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Hybrid Variable and Constant Conductance Heat Pipes for Lunar and Martian Environments and High Heat Flux Space Applications

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Abstract

A hybrid wick heat pipe has a porous wick in the evaporator, and a grooved wick in the adiabatic and condenser sections. This paper will discuss four different applications for hybrid wick heat pipes: 1. Adverse evaporator elevations for landers and rovers, 2. High heat flux applications, 3. Vertical startup with a liquid column during ground testing, and 4. Freeze/thaw tolerant water heat pipes. The next generation of Lunar polar rovers and equatorial landers is among the immediate NASA applications. A Variable Conductance Heat Pipe (VCHP) is required that can operate during large adverse tilts in the evaporator, shut down during the long Lunar night and operate over a wide range of sink temperatures on the planetary surface. Also, future spacecraft and instruments developed for NASA's Science Mission Directorate will include highly integrated electronics, such as for CubeSat/SmallSat. Thermal transport requirements for future missions continue to increase, approaching several kilowatts. At the same time the heat acquisition areas have trended downward, thereby increasing the incident heat flux. A hybrid wick heat pipe will allow such devices to operate at higher heat fluxes as compared to axial groove design. Vertical start-up with a liquid column is mitigated experimentally with a hybrid wick. The experimental results proved that the large number of nucleation sites in sintered wicks facilitates boiling initiation in pool boiling systems and, consequently, the temperature spikes are minimized. Finally, a hybrid titanium/water heat pipe radiator assembly suitable for waste heat rejection from a Spacecraft Fission Power system such as the Kilopower system is also required. A prototype titanium heat pipe and several aluminum face sheets were joined with S-bond and tested for bond quality and overall thermal performance. Tests were performed successfully both in ambient and in vacuum validating the direct bond. The full length versions of the final deliverable hybrid grooved/screened titanium-water heat pipes for Kilopower system with radiators and the hybrid grooved/sintered CCHPs and VCHPs for high heat flux space applications and planetary surface are under development.

Keywords: Constant Conductance Heat Pipes (CCHPs); Hybrid wick; Lunar and Martian environments; Variable Conductance Heat Pipes (VCHPs); High heat flux heat pipe wicks; Vertical start-up

1. INTRODUCTION

As identified in NASA's roadmap for Thermal Management Systems [1] there is a need to develop high temperature heat pipes to provide high heat flux capability (far in excess of 5-10 W/cm^2) with the benefit of being light weight and passive design. The hybrid wick heat pipes will be capable of operating at the higher heat flux requirements expected in NASA's future spacecraft and instruments such as on the next generation of polar rovers and equatorial landers. In many highly powered spacecraft, CCHPs are used to collect the heat and transfer the heat to a loop heat pipe (LHP), which in turn carries the power to a radiator. LHPs have a higher boiling limit than grooved CCHPs. With a moderate heat flux, an LHP could be used to collect the heat instead of a CCHP. However, LHPs are roughly 50 times more expensive than CCHPs. For cases with higher heat fluxes than a LHP can handle, as well as cases when there is more than one high heat flux area, it makes more sense to use CCHPs to collect the high heat flux heat and deliver it to a single LHP, which in turn can carry the power to a radiator.

Future Martian and lunar surface missions using the next generation of the polar rovers and equatorial landers are among the immediate NASA applications. A variable conductance heat pipe (VCHP) is required that can operate during large adverse tilts in the evaporators, shut down during the long Lunar night and operate over a wide sink temperature fluctuations on the planetary surface. This VCHP requires hybrid wick to allow liquid return during operation under unfavorable orientation of the evaporator.

Also, NASA is examining small fission power reactors, such as the Kilopower, which aims to provide roughly 1 kWe of electric power. KiloPower is a NASA/DOE project to validate fission power technology to provide power in space and planet surface. Kilopower program plans to use alkali metal heat pipes to transfer heat from the reactor to a series of Stirling convertors, and

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titanium/water heat pipes to transfer the waste heat from the cold end of the convertors to the ultimate radiators. Previous water heat pipe designs are not suitable for Kilopower program, because they were designed as gravity aided heat pipes (thermosyphons) for surface fission power and are not suitable for space operation. 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. Advanced Cooling Technologies, Inc. (ACT) is developing a hybrid grooved/screen wick titanium/water heat pipe radiator assembly suitable for rejecting of the waste heat from a Spacecraft Fission Power system such as the Kilopower system.

The hybrid screen or sintered/grooved wick will be used for planetary surface and high heat flux applications. The hybrid wick will provide superior liquid return through the wick structure enabling heat flux dissipation levels that could otherwise not be achieved and also it can operate against gravity.

2 BACKGROUND

NASA is examining small fission reactors for future space transportation and surface power applications. The Fission Surface Power System is designed to operate from 10 to 100 kWe while current Radioisotope Power Systems operate below 1 kWe. The Kilopower system as shown in Fig. 1 would address the power gap between current RPS and FPS, providing between 1 and 10 kWe. The nuclear reactor supplies thermal energy to Brayton (or Stirling) convertors to produce electricity. Hybrid wick titanium/water heat pipes carry the waste heat to a radiator for ultimate rejection in space [2, 3, and 4].

Fig. 1. Full-scale nuclear test of reactor core, sodium heat pipes, Stirling convertors, and hybrid wick titanium/water heat pipe radiator system at prototypic operating condition [2].

2.1 Grooved Aluminum/Ammonia Heat Pipes

Grooved wicks are the standard wicks used in spacecraft Constant Conductance Heat Pipes (CCHPs), Variable Conductance Heat Pipes (VCHPs), and diode heat pipes. The benefit of the grooved wick is that it cannot be de-primed by vapor bubbles, since the bubbles can vent into the vapor space. These grooves have a very high permeability, allowing heat transfer for long distances during operation in micro-gravity, typically several meters long. One of their weaknesses 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. Axial grooves CCHPs also have a relatively low heat flux limitation. For reference, typical aluminum grooved extrusions are shown in Fig. 2.

Grooved aluminum/ammonia heat pipes are designed to work in microgravity environments. A 1/10 inch adverse elevation is used for testing on earth prior to insertion in a spacecraft. However, they are very sensitive to adverse elevation. Increasing the heat pipe elevation by 0.10 inch will significantly decrease the performance. For heat pipes operating on the Moon or Mars, grooves can only be used in gravity-aided portions of the heat pipe. Another wick must be developed for sections with adverse elevations. These wicks can be sintered powder wicks, screen mesh, or metal foam wicks [5].

Fig. 2. Grooved aluminum extrusions for ammonia heat pipes. Grooves allow heat transfer over long distances for spacecraft applications, but only work about 0.10 inch against gravity for earth-based testing.

3 HYBRID WICK HEAT PIPES CONCEPT

Fig. 3 shows the concept of hybrid wicks as a combination of screen mesh, or sintered evaporator wicks for the evaporator region, which can sustain high heat fluxes and operate against gravity, where the axial grooves in the adiabatic and condenser sections can transfer large amounts of power over long distances caused by low liquid pressure drop and their high wick permeability.

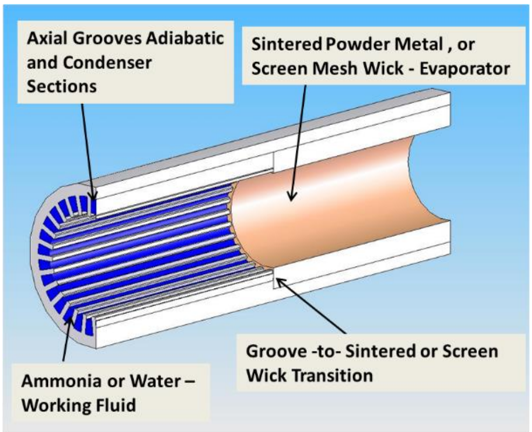

Fig. 3. Ideal groove-sintered wick or grooved-screen wick interface joint.

Hybrid grooved-sintered or grooved-screen wick CCHPs/VCHPs have the following benefits:

- ✓ The sintered powder or the screen mesh evaporator wick is capable of operating against gravity on the planetary surface and also can operate at higher heat fluxes in comparison to the axial groove design.
- ✓ The grooved condenser wick in the hybrid CCHPs/VCHPs allows the heat pipe to operate in space, carrying power over long distances.
- ✓ The grooved condenser wick in the hybrid CCHPs/VCHPs allows the heat pipe to act as a thermosyphon on the planetary surface for Lunar and Martian landers and rovers. Therefore, it is suitable for Lunar/Martian rover and lander applications.
- ✓ The combination has a higher transport capability than an all-sintered or screen mesh wick.

Both hybrid sintered/grooved design for aluminum/ammonia heat pipes and hybrid screen/grooved design for titanium/water heat pipes have been demonstrated by ACT [6, 7, 8, 9],

3.1 Hybrid Grooved/Sintered Heat Pipes

For planetary applications, the heat pipe has to operate both in gravity environment and in micro-g environments, thus a conventional, all grooved wick is not appropriate. As an alternative, a hybrid wick will be developed as shown in Fig.4. All of the adiabatic and condenser sections have axial grooves for liquid return. The evaporator section use sintered wick, which has higher capillary pumping capability than grooves, allowing the evaporator to be tilted as much as 25° against lunar gravity, accommodating tilts caused by the rough lunar surface.

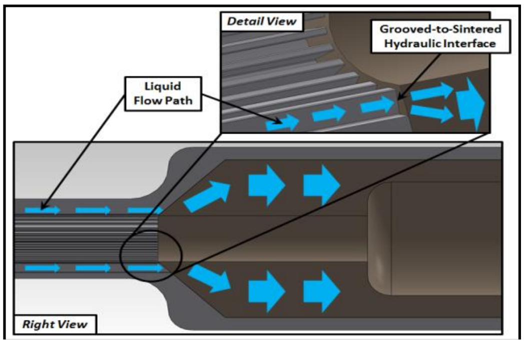

Fig.4. Planetary CCHP evaporator 45° conical interface between the sintered wick in the evaporator and the grooves in the adiabatic section (cross sectional right view and detail view).

Additionally, sintered evaporator wicks may also reduce/eliminate start-up problems in thermosyphons and vertical gravity aided heat pipes. Start-up related difficulties in vertical, grooved aluminum/ammonia heat pipes developed for the Mars SAM (Sample Analysis at Mars) instrument on the Mars Scientific Laboratory (MSL) have been observed by Swanson and Butler [10]. They believe that start-up was delayed because the heat pipe temperature needed to increase until pool boiling was started. As a result, a start-up heater was added to solve this problem. ACT believes that an alternative and passive solution can be provided by a hybrid wick. The reason is that a larger number of nucleation sites in the wick would allow easier boiling initiation in pool boiling systems [11].

The sintered and grooved evaporator wick heat pipes were tested to prove that start-up related temperature spikes in vertical gravity aided heat pipes can be eliminated/reduced by using sintered evaporator wicks. The hypothesis was based on the fact that sintered wicks have a larger number of nucleation sites that will allow easy boiling initiation. Consequently two 12-inch long heat pipes were fabricated and tested. These two heat pipes were: a conventional axial grooved heat pipe, and a hybrid sintered/grooved heat pipe as shown in Fig. 5.

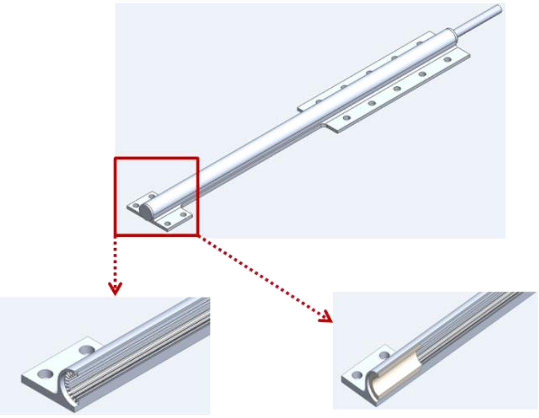

Fig. 5. Top: Drawing for the external geometry for the axial grooved and the hybrid CCHP, Bottom left: axial grooved CCHP, Bottom right: hybrid sintered/grooved CCHP.

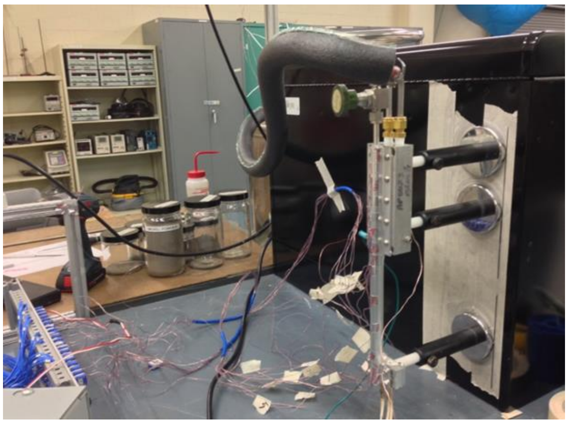

Fig. 6. Testing apparatus for the start-up related difficulties mitigation in vertical heat pipes.

The testing apparatus for the start-up characteristics in vertical heat pipes is shown in Fig. 6. While the testing results for the axial grooved and the hybrid heat pipes at the optimal charged is shown in the figures (Fig. 7 and Fig. 8) respectively. These figures show that the temperature spikes (highlighted using circles) in vertical gravity aided heat pipes are minimized/eliminated by using sintered evaporator wicks.

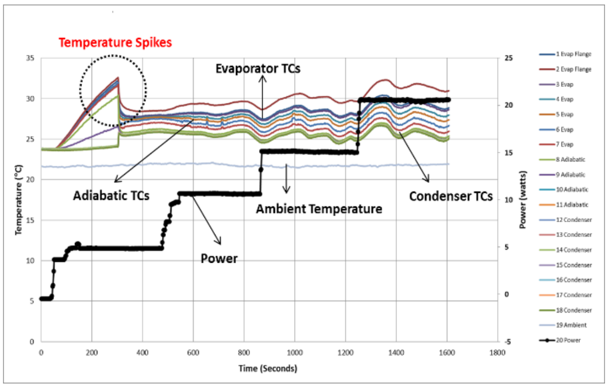

Fig. 7. Thermal performance profile for the axial grooved CCHP with power applied in 5 W increments and 25°C condenser set point with an optimal ammonia charge.

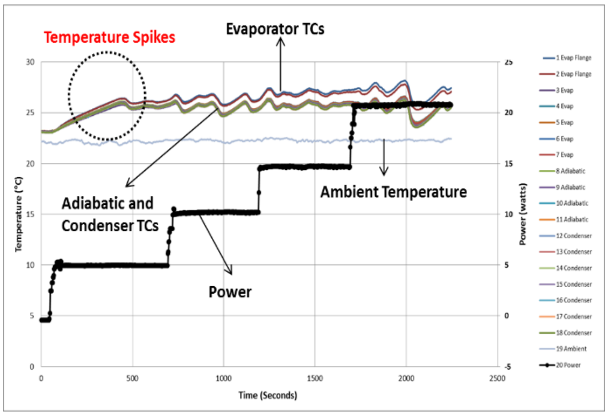

Fig. 8. Thermal performance profile for the hybrid sintered/grooved CCHP with power applied in 5 W increments at 25°C condenser set point with optimal ammonia charge.

Currently, the hybrid CCHPs and VCHPs for high heat flux space applications and planetary surface are under fabrication at ACT for experimental demonstration in the near future.

3.2 Hybrid Grooved/Screened Heat Pipes

ACT developed a successful prototype for a hybrid grooved/screened titanium/water heat pipe suitable for the cold end of the Kilopower system. The heat pipe design needs to support the Kilopower system through four different operating conditions: 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.

Since the titanium/water heat pipes will carry the waste heat to a radiator, where the heat is rejected, a trade study was set up to optimize designs for 1 kWe Kilopower systems in terms of power to mass ratio. Direct bonding of the titanium heat pipes to the aluminum plates using S-bond joining offered by S-Bond Technologies is completed and tested to evaluate the bonding quality. ACT tested the titanium/aluminum radiator system, as shown in Fig.9, in both ambient and vacuum conditions.

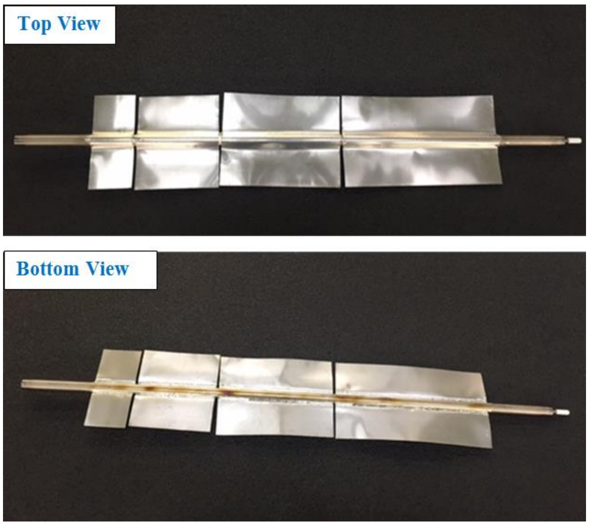

Fig.9. Titanium heat pipe bonded to aluminum plates using S-bond technology.

3.2.1 *Testing in ambient conditions*

The titanium heat pipe was charged with 5 ml of Deionized (DI) water and then tested in ambient environment in a thermosyphon mode as shown in Fig. 10. The thermocouple map for the titanium/aluminum radiator system is shown in Fig. 11.

Fig. 10. Testing the titanium/aluminum radiator system in ambient conditions.

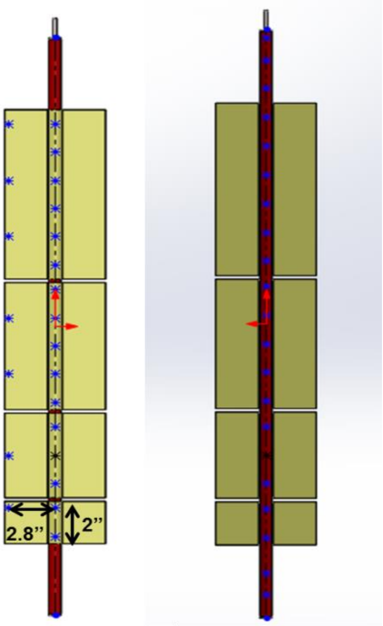

Fig. 11. Thermocouple map for the titanium/aluminum radiator system.

3.2.2 *Experimental results from testing in ambient conditions*

Fig.12 shows the testing results for the titanium/aluminum radiator system in ambient conditions. In order to simulate the real operating conditions, the power is increased until the system’s temperature reached 130°C. For this condition, the amount of power rejected by the radiator system was approximately 200W. In ambient environment, the heat removal mechanisms are radiation and natural convection. The temperature distributions along the titanium pipe and the root of the aluminum panels are relatively isothermal at each power level.

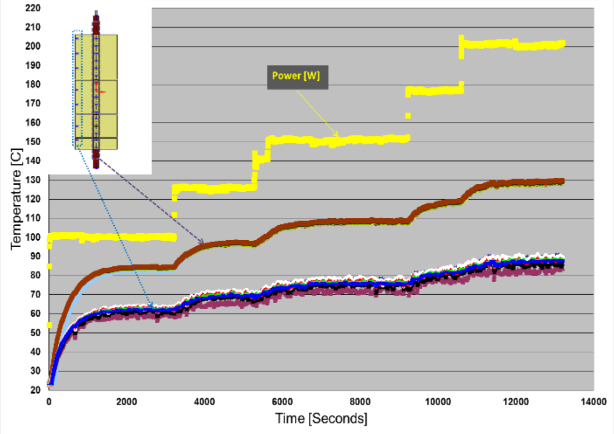

Fig.12. Temperature distribution in ambient conditions for the titanium/aluminum system.

3.2.3 *Testing in vacuum chamber*

For a better evaluation of the quality of the aluminum/titanium bond, the radiator system was tested in the vacuum chamber. Since the heat removal mechanism in space is radiation only, the rate of heat dissipation is:

$$\dot{Q} = \sigma \varepsilon A \left(T_s^4 - T_\infty^4 \right) \quad (1)$$

Where $\dot{Q}$ is the power radiated, σ is the Stefan-Boltzmann constant, ε is the emissivity, A is the radiator area, T_s is the surface temperature, and T_∞ is the apparent temperature of the environment. The aluminum radiator fin has a very low emissivity, so not much heat will be rejected from the bare fin. A high emissivity material Polyurethane coating was used to paint the aluminum panels before testing in the vacuum chamber as shown in Fig. 13. Note that there was no cold shield in the vacuum chamber, so the effective sink was roughly room temperature.

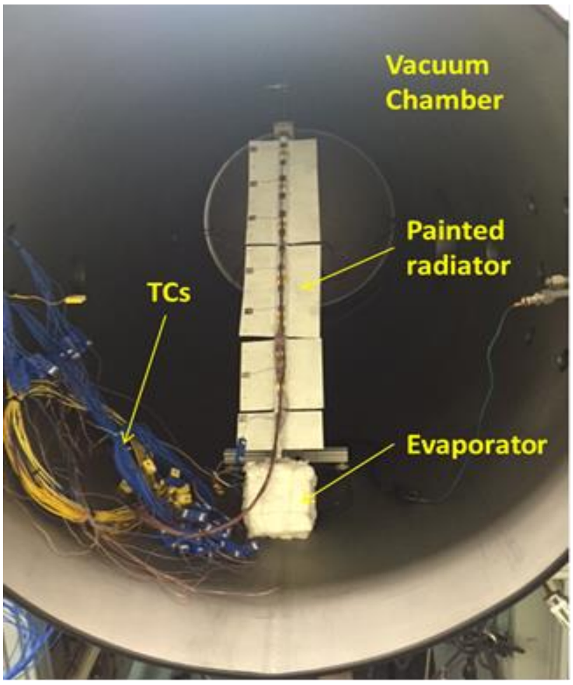

Fig. 13. Testing the titanium/aluminum radiator system in the vacuum chamber.

Polyurethane coating is a reflective, moisture-curing coating designed for product finishing applications on substrates used in aircraft and aerospace applications. This coating can withstand temperatures from cryogenic levels to 131 °C and has been used for space applications for over 30 years. It has been tested at ACT with 95% emissivity.

Fig.14 shows the testing results for the coated radiator panels inside the vacuum chamber. Similar to ambient testing, the power is increased until vapor temperature reached 130°C. The amount of power that the radiator system rejected inside the vacuum chamber was approximately 150W. The temperature distributions for the titanium pipe and the root of the aluminum panels are relatively isothermal at each power level.

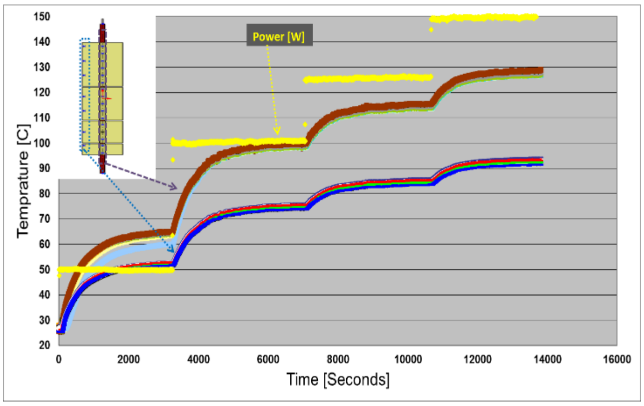

Fig.14. Temperature distribution in vacuum chamber for the coated aluminum panels.

Currently, the full length versions of the final deliverable hybrid grooved/screened titanium - water heat pipes for Kilopower system with radiators are under fabrication.

4 CONCLUSIONS

Hybrid CCHPs and VCHPs with two different designs that are suitable for Lunar and Martian environments and high heat flux space applications are developed: a hybrid grooved/sintered wick and a hybrid grooved/screen wick.

Hybrid VCHPs are required for the next generation of polar rovers and equatorial landers. These hybrid heat pipes can (i) operate against gravity on the planetary surfaces, (ii) operate in space carrying power over long distances and (iii) act as a thermosyphon on the planetary surface for Lunar and Martian landers and rovers. The start-up difficulties is solved with a hybrid wick placed on the evaporator section and the experimental results proved that the large number of nucleation sites in sintered wicks allow easy boiling initiation in the sintered wick evaporator and the temperature spikes are minimized.

A hybrid titanium/water heat pipe radiator assembly suitable for rejecting waste heat from a Kilopower reactor system is needed. A prototype titanium heat pipe and aluminum radiator were joined with S-bond and tested for bond quality and overall thermal performance. Tests were performed successfully in ambient and under vacuum.

Finally, the full length versions of the final deliverable hybrid grooved/screened titanium - water heat pipes for Kilopower reactor with radiators and the hybrid grooved/sintered CCHPs and VCHPs for high heat flux space applications and planetary surface are under fabrication for experimental demonstration in the near future.

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NOMENCLATURE “

ACT : Advanced Cooling Technologies, Inc.
CCHPs : Constant conductance heat pipes
VCHPs : Variable conductance heat pipes
W : Watt

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