Developments in Thermal Management Technologies for Space Nuclear Energy Systems

Calin Tarau, William G. Anderson and Jeff Diebold
Advanced Cooling Technologies, Inc., Lancaster, PA, 17601, U.S.A.

Corresponding authors: calin.tarau@1-act.com, bill.anderson@1-act.com

Abstract

Advanced Cooling Technologies, Inc. (ACT) has extensive experience developing thermal management solutions for nuclear energy applications in space. Since 2005, ACT has been involved in researching and developing innovative thermal management technologies for Nuclear Electric Propulsion (NEP), Fission Surface Power (FSP), and Stirling Radioisotope Generators (SRG). ACT has created specialized high-temperature heat pipes, heat-pipe radiators, pumped loops, heat exchangers, and other thermal systems to manage both high and low temperatures in these nuclear systems for space exploration. This paper summarizes ACT's capabilities and contributions to critical thermal management technologies for nuclear energy in space.

1. Introduction

Space travel requires reliable, efficient power sources that can operate in extreme environments. Nuclear energy can provide sustainable power for deep space missions, space transportation, and surface applications on the Moon and Mars. Effective thermal management is critical for these nuclear systems, from reactor heat extraction to waste heat rejection. For 20 years, Advanced Cooling Technologies (ACT) has specialized in thermal solutions for nuclear power in space.

Since its founding in 2003, ACT has actively researched and developed key parts of nuclear power systems. This includes high-temperature alkali-metal heat pipes and interfaces to transfer heat from reactors to energy convertors like Stirling and Brayton, low-temperature pumped loops and as well as high and low temperature heat pipe radiators to transfer waste heat and reject it to space. ACT has worked on several programs including Kilopower (a successful demonstration on earth of a space reactor), Fission Surface Power (FSP), Nuclear Electric Propulsion (NEP), and Stirling Radioisotope Power Systems including the defunct Advanced Stirling Radioisotope Generator (ASRG). Again, their innovations in heat pipes, pumped loops, interfaces and radiators represent enabling contributions in nuclear energy use for space exploration missions.

2. Background

Passive cooling technologies like heat pipes have accelerated advances in nuclear systems, especially for space applications. By removing heat from reactors without pumps or blowers, passive cooling simplifies design and enables more compact and modular systems. Heat pipes allow nuclear reactors to respond to changing conditions and provide high heat transfer rates over relatively long distances. Their passive operation, high performance as well as high redundancy potential make heat pipes ideal for integrating into nuclear reactors. On Earth and in space, heat pipes' ability to efficiently cool reactors with no moving parts has proven invaluable. As nuclear technology continues advancing, passive cooling solutions like heat pipes will remain critical enablers. Their autonomous operation and effectiveness let nuclear systems be more compact, robust, and configurable while ensuring reliable thermal management.

2.1. Heat Pipe Nuclear Reactors

Several types of space applications can benefit from heat-pipe-cooled nuclear reactors. Nuclear electric propulsion (NEP) systems provide a variety of benefits including increased science payload, reduced flight times and longer mission lifetimes [1], enabling manned missions to the Moon and Mars, as well as unmanned missions to the outer planets and deep space. In addition to NEP, there is also significant interest in the development of fission surface power (FSP) capabilities to provide power to lunar and planetary bases. NASA and the DOE recently awarded contracts to three industry primes and their partners to develop designs for a 40 kWe fission power system for the lunar surface. The thermal management system linking the reactor to the hot end of the power conversion system (Brayton or Stirling) must be efficient, lightweight, and reliable. These requirements become more challenging as the total power scales to the megawatt level.

Heat pipe reactors represent a subset of small modular and microreactor designs that rely on heat pipes to extract thermal energy from the nuclear core. Figure 1a illustrates a potential heat pipe reactor design proposed by Los Alamos National Lab (LANL) [2]. As seen in Fig. 1b, the heat pipes are embedded within a monolithic core alongside the fuel to passively extract heat from the core and provide it to the energy convertors. The cold end (condenser) of the heat pipes can then interface with a heat exchanger to transfer the heat to the power conversion system. Heat pipe reactors require the use of high-temperature alkali metal working fluids such as potassium, sodium, or even lithium.

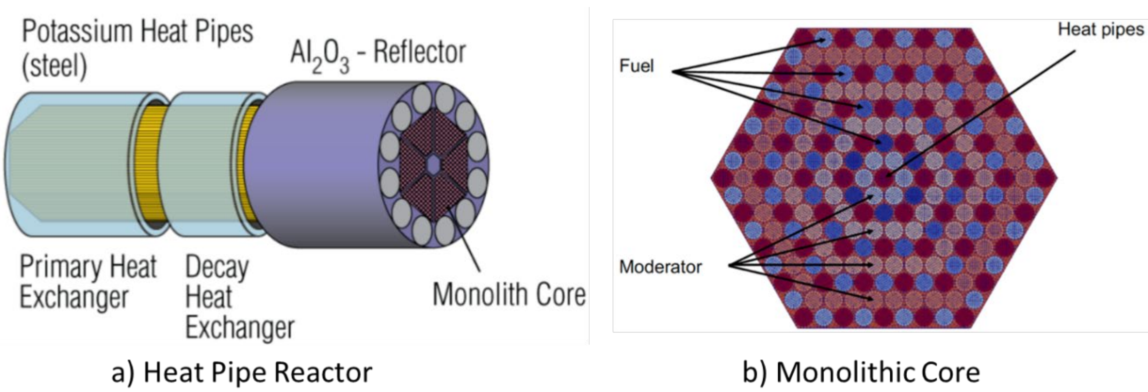


Figure 1. Heat pipe reactor design proposed by LANL [2], b) Pattern of fuel rods and heat pipes in a heat pipe reactor's monolithic core [3].

Heat pipe reactors have several inherent advantages that include:

- ***Reduced Size:*** Heat pipe reactors can generally be <u>*smaller*</u> than other reactor concepts due to the compact design of the monolithic core containing the fuel and heat pipes, as well as the lack of pumps and auxiliary equipment.
- ***Simplicity:*** Heat pipes are solid-state passive heat transfer devices that require no moving parts or power, resulting in a more reliable system with reduced maintenance.
- ***Safety and Redundancy:*** Typical reactor designs utilize pumped coolants (e.g., gas, water or liquid metals) to extract heat from the cores representing a potential single-point failure of the system. Preventing this failure requires the use of redundant components and/or additional passive safety devices. A heat pipe reactor uses hundreds of heat pipes to extract the heat, significantly reducing the impact of the failure of any single heat pipe. In addition, there are no high-pressure systems within the reactor, significantly increasing damage resilience.

Heat pipe reactors can serve a variety of applications. During NASA's Kilopower program, a 10 kWe fission reactor using sodium heat pipes was designed for use in space as well as on the lunar and Martian surface [4, 5]. On Earth, heat pipe reactors are ideally suited for several applications. They can provide power to DoD bases in forward areas, around 50% of which need less than 10 MWe. The reactors also work for remote civilian sites (such as villages in Alaska) and remote mining operations, and they can combine with intermittent renewable sources in hybrid systems that need a reliable power generation source. Many heat pipe reactors were designed for 10's – 100's of kW_e of power. Scaling heat pipe reactors to higher powers requires maximizing the power transfer capabilities of the individual heat pipes, which depends on the heat pipe wick design, geometry, working fluid and operating temperature. In general, increasing the diameter of the heat pipe will increase its maximum power transfer capability; however, increasing the pipe diameter may not be viable in a heat pipe reactor due to constraints on the core size. Increasing the maximum power transfer capability of a heat pipe for a given outer diameter could allow for fewer pipes, higher total power output from the reactor or increased safety margin of the system. By increasing the maximum power through advanced wick design, a heat pipe reactor can be more reliably scaled into the MW range and, in the space nuclear systems, increase the onboard specific power, which is crucially important.

2.2. Heat Pipes for Microgravity (Space) Operation

Heat pipes in thermal management for nuclear power in space (microgravity) must be wicked to enable the liquid return by capillary pumping.

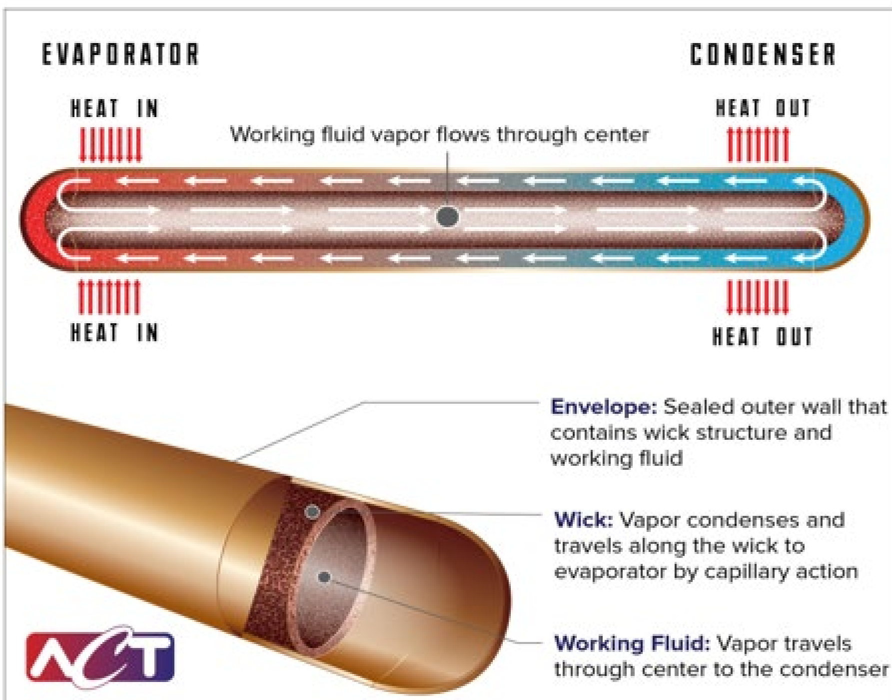


Figure 2. Basic heat pipe internal structure and its operation.

A *heat pipe* is the most basic passive two-phase heat transfer device, which uses the latent heat of vaporization, and the associated evaporation and condensation processes, to efficiently transfer heat across distances with a low thermal resistance. As shown in Fig. 2, a heat pipe generally consists of a vacuum-tight envelope, usually a cylindrical tube, containing an amount of working fluid typically at saturation and a capillary wick structure (sintered powder wick, screen wick, axial grooves, etc.). In the evaporator, a heat input vaporizes the liquid phase of the working fluid. The vapor then flows to the cooler condenser section at the opposite end of the heat pipe, where it condenses and releases its latent heat. The condensed working fluid (liquid) is then returned to the evaporator by capillary action in the wick. Due to the two-phase heat transfer mechanisms, heat pipes can transport heat for relatively long distances with minimal temperature drop. Typical heat pipe equivalent thermal conductivity can range from 10,000 to 100,000 W/m-K. Heat pipes can be designed for various temperature ranges from cryogenics to high temperature (> 1000°C). ACT accumulated a significant number of years of experience in developing alkali metal (cesium, potassium and sodium) heat pipes with envelopes of stainless steel, super-alloys (Haynes 230 and Inconel) [5, 21] and refractory metals (Niobium and TZM) for both terrestrial and space applications.

2.3. Heat Pipes for Gravity Assisted (Planetary Surface) Operation - Thermosyphons

A thermosyphon is a heat pipe that relies on gravity to drive the liquid return. The operation of a thermosyphon is illustrated in Fig. 3. Heat enters the evaporator near the bottom of the thermosyphon where it is absorbed by the latent heat of vaporization of the working fluid. The newly formed vapor rises and passes through the adiabatic section to the condenser. This flow is driven by the pressure difference between the evaporator and condenser. In the condenser, the vapor condenses and gives up its latent heat. The condensate returns to the evaporator driven by gravity. Compared to a capillary-driven heat pipe, a thermosyphon is structurally simpler, and has a lower mass and manufacturing cost. In some cases, a simple wick structure is installed only in the evaporator to provide more uniform liquid distribution at the evaporation sites as well as improved startup. Also, special wick designs can be integrated to improve thermosyphon performance.

Experimental studies [7..11] of thermosyphons show the existence of several operating limits that depend on the evaporator heat input, thermosyphon geometry, amount of working fluid, and fluid properties:

- ***Dry-out limit*** occurs when the fluid fill is inadequate for the thermosyphon to have a continuous circulation of vapor and liquid at a given heat flux. Consequently, the liquid pool dries out, resulting in a sharp increase in the evaporator wall temperature.
- ***Boiling*** or ***critical heat flux limit*** is similar to the critical heat flux condition in the pool boiling mode which also leads to a sharp increase in the evaporator wall temperature.
- ***Viscous limit*** occurs at low temperatures when the vapor drop from the evaporator to the condenser is comparable to the saturation pressure of the vapor. As a result, the pressure difference driving the vapor flow is insufficient to sustain the necessary mass flow rate. The viscous limit is most likely to occur at low temperatures during startup, especially for alkali metal heat pipes.
- ***Sonic limit*** occurs when the vapor velocity approaches the speed of sound, and the vapor can no longer carry additional power. For a fixed vapor temperature, increasing power requires the vapor velocity to increase eventually approaching a maximum value corresponding to the speed of sound in the vapor at that temperature. At the sonic limit, the vapor cannot carry all the power entering the evaporator resulting in a rise in evaporator and vapor temperature until the sonic limit matches the heat input. Unlike other limits, the sonic limit does not result in dry out of the evaporator.
- ***Entrainment*** occurs when the falling liquid is "captured" from the wick by the high-speed, upward vapor flow. This will create a decrease in the liquid return flow rate that reaches the evaporator leading to drying of the evaporator.
- ***Flooding limit*** is similar to entrainment as vapor flow impacts the counter-current liquid return flow. However, it occurs only in thermosyphons in wickless zones where vapor flow "shears" the downward liquid flow impeding the liquid return (falling liquid). This can result in the flooding of the condenser, and starving and dry-out of the evaporator.

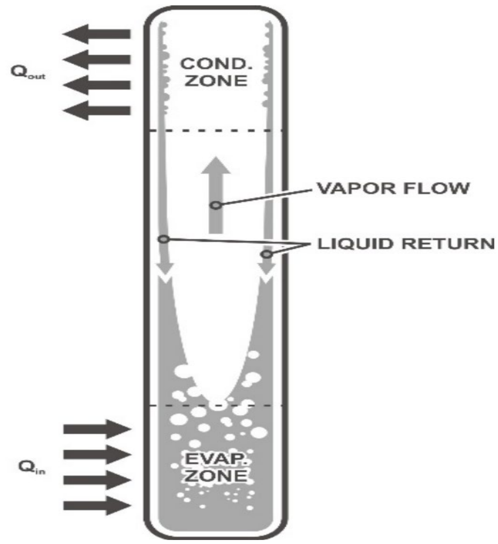


Figure 3. Illustration of thermosyphon.

In traditional thermosyphons the flooding limit is the most common concern, especially for long thermosyphons with large liquid fill ratios and axial heat fluxes. The sonic limit may dominate at low temperatures, especially for alkali metal working fluids during startup, when the low vapor density requires high velocity to carry the power. Under normal operating conditions, other limits are generally much higher than the flooding limit. In particular, heat pipes/thermosyphons in small modular nuclear reactors are relatively long (about 2 meters) and have large axial heat fluxes, which makes the flooding limit the dominant performance limit for these heat pipes. For a given operating condition and working fluid, increasing the flooding limit of a conventional thermosyphon requires increasing the diameter which may not be feasible for Small Modular Reactors (SMRs) or larger reactors. To overcome the flooding limit and boost the maximum performance of a thermosyphon, ACT developed *innovative wick structures* that would separate the vapor flow from the liquid flow to eliminate the flooding limit and increase the maximum power to the next, much higher, dominant limit.

3. ACT's Contributions to Technologies for Nuclear Energy in Space

ACT's work on thermal management for nuclear energy generation in space has been funded by various NASA and DOE programs that include both SBIR and non-SBIR funding mechanisms. In this section of the paper, a brief review of ACT's involvement and contributions to the thermal management of nuclear applications for space is presented.

3.1. ACT's Involvement in NASA's Prometheus – Space Radiator Demonstration Unit (RDU)

Under the project Prometheus, NASA examined space nuclear power systems for several missions. One such mission was the Jupiter Icy Moons Orbital (JIMO) Mission. A conceptual design of the orbiter is shown in Fig. 4.

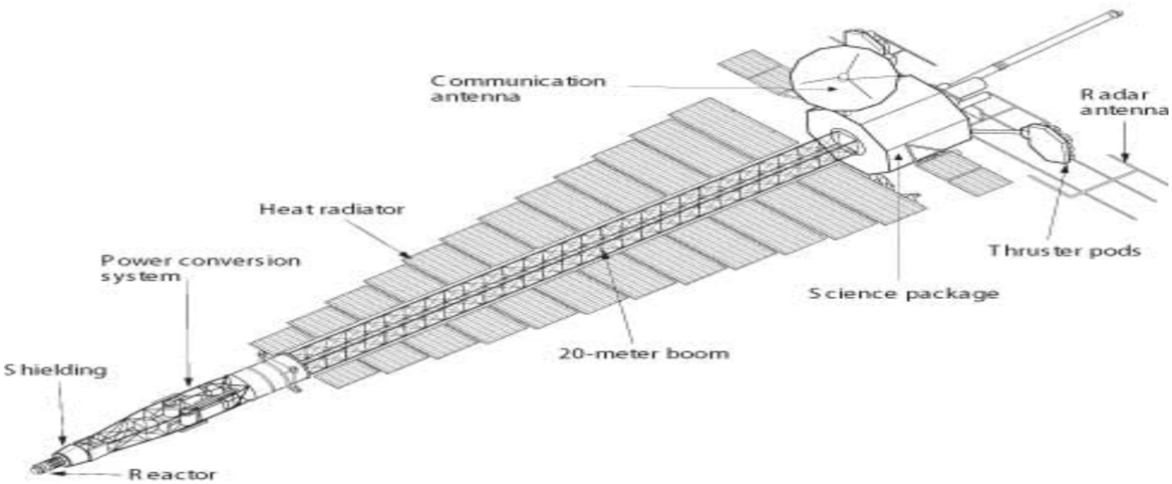


Figure 4. JIMO conceptual design with a system of deployable radiator panels for heat rejection.

Consistent with all large space nuclear systems, the radiator for the cold end (to reject the waste heat) was a substantial portion of the overall system mass. In the JIMO spacecraft, the radiator was planar, and designed to deploy once the craft is in space. The radiator is roughly triangular, to keep it within the cone of the radiation shielding. One possible design that was examined during the Prometheus used a Brayton cycle to generate electricity so the radiator could operate in the "intermediate" temperature range of 450 to 750K, where there are currently no established working fluids for advanced heat-spreading devices such as heat pipes and loop heat pipes.

Under a Radiator Demonstration Unit (RDU) program with NASA Glenn Research Center, ACT developed low-mass, high-temperature titanium/water heat pipe radiators to support the JIMO mission. The program produced three full-size panels, each 1 m by 0.5 m, and each containing three titanium water heat pipes as shown in Fig. 5. These panels were designed to operate at temperatures from 350 to 530 K using water as the working fluid, and were tested in vacuum at NASA Glenn Research Center (GRC). The program achievements [12…17] included:

- Development of an analytical model for optimizing the spacecraft radiators in this temperature range
- Heat pipe life tests to verify the compatibility of titanium and titanium alloys with water at temperatures up to 550 K.
- Heat pipe wicks for water made of titanium.
- Panel materials development and property measurements.
- Subscale panel fabrication and demonstration of the panels withstanding thermal cycling.
- Fabrication of three full size panels, each 1 m by 0.5 m, each with three titanium water heat pipes.

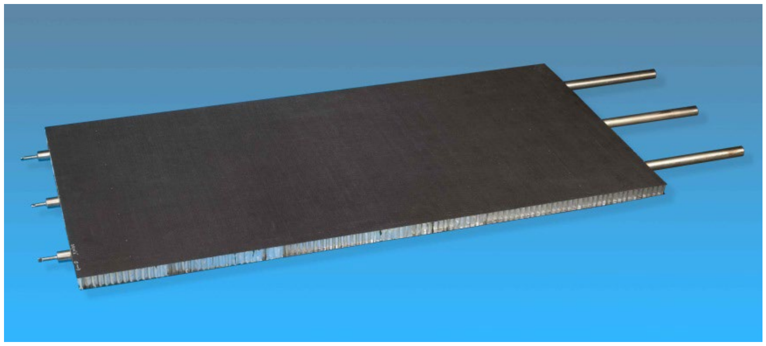


Figure 5. Three RDU panels with Graphite Fiber Reinforced Composite (GFRC) face-sheets and titanium heat pipes were delivered to NASA Glenn for testing. Each panel was 1m by 0.5m, had three heat pipes, and was designed to operate at temperatures up to 550K.

3.1.1. Life Tests: The first step in developing the radiator heat pipes was to select a working fluid. Water has the best merit number of the known heat pipe fluids up to about 550K. Copper/water heat pipes are only suitable up to about 425K, since the copper envelope must be very thick to withstand the saturated water pressure at higher temperatures. Titanium, titanium alloys, Monel 400, and Monel K500 have higher yield strength and lower density than copper, and so are suitable for higher-temperature water heat pipes. When using a new working fluid/heat pipe envelope material combination, life tests are required to verify that the materials and working fluids are compatible. ACT performed life tests for various titanium and Monel alloys with water as working fluid as well as for the so called "intermediate temperature range" (450 to 750K) fluids.

3..1.1.1. Life Tests for RDU (titanium-water):

The main reasons for considering water as the working fluid for the RDU are: its good heat transfer properties in the 350-550K temperature range and its compatibility with titanium that is a high strength and low-density material. During the RDU program, ACT started a large test matrix of life tests [12, 14, 15, 16] to verify that titanium and titanium alloy heat pipes were compatible with water. The tested titanium/water heat pipes include:

- Ti CP-2 Heat Pipe, with CP Titanium Screen
- Ti Grade 5 Cylinder (6% Aluminum, 4% Vanadium), with CP Titanium Screen
- Ti Grade 7 Cylinder (0.2% Pd), with CP Titanium Screen
- Ti CP-2 Cylinder, with 21S foil and CP Titanium Screen
- Ti Grade 9 cylinder (3% Aluminum, 2.5% Vanadium) with CP Titanium Screen
- Ti CP-2 Heat Pipe, with Sintered Cylindrical Wick
- Monel K500 Heat Pipe, with Monel 400 Screen

Table 1 shows the different life test pipes on test. Monel 400 is a solid solution alloy with roughly 63% nickel and 30% copper. It is a single-phase alloy, since the copper and nickel are mutually soluble in all proportions. It can only be hardened by cold working. Monel K500 is a similar nickel-copper alloy, with the addition of small amounts of aluminum and titanium that give greater strength and hardness. The system is age-hardened by heating so that small particles of $Ni_3(Ti, Al)$ are precipitated throughout the matrix, increasing the strength of the material. The advantage of Monel K-500 is that the strength can be partially recovered after a wick is sintered inside.

Several of the heat pipes were selected by destructive analysis [18]. To examine the cross-sections to determine the type and amount of corrosion in the wicks and heat pipes, the heat pipes were cut in half, pressure infiltrated with epoxy and sectioned at a location approximately one-third of the way above the bottom of the heat pipe. The sections were polished through 0.05-micrometer silica and examined using optical and scanning electron microscopes (SEM).

Titanium/water and Monel/water heat pipes are compatible at temperatures up to 550 K, based on ongoing life tests that have been running for up to 72,000 hours (8.2 years) as of May 2013. Analysis of titanium/water heat pipe cross-sections using optical and electron microscopy revealed little if any corrosion even when observed at high magnifications. When any evidence of corrosion was observed, the layer was typically around 1 micrometer thick. Copper depleted zones, as well as copper surface nodules formed on the Monel 400 screen wick. This was not observed on the Monel K500 envelopes. An analysis of the water working fluids showed minimal pickup of metals.

Table 1. Titanium-Water and Titanium-Monel Life Test Pipes – Final Operating Hours.

Initial Quantity	Wall Material	Wick	Operating Temperature	Operating Hours May 6 2013
4	Monel K 500	200x200 Monel 400 Screen 0.064 mm wire	550 & 500 K	72,192 hours
4	CP-2 Ti	150x150CP-Ti Screen 0.069 mm wire	550 & 500 K	72,192 hours
2	CP-2 Ti	Sintered Titanium -35+60 Mesh CP-2	550 K	60,672 hours
2	CP-2 Ti	100 x100 CP-Ti Screen 0.05 mm wire	550 K	61,064 hours
1	CP-2 Ti	Integral Grooves	550 K	41,345 hours
2	CP-2 Ti 21 S Foil Inside	100 x100 CP-Ti Screen 0.05 mm wire	550 K	62,622 hours
2	Grade 5 Ti	100 x100 CP-Ti Screen 0.05 mm wire	550 K	69,845 hours
2	Grade 7 Ti	100 x100 CP-Ti Screen 0.05 mm wire	550 K	60,672 hours
2	Grade 9 Ti	100 x100 CP-Ti Screen 0.05 mm wire	550 K	60,072 hours
2	Monel 400	120x120 Monel 400 Screen 0.05 mm wire	550K	60,168 hours
2	Monel K 500	120x120 Monel 400 Screen 0.05 mm wire	550K	67,536 hours
2	Monel 400	-100+170 Mesh Monel 400 Powder	550K	58,824 hours
2	Monel K 500	-100+170 Mesh Monel 400 Powder	550K	57,792 hours

3..1.1.2. Life Tests for the Intermediate Temperature Range (450-750K): Several applications could benefit from heat pipes in this intermediate temperature range (that is generally defined as the range between 450 and 750 K), and one of these applications is space nuclear power system radiators. Despite of intense efforts by the community to qualify or develop fluids for this temperature range, there is still no commonly accepted working fluid over the entire intermediate temperature range. At temperatures above 700-725 K, alkali metal (cesium) heat pipes start to become effective. Below about 725 K, the vapor density for cesium is so low that the vapor sonic velocity limits the heat transfer. At the lower side of this temperature range, water was historically used at temperatures up to about 425 K. Later, it has been shown that water can be used with titanium or Monel envelopes at temperatures up to 550 K [14].

Potential working fluids in the intermediate temperature range include elemental working fluids such as sulfur, organic compounds, and halides. ACT performed, under various NASA programs, investigation and life tests for these potential fluids. Useful and comprehensive reviews of intermediate temperature heat pipe life tests conducted over the past 50 years, including ACT's life tests and recommendations of suitable working fluid/envelope combinations are presented in [18…23]. 30 different intermediate temperature working fluids, and over 60 different working fluid/envelope combinations have been life tested.

Elemental working fluids: Three elemental working fluids: sulfur, sulfur-iodine mixtures, and mercury were among the tested fluids. However, other fluids offer benefits over these three elemental ones in this temperature range. Mercury is toxic, has a high density, and problems have been observed with getting the mercury to wet the heat pipe wick. Sulfur and Sulfur/Iodine have high viscosities, low thermal conductivities, and are chemically aggressive.

Organic working fluids: Life tests have been conducted with 19 different organic working fluids. As the temperature is increased, all of the organics start to decompose. Typically, they generate non-condensable gas (NCG), and often the viscosity increases. At high enough temperatures, carbon deposits can be generated. The maximum operating temperature is a function of how much NCG can be tolerated, and the heat pipe operating lifetime. Three sets of organic fluids stand out as good intermediate temperature fluids:

1. Diphenyl, Diphenyl Oxide, and Eutectic Diphenyl/Diphenyl Oxide (Dowtherm A, Therminol VP, Diphyl)
2. Naphthalene
3. Toluene

Non-organic fluids: A non-organic working fluid is desirable for ***nuclear fission space power*** and other applications where radioactivity can generate gas with organic working fluids. Long term life tests show that Superalloys/$TiCl4_4$ at 573 K (300°C), and Superalloys/$AlBr_3$ at 673K (400°C) are compatible. $AlBr_3$ and $TiCl_4$ tests have over 59,000 hours (6.7 years) of testing. Hastelloy C-2000 underwent little corrosion when used with TiCl4 working fluid, with the formation of only a 1-2 micrometer thick corrosion layer. Hastelloy C-22 exhibited a 5-10 micrometer thick dual corrosion layer when tested with AlBr3 working fluid. The working fluids of these two heat pipes exhibited total metal contents between 300 and 350 ppm. The results indicate that the tested envelope materials and working fluids can form viable material/working fluid combinations.

Compatibility prediction: Life tests were conducted at NASA Glenn with three halides (AlBr3, SbBr3, and TiCl4) and water in three different envelopes: two aluminum alloys (Al-5052, Al-6061) and CP-2 titanium. The AlBr3 attacked the grain boundaries in the aluminum envelopes, and formed TiAl compounds in the titanium. The SbBr3 was incompatible with the only pipe that it was tested with, Al-6061. Finally, TiCl4 and water were both compatible with CP2-titanium. As shown in [23], a *theoretical model* based on *electromotive force differences* has been developed to predict the compatibility of halide working fluids with envelope materials. The envelope material halide should have a lower decomposition potential than the working fluid halide. AlCl3 and TiCl4 have a high decomposition potential, so should be good working fluids. Molybdenum and iron have a low decomposition potential, so should be good envelope materials. The method almost always predicted the compatibility of halide life tests. For example, it successfully predicted that TiCl4 was incompatible with aluminum and was compatible with mild steel. The only two cases without full agreement were (1) AlBr3 and aluminum, where the AlBr3 attacked the alloying materials at the grain boundaries, and (2) AlBr3 and titanium, where the method predicted incompatibility, but not that TiAl compounds would form.

3.1.2. Titanium Heat Pipe Wick Development: ACT developed several titanium heat pipes with various wicks on the RDU program. Representative samples are shown in Fig. 6. This set of wicks represented the selection for further relevant/suitable applications.

Figure 6. Heat pipe wicks developed on the RDU program. Counter-clockwise from top right: (a) solid groove wick, (b) screen wick for life test pipes, (c) sintered annular wick for life test pipes, (d) sintered vapor-groove wick, (e) slab wick, and (f) sintered liquid groove wick.

3.1.3. Panel Development and Panel Property Measurement: The radiator panels were developed with three different fin materials: K13D2U fibers with 5250-4, EX1551, and HPFE resin. The fin material is 0.38 mm thick and uses a layup pattern that gives a coefficient of thermal expansion (CTE) along the heat pipe that matches the CTE of titanium. ACT has measured the mechanical and thermal properties of these panels after thermal cycling. This information was used to eventually design the actual radiator.

3.1.4. Test Panel Fabrication: As mentioned earlier, the RDU program fabricated three radiator panels, one with each of the three fin materials; see **Error! Reference source not found.**. The panels have an area of 1 m x 0.5 m. Each panel has three 1.91 cm (0.75 inch) O.D. titanium/ water heat pipes. Each heat pipe was designed to carry 360 W at temperatures up to 500 K, which was higher than the requirements of the program. The panels were thermal vacuum tested at NASA Glenn. The restart from a frozen state in the horizontal position was fully demonstrated as shown in [24].

The Prometheus-funded RDU program was in fact one of the precursors for ACT's involvement in Kilopower, FSP and NEP related projects.

3.2. ACT's involvement in NASA's Kilopower

As part of the Game Changing Development (GCD) program within NASA's Space Technology Mission Directorate, the Kilopower project was a result of NASA GRC's assessment of small fission power systems for future spacecraft applications and surface missions. These systems are designed to produce 1 to 10 kWe to address the technology gap between Radioisotope Power Systems (RPS), which operate below 500 We, and Fission Surface Power Systems (FSP), which operate above 10 kWe.

The Kilopower design (shown in Fig. 7), utilizes alkali metal (sodium) heat pipes to transfer thermal energy from the fission reactor to the Stirling convertor's heater heads for electrical power generation, and titanium water heat pipes to transfer waste heat from the converter's cold ends to radiators for ultimate rejection to space. The Kilopower system was designed to operate in space as well as on planetary surfaces.

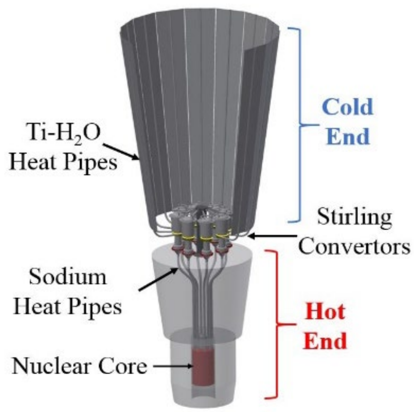


Figure 7. Kilopower system conceptual design and its thermal management system [25].

The heat pipes for the Kilopower system must accommodate four different operating conditions:

1. Operation in space under zero-gravity when the condensate (liquid) must return from the condenser to the evaporator only by capillary forces developed in the wick.
2. Operation on earth with a slight adverse orientation to estimate the zero-gravity performance. In this case, liquid returns from the condenser to the evaporator also by capillary forces in the wick that would need to overcome the corresponding gravitational forces.
3. Operation on the ground in a gravity-aided orientation, for system testing. Liquid returns from the condenser to the evaporator by gravitational forces.
4. Restart after exposure to launch orientation – significant adverse orientation. The wick de-primes during launch and must re-prime in space for operation.

In general, surface fission power generation designs include heat pipes that take advantage of gravity to reliably return the condensate to the evaporator. These heat pipes are widely known as thermosyphons, and therefore, are unable to work in space (microgravity) environments. The Kilopower system, however, uses wicked heat pipes enabling both surface and space operation. ACT's involvement in the thermal management of the Kilopower system included the development of both the heat pipes for the hot end of the system and the heat pipe radiator for the cold end of the system.

3.2.1 Kilopower's Hot End

For the hot end of the Kilopower system, ACT's first objective was to develop alkali metal heat pipes (with sodium as working fluid) containing various types of wicks that would allow the system to operate in both microgravity and planetary surface (gravity assisted) environments. A second objective was to develop two sets of sodium heat pipes to be used by the actual Kilopower system during various stages of its development.

During a NASA Phase I SBIR, ACT performed feasibility studies for heat pipes with three types of wicks that would be suitable for Kilopower: groove wicks, traditional arterial wicks, and self-venting arterial wicks. 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 Non-Condensable Gas (NCG) is generated in the artery due to radiation it would cause the heat pipe to de-prime and, consequently, to fail to operate. Self-venting arterial and grooved heat pipes have an advantage over sintered arterial heat pipes due to their ability to allow the trapped vapor or NCG to escape into the vapor space. During the above-mentioned program, a 1m (39.67in) long, 0.75in (1.91cm) outer diameter self-venting arterial heat pipe and a grooved heat pipe were developed [20]. Thermal performance testing of the two heat pipes was conducted at 725°C while the adverse elevations varied from 0.1in (0.25cm) to 5.0in (12.7cm). The self-venting arterial heat pipe transported at least 2.6kW of power at all adverse elevations except 5.0in (12.7cm) where it transported only 1.4kW. The grooved heat pipe could transport only 846W at 0.1in (0.25cm) elevation and 346W at 1in (2.5cm).

During the two follow-on NASA Phase II SBIRs several heat pipes were fabricated and tested for the Kilopower program (hot end of the system), including self-venting arterial heat pipes, thermosyphons, and a hybrid screen-groove heat pipe. The self-venting arterial heat pipes carried sufficient power while straight but were unable to meet the transport requirements after bending.

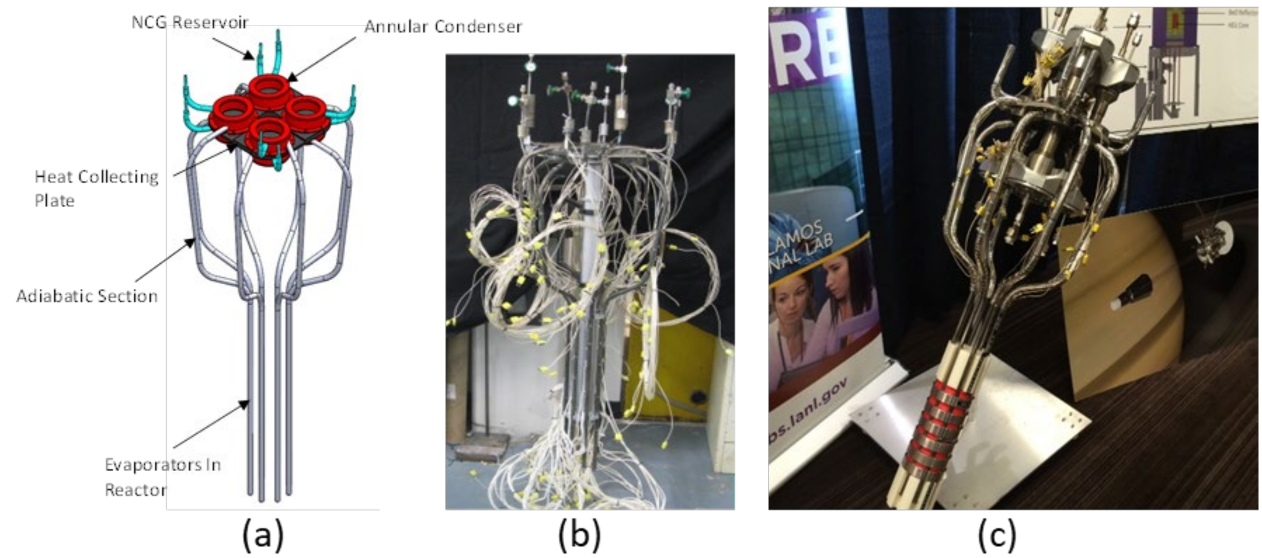


Figure 8. Kilopower system: a) Schematic of the Kilopower heat pipes and heat collector plate. b) Thermosyphons (First Set) fabricated by ACT for the electrically heated Kilopower system c) Sodium heat pipes (Second Set) developed by ACT for Kilopower and displayed by NASA at NETS 2018.

Two sets of thermosyphons were fabricated and delivered to NASA Glenn for integration into Kilopower test setups for two stages of the development. Figure 8a shows a CAD drawing of the first set of heat pipes integrated with the heat collecting plate that was the conduction-based interface between all eight doughnut-shaped condensers and the eight Stirling converters (and simulators) heater heads. It can be observed that the eight heat pipes have small reservoirs (as extensions of each condenser) containing argon that assists the heat pipes during startup. Two of the eight reservoirs are larger than the other six to allow the shutdown of the two corresponding heat pipes to simulate heat pipe failure during system testing. Figure 8b shows the fabricated first set of Kilopower heat pipes, ready for delivery to NASA GRC. Figure 8c shows the second set of heat pipes, also integrated with the heat-collecting nickel plate, as displayed by NASA at the 2018 Nuclear Emerging Technologies for Space Conference (NETS) in Las Vegas, NV.

First Set: Nine heat pipes (thermosyphons) were developed as the “first generation” and delivered for the Kilopower program. The pipes were intensively tested before delivery [27]. The performance for each of the nine thermosyphons is shown in Table 2. The measurements were performed in ambient, and the measured heat loss was 570W. Since the performance requirements were met, as seen in the table, dry-out was not further attempted/reached for any of the heat pipes.

Thermosyphon startup: Alkali metal heat pipes are known for having difficulties at start-up due to several reasons:

- the necessary superheat to initiate boiling
- the low sonic limitation that chokes the pipe during its temperature increase towards the operating point

- the potential freezing of the working fluid in the condenser

Adding NCG inside the heat pipe is a typical method that addresses start-up difficulties. This 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.

Table 2. First set - 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

An example is shown in Fig. 9 [27]. The heat pipe started successfully, but still required a very large amount of superheat in the evaporator before starting up which 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.

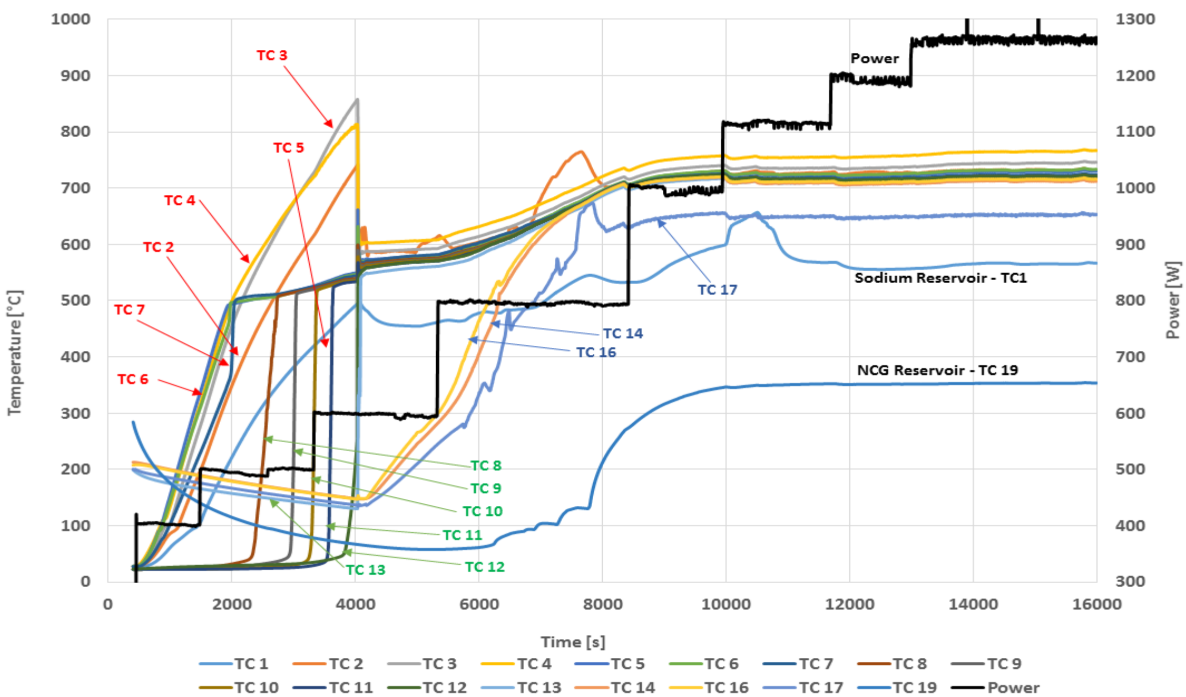


Figure 9. Startup results for the First Set (generation) of thermosyphons.

The large temperature spikes observed during start-up when the heat pipes were tested individually at ACT did not occur. 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 individual radiation-based heaters; when integrated into the reactor simulator at NASA, the evaporators were heated by conduction limiting their exposure to high temperatures and preventing the startup-related temperature spikes.

Second Set: It was delivered in October 2016 for testing on a depleted uranium-based system at NASA GRC. Two modifications were made to the second set to improve the startup behavior of the sodium thermosyphons: additional screen-wick in the evaporator and adjustments in the geometry of the pipe to reduce the required charge volume. The additional screen in the evaporator filled the inner diameter almost entirely except a 0.125 in diameter hole in the center for vapor venting. The additional portion of the screen wick (with the role of retaining the entire amount of liquid before freezing) had a larger pore size allowing the primary wick to further retain the liquid after startup and during normal operation.

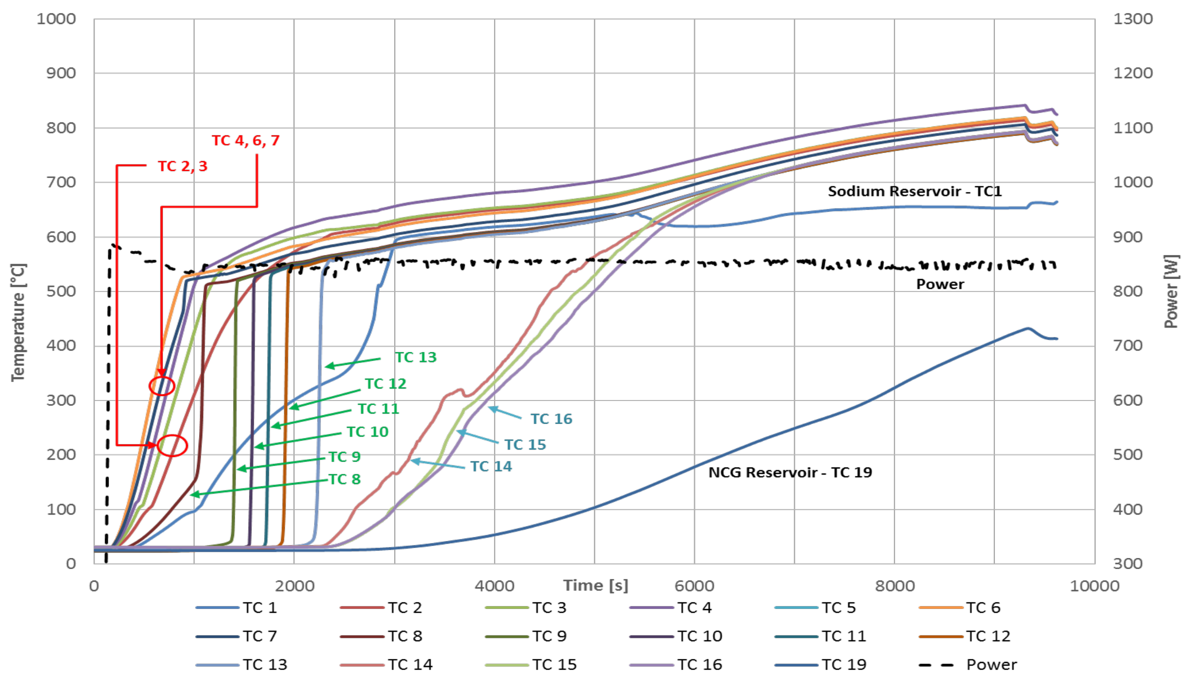


Figure 10. Startup results for the Second Set (generation) of thermosyphons.

The startup performance of the Second Set (generation) thermosyphon is shown in Fig. 10 where the noticeable smooth startup confirms the benefits of the newly inserted wick in the evaporator. The instrumentation layout is shown in Fig. 11.

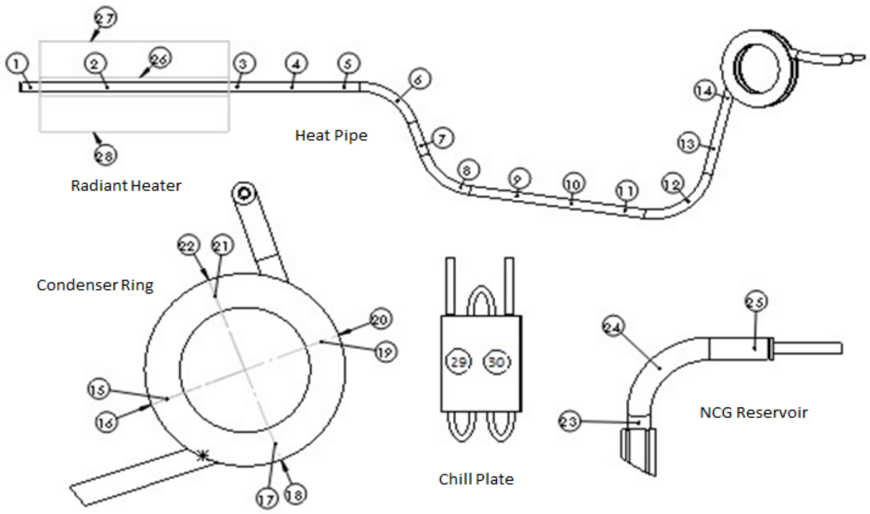
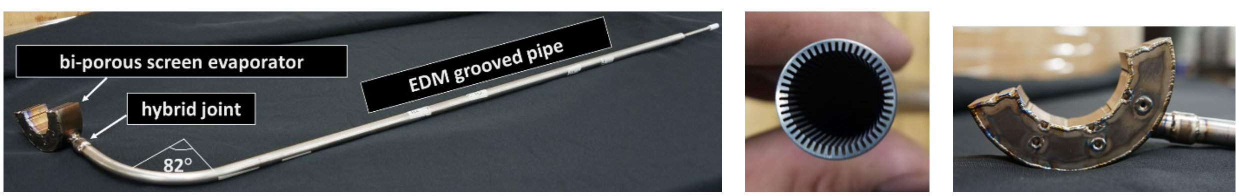


Figure 11. Instrumentation layout of alkali metal Kilopower heat pipes.

3.2.2. Kilopower's Cold End

Under SBIR Phase I/Phase II programs, ACT developed a series of freeze/thaw tolerant titanium water heat pipes with aluminum radiator face-sheets attached to reject the waste heat of a small-scale space nuclear fission power system (i.e. Kilopower system) [28-31]. Since the system is designed to operate in both microgravity and on planetary surfaces (with potential freeze/thaw cycles), the titanium heat pipes have hybrid wicks consisting of a bi-porous screen structure in the evaporator and an axial groove structure in the adiabatic and condenser sections. Figure 12a shows the grooved heat pipe in its final shape. After bending, multiple grooved pipe sections (Fig. 12b) were joined together through electron beam welding. The full-length (~1m) grooved pipe was then coupled with the bi-porous screened evaporator (Fig. 12c) through the screen-groove hybrid joint. The heat pipe was charged with deionized water, and a small amount of argon (NCG) to facilitate the startup and the freeze/thaw processes.



a) b) c)

Figure 12 a) Titanium water heat pipe with bi-porous screen evaporator and hybrid wick for the rest of the pipe. b) Grooved wick manufactured by electrical discharge machining (EDM). c) Evaporator section of the heat pipe that has a semi-circular shape to be mounted on the cold end of the Stirling converter.

Testing results showed good heat transfer capability and isothermality in a slightly unfavorable (3 mm) gravity orientation of the heat pipe. Its freeze/thaw tolerance feature was also demonstrated. As the plot from Fig. 13 shows, the prototype was first operated at steady state at 125°C working temperature with 250W heat input (state 1).

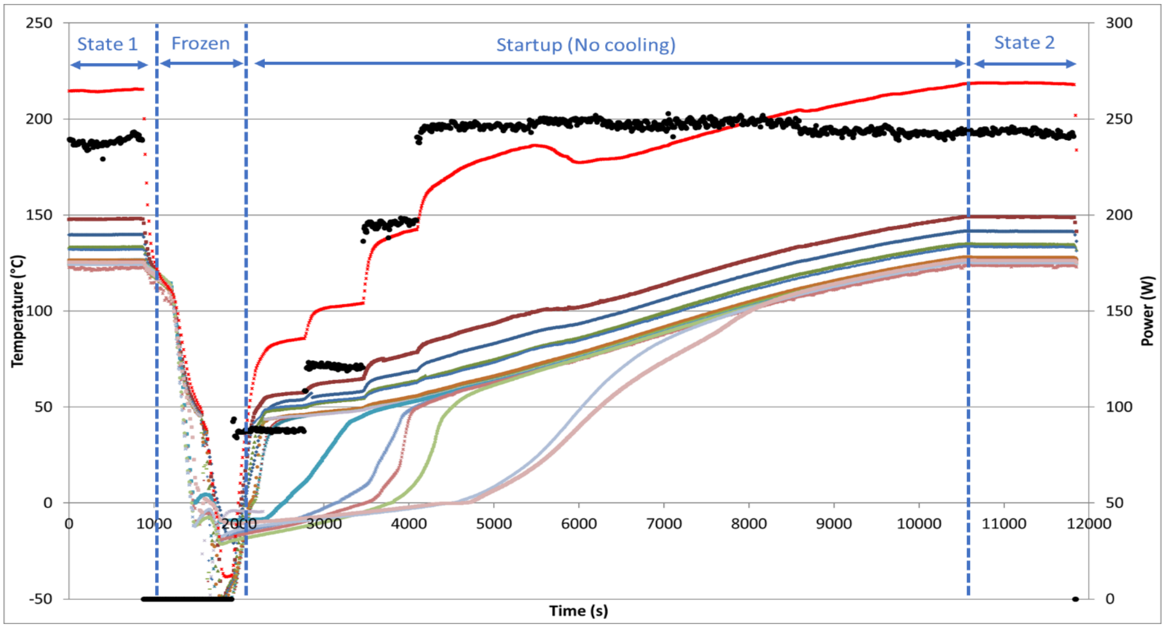
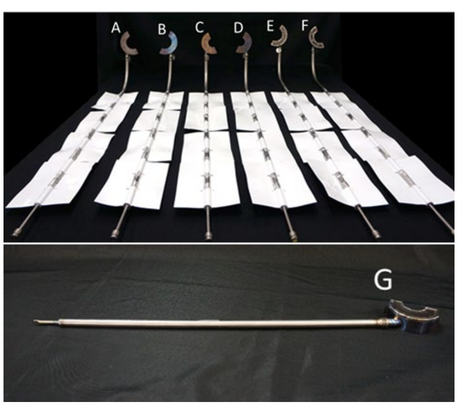
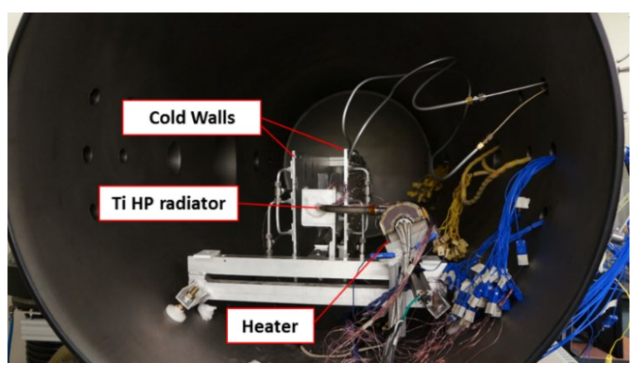


Figure 13. Freeze/thaw startup performance of the titanium water heat pipe.

After 1000 seconds, the heat input was removed, and the entire system was cooled to -50°C. At 2000 seconds, heat was re-applied to start up the pipe, incrementally increasing from 125W to 250W. As the figure shows, a smooth freeze/thaw recovery curve was obtained. As the working temperature reached 125°C at t=10500 seconds, the active cooling was turned ON again to maintain the working temperature. As it can be observed, the heat pipe fully returned to the initial steady state parameters (state 1). This test demonstrated that both the bi-porous screen wick evaporator design and the charged amount of argon enable the survival and startup from frozen conditions.





a) b)

Figure 14. a) Titanium water heat pipes for Kilopower system cooling (top: six full-length heat pipes with S-bonded radiator; bottom: half-length heat pipe for shock and vibration testing) b) Heat pipe radiator thermal performance test setup.

An additional seven titanium water heat pipes with different evaporator configurations to accommodate the cold end geometry and various grooved pipe lengths were fabricated and tested. Six of the heat pipes became heat pipe radiators by integrating them with aluminum face-sheets through S-bonding. The were tested in thermal vacuum chamber. All six heat pipe radiators (shown in Fig. 14a) successfully carried 125W of waste heat at the working temperature of 400K and rejected the heat into the vacuum environment through radiation as shown in Fig. 14b.

3.3. ACT's Involvement in NASA's Fission Surface Power (FSP) Program

NASA and the Department of Energy (DOE) have been working with industry partners to design a 10KW FSP system for planetary surface, particularly for the Moon. It is envisioned that the initial Moon FSP demonstration will open the path for further planetary exploration through sustainable operations and even settlements on the Moon and Mars. The previous Kilopower program that ended in 2018 with the uranium-based testing, is in several ways a precursor for the FSP programs. A baseline lunar FSP design had been developed [32] before the start of Kilopower and is shown in Fig. 15.

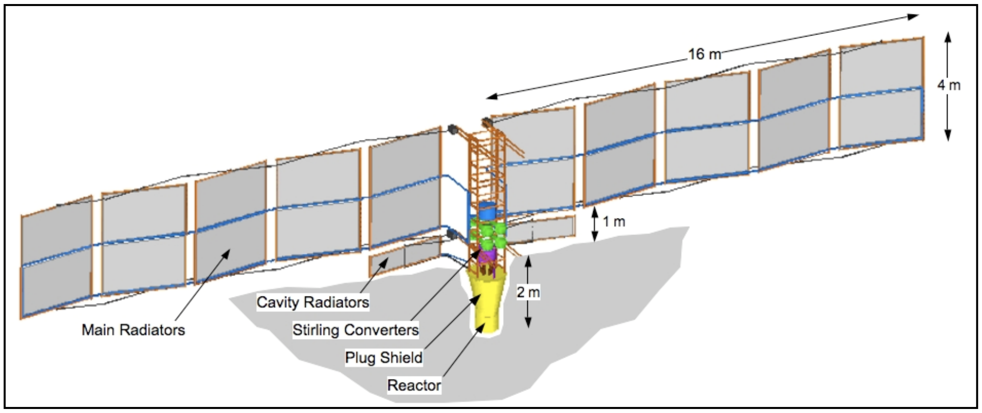


Figure 15. Fission surface power system concept [32].

The nuclear reactor supplies thermal energy to Brayton (or Stirling) converters to produce electricity and uses a heat pipe radiator to reject the waste heat. The radiator panels must reject heat from both sides to achieve the highest efficiency; therefore, the optimum mounting position is vertical. The radiator panels contain embedded heat pipes to improve thermal transfer efficiency. Since the heat pipe evaporator is on the bottom, the heat pipes are gravity-aided and can work as thermosyphons. Heat is supplied to the heat pipes through a titanium/water heat exchanger that is coupled to a single-phase loop that collects waste heat from the cold end of the conversion system.

ACT has been actively developing thermal management technologies specifically for FSP even before the Kilopower program started. Both SBIR programs and non-SBIR funding sources have been at the basis of ACT's FSP related projects.

3.3.1. Variable Conductance Heat Pipe (VCHP) Radiator for FSP

An early ACT contribution to the FSP's thermal management was funded by a NASA Phase I and II SBIR program that developed a VCHP radiator for a lunar fission surface power system [33]. The ability of a titanium/water VCHP to restart after partial and complete freezing was demonstrated [34] initially at ACT facilities. The VCHP had similar dimensions to the heat pipes that would be used in a lunar surface power radiator. The partial freeze represents the most demanding operating state of the VCHP as high vapor pressure exists at the vapor-NCG interface, which presents greater opportunity for vapor to enter the condenser and freeze. Complete freezing represents a material hazard as the envelope may rupture. Testing showed the VCHP operated reliably and without damage after 15 day partial and complete freezing periods. This period is longer than a lunar night and indicates that a VCHP water-titanium radiator would survive freezing if subjected to no or low power operation in lunar conditions. In addition, after delivery to NASA, the VCHP radiator panel was successfully tested in a thermal vacuum chamber at NASA GRC, including start-up from a frozen state [35]. A schematic of the panel design is shown in Fig. 16. The radiator panel consists of a series of titanium/water VCHPs, high conductivity POCO™ foam saddles, high conductivity

Graphite Fiber Reinforced Composite (GFRC) face-sheets, aluminum honeycomb to stiffen the panel for launch loads and bonding material applied at the heat pipe/POCO™ foam and POCO™ foam/face-sheet interfaces. The adiabatic sections are coiled to accommodate the CTE mismatch between the titanium evaporator (8.6 µ/m K) and the Radiator Panel (~ 0 CTE) parallel to the evaporators.

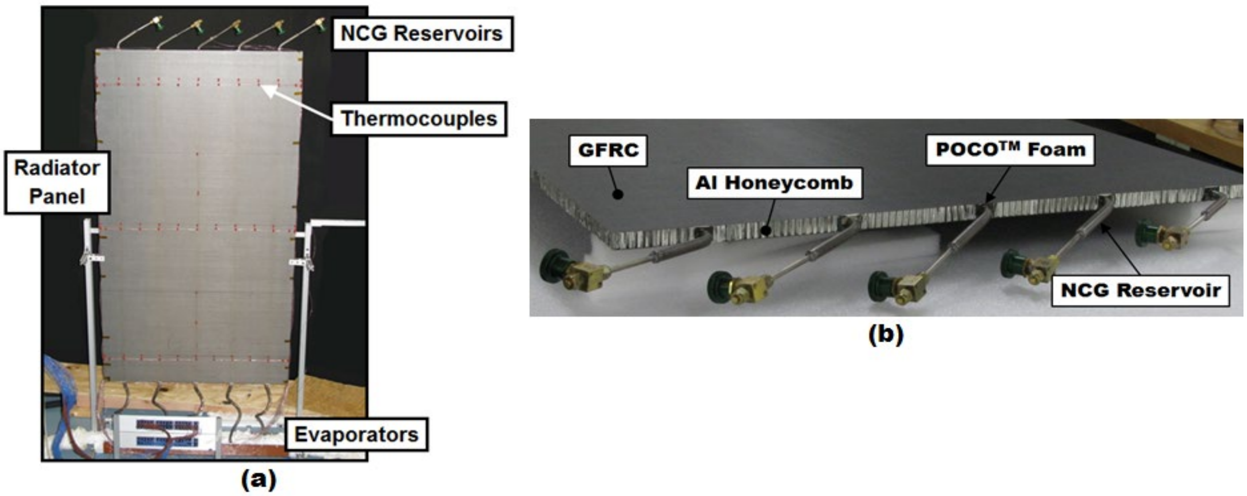


Figure 16. (a) VCHP radiator in testing configuration, (b) cross section of VCHP radiator.

Experiments during the VCHP radiator program indicated that it would be possible to eliminate the POCO™ foam saddles and bond the face sheets directly to the pipe. This was the start of a new heat pipe radiator concept and its development.

3.3.2. Modular Heat Pipe Radiator for NASA Glenn's Technology Demonstration Unit (TDU)

Under NASA Phase I and Phase II SBIR programs, ACT and Vanguard Space Technologies, Inc. (VST) developed a low-cost, modular, direct-bond single-face-sheet VCHP radiator, operating near 400K, to support the TDU for FSP at NASA GRC. The TDU is a non-nuclear demonstration unit that was intended to be tested in thermal vacuum chamber to demonstrate integrated system performance.

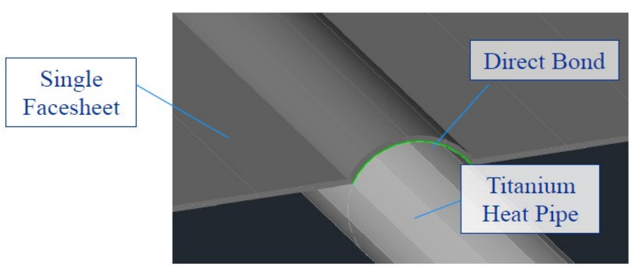


Figure 17. Single face sheet radiator with direct bonding of the face sheet to the heat pipes

In Phase I, ACT and VST fabricated a proof-of-concept radiator specimen [36]. As shown in Fig. 17, the GFRC face-sheet was bonded directly to the heat pipes, reducing mass, thermal resistance and cost. The challenge represented by the coefficient of thermal expansion (CTE) mismatch between the titanium tube and GFRC was resolved as follows:

1. On the axial direction of the titanium tube, the GFRC fibers were oriented to cancel the CTE mismatch.

2. On the perpendicular direction of the titanium tube, the CTE mismatch was just mitigated by inserting/extending the heat pipe adiabatic sections with helicoidal segments to gain the necessary flexibility.

In the next developmental phase, the approach for solving the CTE mismatch along the direction perpendicular to the tube changed. The GFRC face-sheets were split in individual fins for each heat pipe, each heat pipe with its own fin becoming a ***module***, so the CTE mismatch was eliminated and the helicoidal sections could be replaced by short straight sections.

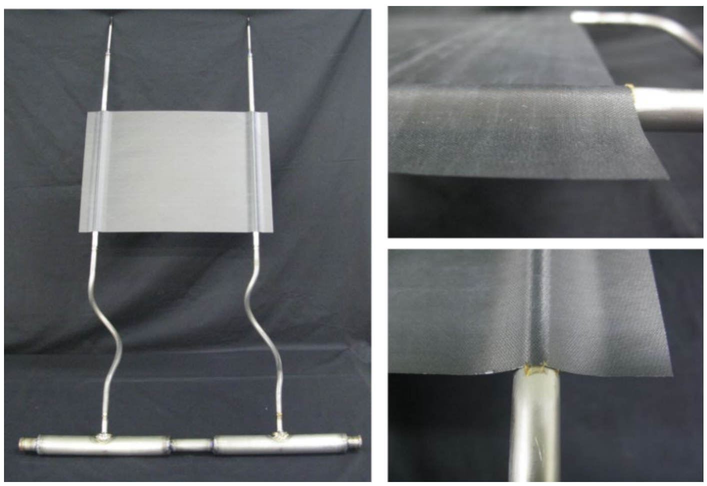
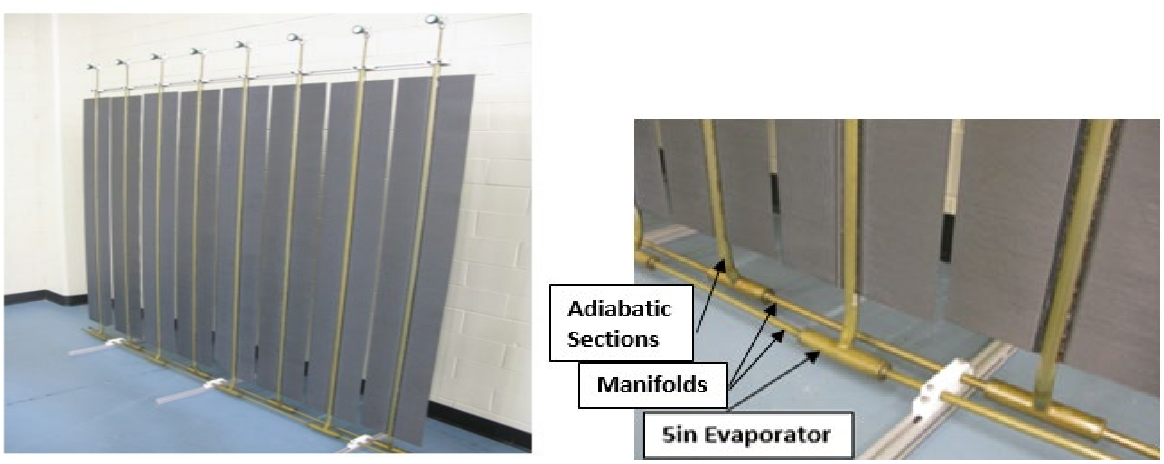


Figure 18. Small-scale, proof of concept titanium/water radiator for Lunar fission power operations. The panel is directly bonded to the heat pipes, reducing mass.

During the subsequent Phase II program, based on the Phase I results and the experience gained during previous NASA SBIR VCHP radiator programs, ACT and VST developed a low-cost, high-specific-power modular radiator for the TDU. The new features of this radiator included direct bonding of the GFRC face sheet to the titanium condenser and the fact that it is modular, therefore the CTE mismatch on the manifold direction (perpendicular to the heat pipe tube) is eliminated. The modular radiator consists of 8 clusters of 8 modules each. ACT designed the modular radiator, fabricated the heat pipes, validated the radiator module, tested one cluster at NASA GRC in vacuum, and tested the rest of clusters at ACT's facilities, in ambient conditions. VST developed the GFRC direct bonding and attached the GFRC fins to all the heat pipes.



a) **b)**

Figure 19. First cluster a) Actual radiator cluster b) Detail showing the manifolds, the heat pipe evaporators and adiabatic sections.

The first (out of the eight delivered to NASA) cluster (shown in Fig. 19), was tested in both ambient (at ACT) and vacuum (at NASA GRC). Ambient testing showed a performance of 3.5 kW at nominal water temperature and flow rate (see Fig. 20). Several conservative conditions impacted the testing results. Sink temperature was high (ambient). In addition, an oversized NCG charge was observed in all 8 heat pipes of the cluster.

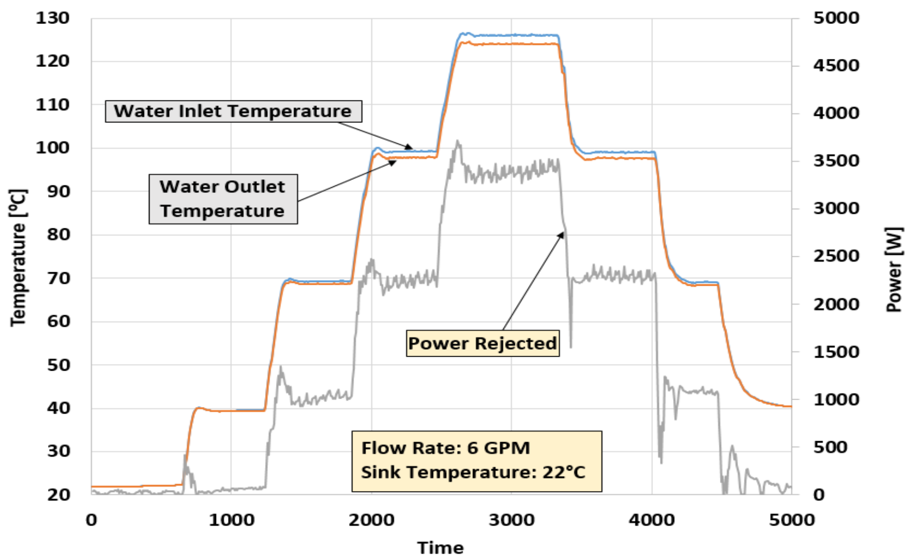


Figure 20. Power test in ambient conditions at ACT: heat was rejected for various water inlet temperatures.

Vacuum testing of the cluster at NASA GRC was conducted in two rounds. The first round included an initial power test and thermo-cycling, followed by another power test. None of the parameters were nominal. Sink temperature was 2ºC (compared to the nominal value of -23ºC), water inlet temperature and flow rate were 100ºC and 3.9 GPM (14.8 L/min) respectively compared to the nominal values of 127ºC and 6GPM (22.7 L/min). The power rejected by the radiator in vacuum was 1.94kW for the highest water inlet temperature (100ºC). Again, the additional power test carried out after thermo-cycling showed no degradation of the direct bond (Fig. 21).

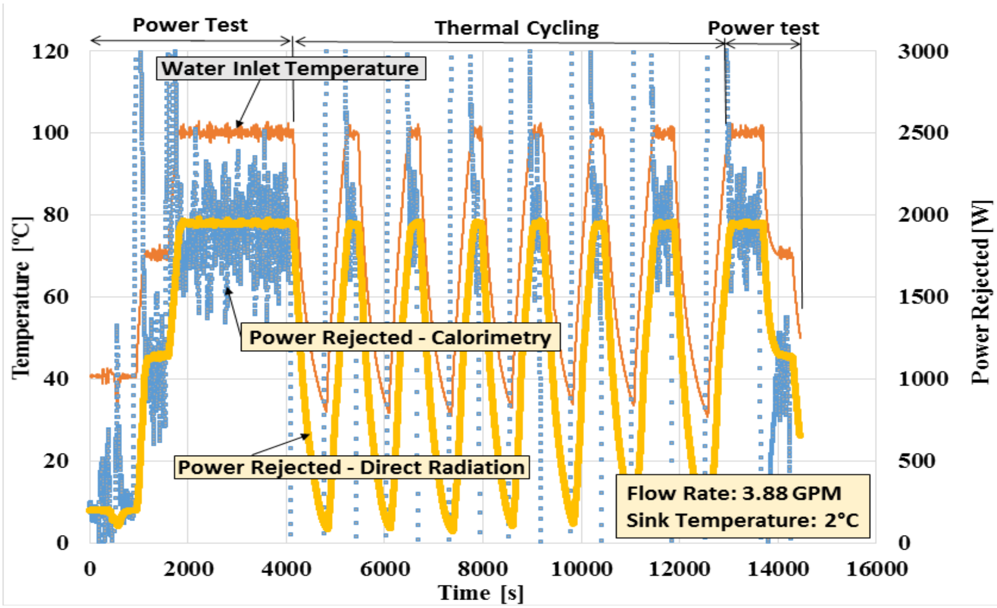


Figure 21. Radiator cluster testing in vacuum at GRC– first round: testing was carried out as power test, thermocycling and power test again.

During the second round of vacuum testing, the maximum temperature of the inlet water was nominal (127-130ºC) while the other parameters were the same as the first round. In these conditions the power delivered by the cluster was ~2.87kW. Again, the previous conservative factor, the oversized amount of NCG, was still present.

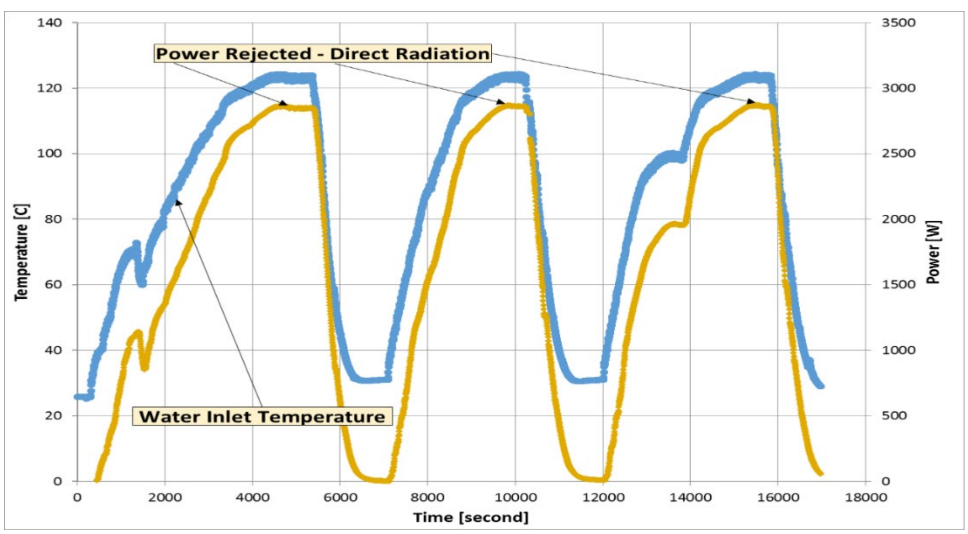


Figure 22. Power rejected in vacuum during the second round of testing when maximum inlet water temperature was 127°C.

3.3.3. Non-SBIR FSP Funding

ACT has also been performing as subcontractor for various industrial primes. During the non-SBIR collaborations, ACT was tasked to develop thermal management solutions for both the hot end and the cold end of the energy conversion system. For the hot end, sodium-TZM heat pipes were developed to extract the heat from the nuclear reactor and sodium-Haynes 230 auxiliary heat pipes were developed to focus the heat effectively on the converter's heater heads (heat collectors). On the cold end, a similar multi-KW radiator design was developed for FSP in an initial phase of funding.

3.4. ACT's Involvement in NASA's Nuclear Electric Propulsion

Enabling long-duration missions through nuclear power and nuclear electric propulsion (NEP) requires a reliable and high-power system to manage the thermal energy generated by the nuclear reactor [1]. Heat pipe reactors can operate at very high temperatures and are highly reliable due to their passive heat transfer mechanism and tolerance to single-point failure.

NASA's Technology Maturation Plan for NEP, developed by NASA's *Space Nuclear Propulsion Project*, [37] specifies that in order to achieve mission goals, an NEP system must operate in the range of 1200-1400K and achieve a specific mass of at most 24 kg/kW$_e$, with a target of 13 kg/kW$_e$. The technology maturation plan identifies heat pipe reactors as one of the key technologies expected to be capable of reaching these goals.

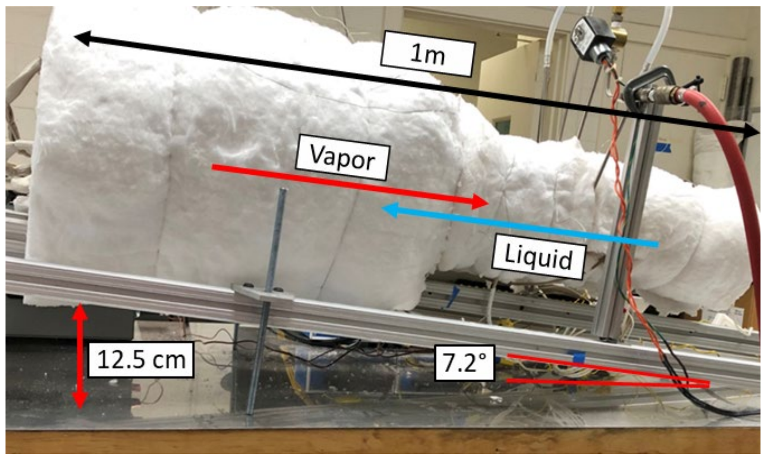


Figure 23. Prototype high-power sodium heat pipe capable of transporting 2kW over 1m at an angle of 7° against gravity.

Beginning in 2022, ACT received SBIR funding to develop heat pipes and other thermal management technologies for the hot end of NEP systems. In a NASA SBIR Phase I and II "Hot End Thermal Management for Nuclear Electric Propulsion" ACT is:

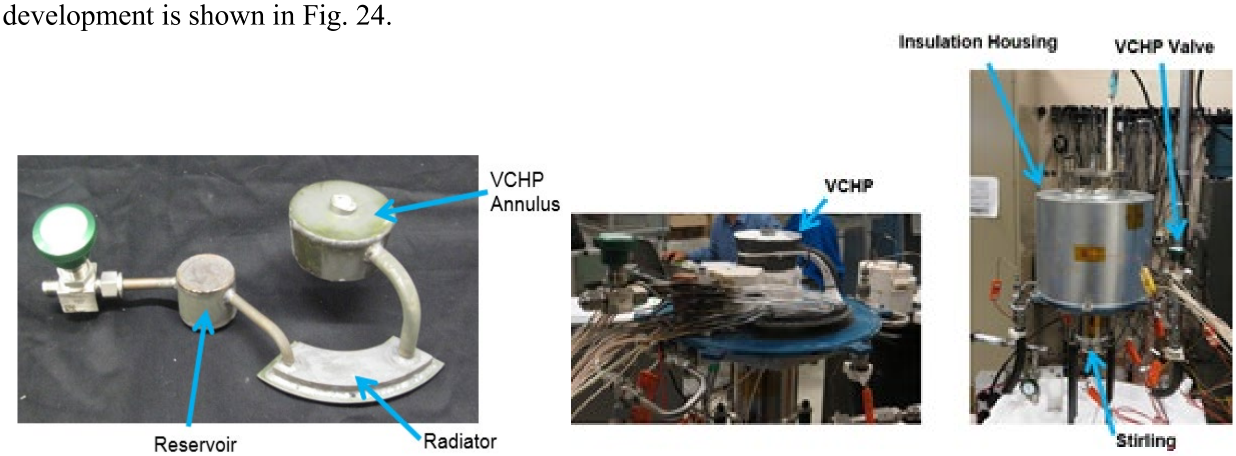
- Developing high-power wicks for alkali metal heat pipes that will be capable of cooling MW-scale nuclear reactors in the temperature range of 1200-1400K. The heat pipes will be capable of transporting heat distances of over 5m.
- Developing designs for heat pipe heat exchanger to transfer heat to the working fluid of the Brayton power conversion cycle.
- Developing an auxiliary startup system that would effectively enhance and even enable the startup of long alkali metal heat pipes for an unlimited number of times during the mission.

A key highlight of the Phase I SBIR program was the performance of a 1m long prototype high-power alkali metal heat pipe, as shown in Fig. 23. The heat pipe carried 2kW of heat for a distance of 1m at an angle of 7.2° against gravity vector. In addition, during this program ACT's collaborator Ultra Safe Nuclear Corp. developed a design for 10MW$_{th}$ heat pipe reactor system for [38]. The complete NEP system based on ACT's high-power heat pipes demonstrated a specific mass of 24.5 kg/kW$_e$, in line with NASA's goals. During the Phase II SBIR program, which began in summer 2023, ACT is further developing the high-power wick designs, startup auxiliary system, and a heat exchanger as an interface between the high-temperature heat pipes and the hot end of the Bryton cycle-based energy conversion system.

In a separate NASA SBIR Phase I program "Additively Manufactured Ceramic Heat Pipes for Space Nuclear Reactors" ACT in collaboration with USNC, is developing high-power high-temperature ceramic heat pipes and heat exchangers for NEP systems. Ceramic heat pipes and heat exchangers have the potential to reduce the mass of NEP system by 1,000's of kg. ACT is currently exploring manufacturing feasibility as well as compatibility between ceramic envelopes and alkali metal working fluids.

3.5. ACT's involvement in NASA's Stirling Radioisotope Power Systems for Space

Radioisotope Power Systems (RPS) represent a smaller scale of nuclear applications (up to 500 – 800We) mainly to be used in space. An RPS converts the heat generated by the natural decay of the radioactive isotope of plutonium-238 into electricity. Typically, the radioactive fuel plutonium-238, is packed in standardized "bricks" as General-Purpose Heat Sources (GPHS) and are the primary energy source (heat) in such a system. NASA has typically used Radioisotope Thermoelectric Generators (RTGs) as the source of electric power for deep space missions. Thermoelectric generator's efficiency is ~6%. A more efficient and potentially more cost-effective alternative to the RTG is the Stirling Radioisotope Generator (SRG) where GPHS modules supply heat to Stirling converters that work at an ~25% efficiency and, therefore, reduce the number of precious GPHS modules for the same electric output. In addition, the specific power of the conversion system would significantly increase. The maximum allowable GPHS module operating temperature is set by the iridium cladding around the fuel. The GPHS module is designed so that it will not release radioisotopes, even under such postulated events as a launch vehicle explosion, or reentry through the earth's atmosphere. However, if the iridium cladding was to overheat, grain boundary growth could weaken the cladding, possibly allowing radioisotopes to be released during an accident. Once the GPHS is installed in the Stirling radioisotope system, it must be continuously cooled. Normally, the Stirling converter removes the heat, keeping the GPHS module at the design temperature and, therefore, continuous operation is required. However, there are three basic times when it may be desirable to stop and restart the Stirling converter: 1) during the installation of the GPHS, 2) during missions when taking scientific measurements to minimize electromagnetic interference and vibration, or 3) during any unexpected stoppage of the convertor under operation on the ground or during the mission. Starting in 2006, ACT developed under Phase I, Phase II and Phase III SBIR programs (Contracts No. NNC07QA40P, No. NNX11CA59C and No. NNC14VC86P) a Variable Conductance Heat Pipe (VCHP)-based Backup Cooling System (see various stages of development in [39-45]) that will passively allow multiple stoppages of the converter at the expense of a small overall temperature increase. The latest prototype from this development is shown in Fig. 24.



a) b) c)

Figure 24. Sodium VCHP as Backup Cooling System for Stirling RPS a) Actual prototype b) The prototype integrated with Stirling converter and c) VCHP and insulation housing installed on the Stirling converter and ready for testing at NASA GRC.

The VCHP prototype (Fig. 24a) was welded of nickel 201 and stainless steel. The VCHP annulus is entirely nickel 201 to match the Coefficient of Thermal Expansion (CTE) of the Stirling's actual heat collector. The connecting tubes are stainless steel as are the upper surface of the radiator and the entire reservoir. The lower face of the radiator is nickel 201 selected for its high thermal conductivity and acceptable strength in the working temperature range. The VCHP wall thicknesses were designed with a minimum Factor of Safety (FOS) of 2 against yielding to maintain a reasonably light but robust prototype. The VCHP mass as built was 358 grams (0.79 lbs) including the sodium charge and screen (wick). In Fig. 24b the VCHP prototype is shown integrated with a Stirling converter where the Cold Side Adapter Flange (CSAF) that normally cools the cold end of the Stirling can be observed as attached to a single-phase cooling loop. Fig. 24c shows the Insulation can added to the system and ready for testing.

Two main experiments were carried at NASA GRC:

1. ***Long duration stoppage*** – to evaluate the VCHP – Stirling convertor interaction during an indefinite period of stoppage.
2. ***Multiple short duration stoppages*** – to evaluate the capacity of the system to return to nominal temperatures after each stoppage during a multiple stoppage regime.

3.5.1. Experiment 1 - Long Duration Stoppage of the Stirling Converter

The experimental results for the *long duration stoppage* experiment are shown in Fig. 25 for a single off cycle of the Stirling convertor where steady state was achieved in each stage. The data shown is the raw data collected except for the input power that was held constant during the experiment at 348 W moderated by a PID controller.

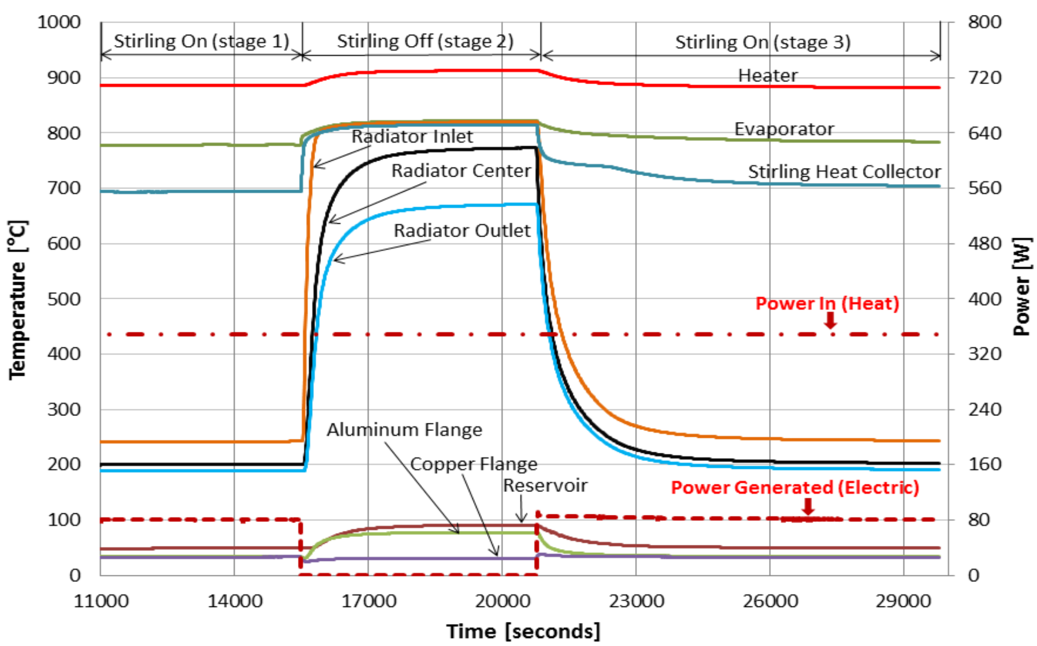


Figure 25. Experimental results for the long duration stoppage test - steady state achieved each time.

The Stirling converter is on during stage 1 (1100 s – 15360 s) and the VCHP radiator temperatures are reasonably low at an average of 210° C. Both sodium vapor and heater reach steady state values of 779° C and 886°C respectively while the Stirling heat collector has a steady state temperature of 694°C given the thermal resistance across the gap between the VCHP and Stirling. The Stirling converter is turned off at approximately 15360s starting stage 2 (15360 s – 20594 s). When the Stirling converter is off the VCHP temperature and sodium vapor pressure rise rapidly, compressing the NCG in the reservoir and activating the radiator. There is a temperature gradient present in the radiator as it is slightly oversized, and the sodium vapor does not need to occupy the entire radiator to reject the bypass heat. The Stirling converter is cycled back on at 20594 s starting the nominal system recovery, stage 3 (20594 s – 29600s). The radiator temperatures drop rapidly as the front is retracted out of the radiator until settles back into the annulus. As seen during stage 3, all the temperatures return to their initial values prior to the Stirling shutdown.

3.5.2. Experiment 2 - Multiple Short Duration Stoppages of the Stirling Converter

One set of experimental results for the multiple short duration stoppages testing case is presented in Fig. 26. The Stirling converter was cycled off three times demonstrating the repeatability of the backup cooling system (VCHP) behavior. The time between each stage was approximately 50 minutes to show the general trend towards steady state event though it is not reached. Overall, the testing results show that the VCHP can passively assist Stirling converter's on and off regime reliably and with full repeatability.

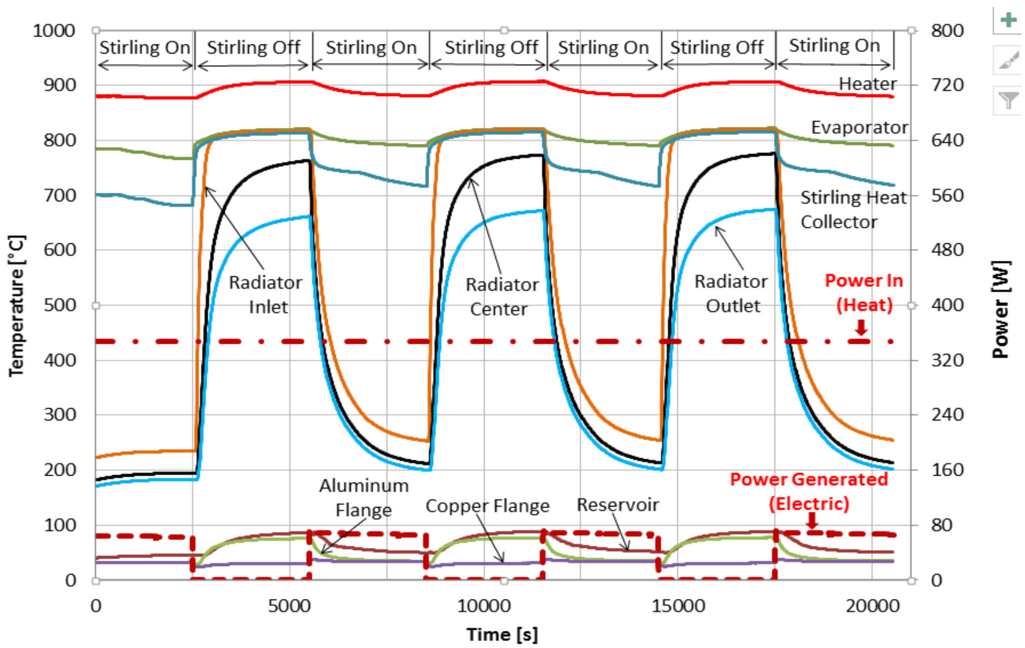


Figure 26. Experimental results for the multiple short duration stoppages testing of the Stirling converter with VCHP.

ACT is currently following the development of the Stirling RPSs at NASA GRC and further generates thermal management concepts that address both the hot end and the cold end of various Dynamic Power Conversion System configurations that will improve their ***specific power*** and ***reliability***.

4. Conclusion

The paper presented a brief review of ACT's activities and contributions mainly related to the advancement of thermal management assisting space nuclear applications. ACT, under NASA, DOE and commercial funding has been developing innovative thermal management components and systems for:

1. Kilopower
    a. Hot End
        i. Sodium heat pipes (thermosyphons, self-venting
        ii. Heat collecting system
    b. Cold End
        i. Titanium-water heat pipe radiators

        1. Freeze tolerant
        2. Hybrid wick (dual pore size in the evaporator and groves in the rest of the pipe

2. Nuclear Electric Propulsion (NEP)
    a. Hot end
        i. Sodium heat pies (superalloys and 3D printed SiC)
        ii. Startup subsystem
        iii. Heat pipe – Bryton cycle heat exchanger
3. Fission Surface Power (FSP)
    a. Hot End
        i. Sodium heat pipes
            1. Envelopes of various nuclear compatible superalloys and refractory metals
        ii. Heat transfer interface (auxiliary heat pipes or heat exchangers) with the conversion cycle (Stirling of Bryton)
    b. Cold End
        i. Titanium-water heat pipe radiators
            1. Receive the waste heat from a single-phase loop
            2. Graphite Fiber Reinforced Composite (GFRC) as face-sheet
            3. Modular radiator
4. Heat pipe life tests
    a. Various titanium purities and alloys with water life testing
    b. Intermediate temperature fluids
        i. Investigation and fluid selection
            1. Elemental fluids
            2. Organic fluids
            3. Inorganic fluids (mainly halides)
        ii. Compatibility with envelope
        iii. Life tests
5. Dynamic power conversion
    a. Backup Cooling System (Haynes 230 – sodium dual condenser VCHP)
    b. GPHS-Heat collector heat transfer interface

Advanced Cooling Technologies strives to established itself as a leader in the field of thermal management for space nuclear energy generation by continuing to innovate and develop new concepts that improve thermal management or enable new features for all the space nuclear systems mentioned above. In addition, as immediate further steps ACT will address: the Cold End of NEP and especially for the currently active program JETSON (radiator panel materials and configuration, advanced heat pipes for heat spreading and radiator efficiency increase, other…) and the GPHS module – Stirling heater head heat transfer interface as well as the Cold Side Adapter Flange for the current and future designs of Stirling Radioisotope Generators.

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