Titanium Loop Heat Pipes for Space Nuclear Power Systems

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Abstract. Space nuclear power systems require a radiator to dissipate the waste heat generated during the thermal-to-electric conversion process. A previously conducted radiator trade study showed that radiators with titanium/water Loop Heat Pipes (LHP) have the highest specific power (ratio of heat dissipation to radiator mass) in the temperature range from 300 K to 550 K. A prototype titanium/water LHP was designed and fabricated to operate within this temperature range. The LHP was all titanium, to eliminate incompatibility problems between water and dissimilar metals. The LHP had a 2.54 cm (1 inch) O.D., 20 cm (8 in.) long evaporator wick, and was designed to carry 500 W of heat load. The liquid and vapor lines were roughly 2 m long, typical of the requirements for a spacecraft radiator. The LHP was tested to more than 550 W, at an adverse elevation of 5 cm and an operating temperature of 413 K. This paper describes the details of the titanium/water LHP design, wick development, and titanium LHP fabrication and tests.

Keywords: titanium, loop heat pipe, space radiator systems, high temperature, wick
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INTRODUCTION

Optimization of many Lunar, Martian, and spacecraft nuclear power systems require a radiator that dissipates at least a portion of the waste heat in the 350 K to 550 K temperature range, for which there is no current loop heat pipe (LHP) radiator design. A recent radiator trade study found that space radiators with titanium/water heat pipes or LHPs had the highest specific power in the temperature range from 300 K to 550 K. In addition, titanium LHPs would increase the specific power by roughly 1/3 when compared with titanium heat pipes (Anderson and Bienert, 2005).

Most current LHPs use ammonia as the working fluid, and are fabricated from aluminum and steel, neither of which is compatible with water (e.g. see Ku et al., 2005). Titanium LHPs have three advantages over other LHPs:

- The high strength and low mass of titanium can reduce the radiator mass.
- The C.T.E. of titanium is a better match for carbon-carbon fins then stainless steel.
- Titanium is compatible with a large number of fluids, including ammonia, water, and the alkali metals. It may also be compatible with some of the intermediate temperature fluids such as toluene.

Titanium has a good combination of low density, high strength and good manufacturability. While titanium has a low thermal conductivity, this is actually a benefit in the evaporator design, since it minimizes the heat leak from the evaporator to the compensation chamber. The overall technical objective was to develop and demonstrate titanium LHPs using water as the working fluid. This included the development of titanium LHP wicks, and the fabrication and testing of a titanium/water LHP.

LHP Envelope/Material Combinations

Table 1 lists typical loop heat pipe envelope and working fluid combinations that have been used to date. Most LHPs are fabricated for spacecraft thermal control systems, and use ammonia as the working fluid. Typically, these

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LHPs use an aluminum evaporator, aluminum lines, and a stainless steel compensation chamber. The wick can be fabricated from titanium or nickel.

Ammonia LHPs are typically used at temperatures up to about 340 K. Since the critical temperature for ammonia is 405.5 K, a different fluid is required for higher temperature LHPs.

TABLE 1. Loop Heat Pipe Envelopes and Working Fluids.

Working Fluid	Envelope	Wick	Reference
Cesium	Titanium	Titanium Aluminide	Anderson, Dussinger, and Saraff, (2006)
Ammonia	Aluminum/SS	Titanium	Ku et al., (2005)
Ammonia	Aluminum/SS	Nickel	Ku et al., (2005)
Propylene	Aluminum/SS	Nickel	Rodriguez, Pauken, and Na-Nakornpanom, (2000)
Nitrogen	Stainless Steel	Stainless Steel	Hoang, O'Connell, and Khrustalev, (2003)
Neon	Stainless Steel	Stainless Steel	Hoang et al., (2002)
Hydrogen	Stainless Steel	Stainless Steel	Hoang et al., (2003a)
Helium	Stainless Steel	Stainless Steel	O'Connell, (2007)

Titanium/Water Compatibility

A survey of working fluids in the temperature range from 450 to 700 K found that water was the best working fluid for temperatures below 550 K, with a merit number roughly ten times higher than other intermediate temperature working fluids (Anderson et al., 2004).

Once water was selected as the best working fluid, the next step was to select the envelope and wick material. Aluminum is not compatible with water, and stainless steel heat pipes typically generate large amounts of non-condensable gas. To prevent corrosion, the entire LHP and wick should be fabricated from a single material.

Anderson, Dussinger, and Sarraf (2006) have shown that commercially pure (CP) titanium, titanium alloys, Monel 400, and Monel K500 are all compatible with water at temperatures up to 550 K. A titanium LHP would have a lower mass than a Monel LHP, so titanium was selected for the LHP. CP-titanium was used, due to its greater availability compared with titanium alloys.

An additional advantage of titanium is that it has been used with a large number of working fluids, so titanium LHP could be used over a wide range of temperatures by varying the working fluid. Titanium has been compatible (at least for short periods of time) when used in heat pipes with the following fluids:

- Sodium (Anderson, Dussinger, and Sarraf, 2006)
- Potassium (Lundberg, 1984; Sena and Merrigan, 1990)
- Cesium (Dussinger, Anderson, and Sunada, 2005)
- Titanium Tetrachloride (Tarau et al., 2007)
- Titanium Tetrabromide (Anderson et al., 2007)
- Naphthalene (Groll, 1989 ; Vasil'ev et al., 1988)
- Dowtherm A (Heine, Groll, and Brost, 1984; Groll, 1989)
- Toluene (Heine, Groll, and Brost, 1984; Groll, 1989)
- Water (Heine, Groll, and Brost, 1984; Groll, 1989; Antoniak et al., 1991; Anderson, Dussinger, and Sarraf, 2006)
- Ammonia (Ishizuka, Sasaki, and Miyazaki, 1985)
- Nitrogen (Swanson et al., 1995)

and in Loop Heat Pipes with cesium (Anderson, Dussinger, and Sarraf, 2006), and ammonia (Ku et al., 2005).

TITANIUM/WATER LOOP HEAT PIPE DESIGN AND FABRICATION

The loop heat pipe was designed to operate at 400-500 K and transfer a thermal load of 500W at an adverse elevation of 5cm. The heat pipe envelope was made from Commercially Pure 2 (CP-2) grade titanium, to avoid any incompatibility problems with water and two dissimilar metals. This includes the evaporator, evaporator wick, transport and condenser lines and compensation chamber. The working fluid was water. At these temperatures the maximum working pressure is 26 atmospheres.

Typical aluminum/ammonia LHP's use an integral saddle type evaporator to readily transmit the heat from electronics to the LHP evaporator. An integral saddle is not suitable for a titanium LHP, due to the low thermal conductivity of titanium (~ 20 W/m K, versus ~ 200 W/m K for aluminum). One design consideration was to embed a cylindrical titanium evaporator in an aluminum saddle, although the C.T.E. mismatch between the titanium and aluminum could result in an increased thermal resistance. Another other possibility was to fabricate the LHP with a cylindrical evaporator. The reason is that a spacecraft radiator will likely have LHPs with cylindrical evaporators embedded in the secondary loop. The secondary loop takes the waste heat from the energy conversion equipment, and distributes it to the LHPs in the radiator. Typical designs use water or NaK as the secondary fluid.

The LHP vapor and liquid line lengths were set at approximately 2 m each to be typical of requirements for a spacecraft radiator and are also similar to the lengths for aluminum/ammonia LHPs used for spacecraft thermal control. The lines were coiled, to allow for a more compact and easily testable design. The condenser design used two parallel legs, rather than one serpentine leg. This is more representative of a typical radiator design. Vapor generated in the evaporator travels down the coiled vapor line. The vapor line splits into two condenser tubes, which are embedded in the condenser plate. Liquid from the two condenser lines flows through two porous isolators. The porous isolators prevent vapor bypassing through one of the lines. The liquid then returns to the evaporator through the liquid return line.

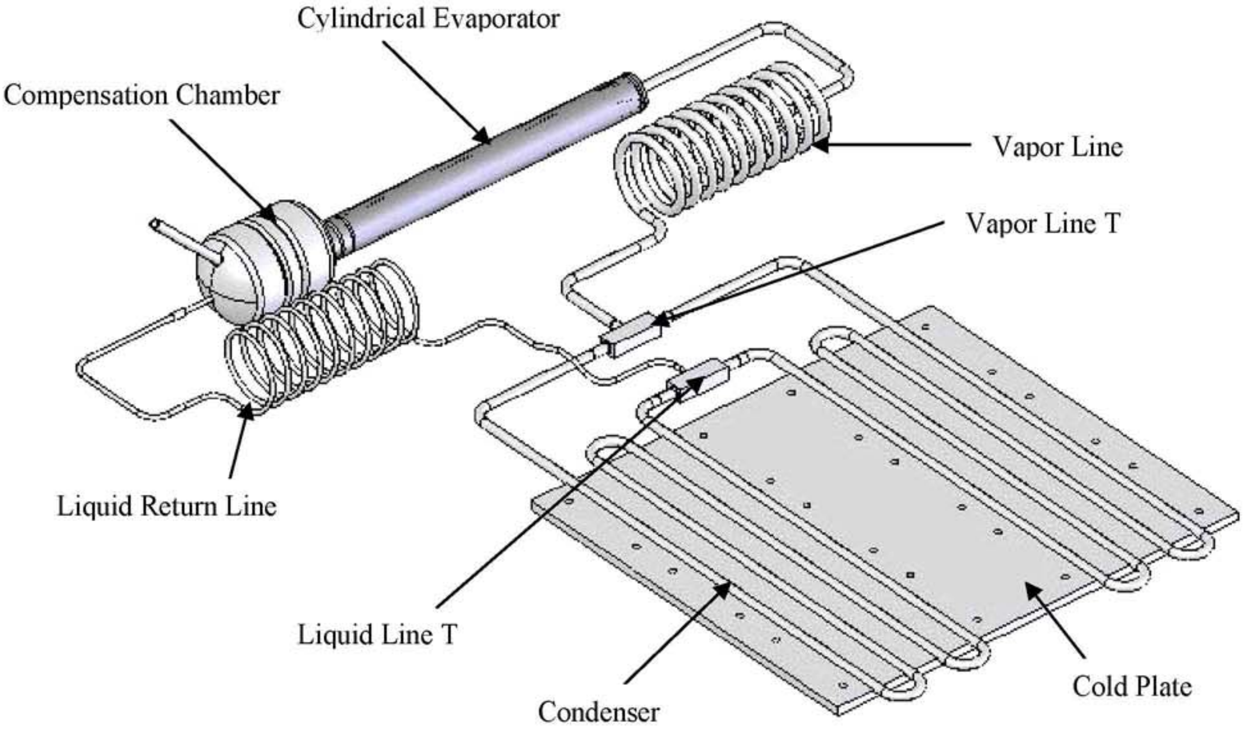

FIGURE 1. Titanium/Water Loop Heat Pipe Layout.

The condenser tubing was designed to be embedded in an aluminum plate. As shown in Figure 1, only the straight portions of the condenser tubing are embedded in the aluminum plate, while the 180° bends are located outside of the plate. The reason for this is the C.T.E. mismatch between the titanium (~ 9 x 10^{-6} m/m K) tubing and the aluminum (~ 20 x 10 $^{-6}$ m/m K) plate. Placing the bends outside the plate allows the bends to accommodate the C.T.E. mismatch, so the only the C.T.E. mismatch of the straight sections need to be considered. The layout of the titanium/water LHP design is shown in Figure 1 and the design parameter details are documented in Table 2.

TABLE 2. Titanium/water loop heat pipe design parameters.

Evaporator Pore Size (μm)	9
Evaporator Permeability (m^2)	1.1 x 10^{-10}
Evaporator ID (mm)	22.9
Evaporator Length (mm)	203
Saddle/Cylinder	Cylindrical Evaporator
Condenser	Two Parallel Legs
Radiator	Tubes embedded in Al Plate
Vapor Line Length (m)	~2
Vapor Line Diameter (mm)	6.35
Liquid Line Length (m)	~2
Liquid Line Diameter (mm)	3.18
Condenser Line Length (m)	~2
Condenser Line Diameter (mm)	6.35
Condenser Plate Dimensions (mm)	305 x 305
Compensation Chamber Diameter (mm)	38.1
Compensation Chamber Length (mm)	22.9

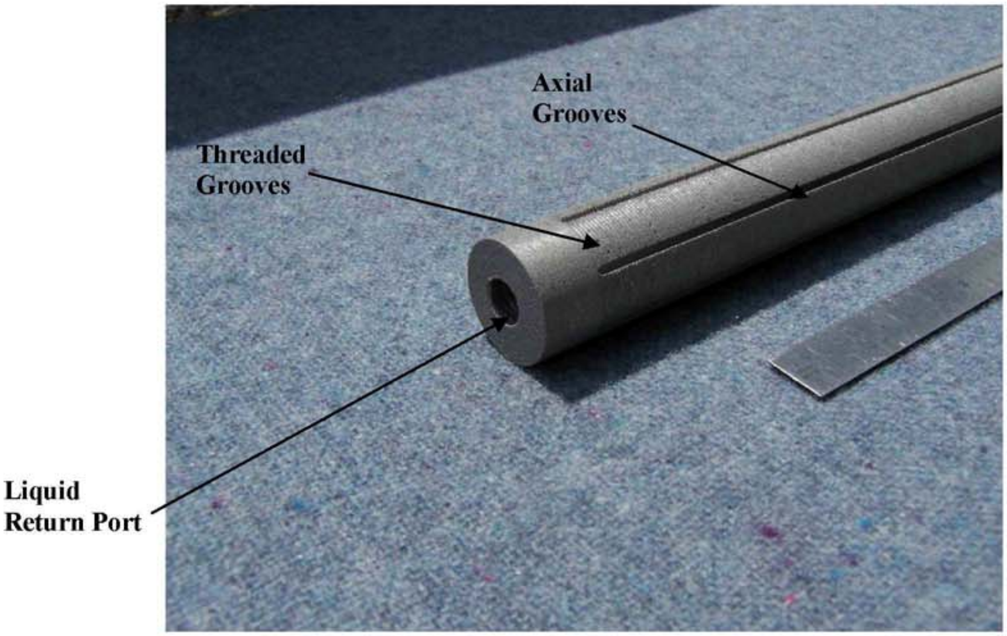

FIGURE 2. Photograph of Machined Titanium Loop Heat Pipe Wick.

Design calculations were performed for the Ti LHP at two different temperatures, 100°C (373 K), and 175 °C (448 K). The following assumptions were made:

- Account for conduction resistance through titanium tube in condenser
- Calculates condensation heat transfer coefficient

- Balances heat leak with returning liquid from condenser
- Assumes adiabatic reservoir and transport lines
- 6.35mm diameter vapor line, 2 meter long
- Dual serpentine condenser, 6.35mm diameter lines, 1.65 m long per leg,
- 3.18mm diameter liquid lines, 2 meter long
- Evaporator conductance of 200 °C/W

The results indicate that at 750 W, there is a roughly 4 K temperature difference between the evaporator interface and the condenser. This gives a maximum heat leak of about 5 W. At the 448 K and the same power loading, there is a roughly 4 K temperature difference between the evaporator interface and the condenser. This gives a maximum heat leak of about 0.2 W.

Titanium/Water LHP Fabrication

The titanium/water LHP was fabricated per the design established. A photograph of the LHP titanium machined wick is shown in Figure 2. The wick had a pore radius of 6.74 μm and a permeability of 3.14 x 10^{-13} m^2. The condenser tubing was bonded to the aluminum plate using Master Bond's EP45HTAN epoxy. A photograph of the fully assembled LHP is shown in Figure 3.

FIGURE 3. Photograph of the fully assembled titanium/water LHP.

TITANIUM/WATER LHP TESTING

The fully assembled LHP was instrumented with a total of twenty-four (24) thermocouples to monitor performance. A water cooled heat sink was bonded to the backside of the condenser plate. An aluminum heater block with integral cartridge heaters was used for the thermal power input. The thermocouple locations are shown in Figures 4 and 5. Table 3 lists the thermocouples and their locations. Testing began by turning on the condenser water and allow the assembly to reach steady state. Approximately 100-300 W was applied to the heaters and the performance monitored. Power was increased in approximate increment in steps of ~100W, reaching steady state at each power level.

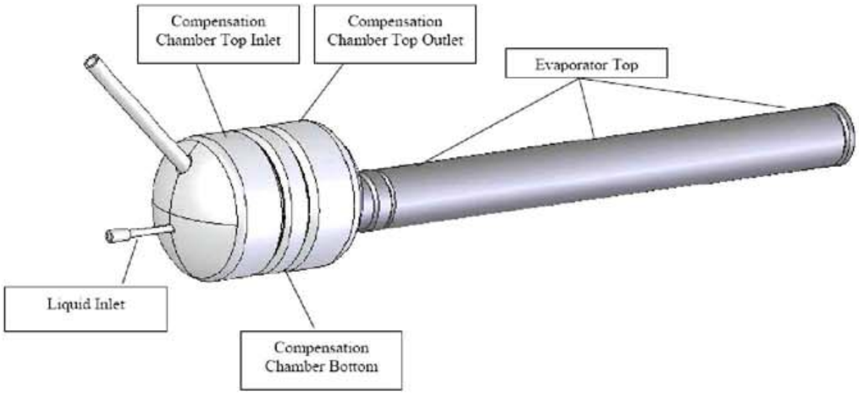

FIGURE 4. Evaporator and compensation chamber thermocouple locations.

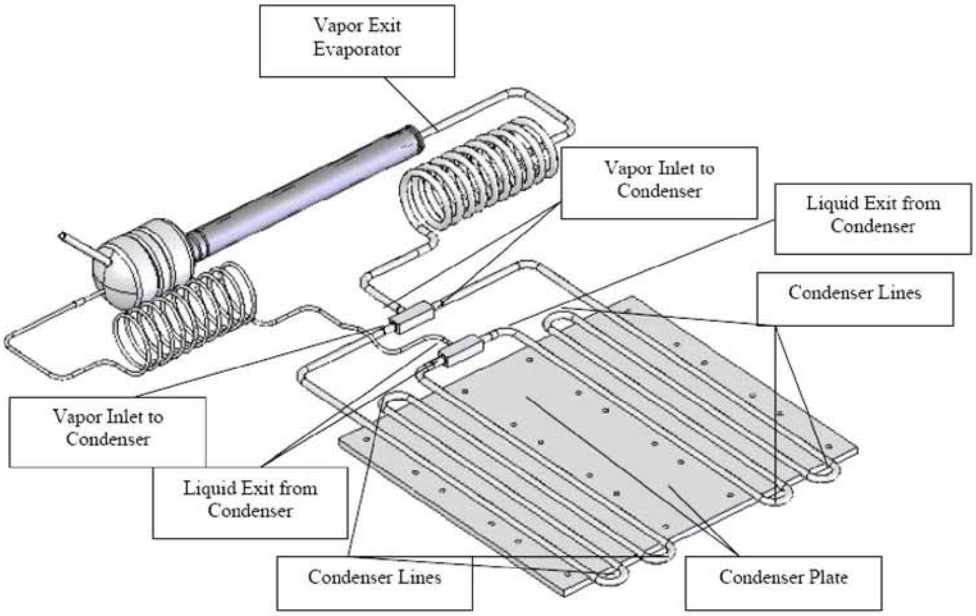

FIGURE 5. LHP Thermocouple locations.

TEST RESULTS AND DISCUSSION

Initial testing began at low powers (200-300W) to process the LHP and remove any non-condensable gas. The water cooled cold plate was de-coupled from the LHP condenser by forming a small air gap between the two surfaces to raise the temperature of the entire LHP. The cold plate water was re-circulated as well to raise the LHP condenser. Data was recorded at various conditions. The performance data for a given thermal run is shown in Figure 6. The data presented is near steady state conditions and details temperature and power within a 10 minute window. The data plotted includes the LHP temperature profile throughout the loop as well as the thermal power transport capability. For this case the LHP vapor temperature was approximately 413 K, while the evaporator temperature was approximately 473 K, the difference possibly being the interface between the evaporator block and the thermocouples. The evaporator thermocouples are sheathed and are inserted into holes within the block. It can be seen that with the exception of the vapor exit temperature, the remaining loop was within several degrees: the temperature of the loop entering the "T" at the beginning of the condenser was 413.6 K and the liquid return was 411.5 K. This corresponds well with the LHP prediction models developed by ACT. The vapor exiting the evaporator measured 430 K. Probing the length of the transport line indicated a temperature drop to near the 413 K "T" temperature after several centimeters. At the 413 K the LHP was transporting approximately 590 Watts: 21.2 K water delta-T at 400 cm^3/minute water flow rate.

TABLE 3. Thermocouple instrumentation.

Thermocouple Location	Quantity	Type
Evaporator Top	3	Type T Sheath
Compensation Chamber Top In	1	Type T Bare Wire
Compensation Chamber Top Out	1	Type T Bare Wire
Compensation Chamber Bottom	1	Type T Bare Wire
Liquid Return Line	1	Type T Bare Wire
Vapor Exit Line	1	Type T Bare Wire
Vapor Entrance to Condenser	3	Type T Bare Wire
Condenser Loop	6	Type T Bare Wire
Condenser Panel	2	Type T Bare Wire
Liquid Exit Condenser	3	Type T Bare Wire
Cold Plate Fluid Inlet	1	Type T Sheath
Cold Plate Fluid Outlet	1	Type T Sheath

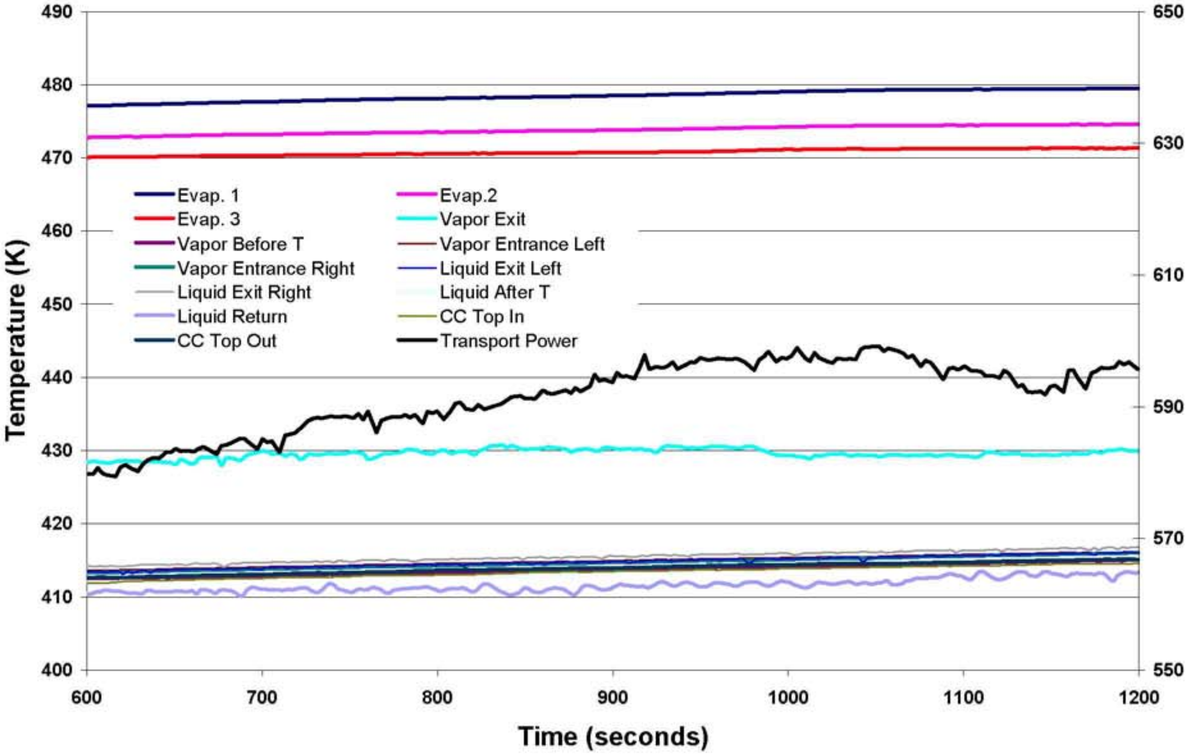

FIGURE 6. Test results from the titanium/water LHP. The LHP carried 590 W at 413 K.

Before titanium/water loop heat pipes can be used for spacecraft thermal control, further work is required on the evaporator and condenser interfaces. A heat exchanger must be designed to transfer heat into the LHP evaporator. Siamidis (2006) proposed a heat exchanger design for a titanium/water heat pipe radiator that used graphite foam as the thermal interface between the heat pipes and secondary loop from the energy conversion equipment. This design could be adapted to a LHP radiator.

In addition, a high temperature radiator panel must be developed. In a typical aluminum/ammonia LHP, the aluminum condenser tubing has flanges to transfer heat to the aluminum radiator fins. In contrast, titanium flanges are not practical, due to titanium's low thermal conductivity. Instead, a thermal interface is required to transfer heat from the round titanium tube to the radiator. In addition, a high temperature radiator will use high conductivity fins, such as carbon-carbon, or graphite fiber reinforced composite. The difference in C.T.E. between the titanium and the fin must be accommodated over the operating range of the radiator.

One potential radiator design is shown in Figure 7. The design uses graphite foam saddles as the thermal interface between the condenser tubing and the fins. The fins are fabricated from a high temperature, high conductivity material such as Graphite Fiber Reinforced Composites (GFRC's) or carbon-carbon. The graphite foam saddles also accommodate the C.T.E. mismatch. This design has already been fabricated and tested for titanium/water heat pipe radiators at temperatures up to 530 K (Anderson, Sarraf, Garner, and Barth, 2006).

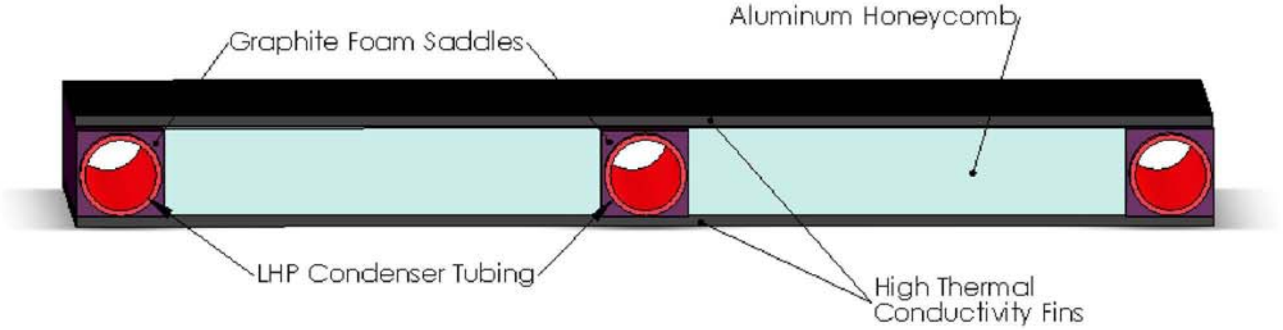

FIGURE 7. Cutaway Section Through a High Temperature Titanium/Water Radiator.

CONCLUSION

Space nuclear power systems require a radiator to dissipate the waste heat generated during the thermal-to-electric conversion process. For the temperature range from 300 K to 550 K, water is the best working fluid. A titanium LHP will have a lower mass than other materials known to be compatible with water, such as Monel 400. An additional advantage of titanium is that it is know to be compatible with many other fluids, including alkali metals, halides, organic working fluids, ammonia, and nitrogen. A titanium LHP can be used over a very wide temperature range, simply by switching the working fluid.

A titanium/water LHP was designed and fabricated. The LHP is all titanium, to eliminate incompatibility problems between water and dissimilar metals. The LHP has a 2.54 cm (1 inch) O.D., wick, 20 cm (8 in. long), and was designed to carry 500 W of power. The liquid and vapor lines are roughly 2 m long. This length was chosen, because it is believed to be typical of the requirements for a spacecraft radiator. It is also similar to the lengths for aluminum/ammonia LHPs used for spacecraft thermal control. The LHP was charged and tested, and carried over 550 W, at an adverse elevation of 5 cm.

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