



Heat Pipes and Heat Rejection Component Testing at NASA Glenn Research Center

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Abstract

Titanium-water heat pipes are being evaluated for use in the heat rejection system for space fission power systems. The heat rejection system currently comprises heat pipes with a graphite saddle and a composite fin. The heat input is a pumped water loop from the cooling of the power conversion system. The National Aeronautics and Space Administration has been life testing titanium-water heat pipes as well as evaluating several heat pipe radiator designs. The testing includes thermal modeling and verification of model, material compatibility, frozen startup of heat pipe radiators, and simulating low-gravity environments. Future thermal testing of titanium-water heat pipes includes low-gravity testing of thermosyphons, radiation testing of heat pipes and fin materials, water pump performance testing, as well as Small Business Innovation Research funded deliverable prototype radiator panels.

Introduction

The NASA Enabling Technology Development and Demonstration Program's Fission Power Systems (FPS) Project develops technologies to enable the option of using fission power systems for future space explorations missions. Heat pipes and heat pipe radiator technology are part of the heat rejection system for various space fission power systems power applications. Conceptually, heat from a reactor would be utilized to power several Stirling convertors to generate electricity. For a 40-kWe installation, radiators would be needed to dissipate approximately 140 kW_t of waste heat. The notional design utilized large radiators of 185 square meters radiating area and operated at heat rejection temperatures ranging from 350 to 500 K. The current radiator designs are envisioned to operate at a temperature near 400 K. A heat pipe is an efficient heat-dissipation and heat-spreading device and in its simplest form is a passive two-phase heat transfer device in a sealed tube.

Nomenclature

ALIP	A Linear Induction Pump
DOE	Department of Energy
FPS	Fission Power Systems
ISS	International Space Station
kWe	kilowatts electric
kWt	kilowatts thermal
LHP	loop heat pipe
MSFC	Marshall Space Flight Center
NASA	National Aeronautics and Space Administration

PCAD	Power Conditioning and Distribution
QCM	Quartz Crystal Microbalance
RGA	Residual Gas Analyzer
SBIR	Small Business Innovation Research
T	Temperature (K)
TDU	Technology Demonstration Unit

Hardware Testing

A radiator concept design can be seen in Figure 1 (Siamidis, 2006). Several technology challenges quickly became evident. The large size meant traditional metal radiators, such as those used on the International Space Station (ISS), would carry a large mass penalty. Second, the rejection temperature was well beyond the capability of existing large flight radiators and would require new heat rejection fluids, or use of existing fluids at temperatures beyond their typical range. Copper-water heat pipes are well established in the electronic cooling industry with operating temperatures in the 300 to 400 K range. The need for heat pipes to operate in the 500 K range led to the development of heat pipe materials that could operate at elevated temperatures and pressures. Copper-nickel and titanium alloys were investigated as well as a variety of potential heat pipe working fluids. Titanium-water compatibility tests have shown promising results, while use of other working fluids would require further investigation and development. Thus water was selected as the primary heat rejection working fluid, and the work with alternate fluids was stopped. Titanium was chosen as the envelope material for its potential long-term compatibility with water, high strength, and low density. NASA determined that the design and fabrication of multiple titanium-water heat pipes was necessary to accelerate heat pipe development and address questions about their true performance capability, long-term durability, and readiness of the manufacturing sector.

Titanium-Water Life Test Heat Pipes

Over 3 years of thermal testing on nine titanium-water heat pipes has been achieved in the Heat Pipe Thermal Testing Laboratory at NASA Glenn Research Center (GRC). The titanium-water heat pipes are being tested at 500 K on a continuous 24-hour/7-day basis. Three manufacturers, Advanced Cooling Technologies, Thermacore, Inc., and Swales Aerospace Inc. (ATK), each produced three 1.25-cm-diameter by 1.1-meter-long titanium-water heat pipes. Each vendor used different internal wick characteristics resulting in slightly different performance. The nine heat pipes have performed as expected with negligible degradation over the 3 years. The life test setup can be seen in Figure 2.

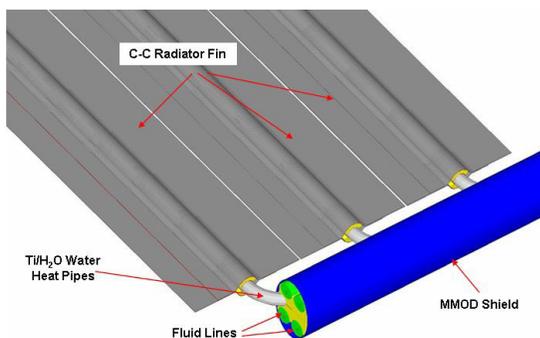


Figure 1.—Heat pipes integrated in a radiator panel.



Figure 2.—Titanium-water heat pipe life test setup.

Thermal Interface Evaluation

The heat exchange from a closed-loop heat source to the evaporator of a thermosyphon was investigated. The evaporator section was either immersed in the closed-loop heat source, with the closed-loop heat source fluid delivering the heat to the evaporator through the evaporator wall, or the evaporator section was clamped adjacent to the closed-loop heat source, with the closed-loop heat source delivering heat to the evaporator wall via conduction through the clamshell arrangement of hardware surrounding the evaporator. Essentially identical thermosyphons were either immersed in the closed-loop heat source or clamped adjacent to the closed-loop heat source, and the wattage transported from the closed-loop heat source through the heat pipe and out through the condenser was carefully measured by a surrounding calorimeter. Thermocouples measuring temperature difference between the closed-loop heat source and the evaporator section of the heat pipes, along with the flow through the calorimeter as measured by a calibrated flow meter, were used to obtain thermal conductance through the immersed or clamped interface. A temperature control unit (manufactured by Sterling, Inc.) operating on tap water was utilized to provide a constant temperature closed-loop heat source. With the immersion hardware installed, stainless steel plumbing allowed fluid flow past the evaporator. With the titanium clamshell hardware installed, flow through the clamshell arrangement could also be achieved enabling the closed-loop heat source to operate at temperatures as high as 394 K. The CP-2 titanium-water thermosyphons were manufactured in house; each was 1.27 cm in diameter and 74 cm in length with a titanium screen wick to line the evaporator wall section only. The thermal interface test setup can be seen in Figure 3. A selection of interface materials were evaluated in the clamped configuration, selected based on high-temperature durability, pliability, and availability. Two GrafTech International grafoil products were evaluated: eGRAF® HITHERM™ 705 and eGRAF® HITHERM™ 1205. The HT-705 has a typical through-thickness thermal conductivity of 6.0 W/mK, while the HT-1205 has a through-thickness thermal conductivity of 10 W/mK. Both grafoil products were plain, with no coatings or adhesives applied. One Aavid Thermalloy product was evaluated: Aavid Sil-Free™ thermal grease. Copper and silver leaf were selected owing to their pliability. The two leaf products were purchased through an art supply house, and were simply wrapped around the evaporator at the time of installation. T-Mate™, a phase change product by Laird Technologies, was selected owing to its attractive phase change temperature in the range of 323 to 343 K combined with its maximum operating temperature of 398 K. Figure 4 shows the many different evaporators tested.

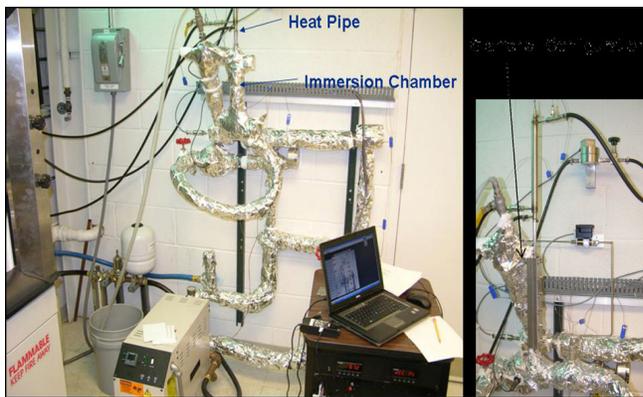


Figure 3.—Thermal interface evaluation system.



Figure 4.—Thermal interface machined evaporators.

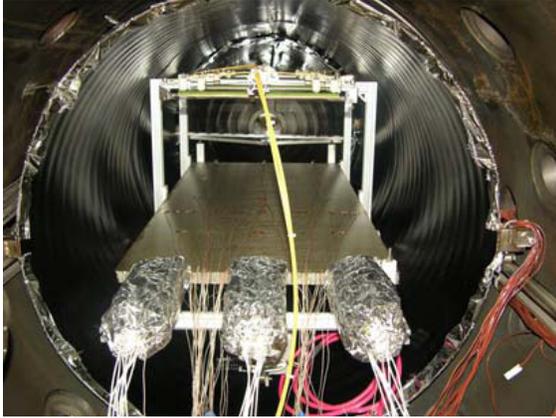


Figure 5.—Framework above the RDU panel with four quartz lamps.



Figure 6.—2nd GEN radiator panel.

RDU (Lamps) Freeze Tests

Radiator panels utilizing titanium-water heat pipes are flat panels approximately 2.54 cm thick by 0.5 m wide and 1 meter long. High thermal conductivity carbon-polymer facesheets are adhesively bonded to an aluminum honeycomb core and three titanium-water heat pipes are embedded within the core to provide heat transport. The heat pipes are adhesively bonded to a graphite foam saddle and the foam is in turn bonded to the PMC facesheets for the purpose of simultaneously providing a thermal pathway and addressing mismatch in coefficients of thermal expansion. A traditional sandwich structure is envisioned where heat pipes are embedded between two high-thermal conductivity facesheets. The heat pipe evaporators are to be thermally connected to the heat source through one or more manifolds containing coolant. Initial radiator operation on the lunar surface would likely follow a cold soak where the water in the heat pipes is purposely frozen. To achieve heat pipe operation, it is necessary to thaw the heat pipes. One option is to allow the sunlight impinging on the surface at sunrise to achieve this goal. Testing was conducted in a thermal vacuum chamber to simulate the lunar sunrise and additional modeling was conducted to identify steady-state and transient response. It was found that sunlight impinging on the radiator surface at sunrise was insufficient to solely achieve the goal of thawing the water in the heat pipes. However, starting from a frozen condition was accomplished successfully by applying power to the evaporators. Figure 5 shows a radiator panel on framework with quartz lamps and inside the vacuum chamber cold wall.

Second Generation Radiator Demonstration Unit

In support of the FPS project, the Second Generation (2nd GEN) Radiator Demonstration Unit (RDU) was developed by Material Innovations Inc. (MII) in Huntington Beach, California, and delivered to NASA GRC in Cleveland, Ohio. The 2nd GEN RDU is shown in Figures 5, 6, and 7. It consists of a titanium-water fluid manifold coupled to 16 titanium-water heat pipes that are sandwiched between two composite facesheets enhanced with white thermal control paint. The radiator assembly is supported by an aluminum frame that can be suspended in the vacuum facility. A thermocouple patch panel below the water manifold provides the interface for instrumentation cabling. The 2nd GEN RDU was designed to reject at least 6000 W to a 250 K thermal sink with 400 K water inlet temperature and both manifolds at 0.25 kg/s. The radiator also was operated over a wide range of water inlet temperatures, flow rates, and sink temperatures.

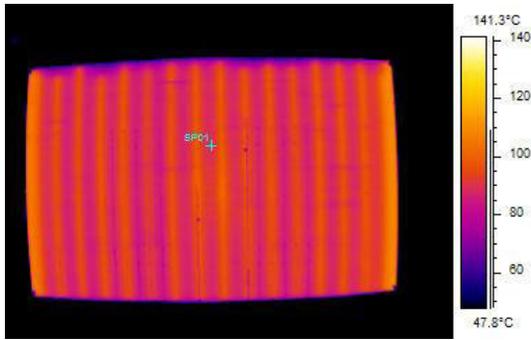


Figure 7.—Infrared camera image (T Inlet 430 K).



Figure 8.—Thermal testing of ammonia LHP.



Figure 9.—Square heat pipe.



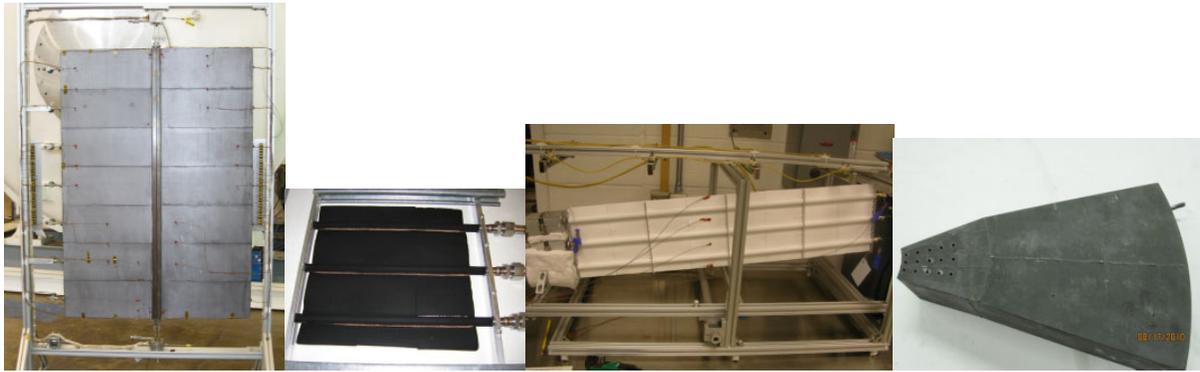
Figure 10.—Low-g flight test.

Loop Heat Pipe

The loop heat pipe (LHP) with ammonia working fluid is a common heat transport device used in spacecraft. The LHP used here was manufactured in 1997 by Thermacore, Inc., and shipped to Goddard Space Flight Center (GSFC). The LHP was shipped to GRC in 2002. In the summer of 2007, the LHP was removed from storage and tested at GRC as part of NASA’s Exploration Technology Development Program. The LHP survived an approximate 10-year dormant period and was in good working order. There were several important accomplishments during this investigation: 1) A mini-loop heat pipe was tested after approximately 10 years in storage and appeared to work normally, 2) this testing demonstrates that this novel method for surviving the cold lunar environment is practical, 3) this testing has shown that an ordinary loop heat pipe was robust enough to withstand temperatures well below the design temperature and well below the temperature of frozen ammonia, 4) it appears that larger startup heat is necessary under these conditions when compared to room temperature startup conditions, and 5) it was shown that the reduced gravity of the Moon does not affect the performance of this LHP, when compared to performance in a zero-gravity environment. Figure 8 shows LHP test setup.

Low-g Heat Pipes

There are several concepts for evaluating thermosyphon performance in a reduced-gravity environment. The simplest technique is to tilt the thermosyphon. The angle of tilt is selected utilizing the cosine function, such that the gravity vector in the axial direction of the thermosyphon is reduced by the desired amount. An angle of 9.5° simulates the lunar surface. Figures 9 and 10 shows a square heat pipe to simulate low-g operation by evaporating and condensing on one surface. Figure 10 shows thermosyphon array controlled operation for zero g flight test article.



Allcomp heat pipe radiator, Creare pyrolytic fin radiator, Creare heat pipe radiator, Thermacore, Inconel 718 life test



ACT heat pipe development, ACT Stirling VCHP, ACT intermediate heat pipe fluids, Alion high temperature coating

Figure 11.—SBIR contributions to the fission power systems project.

Small Business Innovative Research

SBIR grants are an important and continuous source of component development hardware. The FPS Project is continuously seeking unique and innovative component technology innovations. SBIRs have developed several heat pipe radiators, material evaluations such as high-temperature coatings, and life test of materials and reliability models of system functions. Figure 11 illustrates the many SBIR contributions to the FPS Project.

Component Radiation

An important area of space fission power systems is reliability of components. Fission Power Systems components in the proximity of an operating reactor must tolerate radiation exposure, or be shielded. Most FPS components can be constructed of high radiation-tolerant materials; however, the radiation tolerance some radiator materials needed to be characterized for the prescribed configuration and environment of their application in a space fission power system. At the Sandia National Laboratories radiator components will be exposed, which includes titanium-water heat pipes with a composite fin, foam saddle, and a candidate epoxy to hold the components together.

Sodium-Potassium (NaK) Eutectic Detection

The pressure of NaK during a leak event is difficult to measure. The Technology Demonstration Unit (TDU) piping will have multilayer insulation so knowing the exact temperature and pressure of the NaK during an unexpected leak event would be unknown. Several different methods and instruments were reviewed to determine which hardware would be best suited for the task. At completion of the evaluation it was determined that a Residual Gas Analyzer (RGA) and a Quartz Crystal Microbalance (QCM) were the best candidates for near-term evaluation. The test results have given conclusive data that detection of NaK in a space simulated environment can be achieved using both the QCM and RGA methods together. Using sodium as the signature atomic mass, the RGA will be the primary detector with a partial pressure range down to 1.0×10^{-10} torr. Quantifying the amount of NaK being released will be done using the QCM by monitoring the deposition thickness and rate. Together, these instruments should provide enough data to successfully detect a NaK leak and provide opportunity to follow shutdown procedures and minimize any potential damage to the facility and test hardware.

Future Work/Conclusion

The Fission Power Systems Project is in the process of procuring components for a TDU, which will simulate an operating fission power reactor at NASA GRC. All the components (except a fission reactor) have been tested individually and are being upgraded and integrated into an operating system. The reactor simulator loop has been fabricated at NASA Marshall Space Flight Center (MSFC) and satisfactorily tested. A Linear Induction Pump (ALIP) has been fabricated by the Department of Energy (DOE) and installed in the reactor simulator loop and successfully tested. A full-scale radiator panel was fabricated by Material Innovations, Inc., and successfully tested at GRC. Stirling convertors have been successfully tested using pumped liquid metal (NaK) as the heat source at MSFC. A Power Conditioning and Distribution (PCAD) System is jointly being developed by NASA and DOE.

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