Multiple Restart Testing of a Stainless Steel Sodium Heat Pipe Module

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Abstract. A heat pipe cooled reactor is one of several candidate reactor cores being considered for space power and propulsion systems to support future space exploration activities. Long life heat pipe modules, with designs verified through a combination of theoretical analysis and experimental evaluations, would be necessary to establish the viability of this option. A hardware-based program was initiated to begin experimental testing of components to verify compliance of proposed designs. To this end, a number of stainless steel/sodium heat pipe modules have been designed and fabricated to support experimental testing of a Safe Affordable Fission Engine (SAFE) project, a 100-kWt core design pursued jointly by the Marshall Space Flight Center and the Los Alamos National Laboratory. One of the SAFE heat pipe modules was successfully subjected to over 200 restarts, examining the behavior of multiple passive freeze/thaw operations. Typical operation included a 1-hour startup to an average evaporator temperature of 1000 K followed by a 15-minute hold at temperature. Nominal maximum input power during the hold period was 1.9 kW. Between heating cycles the module was cooled to less than 325 K, returning the sodium to a frozen state in preparation for the next startup cycle.

INTRODUCTION

Ambitious space exploration will require systems that provide high specific power; nuclear fission can provide a near term method to meet these needs (Houts, 2000). Development of robust fission power systems will offer a power rich environment that will extend the life and capability of future missions. One of several potential concepts that could be used for a reactor's primary heat transfer is an alkali metal heat pipe system (Houts, 2001). To address near term issues with an early hardware program, the Marshall Space Flight Center initiated an effort to examine a heat pipe system (Van Dyke, 2001). One of these systems, referred to as the Safe Affordable Fission Engine (SAFE), is a 100-kWt Los Alamos National Laboratory design that makes use of 61 stainless steel/sodium heat pipe modules operating at a nominal temperature of 973 K (Houts, 2003) (Van Dyke, 2004). Infrastructure has been established to fabricate, fill, process, and evaluate the heat pipe modules at a component level (Martin, 2004a). A majority of the SAFE-100 heat pipe modules fabricated have been incorporated into the SAFE-100a system, which is currently in test (a configuration identical to the SAFE-100 with the exception that only the central 19 heat pipe modules are used). However, several additional modules were fabricated and are available to support other activities. In an effort to continue evaluation of the capabilities of alkali metal heat pipes, a number of tests are planned using the additional SAFE-100 units. Planned tests include: multiple passive freeze/thaw (startup transient), high power performance, and accelerated life evaluation. The first experiments initiated was the multiple freeze/thaw testing since it was the simplest system to configure. The hardware, control and data systems, along with the lessons learned, shall be fed into the other experiments. Testing with the stainless steel heat pipes also serves as an excellent forerunner to the fabrication and testing of higher temperature (and more delicate) refractory metal heat pipe modules.

APPROACH

The focus of this effort was to conduct a set of simple hardware based experiments to demonstrate multiple restart capability of an alkali metal heat pipe. To meet this goal (moving as rapidly as possible into testing), the use of existing program resources was maximized. The module selected was a SAFE-100 unit since additional units were fabricated during the buildup of the SAFE-100a reactor core, making it a good candidate for initial evaluation. The following sections provide detail regarding the test hardware and evaluation process.

HEAT PIPE MODULE SETUP AND OPERATION

SAFE-100 Heat Pipe Description

The SAFE-100 heat pipe (Ring, 2002 and 2003) consists of the primary heat pipe tube surrounded by three fuel tubes set at 120° intervals forming the evaporator section (Figure 1). All material is stainless steel 316 with a diameter of 1.59 cm and a wall thickness of 0.89 mm. The evaporator and condenser are of nearly equal lengths, with dimensions of 58.4 cm and 55.9 cm, respectively. The heat pipe internal capillary channel was formed by a crescent annular wick composed of 7 layers of 400-mesh 304L stainless steel screen with a wire diameter 0.03 mm. Bubble point tests of the assembled wick structure (using ethyl alcohol and helium pressurant) measured a maximum wick pore diameter of 16 μm. The final geometry leaves a 0.6-mm annular-liquid flow gap between the module inner wall and outer edge of the wick. The three fuel tubes are bonded to the heat pipe envelope using a Hot Isostatic Pressing (HIP) technique to diffusion bond the parts. Each module was evacuated and filled with 35 to 38 grams of sodium working fluid. Design throughput at 1000 K is 12 kWt, providing significant margin over the required 1.6 kWt needed on the SAFE-100 design. The particular heat pipe module selected for the cyclic testing was one of the original program modules and had approximately 600 hours of operation prior to being used for cyclic testing. This particular module was also gas-loaded (approximately 40 torr of argon). The gas was introduced into the module from the protective fill stem cap when a fill stem closeout weld failed during one of the first high temperature (1000 K) operations prior to use in the current cyclic test program. The argon trapped in the protective fill stem cover originated from the fill machine glove box environment (Martin, 2004b) where both oxygen and water vapor concentrations are maintained less than 1 ppm. The result of gas-loading was a reduction in the active condenser length by approximately 10%. This particular module was selected since it represents a worst-case condition with both gas-loading and a failed weld, a planned follow-on test will evaluate a non-gas loaded module.

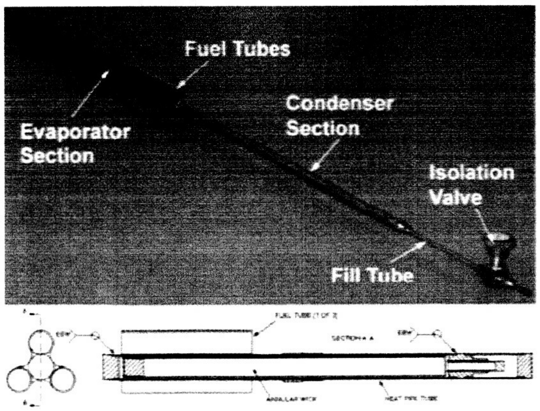

FIGURE 1. Heat Pipe Layout and Schematic.

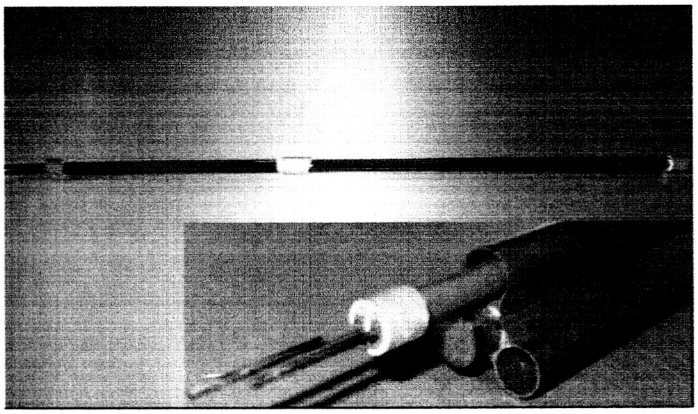

FIGURE 2. POCO Graphite Heating Element.

Hardware Configuration

The heat pipe module was equipped with three POCO graphite-style heater elements (Figure 2) and a total of 16 type-K thermocouples (Figure 3) positioned along the evaporator, condenser and surroundings. The evaporator section was surrounded by Insulfrax® and aluminum foil as insulation to minimize heat losses. The module was mounted on a frame structure positioned horizontally within the test chamber to minimize gravitational effects during the freeze/thaw process. Power was supplied to the three series connected heater elements using a Lambda ESS power supply rated for a maximum output of 15 kW at 150 VDC. The power supply and thermocouple instrumentation was coupled to a National Instruments (NI) SCXI system used to both monitor and control operations. A LabVIEW based data acquisition and control (DAQ) routine was generated to regulate the power supply and sequence of events allowing for automated around the clock operation. This control routine provided inputs for a number of parameters including: full power level, heating ramp interval, hold interval at full power, target cool down temperature, and number of test cycles. The control routine was equipped with a number of safety parameters and continuously monitored thermocouples for both over temperature and open conditions (loss of signal), and the power supply for over/under voltage and current status (generated in the event of an open or short condition). Any violation of these specified safety perimeters resulted in immediate shut down of the power supply and a request for operator intervention.

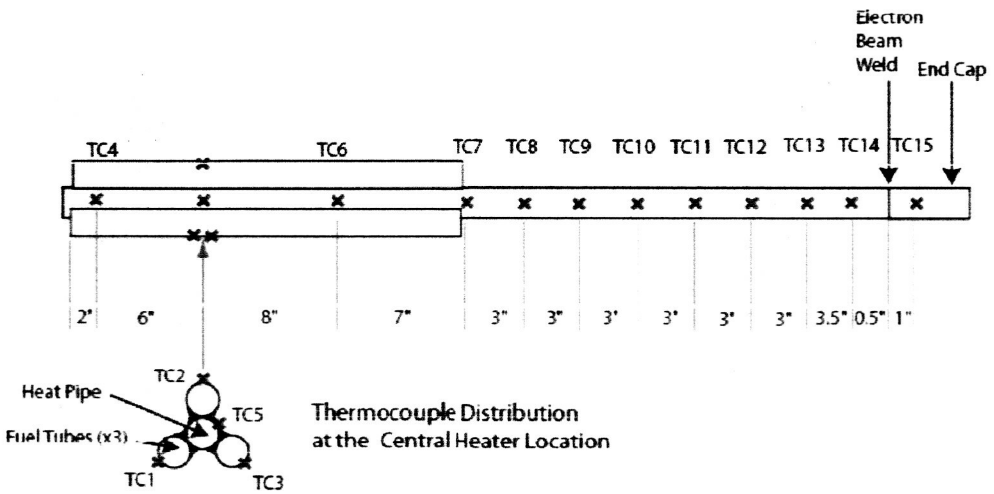

FIGURE 3. Thermocouple Locations on Heat Pipe.

The instrumented module was placed inside a vacuum test chamber that was evacuated to less than 10^{-4} torr using a turbo/roughing pump combination and then back filled with a mixture of approximately 400 torr argon/100 torr helium to improve coupling of the heaters to the evaporator, and condenser to the environment. Three fans mounted above the test chamber cool its outer surface; maximum chamber surface temperature reached during any heating cycle was approximately 100 °C (directly above the exposed heat pipe condenser). To assist in cooling the heat pipe during the power off phase a small 240 cfm electric fan was positioned at the evaporator end, providing forced convection flow along the length of the heat pipe; the fan reduced the cool down interval by approximately 1 hour. Figure 4 shows the complete experimental set up including test chamber, power supply, and DAQ system.

Testing Sequence

The automated control routine sequences the events and monitors both temperature and power parameters to achieve safe around the clock operation of the cyclic test hardware. A typical sequence includes the following steps:

1) Linear power ramp from 0 to 1900 W over a 1-hour interval producing an average heat pipe evaporator/condenser temperature of approximately 725 °C.
2) Steady state hold at 1900 W for a period of 900 seconds maintaining the 725 °C condition (the module design condition).
3) Cooling period of roughly 2.5 hours controlled by a target heat pipe temperature set to 50 °C. This temperature was selected as sufficiently low to allow all sodium to freeze such that the next cycle begins from a frozen state for consistency.

The average cycle time (based on the 214 tests performed) was 3 hrs 37 minutes. To create manageable data files, the typical data sampling interval was set to 1 sample every 10 seconds and a total of 15 startup cycles were sequenced per test segment. After completing a segment, the program automatically shuts down the test hardware, allowing the operator to download the data and then restart it for the next segment of 15 cycles. The control program provides status displays allowing the operator to view current and average heat pipe module conditions, program status, and long-term cycle trends (Figure 5).

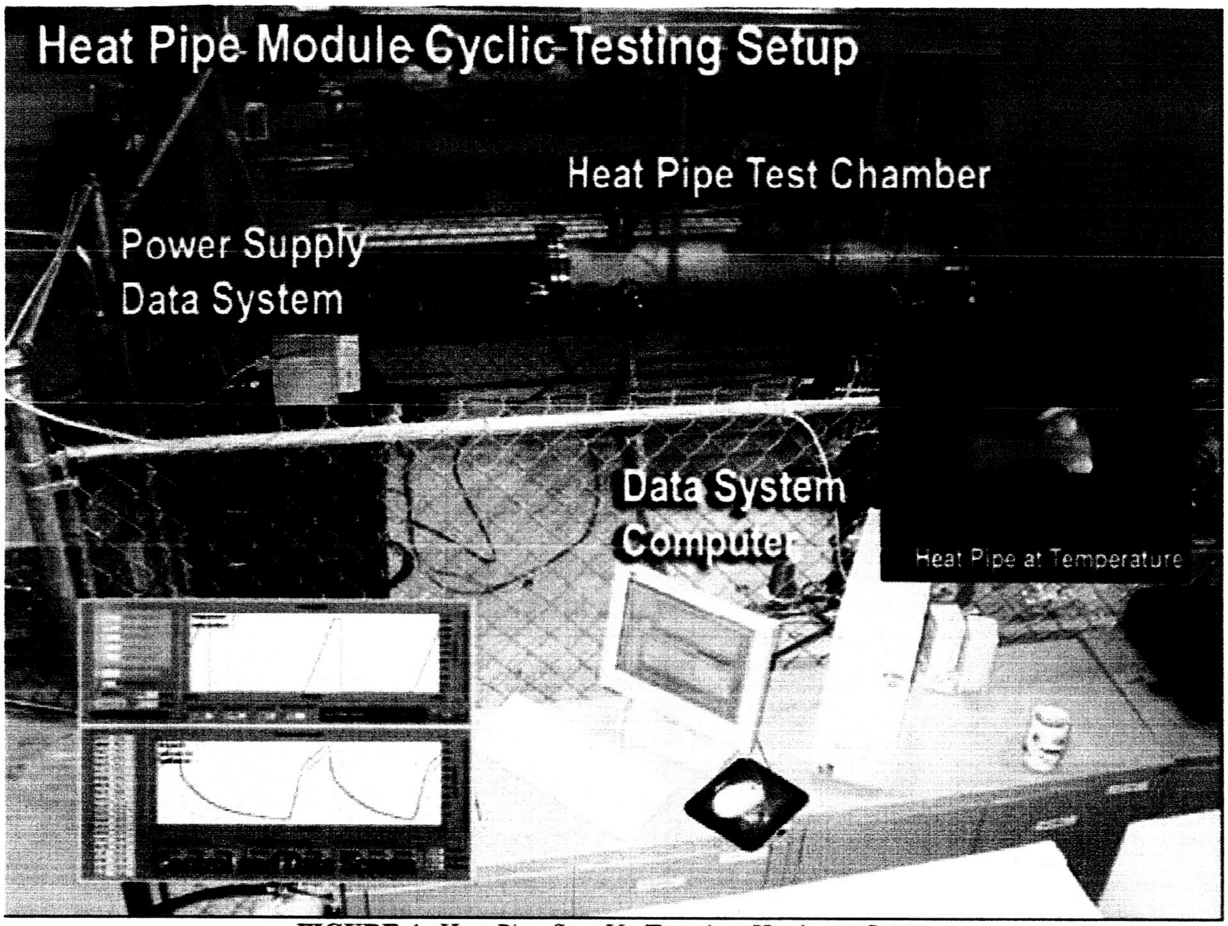

FIGURE 4. Heat Pipe Start Up Transient Hardware Setup.

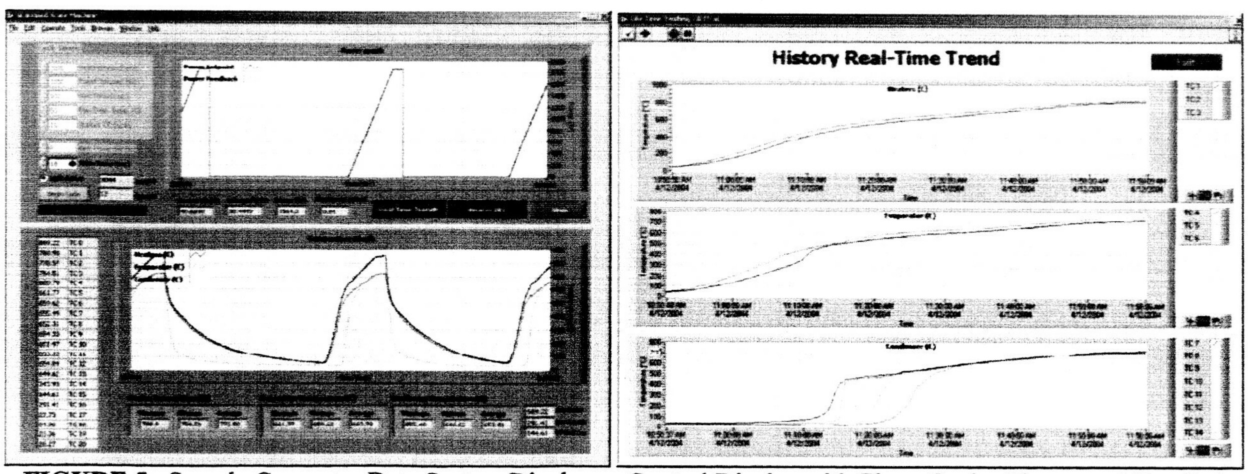

FIGURE 5. Sample Computer Data System Displays – Control Display with Three Cycles Shown and Detailed Module Display with a Single Startup Shown.

DATA AND RESULTS

The first set of startup tests was initiated in early April 2004 and continued through mid-June 2004. In total, 214 cycles were performed at a constant input power setting of 1.9 kW; approximately 58 additional cycles were performed during the early portion of the cyclic test program at various power levels when hardware setup and operations were being worked out. Overall, the experiment setup and operation produced excellent data and indicates that the passive freeze/thaw transient response behavior of multiple heat pipe restarts was highly repeatable and predictable.

Heat Pipe Start Up

Figure 6 illustrates a typical heat pipe condenser startup with distance measurements referenced to the evaporator exit. As power was added to the evaporator (during the first 25 minutes), temperature trends on the condenser section show a slow axial warming; a result of solid conduction in both the metal heat pipe envelope and sodium working fluid. Once the evaporate temperature reaches approximately 850 K there was sufficient vapor pressure to rapidly thaw the remaining condenser and its temperature begins to rise isothermally as power was added. It is noted that in Figure 6, the last 10 cm of heat pipe condenser are at a lower temperature due to the presence of argon gas. The gas was compressed to the end of the condenser by the rising sodium vapor pressure (approximately 350 torr at the final evaporator temperature of 1000 K).

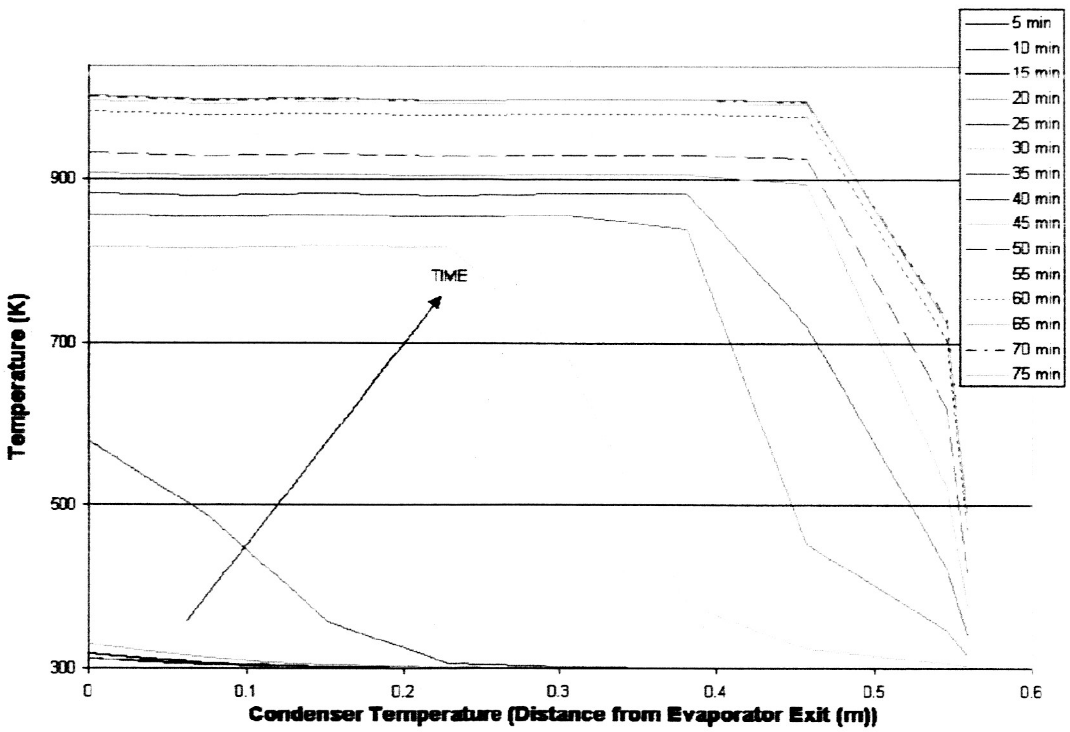

FIGURE 6. Heat Pipe Condenser Temperature Histories During Startup.

Heat Pipe Cycle Testing

Restart reliability of the SAFE-100 heat pipe was demonstrated through a sequence of multiple passive freeze/thaw experiments. It is noted that during the two months of testing a variety of instrumentation and power system failures occurred. These failures included broken thermocouples and loose power leads, and the automated control routine rapidly responded by terminating test operations. However, no problems of any type were encountered with the heat pipe during this period; it behaved as anticipated. The heat pipe module achieved its primary test objective – namely surviving over 200 passive freeze/thaw cycles. Data samples for average evaporator and condenser temperatures were compared for test intervals 25, 50, 75, 100, 125, 150, 175 and 200 and are graphically illustrated in Figure 7. These data show the trends in both temperature and startup performance timing; demonstrating that the module behavior during both the heating phase and hold period was very reproducible. The cool down also tracked well but tended to fan out slightly at lower temperatures (300 °C and below), most likely due to variations in the ambient conditions that affected the surface temperature of the test chamber. An item to note is the random fluctuation in evaporator/condenser temperatures during the heating trend between 725 and 875 K (creates a slight fanning of the data). This was a result of the argon gas-loading in the module; during startup, the low sodium vapor pressure and position of the thaw front are significantly affected by release of gas trapped at random positions in the wick structure (from the previous cooling cycle). These fluctuations typically end at approximately 900 K, when the module was fully thawed and the sodium vapor pressure sufficiently high to confine the argon gas to the last 10 cm of condenser.

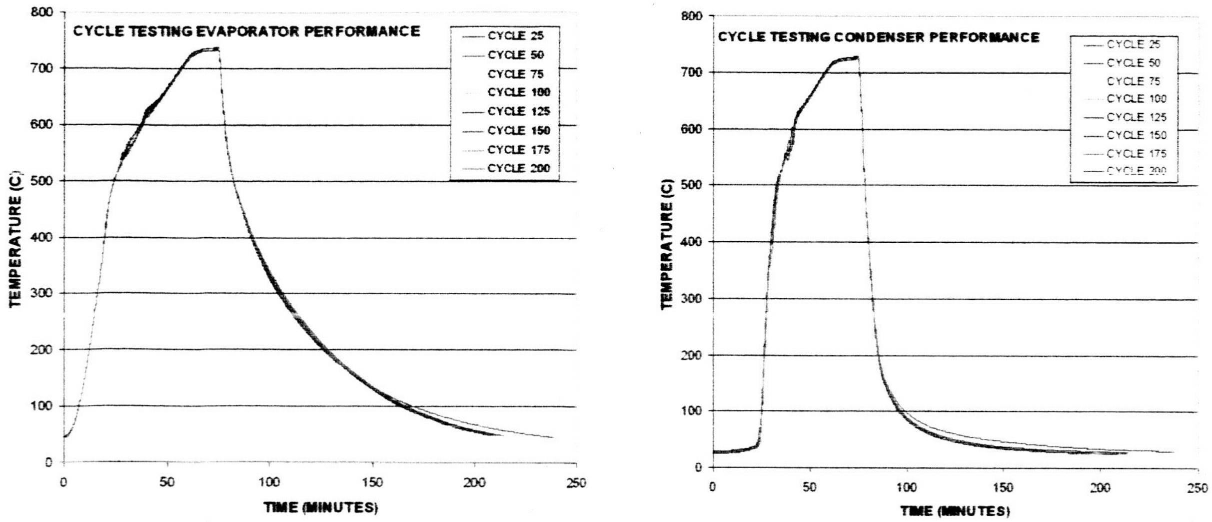

FIGURE 7. Heat Pipe Average Evaporator and Condenser Temperature Histories for Test Cycles 25, 50, 75, 100, 125, 150, 175 and 200.

Performance

Heat pipe performance was assessed for the module during startup and steady state hold operation. A finite difference program was developed to calculate the condenser section thermal losses using the measured experimental data. The condenser was divided into control volumes (as illustrated in Figure 8), which correspond to the locations of thermocouples TC 7 to TC15 (Figure 3). The radiation and convective heat transfer are assessed (eqn. 1) at each of these locations and summed together (eqn. 2) to produce a final axial power throughput for the heat pipe (power flowing from across the evaporator section exit plane).

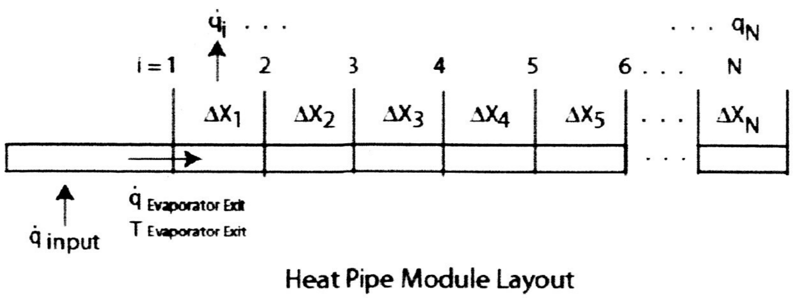

FIGURE 8. Heat Pipe Module Condenser Heat.

$$\dot{q}_i = \varepsilon_i \sigma \pi d_o \left[\frac{\Delta X_i}{5} \left(T_i^4 + T_{i+1}^4 + T_i^3 T_{i+1} + T_i^2 T_{i+1}^2 + T_i T_{i+1}^3 \right) - \Delta x_i T_\infty^4 \right] + h \Delta x_i \pi d_o \left[\frac{(T_i + T_{i+1})}{2} - T_\infty \right] \quad (1)$$

$$\dot{q}_{Total} = \dot{q}_1 + \dot{q}_2 + \dot{q}_3 + \dot{q}_4 + \dot{q}_5 + \dot{q}_6 + \dot{q}_7 + \dot{q}_8 \tag{2}$$

Figure 9 illustrates heat pipe axial power throughput as a function of time covering the startup and hold intervals (final value of approximately 1.6 kW transferred, the nominal expected operating power level for a SAFE-100 heat pipe). The module's experimental performance was also compared to calculated viscous and sonic limits using HTPIPE (Woloshun, 1988), as shown in Figure 10. The variation in the thaw front and condenser surface temperature due to the release and confinement of the argon gas (affecting condenser power loss rate) was evident in the power fluctuations between 725 and 875 K that are shown in the performance. Above 900 K the heat pipe axial power transfer transitions smoothly to the steady state operating condition (module was completely thawed and sodium vapor pressure sufficient to confine the argon to the end of the condenser). It was observed that the heat pipe operates in a sonic limited mode up to approximately 800 K at which point it transitions to a condenser/environment-coupling limit (moving rapidly away from the heat pipe limit curve).

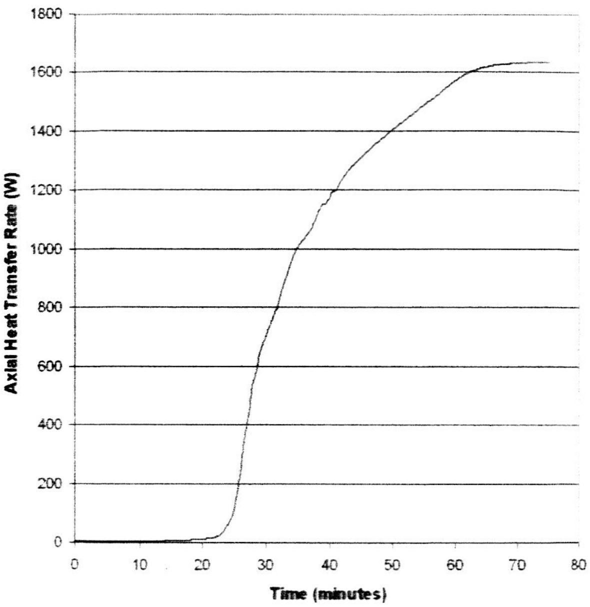

FIGURE 9. Axial Heat Transfer Rate vs. Time.

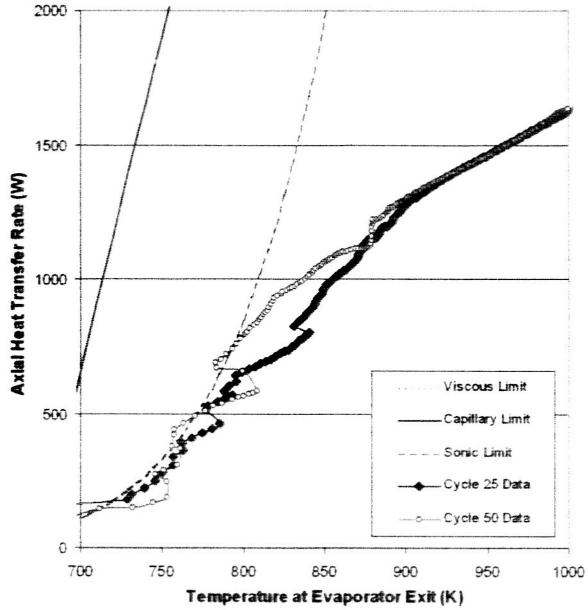

FIGURE 10. Performance (Limits & Experiment).

SUMMARY

A SAFE-100 stainless steel/sodium heat pipe module was successfully subjected to over 200 passive freeze/thaw startup cycles. The particular module selected was a gas-loaded unit containing approximately 40 torr of pure argon. A typical transient cycle included a 1-hour startup to an input power level of 1.9 kW, a 15-minute hold at power (temperature of 725 °C), and followed by cooling to 50 °C to solidify all sodium working fluid. Temperature results show excellent repeatability in all phases of the heat pipe freeze/thaw sequence and no visible physical or performance degradation was observed. The only fluctuations noted are temperature variations during the condenser thaw process as the low vapor pressure competes with the liberated argon gas; fluctuations dampen out when the module completely thaws and the sodium vapor pressure was sufficient to confine the argon to the end of the condenser. In addition, the heat pipe axial power transfer performance was assessed and compared very favorably with limit predictions made using the LANL HTPIPE code. The module was sonic limited up to a temperature of 800 K/700 W, at which point it transitions to a condenser-coupling limit with the environment.

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