SWALES AEROSPACE

CONTRACT NO.: 400023074
TASK NO.: 00551.02

High Temperature HPs Development for Rankine NEP Phase 2

SAI-RPT-706

SEPTEMBER 22, 2005
REVISION -

Prepared by:
SWALES AEROSPACE
5050 Powder Mill Road
BELTSVILLE, MD 20705

SIGNATURE PAGE

This is a controlled document. Any changes require the approval of the Configuration Control Board.

Written by Michael Nikitkin 9/30/05

Michael Nikitkin, Thermal Technologist Date

Reviewed by: David Wolf Sr. 9/30/05

Dave Wolf, Chief Thermal Technologist Date

Project Manager: Dan Mark for S. Krein 9/30/05

Steve Krein Date

DOCUMENT CHANGE RECORD

REVISION	DESCRIPTION	DATE	APPROVAL
-	Initial Release		

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

1.0 Introduction

The effort described in this report was performed under contract — Rankine Nuclear Electric Propulsion (NEP) Phase II, with Oak Ridge National Laboratory. The goal of the effort was to develop and produce prototype heat pipes (HPs) for the Rankine space-based nuclear power conversion cycle. The successful completion of Phase I of the project was devoted to thermal control system trade-offs and concept determination and has resulted in selection of the HP-based Heat Rejection System (HRS) for further development.

Swales started the Phase II activities with high-temperature potassium HP development in 2004. However in early summer 2005, per the direction from NASA Headquarters, all activities related to the Swales-Oak Ridge contract were stopped.

This report summarizes the main results achieved during the Rankine NEP Phase II activity period.

The Rankine cycle heat rejection system architecture is based on the utilization of just one basic component – a HP with the condenser of the Rankine loop cycle integrated with the HP evaporator. Therefore, Phase II of the program focused on the development, improvement, demonstration, and manufacturability of this component.

There were some issues that needed to be addressed during Phase II; they are mostly related to the performance and reliable and stable operation of the high-temperature potassium HP with a Nb-1%Zr body, and its manufacturability and testability.

Further HP development for high-temperature applications will be accompanied with testing the development HP at lower temperatures with water as a surrogate fluid. The low-temperature testing is needed to verify component design and system operation prior to charging and testing with potassium. It is planned that the HP would be charged with potassium and tested at Oak Ridge National Laboratory. Therefore, the surrogate fluid tests would serve as acceptance tests for the HP prior to shipping to Oak Ridge.

The list of the tasks, that Swales was able to address prior to the program closure are presented in Table 1.

TABLE 1. HP TASKS

Task #	Name
I	Literature review
II	Compatibility of the HP material (body, wick, endcaps, welding) and working fluid
III	Wick structure, study of available options, and selection of top three choices
	Design of the HP (design for potassium and check design performance for water)

2.0 Task I. Literature Review:

The first step in the effort was to perform an extensive literature search to identify important aspects related to design, manufacture and operation of high-temperature HPs. Performance issues related to the specific materials used in the HP design were also investigated. This section includes some highlights of the literature search.

Potassium HPs

One of the first potassium HP studies was performed by General Electric Co. in 1971 (Gerrels and Killen). A structurally integrated vapor HP radiator was successfully constructed and evaluated as a potential candidate for rejecting waste heat from the potassium Rankine cycle power plant. Several vapor chamber fin geometries were evaluated. All geometries were constructed from stainless steel.

In 1986, Prenger e. al. conducted experiments with potassium-stainless steel gravity-assisted HPs. Performance limitations due to entrainment or flooding of the liquid return flow were compared to analytical model predictions with favorable results.

Experimental lifetime performance studies were carried out by Sena and Merrigan (1989) using Nb-1%Zr and Ti HPs with potassium as the working fluid. Eight Nb-1%Zr/K HPs were designed, fabricated, and tested. They were gravity-assisted HPs operating in a reflux mode. The HPs were also tested as a set in the horizontal position in a capillary pumped annular flow mode. Each of the HPs was encapsulated in a quartz vacuum container with a water calorimeter over the vacuum container for power throughput measurements. The HPs were operated between 800 and 900 K, with heat fluxes of 13.8 to 30 W/cm^2. Of the Nb-1%Zr/K

HPs, two of the HPs have been in operation for 14,000 h, three for over 10,000 h, and three for over 7,000 h.

Start-up

There are limited references available on start-up characteristics of a potassium HP. Glass et al. (1998) evaluated experimentally the start-up of a liquid-metal HP from the frozen state using a Nb-1%Zr HP with potassium as the working fluid. The HP was fabricated and tested at Los Alamos National Laboratory.

Jang (1992) tested a HP from a frozen state in a vacuum chamber. The test results showed that the HP remained inactive until it reached the transition temperature. In addition, during the start-up period, the evaporator experienced dry-out with a heat input smaller than the capillary limit at steady state. However, when the working fluid at the condenser was completely melted, the evaporator was rewetted without external aid. The start-up period was significantly reduced with a large heat input.

Swales Aerospace (Nikitkin, 2005) has performed an extensive research and development program devoted to studying HP start-up from the frozen condition. The work was performed using ammonia –aluminum HPs. However, the results and main conclusions can be extended into the high-temperature range for potassium –Nb-1%Zr HPs.

Wettability

According to the literature review, rigorous fabrication and cleaning procedures are critical to good wetting, resulting in significantly reduced active nucleation site size and a higher boiling limit. Woloshun et al. (1990) suggested a procedure to clean a Nb-1%Zr HP that included an acid wash, Freon-TF degrease, ethanol wash, high-vacuum firing, and operation with lithium prior to final charging.

3.0 Task II. Material Compatibility Studies

One of the main issues with any HP is material compatibility, because reactions between the materials and the fluid can lead to the generation of noncondensible gas or to failure of the envelope.

The main issues that have been studied are corrosion, creep, thermal stresses due to welding, operation at high temperature, and noncondensible gas generation. Other issues related to the choice of materials, such as machinability and operation at high and low internal pressure, were also addressed and evaluated.

HP envelope material, endcaps, welding materials, and the wick structure were studied for compatibility with potassium (both separately and as a combination). The impact of component cleanliness and the degree to which materials used for component fabrication (machining and cleaning fluids, for example) are removed can be very strong, so these issues were addressed with special care.

In summary the following statements can be made:

The final choice of the material for the HP body was C-103 alloy, which is an enhanced Nb-1%Zr. It is planned that the Wah Chang Company will supply this material to Swales Aerospace. According to the literature provided by Wah Chang (2004), C-103 is the ideal material for the potassium HP application from both structural and thermal perspectives. The material has high thermal conductivity at elevated temperatures when compared to super-alloys. At 800°C, the thermal conductivity is 38.1 W/m-K.

Nb-1%Zr material is easily oxidized. It will oxidize in air above 200°C. The reaction, however, does not become rapid until above about 500°C. At 980°C, the oxidation rate is 0.025 mm/y. The attack is catastrophic at 390°C in pure oxygen, which freely diffuses through the metal causing embrittlement. Nb-1%Zr reacts with nitrogen above 350°C; with water vapor above 300°C; with chlorine above 200°C; and with carbon dioxide, carbon monoxide, and hydrogen above 250°C. At 100°C, Nb-1%Zr is inert in most common gases, e.g., bromine, chlorine, nitrogen, hydrogen, oxygen, carbon dioxide, carbon monoxide, and sulfur dioxide, wet or dry (Wah Chang Co., 2001).

In general, Nb-1%Zr exhibits a complex oxidation behavior that depends on temperature, pressure, and microstructure. At temperatures up to about 650K, oxidation generally follows a parabolic rate law because of the formation of protective oxides. At higher temperatures, oxidation becomes linear, but results are extremely sensitive to pressure and other system variables (DiStefano, 1989).

Gas tungsten arc welding has been used to weld Nb-1%Zr, with some modifications to avoid contamination of the weld metal. A trailing shield and backside purge or welding in a glove box have been successful (Wah Chang Co., 2001).

Nb-1%Zr is resistant to attack in many liquid metals even at relatively high temperatures. These include sodium, potassium, and sodium-potassium alloys below 1000°C. Nb-1%Zr resists attack by potassium vapor both at high temperatures and pressures. The Nb-1%Zr alloys are presently used as the end caps on high-pressure alkali metal vapor lamps (Wah Chang Co., 2001).

The Nb-1%Zr HPs with potassium as the working fluid were successfully tested for up to 14,000 h at 800-900K by Sena and Merrigan (1990) at Los Alamos National Lab.

The reactor design for the DOE SP-100 used Nb-1%Zr/K HPs at over 750K as a part of its main radiator (Reid, 1990). The operation of a Nb-1%Zr/K HP operating with radial heat fluxes in the evaporator region of up to 147 W/cm^2 at 925K is described by Woloshun et al. (1990).

Minimization of impurities, especially oxygen, in potassium is of utmost importance, because the resulting oxides have been shown to be the principal cause of HP corrosion at high operating temperatures (Lundberg, 1987).

There is considerable successful experience with liquid potassium, sodium/potassium, and sodium coolants at temperatures of 650°C or higher for at least 1500 h with Types 304 and 316 stainless steel, which are the main candidates for the capillary structure of a future high-temperature potassium HP. There is also successful experience with boiling potassium in contact with Type 316 stainless steel. These studies all indicated negligible (0.002-0.005 –in. deep) surface effects.

4.0 Task III, HP Design And Analysis

Structural Analysis:

Table 2 lists the C-103 mechanical properties at room temperature and 922K (Wah Chang Co, 2004).

TABLE 2. C-103 ALLOY MECHANICAL PROPERTIES

Temperature (K)	Yield Stress (ksi)	Ultimate Tensile (ksi)	Elastic Modulus (Msi)
298	40	58	11.6
922	23	41	4.1

For the preliminary structural analysis, it was assumed that welding does not cause any material degradation. Stress concentration at the ends of a HP was not considered. This is because the device will be under stresses that could cause buckling. The following safety factors were used: for proof FS = 1.5, for burst FS = 2.5 and for buckling FS = 2.5. For a 2-m long HP with a 2.5 - cm diameter, the required wall thickness is 0.5 mm (0.020 in.). The required thickness of the end caps is estimated to be 5 mm.

Two critical stress cases were considered for sizing the envelope, buckling with potassium as the working fluid (potassium pressure less than atmospheric), and pressure containment with water as the surrogate fluid.

Buckling is the primary failure mode with potassium, due to the low internal pressure of the potassium working fluid at 875K, which is 19,300 Pa (2.8 psia). Using the proposed wall thickness, the margin of safety due to buckling was 7.2. The vapor pressure of water at 220°C is 2.31 MPa (335 psia), and the resultant margin of safety for burst was 0.98 when using the thicknesses stated above, which means that the HP cannot be heated above 200 °C when charged with water.

Materials Fabrication Study

Based on the structural analysis, the required HP wall thickness is 0.5 mm (0.020 in.). To minimize the radial heat transfer resistance and to optimize the thermal performance, it is essential to maintain a thermal device with a small wall thickness. The small thickness, however, presents a fabrication challenge. Such thin wall tubing is not commercially available. However, Swales has teamed with the Superior Tube company, which is comfortable producing such a thin wall Nb-1%Zr tube in the future. The C-103 raw material has to be thinned to meet the thermal performance predictions. Based on discussions with Superior Tube Inc., Swales has determined that this vendor has the capability to develop thin wall C-103 tubes for this task. Superior has experience working with Nb-1%Zr tubes for nuclear applications, which is very close in properties to C-103. Nonetheless, preliminary development is needed prior to the development of the final HP envelope.

Primary Wick Selection

The wick structure will be made from stainless steel, which is commercially available and compatible with the potassium working fluid of the HP. There is no need to develop any advanced wick materials, because the wick will provide only thermal features and does not need to carry any structural loads.

The HP performance greatly depends on the wick structure chosen. Initially, Swales proposed to study and compare two different types of capillary structure designs: fibrous wicks and open artery wicks. Both of these capillary structures are homogeneous; therefore, there are no issues associated with composite or arterial wick behavior. Both approaches are proven to be very reliable. Swales currently is mass-producing flight hardware based on the fibrous wicks.

Figures 1 and 2 schematically show options of the internal capillary structure for the HP as it was proposed at the end of Phase I.

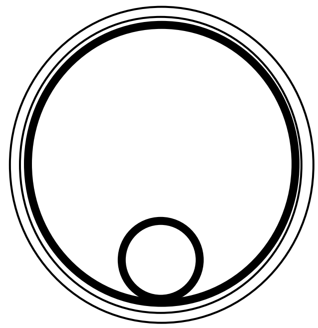

Figure 1. Open Artery Wick.

Figure 1 shows a main wick consisting of an open artery formed from screen for axial transport of the working fluid. A secondary wick, consisting of a layer of screen, lines the wall in the evaporator zone only and is designed to distribute the working fluid from the main wick to the vaporization surface.

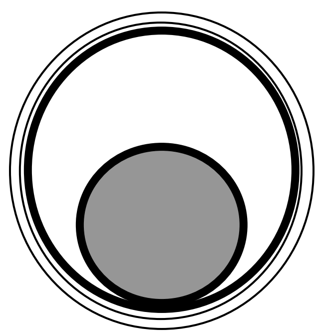

Figure 2. Fibrous Wick

Figure 2 shows the second design concept, where the open artery is replaced with a woven fibrous wick. This wick design also uses a secondary wick consisting of a screen lining the wall of the evaporator.

The two designs are compared below.

TABLE 3. CAPILLARY STRUCTURE COMPARISON

Both designs: Both designs can be made straight or bent Similar materials of construction Same manufacturing processes Same design life Some additional reservoir volume for the noncondensible gas and hot case excess fluid can be added to both designs.
Open Artery HP: Higher performance in 0-g and 1-g Lighter weight (less working fluid, smaller wick) Lower condenser blockage Scalability (performance can be increased with more arteries added) More sensitive to the back pumping in the condenser
Fibrous wick HP: Extensive flight heritage (more than 100 ammonia/stainless steel units flown)

These structures were analyzed, and it was determined that neither design meets the initial goals for the HP thermal transport. As a result, a third concept with multiple arteries (using the advantage of scalability) was proposed for detailed consideration.

The cross section of the updated arterial HP design is presented in Figure 3. The performance characteristics presented herein were obtained during modeling of the HP with Swales in-house modeling tools, based both on Excel and MathCad worksheets. These tools are based on the classical HP modeling technique described in the Heat Pipe Design Handbook (1972). This modeling approach was verified on several generations of arterial wick HPs (ammonia) and a number of high-temperature liquid-metal HP applications. The consistency of model predictions is proven by extensive acceptance test performed for numerous flight HP programs.

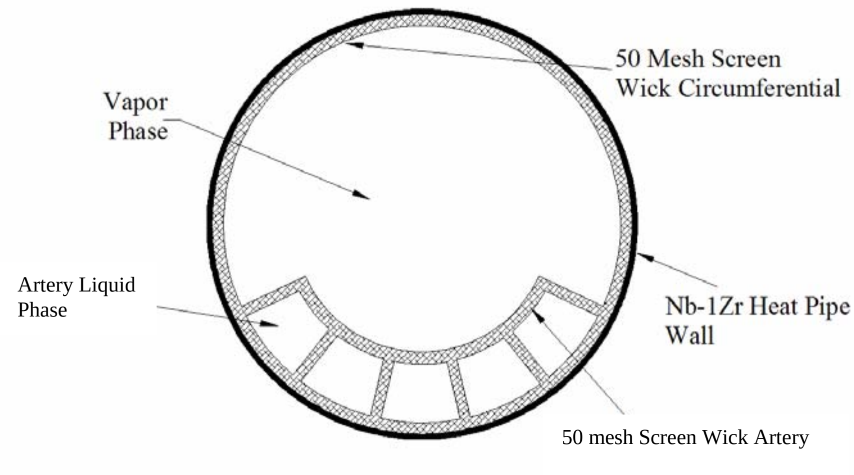

Figure 3. Multiple Artery Wick Design

The performance of the multiple artery wick was analyzed over the entire temperature range with different numbers of arteries (from 1 to 6 arteries). Figures 4 through 9 summarize the heat transport capabilities of a 2-m. long HP with an outer diameter of 25 mm (1 in.) OD and a 0.46 m (18 in.) long evaporator. The curves show the predicted heat transport capability in 0-g and 1-g based on capillary limits, as well as sonic and entrainment limits for this HP, as a function of operating temperature. The size of the artery (*H art*) in each case was selected to maximize the performance of the HP. Legends for the curves in the figures are: Q1HP is the maximum power under 1-g conditions, Q_{sonic} is the maximum power due to sonic limitations, Q_{entr} is the maximum power due to the entrainment limit, Q1HP0g is the maximum HP performance under 0-g conditions. Q_{req} represents the desired performance value. As shown in the figures, HP performance is limited by the capillary pumping of the wick, not by sonic or entrainment limits.

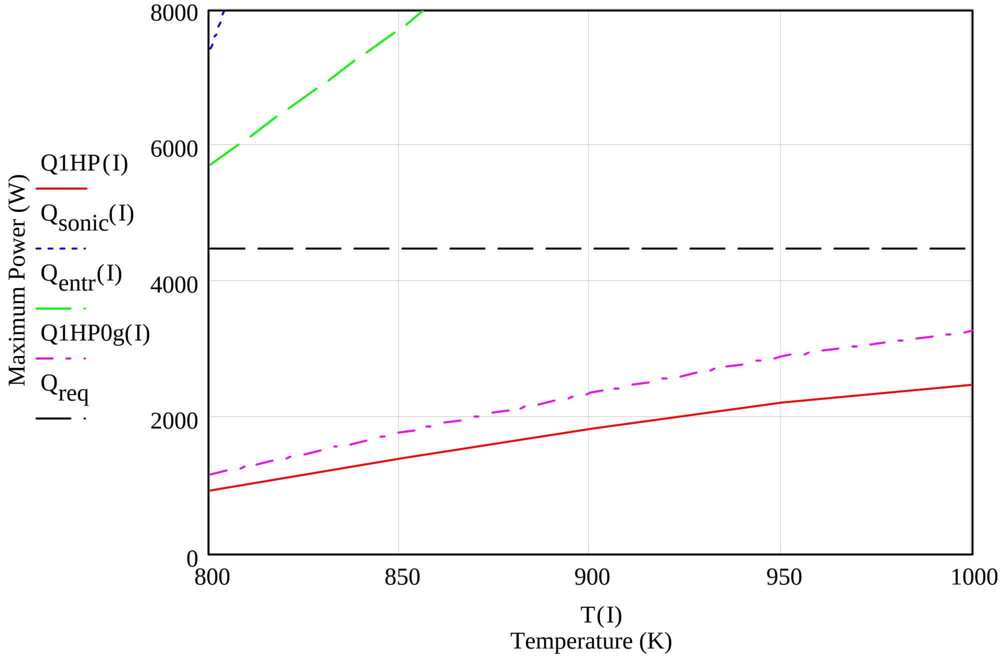

Figure 4. One Artery H art = 0.18 in.

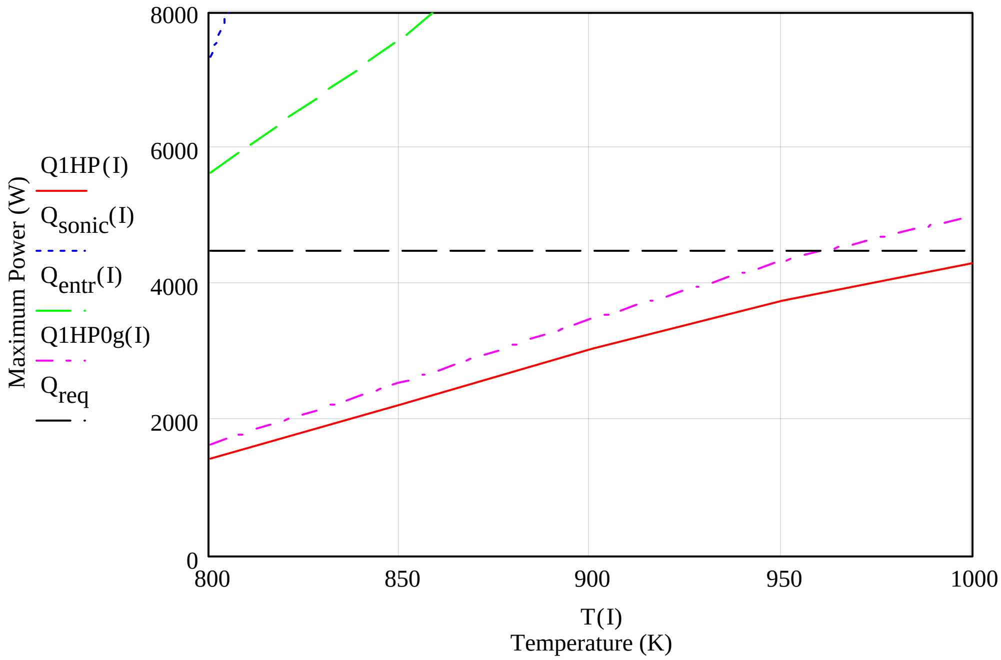

Figure 5. Two Arteries H art = 0.13 in.

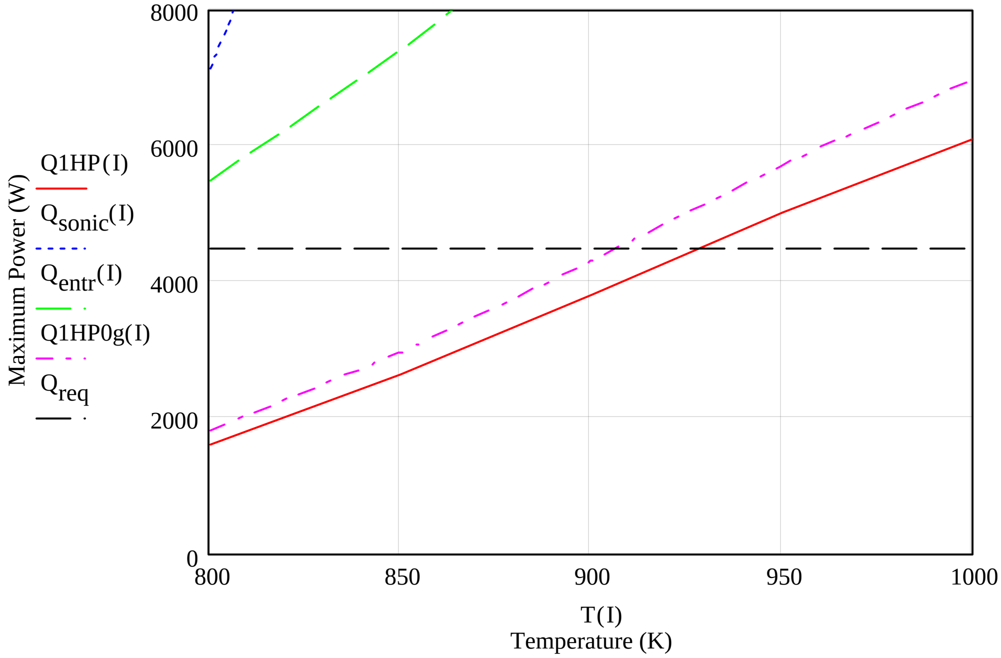

Figure 6. Three Arteries H art= 0.12 in.

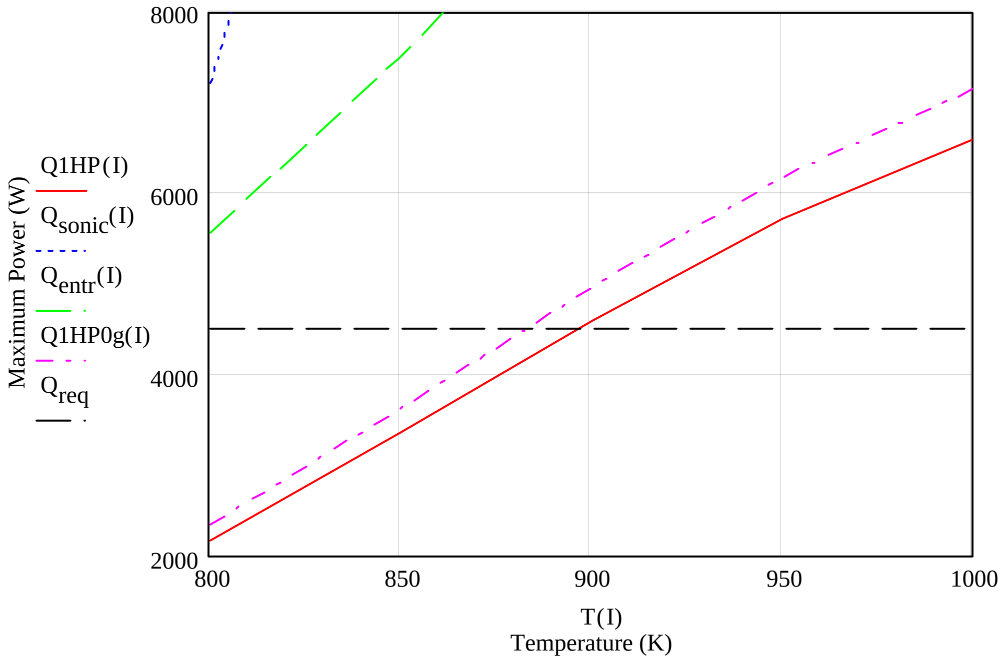

Figure 7. Four Arteries H art = 0.09 in.

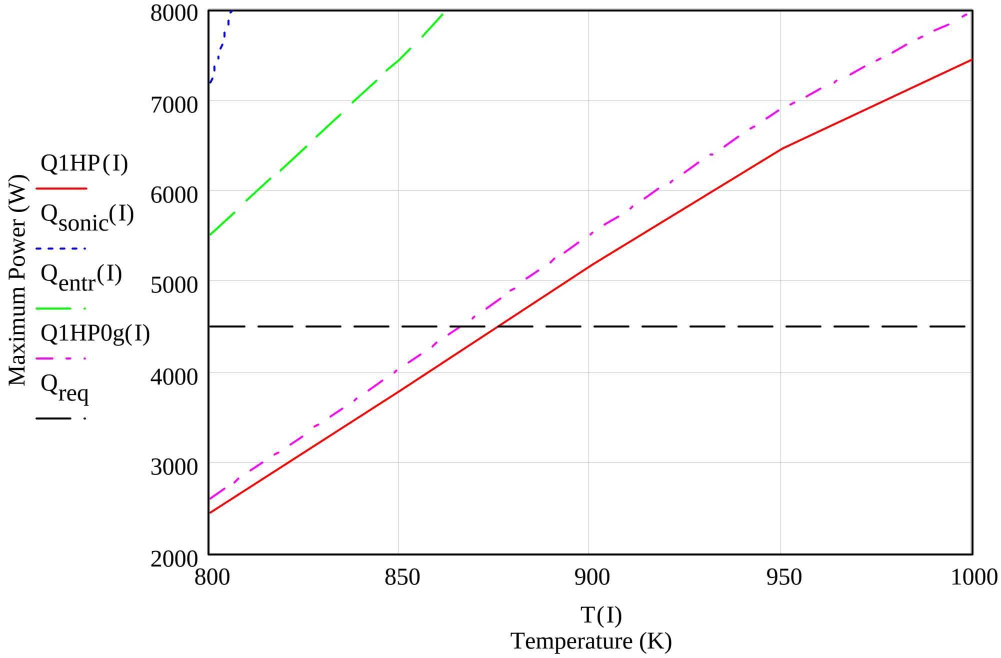

Figure 8. Five Arteries H art = 0.08 in.

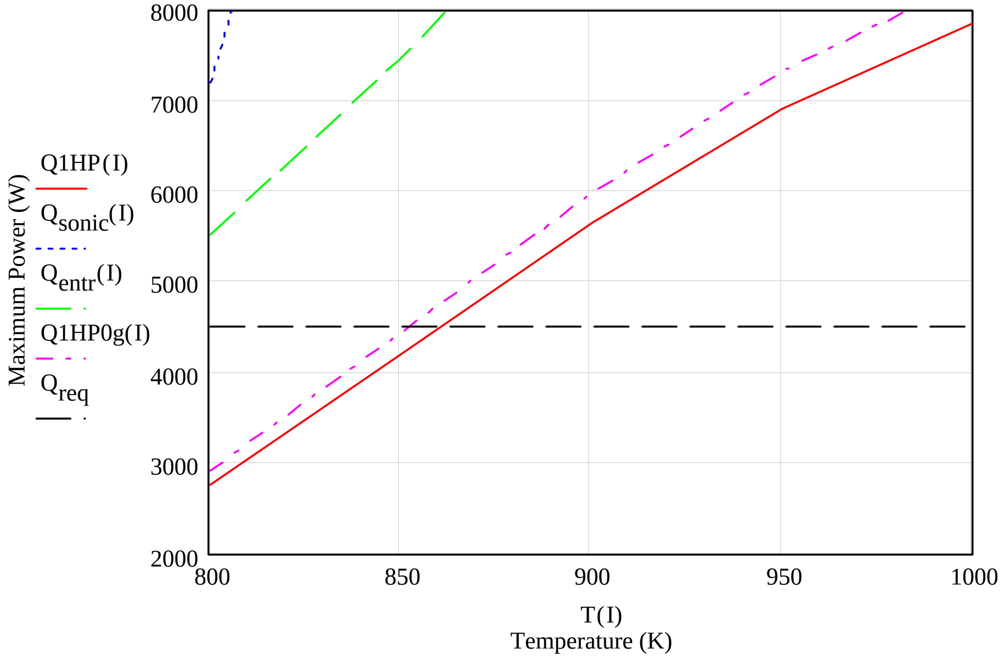

Figure 9. Six Arteries H art = 0.07 in.

As shown by Figures 4 through 9, the highest heat transport is achieved with the six-artery approach, because it satisfies the transport requirements at temperatures above 850K. Using more than six arteries is not deemed to be practical.

Because liquid density decreases with temperature, charging the HP for operation over the temperature range from 800 to 1000K will result in excess liquid at the higher operating temperatures, which will accumulate in the condenser. The length of the excess liquid slug at 1000K for the six-artery design is approximately 1.3 cm (0.5 in.). The calculated values for the hot case condenser blockage will be considered as the maximum possible, and the actual blockage will be updated based on the detailed design of the wick structure once the required operating temperature range is finalized.

In accordance with the performance requirements, the performance of the baseline HP design must be verified using a surrogate fluid that can operate at lower temperature and be easier to work with than potassium. An attractive surrogate fluid is water, which is well suited for operation in the temperature range of 400 to 500K.

The six-artery design was modeled with water as a working fluid. The results of the analysis are presented in Figure 10. Tests with the surrogate fluid would be used to validate the analytical model. The condenser blockage predicted for water in this temperature range is not expected to be more than 2.5 cm (1 in.).

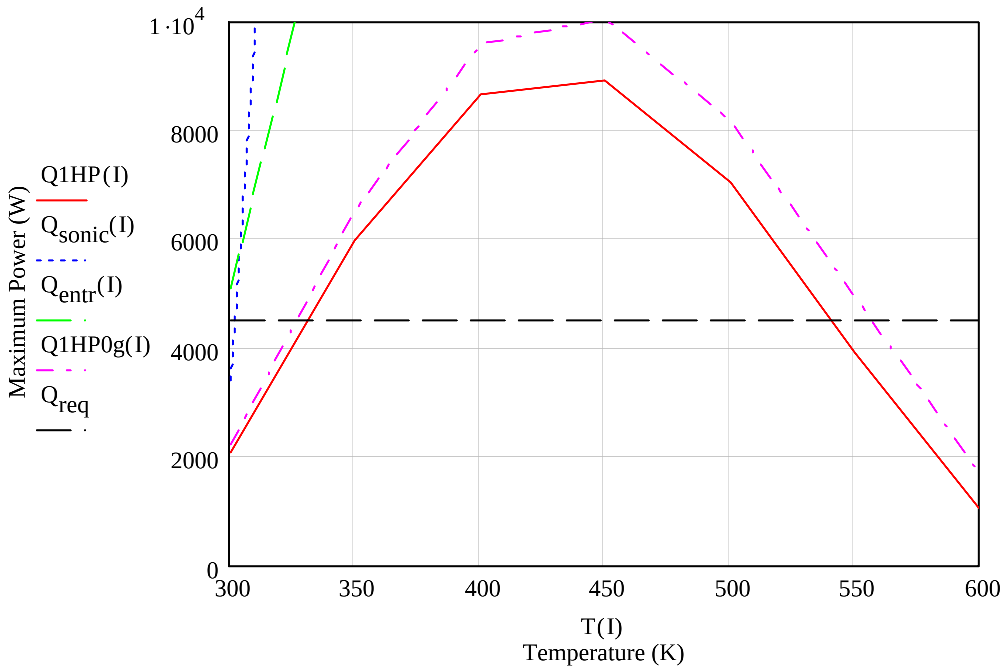

Figure 10. Six-Artery HP Performance with Water

Design issues

<u>Freeze-thaw behavior</u> is traditionally one of the biggest issues with high-temperature HPs. However, Swales has developed a technique, that guarantees reliable and repeatable start-up of a HP from the frozen state. This technique has been flight qualified at low temperatures with ammonia as a working fluid, and flight hardware based on this technique has been delivered.

<u>Wettability</u> is another potential issue, particularly for water. In some cases, water may not perfectly wet the stainless steel/Nb-1%Zr structure; therefore proper cleaning and surface preparation techniques must be used during the manufacturing process.

Circumferential Wick Selection

The selection of the secondary wick was based on a HP radial pumping power analysis as well as the axial transport capability. The analysis shows that two layers of 50-mesh stainless steel screen are capable of transporting 73 W-m (2890 W-in.) circumferentially for an evaporator length of 0.45 m (18 in.). A number of materials were considered for the secondary wick; however, stainless steel was selected due to its well-established heritage and performance history. Swales Aerospace identified Unique Wire Weaving Inc. and Cambridge Inc. as possible suppliers. An example of a stainless steel screen wick is illustrated in Figure 11.

The final wick structure will consist of two screen mesh layers to ensure an optimum circumferential liquid transport.

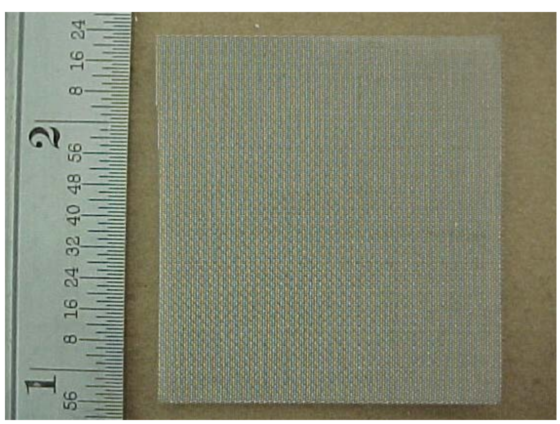

Figure 11. An example of stainless steel screen wick.

5.0 References

DiStefano, J.R., “Review of Oxidation of Nb-1Zr”, Oak Ridge National Laboratory, ORNL TM-10907, 1989.

Glass, D. E., Merrigan, M. A., Sena, J. T., “Start Up of a Nb-1%Zr Potassium Heat Pipe From the Frozen State**”,** NASA/CR-1998-207641, 1998.

Gerrels, E. E., and Killen, R. E., “Potassium Rankine Cycle Vapor Chamber (Heat Pipe) Radiator Study”, NASA Contract Report CR-1866, Sept 1971.

HP Design Handbook, 1972

Jang, H. J., “Study of Start-up Characteristics of a Potassium Heat Pipe from the Frozen State”, *ASME, Heat Transfer Division*, HTD, Vol. 206-3, p 63-69, 1992.

Lundberg, L.B., “Alkali Metal Heat Pipe Corrosion Phenomena”, Sixth International HP Conference, 1987.

Nikitkin M., HP Freeze-Thaw Behavior, Some Useful Observations, Aerospace Thermal Control Workshop, El-Segundo, CA, 2005.

Prenger, F. C., Keddy, E. S., and Sena, J. T., “Performance Characteristics of Gravity-Assisted Potassium Heat Pipes*”, J. Spacecraft Rockets,* Vol. 23, No. 4, 1986, pp 407-410.

Reid, Merrigan, and Sena, “Review of Liquid Metal Heat Pipe Work at Los Alamos”, LA-UR-90-3721, Los Alamos National Laboratory, 1990.

Sena, J. T., and Merrigan, M. A., “Niobium 1 Percent Zirconium/Potassium Life-test Heat Pipe Design and Testing”, Seventh Symposium on Space Nuclear Power Systems, 1990.

Wah Chang Co., “Niobium” Brochure, Albany, OR, 2001.

Wah Chang Co., “C-103 Overview”, Albany, OR, 2004.

Woloshun, K. A., Sena, J. T., Keddy, E. S., and Merrigan, M. A., “Radial heat flux limits in potassium heat pipes: An experimental and analytical investigation” *Symposium on Space Nuclear Power Systems*, Paper No. LA-UR--89-3365, Albuquerque, NM, January 7-11, 1990.