Self-Venting Arterial Heat Pipes for Spacecraft Applications

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NASA is examining small fission reactors for future space transportation and surface power applications, with alkali metal heat pipes to supply energy to the Stirling convertors to produce electricity. Simultaneously, titanium/water heat pipes will be used to carry the waste heat from the convertors to a radiator, where the heat is rejected. The entire system must be tested on Earth before launch, and must be able to operate in micro-gravity, as well as on the Moon and Mars. Grooved and arterial wicks are the default design for heat pipes operating in micro-gravity; however, these heat pipes are not suitable for a nuclear power system. Unlike earlier spacecraft heat pipes, these heat pipes must be capable of operating in the following orientations: operation in space, with zero gravity; operation on earth, with a slight adverse orientation, to estimate performance in space; ground testing, with the heat pipes operating gravity aided; and launch, with the evaporator elevated above the condenser. During vertical ground testing, the heat pipe wick will de-prime, and will need to re-prime for operation in space after launch. Hybrid grooved and arterial self-venting heat pipes offer potential benefits over the standard arterial heat pipes: 1. The grooves cannot be de-primed, and 2. The self-venting pipes are less susceptible to de-priming, as well as having a lower mass. The self-venting arterial wick design was chosen for these heat pipes, since this design is known to automatically re-prime after de-priming, and could carry the required power for the alkali metal pipes with a smaller diameter. A series of sodium/Haynes 230 heat pipes with a self-venting wick were fabricated and tested. These heat pipes will be tested in a complete, electrically heated reactor system next year. Previously, this paper was published at the Joint 18th IHPC and 12th IHPS in June 2016. Further wick development efforts and testing results are shown here.

Nomenclature

ΔP	=	Pressure difference (Pa)
σ	=	Surface tension (N/m)
r_c	=	Wick pore size (m)

I. INTRODUCTION

NASA is examining small fission reactors for future space transportation and surface power applications[1, 2]. The Fission Surface Power System (FSPS) is designed to operate from 10 to 100 kWe while current Radioisotope Power Systems (RPSs) operate below 500 We. The Kilopower system would address the power gap between current RPS and FSPS, with power generation from 1 to 10 kWe.

The Kilopower system uses sodium heat pipes to carry the power from the nuclear reactor to the Stirling convertors to produce electricity; see Figure 1. Simultaneously, titanium/water heat pipes will be used to carry the waste heat from the Stirling to a radiator, where the heat is rejected. The Kilopower system will be designed to operate in space, as well as on Earth, the Moon, and Mars.

Previous spacecraft heat pipe designs have neglected ground testability, and assumed a grooved wick. The Kilopower heat pipes must accommodate four different operating conditions:

1. Operation in space, with zero gravity. Liquid is returned from the condenser to the evaporator by capillary forces in the wick.

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2. Operation on earth, with a slight adverse orientation, to estimate performance in space. The heat pipe is operated with the evaporator slightly oriented above the condenser. The adverse orientations are typically 0.1, 0.2, and 0.3 inches.
3. Ground testing, with the heat pipes gravity aided. The heat pipes will deprime in this orientation.
4. Launch, with the evaporator elevated above the condenser.

II. HEAT PIPE WICKS

The length of the Kilopower titanium/water heat pipes can be up to several meters. There are four types of wicks that carry significant power over these long distances in space:

1. Arterial heat pipes with sintered powder (or screen) wicks
2. Grooved heat pipe wicks
3. Hybrid grooved screen wicks
4. Russian self-venting arterial heat pipes.

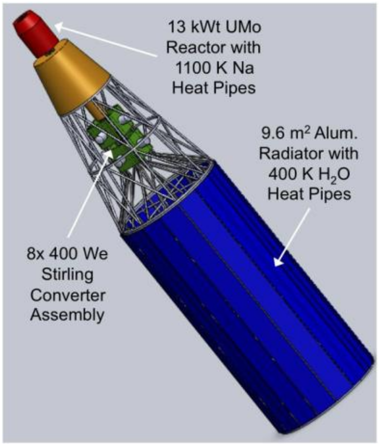

Figure 1. Nominal Kilopower system[1].

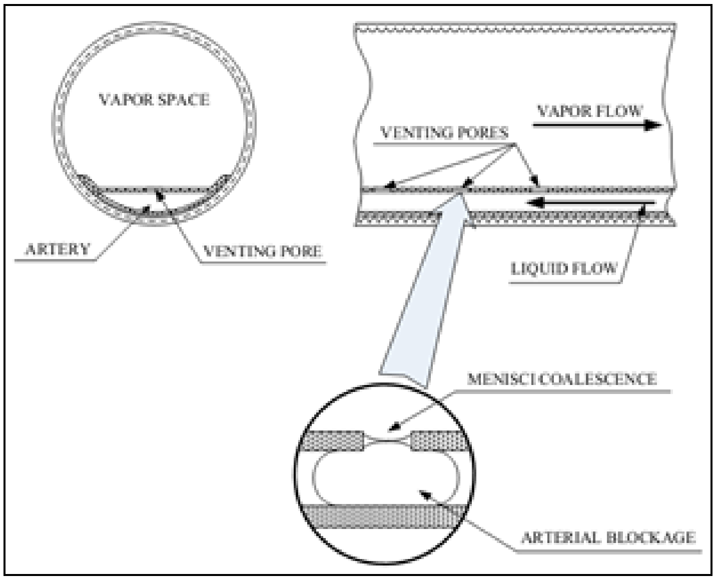

Figure 2. Russian developed self-venting arterial heat pipe with a screen wick.[3]

Arterial and grooved heat pipes are not suitable for this application. The arterial pipes will de-prime during testing and during launch and it is not possible to reliably re-prime arterial pipes. Grooved heat pipe designs that will work in space have also been developed but the grooved wick is unable to prime the evaporator in a vertical orientation, which is necessary for ground testing of Kilopower.

The two wicks that can be used for the Kilopower system are the hybrid grooved/screen wick, and the self-venting arterial heat pipe. The hybrid wick has a porous wick in the evaporator, and grooves in the adiabatic and condenser sections.

The wick design chosen for the Kilopower hot end heat pipes is a self-venting arterial heat pipe developed by Goncharov et al. at Lavochkin in Russia[4]; see Figure 2. Standard arterial heat pipes utilize a single artery as well as a screen or sintered wick for liquid return. The combination of a single artery with a screen wick gives the heat pipe the benefit of a wick with high effective liquid permeability as well as a small pore size and thus 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 non-condensable gas generation or vapor generation in the artery. These standard arterial heat pipes are not suitable for Kilopower, as discussed below, since the arteries will deprime during ground testing. To allow the arteries to reprime, self-venting arterial heat pipes use small venting pores that are located in the evaporator section of the heat pipe.

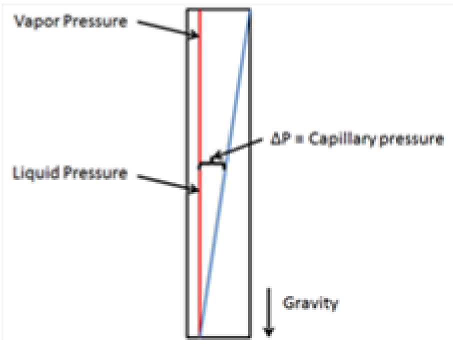

Figure 3. Vapor pressure vs. liquid pressure comparison in a long, vertical heat pipe.

A. Wick De-priming

During ground testing the Kilopower system will be oriented so that the proposed heat pipes will be operating vertically as thermosyphons. In this orientation the arteries in the heat pipe will deprime due to the variation in liquid pressure along the length of the heat pipe due to gravity; see Figure 3. Assume that the heat pipe is in a vertical orientation and not operating. In this case, the vapor pressure and liquid pressure at the bottom of the heat pipe are identical. As the height increases, the liquid pressure drop decreases, due to the hydrostatic head. Figure 3 shows the location along the length of the heat pipe where the pressure ΔP between the liquid and vapor is equal:

$$\Delta P = \frac{2\sigma}{r_c} \tag{1}$$

At higher elevations, vapor will be sucked into the artery, depriming it. Since these heat pipes are more than 1 m high, they are always deprimed when operating vertically.

III. DESIGN AND FABRICATION

A. Design Requirements

The heat pipe developed on the current program will be used in a 1 kWe Kilopower reactor that is being developed by NASA Glenn and the Department of Energy. Table 1 gives the heat pipe design requirements. The minimum power that each heat pipe must carry is 380W, but higher powers are desirable to demonstrate operation if one of the heat pipes fail.

The heat pipes must operate both as gravity aided thermosyphons, and in space. Operating is space is simulated by testing the heat pipes almost level, with a slight adverse elevation (0.1 inch, 0.254 cm).

When tested in a horizontal orientation, the artery spontaneously reprimes. When tested in a vertical orientation, the artery deprimes. Roughly 3 in. (7.62 cm) of the heat pipe extends below the reactor, to provide a small sump to accommodate some of the fluid.

Table 1. Kilopower heat pipe design requirements.

Total Thermal Power, kW	3
Number of Heat Pipes	8
Heat Pipe Power, W	380
Operating Temperature, °C	720 - 800
Working Fluid	Sodium
Envelope Material	Haynes 230
Wick Material	Stainless 316
Heat Pipe O.D., in. (cm)	0.5 (1.27)
Wall Thickness, in. (cm)	0.035 (0.089)
Evaporator Length, in. (cm)	14 (35.6)
Adiabatic Length, in. (cm)	34 (86.4)
Condenser length, in. (cm)	3.5 (8.89)

B. Working Fluid and Envelope Selection

The potential working fluids in the temperature range of interest are sodium and potassium. Potassium was eliminated from consideration, since it reacts strongly with fast neutrons.

A list of stainless and superalloy materials compatible with sodium is shown in Table 2. The 316 stainless steel is suitable for the wick, but not for the envelope, since it has very little structural strength at the operating temperature. Haynes 230 was chosen because it has the best creep strength at elevated temperatures.

Table 2. Sodium/superalloy heat pipe life tests.

Material	Hours	Operating Temperature	Ref.
316L SS	115,000	650 to 700°C	[4]
Hastalloy B	14,400	1020°C	[5]
Hastalloy X	29,600	1000°C	[5]
Haynes 188	22,500	900°C	[5]
Haynes 230	20,000	~ 700°C	[4]
Haynes 230 (NaK)	7500	750°C	[6]
Inconel 601	83,000	600 to 650°C	[4]
Inconel 617	>25,000	680°C	[7]
Inconel 625 (NaK)	800	700°C	[8]
Inconel 718	41,000	~ 700°C	[4]

C. Kilopower Heat Pipe Design

The design considered both self-venting arterial wicks, as well as hybrid screen/groove wicks. Both wick designs can easily carry the required power in a 0.75 in. (1.91 cm) O.D. heat pipe in a slight adverse orientation. From a reactor design consideration, 0.5 in. (1.27 cm) O.D. pipes gave a better design. The hybrid wicks could not carry the required power, so a self-venting arterial design was selected.

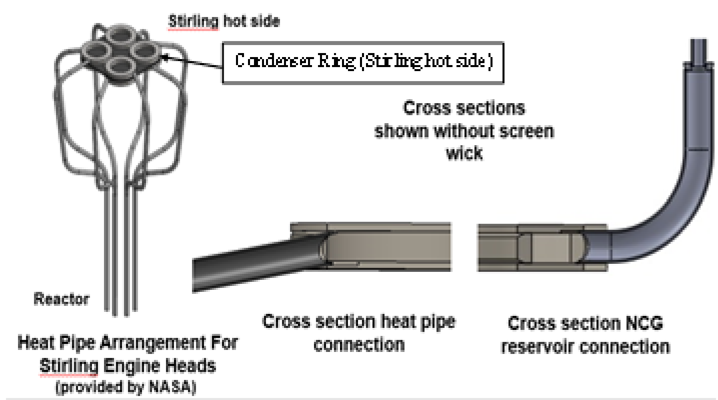

Figure 5. Kilopower sodium heat pipes.

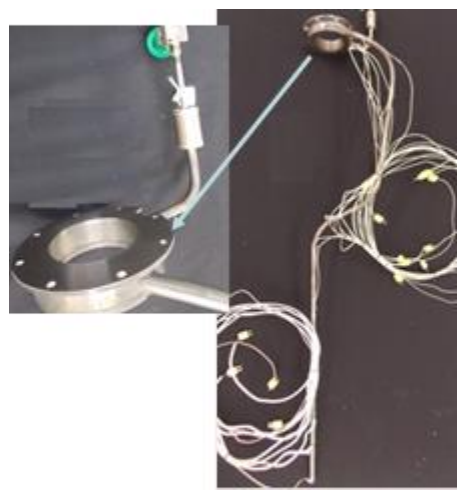

Figure 4. Kilopower heat pipe with thermocouples attached. The insert shows the annular condenser, which for this heat pipe mounts to the underside of the mounting plate.

A schematic of the Kilopower sodium heat pipes is shown in Figure 5 and a picture is shown in Figure 4. The evaporator is located next to the reactor core, fitting into a semi-circular groove. The adiabatic section jogs out and then back in, around the reactor shielding. The annular heat pipe condensers are attached to a mounting plate. Heat is conducted from the condenser to the Stirling convertors through the mounting plate. This design is not thermally efficient; it was chosen so that the Stirling convertors will be easy to remove after testing.

The heat pipes have a Non-Condensable Gas (NCG) reservoir to aid in start-up. Two of the heat pipes have a larger reservoir that can be electrically heated to shut the heat pipe down, simulating a heat pipe failure. Thermocouple locations are shown in Figure 6.

Given the number (8) of heat pipes required by the Kilopower system and the cost and risks associated with the self-venting arterial wick development, it was decided that both thermosyphons and self-venting arterial heat pipes will be developed. Note that the geometry of both types of heat pipes is the same, the only difference being the wick inside the heat pipe envelope.

IV. RESULTS

Repriming of alkali metal heat pipes with self-venting arteries has been demonstrated in a previous paper[10]. This paper reports on vacuum testing of two self-venting arterial heat pipes with 0.4 inches unfavorable elevation and also on ambient testing of the thermosyphons in vertical position.

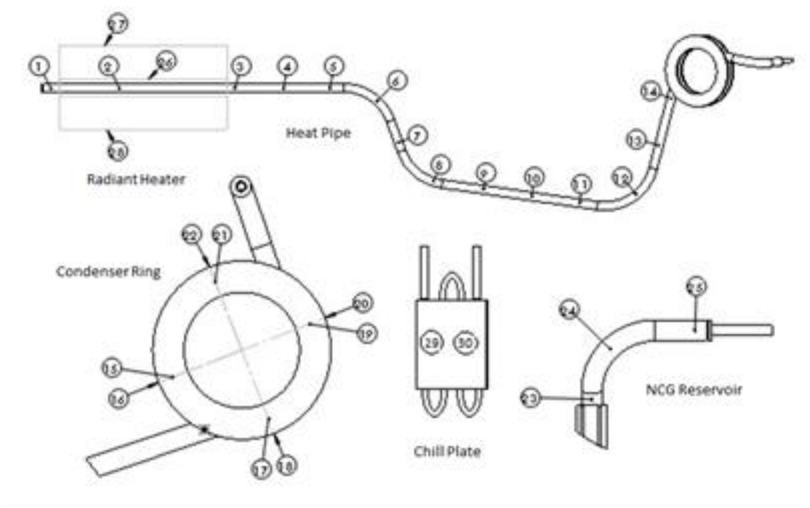

Figure 6. Thermocouple locations and numbering.

A. Self-Venting Arterial Heat Pipes for Space

The arterial wick developed for the two Kilopower heat pipes was made of stainless steel screen with square shaped artery with holes for NCG or vapor venting in the evaporator. The artery went from the bottom of the liquid reservoir below the evaporator all the way up to the entrance of the annular condenser. The condenser wick did not have an artery. A thick layer of screen wick was attached to the internal adiabatic surfaces of the condenser to decrease the hydraulic resistance for the liquid return in compensation for the lack of artery.

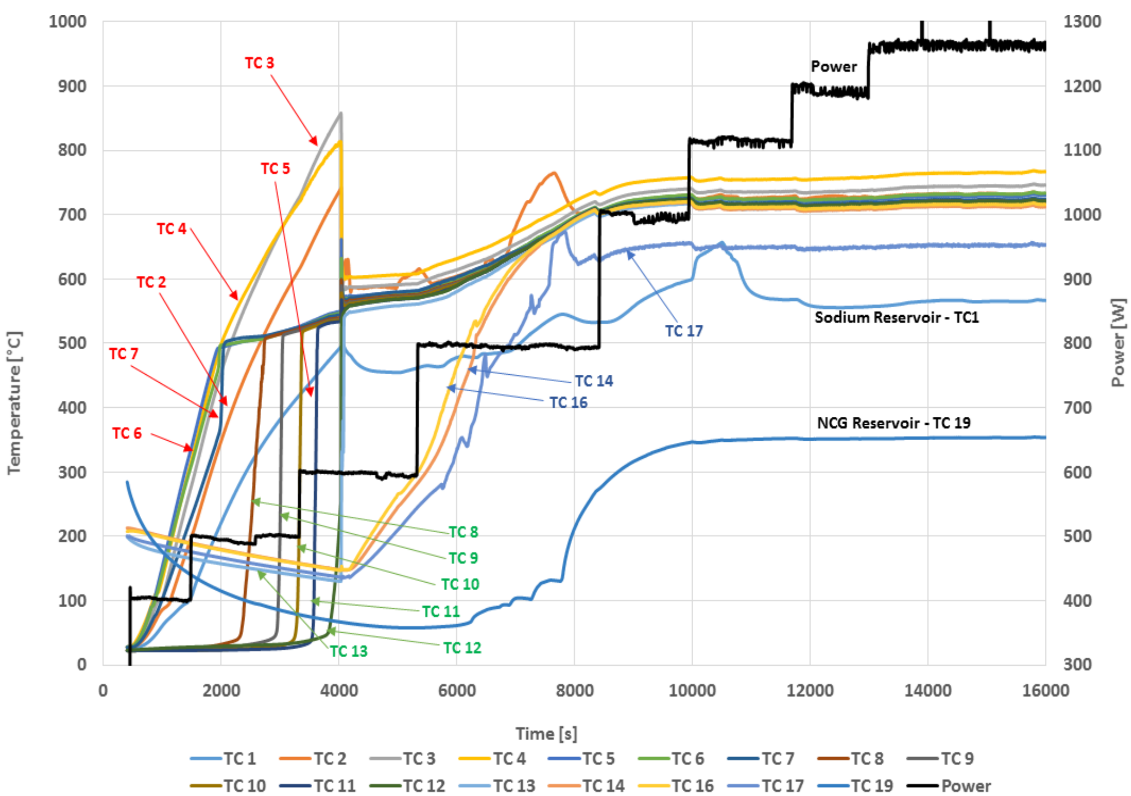

Figure 7. During rapid start-ups, there is a large temperature spike in the heat pipe evaporator temperature, required to initiate boiling.

As mentioned before, the two arterial heat pipes were tested in vacuum at a 0.4 in (1 cm) adverse elevation. Since the fabrication procedure required the bending of the pipes with primed sodium arteries, two tests were performed for each pipe. The first test was performed on straight pipes before bending, to assure the presence of sodium in the artery and the second test was performed after bending, on the final geometry of the heat pipe. The performance of each of the two heat pipes is shown in Table 3 for both straight and bent geometries.

Table 3. Performance of self-venting arterial heat pipes with 0.4 inches of adverse elevation.

Pipe #	Performance (W)	
	Straight	Bent
1	370	210
2	405	290

As seen in Table 3, the heat pipe performance decreased after bending for both pipes. Since the final performance for each pipe was below the requirements (380W), the wick is being redesigned.

Aside from the annular condenser, the wick in the self-venting arterial heat pipe was constructed from a continuous section of screen mesh and includes the artery and the circumferential section in evaporator. The following development effort focuses on this section of the wick.

The redesign effort focused on two artery shapes for the self-venting arterial heat pipe: square and D as well as a grooved wick structure. For comparison purposes, the design efforts assumed a straight heat pipe matching the parameters in except for the condenser, which was assumed to be the last 6” of this pipe. Each wick construction was optimized based on associated geometrical parameters.

The arteries in the previously tested self-venting arterial heat pipes were square in shape. While this construction is not optimal for vapor flow or liquid return, the square shape provided a rigid structure necessary for the small arteries in the 0.5” outer diameter pipes. For this reason, the square artery design was revisited during the wick development effort.

During this design iteration, a wider range of screen meshes were surveyed and a smaller discretization was used in specifying geometry. For comparison to the final heat pipe configuration, the design effort assumed a straight heat pipe matching the parameters in Table 1 except for the condenser, which was assumed to be the last 6” of this pipe. Parameters included the number of wraps of screen in the circumferential wick and the height of the artery. Figure 8 summarizes the results of the design study. The ordinate is the maximum transport predicted in watts which corresponds to the artery configuration having the optimum circumferential wick and artery size and the abscissa is the mesh size in wires per inch. The overall maximum predicted transport is 670 Watts that corresponds to an optimized wick structure constructed from size 400 screen mesh.

A similar design study was performed for a D-shaped artery. The results of the study are shown in Figure 8. While the D-shaped artery is more favorable for vapor and liquid flow, its ceiling sags which can lead to arterial blockage for small arteries. The designs were filtered by excluding all wick geometries below some specified ceiling height. The overall results of the D-shaped artery show little improvement over the square artery; therefore, the performance benefits of this artery shape are not realized, because of the relatively small pipe diameter.

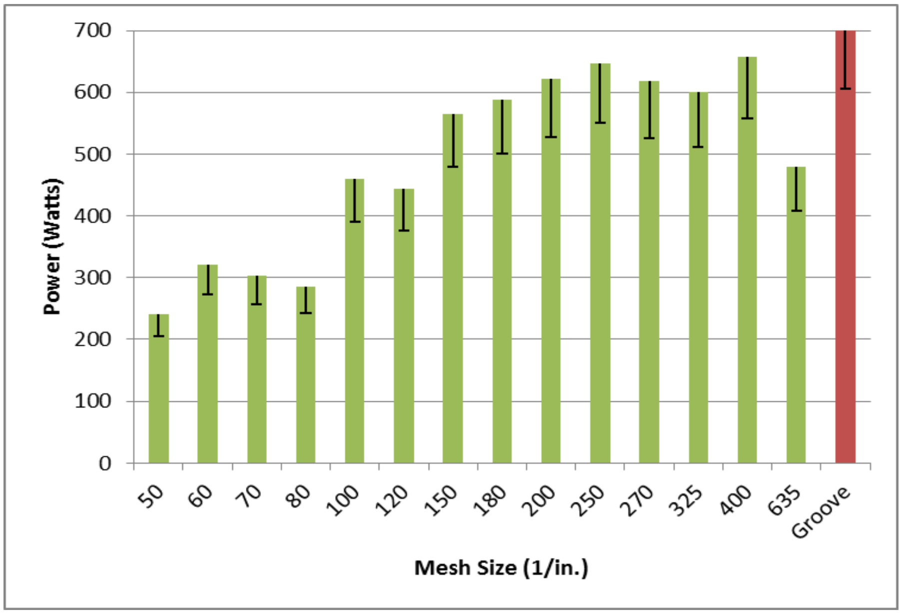

Figure 8. Predicted maximum heat transport for optimized D-shaped artery SVA heat pipe by varying mesh size. Predicted maximum heat transport for optimized grooved heat pipe.

Figure 8 also shows predicted transport for an optimized grooved wick. The design study parameters for the grooved wick included: groove angle, width, depth, number, and radii at the tip and root of the groove. The predicted transport for the grooved heat pipe surpasses the self-venting arterial heat pipe designs. Additional work is needed to incorporate the annular condenser into these optimized wick structures and validate the results through testing, the results of which will be detailed in a following paper.

B. Ground Tests of the Thermosyphons

As mentioned above, the second category of heat pipes developed for the Kilopower program was thermosyphons and they were tested in ambient in vertical position.

When testing vertically, sodium drips down along the walls in the adiabatic section. When the heat pipe is turned off, all of this sodium drains into the evaporator.

The sodium charge was determined experimentally, by adjusting the sodium charge to maximize the power. With our initial heat pipe and heat collector, the charge was much larger than what would be calculated from a falling film analysis. This occurred due to fluid pooling in the flat condenser, and in the "horizontal" portions of the adiabatic section. When the heat pipe was shut down, the sodium occupied 13 inches of the evaporator.

Table 4. Heat pipe performance.

Pipe No	Electric Power	Net Power	Dry Out
1	1250	680	No
2	1250	680	No
3	1200	630	No
4	1050	480	No
5	1150	580	No
6	1250	680	No
7	1200	630	No
8	1250	680	No
9	1200	630	No

Nine heat pipes (thermosyphons) were developed and delivered for the Kilopower program. The pipes were intensively tested before delivery. The performance for each of the nine thermosyphons is shown in Table 4. The measurements were performed in ambient and the heat losses were 570W. As seen in the table, since the requirements were met, dry out was not reached for any of the heat pipes.

Alkali metal heat pipes are known for having difficulties at start-up because of several reasons: the necessary superheat to initiate boiling, the low sonic limitation that chokes the pipe during its temperature increase towards the operating point and finally because of potential freezing of the working fluid in the condenser.

Adding NCG inside the heat pipe is a typical method in addressing the start-up difficulties. One of the effects is that it gives a shorter effective heat pipe length during start-up, since the NCG blocks most of the adiabatic section. However, in the heat pipes under discussion, the presence of NCG did not mitigate entirely the start-up related temperature spikes. An example is shown in Figure 7. The heat pipe started up successfully, but still required a very large superheat in the evaporator before starting up. As discussed below, this is very common with a deep alkali metal pool.

In May 2016, the first generation thermosyphon cluster was tested at NASA Glenn Research Center in an electrically simulated reactor. Start-up and steady performance results of the heat pipes were positive and lacked the large temperature spikes observed during start-up when the heat pipes were tested individually. The thermal mass of the simulated reactor and heat transfer method at the heat pipe evaporator contributed to these results.

When tested at ACT, the heat pipe evaporators were exposed to radiant heaters; however, when integrated into the reactor simulator, the evaporators were heated by conduction. In the latter test configuration, the evaporators were exposed to a much lower temperature, preventing superheat conditions. Figure 9 shows the cluster.

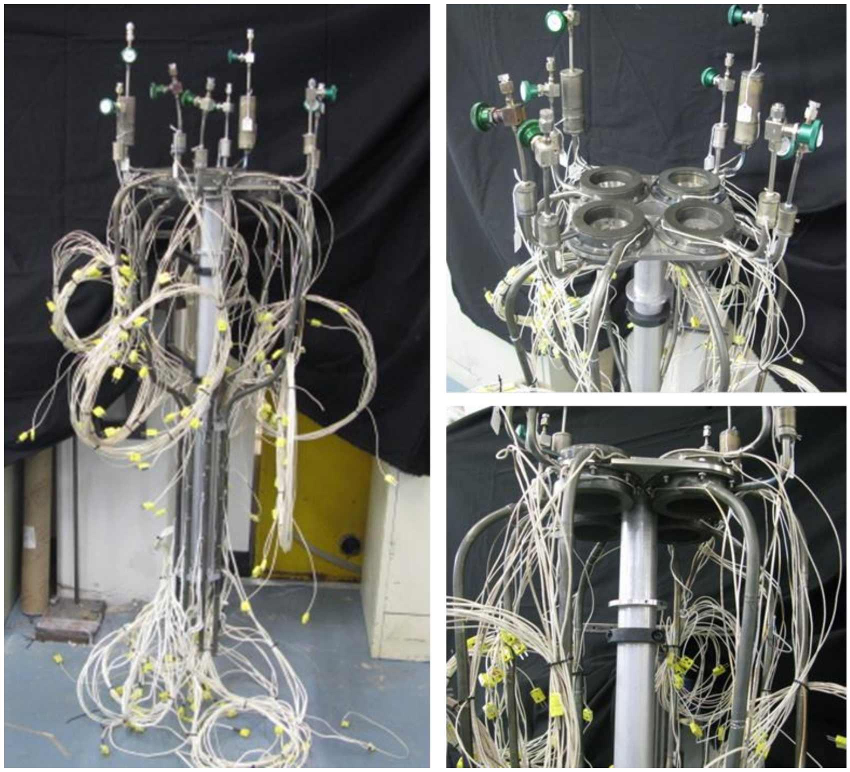

Figure 9. Left: First generation thermosyphon cluster delivered to NASA GRC for testing in electrically simulated reactor with thermocouples attached. Top right: View of top thermosyphon array. Bottom right: View of bottom thermosyphon array.

C. Thermosyphon Modifications

The start-up related difficulties occurred because the evaporator was partly filled with liquid sodium. Two changes were made to the system to reduce the required sodium inventory. First, the slopes of the two roughly horizontal sections of the heat pipes were increased, improving drainage.

Second, the liquid hold-up in the annular condenser was reduced. As shown in Figure 10, the heat collector plate that is the actual heat sink for the condensers was modified so that each condenser sloped towards the adiabatic section of the heat pipe. As discussed below, these changes improved the start-up behavior.

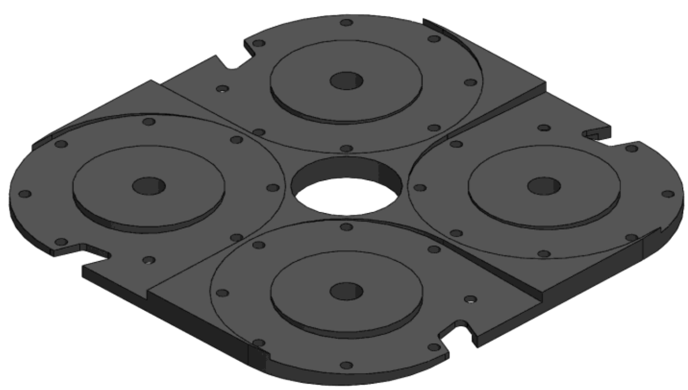

Figure 10. The heat collector plate was modified to add slopes under each condenser, allowing them to drain more easily.

D. Alkali Metal Pool Boilers

Besides reducing the sodium inventory, an additional change was made to improve start-up. As shown in Figure 7, the evaporator wall temperatures can exceed 800°C before the heat pipe starts, with superheats of several hundred degrees. This occurred because most of the evaporator was full of liquid sodium during start-up. High superheat is a known problem with alkali metal pool boilers[9]. For the heat pipe to start operating, boiling in the liquid pool must occur. In alkali metal systems, the alkali metal cleans off the oxides on the surface, suppressing the nucleation sites. The wick helps to suppress the superheat, but further modifications are required.

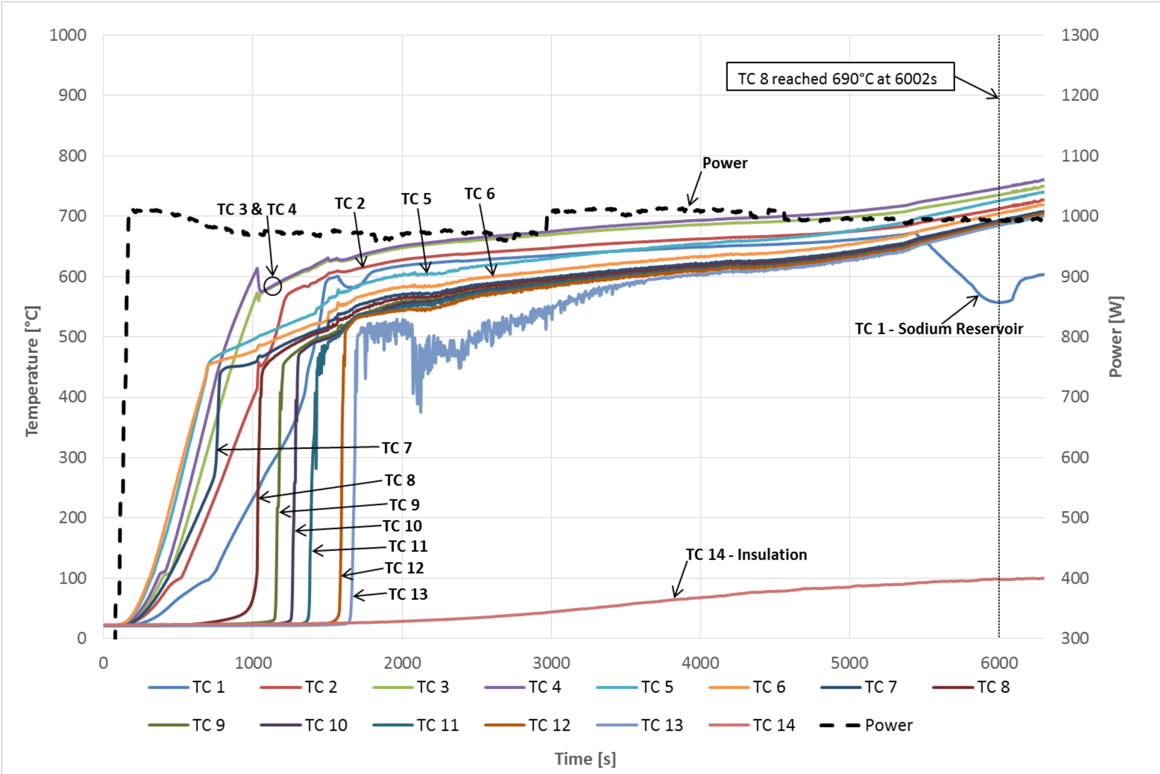

Figure 11. Start-up was improved by modifying the evaporator wick to lower the sodium pool. This start-up at 1000 W has a much lower temperature spike, with improved start-up time.

The easiest solution would be to add a larger sump to hold the liquid sodium during start-up. Unfortunately, the reactor design considerations allowed only a short stub below the reactor. As discussed above, the angled heat transfer interface between the condenser and the heat collector plate increased the slope of the roughly horizontal sections of the heat pipe, both of which lowered the total sodium charge.

In addition, the evaporator wick was modified by adding screen in the evaporator, filling the inner diameter almost entirely except a 0.125 in. (3.2 cm) diameter hole in the center for vapor venting. The additional portion of the screen has a larger pore size allowing the primary wick to retain the liquid during normal operation. Since start-up improvement was a major requirement for the Kilopower program, intensive testing was carried for the new evaporator wick configuration. The new evaporator wick was inserted in a 0.5 inch outer diameter stainless steel tube with 0.35 inch wall thickness and 48 inch length. Four individual tests were carried for four constantly applied powers: 800, 900, 1000 and 1100W. Figure 11 shows as an example the case where a power of 1000W was constantly applied during start-up. As seen in the figure, despite the high power applied constantly, the temperature spikes did not exceed 600ºC. Moreover, all of the four tests showed significant start-up improvement in terms of both temperature spikes and start-up time necessary for the pipe to reach nominal temperature.

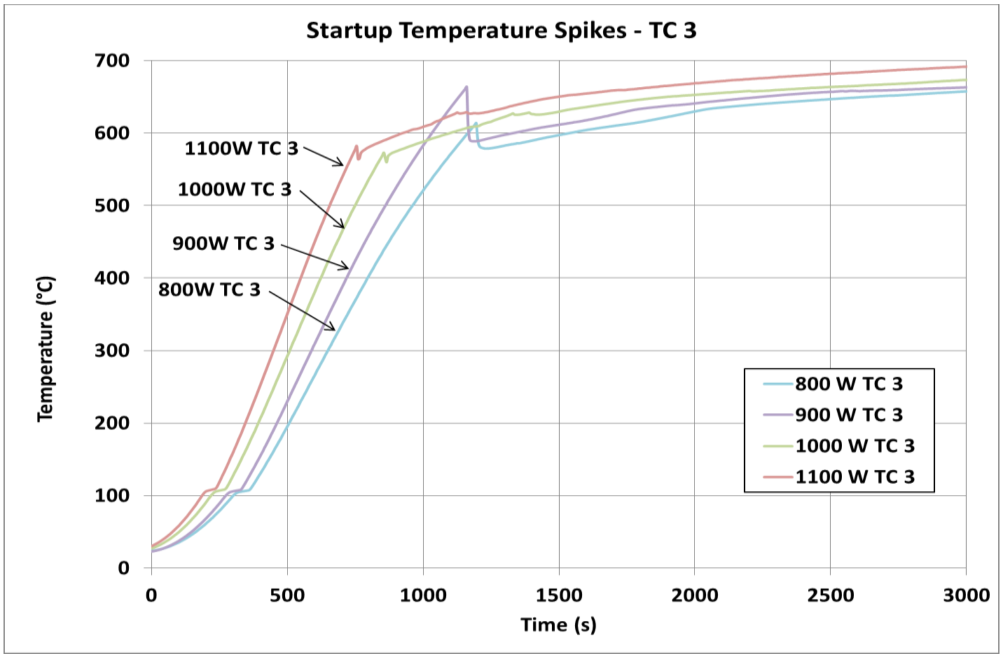

Figure 12. Temperature evolution of TC 3 during start-up for all four powers.

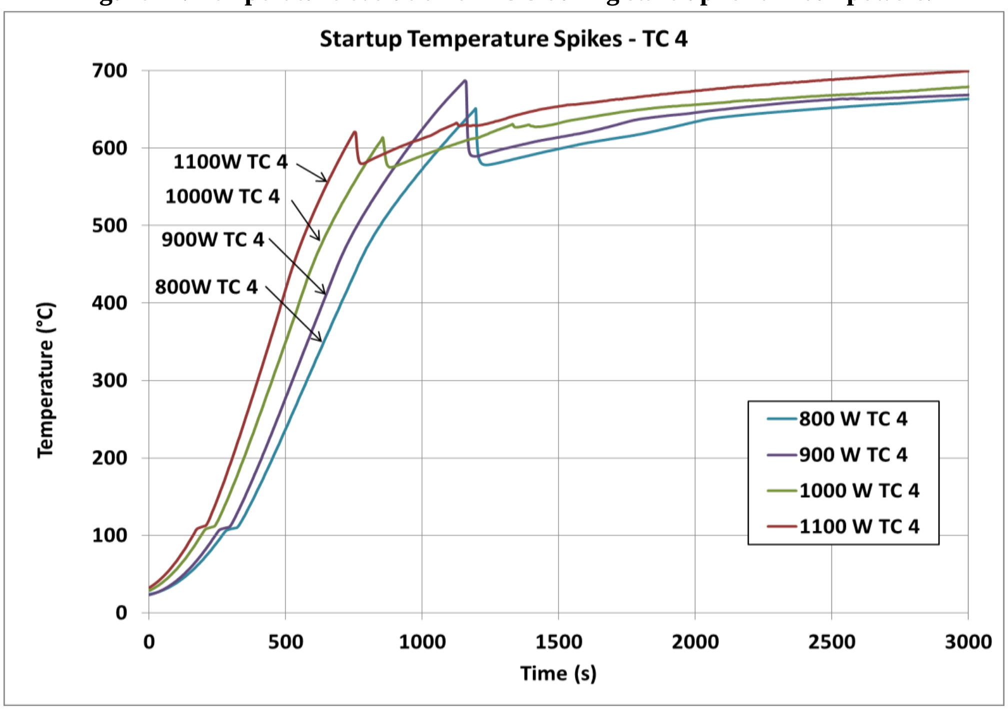

Figure 13. Temperature evolution of TC 4 during start-up for all four powers.

Figure 12 and Figure 13 show the temperatures recorded by TC 3 and TC 4 during start-up for all the four start-up power mentioned above. These thermocouples are attached to the lowest portion of the evaporator and their exact locations are shown above in. As seen in Figure 12 and Figure 13, the value of the highest temperature spike is 692ºC and is recorded at the location of TC 4 when a power of 900W is applied. Taking into consideration that this value is already lower than the nominal operating temperature (720-810ºC) in the actual system while the applied power is significantly higher than in the actual system (400 – 500W per pipe) it can be concluded that the start-up improvement was a success. Moreover, the start-up time was also significantly reduced from several hours to values around two hours depending of the total power applied and the operating point as shown in Figure 14.

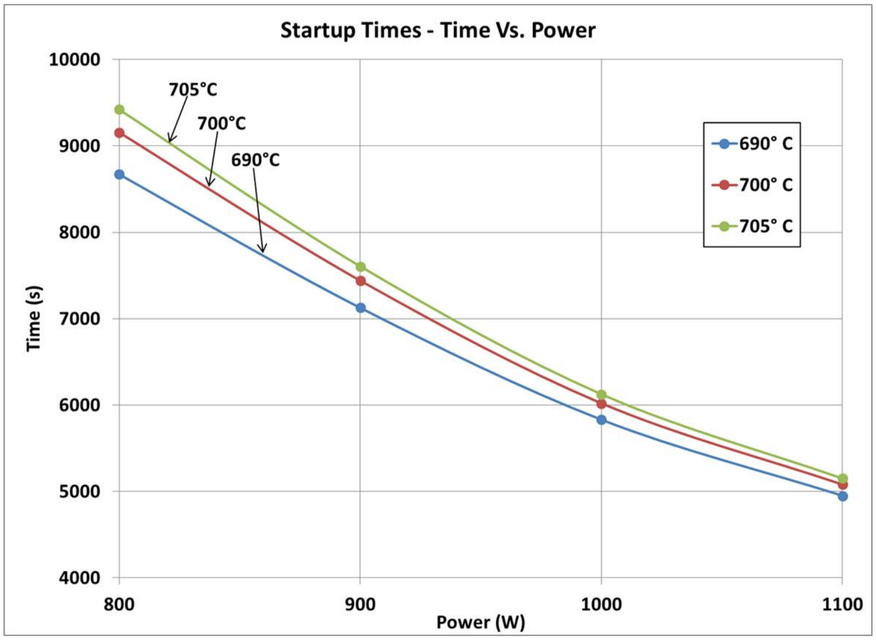

Figure 14. Summary of start-up duration after thermosiphon wick improvement.

In response to the improved start-up behavior of the prototype described above, the modified wick was included in next generation thermosyphon design. Additionally, the second generation thermosyphon design incorporated the change in slopes on the modified heat collector plate and reduced volume NCG reservoirs. Intensive testing was carried out to determine the new NCG charge and validate the modified wick in the final thermosyphon configuration. All testing was carried out in ambient with identical insulation and instrumentation as the first generation of heat pipes (see). Three start-up tests were performed with constant power of 850 Watts and increasing amounts of NCG: none, intermediate, and final.

Figure 15 shows the time history of the thermosyphon without NCG. The large amplitude temperature fluctuations along the pipe correspond with the vapor front reaching the annular condenser, where much smaller fluctuations occur. Here, the greater thermal mass, thermal gradient, and internal volume of the condenser cause large swings in the vapor pressure.

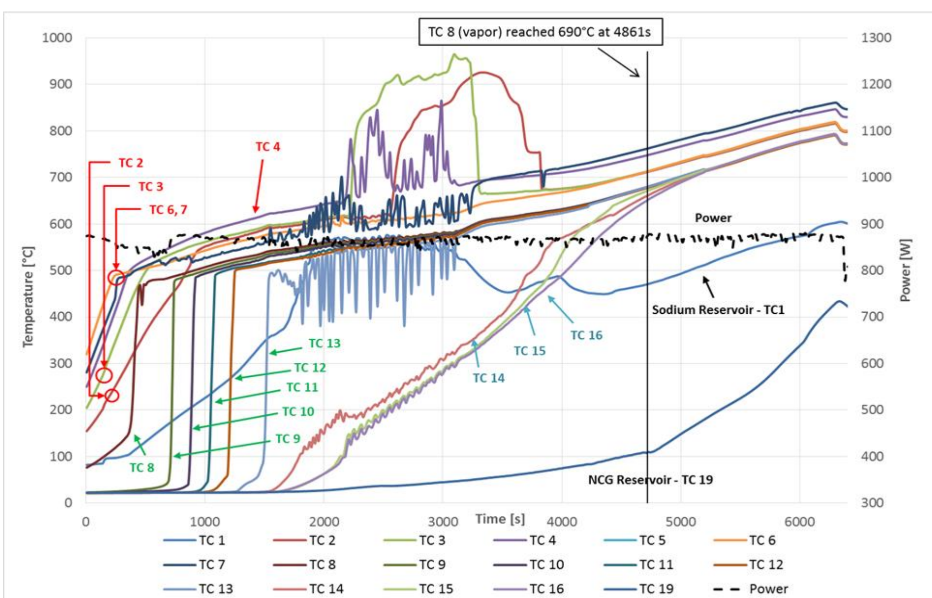

Figure 15. Start-up behavior of second generation thermosyphon without NCG. Large and multitudinous temperature fluctuations are observed.

The addition of NCG mitigates this behavior as seen in the following two test cases. The amount of NCG was determined experimentally by incrementing the charge until stable start-up was observed. Figure 16 shows the temperature evolution for an intermediate amount of NCG. The fluctuations are of much lesser degree in amplitude, duration, and location, confirming the benefits of NCG.

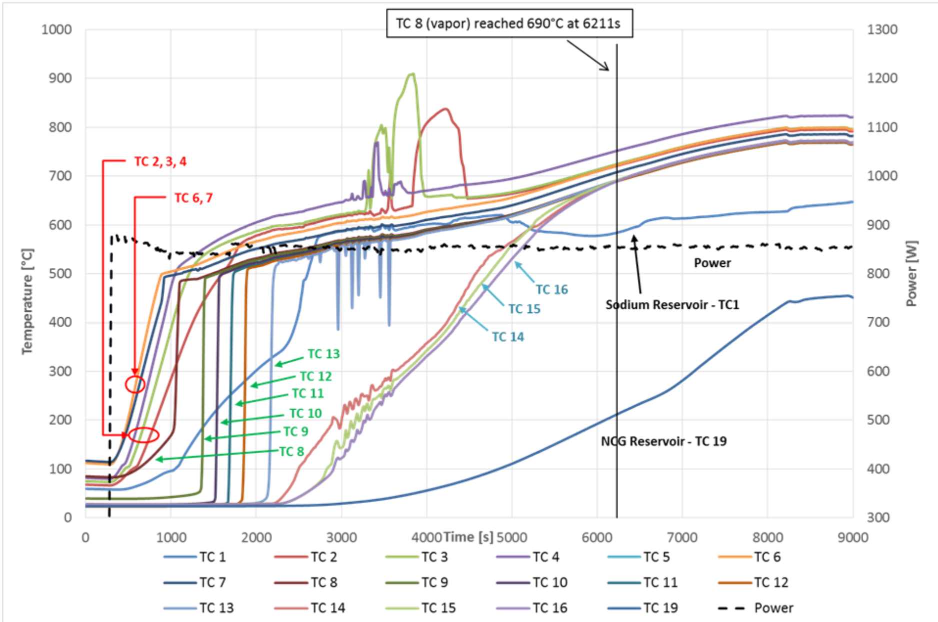

Figure 16. Start-up with intermediate amount of NCG. Fewer and lesser magnitude temperature fluctuations result.

The NCG charge was incremented again and its effects on start-up are shown in Figure 17. A smooth and stable behavior results; therefore, the heat pipe is sufficiently charged and does not require additional NCG. This final NCG amount will be used in the remaining second generation thermosyphons.

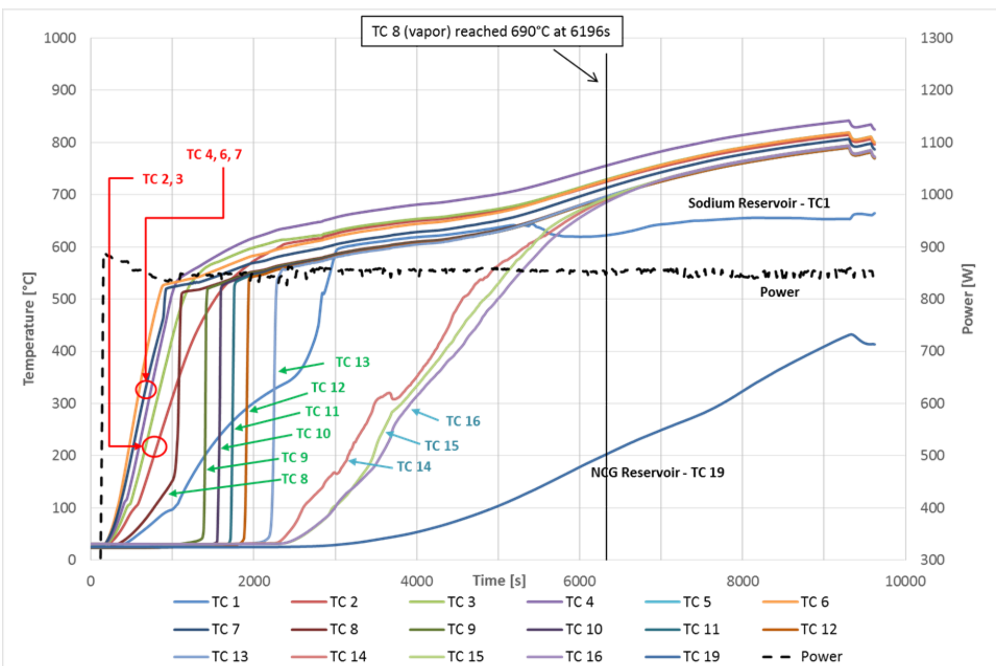

Figure 17. Start-up with final amount of NCG. Smooth and stable behavior is observed throughout the entire duration.

After the NCG charge was set, a performance test was carried out to verify the modified thermosyphon still meets the transport requirements at operational temperature. Throughout the duration of the test, a vapor temperature of 780°C was held constant by adjusting the temperature of the chill block when input power was adjusted. Electrical power ranged from 850W to the power supply limit of 1250W. Since the thermosyphon met the transport requirement with margin and without signs of dryout or significant change in conductance, further testing was not pursued. Results are shown in Figure 18.

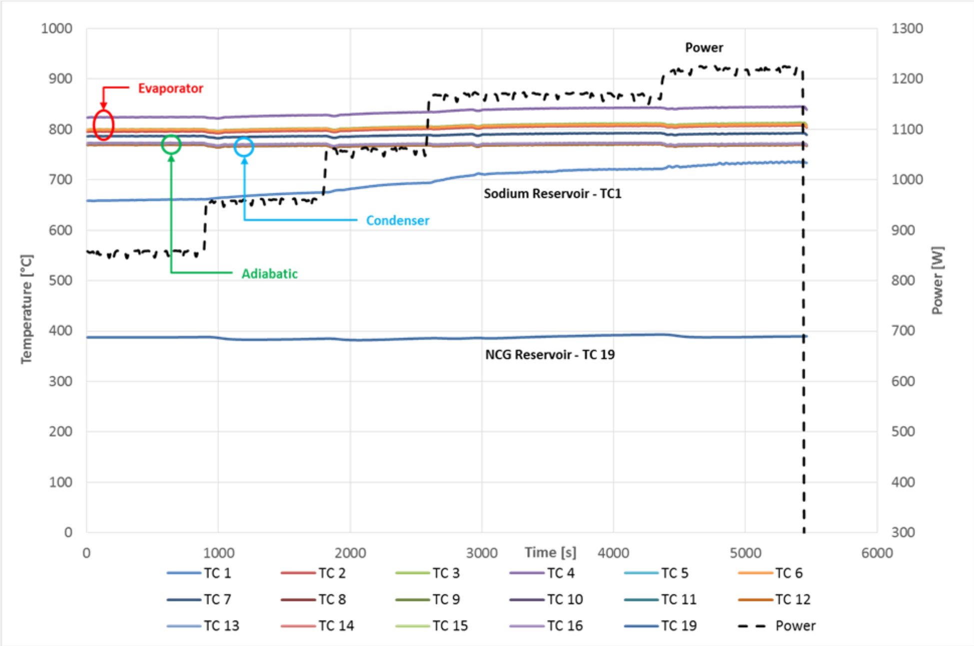

Figure 18. Heat transport test at operational temperature. No significant change in thermal conductance at maximum power.

The rest of the second generation thermosyphons are currently being fabricated and tested with an expected date in August 2016. Two thermosyphons are awaiting NCG charge and pinch weld operations. An additional two thermosyphons have been welded and instrumented and are waiting to be tested. The remaining thermosyphons are ready for welding. Figure 19 shows a picture of the current fabrication status.

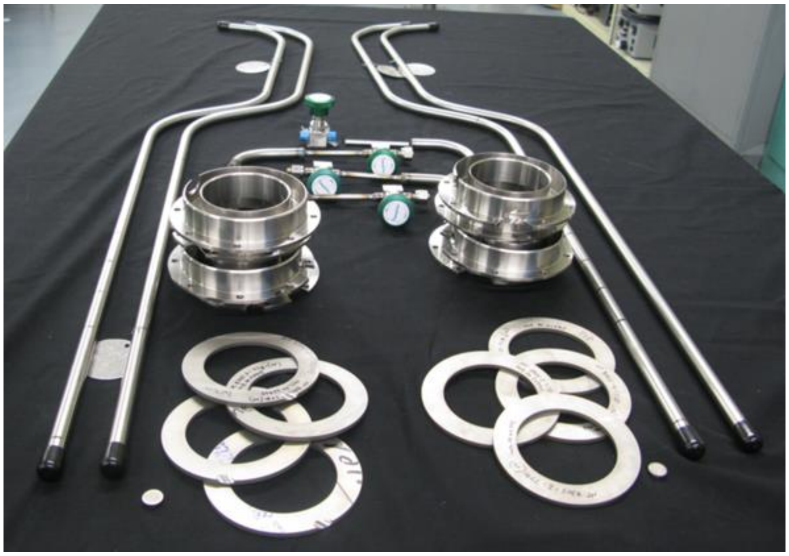

Figure 19. Remaining second generation thermosyphons ready for welding. An additional two thermosyphons are currently being tested.

V. CONCLUSIONS

A series of sodium heat pipes and thermos-syphons were developed for the Kilopower nuclear reactor test. The sodium heat pipes had a self-venting arterial wick, while the thermosyphons had a wick in the evaporator to assist in start-up.

The thermosyphons delivered the required power; however, the self-venting arterial heat pipes did not carry the required power when tested in a slightly adverse elevation. ACT is currently modifying the heat pipe wicks to increase the power.

The evaporator wick in the thermosyphons was successfully modified to mitigate start-up related temperature spikes and also to reduce the duration of the start-up in future pipes.

NASA Glenn Research Center is currently working on a thermal vacuum test of the Kilopower fission power system, including:

1. Electrically heated, depleted uranium core
2. Sodium heat pipes and thermosyphons developed on the current program
3. 8 Stirling Convertors
4. Due to limitations in the vacuum chamber size, the titanium/water heat pipes will be replaced with pumped liquid cooling.

The depleted uranium system will be tested in 2017. In 2018, a second unit will be tested with a live reactor core. ACT is currently developing the heat pipes for the 2018 nuclear test.

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