

## HEAT PIPE DEVELOPMENT FOR SPACE FISSION DEMONSTRATION MISSIONS

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*NASA is currently formulating a flight mission that will demonstrate a 10 kWe nuclear electric fission power system for use on the lunar surface, with extensibility to Mars. While preliminary mission concepts leverage the successful Kilopower Reactor Using Stirling Technology ground prototype demonstration of a 1 kWe reactor, there are significant engineering challenges associated with adapting that prototype reactor for flight. One of these challenges is to modify the high temperature sodium heat pipes for use in space operation. Ongoing technical work at the NASA Glenn Research Center seeks to address several key areas of heat pipe development, focusing on fluid return under reduced or microgravity conditions and improved interfaces for both the reactor and the power conversion ends of the heat pipe.*

### I. INTRODUCTION

Following the successful demonstration of the Kilopower Reactor Using Stirling Technology (KRUSTY) ground prototype reactor in March 2018, NASA has continued formulating a flight mission to demonstrate a nuclear fission capability for use on the lunar surface.<sup>1,2</sup> With a target launch date towards the end of the 2020's, the preliminary mission concept is to land a 10 kW electric power (kWe) fission reactor system near the south pole of the Moon and operate continuously for one year, with additional operation out to ten years for life testing. While detailed design concepts are still a work in progress, with NASA and Department of Energy (DoE) in discussions regarding nuclear core characteristics, the baseline design remains similar to the uranium molybdenum (U-Mo) metal alloy core KRUSTY reactor. An integral part of that design is the high temperature sodium heat pipes that serve as the heat transfer mechanism between the core and the Stirling engine power conversion system. Heat pipes are a passive means of heat transfer based on a two-phase evaporation-condensation cycle, using no moving parts. They are therefore a highly attractive option for long term space missions that rely on robust systems. However, though the KRUSTY test demonstrated the effectiveness of using heat pipes in a reactor system, there remains several key areas of development for this high temperature heat pipe technology before they can be used for flight missions. These areas are divided into four parts: fluid return under

reduced gravity conditions, heat pipe to power conversion interface, heat pipe to reactor core interface, and long-life performance. The Kilopower technical team at GRC has continued to pursue these four heat pipe maturation objectives while the lunar flight mission is being developed.

### II. HEAT PIPE TECHNICAL MATURATION

Over the course of 2019, NASA GRC engineers have performed several tests, supported external work, and developed internal test facilities to foster technical maturation of high temperature heat pipes.

#### II.A. Fluid Return under Reduced Gravity

The basic operation of a heat pipe involves a two-phase fluid cycle between the heat input end (the evaporator) and the heat output end (the condenser) of the heat pipe. As the name implies, the evaporator is where the working fluid is evaporated by the incoming heat from the reactor to produce the vapor pressure that transfers the heated vapor through the pipe. It follows then that the condenser is the point where this heated vapor collects and transfers its heat, returning to liquid form. The issue then lies in how that condensed liquid is returned to the evaporator to complete the cycle. On earth this cycle can be achieved simply through the force of gravity working on the fluid. In micro-gravity this effect is absent and the heat pipe operation must rely on a secondary force to draw the fluid back to the evaporator. This can be achieved through capillary forces using an internal wick or artery system. Various wick designs exist, mostly using metal meshes or sintered metal powders. Thin capillary tubing can be used to provide the return force and separate the returning liquid from the vapor pressure. Some examples are shown in Figure 1. Wickless heat pipes can also be achieved



**Fig. 1.** Examples of capillary tubing and metal screen artery

by designing grooved geometries in the heat pipe to provide capillary forces on corners.

Work is ongoing to see which wick design works the best for the high temperature sodium heat pipes, with the primary figure of merit being the maximum power throughput of a heat pipe design. Several heat pipe designs are planned to be tested using existing test facilities at GRC. In addition, Figure 2 shows a new vacuum test facility that has been designed with the ability to rotate to provide various angles to simulate the reduced gravity on the moon, Mars or in micro-gravity (running the heat pipe in a horizontal position). Despite the imperfections of this method, it is a reasonable way to determine the effectiveness of each wick design in reduced gravity environments.

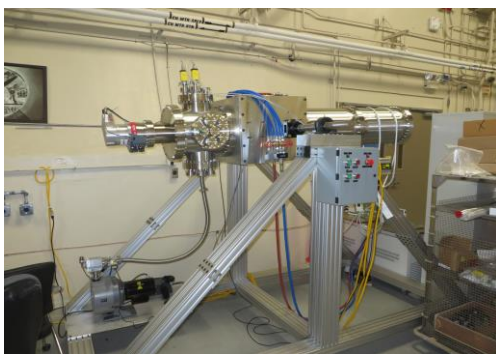


**Fig. 2.** Rotating heat pipe test rig at GRC

## **II.B. Heat Pipe to Power Conversion Interface**

Just as important as the two-phase cycle in the heat pipe are the interfaces to the heat input and output. Different interface solutions will likely be required based on the power conversion technology. For Stirling engines, there is an elegant solution that is likely to significantly increase the heat transfer efficiency of the heat pipe system. The linear Stirling cycle engine has a fairly compact form factor, with the heat acceptor and rejector being on opposite ends of basically cylindrical pressure vessel. The heat acceptor can therefore be fully integrated into the heat pipe, allowing the hot end of the engine to essentially be the condenser of the heat pipe. Figure 3 shows an example of this construction.



**Fig. 3.** Stirling hot end integrated into heat pipe condenser

The hot vapor will condense right onto the Stirling heat acceptor, reducing the drops in temperature through thermal interfaces to a bare minimum. Sunpower, Inc., the vendor that designed the Advanced Stirling Convertors (ASC) under the Advanced Stirling Radioisotope Generator program, is providing GRC with modified ASCs with direct heat pipe condenser interfaces. A new heat pipe condenser design developed by GRC, shown in Figure 4, was additively manufactured to mate with the ASC hot end.



**Fig. 4.** Additively manufactured heat pipe condenser

An ASC hot end and heat acceptor were connected to the additively manufactured heat pipe condenser at GRC and put through a series of break in tests, shown in Figure 5, to ensure that the heat pipe was operating nominally. Following this the whole assembly was shipped to Sunpower to integrate to the rest of the engine. Once assembled, these modified ASCs will undergo testing at GRC to determine the effectiveness of this interface design. This testing will consist of typical GRC Stirling engine tests, as well as additional testing in the rotating heat pipe test stand to determine the effectiveness of the heat pipe interface.

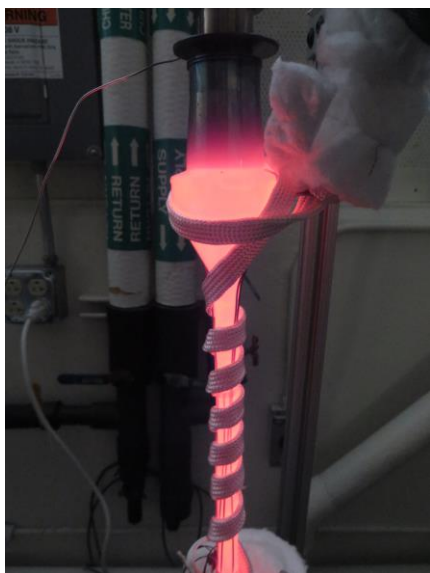


**Fig. 5.** Integrated hot end testing at GRC

### II.C. Heat Pipe to Reactor Core Interface

On the other end of the heat pipe, the evaporate needs to efficiently interface with the reactor core. This ensures both effective heat transfer, as well as robust continuous cooling of the reactor core for safety. For the KRUSTY test, the heat pipes were bonded into machined slots on the periphery of the U-Mo core with a Cu-Mo-Cu foil diffusion barrier between each pipe and the core. This was a simple solution that worked well at the lower thermal power (4 kW thermal for a 1 kWe system) of the demonstration. However, this method will likely not provide enough heat transfer surface for the increase to a 10 kWe lunar surface demonstration. The current proposed method for scaling to 10 kWe is to imbed the heat pipes throughout the reactor core. This provides increased heat transfer area per heat pipe as well as more space to include more heat pipes. Initial 10 kWe reactor designs included up to 24 heat pipes compared to the 8 used in KRUSTY. The challenge with this method is how to create a reliable thermal interface between the heat pipes and the core. Several methods have been proposed. One method is to provide a liquid sodium interface in the space between the pipes and the core. Work was performed at GRC to determine the viability of this option by testing the compatibility of the U-Mo alloy, using a depleted uranium sample shown in Figure 6, with liquid sodium.

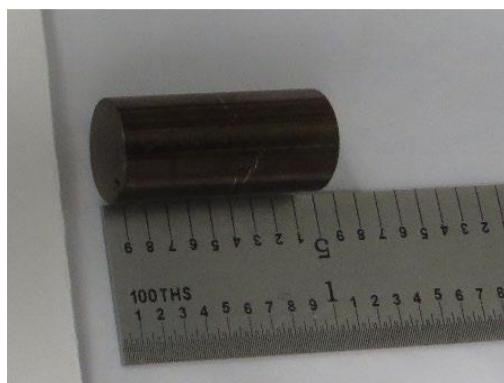


**Fig. 6.** Depleted uranium sample used in sodium compatibility testing

There was no significant mass exchange between the uranium and sodium observed under a scanning electron microscope after 2000 hours of testing at 850°C, supporting the potential viability of this thermal interface method. Another method was explored through an SBIR with the Peregrine Falcon Corporation, focusing on Liquid Interface Diffusion (LID) bonding. This process forms a solid interface between the heat pipes and the core, providing both a thermal and structural bond. Tooling was developed to demonstrate this bonding method between individual heat pipes and a copper surrogate for the uranium core.

### II.D. Longevity Testing

Robustness, reliability, and longevity are key characteristics for space hardware. Long term life testing is planned for the heat pipe designs developed at GRC in order to determine if they are suitable for multi-year missions in a space environment. This life testing will be performed in the rotating vacuum test chambers in order to simulate the mission conditions as closely as possible during the test. With the addition of a modified ASC operating off the heat pipe condenser, this testing will provide an excellent chance to determine the reliability of a complete power conversion string in a space-like environment. Startup transient testing will also take place, including startup at low temperatures to examine the freeze-thaw dynamics of high temperature sodium heat pipes. This testing will be performed using a liquid nitrogen cryojacket that fits into the rotating vacuum rigs.

## III. CONCLUSIONS

The technical team at GRC has continued to pursue technology maturation and hardware development while the next steps towards a space nuclear electric fission demonstration mission are being formulated. Continuing the development of high temperature sodium heat pipes is an important part of preparing for an eventual flight mission. The expertise in heat pipe fabrication and testing developed at GRC through the course of the KRUSTY test program is being put to good use to design the next

generation of heat pipes that may be used in a lunar fission power system. GRC has also relied on the support of several important partners such as Sunpower, Inc. and the Peregrine Falcon Corporation to ensure that the heat pipe technology not only performs well on its own, but also integrates smoothly into the full reactor system.

## **ACKNOWLEDGMENTS**

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