High Temperature Heat Pipes for Space Fission Power

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Future space transportation and surface power applications will require small fission reactors for power generation. The fission reactors would generate up to 13kWt of power for the energy conversion system. The heat generated by the reactor would be collected and transferred by high temperature alkali metal heat pipes to a series of Stirling convertors or thermoelectric convertors for power generation. These heat pipes would be relatively long, 2 meters for a Stirling convertor design, and 4 m for a thermoelectric convertor design. Previous alkali metal heat pipe designs for spacecraft have used arterial, annular, or crescent wicks. All of these wicks can be difficult to fabricate for long heat pipes. Two other wick designs were examined in this study, grooved wicks, and self-venting arterial wicks. 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. A trade study was conducted to compare the maximum transport and specific power for the self-vented artery, arterial, and grooved heat pipe designs. In all cases for a given diameter, the self-vented artery design carried the highest power, and had the highest specific power. Two 1-m long heat pipes were fabricated and tested, a self-venting wick and a grooved wick. The 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 up to 3.0in (7.62cm) without drying out. At an elevation of 5.0in (12.7cm), the self-venting arterial heat pipe is capable of carrying a maximum transport power of 1.4kW. Grooved heat pipes are typically used for spacecraft thermal control, since any NCG in the grooves can easily escape. The 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.

I. 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; see Figure 1. 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, see the requirements in Table 1.

II. Background – Heat Pipe Wicks

Traditionally, there have been three types of heat pipe wicks in long alkali metal heat pipes for space applications, see Figure 2:

1. Arterial heat pipes with sintered powder (or screen) wicks
2. Annular wicks

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3. Crescent wicks

The present work has examined two additional wick designs:

4. Grooved heat pipe wicks
5. Self-venting arterial heat pipes

Arterial or annular/crescent wicks 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 is a potential problem. If vapor or non-condensable gas (NCG) is generated in the artery of a sintered arterial heat pipe, or the liquid gap of annular and crescent wicks, 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.

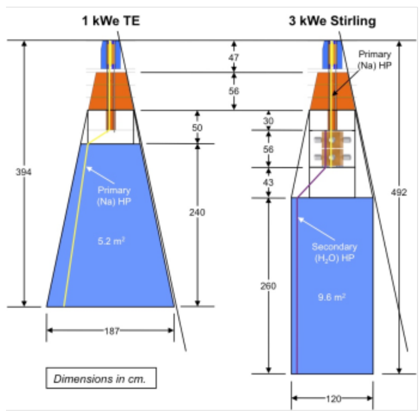


Figure 1. Thermoelectric and Stirling reactor system designs (Mason and Carmichael, 2011).

Table 1. High Temperature Heat Pipe Design Requirements.

	Stirling Design	Thermoelectric Design
Electrical Power	$3kW_e$	$1kW_e$
Reactor Thermal Power	$13kW_t$	$13kW_t$
Power Per Heat Pipe	725W	725W
Fuel Temperature (Average)	1200K (927°C)	1200K (927°C)
Heat Pipe Condenser Temperature	1100K (827°C)	1100K (827°C)
Sink Temperature	200K (-73°C)	200K (-73°C)
Na Heat Pipe Overall Length	1.89m (74.4in)	4.0m (157.5in)
Na Heat Pipe Evaporator Length	45.0cm (18.5in)	47.0cm (18.5in)
Na Heat Pipe Condenser Length	56.0cm (22.1in)	~2.4m (94.5in)
Overall System Length	5.0m (196.9in)	~4.0m (157.5in)
H_2O HP Supplementary Cooling System	Yes	No
H_2O HP Overall Length	~3.59m (141.34in)	N/A
H_2O HP Evaporator Length	56.0cm (22.05in)	N/A
H_2O HP Condenser Length	2.6m (102.36in)	N/A
H_2O HP Operating Temperature	400K (126.85°C)	N/A
Power to Reject from Radiator	$9.6kW_t$	N/A

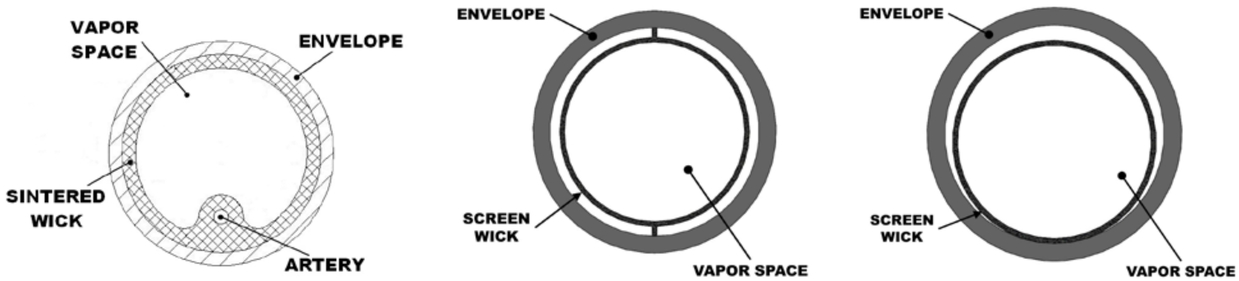
Grooved and self-venting heat pipes offer potential benefits over the standard arterial heat pipes since they are designed to be self-venting:

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

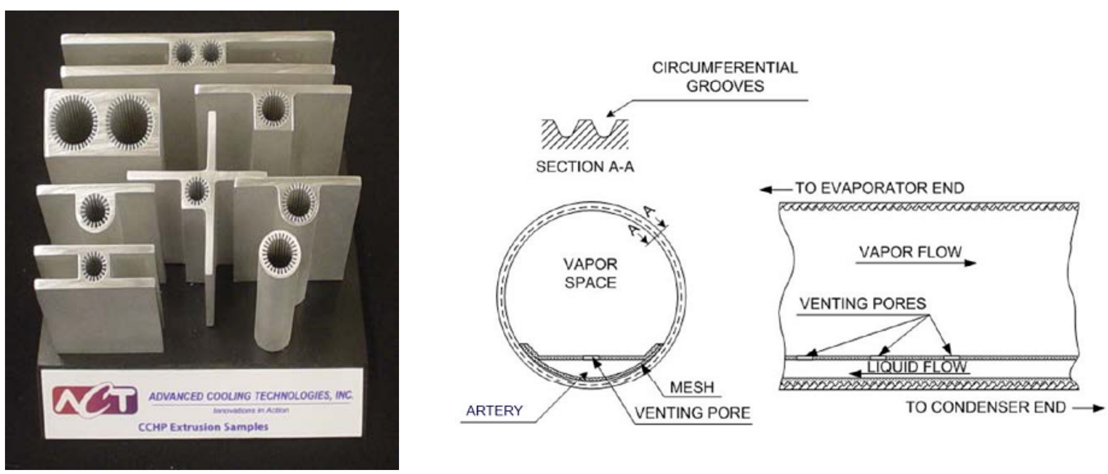
A. Sintered Arterial Heat Pipes

As shown in Figure 2a, arterial heat pipes are type of 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) Sintered Arterial **b) Annular Screen Wick** **c) Crescent Wick**



d) Grooved Wick **e) Self-Venting Arterial Wick**

Figure 2. Heat pipe wicks suitable for long heat pipes in microgravity. a) Arterial heat pipe, b) Annular heat pipe, c) Crescent heat pipe, d) Grooved heat pipes, and e) Self-venting arterial heat pipe.

B. Annular and Crescent Wicks

As shown in Figure 2b and c, the liquid flow path is the gap between the heat pipe I.D. and a cylindrical screen. In an annular wick, the screen is equi-distant from the wall at all angles. In an angular wick, the wick is tangent to the heat pipe in one location, and has the largest gap opposite the tangent. The crescent wick has a smaller liquid pressure drop than an annular wick with the same average gap.

One disadvantage of these wicks versus the arterial wicks is the increased thermal resistance through the wick. As shown in Figure 2a, an arterial design has a thick area near the artery, while the remainder of the wick can be quite thin. In contrast, all of the heat entering the heat pipe in annular and crescent wicks must be conducted through the liquid-filled annulus. As with arterial heat wicks, these wicks are not recommended for non-alkali metal working fluids.

C. Grooved Heat Pipes

The first alternate wick design considered in this program was 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 directly into the vapor space. Typical aluminum grooved extrusions are shown in Figure 2d. These grooves have a very high permeability, allowing very long heat pipes for operation in zero-g, typically several meters long with ammonia or ethane as the working fluid. 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. The standard adverse elevation for testing grooved CCHPs on Earth is 2.54mm (0.1in) against gravity.

As shown in Figure 2d, 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.

D. Self-Venting Arterial Heat Pipes

The second potential heat pipe wick considered is a self-venting arterial heat pipe that was first proposed by Eninger (1974). More recently, it was further developed by Goncharov et al. at Lavochkin in Russia (Goncharov et al., 1999, Kaya and Goncharov, 2010); see Figure 2b and Figure 3. 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. 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 gas to be vented without depriming the artery. 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 standard arterial heat pipes.

The self-venting arterial heat pipe design has been validated in numerous Russian spacecraft, so the TRL level for ammonia, propylene and Freon heat pipes is 9; see Table 2. 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. The design used by Goncharov et al. used grooves to collect and distribute the liquid circumferentially.

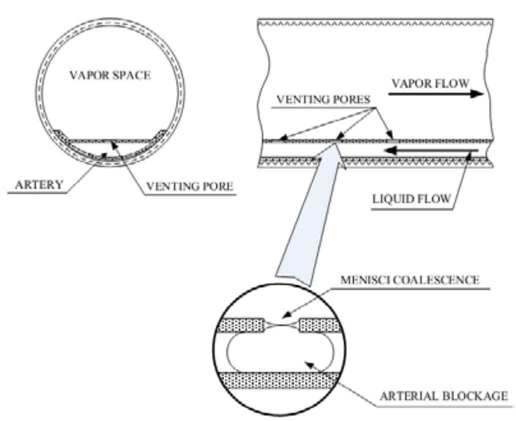


Figure 3. Self-Venting Arterial Heat Pipe has a series of vent holes in the artery to remove non-condensable gas trapped in the artery.

Table 2. Ammonia self-venting arterial pipes have been used on numerous Russian spacecraft, so the technology has a TRL of 9 (Goncharov et al., 1999).

Spacecraft name	In-orbit life time	Number of Arterial HPs	Operation temperature range, °C	Note
BEZOPASNOST-1	1991 - 1995	38	-150 ... +70°C	Freon-22,Propylene
BEZOPASNOST-2	1992 – 1996	38	-150 ... +70°C	Freon-22,Propylene
BEZOPASNOST-3	1994 – 1995	38	-150 ... +70°C	Freon-22,Propylene
OBZOR	1994 – 1999	1	20±1°C	Ammonia
MARS	1996 – 1996	2	-60 ... +50°C	Ammonia
ARAKS	1997 – 1997	32	-60 ... +50°C	Ammonia
COUPON	1997 - 1998	14	-60 ... +50°C	Ammonia

Note that the wick designed used by Eninger and Goncharov et al. had circumferential grooves (screw threads) cut into the heat pipe I.D. The grooves collect the liquid in the condenser and deliver it to the artery. Similarly, the grooves distribute liquid from the artery in the evaporator.

III. Full-Length Heat Pipe Design

E. Heat Pipe Wick Trade Study

A trade study was conducted to compare powers and masses for arterial, self-venting arterial, and grooved heat pipes for the two different spacecraft nuclear fission systems proposed by Mason and Carmichael. The first is a Stirling based system, while the second is a thermoelectric based system. The design requirements for both systems can be seen in Table 1. The main difference between the two systems when it comes to heat pipe design is their overall length. The Stirling based system is the shorter of the two, only requiring 74.4in (1.89m) long heat pipes while the thermoelectric system requires an approximately 157.58in (4m) long heat pipes. Two heat pipe diameters were examined for the trade study for both the Stirling and thermoelectric based systems; 0.75 inch (1.91cm) and 0.50 inch (1.27cm).

Three heat pipe limits of interest were evaluated for the trade study; capillary limit, entrainment limit, and sonic limit. The **capillary limit** evaluates the pumping capabilities of the wick structure itself. When the required interfacial pressure between the liquid in the wick and the vapor in the core exceeds the capillary pressure that the wick can sustain, the pumping rate is no longer sufficient to supply enough liquid to the evaporation sites, causing dry out. The **entrainment limit** evaluates the vapor and liquid interface. Since liquid and vapor are in direct contact and flowing in different direction along the heat pipe, a mutual shear force exists between the two. At low velocities, this shear force will add to the viscous drag in both phases. If the velocity becomes too large, the interface becomes unstable and liquid droplets are torn from the wick and "entrained" in the vapor. The **sonic limit** evaluates the velocity of the vapor as it exits the evaporator. The evaporator section of a heat pipe represents a constant area vapor flow duct with mass addition through the evaporation process. The vapor velocity will increase steadily over the length of the evaporator section eventually reaching a maximum at the evaporator exit. If the vapor flow becomes choked (Mach number = 1), a further increase in the mass flow is not possible without raising the saturation vapor pressure and therefore the vapor temperature.

F. Stirling System Trade Study

The heat pipes for the Stirling based system will be approximately 74.4in (1.89m) in overall length, with a 17.7in (45cm) long evaporator and a 22.1in (56cm) long condenser. The heat pipes are required to carry a minimum of 725W of power, which is based on an 18 heat pipe thermal management design proposed by NASA Glenn (Mason & Carmichael, 2011). Two outer diameter sizes were compared for the Stirling trade study; 0.75in (1.91cm) and 0.50in (1.27cm). The 0.50in (1.27cm) OD is the desired size for system due to limited interfacing space between the Stirling engines and heat pipes, and an improvement in the reactor size.

The performance predictions for the 0.75in (1.91cm) diameter case can be seen in Figure 4. The limits for the self-venting arterial heat pipe are in red, the limits for the sintered arterial heat pipe are in blue and the limits for the grooved heat pipe are in green. The two arterial heat pipes are capable of transporting significantly more power than the grooved heat pipe. The self-venting arterial heat pipe is capable of transporting 2.3 to 7.0kW of power over the operating temperature range. The entrainment limit controls for the majority of the operating temperature range.

The capillary limit controls from approximately 1115K to 1200K. The sintered arterial heat pipe is capable of transporting 3.0 to 6.3kW of power over the operating temperature range. The entrainment limit controls from 900K to approximately 1020K. From 1020K to 1200K the capillary limit controls. The grooved heat pipe is capable of transporting 725W to 1.4kW of power over the operating temperature range. The capillary limit controls for the entire operating temperature range.

The specific power of the three heat pipe wicks was evaluated to determine the wick that provides the best specific power. Haynes 230 was used as the envelope material for the specific power analysis. Nickel powder was used for the sintered arterial wick and stainless steel screen was used for the self-venting arterial wick. Haynes 230 is the lone material used for the grooved heat pipe. The specific power as a function of temperature was calculated as the controlling heat pipe limit over the mass of the heat pipe. The results of the specific power trade study for the 0.75in (1.91cm) diameter case can be seen in Figure 5. The self-venting arterial heat pipe provides the largest specific power of the three wick designs. The self-venting arterial heat pipe is capable of specific powers ranging from 3.0 to 7.6kW/kg over the operating temperature range. The sintered arterial heat pipe is capable of specific powers ranging from 2.0 to 3.8kW/kg over the operating temperature range. The grooved heat pipe is capable of specific powers ranging from 0.6 to 1.0kW/kg over the operating temperature range. The self-venting arterial heat pipe is the lightest of the three wick designs, at 0.92kg. The sintered arterial heat pipe has a mass of 1.67kg. The grooved heat pipe has a mass of 1.77kg.

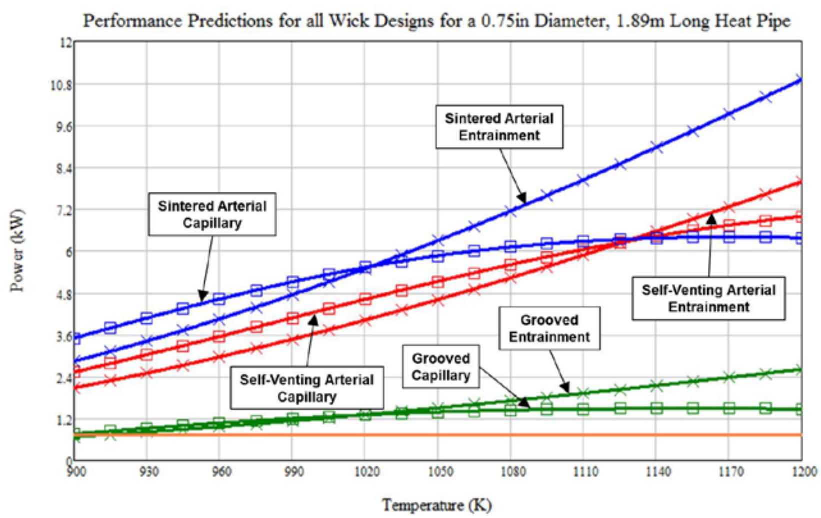


Figure 4. Capillary and entrainment limits for all wick designs for a 0.75in (1.91cm) OD, 74.4in (1.89m) long heat pipe.

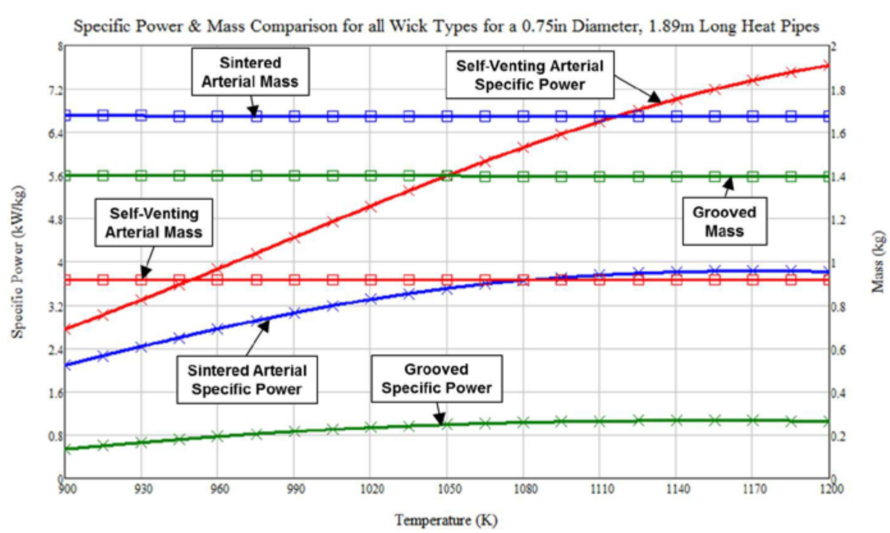


Figure 5. Specific power and mass of 0.75in (1.91cm) OD self-venting arterial, sintered arterial and grooved heat pipes for a Stirling based system.

G. Trade Study Results Summary

Similar calculations were run for the 0.50in (1.27cm) Stirling system, and the 0.50in (1.27cm) and 0.75in (1.91cm) thermoelectric systems. The results are summarized in Table 3. The arterial heat pipes are capable of carrying significantly more power for the Stirling and thermoelectric systems compared to the grooved heat pipes. In all cases, the self-venting arterial wick design has the best power to weight ratio as it is significantly lighter than both the sintered arterial and grooved heat pipe wick designs. The 0.75in (1.91cm) heat pipe can provide more power than a 0.50in (1.27cm) heat pipe; however, the smaller diameter is preferred to reduce the size of the reactor. The 0.50in (1.27cm) outer diameter arterial heat pipes are capable of carrying two to three times more than the necessary power of 725W for both the Stirling and thermoelectric system. This indicates that these heat pipes could also be used for future, higher power systems. The 0.50in (1.27cm) grooved heat pipe for the Stirling system is not capable of carrying the required power until approximately 1100K and the 0.50in (1.27cm) grooved heat pipe for the thermoelectric system is not capable of carrying the necessary power.

Table 3. Trade study results summary for a temperature range of 900 to 1200K (627 to 927ºC).

Heat Pipe Wick Type	Diameter (in)	Length (m)	Minimum Power (kW)	Maximum Power (kW)	Minimum Specific Power (kW/kg)	Maximum Specific Power (kW/kg)
Grooved	0.50	1.89	0.25	0.725	0.3	0.8
	0.75		0.725	1.4	0.6	1.0
	0.50	4.0	0.1	0.5	0.1	0.29
	0.75		0.5	1.8	0.15	0.6
Sintered Arterial	0.50	1.89	1.2	3.8	1.4	4.2
	0.75		3.0	6.3	2.0	3.8
	0.50	4.0	0.8	0.9	0.4	0.5
	0.75		2.9	5.0	0.8	1.5
Self-Venting Arterial	0.50	1.89	1.3	3.8	2.0	5.8
	0.75		2.3	7.0	3.0	7.6
	0.50	4.0	1.0	3.0	0.6	2.4
	0.75		2.2	6.2	1.0	3.2

IV. Grooved and Self-Venting Arterial Heat Pipe Prototypes

To the best of our knowledge, grooved or self-venting artery wicks have not previously been demonstrated with an alkali metal working fluid. One meter long versions of the grooved and self-venting arterial heat pipes were designed, fabricated and tested to provide experimental verification that these heat pipes could transfer the required power. To reduce expense, 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. More details on the design and fabrication of these heat pipes can be found in Walker et al. (2013).

An outer diameter of 0.75in (1.91cm) was chosen for both the grooved and self-venting arterial heat pipes. 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. While previous self-venting arterial heat pipes used a screw thread to collect and distribute liquid, the current pipe used two screen wraps around the entire heat pipe circumference.

H. Experimental Test Set-Up

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 6. Both heat pipes were insulated (not shown in Figure 6) with multiple layers of Kaowool to reduce the overall heat losses from the system.

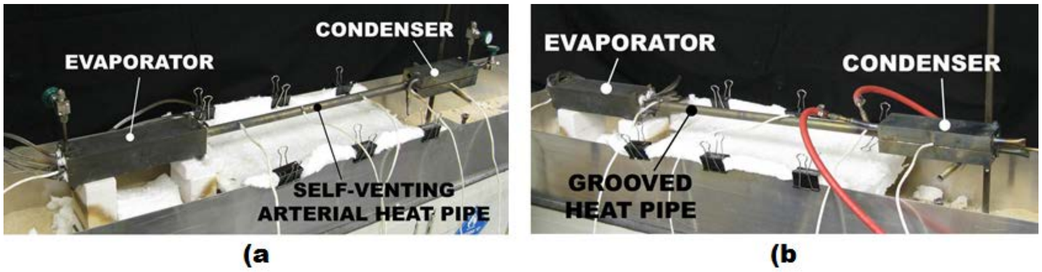


Figure 6.Grooved heat pipe and self-venting arterial heat pipe on test stand.

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.

V. Self-Venting Arterial Heat Pipe Experimental Results

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 7. 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. 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.

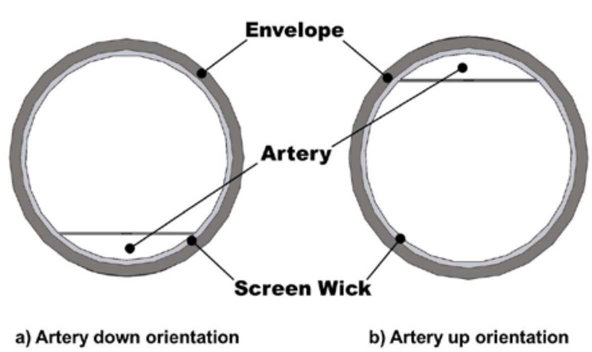


Figure 7. Self-venting arterial heat pipe artery orientation during testing.

A TC map for both the grooved heat pipe and self-venting arterial heat pipe can be seen in Figure 8. Figure 9 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 Figure 9, 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.

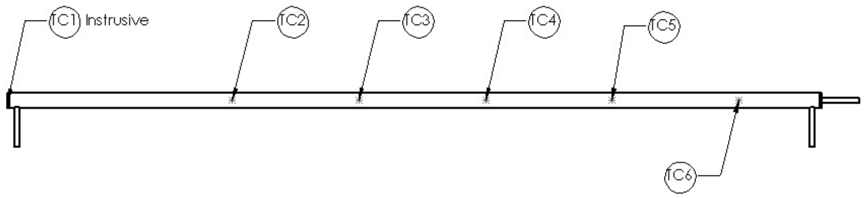


Figure 8. TC map for the grooved heat pipe and self-venting arterial heat pipe.

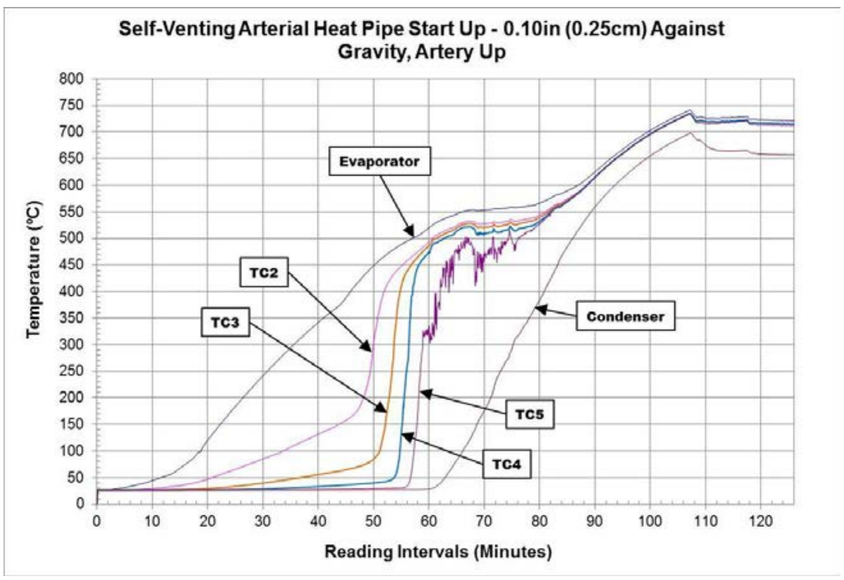


Figure 9. Self-venting arterial heat pipe startup, operating at 0.1in (0.25cm) against gravity with the artery up.

Table 4. 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

Typical thermal performance results for the self-venting arterial heat pipe can be seen in Figure 10 and Figure 11. 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 10 and Figure 11. Dry out of the heat pipe was not achievable until 5.0in (12.7cm) adverse elevation due to insufficient cooling capabilities; see Figure 11. 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 4.

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.

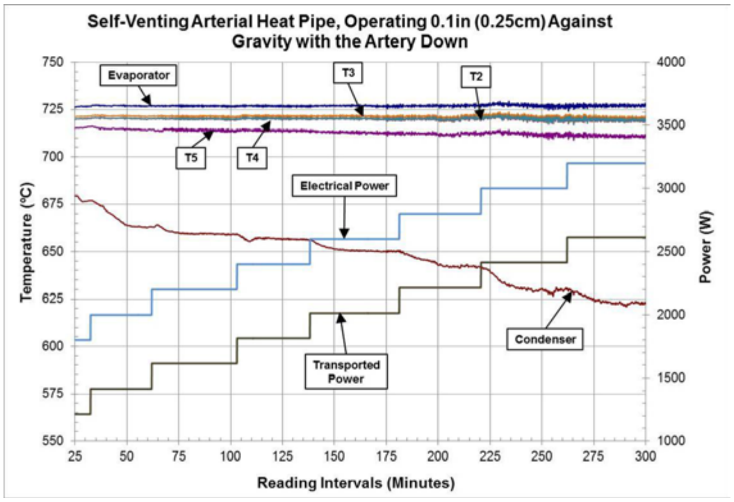


Figure 10. Self-venting arterial heat pipe performance operating at 0.1in (0.25cm) against gravity, artery down.

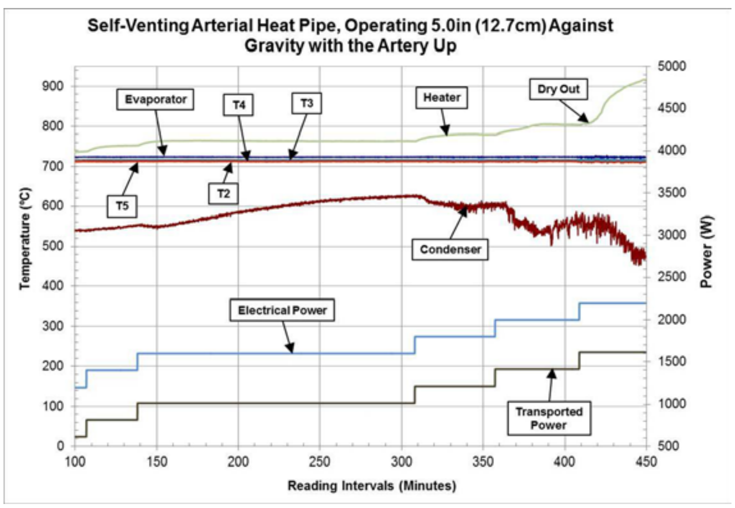


Figure 11. Self-venting arterial heat pipe performance, artery up with a 5.0in (12.7cm) adverse elevation.

VI. Grooved Heat Pipe Experimental Results

Figure 12 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 5. 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

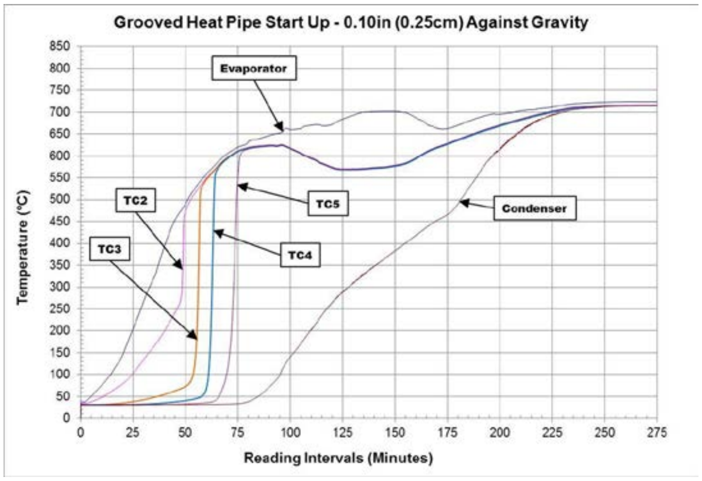


Figure 12. Grooved heat pipe start up, operating at 0.10in (0.25cm) against gravity.

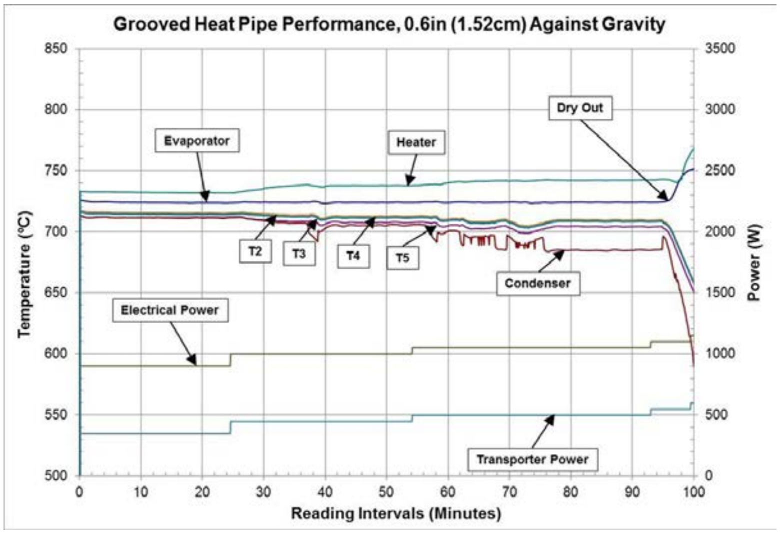


Figure 13. Grooved heat pipe performance, operating at 0.6in (1.52cm) against gravity.

An example of the thermal performance results for the grooved heat pipe can be seen in Figure 13. 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 13 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 5. 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.

I. 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. 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 the 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 14.

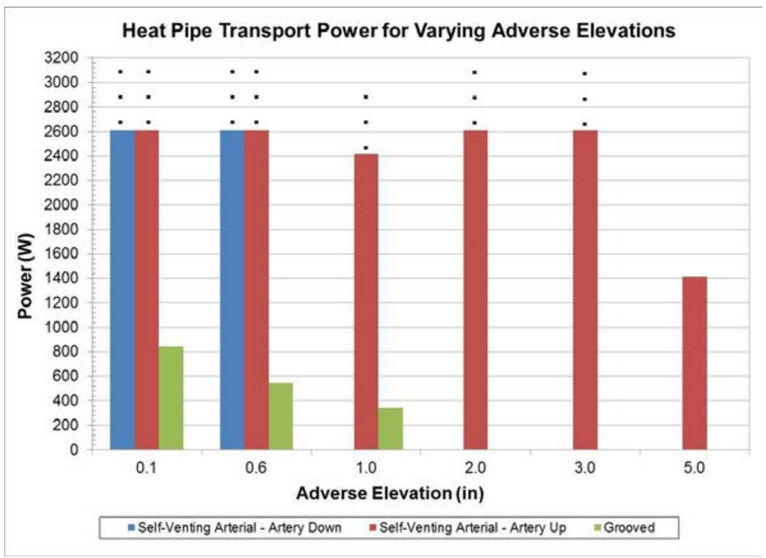


Figure 14. Summary of thermal performance results for the grooved and self-venting arterial heat pipes. The dots above the bars indicate that the power was limited by the test apparatus, not the heat pipe.

VII. 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. Previously, three types of heat pipe wicks had been considered as suitable for long alkali metal heat pipes: arterial, annular and crescent. This program examined an additional two wick designs: grooved and self-venting arterial. The advantage of these designs is that they are self-venting. If non-condensable gas or vapor is generated in the artery or annulus of the other designs, it could cause the heat pipe to deprime and cease operating.

A trade study was conducted to compare the maximum transport and specific power for the self-vented artery, artery, and grooved heat pipe designs. In all cases for a given diameter, the self-vented artery design carried the highest power, and had the highest specific power. The self-vented artery and arterial heat pipes could carry the required power with a 0.50in (1.27cm) O.D. pipe. The 0.75in (1.91cm) grooved pipe can carry the power, but at a lower specific power. The 0.50in (1.27cm) grooved heat pipe for the Stirling system is not capable of carrying the required power until approximately 1100K and the 0.50in (1.27cm) grooved heat pipe for the thermoelectric system is not capable of carrying the necessary power.

A 1m (39.67in) long, 0.75in (1.91cm) outer diameter self-venting arterial heat pipe and a grooved heat pipe with similar dimensions 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

CCHP	Constant Conductance Heat Pipe
EDM	Electrical Discharge Machining
GRC	Glenn Research Center
NCG	Non-Condensable Gas
TC	Thermocouple
TEC	Thermoelectric Convertor
VCHP	Variable Conductance Heat Pipe

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