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Methodology for Life Testing of Refractory Metal / Sodium Heat Pipes

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Abstract – *The focus of this work was to establish an approach to generate carefully controlled data that can conclusively establish heat pipe operating life with material-fluid combinations capable of extended operation. To accomplish this goal acceleration is required to compress 10 years of operational life into 3 years of laboratory testing through a combination of increased temperature and mass fluence. Specific test series have been identified, based on American Society for Testing and Materials (ASTM) specifications, to investigate long term corrosion rates. The refractory metal selected for demonstration purposes is a Molybdenum-44.5%Rhenium alloy formed by powder metallurgy. The heat pipe makes use of an annular crescent wick design formed by hot isostatic pressing of Molybdenum-Rhenium wire mesh. The heat pipes are filled using vacuum distillation and purity sampling is considered. Testing of these units is round-the-clock with 6-month destructive and non-destructive inspection intervals to identify the onset and level of corrosion. Non-contact techniques are employed for providing power to the evaporator (radio frequency induction heating at 1 to 5 kW per unit) and calorimetry at the condenser (static gas gap coupled water cooled calorimeter). The planned operating temperature range would extend from 1123 to 1323 K. Accomplishments prior to project cancellation included successful demonstration of the heat pipe wick fabrication technique, establishment of all engineering designs, baselined operational test requirements and procurement/assembly of supporting test hardware systems.*

I. INTRODUCTION AND APPROACH

Heat pipe life tests described in the literature have seldom been conducted on a systematic basis. Typically one or more heat pipes are built and tested for an extended period at a single temperature with simple condenser loading. A group at Los Alamos National Laboratory began to approach heat pipe life testing using science-based methods[1]. Tests were performed on various alkali metal heat pipes for extended periods at elevated temperature and power. Material examination and assay were often conducted before and after test. During this effort high temperature corrosion modes were proposed based on forensic examination of failed and non-failed heat pipes. Attempts were made to understand complex chemical equilibrium mechanisms using free energy minimization techniques with data supplied or extrapolated from the literature. One such thermal chemical simulation of the Niobium/Potassium (Nb/K) system with typical contaminant levels found no life limiting corrosion after 7 years of operation at 875 K[2].

Los Alamos was also involved in systematically testing heat pipes at several temperatures and mass fluences in support of the SP-100 program. An examination group of eight heat pipes (potassium (K) filled Nb-1%Zr units) was evaluated[3]. Conditions for these eight tests approximated a 3^2 factorial configuration with temperature and radial heat flux to the evaporator as the two controlled factors. As far as it is known, this test was one of the first attempts to develop a multifactor response surface in a heat pipe corrosion test. In this case results from the partial two-level factorial test series could have identified first order effects and interactions between the two factors[4]. The eight K/Nb-1%Zr heat pipes were tested for 7000 to 14 000 hours (h) in the 850 K to 950 K range. One of these pipes developed a small evaporator leak at 13 000 h that did not affect the operation of the heat pipe and was not detected by the vacuum system monitor. Tests on the other heat pipes concluded with no apparent problems. It is believed that Zr in an Nb-1%Zr centering wire of the one failed heat pipe touched the quartz containment tube during test. A wire-quartz contact point on the failed heat pipe surface was discovered after 13 000 h of test. Zirconium, being more stable than quartz, partitioned oxygen (O), causing O to diffuse from the quartz to the condenser wall. Oxygen from the quartz appears to have migrated to the heat pipe and saturated the Zr in the evaporator.

The current effort was focused on extend this approach by developing a systematic experimental test program to establish life-limiting issues for Molybdenum-Rhenium (Mo-Re) alloy/sodium (Na) heat pipes. The planned test methodology made use of an accelerated approach through increased temperature and mass fluence. This technique compresses twelve years of nominal operation into three years of round-the-clock testing. A benefit of this program approach is that periodic inspections can be made early on, producing experimental test data early which can be compared to predicted trends. A test series of 16 reduced length heat pipes was identified for this program. The number was a trade between the cost to manufacture and test and the number of test points. A number of accomplishments were made on this program related to development of test systems and heat pipe fabrication prior to its termination.

II. HEAT PIPE LIFE TEST CONDITIONS

The approach to heat pipe life prediction involves extrapolation of corrosion effects for a reference design from separate tests conducted over different durations. Corrosion or reaction metrics are taken for each test specimen, and the results are plotted versus time. Appropriate metrics include changes in fluid composition, wall and wick integrity as determined by three dimensional x-ray computed tomography, species distribution, and grain boundary condition as well as non-condensable gas production measured by residual gas analysis. A method outlined in ASTM G 68-80 provides for a predictive corrosion rate formulation generated by extrapolating the slope near the longest test time. This slope normally decreases with time allowing early test data to provide a conservative upper bound (Figure 1). Conditions of an extrapolated test series can closely match those of a proposed reference. Extrapolation tests conducted at prototypic temperatures avoid possible problems with elevated temperature acceleration[5].

The approach selected by this program was to combine the normal reference mission test parameters with accelerated condition tests to hasten life-limiting effects. Acceleration by operating at higher temperature and mass fluence is intuitively appealing reducing overall test time required to achieve higher impurity accumulation of elements such as O, Si, and C in the heat pipe evaporator.

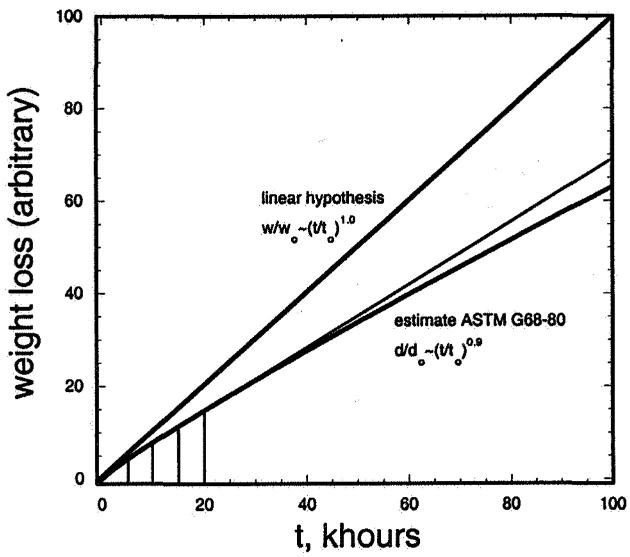

Figure 1. Corrosion rate trends estimated by ASTM G68-80.

Corrosion rate is proportional to this concentration of impurities giving the appearance that corrosion is dependent on mass fluence. The radial heat flux (q_{rad}) applied to the evaporator is given by:

$$q_{\mathrm{rad}}=q(\pi d L_e)^{-1}, \tag{1}$$

where q is the applied evaporator power, d is the heat pipe diameter and L_e is the length of the evaporator section. Mass flux (G) through the evaporator is a function of the radial heat flux,

$$G=q_{\mathrm{rad}}(h_{\mathrm{fg}})^{-1}, \tag{2}$$

where h_{fg} is the latent heat of vaporization. Mass fluence (M'') through the evaporator is then given by:

$$M''=G\,\tau, \tag{3}$$

where τ is the operational time. Mass fluence can easily be increased by applying power along a shortened heat pipe evaporator length. Mass fluence can be used as a metric to accelerate heat pipe life or to affordably test subscale versions of a flight unit. Mass diffusion transfers impurities from the heat pipe structure to the working fluid. The Arrhenius equation relates impurity diffusion rates to heat pipe temperature. Test conditions can be normalized using the expression:

$$\alpha(T)=\exp[(\Delta H/R)(T_0^{-1}-T^{-1})], \tag{4}$$

where ΔH is activation energy, R is the universal gas constant, T_0 is the design temperature, and T is the heat pipe test temperature. It can be argued that since testing at high temperature accelerates the Arrhenius-governed diffusion rate, this same acceleration applies to heat pipe life. Such simplistic views must be approached with caution. The nature of chemical reactions and their kinetics can change dramatically with absolute temperature. Conditions that apply at one temperature do not necessarily hold true for others. Without deeper understanding of the underlying reaction mechanisms, conclusions drawn from such tests may be misleading.

The proposed lfe test evaluation will make use of a series of 16 Mo-44.5%Re/Na heat pipes subject to a combination of operating temperatures and mass fluence to conservatively bound the design point. Nine of these heat pipes constitute a central composite test design (referred to as a Fisher or F-Series) with the remaining 7 units accounting for the ASTM G 68-80 sequence (referred to as the G-Series). Two of the experiments from the extrapolation test G-series (G(2) and G(6)) are used to cross correlate fluence conditions with the F-Series (F(-3) and F(0)) sequence conducted at various temperatures and fluences. Such life tests can establish and isolate corrosion trends as a function of temperature and mass fluence. The proposed test matrix is illustrated in Figure 2.

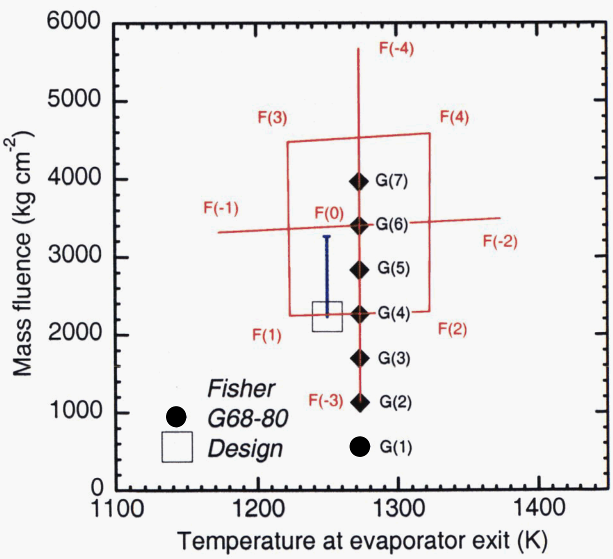

Figure 2. Life test heat pipe test matrix – combination of G-series and F-series experiments positioned about the design.

The target of the proposed test program is to compress twelve years operational life into approximately three years of actual operation. To achieve the target power density and operating temperatures non-contact evaporator heating and condenser calorimetry were to be used. In addition, impurity levels in the heat pipe wall material would be measured and techniques employed to both quantify the sodium working fluid. A number of

III. FABRICATION OF THE SAFE-100 MODULE

The envelopes of the proposed heat pipes are fabricated from a Molybdenum-44.5%Rhenium (Mo-44.5%Re) alloy formed using powder metallurgy techniques (tubing and rod stock available though Rhenium Alloys Inc.). To conserve materials, the heat pipe length was limited to approximately 33 cm with an outside diameter of 1.587 cm (wall thickness of 0.889 mm). Figure 3 illustrates the design and shows a sample stainless steel module fabricated as a forerunner to test assembly, fill and testing.

Figure 3. Life test heat pipe design.

The heat pipe will be operated horizontally to mimic the neutral gravity conditions of space. The internal capillary wick was formed from Mo-5%Re 400x400 screen mesh (existing stock from a previous NASA programs) with a wire diameter of 0.025 mm. An annular gap wick is selected for the life heat pipe because it is simple, robust, and performs well during ground testing. During wick development two techniques were examined including drawing and hot isostatic pressing (HIP'ing); sample wicks were produced with both methods (by Advanced Methods and Materials Inc.) to evaluate the process and final product. As anticipated the drawing technique was fairly simple to implement producing a highly ductile wick (formed at room temperature with no grain growth issues); however layers were only mechanically bonded and separation could easily occur. In contrast the HIP process was more complex in its implementation, however produced a final wick with diffusion bonded layers. This bonding provided excellent dimensional control of the final part while still retaining ductility; re-crystallization of the Mo-5%Re and loss of ductility being a concern since the HIP'ing was performed at a temperature of approximately 1250 K. A final half length wick sample with correct radial and wall thickness dimensions was formed (figure 4).

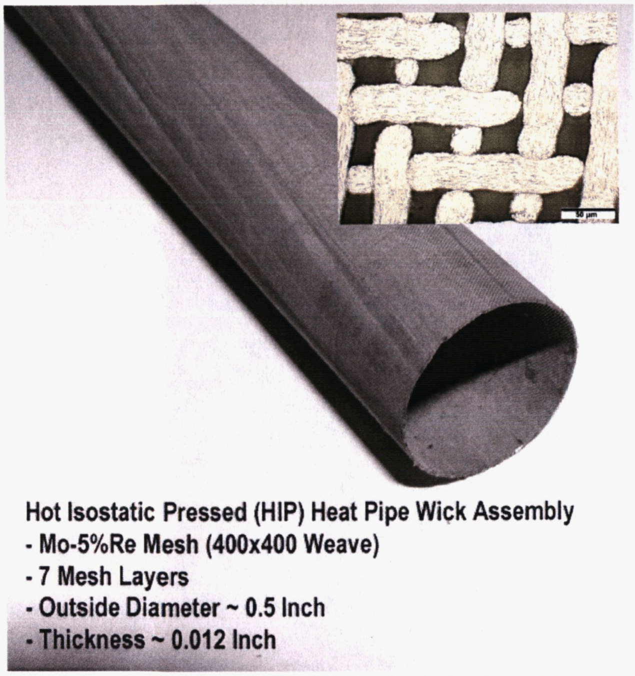

Figure 4. Mo-5%Re HIP'ed wick structure.

Properly designed short heat pipes tested at relevant temperatures and mass fluence are made geometrically similar (L_c/L_e) to the flight heat pipes (Table 1). Such similarity in heat pipe designs form the basis for virtually all long-term heat pipe corrosion testing to date[1]. The length of the heated region is 7.5 cm and the cooled region is 25 cm, reflecting approximate geometric similitude with a flight heat pipe. For the case of an annular gap wick, the channel dimension, *A*, is the concentric distance from the wick's outer and the pipe's inner surfaces. The value for *A* is chosen to optimize life test heat pipe performance at the reference temperature. A wick's maximum pore radius, *r*, most directly influences its capillary pumping capacity. A 45-micron effective pore radius has been assumed for the life heat pipe design. Experimental bubble point testing of the HIP'ed wick element produced by Advanced Methods and Materials Inc. showed a 20-micron pore radius, well within program requirements. Radial power densities applied to the evaporator, operating temperature, and nucleation site radii are key variables in boiling limit calculations. Nucleation site radii of one to three microns are typical for many engineering surfaces and will be assumed for the life heat pipe.

TABLE 1.
Life Heat Pipe Design and Conditions.

Parameter	Value
Wick Shape	Annular Gap
Evaporator Length	Le = 0.075 m
Adiabatic Length	La = ~0.00 m
Condenser Length	Lc = 0.25 m
Container Inside Radius	R = 0.705 cm
Channel Dimension	A = ~0.056 cm
Wick Pore Radius	r = 35 micron nominal
Nucleation Site Radius	n = ~1 micron
Solid Thermal Conductivity	k = 60 W.m-1.K-1
Working Fluid	f = Na
Temperature	T = {1173 to 1373 K}
Design Heat Pipe Power	Q = 3 kWt

The HTPIPE code[6] predicts heat pipe performance limits as a function of evaporator exit temperature and calculates axial temperature and pressure profiles. The computational routines in HTPIPE have been validated on numerous occasions using alkali metal heat pipe test data [7,8]. The code uses a pressure balance in the flow direction for both the liquid and vapor to define the wicking limit or the viscous limit, depending upon whether the wick pumping capacity or the stagnation pressure defines the limiting available pressure. Other heat pipe performance limits calculated by the program are the sonic limit, the entrainment limit, and the boiling limit. Figure 5 superimposes the proposed life test matrix on a heat pipe performance map calculated with HTPIPE. Boiling limits assuming a one-micron and three-micron nucleation site radius are shown. This plot emphasizes the importance of producing heat pipes with honed heated regions.

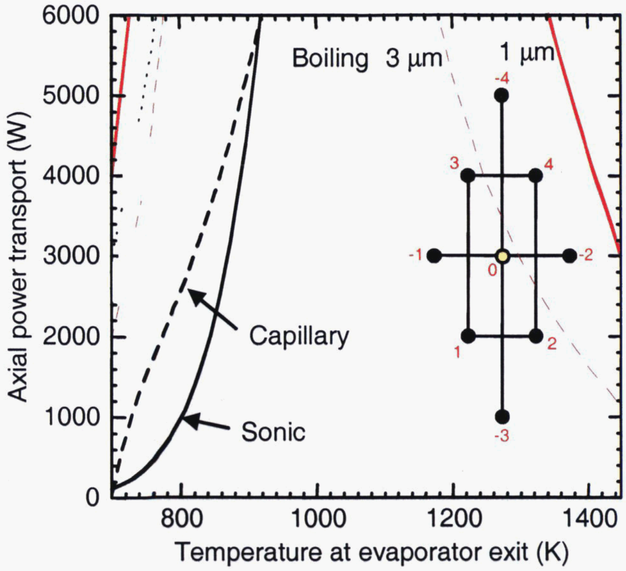

Figure 5. Life test heat pipe performance envelope.

IV. SODIUM LOADING AND PURITY SAMPLING

Sodium distillation filling of the heat pipes was selected as the prefer approach. An advantage of distillation is that transfer of low-pressure sodium vapor pressure is done in vacuum, avoiding the introduction of purified glove box argon into the heat pipe during charging. An additional benefit of distillation is that the sodium can be purified to <1-ppm oxygen. Distillation coupled with hot trapping provided by the vanadium (V) wire technique ensures that closed heat pipes contain known low levels of non-metallic impurities. Distillation requires that sodium be metered into a known volume which is then drained into a distillation pot and finally transferred by vaporization to the heat pipe. Figure 6 illustrates a general layout for the distillation hardware. The known volume and connective tubing is covered with heaters so that the vapor pressure of sodium can be increased. Turbo pumps are used to evacuate the heat pipe and transfer tubing to the 10^{-6} torr range. The connective tubing is baked at 400°C before initiating the transfer (both the heat pipe and sodium isolation valves should be closed during bake out). A typical distillation temperature set point (heater 1) is in the 350°C to 450°C range, adjusted to minimize transfer time (target of 1 hour) and to maximize purity (order of 1 ppm oxygen).

An additional requirement on this program was the sampling of the heat pipe unit's sodium (Na) working fluid after it has been transferred into the unit. This provides insight into the initial oxygen concentration within the unit - the sum of impurities in the dispensed Na and what is picked up from the heat pipe materials.

The current technique of involves bringing a section of vanadium wire into equilibrium with the oxygen contained within the dispensed sodium. This technique, referred to as the vanadium wire equilibration method, is described in ASTM 997-83. Details of this technique are also covered in a NASA technical memorandum[9]. Prior to incorporating this technique into the heat pipe processing sequence, laboratory testing must be performed to confirm the accuracy of the method. In the current approach, the vanadium wire element is sized to fit within the volume constraint of the heat pipe fill stem. The vanadium wire selected has a diameter of 0.25 mm and requires a length of 100 mm to achieve the desired sensitivity (measurements at the 1 ppm oxygen level). The vanadium wire is mounted to a molybdenum alloy wire bow which is inserted into the fill stem. The bow is held in place by a combination of spring force and a hook (holding tab) that is positioned between the valve body and the end of the fill stem.

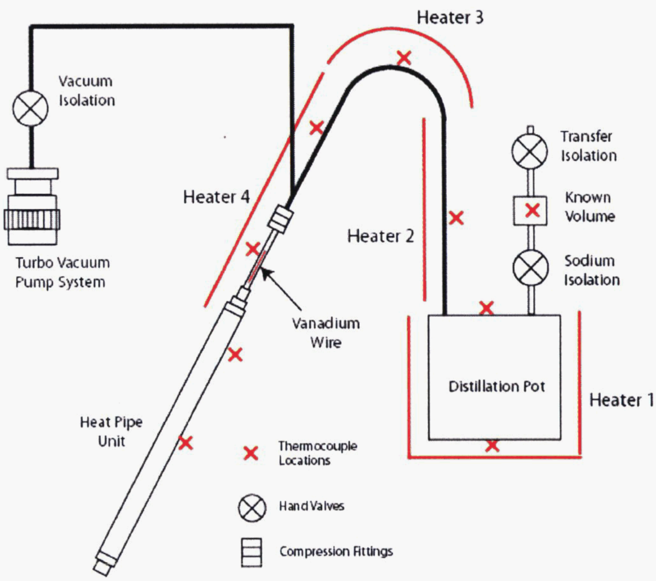

Figure 6. Life test heat pipe performance envelope.

The vanadium (V) wire technique was successfully applied in Na loops in the EBR-II program[10]. A vanadium wire present in the heat pipe during processing appears suitable to characterize oxygen levels in fully-assembled and filled heat pipe modules. A concept method has been devised to remove the wire from the Na during closeout with negligible impurity introduction (Figure 7). The validity of this technique can be independently confirmed by analysis of sample heat pipe modules.

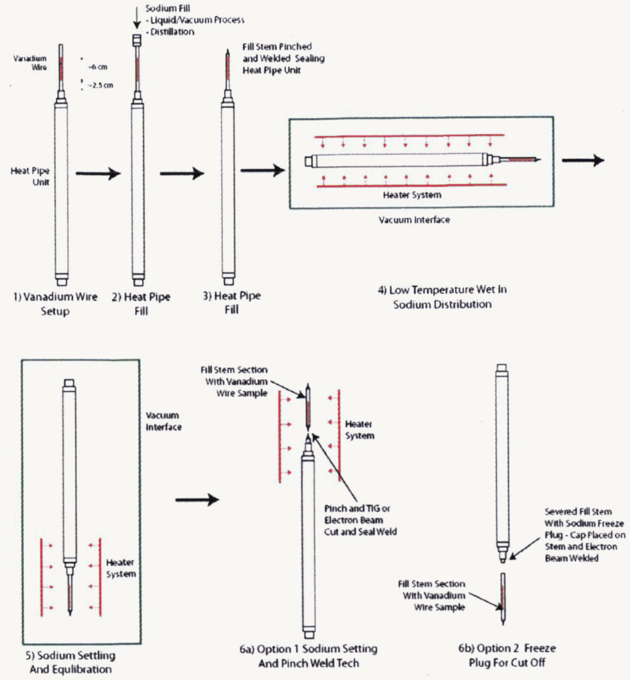

Figure 7. Vanadium wire/heat pipe process flow.

V. TEST CONFIGURATION

Round the clock test evaluation of the sixteen heat pipes requires a number of hardware systems to be fabricated. Non-contact methods were selected for evaporator power deposition (radio frequency induction heating) and condenser power extraction (static gas gap coupled water cooled calorimeter). The use of a background gas (helium, argon and helium/argon mixtures) to thermally link the condenser and calorimeter requires active purification to minimize the random introduction of external contaminents to the heat pipe environment. To test the series of heat pipes a number of environmental test chambers containing the thermal transport systems and gas atmosphere were developed. These include several large chambers, each containing a cluster of five heat pipe/calorimeter assemblies (arranged in a pentagonal configuration) and a small test chamber that contains the single high power heat pipe. The shell and flange arrangement on all chambers made use of commercial off-the-shelf vacuum rated items. In general, commonality will be maintained (to the extent possible) with respect to the designs, selection of hardware items and overall construction to allow flexibility in the final hardware setup. Figure 8 illustrates one of three large test chambers configured to hold five heat pipes.

Induction heating was selected to provide a well-characterized mass transfer boundary at the heat pipe evaporator. Fifteen of sixteen life test heat pipes are inductively heated in clusters due to like conditions and to conserver hardware; the single high power heat pipe is inductively heated in its own test chamber.

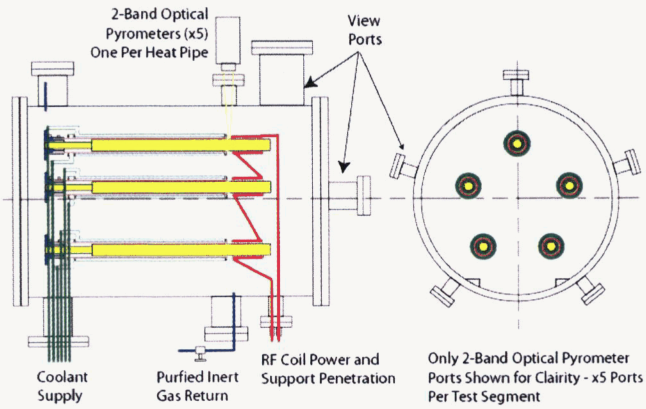

Figure 8. Environmental chamber and heat pipe envelope.

The RF pentagonal cross arrangement minimizes inductive interference among positions and provides an economical method to test a large number of heat pipes (figure 10). Numerical assessments were made of the RF system to establish voltage, current, and frequency requirements was performed using 1-D (ELTA software package by Electro-Thermal Analysis marketed by BNV Corp) and 2-D (using Flux2D software by CEDRAT Technologies) modeling software. These assessments also included the use of magnetic flux concentrators attached to the inductive coils to minimize calorimeter coupling and provide enhanced power uniformity within heat pipe evaporator. Results indicate coupling efficiencies in the 60% to 80% range at frequencies above 10 kHz. Additional considerations factored into the analysis included the potential for voltage breakdown and thermal loss from the hot heat pipe to the cold inductive coils. At the typical chamber operating pressures of 50 to 100 torr a glow discharge (Paschen minimum) could potentially damage the part under test (either by sputter or direct arc impingement). To minimize the potential for voltage breakdown it is desirable to set the voltage drop between the inductive coil and the heat pipe as low as possible and the physical distance between the components as large as possible. Based on the breakdown information and overall RF efficiency it was found that a 6.4 mm inductive coil offset provides a good configuration compromise. At this setting, the series cluster inductive coils operate at a maximum of approximately 225 V providing a margin of 2 on the estimated Paschen minimum. This offset also results in an estimated 350 W of heat loss per heat pipe/coil assembly due to combined radiation and gas conduction heat transfer, well within the overhead allowance of the selected RF power supply. Figure 9 illustrate the pentagonal arrangement the RF coils.

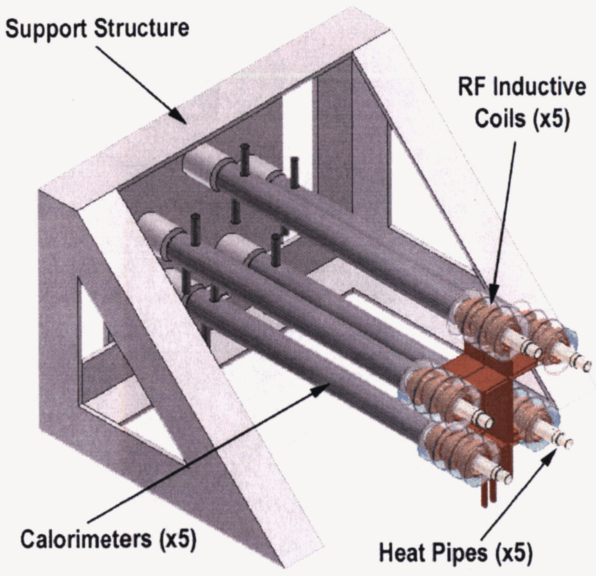

Figure 9. Pentagonal Inductive coil assembly.

A non-contact static gas conduction gap calorimetry system was devised for extracting power from the heat pipe. The inert gas couples the heat pipe condenser section and the inner wall of the calorimeter while flowing water contained in the calorimeter removes the heat. The heat pipe temperature and power can be controlled by setting the width of the gas gap and gas composition. The selected baseline calorimeter was a copper smooth tube laminar design lending itself to simple performance estimates supporting initial concept feasibility assessment. It is comprised of three concentric tube shells referred to as the channel tube (separating the gas gap and water film annulus), shell tube (separating the water film annulus and water return annulus), and cover tube (separating the water return annulus and test chamber environment). Plenums are mounted at the far condenser end to distribute water between the inlet and exit. Figure 10 illustrates a single heat pipe unit with calorimeter and RF inductive coil. To minimize this possibility of leakage, the calorimeter and all water feed lines will be welded or brazed to avoid mechanical connections.

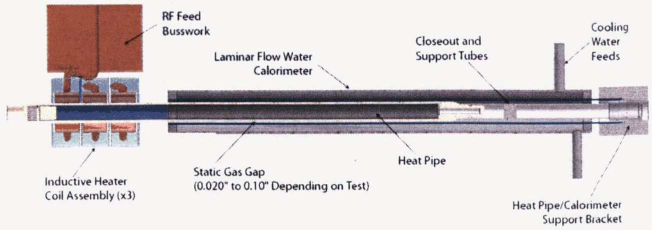

Figure 10. Illustration of a heat pipe unit with calorimeter and RF coil.

Primary system instrumentation includes a heat pipe evaporator exit temperature measurement just upstream of the calorimeter (using a 2-band optical pyrometer) and calorimeter water flow rate (magnetic flow meter) and inlet/outlet temperatures (thermocouples).

For the proposed heat pipe testing, the refractory metal components will be operated in low-pressure, ultra high purity (UHP) noble gas environment (argon and helium) so that the thermal coupling between the heat pipe and calorimeter can be controlled. Residual oxygen concentration in this gas is critical to the survivability of refractory metals operated at increased temperature for a relatively long time. A generally accepted vacuum level for testing Mo-Re alloys is in the 10^{-6} torr range which has an approximate oxygen concentration of 0.28 ppb. Hence, the target maximum oxygen concentration in the test chambers will be 0.28 ppb at the desired operating pressure of approximately 75 torr. To achieve the desired gas purity the initial step is to perform successive pump-downs/dilutions and component bake-out to at least 500 K are required to remove water and other volatiles. With this approach a level of 0.1 ppm is achievable and is the limit based on the purity of supplied UHP bottled gases. To reduce purity level to the targeted value and maintain the test chamber environment during operations, a SAES MonoTorr Phase II 3000 point-of-use purifier with recirculation pump will be incorporated in a test chamber mounted recirculating gas loop. These purifier can remove molecules of H_2O, O_2, H_2, CO, CO_2, N_2, and hydrocarbons to a level less then 0.1 ppb (at an absolute pressure of 75 torr). For the three chamber configuration the approximate volume is 800 liters containing nearly 0.018 kgs of helium. At a pressure of 75 torr the purifier throughput is approximately 0.023 kg/hr resulting in approximately 1.25 gas exchanges per hour. To determine the effectiveness of the bake-out and gas purification processes a residual gas will be employed to verify the partial pressure of various gaseous components in the test chambers throughout test.

VI. SEQUENCE FOR TESTING APPROACH

To adequately characterize the heat pipes prior to initiating long term life evaluation a performance verification is required. These performance tests are used to determine the heat pipes overall capability and look for defects that may prevent it from use in life testing. One such critical issue would be a reduced boiling limit (especially for those heat pipes operated at high temperature and fluence). A typical heat pipe performance test is expected to follow three distinct stages. The first tracks the sonic limit curve to a point at which the condenser coupling to the calorimeter provides the limiting thermal resistance. The second tracks across the operating envelope (moving off the sonic limit curve) with an increase in temperature and fluence. The third is arrival at the boiling limit characterized by a drop in condenser power and a corresponding increase in evaporator outlet temperature. The boiling limit is typically accompanied by bright spots or flashes from the heat pipe evaporator. Great care must be exercised during this type of testing since the evaporator is covered by the RF inductive coil making visual inspection difficult. Figure 11 illustrates the expected transients for a typical performance test cycle using the test matrix condition F(-4) at two environmental test chamber gas mixtures.

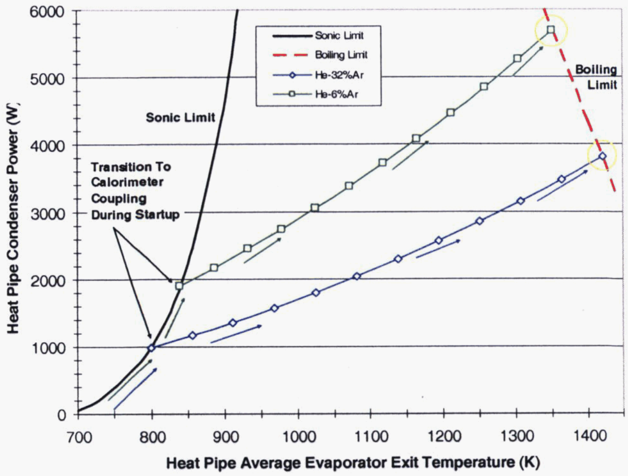

Figure 11. Typical operating trend for heat pipe performance testing.

Successful completion of performance testing indicates that the heat pipe is ready for use in the accelerated life test matrix. However prior to this testing the heat pipes must be vacuum heat treated at high temperature to assure uniform wetting of all wick surfaces with sodium (no residual effect of the performance test). Since the heat pipes will be tested in clusters during life test operations, a minimum of five heat pipes must be readied before initiating a life test sequence.

The typical accelerated life test operation follows the first two stages described for the performance test namely tracking of the sonic limit curve during startup followed by a transition (due to calorimeter coupling limit) across the operating envelope. Power is increase until it reaches the required operating condition; during this interval the heat pipe temperature will increase (based on calorimeter gap width) to the final steady-state conditions. A typical startup transient is estimated to required 1 to 2 hours, once at steady-state condition it will be maintained for up to 6 months (the nominal inspection interval). The test setup makes use of an autonomous control/data system to monitor operations and record test data. In the event of power outages/facility interruptions or heat pipe temperature, power or pressure excursions this control system will safely shut down the operation. Figure 12 shows the typical transients and final test points expected for several test matrix conditions. It is noted that several of these conditions are in close proximity to the boiling limit curve.

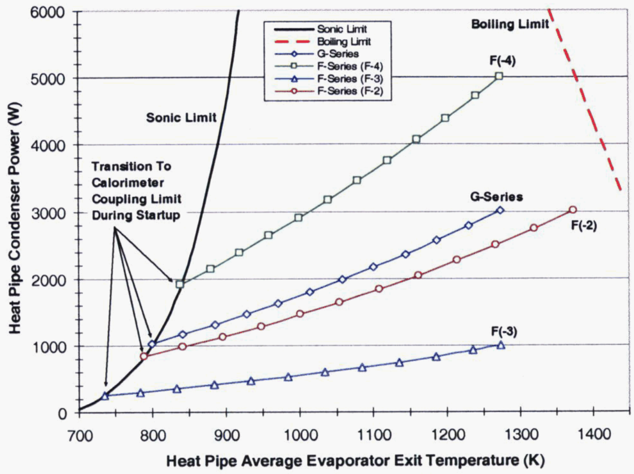

Figure 12. Typical operating trend for heat pipe life testing.

Heat pipe inspections are planned at approximate 6-month intervals to accumulate data early and often in the program. These tests will include a combination of non-destructive and destructive evaluations (NDE/DE). Initial baseline inspections would be taken for all heat pipes to gather data on the "as-fabricated" condition. The method currently envisioned for NDE is a 3-D X-Ray tomography technique such as that provided by HYTEC Inc. To accurately compare data collected from the heat pipe units throughout the three years of expected testing, two or more fiducials shall be placed on each unit. This will allow for accurate alignment of x-ray images taken at each inspection interval so that changes can be readily interpreted. The HYTEC inspection technique has a native resolution of 0.004 inches (0.01 cm) and would need to be extended to enable measurements <0.002 inches (0.005 cm) to resolve expected distortions or corrosion. Figure 13 illustrates a sample HYTEC analysis for a stainless steel heat pipe mesh wick used in the SAFE-30 heat pipes[11]. This wick has a diameter of approximately 2.22 cm and is composed of 400x400 mesh wire with a diameter of 0.025 mm (resolution in this examination approaches 0.004 inches).

Figure 13. HYTEC 3-D X-Ray tomographic examination of a SAFE-30 wick structure.

VII. SUMMARY

The proposed Mo-Re/Na heat pipe design and test matrix systematically addresses the issues related to corrosion rates at operating temperatures anticipated for space nuclear operations. Data could be expected within 6 months of starting the first heat pipe, providing early indications of the aging effect. Confidence is established in extrapolations as additional data is obtained over the course of the planned 3-year operation. This approach also provides insight into possible random manufacturing and processing defects. To minimize program cost, the heat pipes are shortened versions of a flight prototype. To reduce the number of test chambers and ancillary equipment required the heat pipes were arranged in clusters of five units for testing. Planned power throughput covers a range from 1000 to 5000 W with temperatures range from 1173 K to 1373 K. Performance testing of the initial heat pipes will be necessary to determine if the high power/temperature conditions in the test matrix can be achieved. Radio frequency heating was chosen as the method to power the heat pipe evaporators requiring a number of series inductors that operate below voltage breakdown limits. To absorb energy from the heat pipe condenser a static gas gap coupled laminar flow water calorimeter concept appears feasible. Initial analysis of the coupling gas purity indicates that an oxygen level on the order of 0.1 ppb (within the test chamber) is required for consistency with vacuum testing conditions (10^{-6} torr range) typically used for Mo-Re alloys. Additionally, significant progress was made related to fabrication of an annular wick structure. This wick was fabricated from Mo-5%Re screen material (400x400 mesh) by a hot isostatic pressing (HIP) technique producing a final product with a maximum pore radius of 22 microns while retaining ductility. Execution of the described accelerated heat pipe life test project was terminated due to a shift in program direction.

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NOMENCLATURE

d_o	=	heat pipe diameter (m)
A	=	heat pipe channel width (cm)
d	=	heat pipe diameter outside (m)
D_i	=	heat pipe inside diameter (m)
G	=	mass flux (kg/cm^2-sec)
h_{fg}	=	latent heat of vaporization (J/kg)
ΔH	=	activation energy (J/mole)
k	=	thermal conductivity (W/m-K)
L_a	=	adiabatic length (cm)
L_c	=	heat pipe condenser length (cm)
L_e	=	heat pipe evaporator length (cm)
M''	=	mass fluence (kg/cm^2)
q	=	applied evaporator power (W)
q_{rad}	=	radial heat flux (W/cm^2)
Q	=	design heat pipe power (W)
r	=	wick pore radius (micron)
R	=	universal gas constant (J/mole-K)
T	=	temperature (K)
T_0	=	design temperature (K)
$\alpha(T)$	=	normalized Arrhenius diffusion rate
τ	=	time (sec)

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