

Viability of Loop Heat Pipes for Space Solar Power Applications

Jane Baumann
C&R Technologies, Inc.

Suraj Rawal
Lockheed Martin Space System Company
Astronautics Group
Denver, Colorado

ABSTRACT

The primary thermal management issue associated with Space Solar Power (SSP) is the need to acquire, transport and reject waste heat loads, on the order of 3.8 GW, from the transmitter to remote radiator locations. Previous conceptual studies have focused on transporting these loads to large remote radiators. These concepts assumed the ability to transport the heat either passively or mechanical over large transport distances of 100 meters or more.

A recent study, Innovative Deployable Radiators (IDR) for Space Solar Power, focused directly on the thermal control issues. This study has produced new concepts which break the system into small clusters of radiators which have more reasonable transport lengths of 1-2 meters. This study considers a system based on the klystron conversion technologies with a system architecture based on cluster radiators located near the waste heat source. The study evaluated various fluids for use between 50 and 500°C to determine their viability for use in LHPs. The

evaluation considered fluid properties in addition to material compatibility with traditional LHP wick and containment materials.

The results of this study have provided new insight regarding the feasibility and limitations of LHPs for Space Solar Power applications. New technology development areas have been identified for both traditional LHPs and liquid metal LHPs.

INTRODUCTION

The Integrated Symmetrical Concept (ICS) baselined for this study is depicted in Figure 1. In this concept, 48 primary mirrors focus solar radiation to two solar arrays. The total solar energy collected is 13.377 GW. The concentration ratio is 3.8:1. The solar arrays generate 4.414 GW of electricity, which is converted to radio-frequency energy by klystrons on the transmitter. The diameter of the solar arrays is 1.55 km each. The diameter of the transmitter is 1 km.

Solid state conversion technologies produce waste heat with a source temperature of 100°C, versus klystrons which produce waste heat at multiple

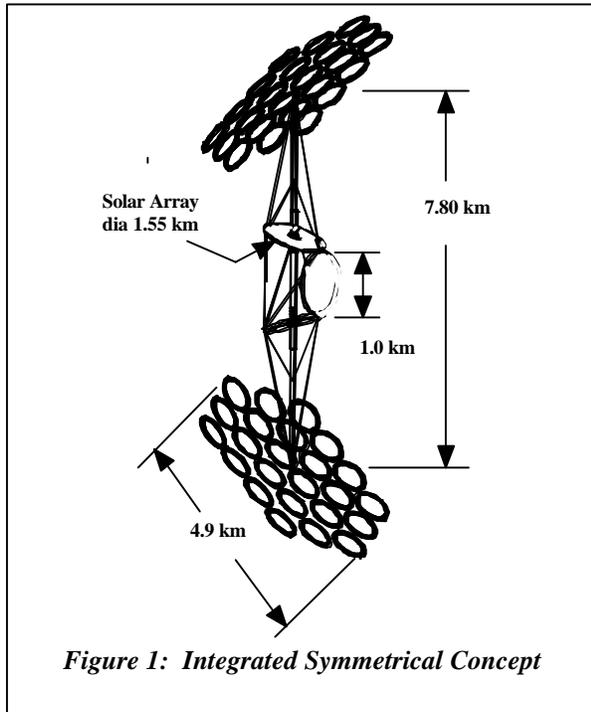


Figure 1: Integrated Symmetrical Concept

source temperatures of 50, 125, 300, and 500°C. The klystrons architectures are preferred¹ due to the higher conversion and heat rejections efficiencies. Estimates of total radiator area for the solids state technology is in the order of 2.3 million m² versus the klystron system which requires 0.7 million m².

Previous conceptual designs have focused on transporting the waste heat loads to remote radiators far from the view of the solar arrays. These concepts required active thermal control for acquisition and transport, such as mechanical or

capillary pumped heat transport loops with transport distances of 100 meters or more. Capillary loops are preferred from the aspect of long life and low maintenance. Two types of capillary loops are available. The traditional capillary pumped loop and a loop heat pipe.

The thermal design approach selected for the IDR contract was to create a modular system (shown in Figure 2) to support maintainability and eliminate the design hurdles of large loads and very long transport distances for the thermal control system. Each radiator would be dedicated for heat rejection at a specific temperature level and would be deployable as depicted in Figure 3. This concept reduces the transport load down the order of 1kW per loop with transport distances of 1-2 meters.

The primary purposes of this study was to determine the feasibility of using LHP technology for managing the waste heat and to identify future technology development if required. To meet this goal, several working fluids were considered initially. The study reduced the fluid to a few strong candidates and then proceeded with full thermal/fluid analyses of the LHPs using SINDA/FLUINT and its graphical user interface SinapsPlus®.

LHP DESIGN

As previously stated these system architectures require an active means of acquiring and

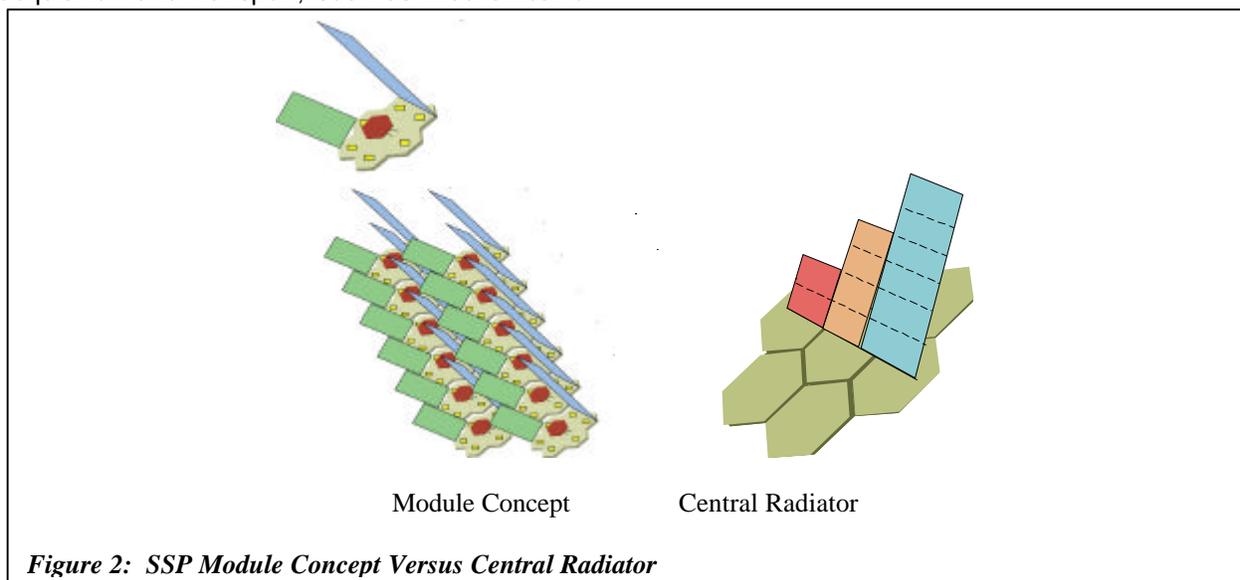


Figure 2: SSP Module Concept Versus Central Radiator

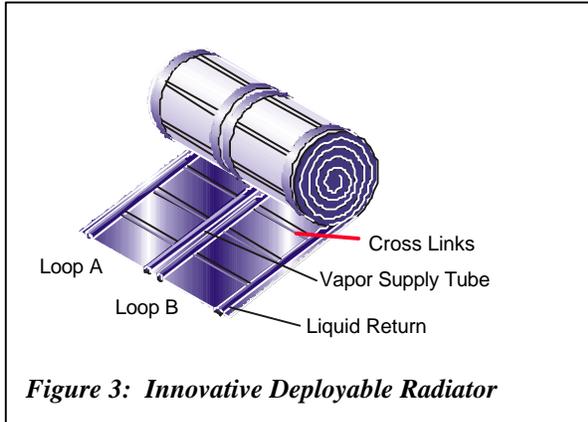


Figure 3: Innovative Deployable Radiator

transporting the waste heat from the transmitter to the deployable radiators. Previous SSP studies have considered mechanically pumped loops, liquid droplet radiators, and loop heat pipes. The SSP architecture has a 40 year life which makes mechanically pumped systems undesirable due to maintenance and pump reliability.

The development of liquid droplet radiators has yet to transition beyond development testing. The mass of the overall liquid management system and the loss of fluid through dispersion reduces the feasibility of this type of thermal management.

The traditional capillary pumped loop (CPL) with an off-line control reservoir is ideal for isothermalization and acquisition of waste heat from multiple heat sources such as the central radiator concept in Figure 2. This traditional CPL technology has witnessed failures associated with the reliability of start up, however these issues have been resolved. Despite resolution the technology CPLs have been slow to regain popularity. The major obstacle for CPLs becomes the wick material. CPLs require low conductivity wicks which tend to have low pumping capacity. The 15 μm pore radius associated with a polyethylene wick is insufficient to support the transport distances and adverse elevations required for the SSP application. Metal wicks are capable of providing an order of magnitude more pumping capacity, however the increased conduction through the wick adversely effects the subcooling required for operation (resulting in larger radiator area) and reduces the overall reliability of the CPL.

Loop heat pipes², currently being baselined on several satellite missions, are similar to the traditional CPL. Unlike the CPL, an LHP has an

inline reservoir called a compensation chamber or accumulator. LHPs are limited to the amount of heat a single evaporator can acquire which is about 1 kilowatt. Some development has been performed on multi-evaporator LHPs but uniform fluid management is difficult³. When considering a modular approach to SSP, LHPs become capable of handling the required heat loads. Traditionally, LHPs have been used for room temperature applications. The expansion to higher temperatures is feasible but will require alternate working fluids. The remainder of this report will focus on the evaluation of alternative fluids and associated development issues.

WORKING FLUIDS

The SSP application of LHPs has four temperature regimes to be addressed: 50, 125, 300 and 500°C. When evaluating alternative working fluids the key properties to be considered are surface tension, vapor pressure, liquid conductivity and material compatibility with the wick materials and the containment vessel. Table 3 provides a list of candidate working fluids and their temperatures ranges.

It is evident from this chart that freezing of the working fluid will be an issue to overcome in this development. The SSP concept will have a 72 minute eclipse period in which no power is being generated. During this period, guard heaters on transport lines will be required. The require heat will be minimized by returning the radiator to a stowed position. Ammonia, toluene or water are the best candidates for the low temperature operation although water has material compatibility issues. Water reacts with most traditional LHP containment and wick materials resulting in the generation of non-condensable gases (NCG). Some NCG generation is tolerable in LHPs, unlike traditional heat pipes, however insufficient data exists to characterize the amount of gas generation expected over a 40 year life. Ammonia has substantial heritage at 20°C operating range. Limited work has been performed at 50°C.

For the 125°C application only two fluids are viable, water and toluene. There have been no previous efforts to evaluate toluene as a loop heat pipe working fluid but preliminary evaluations

show it may be a good candidate although it has a low heat of vaporization when compared to water. Water is the only viable candidate for the 300°C application due to the toxicity of mercury despite its incompatibility to standard wicks and containment materials. The 500°C application will require the development of cesium liquid metal LHPs. No published work has been performed in this area.

corrosion of the container and/or wick materials, and the generation of non-condensable gases (NCGs) from outgassing or chemical reactions. Unlike heat pipes, LHPs are tolerant to some amount of NCG generation however the expected mass of generated gas must be quantifiable. Typically the gas will come out of solution in the compensation chamber. This requires that the compensation chamber be properly sized to contain the gas volume expected at end of life.

MATERIAL COMPATABILITY

A distinguishing factor in the selection of a working fluid for an LHP is the compatibility with other materials in the system such as the evaporator wick and the containment vessel. With a 40 year design life two factors must be considered,

Although no NCG generation tests have been previously performed on toluene, it is reasonable to expect the compatibility to be similar to other hydrocarbons. In general hydrocarbons have been found to be compatible with most LHP materials (stainless steel, aluminum, nickel, titanium).

Table 1: Candidate Working Fluids

Working Fluid	Range °C	Application				Comments
		50°C	125°C	300°C	500°C	
Propylene	-120 to 80	X				Low surface tension, reduced pumping capacity
Ammonia	-70 to 125	X				Will freeze during eclipse
Toluene	-90 to 150	X	X			Will freeze during eclipse
Water	0 to 300	X	X	X		Will freeze during eclipse, poor material compatibility
Mercury	47* to 1000			X	X	Toxic, liquid metal development required
Cesium	28* to 800				X	Liquid metal development required
Potassium	63* to 1300					Liquid metal development required

* These are the freezing points. The lower limit for operation as an LHP is much higher.

Extensive compatibility testing has been performed on water for heat pipe applications. Water has been shown to be incompatible with aluminum and sensitive to the cleaning of stainless steel. Typically water heat pipes use copper as the containment vessel. Since this testing has historically supported heat pipe development, little extended life testing has been performed to fully characterize the NCG generation. Since heat pipes are not tolerant to NCG, compatibility testing was typically stopped as soon as NCG was evident.

FLUID PROPERTIES

Capillary Pumping Limit

The capillary pressure drop across the wick of the LHP is defined by the pore radius of the wick (r), the surface tension of the fluid (σ), and the contact angle between the fluid and the wick (θ) in accordance with the following equation.

$$\Delta P = \frac{2\sigma \cos \theta}{r}$$

Given a predefined wick material and pore radius, a fluid capable of providing sufficient capillary pressure to overcome long transport lines and adverse elevations must have a high surface tension. The surface tension for propylene and ammonia drop off rapidly between 77°C and 125°C making both these fluids unacceptable for the 125°C and above applications.

Vapor Pressure

The vapor pressure of the fluid at the maximum expected operating/non-operating temperature is critical for sizing the containment vessel. The vapor pressure at the maximum expected temperature is referred to as the maximum expected operating pressure (MEOP) to which the vessel must be sized for proof and burst. Traditionally LHP components have been sized for MEOPs associated with ammonia at 80°C. Toluene and water have significantly lower vapor pressures than ammonia at 80°C. Therefore, sizing of LHP components for either of these alternative fluids should not be an issue.

Too low of a vapor pressure is also a concern for LHPs. If the working fluid vapor pressure is too low, the required pressure drop across the wick to provide pumping in the system cannot be achieved.

Liquid Conductivity

The liquid thermal conductivity has two significant effects on the performance of an LHP. Low liquid conductivity reduces the heat transfer coefficient in the evaporator thus limiting the transport capacity. Secondly, low thermal conductivity reduces the LHP temperature differential by reducing wick back conduction.

THERMAL/FLUID ANALYSIS

Thermal/fluid analyses were performed using SINDA/FLUINT and its graphical user interface SinapsPlus®. SINDA/FLUINT has been used extensively over the past 15 years to model similar systems with ammonia as the working fluid. Two primary objectives were set for the analysis effort:

- 1) To characterize the ability of the LHP to maintain temperatures for the given strawman design.
- 2) To quantify the pressure drop across the loop and demonstrate 20% margin on the wick pumping capacity.

The secondary objective of the analysis was to identify any design concerns and recommend areas for future technology development.

Details of the model are available in reference 4.

STRAWMAN DESIGN

The strawman LHP design, summarized in Table 2, focused on managing the waste heat associated with the 398°K (125°C) source temperature.

Table 2: Strawman Requirements

Heat Load	1 kW
Control Temp	398°K
Evaporator Length	12 inches
Radiator Area	0.67 meter
Transport Length	1 meter
Environment	173°K to 293°K
Adverse Tilt in 1-g	0.75 meter
Transport lines	wall material 316 stainless OD/ID: 0.25/0.18 inch
Condenser	wall material 316 stainless OD/ID: 0.094/0.078 inch 8 parallel legs

TOLUENE ANALYSIS

As a working fluid, water is well characterized as a SINDA/FLUINT standard library fluid. However little data was available for toluene. A toluene fluid property data was developed for this study based on property data purchased from NIST. These properties are considered, by NIST, to be unverified below 293°K.

Degradation of Heat Transfer Coefficient

The toluene model includes a degraded heat transfer coefficient in the evaporator due to the low liquid conductivity. The observed coefficient for propylene, also a hydrocarbon with a very similar liquid conductivity (roughly 1/6 that of ammonia), is about 55% of the observed coefficient for ammonia. The effect of the decreased heat transfer coefficient is a slight increase in the temperature differential across the loop.

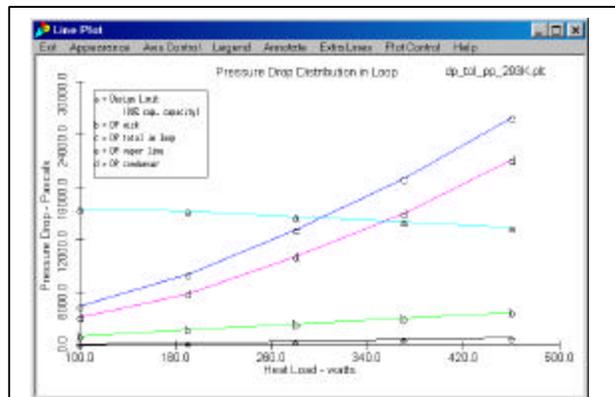
LHP Pressure Drop

LHPs use a porous wick structure to passively pump the working fluid through the loop. The

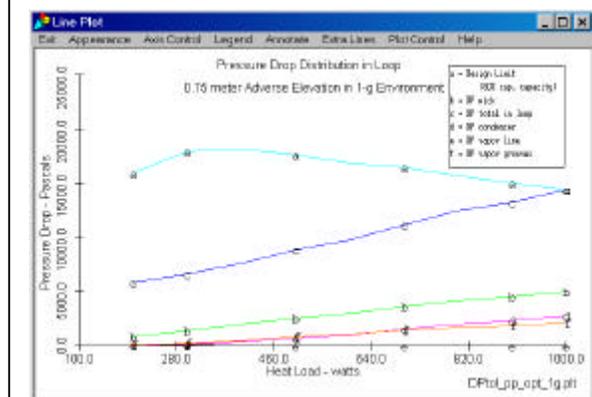
wicking capacity is the maximum pressure drop produced across the wick for a given working fluid. This wicking capacity must overcome the pressure drop through the loop and internal to the wick. Figure 4 depicts a summary of 0-g pressure drops for the strawman LHP using Toluene as the working fluid. The curve labeled “a” represents the capillary design limit (80%) of the wick capacity. For the initial strawman design the design limit is exceeded for heat loads above 300W.

A series of sensitivity analyses were performed to assess how the pressure drop can be reduced. The results identified the need to:

- 1) Increase the vapor line diameter from the strawman design of 0.25 inch to 0.5 inch
- 2) Increase the liquid line diameter from 0.25 to 0.375 inch
- 3) Increase the condenser legs to 10



Initial Pressure Drop Profile



Final Pressure Drop Profile

Figure 4: Toluene System Pressure Summary

These changes produce a design capable of sufficiently maintaining the required capillary margin for heat loads up to 1000W. The lower portion of Figure 4 depicts the resulting pressure drop summary for the revised toluene LHP.

Predicted LHP Performance

The SINDA/FLUINT models were used to characterize the 0-g performance of the modified loop over the full span of potential sink temperatures. The requirement for the LHP is to maintain the source temperature at 398°K in the cold sink condition. Since the sink temperature is uncertain, a parametric analysis was performed.

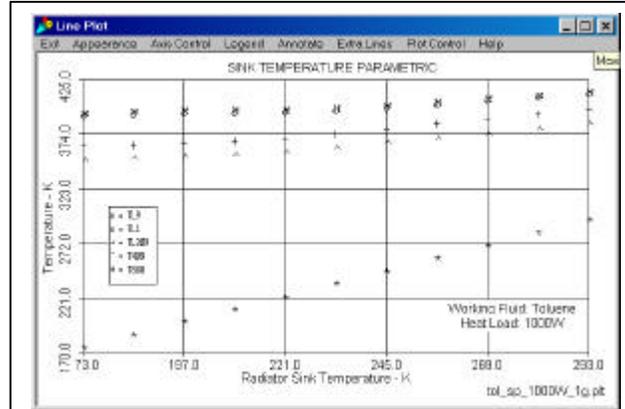
The upper portion of Figure 5 depicts the source temperature as a function of sink temperature for the LHP. This chart shows that the LHP is capable of maintaining the source below the required 398°K at the cold sink of 173°K (-100°C) in a 1-g environment. A summary of temperatures is provided in the table within Figure 5. The minimum expected fluid temperature of 363°K is well above the freezing point of 178°K for toluene. However, it should be noted that if the load is reduced or turn off during an eclipse, the working fluid can potentially freeze and either guard heaters will be required or a freeze tolerant design developed.

The maximum sink temperature is representative of ambient 1-g testing. The toluene design exceeds the 398°K maximum source temperature requirement by 17°K.

WATER ANALYSIS

In general water is considered incompatible with traditional LHP materials (stainless, nickel, aluminum). Contact with these materials will result in the generation of non-condensable gases in the working fluid and possible corrosion of materials. The following options are available if the use of water as the working fluid is desired.

- 1) *Use of an all copper system.* Although copper wicks are not currently available, they can be developed, however the high conductance of copper will significantly degrade the performance of the LHP.



	Hot Sink	Cold Sink
Sink Temp	293K	173K
Source Temp	415K	395K
Loop Saturation	413K	392K
Min. Fluid Temp	398K	363K
Min. Radiator	382K	348K

Figure 5: Toluene Sink Temperature Parametric

- 2) *Size the system to accept NCG generation.* Unlike traditional heat pipes, LHPs are tolerant of NCG in the working fluid. NCG is expected to accumulate in the compensation chamber. The compensation chamber volume must increase to contain NCG.

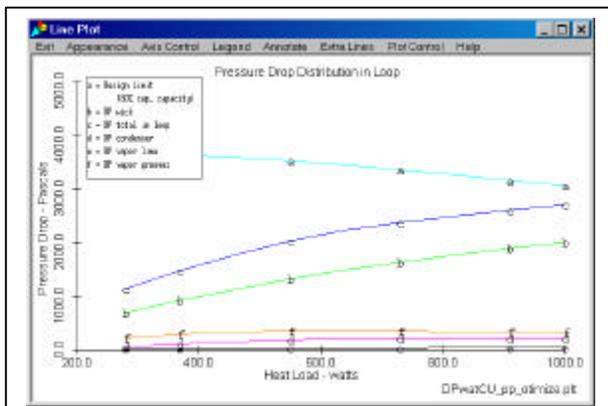
Table 2 provides a comparison of water and toluene as working fluids. The surface tension of toluene restricts the lower limit on transport diameters and lengths. Water on the other hand has minimal restrictions in this area. In addition, the low heat of vaporization and liquid density limits the heat transport capacity for toluene.

Table 3: Working Fluid Comparison

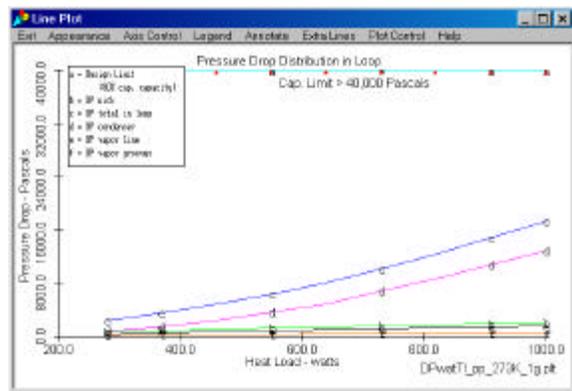
Water	Toluene
temperature range: 273-647	temperature range: 178-593 K
high heat of vaporization	low heat of vaporization
high surface tension	moderate surface tension
higher liquid density	

Pressure Drop and Predicted Performance

A preliminary analysis was performed using an all copper system with water as the working fluid. The availability of copper as a wick material is uncertain and the following properties are an



Copper Wick Pressure Drop Summary



Copper Wick Pressure Drop Summary

Figure 6: Water Pressure Drop Summary

estimate of what could be developed.

Wick Material: Copper

- conductivity: 386 W/mK
- pore radius: 25.0 μm
- permeability: 2.5 E-14
- porosity: 45%

The top of Figure 6 depicts the pressure drop summary for the copper water analysis. In order to provide design margin on the capillary limit, the condenser lines needed to be increased from 0.094 inch to 0.125 inch diameter.

A similar analysis was performed using a titanium wick with the following properties:

Wick Material: Titanium

- conductivity: 20 W/mK
- pore radius: 2.0 μm
- permeability: 2.5 E-14
- porosity: 40%

The resulting pressure drops (lower portion of Figure 6) show significant margins on the capillary limit for the strawman design with only two parallel condenser legs. Based on these performance curves and the availability of the wick materials, the titanium is preferred. However titanium is not compatible with a copper containment system due to thermal expansion mismatch. Hence, NCG becomes an issue with the titanium wick design.

The performance of water LHP with a titanium wick is summarized in Figure 7. In summary the water system is not quite capable of maintaining the source temperature below the 398°K limit. The water loop exceeds the limit by 10° due to the fact that water has a liquid conductivity 6 times that of toluene significantly increasing the wick back conduction in the system. In addition, the minimum fluid temperature is only 5° above the freezing point of water - too close for comfort. Further sensitivity analyses performed identified any increase in radiator area to meet the source temperature limit of 398°K will result in the working fluid freezing.

CONCLUSIONS

In summary toluene appears to be the best fluid selection for the 125°C application while water is the best choice for the 300°C application. Toluene is expected to be compatible with most the traditional LHP materials (stainless, aluminum, and nickel.) Toluene has the major disadvantage of a low surface tension resulting in a low capillary limit for the system. This places the following restrictions on the condenser and transport sections of the loop heat pipe assuming a 20% design margin on wicking limit.

- 1) The condenser line can be as small as 0.078 inch I.D. however this requires a minimum of 10 parallel lines no longer than 0.83 meters in length. The condenser lines are to be evenly spaced 0.1 meter on center.
- 2) The toluene also requires the vapor line to be a minimum inner diameter of 0.484 inch with the liquid return line no smaller than 0.359 inch I.D.
- 3) The transport section can be no longer than one meter.

The analyses also considered an extrapolation to the higher operational temperature of 300°C. The toluene will not be a candidate due to the degradation of fluid properties (near critical temperature.) The water becomes a very good candidate at these temperatures for two reasons. First the decrease in liquid density and heat of vaporization at the higher temperature results in an increased flow rate offsetting the wick back conduction hence reducing the minimum subcooling required for the system. Secondly, the higher operational temperature moves the minimum temperature away from the liquid freezing point and results in an 84% reduction in radiator area.

TECHNOLOGY DEVELOPMENT ISSUES

The following technology issues are recommended for future development activities.

- 1) Further application of a toluene loop for the SSP application would require

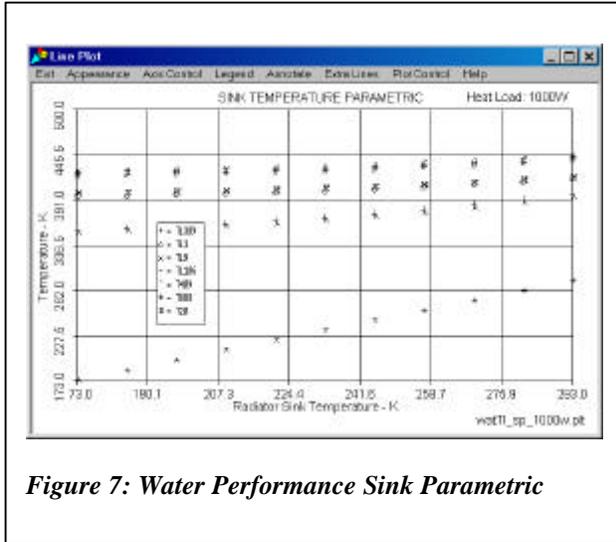


Figure 7: Water Performance Sink Parametric

Extrapolation to 300C Source Temperatures

Analyses were performed to evaluate water as a potential working fluid for a source temperature of 573°K (300°C) using the titanium wick option. The performance as a function of sink temperature is depicted in Figure 8.

The analysis showed that the wick back conduction problem is reduced at the higher source temperature due to the increased flow rate required to offset a decrease in heat of vaporization at the higher temperatures. In addition, the radiator can be reduced. The water appears to be a viable fluid for the 573°K source temperature application.

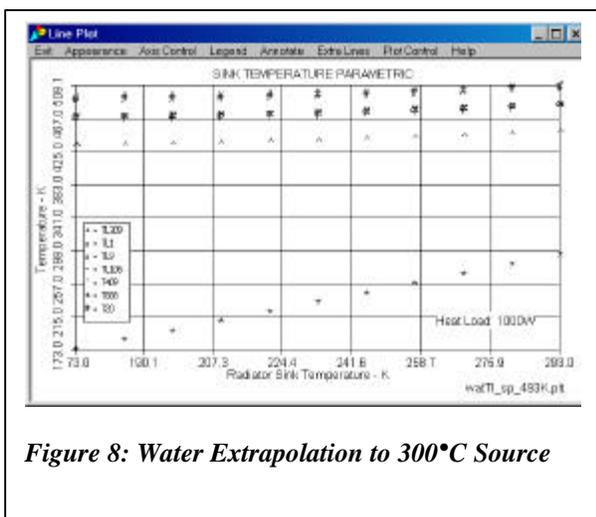


Figure 8: Water Extrapolation to 300°C Source

additional evaporator development activities. Current evaporator designs have focused on the room temperature (ammonia) applications. Thus present manufacturing methods and wick materials experience a significant degradation in heat transfer coefficients at 125C due to thermal expansions.

- 2) Test programs need to be initiated to demonstrate the viability of both toluene and water at the 125°C source temperature.
- 3) Long term compatibility testing should be performed for toluene using the standard LHP materials. Materials to consider are stainless, aluminum and titanium.
- 4) Long term gas generation for water needs to be further characterized for the 300°C application. This will require long term NCG testing to provide sufficient data a prediction for 40 year gas generation. Materials to consider are stainless, aluminum and titanium.
- 5) More efforts need to be initiated in the area of liquid metal LHPs; in particular cesium and potassium. To date limited development has been performed in this area.
- 6) The lowest source temperature of 50°C is above the heritage of ammonia LHPs. It is recommended that development testing be performed at this increased temperature to demonstrated the viability

of ammonia and identify and performance degradation due to hardware or fluid properties.

CONTACT INFORMATION

For more information on the modeling tools (SINDA/FLUINT and SinapsPlus) or the development of analytical methods for modeling two-phase heat transport loops please contact C&R Technologies through their webpage at www.crtech.com.

The authors can be contacted directly via email: Jane Baumann, jane@crtech.com and Dr. Suraj Rawal, suraj.p.rawal@lmco.com.

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