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Alkali Metal Heat Pipes for Space Fission Power

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Abstract. Future space transportation and surface power applications will require small fission reactors for power generation. The fission reactors would generate up to 13kW$_t$ of power for the energy conversion system. The heat generated by the reactor would be collected and transferred to a series of Stirling convertors or thermoelectric converters for power generation. This heat collection and transfer can be done by high-temperature alkali-metal heat pipes. Two 1m long sodium heat pipes were designed, fabricated, and tested; a self-venting arterial heat pipe and a grooved heat pipe. Artery de-priming by trapped vapor or non-condensable gas in an artery has been a single point failure for traditional arterial heat pipes. A self-venting arterial heat pipe has a screen artery that contains small venting pores in the evaporator section that allow for any trapped vapor or non-condensable gas (NCG) to escape. ACT has demonstrated that a 1m long, 0.75in. (1.91cm) outer diameter sodium self-venting arterial heat pipe is capable of carrying 3.4kW of power at adverse elevations of 0.1in (0.25cm), 0.3in (0.76cm), 0.6in (1.52cm), 1.0in (2.54cm) and 3.0in (7.62cm) without drying out. The sodium self-venting arterial heat pipe is capable of carrying a maximum transport power of 1.4kW at an adverse elevation of 5.0in (12.7cm). Grooved heat pipes are typically used for spacecraft thermal control, since any NCG in the grooves can easily escape. ACT has also demonstrated that a 1m long, 0.75in (1.91cm) outer diameter sodium grooved heat pipe is capable of carrying 846W, 546W and 346W at adverse elevations of 0.1in (0.25cm), 0.6in (1.52cm) and 1.0in (2.54cm), respectively.

Keywords: Alkali metal heat pipes, arterial heat pipes, space fission reactor thermal control

INTRODUCTION

NASA Glenn Research Center (GRC) is examining small fission reactors for future space transportation and surface power applications (Mason and Carmichael, 2011). The reactors would have an 8 to 15 year design life and could be available for a 2020 launch to support future NASA science missions. Both 1 kW$_e$ thermoelectric (TE) and 3 kW$_e$ Stirling systems have been examined. The proposed design would use alkali metal heat pipes to transfer heat from the reactor to the Stirling or Thermoelectric convertors for electrical energy generation and water heat pipes to transfer the waste heat from the Stirling engines to a radiator panel. Water heat pipes would not be necessarily in the TE version of the fission reactor, due to their much higher heat rejection temperature and smaller radiator area. The heat pipes will need to be several meters long. There are three types of heat pipe wicks that carry significant power over these distances:

1. Arterial heat pipes with sintered powder (or screen) wicks
2. Grooved heat pipe wicks
3. Self-venting arterial heat pipes

Arterial heat pipes have traditionally, been the default design for spacecraft nuclear reactors due to their ability to carry significant power; however, de-priming of the artery due to NCG generation due to radiation in a nuclear reactor is a serious potential problem. If vapor or non-condensable gas (NCG) is generated in the artery of a sintered arterial heat pipe, it will hinder liquid return flow through the artery and will therefore de-prime the heat pipe. There is no method to remove the vapor or NCG from the artery once the heat pipe is operating; therefore re-priming the heat pipe becomes impossible.

Grooved and self-venting heat pipes offer potential benefits over the standard arterial heat pipes in regards to the de-priming issue that may be experienced due to operation in a reactor:

1) The grooves cannot be de-primed due to the liquid flow path being open to the vapor space
2) The self-venting pipes are less susceptible to de-priming due to venting pores located in the evaporator that allow trapped NCG or vapor to escape into the vapor space

One meter long versions of the grooved and self-venting arterial heat pipes were designed, fabricated and tested to transfer the thermal energy from the reactor to the Stirling engines or Thermoelectrics for electrical energy conversion. The heat pipes were fabricated from stainless steel with sodium as the working fluid and were operated at a reduced temperature of 725°C during experimental testing. The two heat pipes were tested at various adverse elevations to an evaporator dry out to determine their maximum transport capability. The sintered arterial heat pipe design was not fabricated and tested due a long standing history of conventional arterial heat pipes working with alkali metals in a non-radiation environment. Grooved and self-venting arterial heat pipes have not previously been tested with alkali metal working fluids.

BACKGROUND – CONSTANT CONDUCTANCE HEAT PIPES (CCHPS)

Sintered Arterial Heat Pipes

As shown in Figure 1a, arterial heat pipes are a variation of a heat pipe wick that utilize one or more arteries and a screen or sintered wick for liquid return. During operation, the condensate flows from the condenser circumferentially to the artery. The liquid is transported through the artery to the evaporator, where the sintered (or screen) wick distributes it. The combination of a single artery with a sintered wick gives the heat pipe the benefit of a wick with high wick permeability and a small pore size, generating a high capillary limit. When the artery is primed (full of liquid), arterial heat pipes can transfer high heat loads over long distances. On the other hand, the heat pipe fails if the artery is de-primed by NCG or vapor generation in the artery.

Arterial heat pipes were historically considered for heat pipes with conventional working fluids, such as water or ammonia. After numerous tests, arterial heat pipes were abandoned for all fluids except the alkali metals, since it was impossible to prevent the artery from de-priming. Artery de-priming is generally due to the formation of an initially small bubble of vapor or NCG in the artery. The bubble expands due to the vaporization of the working fluid once it is transported to the evaporator, effectively blocking the artery. After a de-priming of the artery has occurred there is no method to re-prime the system, creating a single point failure for this type of heat pipe wick design.

a) Arterial heat pipe b) Grooved heat pipes c) Self-venting heat pipe

FIGURE 1. Variations of constant conductance heat pipe wicks that are suitable for use in a nuclear reactor.

Grooved Heat Pipes

One alternate to arteries is the grooved wick, which is the standard wick used in spacecraft Constant Conductance Heat Pipes (CCHPs), Diodes, and Variable Conductance Heat Pipes (VCHPs). The benefit of the grooved wick is that it cannot be de-primed by vapor bubbles because they can vent into the vapor space. Typical aluminum grooved extrusions are shown in Figure 1b. These grooves have a very high permeability, allowing very long heat pipes for operation in zero-g, typically several meters long. Their only flaw is that they are suitable only for space or for gravity aided sections of a heat pipe. The reason is that the same large pore size responsible for the high permeability results in low pumping capability.

As shown in Figure 1b, aluminum heat pipes are typically extruded with very fine grooves. This is possible due to the relatively low yield strength, and high ductility of aluminum. The same process cannot be used with the heat pipe envelopes suitable for use with alkali metals, due to their higher yield strength and lower ductility. ACT has successfully developed a new method for non-aluminum grooved heat pipe fabrication that consists of electrical discharge machining (EDM) the internal grooved structure of the pipe from a solid rod in short sections and orbital welding the sections into a full length heat pipe.

Self-Venting Arterial Heat Pipes

A third potential heat pipe wick is a self-venting arterial heat pipe developed by Goncharov et al. at Lavochkin in Russia (Goncharov et al., 1999, Kaya and Goncharov, 2010); see Figure 1. The artery in this variation of heat pipe is created using a screen wick at the base of the heat pipe envelope that creates a single artery for the liquid return flow. The difference from conventional arterial pipes is small venting pores located on the top of the artery in the evaporator section. If vapor or NCG is introduced into the artery, the venting pores prevent the typical de-priming that would be experienced in a standard arterial heat pipe. Any vapor blockage will travel through the artery and into the evaporator where the venting pores are located. This method of venting vapor or NCG from a heat pipe artery was first introduced by Eninger (1974). The vent pores are designed in a manner that when a blockage occurs the menisci formed on both sides of the venting pore will coalesce to allow the artery to prime. Essentially, the venting pores provide an escape route for any trapped vapor or NCG in the artery. The design eliminates the single point failure nature of previous arterial heat pipes.

The self-venting arterial heat pipe design has been validated in numerous Russian spacecraft, so the TRL level is 9. It is important to note that self-venting ammonia heat pipes have been built and tested in space. This contrasts with conventional arterial heat pipes, which will not work reliably with ammonia.

HEAT PIPE DESIGN

Grooved Heat Pipe and Self-Venting Arterial Heat Pipe Design

A model was developed to generate performance predictions for the grooved and self-venting arterial heat pipes. These performance predictions were then used to determine the overall design of the two 1m (39.37in) long alkali metal heat pipes. An outer diameter of 0.75in (1.91cm) was chosen for both the grooved and self-venting arterial heat pipes. NASA GRC has stated that they would like the heat pipe's outer diameters to be under 0.50in (1.27cm) in diameter, however, a larger diameter was desired for preliminary testing.

An evaporator length of 10.0in (25.4cm) and a condenser length of 8.0in (20.3cm) were chosen for both the grooved and self-venting arterial heat pipes. Capillary, entrainment and sonic limits were calculated for the grooved and self-venting arterial heat pipes. The results for the limiting power (entrainment limit) and design power (capillary limit) for the grooved and self-venting arterial heat pipes can be seen in Figure 2. The self-venting arterial heat pipe's lowest power limitation is 2.1kW for a temperature of 900K and is limited by entrainment. The self-venting arterial heat pipe is capable of transporting 5.7kW of power at the highest temperature of 1100K. The self-venting arterial heat pipe is capable of transporting approximately 3.6kW of thermal power, at the operating temperature of 998K. The grooved heat pipe's lowest power limitation is 550W for a temperature of 900K and is limited by entrainment. The grooved heat pipe is capable of transporting 1.5kW at the highest temperature of 1100K. The grooved heat pipe is capable of carrying approximately 995W of power at the operating temperature of 998K. The grooved heat pipe and self-venting arterial heat pipe are limited by the entrainment limit for the entire operating temperature range. The break in the capillary limit seen in Figure 2 is due to a transition from laminar to turbulent.

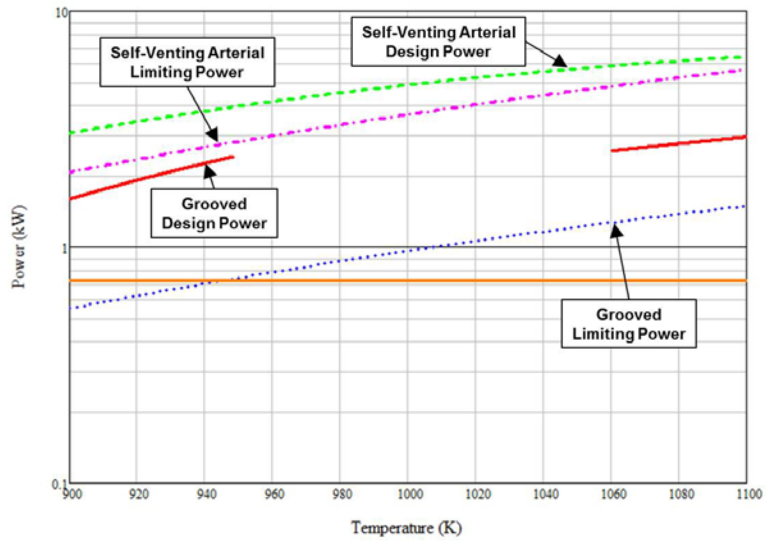

FIGURE 2. Heat pipe performance predictions for a 0.75in (1.91cm) outer diameter grooved heat pipe and a 0.75in (1.91cm) outer diameter self-venting arterial heat pipe operating in a horizontal position on earth.

EXPERIMENTAL TESTING

Heat input to the grooved and self-venting arterial heat pipe was provided by a heater block. The heater block was machined from stainless steel and accommodates eight, 750W embedded cartridge heaters. A condenser block, similar to the heater block, was machined from stainless steel. A Liquid Nitrogen (LN) Dewar was connected to the condenser block to provide cooling. The grooved heat pipe and the self-venting arterial heat pipe were tested separately using the same test assembly; see Figure 3. Both heat pipes were insulated (not shown in Figure 3) with multiple layers of Kaowool to reduce the overall heat losses from the system.

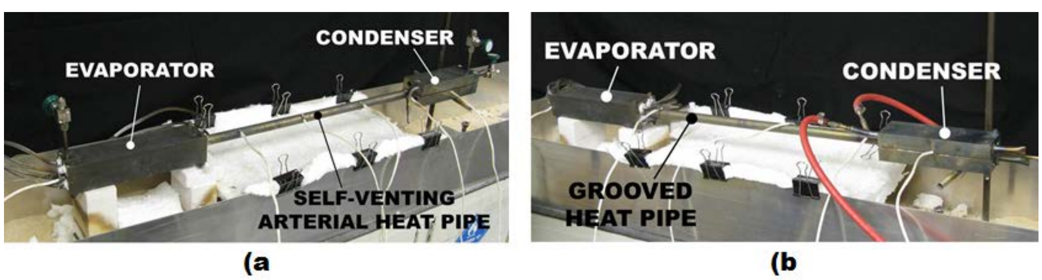

FIGURE 3. Grooved heat pipe and self-venting arterial heat pipe on test stand.

Heat loss testing was performed prior to thermal performance testing. It is essential to accurately determine the heat losses from the system in order to calculate the transported power for the heat pipe. Testing was performed for both the grooved and self-venting arterial heat pipes. The heat losses for a heat pipe with an 8.0in (20.3cm) condenser were then calculated as 80% of the total heat losses. The heat losses at an operating temperature of 725°C for the grooved and self-venting arterial heat pipes are 554W (grooved) and 586W (self-venting arterial), respectively. These values were used to determine the total power transported by both heat pipes during performance testing. The variations observed during heat loss testing are due to an increased amount of Kaowool used on the grooved heat pipe compared to the self-venting arterial.

Thermal performance testing was performed for both heat pipes to determine their overall maximum transport capabilities and compare with predictions. The heat pipe is operated until dry out occurs to determine the maximum transport capabilities. Dry out is indicated by a sudden spike in the evaporator or heater temperature. Thermal performance testing is performed at adverse elevations where the evaporator is positioned higher than the condenser, forcing the heat pipe to operate against gravity. The following adverse elevations were used for both the grooved heat pipe and the self-venting arterial heat pipe; 0.1in (0.25cm), 0.6in (1.52cm), 1.0in (2.5cm). For the self-venting arterial heat pipe, the adverse elevations were increased to 2.0in (5.1cm), 3.0in (7.6cm) and 5.0in (12.7cm). The heat pipes were tested at a reduced operating temperature of 725ºC. The required operating temperature for the heat pipes in a nuclear reactor will be 827ºC (1100K); however, stainless steel was used as the envelope for these proof-of-concept tests at reduced temperature, due to the high cost of the superalloys that can operate at higher temperatures.

EXPERIMENTAL RESULTS

Self-Venting Arterial Heat Pipe

The self-venting arterial heat pipe was tested in two orientations; artery up and artery down. A visual representation of these two orientations can be seen in Figure 4. Testing was performed for both orientations to determine if the artery location had an impact on heat pipe performance. The artery up orientation provides the more difficult test conditions of the two.

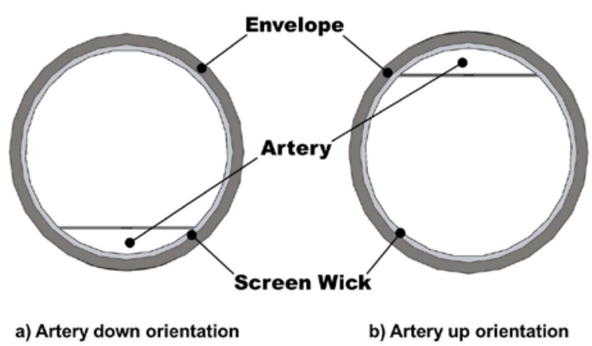

FIGURE 4. Self-venting arterial heat pipe artery orientation during testing.

A TC map for both the grooved heat pipe and self-venting arterial heat pipe can be seen in Figure 5. Figure 6 shows the startup of the self-venting arterial heat pipe operating 0.1in (0.25cm) against gravity, with the artery down. An initial power input of 2.0kW was applied to the system. As seen in the figure, the evaporator and heater block temperature being to steadily increase. The system begins to warm up and the sodium in the evaporator begins to evaporate and generate vapor. This vapor then begins to travel the length of the heat pipe to the condenser. This is observable during testing as a sudden increase in temperature at the various TC locations. As seen in the figure, the evaporator warms up first, then TC2, TC3, TC4, TC5 and then finally the condenser as the vapor moves the full length of the heat pipe. The heat pipe temperatures eventually begin to isothermalize, as seen in the figure around 100min. The condenser temperature remains slightly lower than the rest of the heat pipe due to the LN fed cooling block attached to it.

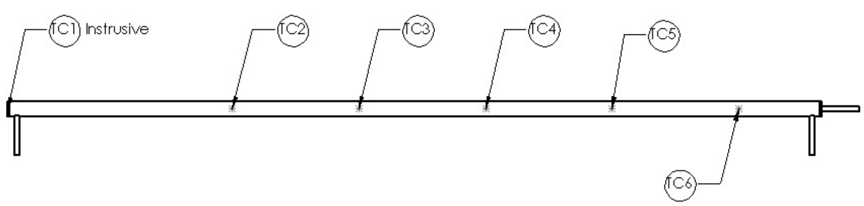

FIGURE 5. TC map for the grooved heat pipe and self-venting arterial heat pipe.

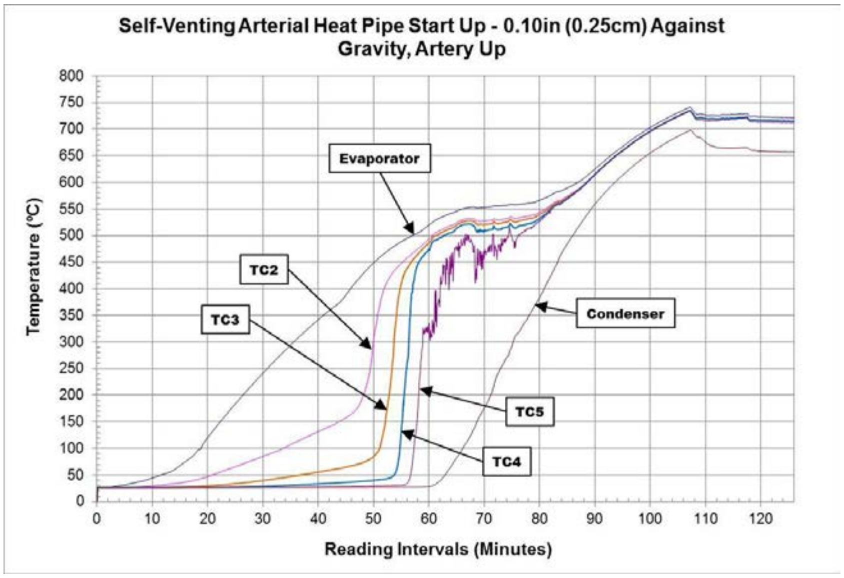

FIGURE 6. Self-venting arterial heat pipe startup, operating at 0.1in (0.25cm) against gravity with the artery up.

The heat pipe was tested in the artery-down orientation for only two adverse elevations because the artery-up condition provides the most difficult operating conditions for the heat pipe. Theoretically, if the heat pipe is capable of transporting a certain power in an artery-up condition, the performance will only improve if it is rotated to the artery-down condition. For this reason, testing of the artery down for the higher adverse elevations was deemed unnecessary.

A selection of thermal performance results for the self-venting arterial heat pipe can be seen in Figures 7 through 9. The self-venting arterial heat pipe was capable of transporting 2.4kW to 2.6kW of power for the adverse elevations of 0.1in (0.25cm) to 3.0in (7.6cm). The thermal performance results for the 0.1in (0.25cm) adverse elevation for both artery up and artery down conditions can be seen in Figure 7 and Figure 8. Dry out of the heat pipe was not achievable until 5.0in (12.7cm) adverse elevation due to insufficient cooling capabilities; see Figure 9. The maximum power transport at capability was 1.4kW. A summary of the tested adverse elevations and their maximum power can be seen in Table 2.

TABLE 1. Adverse elevations and maximum powers for the 0.75in (1.91cm) self-venting arterial heat pipe.

Adverse Elevation	Artery Location	Maximum Power	Limiting Factor
0.1in (0.25cm)	Down	2.6kW	Test Apparatus
0.6in (1.52cm)		2.6kW	Test Apparatus
0.1in (0.25cm)	Up	2.6kW	Test Apparatus
0.6in (1.52cm)		2.6kW	Test Apparatus
1.0in (2.5cm)		2.4kW	Ran Out of LN
2.0in (5.1cm)		2.6kW	Test Apparatus
3.0in (7.6cm)		2.6kW	Test Apparatus
5.0in (12.7cm)		1.4kW	Dry Out

For all testing conditions, the evaporator was maintained at a steady operating temperature of 725ºC. A reduced overall transport power was measured for the 2.0in (5.1 cm) adverse elevation case because the test was stopped early due to a lack of LN. It is safe to assume that a transport power of 2.6kW would also be achievable for the 2.0in (5.1cm) adverse elevation condition. The self-venting arterial heat pipe performed extremely well for all testing conditions. The artery orientation did not have a significant impact on heat pipe performance. The increased adverse elevations also did not have a significant impact on heat pipe performance, with the exception of the 5.0in (12.7cm) adverse elevation case. A transport power of 2.6kW was achieved for all testing conditions, with the exception of the 5.0in (12.7cm) case, where a maximum transport power of 1.4kW was determined.

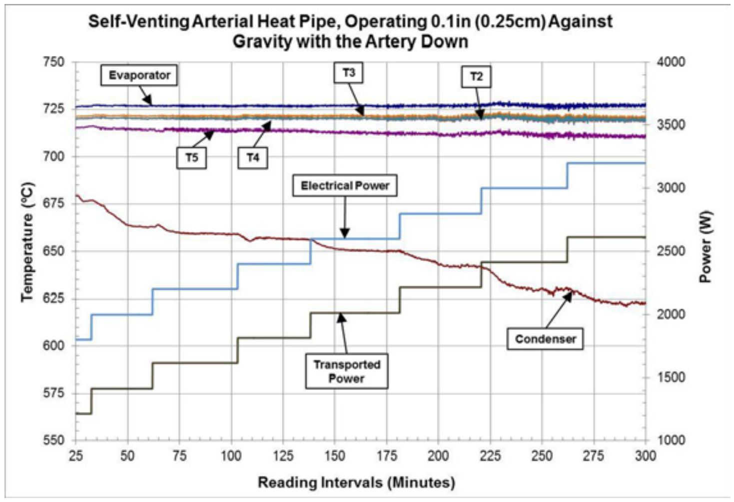

FIGURE 7. Self-venting arterial heat pipe performance operating at 0.1in (0.25cm) against gravity, artery down.

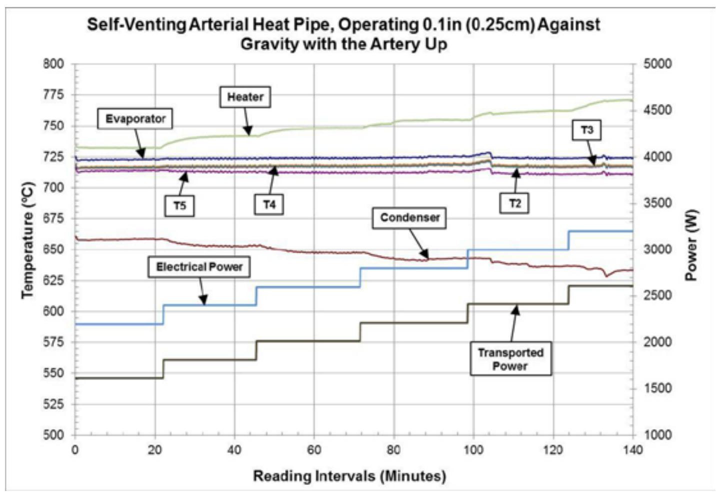

FIGURE 8. Self-venting arterial heat pipe performance, artery up with a 0.1in (0.25cm) adverse elevation.

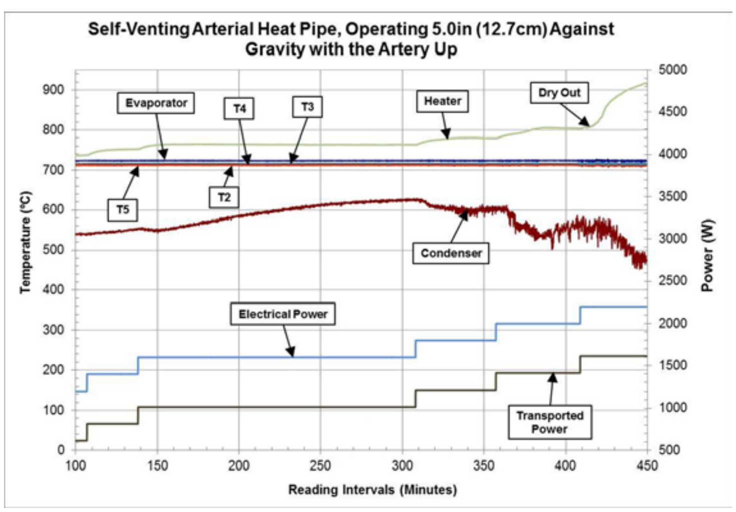

FIGURE 9. Self-venting arterial heat pipe performance, artery up with a 5.0in (12.7cm) adverse elevation.

Grooved Heat Pipe

Figure 10 shows the startup of the grooved heat pipe. An initial power input of 1.0kW was applied to the grooved heat pipe. As seen in the figure, the evaporator and heater temperatures are the first to steadily increase. As the vapor begins to be generated in the evaporator and move to the condenser, the remaining TCs increase in temperature. The condenser temperature is the final temperature to increase. The heat pipe finally reaches a uniform temperature around 225min. The grooved heat pipe takes longer to start up, compared to the self-venting arterial heat pipe. The large ΔT between the evaporator and remaining TCs observed in the middle of the figure is caused by increasing the power into the system too rapidly. It assumed that this may be an indication of some dry out. The power was decreased slightly and, as seen in the figure, the temperatures began to isothermalize.

TABLE 2. Adverse elevations and maximum powers for the 0.75in (1.91cm) grooved heat pipe.

Adverse Elevation	Maximum Power	Limiting Factor
0.1in (0.25cm)	846W	Dry Out
0.6in (1.52cm)	546W	Dry Out
1.0in (2.5cm)	346W	Dry Out

An example of the thermal performance results for the grooved heat pipe can be seen in Figure 11. For all testing conditions, the evaporator was maintained at a steady operating temperature of 725ºC. The grooved heat pipe was operated until dry out for all testing conditions. At an adverse elevation of 0.1in (0.25cm), the grooved heat pipe was capable of transporting 846W of power, while it transported 546 W of power at an adverse elevation of 0.6in (1.52cm). The dry out is easily indicated in Figure 11 by the sudden increase in evaporator and heater temperatures and the sudden decrease in the condenser and remaining TCs. At an adverse elevation of 1.0in (2.5cm) against gravity, the grooved heat pipe was only capable of transporting 346W of power. A summary of the testing conditions and the maximum powers achieved can be seen in Table 3. The grooved heat pipe was significantly impacted by the increase adverse elevation. This tends to be true of grooved heat pipes as they are only suitable for zero-g or gravity aided applications. The same large pore size responsible for the high permeability results in low pumping capability and therefore the maximum transport capability will be affected by increasing adverse elevations.

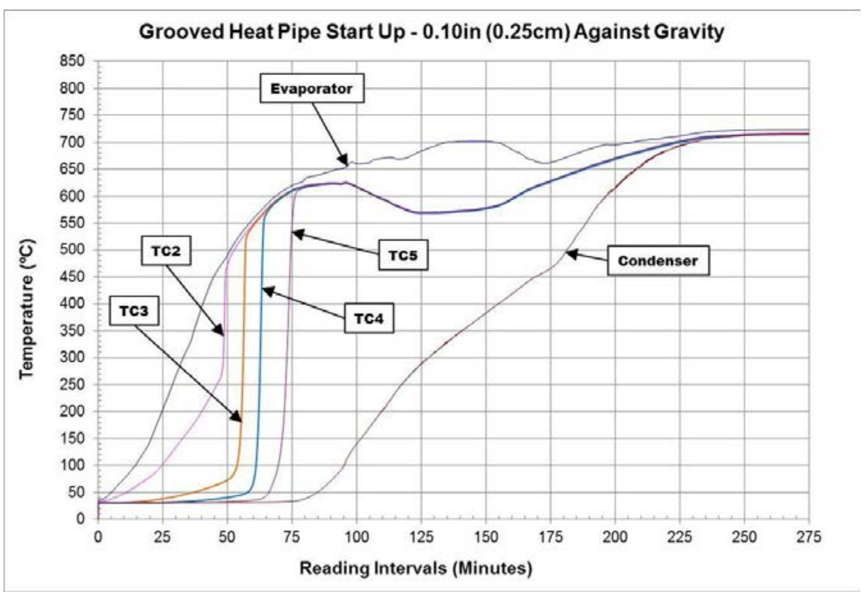

FIGURE 10. Grooved heat pipe start up, operating at 0.10in (0.25cm) against gravity.

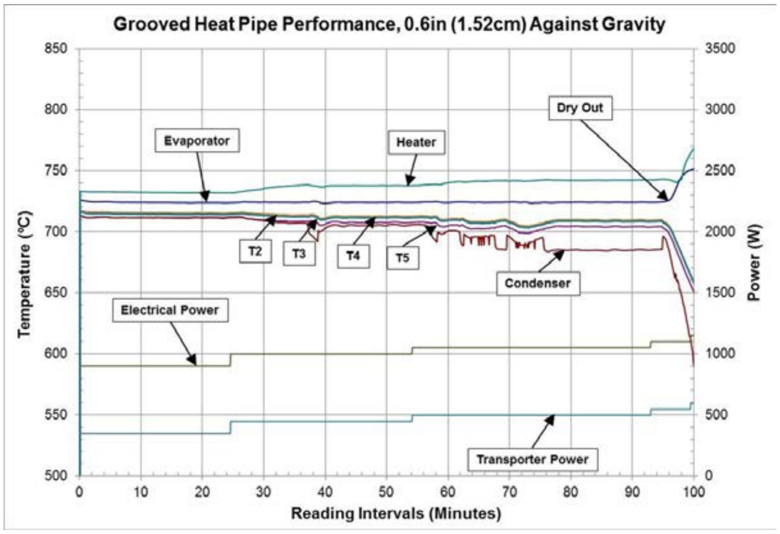

FIGURE 11. Grooved heat pipe performance, operating at 0.6in (1.52cm) against gravity.

Self-Venting Arterial Heat Pipe and Grooved Heat Pipe Results Summary

Thermal performance testing was conducted on both the self-venting arterial heat pipe and the grooved heat pipe to determine their maximum transport capability. The intention was to run each case until dry out condition. At the lower adverse elevations, dry out was not achievable for the self-venting arterial heat pipe due to insufficient cooling capacity. At a 5.0in (12.7cm) adverse elevation, dry out was experienced at 1.4kW. The self-venting arterial heat pipe was capable of at least 2.4 to 2.6kW of transported power for all testing conditions, except 5.0in (12.7cm) adverse elevation. Its performance did not appear to be affected by the artery orientation. The grooved heat pipe was capable of transporting 846W of power for an adverse elevation of 0.1in (0.25cm), 546W of power for an adverse elevation of 0.6in (1.52cm) and 346W of power for an adverse elevation of 1.0in (2.5cm). Dry out was achievable for all testing conditions of the grooved heat pipe and therefore the maximum transport capability has been determined. The grooved heat pipe was significantly affected by the increased adverse elevations. It had a decrease in maximum transport capability of 500W from 0.1in (0.25cm) to 1.0in (2.5cm) adverse elevations. A summary of the thermal performance results for both heat pipes for all testing conditions can be seen in Figure 12.

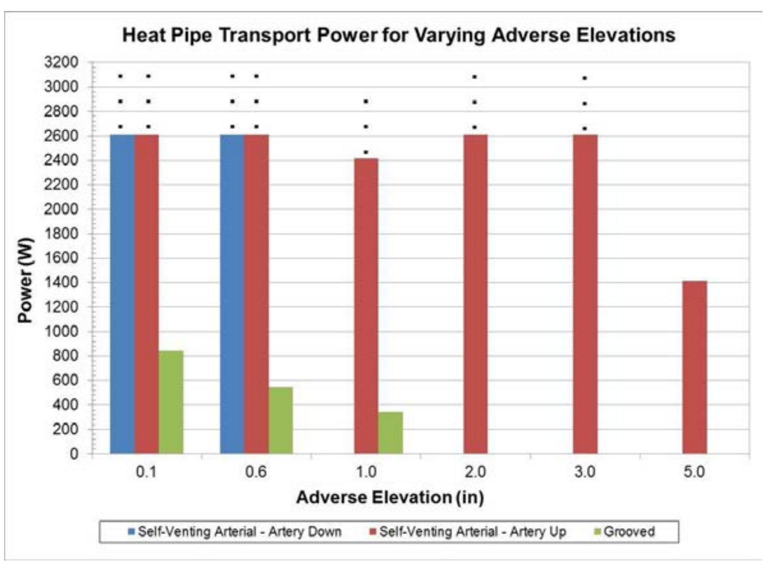

FIGURE 12. Summary of thermal performance results for the grooved and self-venting arterial heat pipes. The dots above the bars indicate that the power was limited by the test apparatus, not the heat pipe.

CONCLUSION

High temperature, alkali metal heat pipes have been developed to transfer the thermal energy generated by a spacecraft fission reactor to electrical convertors for power generation. The three types of heat pipes that would be suitable for this application are grooved, traditional arterial, and self-venting arterial. Sintered arterial heat pipes have traditionally been specified for this application due to their ability to transport large powers over long distances, but if vapor or NCG is generated in the artery due to radiation it would cause the heat pipe to de-prime and cease operating. Self-venting arterial and grooved heat pipes have an advantage over sintered arterial heat pipes due to their abilities to allow the trapped vapor or NCG to escape into the vapor space. A 1m (39.67in) long, 0.75in (1.91cm) outer diameter self-venting arterial heat pipe and grooved heat pipe were designed, fabricated and tested. Thermal performance testing of the two heat pipes was conducted at an operating temperature of 725°C and at adverse elevations ranging from 0.1in (0.25cm) to 5.0in (12.7cm). The self-venting arterial heat pipe was capable of transporting at least 2.6kW of power at all adverse elevations except 5.0in (12.7cm) where it transported 1.4kW. The grooved heat pipe was capable of transporting a maximum power of 846W at 0.1in (0.25cm) elevation and 346W at 1in (2.5cm).

ACRONYMS

ACT	Advanced Cooling Technologies, Inc.
CCHP	Constant Conductance Heat Pipe
EDM	Electrical Discharge Machining
GRC	Glenn Research Center
NCG	Non-Condensable Gas
TC	Thermocouple
TE	Thermoelectric
VCHP	Variable Conductance Heat Pipe

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