Design and Testing of Titanium/Cesium and Titanium/Potassium Heat Pipes

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Alkali metal heat pipes are ideal radiator elements for large area, high temperature, waste heat rejection radiator panels. Proposed low mass designs include a thin walled titanium (foil) / cesium or potassium heat pipe encased in a structural carbon-carbon shell. In this paper , the results of a preliminary design study are presented that explored heat pipe performance as a function of operating temperature, physical dimensions, working fluid (Cesium or Potassium), and wick structure selection. At the lower end of the operating temperature range 550K to 740K, in general cesium/titanium heat pipes can be designed to transfer more power than potassium. For heat pipes in the 50 to 75mm diameter range, cesium heat pipes can be designed to transfer 1 to 5 kW. Above 740K, potassium is a significantly better working fluid than cesium, with a capacity to transfer 5 to 15kW. The study also included the fabrication and initial testing of two heat pipes: one titanium/cesium (Ti/Cs) and one titanium/potassium (Ti/K). Long term compatibility data for standard wall thickness titanium/cesium and titanium/potassium heat pipes is scarce. Two life test pipes were fabricated and tested for 48 hours with no sign of degradation. This study provides further evidence that Ti/Cs and /or Ti/K heat pipes are capable of meeting the mass and performance goals for radiator systems of future nuclear-electric propulsion missions.

I. Introduction

Future NASA missions, such as the Jupiter Icy Moons Orbiter mission (JIMO), will require nuclear-electric propulsion (NEP). NEP systems, whether utilizing a Brayton cycle or thermoelectric modules, require large area radiators to reject the unconverted heat to space. In particular, thermoelectric generators will need a radiator that operates in the temperature range of 550K to 900K. Alkali metal heat pipes are ideal radiator elements for this application. They provide nearly isothermal heat transfer from the main coolant loops to the radiator panels; and by design, they operate independently, which provides a high degree of redundancy should one of the elements fail due to micro meteor penetration.

Heat pipe performance at a given operating temperature is limited by viscous, sonic, boiling, and capillary limits. These limits are a function of the heat pipe working fluid properties, the heat pipe dimensions, and the heat pipe wick structure design. At the lower end of the range of interest, 550K to 750K, the performance of cesium and potassium heat pipes is limited primarily by the two vapor limits, viscous and sonic. At the higher operating temperatures, above 750K, the performance is primarily a function of the capillary limit.

The selection of the optimum operating temperature of the entire NEP system will be based on a complex trade study involving many subsystem inputs and constraints, the heat pipe radiator elements being only one of these subsystems. This paper details a preliminary study that was performed to provide radiator panel designers with sufficient and accurate heat pipe design space to aid their heat rejection system (radiator panels) design and to begin to provide input for the system level optimization task.

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In addition to analytical work, a titanium/cesium heat pipe and a titanium/potassium heat pipe were also fabricated and tested. In general, the alkali metals are compatible with stainless steel, superalloys, and refractory metals. While there have been a few titanium/potassium life tests (e.g., see Lundberg, 1987, Sena and Merrigan, 1990) we are not aware of any life test data with titanium/cesium. The fact that compatibility issues have not been uncovered to date indicates that compatibility is likely and simply needs to be confirmed through dedicated testing. These two pipes were fabricated for the sole purpose of demonstrating long life compatibility.

II. Application and specific goals

Figure 1 is a conceptual sketch of a radiator panel, showing a proposed heat pipe, saddle, filler, and face sheet configuration. Based on a conceptual design of this type, the following parameters are provided as design goals:

- Heat Pipe Throughput Power: 1,000 – 9,000 Watts
- Evaporator Heat Flux: ≥ 35 W/cm^2
- Mass goal of Radiator Panel: < 6 Kg/m^2
- Mass goal of Heat Pipe: < 0.35 Kg/m
- Heat Pipe Diameter: 15mm – 100mm
- Heat Pipe Length: 1 – 2 meters (125mm evaporator, 50mm adiabatic, and 825 to1825mm condenser)

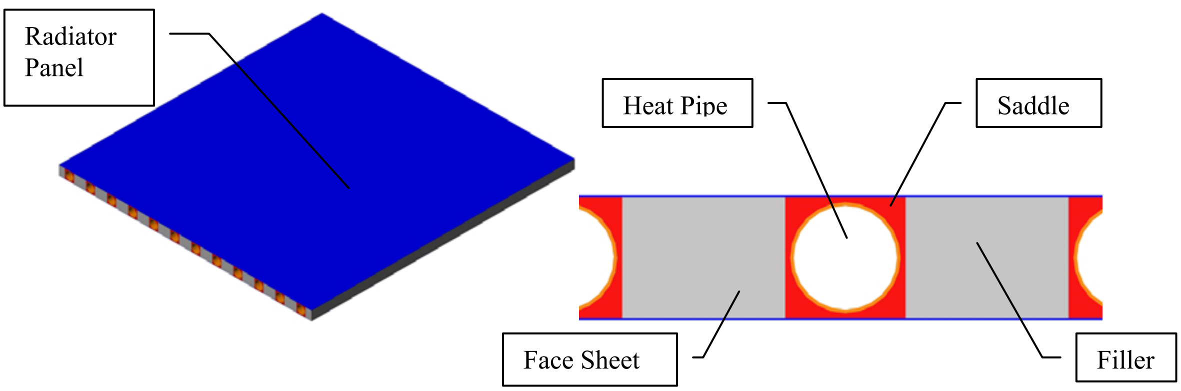

FIGURE 1. Conceptual Sketch of a Heat Pipe Radiator Panel.

ENVELOPE MATERIAL AND WORKING FLUID SELECTION

Envelope materials of interest are titanium, stainless steel, and nickel based superalloys, primarily because they are relatively low cost, relatively easy to fabricate, and they are generally believed to be compatible with cesium and potassium. Titanium and its alloys are of particular interest because their density is 50% of stainless and nickel based superalloys. For example, a heat pipe cylinder constructed with a metal liner 0.125 mm thick, 76mm diameter, and 2 meters long, will have a mass of approximately 270 grams vs. 540 grams for the equivalent liner constructed of stainless steel or a nickel based superalloy. With a mass target of approximately 350 grams per meter, it is obvious the mass percentage of the liner is significant and using titanium or a titanium alloy will be of high importance in the pursuit of a heat pipe that can meet the mass target.

Stainless steel and nickel based superalloys have been demonstrated to show long term (100,000+hours) compatibility with sodium (Rosenfeld et al., 2004). Typically if a material is compatible with sodium, it is also compatible with potassium and cesium. In fact, one of ACT's commercial product lines, the isothermal furnace liner, a product developed over 30 years ago by Dynatherm Corporation, includes superalloy/potassium and superalloy/cesium heat pipes. These heat pipes have been in commercial service, in some cases for many years, with no sign of thermal degradation. Depending on the development of bonding techniques to join a carbon-carbon shell to a thin foil liner, stainless steel and/or nickel based superalloys may be required should diffusion of bonding constituents render titanium unusable. Otherwise, at this early stage of this development project, the envelope material of choice is titanium.

The working fluids of interest for this paper are primarily potassium and cesium based on their relatively good thermal properties in the temperature range of interest. When looking for possible heat pipe working fluids over a given temperature range, there are two simple evaluation tools; the liquid figure of merit (or Liquid Transport Factor, Dunn and Reay, 1994), M_l and the vapor figure of merit M_v.

The liquid figure of merit varies with temperature and with individual fluids, and is a qualitative way of ranking the working fluid's ability to circulate the liquid within a wick structure, but says nothing about the vapor's ability to transport the heat. Likewise the vapor figure of merit is a qualitative way of determining if there is sufficient vapor to transport the heat. The Vapor Figure of Merit (Ernst, 2004) is defined as:

$$M_v \sim P_v * \rho_v \quad kg^2/s^2*m^4$$

Like the liquid figure of merit, the vapor figure of merit is a qualitative way of determining if there is sufficient vapor to transport the heat. In the meter/kilogram/second units system, the vapor figure of merit should be above 1 for the heat pipe to be able to transport any heat. While a figure of merit of 1 indicates a heat pipe can transfer some heat, experience tell us that a figure of merit of 10+ is required to transfer significant quantities of heat.

The Vapor Figure of Merit falls out of the equations for the viscous and sonic limits defined by Busse (1973):

$$q_{Sonic} = 0.474 L \cdot \sqrt{\rho_v \cdot P_v}$$

$$q_{Viscous} = \frac{r_v^2 \cdot L \cdot \rho_v \cdot P_v}{16 \cdot \mu_v \cdot L_{eff}}$$

Plotting the Liquid and Vapor Figures of Merit versus temperature, as shown in Figure 2, is a first level approach often used to screen potential working fluids. These merit numbers are a means of ranking heat pipe fluids, with higher merit numbers being more desirable. In the meter/kilogram/second units system, the vapor figure of merit should be above 1 for the heat pipe to be able to transport any heat. While a figure of merit of 1 indicates a heat pipe can transfer some heat, experience tell us that a figure of merit of 10+ is required to transfer significant quantities of heat

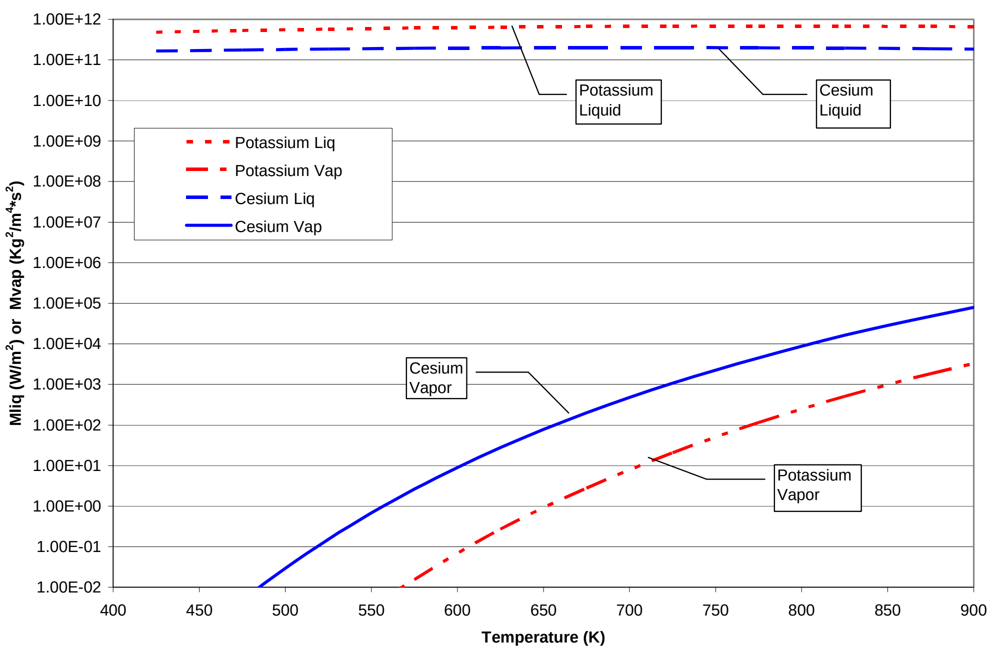

FIGURE 2. Liquid and Vapor Figure of Merits – Cesium and Potassium.

Simply comparing cesium to potassium using the figures of merit and the expected capacity as a function of operating temperature, one would tend towards cesium. Cesium will begin to operate at a lower temperature and the liquid figure of merit is similar, even though slightly less. Specific designs and the viscous, sonic, and capillary limits must be evaluated before a definitive selection can or should be made for cesium versus potassium.

The Vapor Figure of Merit falls out of the equations for the viscous and sonic limits defined by Busse (1973). When applying these limits, one has to be mindful of the fact that at sonic operating conditions, the ΔP in the heat pipe evaporator is ~50% of the saturated vapor pressure at the beginning of the evaporator; and therefore, will have a large ΔT in the evaporator vapor. Likewise, when a heat pipe is operating at the viscous limit, there is insufficient vapor pressure to sustain vapor flow and the end of the condenser will be at ambient temperature thus the ΔT in the heat pipe is equal to the evaporator temperature minus ambient temperature.

Figures 3 and 4 show the sonic and viscous limits for cesium and potassium heat pipes of 1.27cm and 2.54cm in vapor core radius and 75cm and 200cm in total length. For the selected dimensions, the charts indicate that cesium is an acceptable fluid for operation above 600K and potassium above 650K. Below these temperatures viscous and sonic limits prevent the heat pipes from transferring significant power.

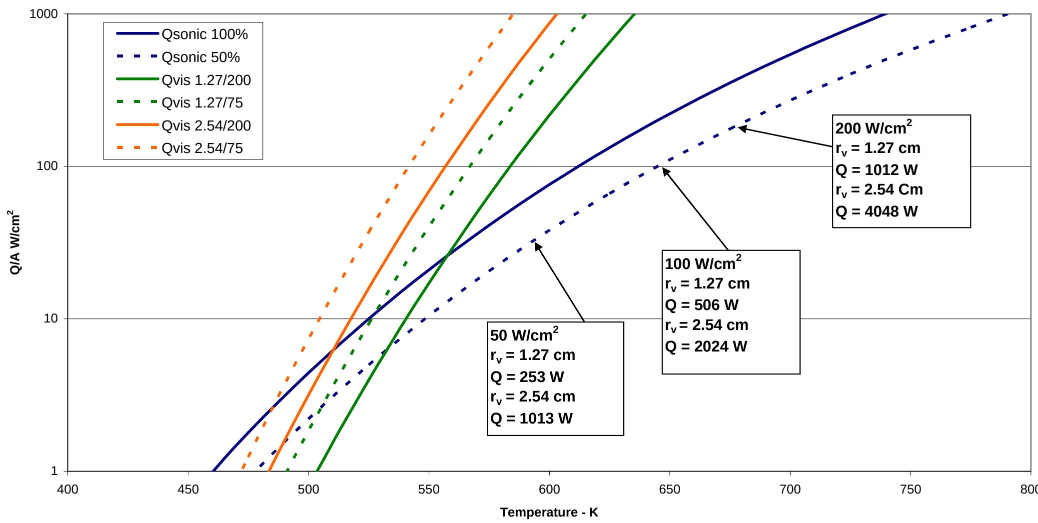

FIGURE 3. Sonic and Viscous Q/A vs. Temperature – Cesium Working Fluid.

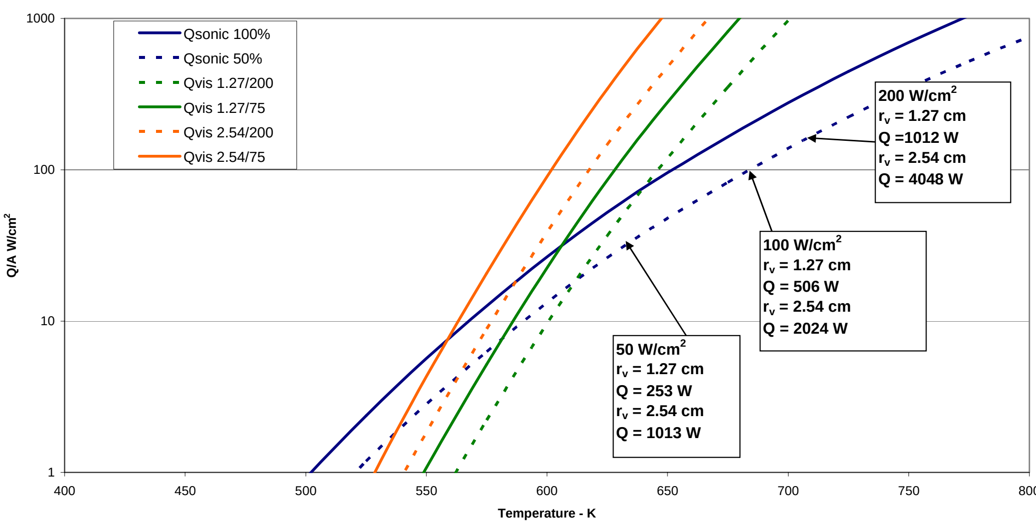

FIGURE 4. Sonic and Viscous Q/A vs. Temperature – Potassium Working Fluid.

Figure 5 shows the sonic limit as a function of heat pipe diameter. This chart is another way of looking at the vapor transport limitations of a heat pipe. Specifically, if the desire is to transport 5000 Watts through a cesium heat pipe, then from the chart, it can be seen that a 1” diameter heat pipe must be operated above 735K, a 2” diameter heat pipe must be operated above 655K, a 3” heat pipe must be operated above 620K, and a 4” diameter heat pipe must be operated above 590K. Understanding the relationship of heat pipe diameter to power transferring capacity as a function of temperature is essential when performing radiator heat pipe optimization studies.

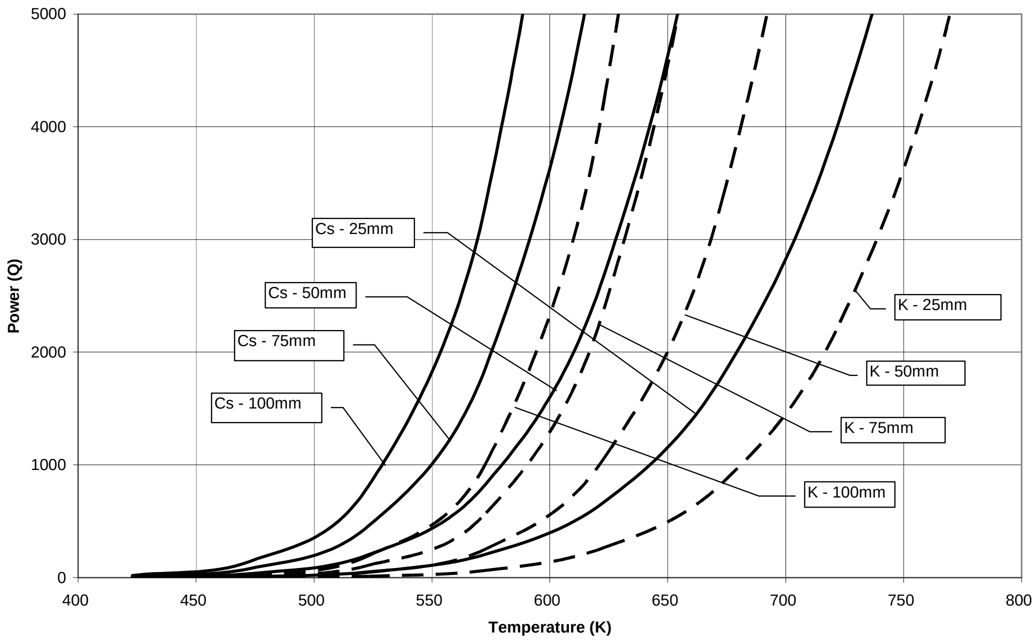

FIGURE 5. Sonic Limit as a Function of Heat Pipe Diameter – Cesium and Potassium

III. High performance wick structures – capillary limit

At steady state, there are 5 different limits that control the heat pipe power (Dunn and Reay, 1994):

- Sonic Limit
- Viscous Limit
- Entrainment Limit
- Wicking Limit
- Boiling Limit

The first two limits, sonic and viscous, are set by the vapor flow, and heat transport capability increases as the vapor flow area increases. The entrainment limit depends on the pore size and the vapor flow rate. The wicking limit depends on both the vapor flow, as well as the wick design. And, the boiling limit is a very high heat flux phenomena for alkali metal heat pipes that is extremely unlikely at the heat fluxes that are expected in this application.

The viscous and sonic limits were discussed above. The wicking and entrainment limits were calculated using the standard heat pipe equations. In the remainder of this paper, the maximum power and temperature range for cesium and potassium heat pipes will be evaluated.

Two heat pipe wick structures were evaluated to determine the performance limit as a function of temperature. One design utilizes sintered powder metal wick with dual tunnel arteries and the other is multiple wraps of screen incorporating 2 to 4 screen tunnel arteries. The evaporator section is 125mm long. The adiabatic section is 50mm long; and, the condenser section varies from 825mm (1 meter overall) to 1825mm (2 meters overall).

At any temperature, the maximum allowable heat pipe power is the smallest of the four limits, when each is multiplied by an appropriate safety factor. The safety factor for the wicking and entrainment limits is 0.75 to account for any minor fabrication defects. For the sonic and viscous limits, a safety factor of 0.5 was chosen to avoid large temperature drops between the evaporator and the condenser.

$$Q_{MaxHeatPipePower} = \text{minimum}\left(0.75 \cdot Q_{WickingLimit}, 0.75 \cdot Q_{Entrainment}, 0.5 \cdot Q_{Sonic}, 0.5 \cdot Q_{Viscous}\right)$$

Heat pipe limits for a typical cesium heat pipe are shown in Figure 6 for operation in zero gravity. Other dimensions are specified in the figure. The heat pipe design has a sintered powder metal wick with two tunnel arteries. Note that this heat pipe is not an optimum design, it was chosen as a representative sintered design, to get an idea of what limits control the cesium heat pipe at different temperatures. The plot shows the viscous limit dominates at the lowest temperatures, followed by the sonic limit. At higher temperatures, the entrainment limit, then the wicking limit dominates. The entrainment limit may or may not limit the power, depending on the wick chosen.

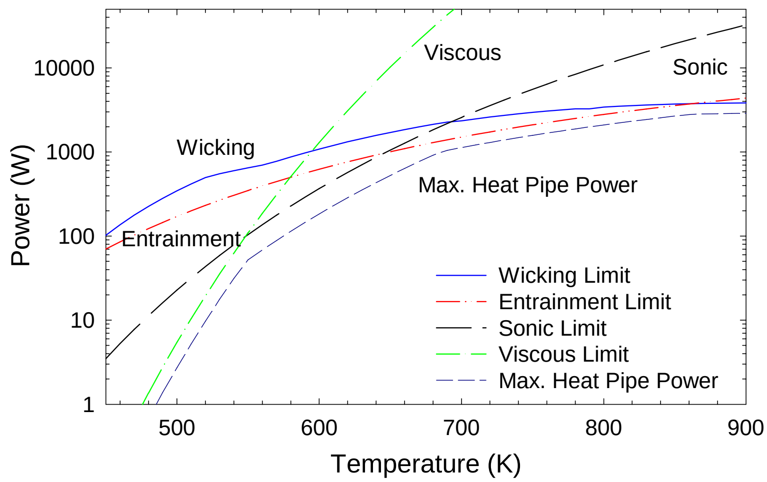

FIGURE 6. Heat Pipe Power Limits versus Operating Temperature. Cesium, 25mm ID, 125mm Evaporator, 50mm Adiabatic, 1m Condenser, 1.5mm Thick (-50+100) Sintered Powder Wick, in Space.

Heat pipe performance limits were calculated for various heat pipe lengths, diameters, wick structure types, and working fluids. Figure 7 is an example of the type of performance curves that were generated.

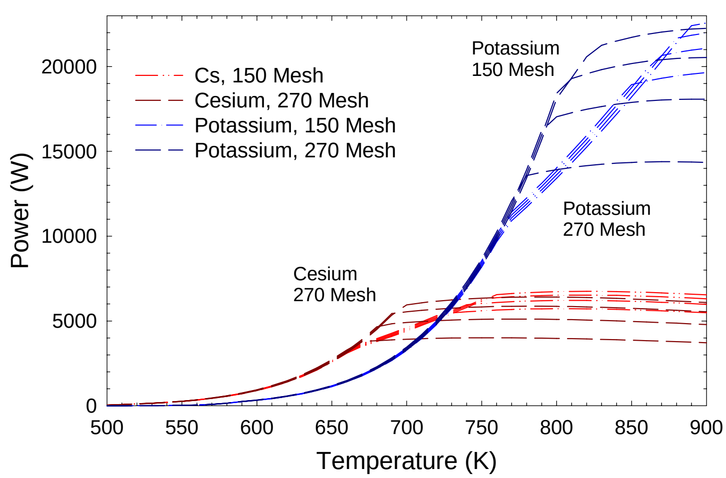

FIGURE 7. Cesium and Potassium Heat Pipe Limits for 50mm ID, 125mm Evaporator, 50mm Adiabatic, 2m Overall, Various Screen /Screen Artery Wicks (Each Line Within a Subgroup Represents a Different Evaporator Wick Thickness), in Space.. The Cross-Over Point for Potassium versus Cesium is Around 740 K.

This plot, along with the balance of the performance curves generated but not shown in this paper shows the following:

- Cesium is a better working fluid choice than potassium when operating in the 550K to 740K range. In this range the vapor limits dominate and the vapor properties of cesium are better than potassium.
- Above 740K, potassium is a better working fluid choice than cesium. In this range, the vapor properties are sufficiently equal or better than cesium and the potassium liquid properties are clearly superior to cesium.
- Powder metal wick structure designs and screen wick structure designs were both capable of transferring significant quantities of heat. Screen wick structures will likely be lower mass and perhaps a powder metal wick in the evaporator and a screen wick in the condenser will provide the best combination. Additional detailed design work is necessary.
- Increasing the diameter of the heat pipe results in a sharp increase in the power transferring capability of the heat pipes, especially at the lower operating temperatures. Diameters of 50 to 75mm will likely be required to meet the upper range of the space radiator design specification at temperatures below 740K.

Potassium and Cesium Life Test Heat Pipes

Life test pipes are run to determine compatibility/incompatibility of the working fluid and the wall/wick materials under actual operating conditions. The temperature profile of the heat pipe is typically monitored as a function of time to look for any changes that might signify an incompatibility. For example, if non-condensable gases (NCG) are generated inside the heat pipe, this NCG will be pushed to the far end of the condenser and block vapor from condensing at that location. This will result in a temperature drop in the sensor readings at the far end of the condenser. The design parameters selected for the life test pipes are shown below in Table 1.

Table 1. Life Test Heat Pipe Design Parameters

Parameter	Description
Envelope Material	CP Grade 2 Titanium
Outer Diameter	38.1mm (1.5 inches)
Wall Thickness	0.711mm (0.027 inches)
Overall Length	610mm (24 inches)
Evaporator Length	150mm (6 inches)
Condenser Length	460 mm (18 inches)

The length of the heat pipe was selected to readily fit into existing charging, processing, and testing (in vacuum) facilities. The diameter of the pipe was selected as a reasonably representative size for the length. From a vapor limit point of view (50% sonic and viscous limits), these pipes should be able to transfer approximately the thermal power shown in Table 2 below.

Table 2. Approximate Thermal Power Transfer Limit

Temperature (K)	Cesium	Potassium
525	46 W	2 W
575	189 W	58 W
625	609 W	240 W
675	1,618 W	758 W
725	3,695 W	2050 W
775+	>5,000 W	>2,125 W

The pipes were operated in the gravity aided position (evaporator down); and therefore, the capillary limit did not come into play for these pipes. However, since both sintered wicks and screen wicks are being considered for improved capillary performance, the life test pipes include both. The wick structure in the evaporator (sintered powder metal) serves to distribute the working fluid uniformly around the circumference and to provide a stable, uniform surface for evaporation. The condenser wick structure (screen mesh) serves to distribute the working fluid uniformly and to minimize the effects of entrainment.

The heat pipes were charged with working fluid, processed under vacuum to remove any non-condensable gases, and sealed using a proprietary electrical resistance welding technique. During processing, the pipe was operated at up to 900K with the vapor space open to vacuum, so that any non-condensable gases were pushed to the condenser end of the heat pipe and evacuated into the vacuum bell jar prior to final sealing. Figure 8 shows the heat pipe processing and testing setup.

Six (6) thermocouples were attached to each heat pipe. TC#1 was attached to the evaporator end cap, TC#2 was in the center of the evaporator section, TC#3 was at the exit of the evaporator, TC#4 was 150mm into the condenser section, TC #5 was 300mm into the condenser section, and TC#6 was at the condenser end cap. The power input to the evaporator heater was adjusted to achieve the desired temperature set point. The power output was radiated to the surroundings.

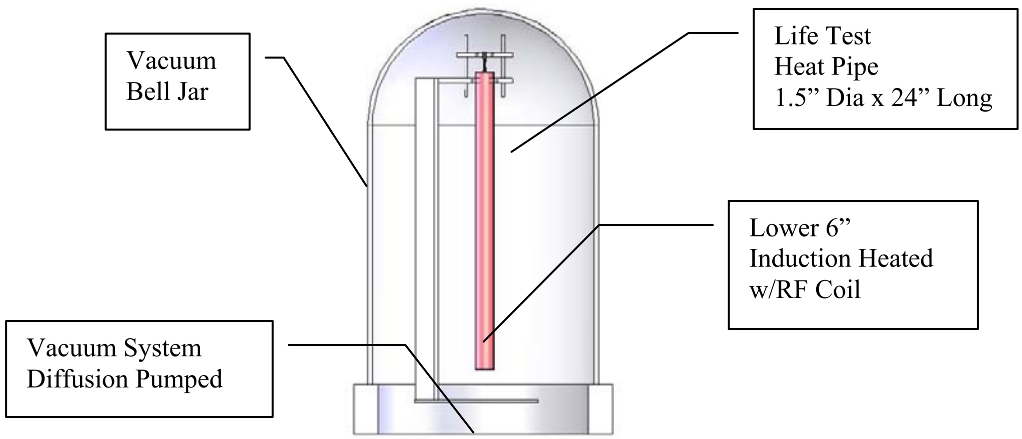

FIGURE 8. Heat Pipe Processing and Testing Setup.

Although it is intended for these two heat pipes to be life tested for several thousands of hours, only a short 48 hour test has been run to date. For the 48 hour life test, operating temperatures of 600K for the Cesium/Titanium heat pipe and 700K for the Potassium/Titanium heat pipe were selected. Figure 9 shows the temperature profile of the heat pipes at the start and finish of the testing period.

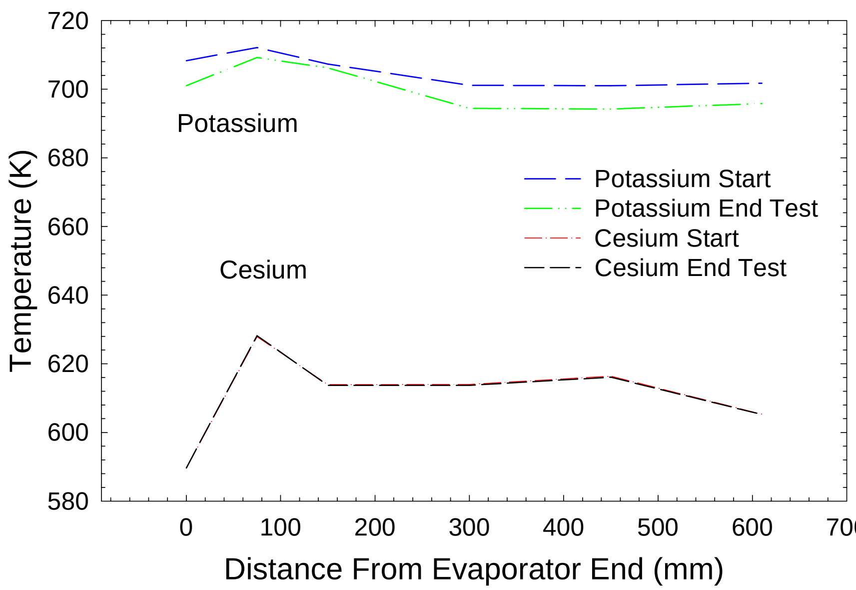

FIGURE 9. Life Test Heat Pipe Temperature Profiles at Start and Finish of 48 Hour Test.

The data shows that there is no sign of thermal degradation. The heat pipes operated as designed and the plan is to continue testing on a follow on program.

IV. Conclusion

Alkali metal heat pipes are ideal radiator elements for large area, high temperature, waste heat rejection radiator panels. Low mass designs, such as thin walled titanium (foil) / cesium or potassium heat pipes encased in a carbon-carbon covering have the potential to meet the mass and performance goals for radiator systems of future nuclear-electric propulsion missions.

At the lower end of the operating temperature range 550K to 740K, in general cesium/titanium heat pipes can be designed to transfer more power than potassium. For heat pipes in the 50 to 75mm diameter range, cesium heat pipes can be designed to transfer 1 to 5 kW per pipe. Above 740K, potassium is a significantly better working fluid than cesium, with a capacity to transfer 5 to 15kW per pipe.

Long term compatibility data for standard wall thickness titanium/cesium and titanium/potassium heat pipes is scarce. Two life test pipes were fabricated and tested for 48 hours with no sign of degradation. These pipes are available for additional long term testing in follow on work. Significant additional development work is necessary, to fully characterize and qualify thin foil/cesium or potassium heat pipes encased in carbon-carbon.

V. Nomenclature

M_v	Vapor Figure of Merit, Kg^2/s^2*m^4
P_v	vapor pressure – N/m^2
ρ_v	vapor density – Kg/m^3
L	latent heat of evaporation – watt-sec/gram
r_v	radius of vapor space – cm
μ_v	viscosity of vapor - $dy\text{-}sec/cm^2$
l_{eff}	effective length of heat pipe – cm
q_{Sonic}	heat flux at the sonic limit, W/m^2
$q_{Viscous}$	heat flux at the viscous limit, W/m^2

VI. Acknowledgements

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VII. References

Busse, C.A., "Theory of Ultimate Heat Transfer Limit of Cylindrical Heat Pipes," *Inst. J. Heat and Mass Transfer. Vol.16*, pp 169-186, (1973).

Dunn, P. D., and Reay, P. A., *Heat Pipes*, Pergamon Press, New York, New York, 1994.

Ernst, D.M., Personal Communication, 2004.

Lundberg, L. B. (1987) "Alkali Metal Heat Pipe Corrosion Phenomena," *VI International Heat Pipe Conference,* Grenoble, France, May 25-28, 1987.

Rosenfeld, J.H., Ernst, D.M., Lindemuth, J.E., Sanzi, J.L., Geng, S.M., and Zuo, J., "An Overview of Long Duration Sodium Life Tests," *Space Technology and Applications International Forum (STAIF-04)*, edited by M. S. El-Genk, American Institute of Physics, Volume 699, Issue 1, Melville, New York, pp. 140-147, 2004.

Sena, J. T., and Merrigan, M.A., "Niobium 1 percent Zirconium/Potassium and Titanium/Potassium Life-Test Heat Pipe Design and Testing," *7th Symposium on Space Nuclear Power Systems*, Albuquerque, NM, Jan. 1990.