & \frac{4T_a T_b^3}{(a-b)^4} \left[-\frac{b^5}{20} + \frac{b^4 a}{4} - \frac{b^3 a^2}{2} + \frac{b^2 a^3}{2} + \frac{a^5}{20} - \frac{ba^4}{4} \right] \end{aligned} \quad (9)$$

Linear interpolation is also used to fix the heat pipe surface temperatures on either side of the refractory mounting bricks and to establish the temperature boundaries around those short adiabatic regions. The effective perimeter of each condenser segment is reduced by insulating ceramic thermocouple leads, α in number, and having diameter δ :

$$p_i = \pi d - \alpha_i \delta \quad (10)$$

The emittance of molybdenum without a surface oxide layer has a strong spectral dependence at wavelengths below $3 \mu\text{m}$. To simplify computation, the heat pipe surface is treated as a body with temperature dependent emittance. A polynomial curve fit is calculated using the total hemispherical emittance data for unoxidized molybdenum as a function of surface temperature found in Gubareff (1960).

$$\varepsilon_m \equiv \varepsilon_m(T_A) \quad (11)$$

Total hemispherical emittance of the molybdenum requires computation of a segment-average heat pipe surface temperature.

$$T_A = \sqrt[4]{\frac{1}{b-a} \int_a^b T^4 dz} \quad (12)$$

During testing, the heat pipe was enclosed in a quartz vacuum tube. Thermal power was rejected from the heat pipe condenser by radiant exchange with the quartz tube and the surfaces surrounding it. Quartz is effectively transparent to infrared radiation below 4- μm wavelength and effectively opaque above 4 μm . Data illustrating this spectral dependence are shown in Figure 11. For reference, data for molybdenum spectral emittance are also plotted. To account for the spectral properties of quartz, a two-waveband approximation is used to determine the coupling between the condenser, quartz, and surroundings. The two-waveband approximation is especially important as the peak of the black body spectrum approaches the quartz-transmittance-transition wavelength, just above 900 K.

To establish a radiation background condition for the heat pipe condenser, measurements were taken, during a startup from the frozen state, of the temperature at heat pipe surface and the quartz tube that surrounds it. The plot of heat pipe surface temperature for the calibration startup shown in Figure 9 also shows the temperature at the surface of the quartz tube versus time. The quartz temperature is then plotted versus the temperature of the adjacent heat pipe surface and shown in Figure 12. To track the various twists and turns a fifth degree polynomial is fitted to this data

$$T_q \equiv T_q(T_A) \quad (13)$$

The quartz temperature is then fixed for a given heat pipe surface temperature. This approach to specifying the condenser boundary condition avoids the complexity associated with characterizing the coupled radiation and natural-convection boundary conditions on the outside surface of the quartz tube.

The two-band calculation requires the integration of Planck's radiation law. The result of the integration can be approximated using a relation suggested by Wiebelt and found in Siegel and Howell (1981).

Figure 11. Spectral emittance for polished molybdenum (Gubareff, 1960).
Spectral transmittance for fused quartz (Wolfe, 1985).

Figure 12. Quartz temperature versus heat pipe surface temperature during horizontal startup of the 1.8-m Mo-Li heat pipe. This plot was used to establish the condenser-radiation boundary condition.

$$F' = \frac{1}{\sigma T^4} \int_0^\lambda e_{\lambda b} d\lambda \approx \frac{15}{\pi^4} \sum_{m=1,2,\dots} \frac{e^{-\nu}}{m^4} \{[(m\nu + 3)m\nu + 6]m\nu + 6\} \quad , \quad (14)$$

where $\nu = C_2/\lambda T \geq 2$ and C_2 is the second constant in Planck's spectral energy distribution. For the conditions here, use of the first three terms under the summation produces a discrepancy with the exact result of less than one percent. This relation is evaluated at 4- μm wavelength at the quartz and the surrounding temperatures.

The results of the condenser power calculation for the calibration test are shown in Figures 13 through 21. Figure 13 gives condenser power throughput and estimated power applied to the evaporator versus power setting. The power applied to the evaporator was estimated accounting for the energy absorbed by the heat pipe using Equations (1), (2), (3), and (5). The heat rejected from the condenser sections on either end of the evaporator was found using Equation (9). A different view of the startup is given in Figure 14 that shows the thermal-energy-removal rate from the condenser versus time. Note the dramatic change in profile slope at 11,000 seconds once the heat pipe becomes fully active along its length. The incremental increases in power shown on this figure reflect the step-wise fashion in which power from the induction generator was applied.

Figure 15 shows the heat pipe axial temperature profile versus position at various condenser power throughputs. These profiles are selected from a much larger data set. A new profile is plotted for each 100°C change from the preceding profile. Several interesting features are apparent. The magnitude of condenser temperature gradient monotonically decreased down the condenser length for temperature profiles up to 18 W condenser power throughput. A slight convex bow in the temperature data emerged between 50 and 80 cm for the profile at 25-W power throughput. This was the first evidence of vapor transport into the condenser. Lithium vapor approaches the continuum flow regime around 1000 K. The convex bow became more pronounced as power was increased. The melt front led the continuum flow front by 50 cm until reaching the end of the heat pipe. An isothermal wall temperature profile was established once the evaporator exit temperature reached 1150 K. A temperature gradient remained across the surplus liquid pool that accumulated at the condenser end of the heat pipe. The peak heat rejection rate was computed to be 3200 W when the evaporator exit reached 1500 K. The radial Reynolds number in the condenser at this state was approximately unity. This indicates that the vapor movement at steady state balanced inertial and viscous forces.

Figure 13. Condenser throughput and estimate of power applied to the evaporator during horizontal startup of the 1.8-m Mo-Li heat pipe.

Figure 14. Thermal energy removal rate from condenser during horizontal startup of the 1.8-m Mo-Li heat pipe.

Figure 15. Condenser surface temperatures measured during horizontal startup of 1.8-m Mo-Li heat pipe. Heat rejection rates from the condenser are listed on the left-side legend.

Figure 16 compares measured to calculated condenser axial temperature profiles at three different power levels. Measurements, represented by symbols connected by hairline curves, span the distance from the evaporator exit to the condenser end of the pipe. Calculated values, shown as solid curves, were made using the HTPIPE computer code (Woloshun, 1988) with heat input rate and evaporator exit temperature as specified conditions. The calculation covers the region from the evaporator entrance and extends up to the start of the condenser pool. At 484-W condenser throughput, the heat pipe was in transition between the viscous and radiation limit regimes. The temperature profile slope in this phase of the startup was a strong function of evaporator exit temperature. The dashed line represents the calculated wall temperature profile if the temperature at the evaporator exit were just 6°C lower than the calculation represented by the solid line. At this point, a difference of 6°C at the evaporator exit yields a 95°C difference at the condenser end.

The agreement between the data and calculation is surprising. A number of factors might be expected to cause a difference between these profiles, the most obvious being the questionable application of a steady-state model to data with an unsteady component. However, at 1100 K the contribution to internal energy in the metal is a small fraction of the total power applied to the evaporator. There were some differences between the modeled and actual heat pipe configurations. A short heat-removal zone existed between the evaporator entrance and the evaporator-side end cap. The mounting bricks formed two short adiabatic sections ($L/D \sim 3.3$). In addition, an excess liquid pool accumulated at the condenser end of the heat pipe, which was handled by shortening the effective length of the condenser. As currently written, these details are not explicitly included in HTPIPE.

Despite these differences, the similarity between the data and calculation profiles suggests that the temperature measured at the wall was close to the actual vapor space temperature. The conduction temperature drop across the heat pipe wall in the region of the evaporator exit was less than 1°C under these conditions. However, thermocouple uncertainty and the data scatter suggest that temperature measurement was, at best, good to within $\pm 15^\circ\text{C}$. The agreement obtained in the test, within a few degrees of theory, could not be consistently expected. Alas, such good agreement must be attributed, in part, to luck.

The two remaining temperature-versus-position curves at 1301-W and 3141-W condenser throughput are uninteresting uniform temperature predictions around the usual data scatter. These curves also reveal an isothermal profile across the evaporator at all three power levels.

Figure 16. Condenser surface temperatures measured during horizontal startup of 1.8-m Mo-Li heat pipe at three different power levels. The solid lines represent steady state predictions made by the HTPIPE computer code.

Figure 17 relates the position of the lithium melt-front to the thermal-energy-removal rate from the condenser. Periodic changes in slope occur in the energy-removal rate curve. These changes appear when the melt front approaches thermocouple measurement locations and stem from scatter in the temperature data. The thermal energy removal rate calculation outlined in Equations (6) through (12) is also sensitive to the calculated background temperature early in the startup period. The melt front reached the end of the heat pipe as about 350 W of thermal power was radiated from the condenser. In this state, the evaporator exit hovered around 1100 K, and the active region of the heat pipe extended 130 cm from the evaporator end cap. The linear temperature profile between the termination of the active region and the condenser end of the heat pipe indicates that, at that location, axial conduction in the heat pipe wall and wick was the dominant heat transfer mechanism.

Figure 18 compares condenser heat rejection rate to the steady-state sonic and viscous limits at various evaporator exit temperatures. The dashed line represents the sonic limit curve; the solid line represents the viscous limit curve. At 950 K, axial conduction through the molybdenum wall was the dominant heat transfer mechanism, and the melt front had progressed only half the distance to the condenser end of the pipe. As the evaporator temperature increased, the vapor density and the axial pressure gradient in the core region became sufficient to move vapor into the heat pipe condenser.

In this test, power to the heat pipe evaporator was increased at a sufficiently gradual rate so that heat pipe state changes occurred in quasi-steady increments. Typical values for the quantity of energy needed to bring the heat pipe to temperature were calculated. Equations (1) through (3) were used to estimate the internal energy in the heat pipe and Equation (6) for condenser power throughput during startup. Most of the thermal energy transferred from the evaporator to regions below 600 K was held as internal energy in the wick, fluid, and wall. For surfaces at 950 K, about 15 percent of the applied power went to internal energy in the metal with the remaining 85 percent of the energy radiated to the surroundings. This diminished to below 5 percent for surfaces above 1100 K. The calculated condenser heat rejection rate follows the viscous heat transport limit up to 1125 K. Above this temperature, the heat pipe was isothermal along its active length. Radiation coupling between the heat pipe and its surroundings limited the heat rejection rate from the condenser. In the radiation-limited mode, there was a reduction in the slope of the heat rejection rate versus temperature curve. The condenser power curve continued in the radiation-limited mode up to the peak 3200 W throughput at 1500 K.

Figure 17. Location of the lithium melt-front versus condenser thermal energy removal rate during horizontal startup of the 1.8-m Mo-Li heat pipe.

Figure 18. Condenser heat rejection rate versus evaporator exit temperature for a horizontal startup of the 1.8-m Mo-Li heat pipe. Also plotted are the sonic and viscous limit curves.

Another view of this data, focused at the lower power portion of the curve, is shown in Figure 19. The horizontal bars about each data point indicate the thermocouple error limit of 0.75 percent of reading above 0°C. The vertical bars in Figure 19 show the estimated uncertainty in condenser throughput calculation using the relation

$$w_q = w_T \sigma \epsilon A 4T^3 \quad (15)$$

Below 250-W condenser power throughput, the calculated throughput somewhat exceeds the steady-state viscous limit calculation. Axial conduction through the molybdenum wall between thermocouple locations, not included in the heat pipe limit calculation, typically accounts for 10 W of this difference at the temperature gradients encountered around 1000 K. Another difference is the use of data from a thermocouple placed several centimeters from the evaporator as the evaporator exit temperature. There is also some uncertainty associated with the degree of contact maintained between the thermocouple and the surface of the heat pipe. Local heat removal from the bare thermocouple wires leading away from the heat pipe surface is also believed to have lowered the measured temperature readings.

Figure 20 illustrates the transient response of the condenser heat-rejection rate to changes in evaporator-exit temperature as the active region moves into the condenser. The data are plotted so that the more recently measured points are stacked atop preceding data. As the continuum flow front moved forward, marked increases in condenser power throughput occurred in a stepwise fashion at near constant evaporator-exit temperature. This reveals that in response to increases in generator power, the active region of the heat pipe, in combination, progressed forward while the evaporator exit temperature remained nearly fixed. Conversely, increased evaporator exit temperature was associated with more modest increases in temperature and active length further down the condenser.

The difference between measurement and theory at low power is highlighted in the log-linear version of Figure 18 shown in Figure 21. The solid line represents the viscous limit. The thermal energy emitted from heat pipe's bare-molybdenum condenser surface limited the total heat transport rate above 1100 K. If the heat pipe condenser coupling were increased sufficiently; the viscous limit curve would be followed up to the sonic limit curve. The throughput power from the heat pipe would then follow the sonic limit curve until a condenser coupling or other limit was encountered at higher temperature. A similar Los Alamos-built heat pipe, SPAR-7, had a condenser with 0.61 total hemispherical emittance and reached the radiation limit from the sonic limit curve.

Figure 19. Condenser heat rejection rate versus evaporator exit temperature for a horizontal startup of the 1.8-m Mo-Li heat pipe. Also plotted are the sonic and viscous limit curves. Uncertainty intervals are shown for both quantities.

Figure 20. Condenser heat rejection rate versus evaporator exit temperature for a horizontal startup of the 1.8-m Mo-Li heat pipe. Also plotted are the sonic and viscous limit curves. Plot focuses on heat pipe behavior early in startup period.

Figure 21. Condenser heat rejection rate versus evaporator exit temperature for a horizontal startup of the 1.8-m Mo-Li heat pipe. Also plotted are the sonic and viscous limit curves. Plot is presented in log-linear coordinates.

Startup and Operation with Condenser Inclined 45° Above the Horizon

Another heat pipe startup was made over a similar time interval with the heat pipe's condenser inclined 45° above the horizon. Figure 22 shows the power setting versus time profile for this startup. This power ramp was steadier with time than the ramp shown in Figure 8. The maximum power setting was reached after 4 hours with the evaporator exit about 100°C below the level obtained in the horizontal startup. The final generator power setting was 5.3 compared with 6.0 for the horizontal startup run.

The melt-front location versus time for this test is given in Figure 23. Generator power was applied so that the melt front reached the condenser end of the heat pipe after 2 hours. The front progressed forward in steps each with a small convex bow. The timing of these steps did not directly correspond to the increases in power shown in Figure 22, rather, to front movement between thermocouple locations. As in the previous melt-front position versus time plot, these steps appear to be a measurement artifact.

Figure 24 gives the surface temperature versus time at various locations for a startup at 45° inclination. Oscillations began in the wall temperature as the melt front moved beyond 140 cm from the evaporator end cap and the heat pipe surface temperature at the evaporator exit exceeded 1000 K. These oscillations were most pronounced near the condenser entrance. Figure 25 plots thermal energy-removal rate from the condenser versus time. This plot reveals two superimposed effects: 1) step changes in condenser power throughput corresponding to increases in generator power 2) condenser power throughput oscillations. Interestingly, there was a hiatus in the oscillations once the heat pipe became isothermal at 1150 K. Larger magnitude oscillations with lower frequency were again observed after the heat pipe reached 1225 K. The first series of oscillations were probably caused by surplus liquid near the end of the heated zone being entrained into the high-velocity vapor region. The liquid deposited in the condenser region and moved back toward the evaporator by gravity and capillary forces. These oscillations were suppressed at higher temperature once excess condenser inventory had drained and the vapor exiting the evaporator became denser and its velocity diminished. The second set of oscillations was generated from periodic slugging of superheated liquid originating in the evaporator. Oscillations of this sort are commonly associated with uniform heating of an alkali metal below an internal liquid surface. The onset of the second oscillation set occurred immediately after a uniform 20°C reduction in condenser surface temperature 3 hours 15 minutes into the startup.

Figure 22. 100 kW induction generator power setting versus time for startup at 45° inclination of 1.8-m Mo-Li heat pipe.

Figure 23. Location of lithium melt front during startup of 1.8-m Mo-Li heat pipe with condenser 45° above the horizon.

Figure 24. Condenser surface temperatures measured during startup of 1.8-m Mo-Li heat pipe with condenser inclined 45° above the horizon. The large circles track the temperature of the surrounding quartz tube.

Figure 25. Thermal energy removal rate from condenser during startup of the 1.8-m long Mo-Li heat pipe with condenser inclined 45° above horizon.

Axial temperature profiles at various condenser power throughputs are shown in Figure 26. The heat pipe became isothermal around 1150 K with 540-W condenser power throughput. The smaller variation between the measurement at the third thermocouple location and adjacent locations suggests that the mechanism responsible for depressed temperature at the third thermocouple in the previously mentioned test was less important during this test. The pipe was brought to a peak temperature of 1400 K corresponding to a condenser power throughput of 2340 W.

At 1400 K, the liquid pool extended several centimeters into the heated region. Slugs of liquid were ejected from the evaporator at about 30-s intervals (both mean and mode). The slugs caused brief liquid depletion over a short part of the heated zone. Liquid, originating in the condenser, then flowed back toward and re-wetted the depleted region. The temperature oscillations in the condenser were smaller in magnitude but over a larger area than the temperature oscillations in the evaporator. Calculations, based on optical temperature measurements of the evaporator transient during slugging, confirm the equivalence of energy removed by the slug in the evaporator and the resulting energy deposition in the condenser. Saturation pressure calculations were also made based on changes in heat-pipe-condenser temperature and were compared to sustainable superheat pressures using the Laplace equation. The conclusions drawn suggest that the underlying slugging mechanism in the evaporator occurred by discharge of superheated liquid from the free surface inside the partially filled annulus.

A plot of condenser heat-rejection rate versus evaporator exit temperature is shown in Figure 27. Between 1000 K and 1100 K the power throughput considerably exceeded the calculated steady state viscous limit. The difference may be related to the movement toward the evaporator end of the pipe of excess condenser inventory that was subcooled by several hundred degrees centigrade with respect to the saturation vapor pressure. Oscillations attributed to entrained liquid movement through the vapor space are clearly seen in the evaporator-exit temperature data starting at 1050 K. This effect also appears associated with variations from predicted power throughput profile.

The transition between the viscous and radiation limit curves occurred at the same evaporator exit temperature as the horizontal startup test. The slope in the radiation limit curve during the 45° startup was greater than that found during the horizontal startup. This is directly attributable to the absence of a pool at the condenser end of the heat pipe. Pictured in Figure 28 is the 1.8-m Mo-Li heat pipe operating at steady state and inclined with the condenser 45° above the horizontal.

Figure 26. Condenser surface temperatures measured during startup at 45° inclination of 1.8-m Mo-Li heat pipe.

Figure 27. Condenser heat rejection rate versus evaporator exit temperature for 1.8-m Mo-Li heat pipe with condenser inclined 45° above the horizon. Also plotted are the sonic and viscous limit curves.

Figure 28. Picture of 1.8-m Mo-Li heat pipe operating at steady state with condenser inclined 45° above horizon.

Test of 1.8-m Mo-Li Heat Pipe Above the Design Temperature

The pipe was returned to the horizontal orientation and brought to 1540 K at the evaporator exit to test operation above the heat pipe-design temperature. When the power to the heat pipe was increased further, a hot spot developed at the beginning of the evaporator in the same location as before. The hot spot at 1540 K in the horizontal orientation may have resulted from a decrease in the wetting angles of the lithium-wick interface. The cause of the wetting angle change is usually altered surface chemistry of the screen wick. The surface chemistry change would be likely related to liquid depletions in the preceding series of tests. After the hot spot developed, the heat pipe was brought to 1300 K. The hot spot soon disappeared, and the heat pipe was operated for several hours to rewet the evaporator region. The pipe was then shut down in the horizontal orientation. The induction coil was moved forward to separate the liquid pool from the heated region when the heat pipe was operated at positive inclination.

Test at Various Inclinations

The 1.8-m Mo-Li heat pipe is of annular design similar to one previously tested at Los Alamos for a space reactor application. As built, the heat pipe purposely lacked closure of the annulus at the condenser end. This configuration is not specifically intended to operate optimally at positive tilt. The slugging of liquid from the lithium free surface in the annulus, was observed during tests at inclinations of 45° and greater. By closing the annulus, hydraulic continuity would be maintained, and the pipe should operate inclined without slugging, even using uniform heating in the evaporator. The tests at various inclinations are still interesting for the insight they give into the heat pipe's operating characteristics.

The following paragraph summarizes the test sequence that will be subsequently described in more detail. With the heat pipe at a 45° inclination, the pipe was brought from room temperature to 1200 K in 45 minutes. The pipe was then brought to 1300 K after another 20 minutes. It was then moved to a horizontal orientation, and the generator power was adjusted until the thermocouple at the evaporator exit read 1300 K. The pipe was left in this state for several hours. Temperature profile measurements were taken of surface temperature around the condenser pool. Figure 29 compares measurements made of condenser pool temperature taken with an infrared pyrometer and thermocouple.

Figure 29. Surface temperatures near condenser pool of 1.8-m Mo-Li heat pipe.

The pipe was then brought to 30° above the horizon for 5 minutes, moved to 45° for another 5 minutes, and then moved to 60° and finally 90° above the horizontal.

The desire to better characterize heat pipe internal operation motivated an estimate of the inventory distribution during inclination maneuvers at 1300 K. The total mass of lithium in the heat pipe was known from measurements taken after filling. Given the total fluid mass, the heat pipe geometry (confirmed by radiography), the capillary heights of the wick and the annulus, the length of the condenser pool at a given operating condition, and the heat pipe temperature, an estimate can be made of the distribution of the working fluid in the heat pipe as a function of angle. Even at full operating power, the mass of lithium vapor in the core space is negligible compared to the lithium mass in the saturated wick and is neglected. The lack of an annulus closure at the condenser end of the pipe causes hydraulic continuity to be broken once the condenser-evaporator height difference exceeds the annulus capillary height. Drainage also causes the liquid pool that accumulates in the condenser region to move toward the evaporator end of the heat pipe. The capillary height of the annulus is found by balancing surface tension and gravity forces

$$h_a = \frac{4\sigma \cos(\theta)}{\delta\rho_l g} \quad (16)$$

The annulus begins to drain when the condenser end of the heat pipe exceeds the annulus capillary height. This occurs once the heat pipe condenser reaches ϕ_d above the horizon

$$\phi_d = \sin^{-1}\left(\frac{4\sigma \cos(\theta)}{\delta\rho_l g L}\right) \quad (17)$$

Making use of the Heaviside function, the working fluid mass in the annulus as a function angle ϕ above the horizon can then be described in terms of the capillary height

$$m_a(\phi) = M_a \left[1 + \left(\frac{1}{2} + \frac{1}{\pi} \int_0^\infty \frac{\sin[(\phi - \phi_d)]t}{t} dt \right) \left(\frac{h_a}{L \sin \phi} - 1 \right) \right] \quad (18)$$

the mass, M_a , of working fluid in a completely filled annulus is a function of the heat pipe temperature distribution. The working fluid is assumed to saturate the wick at all angles since $2\sigma/\rho_l g r_p \gg L$. At shallow angle, the surplus inventory accumulates in the condenser. The mass of lithium in the condenser pool as a function of angle is estimated from measurements of pool length taken at temperature.

$$m_c(\phi) = \rho_l A_c l_p \left[1 - \left(\frac{1}{2} + \frac{1}{\pi} \int_0^\infty \frac{\sin[(\phi - \phi_d)]t}{t} dt \right) \right] \quad (19)$$

Neglecting the small inventory held in the vapor space, the lithium mass in the evaporator pool as a function of angle is then

$$m_e(\phi) = m_T - m_w - m_a(\phi) - m_c(\phi) \quad (20)$$

Figure 30 shows the estimated working fluid distribution in these regions as a function of condenser inclination. Below 13° inclination, surplus liquid resides at the condenser end of the heat pipe. The annulus holds about 12 g of lithium with the remainder in the saturated wick. The inventory in the annulus and condenser pool begins to drain once the height of the condenser end exceeds the wicking height of the annular gap. As the condenser is further raised, the excess inventory accumulates on the evaporator end of the heat pipe. The angular variation in liquid height in the annulus and the length of the evaporator pool is shown in Figure 31 for the Mo-Li heat pipe operating at 1300 K. The pool that accumulates on the evaporator end extends into the heated zone under the induction coil at inclinations greater than 20°. The liquid interface in the annulus approaches the exit of the heated zone as the heat pipe reaches 50° inclination. The manner in which the pool drains can be expected to depend on the heat pipe operating history and the path followed by the heat pipe during the transition. The temperature distribution of the pool also plays a role. Not surprisingly, the idealization shown in Figure 30 and Figure 31 applies to equilibrium conditions and agrees with observation only after sufficient time has elapsed at angle.

Temperature data were collected during the 30-minute transition from 3° to 90° above the horizontal. Figure 32 shows the heat-pipe surface temperatures during this period. The thermocouple 82 cm from the evaporator end cap was partially detached from the wall and its data were spurious. The remaining thermocouples are believed to have given valid data. The thermal-energy-removal rate from the condenser during these maneuvers is shown in Figure 33.

From a series of energy balances based on measured wall temperature data it was found that during this transition the pool that had accumulated at the condenser end during horizontal operation split in half and flowed toward the evaporator in two discrete movements. During the transition from 3° to 30°, gravity forces pulled the entire condenser pool several centimeters away from the condenser end. The pool then moved down the

Figure 30. Distribution of working fluid inventory as a function of angle above the horizontal
For 1.8-m Mo-Li heat pipe.

Figure 31. Distance from evaporator end cap to annular meniscus and top of evaporator pool as a function of angle above the horizon for 1.8-m Mo-Li heat pipe.

Figure 32. Surface temperatures on 1.8-m Mo-Li heat pipe with condenser inclination from 0° to 90° above the horizon. Distance in legend is measured from the evaporator end cap.

Figure 33. Thermal energy removal rate from condenser of 1.8-m Mo-Li heat pipe as inclination of condenser moves from 0° to 90° above the horizon.

vapor core in the form of a liquid film. The film extended to the thermocouple located 159 cm from the evaporator end cap. The hot side of the liquid pool became detached during the transition from 30° to 45° and moved to the evaporator. Over the next three minutes, the liquid that remained spread over the condenser end of the heat pipe. The remaining liquid moved toward the evaporator end after the heat pipe was raised above 60°.

This last liquid movement to the evaporator coincided with the onset of liquid slugging. The slugs moved from the evaporator to the condenser region of the pipe. Two modes of slugging were observed. The first slugging mode began 2 minutes after the pipe reached 60° inclination. Slugs with a period of about a minute and containing 4000 to 6000 J of energy were ejected three successive times from the evaporator. After that, a series of slugs having a 15-s period and containing about 1000 J were ejected. These short-period slugs continued to be ejected until the pipe was raised to the vertical. At the vertical, another 5000 J slug having a 1-minute period was ejected. At this point fogging was observed on the quartz near the condenser end cap. The heat pipe was returned to the horizontal and was shut down. The cooling curve is shown on the right side of Figure 33.

The fogging on the quartz was colored white indicating that lithium vapor had leaked from a fill stem crack. In anticipation of this possibility, a molybdenum end cap had been previously fabricated. The heat pipe was removed from the test fixture and the end cap was electron beam welded to the condenser end of the heat pipe.

Rapid Startup Transient Tests

After the end cap was welded, the pipe was wet in with a full-length induction coil and returned to the variable-angle test fixture. In the horizontal orientation, a series of startups from the frozen state were conducted following predetermined generator power setting versus time profiles. Figure 34 shows these power-setting profiles for three different rapid startup tests. In each test, the generator power setting was raised every minute. For the three tests labeled "D9805041300", "D9805071321", and "D9805060846" the generator power setting was increased by 0.20, 0.25, and 0.30 per minute, respectively. Based on experience gained from the power calibration tests, it was known that increasing power at these rates would be sufficient to bring the heat pipe to 1200 K in 17, 14, and 11 minutes, respectively.

Figure 34. Induction generator power settings versus time for rapid startups of 1.8-m Mo-Li heat pipe.

The power setting curve for the 17-minute startup is shown on the solid line on Figure 34, labeled D9805041300. Power to the heat pipe evaporator was steadily increased until the heat pipe reached 1450 K, 20 minutes after the startup was initiated. The heat pipe was then operated at steady state for another twenty minutes and then put through a series of cyclic transients. The cyclic transients will be discussed in the next section. The wall temperature at locations along the pipe during the startup is shown in Figure 35. The slope of the temperature versus time profile at the first thermocouple location increased from near zero at 2 minutes to 500 K/minute at 7 minutes. Similar slope changes occurred further down the heat pipe, but much more abruptly. The slope of the temperature versus time profile diminished as continuum flow was approached locally. Except for the condenser pool, the heat pipe became isothermal at 1175 K 15 minutes into the startup.

Figure 36 gives the melt front location versus time for the previous and two other rapid-startup transient tests. For the previous test, the melt front reached the end of the heat pipe at 15 minutes into the transient represented by the solid line and marked D9805041300. Figure 37 shows the thermal-energy-removal rate from the condenser for the same three tests. The transient marked by the solid line achieved its steady state power level of 2300 W 22 minutes into the startup. During the first ten minutes, most of the heat applied to the evaporator went to internal energy in the heat pipe wall and working fluid. Almost no latent heat reached the condenser region during this period. As the active region lengthened over the next ten minutes, there was a near linear increase in condenser throughput with time.

A hot spot developed in the evaporator 13 minutes into the 17-minute transient. At this point, the condenser throughput was about 400 W. The hot spot formed 8 cm from the evaporator-end-cap end of the coil. However, the spot was not large, was not significantly hotter than the surrounding surfaces, and diminished in intensity as power was increased. By the time the heat pipe reached 1400 K, it had completely disappeared.

The curve on Figure 34 labeled, D9805060846, shows the generator power setting profile for an attempt to bring the pipe from the frozen state to 1200 K in 14 minutes. The generator was brought to 4.7 when a dry out in the evaporator began. A videotape record of this startup was also made and later synchronized with the collected wall temperature data. At 4 minutes into the startup a glow was first visually detected under the induction coil indicating that the evaporator had reached the Draper point temperature of 800 K.

Figure 35. Surface temperature versus time for first rapid startup test of 1.8-m Mo-Li heat pipe. Distance in legend is measured from the evaporator end cap.

Figure 36. Melt front location for three different rapid startup transients of 1.8-m Mo-Li heat pipe.

Figure 37. Thermal energy removal rate from condenser for three different rapid startup transients of 1.8-m Mo-Li heat pipe.

Figure 38. Heat pipe startup temperature for second rapid transient test. Evaporator dry out begins at 507 s.

A minute later the Draper-glow moved past the limits of the induction coil into the condenser section. The Draper point front continued to advance in a steady fashion down the length of the heat pipe. At eight minutes 43 seconds into the transient, the Draper-point front suddenly advanced from 130 cm to 160 cm from the evaporator end cap. Within ten seconds of this rapid movement, a hot spot began to form at the evaporator in the same location as before. The spot's intensity was marked, so generator power was kept constant in the hope that the working fluid would redistribute and the evaporator would rewet.

Figure 38 shows the heat-pipe surface temperatures versus time for this startup. Interestingly, the heat-pipe condenser surface cooled while the generator power setting remained constant. Vapor transport to the condenser region was partially suppressed during the dry out. This is also reflected in Figure 37 that shows condenser throughput versus time. The power versus time curve steeply rose, reaching 600 W at 450-s into the transient. Condenser throughput then dropped precipitously. The power induced to the dried-out portion of the evaporator was apparently held as internal energy in the evaporator wall. Figure 35 shows the location of the melt-front during this test. The evaporator dry out coincided with the lithium melt front reaching the condenser end of the heat pipe. About 90 s after the onset of dry out, it became apparent that the evaporator would not recover at constant power. Generator power was then reduced, and the pipe was tilted 10° to return liquid to the dry out region. The pipe was then slowly brought to 1300 K and operated horizontally for several hours to allow the evaporator region to rewet.

Another attempt to bring the heat pipe to 1200 K in 14 minutes also resulted in a dry out in the evaporator region. Figure 35 shows the locations of the melt front during all three rapid startup runs. Again, the evaporator dry out coincided with the lithium melt front reaching the condenser end of the heat pipe. Figure 37 shows the thermal-energy-removal rate from the condenser versus time. This time the dry out in the evaporator region occurred at 650 s as 550 W of power was being rejected from the condenser. Figure 39 shows the condenser temperature versus time profile for this test. As before, the dry out began as the heat pipe began to become isothermal at 1175 K. This time, the temperature drop in the condenser was less pronounced after the onset of dry out. Generator power was then reduced slightly to allow the evaporator to rewet. Over the next hour, the heat pipe was slowly brought to 1400 K and operated horizontally.

Figure 39. Heat pipe startup temperatures for third rapid transient test. Evaporator dry out begins at 640 s.

Thermal Cycle Tests

The heat pipe was thermally cycled on numerous occasions. Cycling was done periodically during startup and rewetting operations. The generator power setting versus time for a deliberate power cycling maneuver is shown in Figure 40. A plot showing the heat pipe temperature response to this generator power setting profile is given in Figure 41. During this maneuver, the condenser was held at 1475 K for five minutes. The power to the induction coil was then shut off for another five minutes. The power to the induction coil was then increased in five one-minute increments until the heat pipe returned to the power state for 1475 K operation.

The evaporator region of the heat pipe remained isothermal throughout these cycles. The condenser pool temperature followed the temperature trends of the active region, though the oscillation magnitude in the pool was smaller. There was no noticeable phase lag in temperature response between the pool and the active region. Throughout the test, the active region of the heat pipe remained in the continuum flow region. Figure 42 shows the heat emitted from the condenser surface versus time. With the active region at 1475 K the condenser throughput was 2350 W. Over the five minute cooling interval, the amount radiated from the condenser dropped to 700 W. The five steps at which power was increased to the induction generator are clearly seen on the return side of the curve.

Post-test Analysis

After the rapid transient tests were completed, the 1.8-m Mo-Li heat pipe was removed from the test fixture and its wick and wall structure were examined by radiography. No corrosion was detected in the region of the wick that was directly under the induction coil. Minor corrosion was found near the stagnation end of the evaporator. However, there was substantial corrosion in the condenser region wick. Near the end of the condenser a section several inches long and covering 45° of circumference completely dissolved. A few small flakes of screen had flowed into the annulus.

The current understanding of corrosion in molybdenum-lithium systems is based on the concentration of non-metallic impurities in the evaporator. This mechanism is discussed at length by Feber and Merrigan (1987). As soluble impurities move toward the evaporator, their activity becomes great enough to make the formation of soluble ternary compounds

Figure 40. Induction generator power settings versus time for cyclic test 1.8-m Mo-Li heat pipe.

Figure 41. Surface temperatures on 1.8-m Mo-Li heat pipe during cyclic horizontal operation.

Figure 42. Thermal energy removal rate from condenser of 1.8-m Mo-Li heat pipe during cyclic horizontal operation (solid curve). Calculated energy transport from evaporator using Equations (1) through (3) is shown with the broken line.

thermodynamically possible. The molybdenum dissolves forming ternary oxide or ternary nitride. Oddly, the observed corrosion occurred mostly in the condenser region.

Several possible explanations have been considered to account for preferential corrosion in the condenser. The now-favored story involves air entry into the heat pipe. After the fill stem leak developed at the conclusion of the inclination test, the heat pipe was shut down in the horizontal orientation to form a solidified lithium plug at the crack. During the test, the heat pipe was surrounded by a vacuum of better than 10^{-5} -torr. After the heat pipe had cooled, it was moved to the fusion welding facility where it was exposed to air. It is now believed that the lithium plug did not form as intended, and during the transfer some air entered the heat pipe through the crack. Heat pipe evacuation by the electron-beam welder may have been insufficient to purge the air. The molybdenum end cap was then attached with trapped air, oxide, or nitride inside the heat pipe.

The condenser corrosion would then form from nitrogen impurity, held in the condenser pool, which dissolved the molybdenum. The formation of ternary oxides are also possible, but more likely, any oxygen formed highly stable lithium oxide. There is little quantitative data on the solubility of molybdenum in lithium. This leaves open the question whether such corrosion could occur during the subsequent 10-hour operating period when the condenser pool temperature was typically 1000 K.

Conclusions Drawn from 1.8-m Long Mo-Li Heat Pipe Tests

Quasi-steady heat pipe operation resulted in good agreement with theory once the heat pipe reached continuum flow. During start ups the heat pipe transitioned from the viscous to the radiation-limited modes. The heat pipe was operated at temperatures of up to 1540 K. Condenser coupling was sufficient for the heat pipe condenser to radiate 3.2 kW to its surroundings at 1500 K. This corresponds to an axial heat flux at the evaporator exit of 2-kW/cm² and a radial heat flux in the evaporator of 23 W/cm².

Some liquid slugging from free surfaces inside the annulus in the evaporator region was observed when operating with the condenser inclined greater than 45° above the horizon. The heat pipe was found capable of transitioning from the frozen state to 1450 K in 20 minutes. Attempts to bring the pipe from a frozen condition to 1500 K in less than 20 minutes resulted in an evaporator-region dry out. The heat pipe fully recovered from each dry out after the induction generator power was reduced and the heat pipe was tilted slightly. The heat pipe also operated well in cyclic fashion from full operating power to zero power and back to full power in successive five-minute intervals.

2.0 Construction and Test of 23-cm Mo-Li Heat Pipe

During this period a 23-cm long Mo-Li heat pipe, identical in cross section and wick geometry to the 1.8-m long Mo-Li heat pipe described above was assembled from the remaining tubing and wick materials. This pipe was developed for use in combustion heated tests at Bettis. Absent from this pipe was the hafnium getter pack that was placed inside the 1.8-m long pipe. This heat pipe will be used for coating evaluation for external oxidation resistance and improved emittance of molybdenum.

At first, use of MoSi_2 coating on the outside surface of this heat pipe was considered. A sample of molybdenum tube was sent to a commercial vendor for MoSi_2 coating trials. This tube was returned to Los Alamos in mid-January and temperature-cycled to verify coating integrity. The coating was found to be satisfactory. This vendor had agreed to coat the 23-cm long lithium-filled heat pipe. However, because of a change in plans by Bettis, an alternative coating was later selected.

The required hardware for the filling of the 23-cm Mo-Li was fabricated, and a known-volume pot was charged with lithium. The lithium fill stand was assembled, and the pipe was charged with 4.5 g of lithium. After the pipe was charged, a lithium plug was formed in the fill stem, and the pipe was wet in for several hours at 1150 K. The pipe was then vertically oriented, placed under a short induction coil, and repeatedly brought to 1500 K.

A plot of evaporator exit temperature versus time from start up is shown in Figure 43. This startup was smooth with no hot spots developing in the evaporator region. The constant 525 K recorded during the first 10 minutes of startup is an artifact of measuring device insensitivity. The infrared pyrometer used detects emitted radiation at 0.65μ wavelength, largely absent from the thermal spectrum below that temperature. Power was adjusted six times during startup. Figure 44 shows the 23-cm long heat pipe operating at 1530 K. The pipe was operated at a constant 1500 K for two hours, and then power was cut. The cooling curve after the power was cut is shown on the right side of the Figure 43. After this test, a molybdenum end cap was electron beam welded to this heat pipe, and a final wetting operation was completed. The pipe was then sent to Bettis for coating and combustion-fire testing.

Figure 43. Heat pipe surface temperatures on 23-cm Mo-Li heat pipe in vertical orientation. Measurements were made with an infrared pyrometer at the evaporator exit.

Figure 44. Picture taken during startup of 23-cm Mo-Li combustion fired heat pipe. The measured temperature is 1530 K at the exit of the evaporator.

3.0 Sodium Heat Pipe Safety Tests

A series of tests were conducted to characterize the reaction from water intrusion into a sodium heat pipe with penetrations of different diameters 0.25-mm (0.010-in) and 0.58-mm (0.023-in) in the fill stem. An additional test was conducted at 7000-ft-above-sea-level atmospheric pressure 77-kPa (11.7-psia) with a 4.8-mm (0.188-in) diameter penetration. The information gathered from these tests included heat pipe surface temperature versus axial position, heat pipe internal pressure, reaction products (H_2 , $NaOH_{(aq)}$) heat evolved by the reaction, and deformation of the heat pipe. A remote explosives firing area was selected for the test location to simplify the required administrative approvals.

These tests confirmed, for the conditions considered, that the movement of water into the heat pipe is limited by hydrogen generation from the sodium-water reaction. The pressure at which water is introduced drives the reaction extent. The penetration area also has some effect on the reaction rate and the equilibration time of the reaction. In addition, the amount and location of the sodium in the heat pipe may have some effect, but for a hydrogen-limited reaction, this applies only to very small quantities of the sodium.

Two heat pipes, 30-cm long and built out of 3/8"-in Schedule 40, Haynes 230 pipe were made. Three layers of 100-mesh stainless steel screen line the inside of the heat pipe. Figure 45 shows orthogonal views of one of the safety-test heat pipes. Each pipe was charged by vacuum distillation with 4.5 g (0.2 mole) of sodium that, with a saturated wick, left about a gram of free sodium in the vapor space. The heat pipes were then wetted for several days at 1173 K and then tested at 1123 K to ensure proper heat pipe operation. The safety test heat pipes were x-rayed before and after testing to verify the condition of the wick. Another pipe was built for use in a diagnostic test. This pipe was similar in geometry to the other two pipes but lacked a wick and was directly filled with sodium without using the distillation procedure.

Analysis of Water Intrusion into a Sodium Heat Pipe

A design calculation was made to anticipate instrumentation requirements. Figure 46 shows a schematic representation of the physical system modeled in this design calculation. The

MATERIAL REQUIRED

1. 3/8" SCHEDULE 40 PIPE, HAYNES 230
2. BAR STOCK FOR END CAPS, HAYNES 230
3. 1/4" TUBE FOR FILL STEM, HAYNES 230
4. 100 MESH SCREEN, 304 STAINLESS STEEL

Drawing 4/1/98 Bob Reid

Figure 45. Orthogonal representation of heat pipe used in the sodium safety test.

Figure 46. Schematic representation of model used to simulate water intrusion into a sodium heat pipe.

dominant chemical reaction for the pressure and temperature conditions encountered in this test was

The heat evolved from this reaction as water enters the heat pipe can be written

$$\dot{Q}''' = \Delta H \cdot m_{H_2O} \quad . \quad (22)$$

The thermal response of the system to the heat evolved by the sodium-water reaction was found using an electrical analogy thermal model. Heat pipe temperature is described by

$$m_{hp} c_p \frac{dT}{dt} = \dot{Q}''' - h p d L (T - T_\infty) \quad . \quad (23)$$

The heat transfer coefficient by free convection from the heat pipe surface is

$$h = \frac{k}{d} 0.42 Gr^{0.25} Pr^{0.012} \left(\frac{l}{d} \right)^{-0.3} \quad . \quad (24)$$

Bulk temperature change in water surrounding heat pipe was estimated to be no greater than 5°C, so the water temperature surrounding the heat pipe was assumed to remain constant. Several equations were used to describe the state of the reactants and the products inside the heat pipe. Dalton's law was used to model the total pressure inside heat pipe vapor space that consisted of the partial pressures of the water vapor and the generated hydrogen

$$P_{hp} = P_{H_2O} + P_{H_2} \quad . \quad (25)$$

An ideal gas relation was used to fix the water vapor partial pressure. This pressure depends on the pipe temperature and the mass of the water vapor entering the pipe.

$$P_{H_2O} = \frac{m_{H_2O}}{V_{hp}} RT_{hp} \quad . \quad (26)$$

The hydrogen generated by the water-sodium reaction was taken to be proportional to the total mass of water entering the heat pipe. Once water passes through the penetration it is assumed to come in contact with and react instantaneously with the sodium. The ideal gas law describes the hydrogen-partial pressure.

$$P_{H_2} = \frac{m_{H_2}}{V_{hp}} RT_{hp} \quad . \quad (27)$$

The density of any liquid water that flows into the vapor space during the reaction is assumed to be $\rho_{H_2O} = \text{constant}$.

Water enters the initially evacuated heat pipe through the penetration in a sequence of three flow regimes. The first regime is critical isentropic flow of water vapor. The flow remains choked so long as the pressure ratio between the reservoir and the heat pipe vapor space remains $P_{total}/P_{sat} < 0.58$. The mass transfer rate through the penetration is

$$\dot{m}^* = \gamma^{1/2} \left(\frac{2}{\gamma+1} \right)^{\frac{1(\gamma+1)}{2(\gamma-1)}} \frac{\pi}{4} \delta^2 \rho_o (RT_o)^{1/2} \quad (28)$$

For water vapor, the ratio of specific heats is $\gamma = 1.12$. Once $P_{total}/P_{sat} > 0.58$, the flow of water vapor into the heat pipe becomes subsonic. An isentropic flow relation is used to model the transfer of water vapor through the penetration

$$\dot{m} = P_{sat} M \frac{\pi}{4} \delta^2 \left(\frac{\gamma}{RT_o} \right)^{1/2} \left(1 + \frac{(\gamma-1)}{2} M^2 \right)^{-\frac{1(\gamma+1)}{2(\gamma-1)}} \quad (29)$$

where the Mach number squared is found using

$$M^2 = \frac{2}{\gamma-1} \left[\left(P_{sat}/P_{total} \right)^{\frac{\gamma-1}{\gamma}} - 1 \right] \quad (30)$$

Liquid water can exist in equilibrium inside the heat pipe once the total pressure inside it approaches the saturation pressure. After this point is reached, laminar flow of liquid water is assumed to pass through the penetration. The mass transfer rate becomes

$$\dot{m} = \frac{(P_B - P_{hp}) \pi \delta^4}{128 l \nu} \quad (31)$$

Water continues to enter the heat pipe until a balance is reached between the pressure, P_B , forcing the water into the pipe and the pressure generated, P_{hp} , by the hydrogen evolved by the sodium reaction with the entering water.

Figure 47 gives results from the model showing the heat of reaction versus time for two different penetration diameters. Heat is generated in four successive phases. At first, the

Figure 47. Model results showing the heat released from water flow into a sodium heat pipe versus time. Curves for two different orifice diameters are shown.

water vapor flows sonically through the orifice and reacts with the sodium to produce heat at a logarithmic rate. As the flow of water vapor into the pipe becomes subsonic at the orifice, the heat generated by the reaction enters a brief stationary phase. The heat generation then enters another logarithmic phase that corresponds to the flow of liquid water into the heat pipe. A final stationary phase is reached as the hydrogen pressure in the heat pipe equalizes with the pressure that drives water into the heat pipe.

From this analysis several factors important to water-sodium reaction become apparent. The pressure at which water is introduced into the pipe largely determines the extent of the reaction and the maximum heat pipe temperature. The size of the penetration into the heat pipe affects the reaction rate and the equilibration time of the reaction. The amount of sodium in the heat pipe should have some effect, but for a reaction limited by hydrogen generation this applies only to very small amounts. Other factors that influence the heat pipe response to the reaction are the temperature of the heat pipe surroundings, the heat transfer boundary condition at the surface of the heat pipe, and the penetration location with respect to the sodium.

Safety Test Apparatus

Figure 48 shows a schematic representation of the safety test apparatus. A sodium heat pipe is contained inside a stainless steel chamber. This chamber, also called the lower reservoir, establishes the thermal boundary condition surrounding the heat pipe. Tests were conducted with the chamber holding air at atmospheric pressure and pressurized water. On one end of the chamber is a flange to which the heat pipe fill stem is connected. The fill stem provides a flow path to a water charge volume located above the flange.

The charge volume held 42 ml of distilled water, sufficient to completely fill the heat pipe. Between the heat pipe and the water charge volume is a solenoid valve that isolates pressurized water from the heat pipe before test, and an orifice, which is used to control the size of the simulated leak. Also in the line between the heat pipe and the water volume is a pressure relief valve and a purge line used to evacuate the line leading up to the heat pipe fill stem. Above the water charge volume is another pressure relief valve and an upper reservoir, designed to hold the pressurizing gas that is used to simulate the hydrostatic pressure of the water entering the heat pipe. The upper reservoir is connected to a source of compressed gas and a line used to introduce water into the charge volume.

Figure 48. Schematic of sodium heat pipe safety test assembly,

Five chromal-alumal thermocouples were attached by spot welding along the length of the pipe. Piezoresistive transducers read the pressure inside the heat pipe, charge volume, and upper reservoir. A thermocouple was used to measure the temperature surrounding the heat pipe. Thermocouple and transducer measurements, taken at 2-s intervals, were recorded by a LabVIEW data acquisition system. A pressure gauge was connected to the gas supply line. Before installation, each pressure transducer was calibrated against a series of known pressures. The resulting curves were compared to manufacturer-supplied data for each transducer, with consistent agreement.

Safety Test Procedure

Each heat pipe tested was filled by distillation with 4.5 g of sodium. A complete sodium-water reaction would liberate 91 kJ, sufficient to bring the heat pipe to 925 K. The hydrogen pressure generated by a reaction moving towards completion would be more than adequate to breach the wall of the heat pipe. To insure personnel safety and to avoid data loss, a pre-test procedure was strictly followed.

The test began by introducing distilled water into the lower reservoir. The video camera was started and a check was made to verify proper operation. Diagnostic tests were then made on the alternating and direct current legs of the trigger circuit. A three-person firing team remained above the bunker. The alternating current leg of the trigger circuit was then verified de-energized. The firing team then introduced distilled water into the upper reservoir with a syringe, sealed and pressurized the upper and lower reservoirs, connected the trigger circuit to the solenoid, and opened a ball valve between orifice and heat pipe. Once the trigger was connected and ball valve opened, the firing team moved to the bunker.

The firing team then conducted a final check of the direct current leg of the trigger circuit, the data acquisition system, and the video system. The bunker door was sealed, and a voltage was applied across the alternating current leg of trigger circuit. After a brief countdown, the trigger was activated and the solenoid valve opened. The firing area was remotely viewed by video camera, and the response of the data system was monitored. The solenoid valve was kept open until no further response was observed on the data acquisition system.

Water Injection through a 0.25-mm Orifice into an Acrylic Pipe

The first test measured the water flow rate through a 0.25-mm diameter orifice into an evacuated acrylic pipe, not filled with sodium. This was done to verify water flow through the orifice. The use of acrylic wall material allowed a video record to be made of the water flowing into the pipe. In this test the upper reservoir was charged with 42 ml of water, pressurized to 550 kPa, and then isolated from the pressure line. The heat pipe was evacuated to less than 100 microns pressure. The solenoid valve was then opened. Figure 49 shows the pressure measured at the upper reservoir and at the solenoid valve for the first two minutes after the solenoid valve was opened. Water began flowing into the pipe within seconds of opening the valve. Gas pressure from the upper reservoir pushed water through the orifice and into the pipe. The pressure decrease during the first minute reflects a small amount of gas expansion from the water moving out of the charge volume. A minute after opening the solenoid valve, the charge volume was completely purged of water. After this time the slope of the pressure versus time curve increased, controlled by the expansion of the gas out of the upper reservoir and into the pipe volume. The mean water flow rate into the acrylic pipe during the charge volume purge was 0.7 g/s.

Water Injection through a 0.25-mm Orifice into a Sodium-Filled Pipe

A second test, intended to be a diagnostic, measured the response of a sodium-charged pipe to the flow of water through a 0.25-mm diameter orifice. This pipe's internal surface was without a wick, and after filling, a sodium pool had accumulated at the end opposite the fill stem. After filling, the pipe was evacuated below 100 microns pressure.

The heat pipe was placed into the fixture represented by Figure 48. The upper reservoir was brought to 550-kPa with compressed argon. The lower reservoir, containing the pipe, held air at atmospheric pressure. The lines between the orifice and the heat pipe were evacuated to 150 microns pressure. The solenoid valve was opened. After a brief delay the temperature of the thermocouple attached to the pipe wall outside the sodium pool began to rise.

Figure 50 shows the temperature response of this section of the pipe wall to the sodium-water reaction. The pipe temperature measured at the end opposite the fill stem moved sharply upward during the first 3 minutes after water was introduced. The brief change in slope 35 s into the reaction was produced by a trigger circuit fault that caused a 10-s closure of the solenoid valve. A peak temperature of 349 K was reached two minutes into the reaction. For the next eight minutes the pipe cooled at a 0.05°C/s rate. A brief 2°C rise in

Figure 49. Pressure response to water flowing into acrylic tube through a 0.25-mm diameter penetration with a reservoir pressure of 550 kPa. The upper reservoir is isolated from the gas supply line.

Figure 50. Temperature response of a sodium-charged pipe to the flow of water into it through a 0.25-mm diameter penetration, 550 kPa reservoir pressure. The solid line shows the prediction from the design calculation.

wall temperature occurred 10 minutes into the test. During this period, the other three thermocouples remained near ambient temperature. Based on wall temperature measurements, 1800 J of heat were liberated by the initial reaction. If the reaction given by Equation (21) was dominant, only 2 percent of the total sodium inventory in the pipe reacted with water. The hot region of the pipe cooled to 320 K within twenty minutes.

The predicted temperature response of the pipe to the sodium-water reaction is shown in Figure 50. The peak predicted temperature is 345 K, compared with the measured peak temperature of 349 K. The calculated reaction rate was faster than the measured rate. In addition, the predicted heat release was 5900 J, compared to the measured 1800 J heat release. The heat release in the model is absorbed by the entire heat pipe thermal mass, while the actual heat released by the reaction was concentrated in a small portion of the heat pipe. This accounts for the apparent peak temperature agreement despite the large difference in the heat release. The faster reaction rate in the model is a reasonable result based on the assumption that once water passes through the penetration it instantaneously reacts with the sodium. Not all water entering a heat pipe can be expected make contact with sodium. Such niceties as accounting for water trajectory with respect to the sodium are not included in the model. The heat balance calculations from measured wall temperature data indicate that 72 mg of water reacted with 90 mg of sodium. In the cooling phase, the slope of the wall temperature versus time curve exceeded the model's prediction. Axial conduction through the wall of the pipe, not included in the model, partly accounts for the difference.

The wall temperature data also show a brief 2°C rise 10 minutes into the test. This temperature rise was possibly related to the contraction of the cooling hydrogen bubble inside the pipe. The change in hydrogen pressure and volume inside the pipe from a 20°C reduction in hydrogen temperature is more than sufficient to clear the penetration. The volume of contraction also suggests that the hydrogen bubble may have extended a short distance upstream of the orifice after the maximum pipe temperature was reached. The pressure gradient produced by the cooling of the pipe would then drive a small quantity of water through the orifice. Heat balance calculations indicate that 3 mg of water reacting with 4 mg of sodium would be enough to produce a temperature change in that region of the heat pipe wall of 2°C.

Water Injection through a 0.58-mm Orifice into an Acrylic Pipe

Figure 51. Pressure response to water flowing into acrylic tube through a 0.58-mm diameter penetration with a reservoir pressure of 480 kPa. The upper reservoir is isolated from the gas supply line.

Another test measured the water flow rate through a 0.58-mm diameter orifice into an acrylic pipe without sodium. The upper reservoir was charged with 42 ml of water, pressurized to 490 kPa, and then isolated from the pressure line. The heat pipe was evacuated to less than 100 microns pressure. The solenoid valve was then opened. Figure 51 shows the pressure measured at the upper reservoir and the solenoid valve for the first two minutes after the solenoid valve was opened. Water began flowing into the pipe within seconds of the valve being opened. Gas pressure from the upper reservoir pushed water through the orifice and into the pipe. The reservoir pressure decrease during the first 10 s reflects the gas expansion from the movement of water out of the charge volume. The heat pipe pressure transits from 0 kPa to 40 kPa during the same period. About 10 s after the solenoid valve opened, the charge volume was completely purged of water, and the gas from the upper reservoir was pushed into the pipe. A pressure relief valve set to 200 kPa opened at one end of the pipe. After this, the pressure dropped precipitously, controlled by the expansion of the gas from the upper reservoir to the relief valve opening. The mean water flow rate through the 0.58-mm orifice was 4.2 g/s during the charge volume purge.

Water Injection through a 0.58-mm Orifice into a Sodium-Filled Heat Pipe

This test measured the response of a sodium-charged heat pipe to the movement of pressurized water through a 0.58-mm diameter orifice. This heat pipe's internal surface was covered with three layers of 150-mesh stainless steel screen. After being distillation-filled with sodium, the heat pipe was operated for several hours in the vertical orientation with the fill stem pointed upward. The heat pipe was then shut down and the fill stem was cleared of sodium. During shutdown sodium accumulated at a pool on the end opposite the fill stem.

The heat pipe was placed inside the test fixture shown in Figure 48. The upper reservoir was brought to 490-kPa with compressed air. The lower reservoir, containing the pipe, was filled with distilled water. The lines leading to the heat pipe were evacuated to less than 100 microns pressure. The solenoid valve was opened. After a brief delay, the temperature of the thermocouples attached to the heat pipe wall 2.5 cm and 11 cm from the end opposite the fill stem began to rise. Figure 52 shows the pressure response at the gas supply line, the reservoir, and inside the heat pipe. The pressure inside the heat pipe increased from 0 kPa to 520 kPa within two seconds of opening the solenoid valve. Two 20-kPa oscillations occurred in the heat pipe that decayed to a steady pressure within 10 s.

Figure 52. Pressure response to water flowing into a sodium heat pipe through a 0.58-mm diameter penetration with a reservoir pressure of 482 kPa. The upper reservoir is connected to the gas supply line.

Figure 53 shows the temperature response of the heat pipe wall to the sodium-water reaction. The thermocouple readings moved sharply upward during the first 10 s after water was introduced. A peak temperature of 338 K was reached at the thermocouple 2.5 cm from the end opposite the fill-stem 10 s into the reaction. Over the next 30 s the pipe cooled to 310 K and approached room temperature after 2 minutes. Based on wall temperature measurements, 1045 J of heat were liberated by the reaction.

The predicted temperature response of the heat pipe to the sodium-water reaction is shown in Figure 53. The peak temperature predicted by the model is 343 K, compared with the measured peak temperature of 337 K. Heat balance calculations, based on measurement, indicate that 41 mg of water reacted with 52 mg of sodium. In the cooling phase, the slope of the wall temperature versus time curve exceeds the model's prediction. The model limitations discussed for the preceding test apply equally here. X-rays, taken of the heat pipe before and after testing, indicate no measurable deformation to the wick or wall from the reaction. The heat pipe was then cut open and examined, confirming the presence of most of the original sodium charge.

Water Injection through a 4.8-mm Orifice into a Sodium-Filled Heat Pipe

This test measured the response of a sodium-charged heat pipe to the flow of atmospheric pressure (77-kPa) water through a 4.8-mm diameter orifice. As in the previous test, the heat pipe's internal surface was covered with three layers of 150-mesh stainless steel screen.

The fill stem of the heat pipe was connected to a solenoid valve and placed in an open trough pictured in Figure 54. The trough was then filled with distilled water. The closed solenoid valve prevented the flow of distilled water into the vapor space of the evacuated heat pipe. The video camera positioned on the left side of the picture recorded any evidence of the reaction at the solenoid valve entrance.

The solenoid valve was opened. Figure 55 shows the heat pipe temperature response to the sodium-water reaction. After a brief delay, the temperature of the thermocouples attached to the pipe wall began to rise. The temperature change occurred more uniformly along the length of the heat pipe than in the previous test. The peak temperature was reached 24 cm from the end opposite the fill-stem 5 s into the transient. The heat released by the initial

Figure 53. Temperature response to water flowing into a sodium heat pipe through a 0.58-mm diameter penetration with a reservoir pressure of 482 kPa. The solid line shows the prediction from the design calculation.

Figure 54. Picture of a sodium heat pipe inside the water-filled trough.

Figure 55. Temperature response to water flowing into a sodium heat pipe through a 4.8-mm diameter penetration. The water is driven into the evacuated heat pipe by air at 77 kPa.

reaction was about 1500 J. The heat pipe temperature decays to 308 K 30 s into the test. A second 5°C rise occurs near the fill stem, 45 s after the solenoid was opened. This change occurred over a longer period than the initial reaction. The heat generated by the reaction at 45 s was 100 J. After 2 minutes, the heat pipe cooled to ambient temperature. During the test, bubbles, believed to be hydrogen, were periodically expelled from the solenoid valve entrance and into the water-filled trough. The model could not be used to simulate this test. The water in this test moved through a large-diameter penetration, requiring the use of more sophisticated numerical techniques than for the other tests.

Interpretation of Safety Test Results

Tests simulating a near-surface casualty indicate that the reaction from water entering a sodium-filled heat pipe is limited by hydrogen production. Tests were made with penetrations of different diameters: 0.25-mm and 0.58-mm in the fill stem. Water was introduced into the heat pipe at 500 kPa. An additional test was conducted with a 4.8-mm diameter penetration at atmospheric pressure 77-kPa. At no time during any of these tests did the heat pipe wall temperature rise by more than 50°C.

These tests confirm, for the conditions considered, that the extent of the sodium-water reaction inside a heat pipe is driven by the pressure at which water is introduced. In these tests driving pressure served as a proxy for hydrostatic pressure experienced by the heat pipe at depth. The size of the penetration into the heat pipe affects the reaction rate and the equilibration time of the reaction. The penetration size had a weak influence on reaction extent. The amount of sodium in the heat pipe may have some effect, but for a reaction limited by hydrogen generation this applies only to very small amounts.

Considering the dynamic nature of the reaction, the qualitative agreement between experiment and theory was surprisingly good. The abrupt changes observed in heat pipe temperature as a function of time were consistent with the model. The model predicted that 6.5 percent of the sodium would be reacted by the entering water. This compares with the twice-measured values of slightly less than 2 percent. Important differences between model and observation are due to the model's reaction kinetics being too fast and the model's calculated water flow rate into the pipe being higher than observed. Follow-on tests will be conducted during FY99 to characterize the reaction with larger penetration sizes and at greater simulated depth.

4.0 Thermochemical Model

A thermochemical model, designated HPLT-8, was developed from a series of ten computer programs that model mass transport in high-temperature heat pipes. HPLT-8 was specifically developed to model such processes in a Haynes 230-sodium life test system. The HPLT-8 model is based on an earlier model, HPLT-7, developed for a Nb-1%Zr potassium system operating at 900 K. Other versions of the HPLT model series were used to obtain thermodynamic data from the large number of chemical reactions in the model. Working fluids in these previous models include alkali metals or mercury; heat pipe materials such as molybdenum-rhenium, niobium-zirconium, titanium, and stainless steel; and possible non-metallic impurities such as oxygen, nitrogen, carbon, or silicon. The input data file format for the HPLT-7 and HPLT-8 models are similar. Both model versions use the computational algorithms from the SOLGASMIX-PV code to calculate complex chemical equilibria in multiphase systems. The original version of SOLGASMIX-PV was described by Besmann (1977) and was a modification of Eriksson's program SOLGASMIX (Eriksson, 1975). The application of the HPLT model to refractory metal heat pipes is described by Feber and Merrigan (1987). All of these models assume ideal gas phases, condensed phase solutions, and unit activities for the condensed phases.

The HPLT-8 model includes an increase in the number of elements to enable thermochemical calculations of complex-alloy-alkali metal systems. The model specifically simulates the thermochemical response of a Haynes 230 heat pipe operating at 1300 K using sodium as a working fluid.

The earlier versions of the HPLT models were written for use on a mainframe computer. To maximize portability the current code was developed for a PC using a Watcom Fortran 77 compiler. During conversion between mainframe and PC compilers the Nb-1%Zr output decks computed by both versions were compared. Throughout development of the HPLT-8 model, emphasis was placed on the collection and estimation of thermodynamic data for the numerous constituents in the Haynes 230 material.

HPLT-8 simulates the time-dependent distribution of chemical species along the length of a Haynes 230-sodium heat pipe. The pipe is divided into a number of sections in the condenser, adiabatic, and evaporator regions. Each section may contain a vapor phase, a liquid metal phase, wall and wick material (in solid form), and one or more liquids at equilibrium. Except for diffusion of contaminants from the wall, chemical equilibrium is

assumed to be a reasonable approximation locally along the pipe at the end of each computational time step. This assumption is usually justified since the high temperatures in a liquid metal heat pipe hasten the kinetics for most reactions. Adjustment of the iteration time step can be made for systems with specie interactions having slow reactions rates. The equilibrium calculation defines the identities and amounts of chemical species in each of the phases. The calculation is then converted to a time-dependent model by coupling equilibrium calculations to a hydrodynamic model of the heat pipe and by taking diffusion of contaminants from the walls to the working fluid to be concentration- and time-dependent.

The HPLT-8 model uses dimensions and evaporator heating rates typical of the proposed life test heat pipe systems. Results from the HTPIPE program are used to define the working fluid vaporization rate corresponding to the heating rates, vapor and liquid volumes, wick/artery configuration, and lengths of the evaporator, adiabatic, and condenser sections.

The equilibrium model is a modification of the SOLGASMIX-PV program, which computes complex chemical equilibria in multiphase systems. SOLGASMIX-PV determines the identity and amounts of species and compositions of solutions present at equilibrium in a system containing a gas phase, one or more condensed-phase mixtures, and other condensed phases of invariant stoichiometry. The solution algorithm makes use of the method of Lagrangian multipliers to find the minimum of the Gibbs function with respect to all species concentrations. The total Gibbs free energy of the system is defined as

$$G = \sum_{i=1}^{np} \sum_{j=1}^{ns} n_{ij} (G_j^o + RT \ln a_{ij}) \quad , \quad (32)$$

where np is the number of phases, ns is the number of species in the i th phase, n_{ij} is the number of moles of species j in phase i . G_j is the standard Gibbs free energy of formation of that species, a_{ij} is its chemical activity, R is the gas constant, and T is temperature. For gas phase species: $a_j = X_j P$, where X_j is the mole fraction of the specie in the gas phase, and P is the total pressure. For condensed phase mixtures: $a_{ij} = X_{ij}$, and for pure condensed phases $a_{ij} = 1$. A mass balance for each specie completes the solution set:

$$\sum_{i=1}^{np} \sum_{j=1}^{ns} c_{ijk} n_{ij} = b_k \quad , \quad (33)$$

where c_{ijk} is the number of atoms of the k th element in a molecule of the j th specie in the i th phase.

Sections in the modeled heat pipe can include one or more liquid pools of working fluid, a condenser zone, an adiabatic zone, an evaporator zone, a dry region, and a getter zone. Each of these sections may be subdivided. Between each set of equilibrium calculations, the elemental composition in each section is modified to correspond with net species transfer by the countercurrent flow of gas and liquid. Diffusion mass transfer of impurities from the wall into the gas-liquid phases is also computed. Liquid distribution in the pipe was estimated using a Nussult film condensation relation found in Rohsenow (1972). Thermodynamic data were assembled for the temperature range 1100 to 1400 K. The preliminary calculations were made at 1300 K.

The composition used for Haynes 230 was based on Knolls-supplied information: weight percent, Fe, 1.47; Ni, 59.56; Co, 0.54; Cr, 21.69; Mo 1.27; W, 14.15; Mn, 0.48; Al, 0.33; La, 0.015; C, 0.1; Si, 0.39; and B, 0.004. Some uncertainty remains concerning the calculated fate of some impurities since the solubility dependencies of C, Si and B in Haynes 230 are unknown. A statement in literature about Haynes 230, referring to stability to long-term thermal exposure, was taken literally: "Principal phases precipitated from solid solution are all carbides." Thermodynamic data for the formation of possible ternary oxides were also reviewed. A brief review of the free energies of formation of those ternary sodium oxides containing metals in Haynes 230 was made. In addition, the effect of the initial chemical form of trace components in Haynes 230 was considered.

An annotated list of program input parameters are summarized in Appendix A. The program output consists of a listing of the initial amounts for all species (X^*/MOLE), the equilibrium amounts of all species (Y/MOLE), the partial pressures for the gases (P/ATM), the mole fractions for the species in the condensed mixtures (MOLE FRACTION), and the activities for the species in all mixtures (ACTIVITY). These listings are repeated for each iteration step and heat pipe section. The frequency of output can be controlled through the "npr" parameter specified in the input file. At the conclusion of the output file a summary of the distribution of non-metallic impurities with position and time is printed.

The program Hp8.for, an input data file Hp8d.dat, and two output data files for one run were included with the HPLT-8 code deliverable. The program is a PC version, and it uses

the version 11 of the Watcom Fortran 77 compiler. The output for the first sample run was for 170-ppm oxygen in the Sodium at 1300 K. The second run was for 1700-ppm oxygen in the sodium, also at 1300 K, and the third run was for 170-ppm oxygen at 1000K. Input data files for these last two runs were not included. The simulation time was over a two-hour period. The output for all runs indicated formation of Cr_{23}C_6 and FeSi. Movement of oxygen and carbon out of the condenser and into the evaporator also occurred. Nitrogen movement was in the opposite direction. Gettered and mobile silicon remained mostly stationary.

5.0 Heat Pipe Life Test Development

During this period, preparations were made for long-term tests of a series of sodium-complex-alloy heat pipes. These tests are intended to assess the compatibility with sodium of currently feasible heat pipe-material combinations in a high-temperature oxidation environment. The information gathered will allow evaluation of previously reported test results. Most of the KAPL-supplied materials needed for the life test arrived at Los Alamos by early April. A limited quantity of tube material was available, especially of MA 956. Fill stem pinch trials for the MA-754 and MA-956 alloys were combined with the fill-stem weld tests to conserve stock.

Heat pipe designs were first considered with homogeneous material and wick combinations. Since suitable wick materials are not available for the materials-combinations considered, the use of surface texturing methods was explored. These methods included knurled, upset, and threaded surfaces. Both knurls and threads were successfully cut into sections of Schedule 40 Haynes 230 pipe. However, knurled textures were ruled out because of tolerance constraints, uncertain machining properties of the gun-drilled MA materials, and the long lead time required for tooling.

Surface texturing of these materials (especially the MA materials) proved to be non-trivial. Screen wicks have now been selected for the initial life tests to allow a more rapid progression into testing. Table 1 gives a listing of the initial set of life-test heat pipes. The material combinations were selected to minimize technical risk in the development phase. The composition of the wick and wall materials selected are compared in Table 2. After the first set of heat pipes is produced and testing begins, other promising material combinations will be considered.

The selected test sequence allows a direct comparison of gun-drilled-Haynes 230 tubes to non-gun-drilled Haynes 230 pipe without introducing ambiguity associated with residual stresses produced by the surface texturing technique. This sequence is used to ensure, however imperfectly, that the tests are truly evaluating the compatibility of material combinations and not fabrication techniques. HTPipe performance predictions were made for each of the heat pipe configurations. The output files are included in Appendix B to this report. The target radial heat flux to the evaporator was 30 W/cm^2 , a factor of three higher than the current KAPL base-line heat flux.

Table 1. Initial Life Test Heat Pipe Material Combinations

Wall Material	Wall Type	Wick Material	Status
Haynes 230	Drawn Tubing	150 Mesh	Built
		Stainless Screen	
Haynes 230	Gun Drilled Pipe	150 Mesh	Built
		Stainless Screen	(Zr Getter)
Haynes 230	Gun Drilled Pipe	150 Mesh	Built
		Stainless Screen	
Haynes 230	Gun Drilled Pipe	100 Mesh	Built
		Nickel Screen	
MA 754	Gun Drilled Pipe	150 Mesh	Fabrication in
		Stainless Screen	Progress
MA 956	Gun Drilled Pipe	150 Mesh	Fabrication in
		Stainless Screen	Progress

Table 2. Elemental Components of Alloys Used in Heat Pipe Life Test

Component	Haynes 230	MA 754	MA 956	304 Stainless
Nickel	57.	78.		9.
Chromium	22.	20.	20.	20.
Tungsten	14.			
Molybdenum	2.			
Iron	3.	1.	74.	68.
Cobalt	5.			
Manganese	0.5			2.
Silicon	0.4			0.75
Aluminum	0.3	0.3	4.5	
Carbon	0.1	0.05		0.15
Lanthanum	0.02			
Boron	0.015			
Titanium			0.5	
Y ₂ O ₃		0.6	0.5	
Phosphorus				0.045

To date, four sodium life test heat pipes have been built using the KAPL-selected and supplied tube and closure materials. The MA alloy heat pipes are now being similarly processed.

Figure 56 shows the Schedule 40 Haynes 230 heat pipe undergoing a proof test at full operating power. All life test heat pipes are 45-cm long with a 7.6-cm long evaporator. The heat pipes are vertically oriented (gravity assisted) and placed inside a quartz tube, which is then slid into a water-cooled calorimeter. The quartz tube is opened to air at the top end. The dimensions on the legend are axial distance from the evaporator end cap. The induction coil starts 2.5-cm above the evaporator end cap and ends 7.6-cm further up. Figure 57 shows the measured startup temperatures at various locations on the surface of the Schedule 40 Haynes 230 heat pipe. The heat pipe became active along its entire length as the wall temperatures reached 800 K. The temperatures on either side of the induction coil tracked closely during the first 90 minutes. As the heat pipe reached 1000 K, the sodium in the wick expanded sufficiently to begin accumulating above the evaporator end cap. This pool continued to grow, increasing the temperature difference between the pool and the active regions. The active length of the heat pipe was brought to 1200 K over a two-hour period. Near the peak temperature, the induction coil was raised 1-cm to prevent liquid slugging from the pool at the evaporator end of the heat pipe. The evaporator region had a uniform temperature throughout the startup period. After 1200 K was reached, the generator was shut down and the heat pipe was allowed to cool.

Figure 58 shows the measured heat transfer from the condenser to the calorimeter during the startup. The thermal spike 80 minutes into the startup results from the response of the instrumentation system to an increase in calorimeter water flow. The instrumentation system registers the flow rate change faster than the temperature response at the differential thermocouple gauge. The total measured heat pipe throughput was 1450 W at 1200 K. For the Schedule 40 Haynes 230 heat pipe this corresponds to 49 W/cm² radial heat flux on the inside surface of the evaporator wall. The axial heat flux at this level is 1.1 k W/cm².

Some welding and processing issues with the MA alloys remain to be resolved. Electron beam welding of the MA 956 has met with mixed results using a 110-kV, 10-mA beam and a feed rate of 60 inches per minutes. Initial joint cross sections appeared unsatisfactory with agglomeration of dispersoids around the heat-affected zone. Results of the initial electron-beam welding trials with the MA 754 alloy were more satisfactory. Some voids formed in the deep-penetration region of the weld, but the joint itself appeared to coalesce well.

Figure 56. Picture of Haynes-230 sodium life test heat pipe in proof test

Figure 57. Startup temperatures on the surface of the 45-cm long Schedule 40-Haynes 230-sodium heat pipe. The pipe is gravity assisted. Distance is measured from the evaporator end cap.

Figure 58. Condenser throughput during startup of the 45-cm long Schedule 40-Haynes 230-sodium heat pipe. Measurements are made of heat transfer between the condenser surface, which has a 0.61 total hemispherical emittance and a water cooled calorimeter.

Life Test Heat Pipe Fabrication Procedure

All internal heat pipe parts are chemically cleaned and vacuum-fired at 1223 K before electron-beam welding. Before sodium charging, the heat pipe assemblies are again vacuum-fired at 1200 K. Sodium is introduced into the heat pipe by vacuum distillation. After distillation is finished, the heat pipe is positioned horizontally and heated uniformly over its entire length to distribute the sodium charge and to ensure complete wetting of the interior surfaces.

Each life test heat pipe is instrumented with stainless-steel-sheathed iron-constantan thermocouples for temperature monitoring during testing. The thermocouples are attached by spot welding them to the surface of the heat pipe. The instrumented heat pipe is inserted into a quartz tube that is open at one end. This subassembly is then placed in a single-pass water calorimeter.

The calorimeter is constructed of two copper tubes joined and sealed at the ends to form a single passage with an inlet port at one end and an outlet port at the opposite end. Attached to the inlet and outlet ports of the calorimeter is a water flow meter and a differential temperature transducer. The calorimeter is designed to measure power throughput from the heat pipe condenser. The heat pipe-calorimeter assembly is one of three subassemblies that are placed into a single test fixture. An induction coil is slid over the quartz envelope to supply heat to the heat pipe evaporator. Water flow rate through the calorimeter and heat pipe wall temperatures are monitored continuously during testing. The induction generator supplying power to the heat pipes had been temperature interlocked. The system is designed to shut down when the temperature deviates from preset values.

Initially, a performance test is conducted on each heat pipe to verify heat pipe startup operation from the frozen state and to demonstrate freedom from noncondensable gas contamination. The heat pipe was oriented vertically and heated from the bottom end. Each heat pipe is operated to a minimum of 1200 K. The test also serves to move excess liquid to the bottom end of the heat pipe, giving an indication of void space in the wick. After this test, each heat pipe was x-rayed and the liquid distribution determined. Performance data from these tests are archived as an initial record of the heat pipe performance before testing.

After each life test is complete, wall and wick samples will be analyzed for the extent of diffusion between Haynes and nickel or the nickel in the stainless and MA 956. Oxygen

concentration measurements in the sodium working fluid will be made to characterize oxygen levels in the sodium heat pipe system after a distillation fill. For the activation analysis 6.5-g of sodium will be distillation-filled into a 1.75-cm outside diameter stainless steel tube. Before fill, the stainless steel tube will be activated to measure oxygen levels in the metal surface.

Two techniques were considered to measure oxygen concentration in the sodium working fluid, an initial condition for the thermochemical model. The first technique measures the equilibrium oxygen concentration in a vanadium wire that has been exposed to 1120-K sodium for 4 hours. The vanadium wire technique is most suitable for measurement of oxygen concentrations in sodium of less than 20 parts per million, but requires substantial sodium inventory for an accurate measurement. The other technique measures oxygen content in sodium by interaction of the oxygen nuclei with 14 MeV neutrons. Through a $^{16}\text{O}(n,p)^{16}\text{N}$ reaction, 6.129 MeV gamma rays are emitted and detected during the 7.10-s half life of ^{16}N . Neutron activation gives accurate results for oxygen concentrations above 20 parts per million. The container that will be filled with sodium has been sent for initial oxygen measurement. Results will be available within the next month.

Prototype Life Test Heat Pipe

An initial prototype Haynes-230 heat pipe was built within six weeks of the arrival of the KAPL-supplied materials. This heat pipe design was 90-cm long with a 1.9-cm outside diameter. An internally threaded surface texture was cut along 15.2 cm of one of the gun drilled Haynes 230 pipes. This texture extended a few centimeters into the nominal condenser region. Calculations for a smooth-walled pipe indicated that entrained liquid from the returning film into the vapor space of the heat pipe would not cause dry out in the evaporator region. A knurled section, 1.27-cm long, was removed from this tube for use in later metallurgical tests. This heat pipe was degreased and prepared for vacuum firing. The tube was tungsten-inert-gas welded to the end caps and fill stem. After welding the pipe was again vacuum fired and then charged with sodium. The sodium charge quantity was calculated using Nusselt film theory for constant wall heat flux and provided an allowance for a pool at the evaporator end of the pipe at the operating temperature and an allowance for hold up at the condenser end of the pipe. The heat pipe was then wetted in the horizontal orientation.

The heat pipe was then tested to verify performance. The pipe was vertically oriented and heated from the bottom with an induction coil. The induction coil was raised sufficiently

above the end cap to prevent liquid slugging from the excess liquid at the bottom of the pipe. The distribution of the solidified sodium after wet-in required some adjustments to be made during startup. A heat gun was used to move working fluid into the heated zone. To reduce the startup condenser coupling to the levels expected in the calorimeter, the condenser was covered with refractory insulation. The heat pipe was brought to full-length operation at 1200 K in three hours. The pool on the evaporator end of the heat pipe was of the expected length. A cold region at the condenser end of the heat pipe was also observed. This was caused by some accumulation of liquid sodium by surface tension and pressure forces. Insulation was removed over a 12-inch length to test operation at increased condenser heat-rejection rates. A hot spot developed in the evaporator region.

The test continued for another twenty minutes with a modest reduction in peak evaporator temperature. At this point, a flash of light was emitted from the evaporator region of the pipe with a brief "thud" noise and some white smoke. The generator was turned off within 15 s of the flash, and the heat pipe was allowed to cool. The heat pipe and adjacent surfaces were inspected. A crack was found that had sheared the evaporator into two pieces. Surface melting also appeared to have occurred on the crack around the outside diameter of the pipe. Absent any heat removal mechanism, 10 W/cm^2 would be sufficient to bring that region to the nickel melt point, 1725 K in 15 s. After examining the crack shape, the breach was attributed to the cold working done on the pipe by threading in conjunction with the gun-drilling operation. Considerable torsional stress was applied to the pipe during gun drilling and thread formation that likely weakened the wall before processing. The development of this crack prompted a reassessment of the approach taken for life-test heat-pipe fabrication.

Life Test Interim Status

The fixtures for the testing of up six life-test heat pipes were assembled during this period. Four Haynes 230 heat pipes have been built thus far. Successful startup of the first of these heat pipes has been achieved. The measured heat pipe throughput was 1450 W when the temperature measured 1200 K at the evaporator exit. This value corresponds to 49 W/cm^2 radial on the inside surface of the evaporator wall: five times the target radial heat flux for the current baseline KAPL design. The axial heat flux at this level is 1.1 kW/cm^2 . The remaining Haynes heat pipes will be similarly tested and installed into the life test fixture early in FY99. Some welding and processing issues with the MA alloys remain to be resolved. Electron beam welding of the MA 956 has met with mixed results using low heat input and fast feed rates.

6.0 Support of KAPL Sodium-Stainless Steel Heat Pipe Tests

In mid April KAPL sent to Los Alamos startup data from the stainless steel paddle heat pipe tested at KAPL on April 9. The data were compared to test data from the same heat pipe collected at Los Alamos in June 1997, checking both data sets for internal consistency.

The region around the evaporator in a quasi-steady condition 12,000 s after the startup began was examined. At 12,000 s the evaporator stagnation temperature is 840 K. A steady, 1-D compressible flow of monatomic sodium with mass removal normal to the main flow stream was assumed. The condensation heat transfer (and mass removal) rate was estimated by accounting for convection to the environment and integrating Stefan-Boltzmann's law between the evaporator exit (using the static temperature predicted for choked flow) and the temperature measured at the end of the cylindrical transition region.

Under these conditions the sonic heat transfer limit at the evaporator exit is 2.5 kW with choked flow at $Ma \sim 6$ entering the transition region. The sonic limit value differs from a conservative estimate of heat pipe power throughput from the wall temperature data. Assuming a $5 \text{ W/m}^2\text{-}^\circ\text{C}$ heat transfer coefficient and 0.8 emittance, the overall heat pipe power throughput at the evaporator exit (ignoring axial conduction) is 4.1 kW. If the power rejected in the evaporator and end cap regions is considered, this estimate agrees with the 4.8 kW input rate measured by the power meter on KAPL's induction generator.

Based on these inconsistencies, the thermocouple measurements taken at both Los Alamos and KAPL appear to be reading $\sim 50^\circ\text{F}$ too low, which is larger than the $\pm 20^\circ\text{F}$ measurement uncertainty for a well-attached type-K thermocouple. Local heat transfer to the surroundings from the bare thermocouple wire leading a short distance away from the heat pipe surface could cause a low temperature reading. An analytic calculation of a thermocouple wire attached to a semi-infinite solid surface indicates that a temperature offset of this magnitude is plausible. This can be confirmed experimentally by measuring optically the temperature on a heat pipe surface of known emittance near a thermocouple. Better yet, a comparison can be made of readings taken before and after refractory insulation is placed around the wires at the thermocouple attachment point

In July Los Alamos personnel made a visit to the KAPL heat pipe experimental facility. Limited time and an unexpected interlock trip allowed only a partial startup of the paddle

heat pipe to be observed. The paddle heat pipe was enclosed inside the cabinet, which provided a nice safety feature and gives an easily characterized convection heat rejection boundary. During the visit several suggestions were made to KAPL personnel, these include:

1. Consider positioning the equipment so that the operator can simultaneously view the heat pipe, manipulate the power controls, and read thermocouple data during startup.
2. Consider attaching a full-length mirror to the rear cabinet wall so that the opposite side of the heat pipe can be viewed during startup.
3. Consider investing in an infrared or optical pyrometer sensitive in the 0.65-micron range. Given the correct spectral emittance, such pyrometers can make accurate temperature measurements through quartz glass and augment the thermocouple measurements. A pyrometer also affords positional flexibility not possible with attached thermocouples once startup is initiated. When selecting a pyrometer, account for the transmittance of radiation through the cabinet glass.
4. Halfway through the July 22 startup, an induction generator power interlock activated, cutting off power and requiring a partial heat pipe restart. Apparently, the dT/dt measured by the evaporator thermocouple initiated the trip condition. At the time of the trip, the region near the thermocouple did not appear to be very hot. Consider relaxing the dT/dt condition or just setting the interlock to trip near the material limit temperature.

The startup performance on July 22 appeared consistent with the data sent to Los Alamos in April. During startup supersonic vapor flows through the transition region, and there are possibly one or more recompression shocks around thermocouples 6 and 7. There also may be a sodium pool at the condenser end of the heat pipe.

5. Before startup, establish a material limit temperature for the wall material. With the thermocouple instrumentation as configured, don't exceed 1600°F locally for more than a few minutes, and in no case exceed 1650°F.
6. Increase the induction generator power level to the heat pipe evaporator in small, frequently applied steps. Starting early in the morning, so that the desired final condition can be reached an hour or so before quitting time, would be optimal. Once steady state is

reached a time or two by the full day method, experiment with more aggressive power versus time profiles.

7. When the measured stagnation-end temperature reached 993°F, a region formed under the evaporator coil about 120°F above the surrounding temperatures. This kind of temperature gradient is no cause for alarm unless the material limit temperature is approached. This temperature difference will not necessarily continue up to the full power condition. Hot spots can temporarily form in the evaporator during startup until the vapor removal and condensation return rates balance. The temperature difference between the evaporator and its surrounding surfaces typically diminishes once the full heat pipe becomes active.

8. For the first couple of full startups, consider equalizing the condenser temperatures with heater tapes until the flow through the transition region becomes subsonic.

9. Consider the attachment of an additional thermocouple near the exit of the evaporator. This measurement provides an important sanity check for the analyst who will examine the startup test data.

10. The local heat pipe surface became red before the adjacent thermocouples readings reached the Draper point temperature, 980°F. This would confirm that the thermocouple readings are low.

11. Radiographs of the heat pipe can provide useful information about the internal condition of the heat pipe wick and, with favorable exposure, the location of the working fluid.

12. The heat pipe has undergone a number of partial startups. Apparently, the evaporator has, at no time, reached temperatures exceeding the nominal steady state operating temperature. While the chance of evaporator de-wetting from these startups seems remote, if problems continue during startup and the x-rays don't reveal anything interesting, consider a re-wetting operation using heater tapes to cover the entire length of the heat pipe. To rewet, bring the heat pipe to 1020°F and then keep it there for about 48 hours. Before allowing it to cool, tilt the pipe to allow surplus working fluid to accumulate in the evaporator.

References

- Besmann, T. M. (1977) "SOLGASMIX-PV, A Computer Program to Calculate Equilibrium Relationships in Complex Chemical Systems," Oak Ridge National Laboratory report TM-5775.
- Eriksson, G. (1975) "Thermodynamic Studies of High Temperature Equilibria," *Chemica Scripta*, 8, 100-103.
- Feber, R. C. and Merrigan, M. A. (1987) "Thermochemical Modeling of Mass Transport in High-Temperature Heat Pipes," Proceedings of the Sixth International Heat Pipe Conference, Grenoble, France, May 25-29, 1987, 308-313.
- Gubareff, G. G. (1960) "Thermal Radiation Properties Survey," Honeywell Research Center, Minneapolis, Minnesota.
- Lundberg, L. B. and Martinez, H. E. (1980) "Fabrication of High-Temperature (1400-1700 K) Molybdenum Heat Pipes," in Proceedings of the 15th IECEC, Seattle, WA.
- Merrigan, M. A., Keddy, E. S., and Sena, J. T. (1986) "Transient Performance of a Space Power System Heat Pipe," AIAA/ASME 4th Joint Thermophysics and Heat Transfer Conference, June 2-4, Boston, MA.
- Rohsenow, W. M. (1972) "Film Condensation of Liquid Metals," Transactions of the CSME, Vol. 1, No. 1, pp. 5-12.
- Siegel, R. and Howell, J. R. (1981) "Thermal Radiation Heat Transfer," Hemisphere Publishing Corporation, Washington, DC, p. 769.
- Wolfe, W. L. and Zissis, G. J. (1985) "The Infrared Handbook," Environmental Research Institute of Michigan for the Office of Naval Research, Department of the Navy, Washington, DC.
- Woloshun, K. A. (1988) "HTPIPE: A Steady-State Heat Pipe Analysis Program," Los Alamos National Laboratory manual, LA-11324-M.

Symbols

Alphabetic

a	thermocouple position on heat pipe
A	area
b	thermocouple position on heat pipe
c_p	specific heat capacity
d	diameter
F	integration of Planck's law
g	gravitational acceleration
Gr	Grashof number
h	height or heat transfer coefficient
h_{sf}	latent heat of fusion
J	emitted radiant energy transfer rate
k	thermal conductivity
L	heat pipe length
l	length
m	mass
M	total mass or Mach number
p	heat pipe perimeter
P	pressure
Pr	Prandtl number
q	thermal energy
$\dot{Q}$	energy transfer rate
r	radius
R	universal gas constant
T	temperature
t	time
V	volume
z	axial position

Greek

α	number of ceramic insulators
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δ	diameter of ceramic insulators
ΔH	heat of reaction
ε	total hemispherical emittance
γ	specific heat ratio
ν	kinematic viscosity
Φ	angle above horizon
ρ	density
σ	Stefan-Boltzmann constant
τ	transmittance
θ	contact angle

Subscripts

a	annulus, average, or at location a
b	at location b
B	back volume
c	condenser or cross-sectional
d	departure
e	evaporator
hp	heat pipe
i	node index
liq	liquid
m	melt or mean
o	background
o	stagnation condition
p	pore or pool
q	quartz
sat	saturation
t	total
$total$	total
w	wick

Superscripts

*	critical condition
n	node index
'''	per unit volume
''	greater than 4 μm
'	0 μm to 4 μm
.	rate

Appendix A HPLT-8 Input Parameters

A description of the input data file for the computer program HP8 follows.

Requires documentation to the parent program SOLGASMIX-PV.

The current input data file is incomplete in at least three respects:

1. Some pertinent chemical species are not included.
2. At the time work was suspended on the program, the chemical form in which lanthanum was present in the alloy was not clear. Is there free La, or has it all been reacted to form sulfides or oxides? This is of interest because lanthanum is obviously a potential getter for oxygen. Parenthetically, what is the oxygen content of the alloy, dissolved or reacted?
3. Modifications to the input data file are required for the use of a (hafnium) getter.

Line	Columns	Variable	
1	1-80	title()	The format is 10A8.
2	1-16	fff	A variable format used to read in chemical formulas of species in the system and their standard free energies of formation. (See line 85 for additional detail.)
3	1-2	ir	If ir = 0, the input thermodynamic data are in calories; otherwise the data are in joules. The format is I2. The thermodynamic data here are in calories, and the pressure reference state is 1 atmosphere. Therefore, because the standard state pressure for most current thermodynamic tables is 0.1 MPa, a correction to a standard state of 1 atmosphere is necessary.
4	1-2	l	The number of elements in the system. (≤ 20)
	3-4	mp	Total number of gaseous, liquid, and solid mixtures. The first mixture must always be a gas.
	5-6	mr	The number of condensed phases of invariant stoichiometry.
	7-8	ml()	The number of species in mixture #1 (the gas phase).
	9-10		The number of species in mixture #2 (the liquid working fluid), etc. The format is 40I2.
	etc.		
5	1-5	nvv	The number of vapor volumes - an arbitrary multiple of a reference amount of working fluid. The reference amount is the number of gm-atoms of working fluid in the vapor phase of a designated section of the heat pipe. The designated section is read in below in line 7 as <u>nsc</u> , and the reference amount is determined by the program in subroutine SPEQUA. The product of <u>nvv</u> and the reference amount is <u>amt</u> , which is

amount of working fluid, with dissolved contaminant-containing or other species, which is transferred between sections as gas (toward the condenser) or as liquid (toward the evaporator) after each set of equilibrium calculations. Amt is also used to calculate $\text{delt} = \text{amt} \times \text{mwwf}/\text{mdot}$, which ideally is a measure of the real time between successive calls to the set of equilibrium calculations. Here mwwf is the molecular weight of the working fluid, and mdot, the moles of working fluid evaporated/second, is q/hfg , where q is the power of the heat pipe in watts (read in at line 9) and hfg is the latent heat of vaporization in joules/gm, obtained by a call to the subroutine FLUID.

6-10	nts	The number of time steps in the calculation.
11-15	npl	The distributions of the impurities oxygen, nitrogen, silicon, and carbon between heat-pipe sections are saved (as gm-atoms) every <u>npl</u> time steps in subroutine SPEQUA. The distributions of each impurity are saved as total amount, amount gettered, and amount which is mobile (sum of that in the gas phase and in the working fluid). The quantities are printed out at the end of the calculation from the MAIN program in output file <u>Tape 7</u> .
16-20	npr	The results of the equilibrium calculations from subroutine SOLGAS are printed out from MAIN to the <u>output</u> file every <u>npr</u> time steps, as are (1) the elemental distributions by pipe section for gas, liquid, and solid phases before the composition adjustments between iterations, and (2) the total elemental distributions by pipe section after compositional adjustments. The latter also contains the deviations from elemental balances (which are corrected after each iteration) and the cumulative change of the elemental amounts from the initial conditions. Also, after every <u>npr</u> time steps the cumulative corrosion/deposition of each metal in Haynes 230 is printed from subroutine SPEQUA into output file <u>Tape 7</u> for each heat-pipe section.
21-25	nsr	The number of impurities (oxygen, nitrogen, silicon, or carbon) diffusing from the heat-pipe wall into the interior of the pipe. The number may be 0. Other data for this diffusion process are read in below at lines 14 and 15. This option is intended primarily to be used for the diffusion of oxygen from the wall into the working fluid. In fact, <u>nsr</u> has always been set to 0 for

			a Haynes 230 heat pipe because we have not located any data for the solubility of oxygen therein.
26-30	iget		A getter for oxygen is added as a wick or to some section of the heat pipe if <u>iget</u> .ne.0. In this connotation, the reference is typically to hafnium. Because the list of chemical species in data base is doubtless incomplete, the option of an added getter has never been exercised with the Haynes 230 heat pipe.
31-35	lget		The element number of the getter. Currently, the 16 elements in the data base do not include hafnium. It is read in as element no. 17 at this point, but any number would do because <u>iget</u> = 0.
6	1-2	is()	Number of sections in the condenser zone of the heat pipe.
	3-4		Number of section in the adiabatic zone.
	5-6		Number of sections in the evaporator zone.
	7-8		Number of sections in the pool (nominally always 1). Therefore in the present case there are 7 sections in the heat pipe - sections 1-4 in the condenser, sections 5-6 in the evaporator, and the pool is section 7. The total number of sections is <u>ns</u> .
7	1-2	nsc	Number of the section in the evaporator in which the reference vapor volume is taken (see line 5)
	3-4	nsg	Number of section to which oxygen getter added (if localized).
	5-6	ifluid	Identification number of working fluid in subroutine FLUID (Li, 1; Na, 2; K, 3; Hg, 4).
8	1-6	dx()	Length (in cm) of pipe section #1.
	7-12, etc.		Length of section #2, etc. The format is 10F6.0.
9	1-10	q	Power of the heat pipe in watts. (See line 5). The format is F10.0.
10	1-10	ro	Inside radius of the heat pipe, cm. Although <u>ro</u> is not used in the calculations, it is printed out to add to the documentation of the heat pipe.
	11-20	av	Vapor passage cross-sectional area of the heat pipe, sq. cm.
	21-30	al	Liquid flow cross-sectional area of the heat pipe, sq. cm. The quantities <u>av</u> and <u>al</u> are used in the calculation of the amount of working fluid needed to fill the heat pipe.

31-40	pf	Estimated pool flow factor. This quantity, which is <1 , is multiplied by <u>amt</u> (see line 5) in subroutine SPEQUA to give <u>amtp</u> , the amount of working fluid transferred between the section at the far end of the evaporator and the pool. The program assumes liquid working fluid flows from the evaporator to the pool, and gaseous working fluid flows in the opposite direction.
		The following two lines are illustrative of input required if <u>nsr</u> $\neq 0$; i.e., if an impurity is diffusing from the wall into the working fluid. Some results from the calculations of this process are summarized every <u>npr</u> iterations in output file <u>Tape 4</u> . Impurities taken as present in the working fluid are treated separately and are entered below in lines 158-159.
Ia	1-14	dgc() Constant term of a quartic expansion of $-RT \ln(\text{distribution coefficient})$, where that coefficient is the ratio of the solubility of the impurity (nominally oxygen) in the wall to its solubility in the working fluid. Solubilities are in mol-fractions.
	15-28, etc.	Second coefficient of the polynomial expansion for the first impurity source, etc. The format is 5D14.0.
b	1-14, etc.	Analogous data for any other diffusing impurities present.
IIa	1-5	isr() The element number of the first diffusing impurity (nominally oxygen).
	6-10	jsr() The species number of the species in the working fluid, which is taken to be bound with dissolved oxygen.
	11-20	tsr() Initial gram-atoms of the first diffusing impurity per mole of metal in the heat pipe wall.
	21-30	alph() A "diffusion coefficient" for the transport of impurity from the wall to the working fluid The format for this line is 2I5,2E10.0.
b	1-5, etc.	If <u>nsr</u> > 1 , analogous quantities for additional diffusing species follow.
11	1-10	vhp The total volume of metal in the heat pipe wall, cc.
	11-20	dnhp The density of the metal in the heat pipe wall.
	21-23	nme The number of metals in the Haynes 230 alloy (Fe, Ni, Co, Cr, Mo, W, Mn, Al, and La).
	24-26	nnme The number of non-metallic contaminants in the alloy for

which analyses were available (C, Si, and B).
The format for this line is 2D10.0, 2I3.

12	1-72	awme()	The atomic weights of the <u>nme</u> metals in the heat pipe walls in the order given above. The format is 10D8.0. The composition of the alloy is read in below as percents by weight, and the atomic weights are used to convert quantities to gm-atoms.
13	1-24	awnme()	The atomic weights of the <u>nnme</u> non-metallic-contaminants in the alloy in the order given above.
14	1-2
3-4,
etc.		These are identifications given to selected element numbers to simplify program recoding if the order of the elements is changed: <u>lo</u> , oxygen; <u>ln</u> , nitrogen; <u>li</u> , inert gas; <u>lc</u> , carbon, and <u>lsi</u> , silicon. The format is 40I2.
15	1-4
5-8, etc.	el()	Right-justified chemical symbol for element #1.
Chemical symbol for element #2, etc. The format is 20A4.
16	1-5
6-10,
etc.	a(,)	Subscript on element #1 in formula for species #1.
Subscript on element #2 in formula for species #1, etc.
The format is 20F4.0. The entries are written here as right-justified integer constants for clarity. There is one line per species, and the order of the species is important. Gas-phase species are listed first, followed by species in the working fluid, then those in each of any additional mixtures, and finally the condensed phases of invariant stoichiometry. The order here is preserved in the tabulation of standard free energies of formation in lines 85 to 150. There are currently a total of 66 species in the data base.
82	1-2
3-4,
etc.	iel()	The species number for element #1 in its reference state taken from the order of the species in lines 85 to 150.
The species number in element #2 in its reference state, etc.
The format is 40I2.
83	1-2	kval2	Used for program control in the original SOLGASMIX-PV to select between alternate ways of inputting thermodynamic data. It is always equal to 1 in this application.

- 84 1-2 mgt The maximum number of coefficients for the free energy of formation of the species,

$$\Delta G^0 = a / T + b + cT + dT^2 + eT^3 + fT \ln T$$
 ,
 which are different from zero. Because tabulated values of the free energies are used here, mgt is 1.
- 3-4 igt() The number of one of the non-zero coefficients used in the expression for ΔG^0 . The one non-zero coefficient here is #2.
- 5-6, etc. If there had been more than one non-zero coefficients, the additional numbers would follow with an I2 format.
- 85 1-8 text() A chemical symbol for species #1. in an A8 format.
 9-10 blank
 11-60 ge(,) ΔG^0 for species #1 at five temperatures (1000-1400K at 100K intervals. The format is 6E10.3. Data for the desired temperature are selected by the variable format fff - see line 2. That format is equivalent to (A8,10n+2, 6E10.3). If n is 0, the first column of free energies of formation at 1000K would be read. If n=5, the last column for data at 1400K would be recovered. An analogous line is entered for each additional species in the same order as for the stoichiometric coefficients in lines 16-81.
- 151 1-10 t The heat-pipe temperature, deg. K (currently 1000-1400K at 100K intervals).
- 11-20 elna The species number of liquid Na. The reference state of Na (boiling point - 1172K) is initially taken to be the gas. If the temperature is less than 1200K, the reference state is changed to the liquid.
- 152 1-2 kval1 A variable in the original SOLGASMIX-PV which is used for program control and can have values from 1 to 10. Most of the options produced are not of interest in this application. The variable is initially set equal to 9 in the program, and the value read in here is used to read in ptot, a total pressure not equal to 1 atm. Although not used in this program, the option of entering kval1 = 1 at the appropriate place could be used if it is desired to supply initial estimates of the amounts of . species rather than use estimates generated by the program. Kval1 is also used in subroutine HETTA, which has been retained in the program for possible future use although not

currently used.

- 153 1-10 ptot The total pressure in atmospheres. It is greater than the vapor pressure of the working fluid at temperature, which is obtained by the call to subroutine FLUID. The program then calculates the amount of an inert gas required to produce ptot.
- 154 1-2 kval1 See line 152.
- 155 1-2 npkt The number of equilibrium calculations done at each time step. It is read in here as 1 for program initialization, in which a single equilibrium calculation is made which includes the elemental content of the entire heat pipe. The resulting elemental compositions of (1)the gas phase, (2) the working fluid, and (3) other condensed-phase mixtures plus the condensed phases of invariant composition are each partitioned appropriately by the program between the heat-pipe sections. The program re-sets npkt to the number of sections.
- 156 1-2 kh() The nature of the variation in the amount of element #1 or the log of its equilibrium activity. In this case kh(1) is taken to be 2 (the total amount is constant).
3-4,
etc. Analogous specification for element #2, etc. The format is 40I2.
- 157 1-10,
etc. b(,) As originally written, SOLGASMIX-PV read in for the array b the initial gm-atoms of each of the elements. In the present application, the program calculates these quantities for the working fluid, the heat-pipe metals, and the inert gas from other input data. Impurities oxygen and nitrogen are taken to be introduced by the working fluid, and therefore their amounts are read in as gm-atoms per gm-atom of working fluid. The amounts of the heat-pipe metals and the impurities carbon and silicon are read in as percents by weight of the alloy. The order of entry of the elements is the same as in line 15 with one line per element and a D10.0 format.
- 158 1-10 aget The amount in gm-atoms of a (hafnium) getter if one is located in heat-pipe section nsg.

Appendix B: HTTPPIPE Calculations for Life Test Heat Pipes

HTPIPE Calculations for the Haynes 230 Heat Pipe with a Drawn Tubing Wall

Heat Pipe Analysis: Power vs Evaporator Exit Temperature

	4	geometry: homogeneous wick				
	2	working fluid: Na				
	7.62000	evaporator length (cm)				
	0.00000	adiabatic length (cm)				
	35.56000	condenser length (cm)				
	90.00000	tilt angle (0 to 90, positive for assist)				
	0.72390	pipe inside radius (cm)				
	0.15000E-05	wick permeability (cm**2)				
	0.65000	axial porosity (0.< poro < 1.)				
	0.00381	half of wire diameter (cm)				
	0.05334	wick thickness (cm)				
	0.00850	effective pore radius of liq-vap interface (cm)				
	0.63000	wick surface porosity (0.<poro<1.)				
	1.00000	thermal conductivity of pipe wick (W/cm K)				
	0.00127	nucl. site radius (cm),if 0.0 defaults to .00127				
	1.41262	vapor passage area (cm**2)				
	0.23367	total liquid flow area (cm**2)				
	-----pressure drops-----					
tee	capillary liquid hydrostatic	evaporator adiabatic condenser	temperature tbe tbeson	tbc tbcson	power limits qsonic qentrm qcap qboil	
750.	35706. 44953. -35460.	30898. 0. -4686.	875. 786.	750. 750.	397. 3480. 1062. 5249.	
800.	34635. 54766. -34955.	19600. 0. -4776.	865. 841.	800. 800.	1037. 5434. 1351. 10498.	
850.	33565. 59979. -34452.	11209. 0. -3171.	875. 896.	850. 850.	2410. 8011. 1535. 11719.	
900.	32494. 62074. -33950.	6236. 0. -1867.	908. 952.	900. 900.	5109. 11285. 1642. 20813.	
950.	31424. 62431. -33449.	3514. 0. -1073.	952. 1007.	950. 950.	10055. 15319. 1702. 19531.	
1000.	30353. 61886. -32948.	2040. 0. -625.	1001. 1063.	1000. 1000.	18583. 20151. 1736. 15869.	
1050.	29282. 60876. -32446.	1227. 0. -374.	1050. 1119.	1050. 1050.	32485. 25779. 1753. 12336.	
1100.	28212. 59622. -31944.	765. 0. -230.	1100. 1176.	1100. 1100.	53940. 32137. 1757. 8819.	
1150.	27141. 58235. -31441.	493. 0. -146.	1150. 1236.	1150. 1150.	85281. 39083. 1748. 6151.	
1200.	26071. 56773. -30936.	327. 0. -94.	1200. 1297.	1200. 1200.	128660. 46405. 1725. 4358.	
1250.	25000. 55267. -30429.	223. 0. -61.	1250. 1359.	1250. 1250.	185856. 53859. 1686. 3177.	

HTPIPE Calculations for Gun Drilled Haynes 230 Tube with 100 Mesh Nickel Screen

Heat Pipe Analysis: Power vs Evaporator Exit Temperature

```

4          geometry: homogeneous wick
2          working fluid: Na
7.62000    evaporator length (cm)
0.00000    adiabatic length (cm)
35.56000   condenser length (cm)
90.00000   tilt angle (0 to 90, positive for assist)
0.62230    pipe inside radius (cm)
0.15000E-05 wick permeability (cm**2)
0.65000    axial porosity (0.< poro < 1.)
0.00381     half of wire diameter (cm)
0.05334     wick thickness (cm)
0.00850     effective pore radius of liq-vap interface (cm)
0.63000     wick surface porosity (0.<poro<1.)
1.00000     thermal conductivity of pipe wick (W/cm K)
0.00127     nucl. site radius (cm),if 0.0 defaults to .00127
1.01698     vapor passage area (cm**2)
0.19962     total liquid flow area (cm**2)

```

tee	-----pressure drops-----		temperature		power limits
	capillary liquid hydrostatic	evaporator adiabatic condenser	tbe tbeson	tbc tbcson	qsonic qentrm qcap qboil
750.	35706. *	1646.	769.	750.	286.
	7361.	0.	786.	750.	2505.
	-35460.	3494.			149.
					5249.
800.	34635.	23060.	872.	800.	746.
	49605.	0.	841.	800.	3912.
	-34955.	-3075.			1045.
					5859.
850.	33565.	14253.	880.	850.	1735.
	56607.	0.	896.	850.	5768.
	-34452.	-2843.			1238.
					10742.
900.	32494.	8310.	910.	900.	3678.
	60037.	0.	952.	900.	8125.
	-33950.	-1903.			1356.
					11719.
950.	31424.	4809.	953.	950.	7239.
	61225.	0.	1007.	950.	11028.
	-33449.	-1162.			1426.
					19531.
1000.	30353.	2834.	1001.	1000.	13379.
	61164.	0.	1063.	1000.	14507.
	-32948.	-697.			1465.
					15625.
1050.	29282.	1719.	1050.	1050.	23387.
	60432.	0.	1119.	1050.	18559.
	-32446.	-423.			1486.
					10305.
1100.	28212.	1077.	1100.	1100.	38832.
	59340.	0.	1176.	1100.	23137.
	-31944.	-261.			1494.
					7478.
1150.	27141.	696.	1150.	1150.	61396.
	58050.	0.	1236.	1150.	28137.
	-31441.	-165.			1488.
					5243.
1200.	26071.	463.	1200.	1200.	92626.
	56648.	0.	1297.	1200.	33408.
	-30936.	-105.			1470.
					3719.
1250.	25000.	317.	1250.	1250.	133802.
	55181.	0.	1359.	1250.	38774.
	-30429.	-68.			1438.
					2712.

HTPIPE Calculation for Gun Drilled Haynes 230 Tube with 150 Mesh Stainless Steel Screen

Heat Pipe Analysis: Power vs Evaporator Exit Temperature

4	geometry: homogeneous wick				
2	working fluid: Na				
7.62000	evaporator length (cm)				
0.00000	adiabatic length (cm)				
35.56000	condenser length (cm)				
90.00000	tilt angle (0 to 90, positive for assist)				
0.72390	pipe inside radius (cm)				
0.18000E-05	wick permeability (cm**2)				
0.65000	axial porosity (0.< poro < 1.)				
0.00572	half of wire diameter (cm)				
0.08000	wick thickness (cm)				
0.01300	effective pore radius of liq-vap interface (cm)				
0.63000	wick surface porosity (0.<poro<1.)				
1.00000	thermal conductivity of pipe wick (W/cm K)				
0.00127	nucl. site radius (cm),if 0.0 defaults to .00127				
1.30253	vapor passage area (cm**2)				
0.34377	total liquid flow area (cm**2)				
	-----pressure drops-----	temperature			power limits
tee	capillary	evaporator	tbe	tbc	qsonic
	liquid	adiabatic	tbeson	tbcson	qentrm
	hydrostatic	condenser			qcap
					qboil
750.	23346.	38953.	889.	750.	366.
	26399.	0.	786.	750.	2620.
	-35460.	-6546.			1101.
					5371.
800.	22646.	30763.	885.	800.	956.
	35996.	0.	841.	800.	4091.
	-34955.	-9158.			1568.
					10498.
850.	21946.	19652.	889.	850.	2222.
	41707.	0.	896.	850.	6032.
	-34452.	-4961.			1884.
					10742.
900.	21246.	12470.	915.	900.	4711.
	46156.	0.	952.	900.	8496.
	-33950.	-3430.			2155.
					19531.
950.	20546.	7666.	955.	950.	9272.
	48527.	0.	1007.	950.	11533.
	-33449.	-2199.			2335.
					15625.
1000.	19846.	4701.	1002.	1000.	17135.
	49468.	0.	1063.	1000.	15171.
	-32948.	-1375.			2449.
					11719.
1050.	19146.	2927.	1051.	1050.	29953.
	49529.	0.	1119.	1050.	19408.
	-32446.	-863.			2518.
					9094.
1100.	18446.	1866.	1100.	1100.	49736.
	49075.	0.	1176.	1100.	24195.
	-31944.	-550.			2553.
					6350.
1150.	17746.	1221.	1150.	1150.	78634.
	48324.	0.	1236.	1150.	29424.
	-31441.	-358.			2560.
					4379.
1200.	17046.	821.	1200.	1200.	118633.
	47399.	0.	1297.	1200.	34937.
	-30936.	-238.			2542.
					3082.
1250.	16346.	565.	1250.	1250.	171371.
	46371.	0.	1359.	1250.	40548.
	-30429.	-161.			2498.
					2291.

Appendix C. Interim Reports during FY98

Los Alamos

NATIONAL LABORATORY

Date: January 13, 1998

Refer to: ESA-EPE:98-82

Engineering Sciences and Applications

ESA-EPE, Energy and Process Engineering, MS J576

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Tom Ellison
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Niskayuna, NY 12301

Dear Tom,

This letter summarizes progress in the Heat Pipe Technology Development for Advanced Energy Transport Concepts (Phase II) program for the period October 1, 1997 to December 31, 1997. Work on the Mo-Li heat pipe is described here in some detail along with preliminary results. A formal report describing fabrication, processing, and testing of the Mo-Li heat pipe will be sent to you after the tests are completed. Brief mention is also made here on the status of the heat pipe life tests, heat pipe coating development, axially compliant heat pipe, and the sodium heat pipe safety test.

At the beginning of this report period, the Mo-Li heat pipe was being vacuum fired and distillation charged with lithium. By mid-October the heat pipe was charged with 43 g of lithium and the wick was wetted with lithium using a horizontal, full-length induction coil. A picture of the lithium wetting operation is shown in Figure 1. The heat pipe was then installed horizontally in a cryopumped vacuum chamber. A 30-cm-long induction coil was placed around the heat pipe between 3 and 33 cm from the evaporator end. Water was allowed to flow through a chill block on the fill stem to keep a lithium plug solid during heat pipe operation. This solid plug isolated the heat pipe vapor space from a charge valve located further down the fill stem.

Figure 1. Picture taken during an internal surface wetting operation when outside heat pipe surface temperature measured 1120 K.

An initial diagnostic run was made. Starting from room temperature, power to the induction coil was increased until the thermocouple at the evaporator exit measured 1160 K. Two problems were seen here: (1) a hot region (100 to 200°C above the surrounding surface temperature) along 10 cm of the heat pipe surface under the induction coil, and (2) a sharp decrease in surface temperature (300°C) starting 70 cm from the end of the condenser. The hot region under the induction coil was attributed to blockage of the annular gap by trapped noncondensable gas. The temperature gradient observed in the condenser region was assumed to be caused by residual noncondensable gas in the vapor space.

A series of adjustments were made to improve the heat pipe's operating characteristics. To

remove the noncondensable gas trapped in the annular gap, the heat pipe was placed, with the condenser side up, inside a vertical quartz tube. An induction coil was placed around the quartz tube along the entire length of the heat pipe. Water was allowed to flow through a chill block

attached to the fill stem. Power was applied to the induction coil and was increased until a pyrometer focused on the heat pipe surface read 1120 K. The pipe was kept at this temperature for 4 hours to allow buoyancy forces to push noncondensable gas out of the annulus and into the vapor space. An attempt was then made to purge the vapor space of noncondensable gas.

The heat pipe was then returned to the vacuum chamber. As before, the 30-cm induction coil was placed around the evaporator end of the heat pipe. Power was increased to the induction coil until the thermocouple at the evaporator exit read 1400 K. Noncondensable gas still remained in the condenser vapor space, but the temperature of the evaporator region appeared uniform.

To remove noncondensable gas and excess lithium from the vapor space, a chill block, a known-volume cold trap, and a cryopump were connected to the fill stem. Power was increased to the induction coils until the thermocouple at the evaporator exit read 1400 K. Soon after, the cryopump connected to the fill stem was started. With no water flowing through the chill block, conduction along the fill stem was sufficient to melt and vaporize the lithium fill plug. Lithium from the fill stem condensed and solidified in the cold trap. After the fill stem was cleared of solid lithium, noncondensable gas and lithium vapor from the heat pipe moved down the fill stem and into the cold trap. The lithium condensed and solidified in the cold trap. Any noncondensable gas moved through the cold trap and toward the cryopump. This continued until the condensed and solidified lithium filled the cold trap and isolated the heat pipe from the cryopump. Water was then allowed to flow through the chill block to form a freeze plug in the fill stem. Measurements made later indicated that 14 g of lithium were transferred from the heat pipe to the cold trap during this operation.

The pipe was then restarted. When the thermocouple at the evaporator exit measured 1360 K, the condenser surface temperature was uniform to within a couple of centimeters from the fill stem. A small pool of lithium remained at the condenser end. Another pool of similar size formed at the part of the evaporator end not covered by the induction coil. A local hot spot covering 30° of pipe circumference and 0.7 cm of length developed under the induction coil about 6 cm from the evaporator end. This hot spot was much smaller than the one previously observed. Optical measurements made between the induction coils indicated that the spot was 100°C hotter than the surrounding surface. The hot spot may have been caused by local dewetting of lithium from either the heat pipe's inner wall surface or in the wick as a residual effect of the gas seen previously.

In an effort to rewet the evaporator region, the heat pipe was placed horizontally inside a quartz tube. A full-length induction coil was placed over the quartz tube and was used to bring the pipe to 1120 K. The heat pipe was kept at this temperature for 4 hours.

The heat pipe and quartz tube assembly was then installed in a variable-angle-tilt fixture. A 30-cm induction coil was placed over the quartz tube with the coil's end about 3 cm from the evaporator end of the heat pipe. The heat pipe was oriented with the condenser tilted 10° above the evaporator. The pipe was started from the frozen state and was brought to 1330 K in 4 hours. Figure 2 shows measured heat-pipe-surface temperatures in the condenser versus position at various times during start up. A picture of the heat pipe operating near 1330 K is shown in Figure 3. The total heat pipe throughput at this temperature was 5.7 kW based on a measured 0.37 total hemispherical emittance. The thermocouple mounted nearest to the fill stem read about 30°C cooler than the other six thermocouples. The remaining thermocouples read temperatures that were all uniform to within the $\pm 10^\circ\text{C}$ thermocouple error limit. At 1330 K no hot spots were observed under the induction coil. The power to the induction coil was then reduced to zero in a single step, and the heat pipe was cooled to room temperature. During this shutdown, all thermocouples read below 700 K within 20 minutes of turning off the power to the induction coils. Performance tests of the Mo-Li heat pipe

will continue in January. These tests will be performed at various operating angles and transient conditions.

Also during this period, work began on the heat pipe life-test, scheduled for turn-on later this fiscal year. Drawings of the life-test heat pipes and test assemblies were generated. Existing life-test assemblies were inventoried, and components in need of repair or replacement were identified. Orders were placed for needed materials, with particular attention paid to items having long lead times. In anticipation of future high-power heat pipe tests, repairs were made to a 100-kW radio frequency generator located in one of the high-test bays. A LCAC molybdenum tube was sent to a vendor for coating with a 0.15-mm-thick layer of MoSi_2 . If this trial coating is found to be satisfactory, then a 25-cm-long, 1.8-cm-outside-diameter, lithium-filled molybdenum heat pipe will be sent there for coating. Design work began during this period on an axially compliant heat pipe. Several approaches have been identified that will allow a sodium-filled Haynes 230 heat pipe to operate while held by two rigid supports. Design work will begin in early January on safety tests of a sodium heat pipe submerged in seawater.

Sincerely,

Robert S. Reid

Robert S. Reid
Technical Staff Member

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ESA-EPE Serial File

Figure 2. Heat pipe surface temperature versus position at various times during a four hour startup. The heat pipe is oriented with its evaporator 10° below its condenser providing a slight gravity assist.

Figure 3. Picture taken during the run plotted in Fig. 2 when the heat pipe was operating near 1330 K at its evaporator exit.

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Date: March 16, 1998
Refer to: ESA-EPE:98-130

John M. Ashcroft
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Dear John,

This letter summarizes progress in the Heat Pipe Technology Development for Advanced Energy Transport Concepts program for the period January 1, 1998 to March 13, 1998. During this period work continued on the 1.8-m long Mo-Li heat pipe tests, the heat pipe life tests, heat pipe MoSi₂ oxidation coating, sodium heat pipe safety test, and the axially compliant heat pipe.

At the beginning of this period, the 1.8-m Mo-Li heat pipe was installed in a variable-angle-tilt fixture. A 30-cm long induction coil with circular cross section was connected to a 60 kW radio frequency generator and placed over a 5-cm diameter quartz tube enclosing the heat pipe. In that configuration, the 60 kW generator only had enough capacity to bring the heat pipe to 1330 K at the evaporator exit. The heat pipe was moved to a 100 kW generator which brought the heat pipe to 1400 K at full capacity, still 100°C short of the goal. Generator adjustments to improve load matching produced only a modest increase in maximum heat pipe temperature.

It became apparent that 1500 K operation would require better coupling between generator and heat pipe. A 30-cm long induction coil with a rectangular cross section and 1.3-cm inside radius was selected to enhance coupling and reduce $1/r^2$ attenuation. A quartz tube, made to fit the coil and heat pipe, was evacuated and the heat pipe was restarted. Generator plate voltage was increased until the thermocouple nearest the evaporator exit read 1480 K. There, generator capacity, as indicated by plate voltage, was ample to bring the pipe well above 1500 K. This test was ended because of a vacuum leak in an improperly seated o-ring. After shutdown, plated MoO₃, formed by the leak, was removed from the inside surface of the quartz tube.

Figure 1. Typical 1.8-m Mo-Li heat pipe startup temperatures. Distance is measured from the evaporator end-cap.

The heat pipe was brought to 1400 K to remove a oxide layer that had formed over a portion of the condenser. The pipe was then placed inside a clean quartz tube and restarted in the horizontal position. Power was increased until the thermocouple at the evaporator exit read 1500 K. A plot of heat pipe surface temperature, at several axial locations, versus time from the beginning of startup is shown in Figure 1. The lower temperature reading at 179 cm resulted from a liquid pool near the condenser end-cap. The pipe was then tilted with the condenser end 15° above the horizontal and operated in that orientation for 30 minutes. The tilt was then increased to 45° above the horizontal and operated there for about 10 minutes. The pipe was then rapidly returned to the horizontal.

Figure 2. Temperature of 1.8-m Mo-Li heat pipe during maneuver from 15° to 45° to 0°.

Soon after, a dry out occurred in the heated zone, possibly related to the sudden movement of excess working fluid to the condenser region. Figure 2 shows a plot of heat pipe surface temperature during the maneuvers from 15° to 45° to 0°. The large swing in temperature at 179 cm from the evaporator end cap was caused by the shift in pool position. A test was then performed to calibrate the generator power settings to heat pipe temperature profile. From this information heat pipe throughput versus power setting can be estimated, assuming constant surface resistivity with temperature where power is induced. The heat pipe was later started from the frozen state at a 45° orientation and brought to a temperature of 1200 K in 3 hours.

Pictured in Figure 3 is the 1.8-m Mo-Li heat pipe at a 45° orientation. Here the liquid pool extends several centimeters into the heated region. When the pipe reached 1400 K in this orientation, slugs of liquid were ejected from the evaporator at about 30 s intervals (both mean and mode). The slugs caused brief liquid depletion over part of the heated zone. The pipe was returned to the horizontal orientation and brought to 1540 K to test over-temperature operation. When the power to the heat pipe was increased further, a hot spot developed in the heated zone. The heat pipe was brought to 1300 K and operated for several hours to rewet the evaporator. The pipe was then shut down. The radio frequency coil was moved 10 cm forward to separate the liquid pool from the heated region when the heat pipe is operated at positive inclination. Tests resume this week to demonstrate operation at 90° inclination and rapid startup.

Work continued during this period on the heat pipe life tests. Fabrication of eight custom quartz tubes for containing the life test heat pipes was completed. Most of the materials needed for the life test have arrived at Los Alamos. Several unused Gifford-McMahon refrigerator cold heads were found in salvage suitable for the test. Material arrived from Knolls for fabrication of the end caps and fill tubes of the first three life test heat pipes. Fill-tube close-out trials are now in progress. A satisfactory seal has been obtained on a sample of Haynes 230 tube. Because of the limited quantity of tube material provided, close-out trials for the MA-754 and MA-956 alloys will be combined with the fill stem weld tests. The machining of end-caps for the first three life test heat pipes has been completed.

Figure 3. Picture taken of 1.8-m Mo-Li heat pipe during steady operation with the condenser region inclined 45° above the horizontal.

Two sections of schedule 40 Haynes 230 pipe also arrived for surface texturing trials. Several texturing methods were considered for the inside surface of the life test heat pipes. These included an internal knurl, upsetting tool, and a helical thread. Both knurling and threading were successfully tried on sections of Haynes 230 pipe. However, knurling is no longer being considered because of tolerancing constraints, uncertain machining properties of the gun

drilled MA materials, and the long lead time required for tooling. A helical thread, sufficient to cover the length of the evaporator has been machined into the Haynes 230 pipe. The gun drilled tubes to be used for the first three life test heat pipes are scheduled to arrive at Los Alamos the week of March 23. Once these tubes arrive, electron beam weld tests will begin on sample end cap materials and surface texturing trials will begin.

A thermochemical model of the Haynes 230-Na life test system is being developed by Roy Feber, a former Los Alamos Staff Member, now acting as a Los Alamos consultant. The enhancements to this model, designated HPLT-8, include an increase in the number of elements to enable thermochemical calculations of complex alloy-liquid metal systems. Liquid distribution in the pipe was estimated using a Nussult film condensation relation found in Rohsenow¹. Thermodynamic data have been assembled for the temperature range 1100-1400 K, and preliminary calculations have been made at 1300 K. The composition used for Haynes 230 was based on Knolls-supplied information: weight percent, Fe, 1.47; Ni, 59.56; Co, 0.54; Cr, 21.69; Mo 1.27; W, 14.15; Mn, 0.48; Al, 0.33; La, 0.015; C, 0.1; Si, 0.39; and B, 0.004. Some uncertainty remains about the calculated fate of some impurities because of the unknown solubility dependencies of C, Si and B in Haynes 230. A statement in the Haynes 230 literature, referring to stability to long-term thermal exposure, was taken literally: "Principal phases precipitated from solid solution are all carbides." Thermodynamic data for the formation of possible ternary oxides is now being reviewed.

Two techniques have been identified to measure O₂ concentration in the Na working fluid, an initial condition for the thermochemical model. The first technique measures the equilibrium O₂ concentration in a V wire that has been exposed to 1120-K Na for about 4 hours. The vanadium wire technique is most suitable for measurement of O₂ concentrations in Na of less than 20 parts per million. The other technique measures O₂ content in Na by interaction of the oxygen nuclei with 14 MeV neutrons. Through a ¹⁶O(n,p)¹⁶N reaction, 6.129 MeV gamma rays are emitted and detected during the 7.10 s half life of ¹⁶N. Neutron activation gives accurate results for O₂ concentrations above 20 parts per million. Procedures for the activation and vanadium wire tests have been outlined and arrangements have been made for these tests to be performed at several different laboratories.

A sample of molybdenum tube was sent to a commercial vendor for MoSi₂ coating trials. This pipe was returned to Los Alamos in mid-January and was temperature cycled to verify coating integrity. The coating was found to be satisfactory. This vendor has agreed to coat the 23 cm long lithium-filled heat pipe. The required hardware for the filling of the 23-cm Mo-Li has been fabricated and a known volume pot has been charged with lithium. The fill stand has been assembled and the fill will be completed after the 1.8-m Mo-Li heat pipe test.

Figure 4. Axially compliant heat pipe.

Following your instructions of January 20, we have accelerated the schedule for the sodium heat pipe safety test. The objective of this test is to characterize the reaction from a sudden salt water breach of a sodium-charged heat pipe. Arrangements have been made for a June test at a remote explosives firing area. Selection of this area has greatly simplified the required administrative approvals. Orders have been placed for necessary test hardware. Two safety test heat pipes will be built along with the first three life test heat pipes.

¹ W. M. Rohsenow (1972) "Film Condensation of Liquid Metals," Transactions of the CSME, Vol. 1, No. 1, pp. 5-12.

March 16, 1998

Design work continues on an axially compliant heat pipe. Several approaches have been considered. Figure 4 shows a drawing of a heat pipe incorporating bellows proposed by a Texas company. The 30-cm compliant section in Fig. 3 allows 1.3 cm of compression and has a 3.8-cm outside diameter and 1.6-cm inside diameter. We anticipate potential difficulties with this design after working fluid resolidification. An alternative design which may be less prone to problems is being proposed by a Swiss firm who has previous experience using Haynes 230 as bellows material. We are also exploring the feasibility of using refractory metal bellows for later compliant heat pipe development work.

Sincerely,

Robert S. Reid
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Date: May 15, 1998
Refer to: ESA-EPE:98-130

John M. Ashcroft
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Dear John,

This letter summarizes progress in the Heat Pipe Technology Development for Advanced Energy Transport Concepts program from March 13, 1998 to May 8, 1998. During this period, work continued on the heat pipe life tests, combustion-fired molybdenum-lithium heat pipe, and the sodium heat pipe safety test. Additionally, testing was completed on the 1.8-m long molybdenum-lithium heat pipe.

At the beginning of this period, the 1.8-m molybdenum-lithium heat pipe was installed in a variable-angle-tilt fixture. With the heat pipe at a 45° inclination, the pipe was brought from room temperature to 1200 K in about 45 minutes. The pipe was then brought to 1300 K after another 20 minutes. It was then moved to a horizontal orientation and the generator power was increased until the thermocouple at the evaporator exit read 1300 K. The pipe was left in this state for several hours. The pipe was then tilted 30° for five minutes, moved to 45° for another 5 minutes, and then moved to 60° above the horizontal. The pipe was kept at 60° for about 13 minutes. Observations were made of temperature changes in the heated zone during this period. The pipe was then moved to the vertical for 5 minutes. At this point fogging was observed on the quartz near the condenser region end cap. The pipe was returned to the horizontal and was shut down.

The fogging on the quartz was colored white indicating lithium vapor had leaked from a fill stem crack. In anticipation of this possibility, a molybdenum end cap had been previously fabricated. The pipe was removed from the test fixture, and the end cap was electron-beam-welded to the pipe.

Figure 1. Performance of the 1.8-m Mo-Li heat pipe undergoing cyclic heating and cooling. Distance is measured from the evaporator end cap.

The pipe was then wet in with a full length induction coil and returned to the variable-angle test fixture. In the horizontal orientation, a start-up from the frozen state was conducted with the pipe reaching 1200 K in just under 13 minutes and 1500 K in another 7 minutes. A subsequent attempt to start the pipe from the frozen state in under 6 minutes resulted in an evaporator dryout. The pipe was then thermally cycled several times between 1200 K and 1500 K for a cycle period of 10 minutes. A plot showing this maneuver is given in Figure 1. This pipe has been removed from the test fixture and is being readied for post-test analysis to include radiography of the wick and wall structure.

Figure 2. Temperature of 23-cm Mo-Li heat pipe during start-up and shutdown.

Work continued during this period on the heat pipe life tests. The fill hardware has been fabricated for the Haynes 230, MA-754, and MA-956 life test heat pipes. An internally threaded surface texture has since been cut along 15.2 cm of one of the gun-drilled Haynes 230 tubes. A textured section, 1.27 cm long, has been removed from this tube for use in later metallurgical tests. This pipe will be degreased and prepared for vacuum firing later this week. Next week the tube will be tungsten inert-gas-welded to the end caps and fill stem. After the weld, the pipe will be again vacuum-fired and then charged with 10 g of sodium. The heat pipe will then be tested to verify proper performance. Once successful operation is demonstrated with the Haynes 230 pipes, the pipe's fill stem will be sealed, and the MA alloy pipes will be similarly processed.

In an item related to the life tests, the thermochemical model of the Haynes 230-Na life test system is nearing completion. During this period, a brief review of the free energies of formation of those ternary sodium oxides containing metals in Haynes 230 was made. Also, the effect of the initial chemical form of trace components in Haynes 230 was examined.

As mentioned in the March progress report, oxygen concentration measurements in the sodium working fluid will be made to characterize oxygen levels in the sodium heat pipe system after a distillation fill. For the vanadium wire test, 60 g of sodium will be loaded into a Haynes 230 container using customary distillation procedures. This container will then be heated to 1120 K for about 4 hours to allow oxygen to equilibrate with the vanadium wire. For the activation analysis 6.5 g of sodium will be distillation-filled into an 11/16-in. o.d. stainless-steel tube. Before filling, the stainless-steel tube will be activated to measure initial oxygen levels in the metal.

Also, during this period the 23-cm-long molybdenum-lithium heat pipe was charged with 4.5 g of lithium. A lithium plug was then formed at the fill stem and the pipe was wet in for several hours at 1150 K. The pipe was then placed under a short radio frequency coil and repeatedly brought to 1500 K. A plot of evaporator exit temperature versus time from start up is shown in Figure 2. The constant 525 K recorded during the first 10 minutes of startup is an artifact of the measuring device that detects emitted radiation at 0.65- μ wavelength. Figure 3 shows the 23-cm-long heat pipe operating at 1530 K. After a molybdenum end cap is welded to this heat pipe and a final wetting operation is completed, this pipe will be sent to Bettis for coating and combustion-fire testing.

Figure 3. Picture taken during initial trial of 23-cm Mo-Li combustion-fired heat pipe. The optically measured temperature is 1530 K at the exit of the heated zone.

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Also during this period two safety test heat pipes were fabricated. Each safety test heat pipe is 30 cm long and is built out of 3/8" Schedule 40 Haynes 230 pipe. Three layers of 100 mesh stainless steel screen line the inside of the heat pipe. Each pipe was charged with 5 g of sodium which, with a saturated wick, will leave a 3 cm long sodium pool in the vapor space. Wet in and testing to insure proper heat pipe operation will be finished in the coming weeks. After that, the safety test heat pipes will be x-rayed to verify the location of the sodium pool. The test site has been changed because of a conflict with an unanticipated weapons-test at the original site. The test at the new location is set for the week of July 7.

Last month, Joe Nehrbauer sent start up data from the stainless steel paddle heat pipe tested at KAPL on April 9. I compared Joe's data to test data from the same heat pipe collected at Los Alamos last June, checking both data sets for internal consistency.

I focused on the region around the evaporator in a quasi-steady condition 12,000 s after the startup began. At 12,000 s the evaporator stagnation temperature is 840 K. I assumed steady, 1-D compressible flow of monatomic sodium with mass removal normal to the main flow stream. The condensation heat transfer (and mass removal) rate was estimated by accounting for convection to the environment and integrating Stefan-Boltzmann's law between the evaporator exit (using the static temperature predicted for choked flow) and the temperature measured at the end of the cylindrical transition region.

Under these conditions the sonic heat transport limit at the evaporator exit is 2.5 kW with choked flow at $Ma \sim 6$ entering the transition region. The sonic limit value is at odds with even a conservative estimate of heat pipe throughput from the wall temperature data. Assuming a $5 \text{ W/m}^2\text{-}^\circ\text{C}$ heat transfer coefficient and 0.8 emissivity, the overall heat pipe throughput at the evaporator exit (ignoring axial conduction) is 4.1 kW. If you account for the power rejected in the evaporator and end cap regions this estimate agrees with the 4.8 kW heat input rate measured by your power meter.

Based on these inconsistencies, the thermocouple measurements taken at both LANL and KAPL appear to be reading $\sim 50^\circ\text{F}$ too low, which is larger than the $\pm 20^\circ\text{F}$ measurement uncertainty for a well-attached type-K thermocouple. Local heat removal by the bare thermocouple wire leading a short distance away from the heat pipe surface could cause a low temperature reading. An analytic calculation of a thermocouple wire attached to a semi-infinite solid surface indicates that a temperature offset of this magnitude is plausible. To confirm this experimentally you might want to measure optically temperature on a heat pipe surface of known emissivity near a thermocouple. Better yet, compare readings taken before and after refractory insulation is placed around the wires at the thermocouple attachment point.

Sincerely,

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