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Heat Pipe Powered Stirling Conversion for the Demonstration Using Flattop Fission (DUFF) Test

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Abstract

Design studies have shown that heat-pipe-cooled reactors provide a passive, redundant, and lower mass option to transfer heat from the reactor fuel to the power conversion system, as opposed to pumped loops, typically associated with larger fission power systems (FPSs). These small FPSs, designated as “Kilopower,” have been identified as mission-enabling technology capable of providing long-term abundant power for higher power science missions and lower power exploration missions. Although many research concepts have been examined and a few tested using electrical heating, none have been coupled to a real nuclear reactor. The Demonstration Using Flattop Fission, or DUFF, test was planned by the Los Alamos National Laboratory (LANL) to use the existing “Flattop” criticality experiment at the Nevada National Security Site to provide the nuclear heat source. A team from the NASA Glenn Research Center in partnership with the LANL reactor design team designed, built, and tested a heat pipe and power conversion system to couple to Flattop with the end goal of demonstrating electrical power production using technology applicable to Kilopower concepts. This paper will focus on the research and testing performed in preparation for the DUFF test.

Nomenclature

DAF	Device Assembly Facility
DUFF	Demonstration Using Flattop Fission
FPS	fission power system
I.D.	inner diameter
kWe	kilowatt electric
LANL	Los Alamos National Laboratory
O.D.	outer diameter
RPS	Radioisotope Power System
SNAP	Systems Nuclear Auxiliary Power
SRG	Stirling Radioisotope Generator
^{235}U	uranium isotope

Introduction

NASA's nuclear power portfolio has been focused on plutonium-fueled radioisotope systems using thermoelectric power conversion since the 1960s with many successful exploration and science missions. Historically, Radioisotope Power Systems (RPSs) have delivered up to a maximum of 290 W/unit and are most practical for deep space science missions where long-term dependable power is needed and solar intensity is limited. The first and last U.S. fission power system (FPS) to fly in space, to date, was SNAP–10A (Systems Nuclear Auxiliary Power) in 1965, during a time period when solar cell technology was just as precarious as fission power, and the country was uncertain which technology would power larger space systems, not suitable for RPSs. Since then, NASA has made significant progress in larger FPS developments (>10 kWe) for surface (Ref. 1) and in-space applications but has been reluctant to flight qualify such a system, mostly due to development cost and its uncertainty, and a lack of near-term mission pull. Today, there exists a portfolio gap between the flight-qualified lower-power RPS and the nonflight-qualified higher power FPS. Existing development efforts to fill this gap include a 500-W Stirling Radioisotope Generator (SRG5) and an extensible 1- to 10-kWe FPS (Kilopower). The development of a new RPS will be fairly well understood using past flight and development programs to predict future costs, but the same cannot be said for FPS with the last flight program taking place almost 50 years ago, during a much different nuclear era. The most successful FPS developments since the SNAP program typically have an end goal of a ground test demonstration using an electrically heated reactor core to simulate the performance of the uranium fuel. This is a practical test philosophy and addresses many key technology concerns but does not address the certainty of the reactor design and control, fuel manufacturing, and nuclear ground testing that make up a significant portion of the cost and development time to achieve a flight-qualified FPS. Careful consideration is needed to effectively determine which tests, both nuclear and nonnuclear, will bring the FPS technology to an advanced state where it will be converted from a technology demonstration into a flight program as mission pull increases.

A new emergence of small FPS is on the forefront with designers envisioning power-rich spacecraft that will enable exploration of new frontiers and pave the way for more advanced fission systems. The 1- to 10-kWe power gap can be filled with Kilopower and allow the plutonium-fueled RPS to continue their legacy for smaller science payloads. The current nuclear systems team, which includes NASA and the Department of Energy (DOE), has recognized the opportunity for the Kilopower FPS and initiated plans to address the development of these systems. During initial planning, the Los Alamos National Laboratory (LANL) reactor design team investigated using existing nuclear facilities to support development of the Kilopower concepts with the idea that proof-of-concept nuclear testing could be affordable and achievable. The LANL team identified a criticality experiment named "Flattop," located in the Device Assembly Facility (DAF) at the Nevada National Security Site, that had specific characteristics to facilitate a substantial proof-of-concept test. The Demonstration Using Flattop Fission, or DUFF, test was initiated with the goal of producing electrical power from the Flattop reactor (Figure 1). The Kilopower system concept designs all stemmed around a heat-pipe-cooled reactor coupled to either thermoelectric or Stirling power conversion systems (Ref. 2). Continuing with this principle, a heat pipe would be inserted into Flattop's ^{235}U (uranium isotope) fuel with the purpose of transporting the heat out to a pair of Stirling engines where conversion from heat to electricity could be made. A portion of the electricity produced would power a light to signify the proof of concept was complete, in addition to other engineering conclusions.

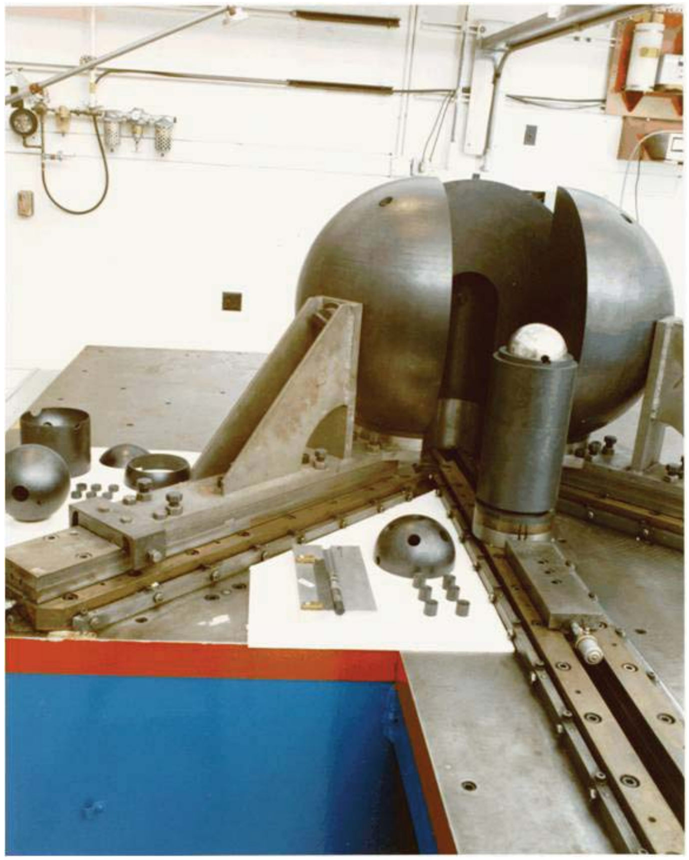

Figure 1.—Flattop reactor showing reflector safety blocks, fuel and pedestal, hemispherical reflector, and assorted components.

DUFF System Requirements

The Kilopower proof-of-concept test using the Flattop reactor was initiated in May 2012 with goals of completing the testing by summer's end. The system design would be driven by Flattop requirements concerning hardware integration, thermal characteristics, and safety processes. The higher temperature Kilopower flight concepts and associated design requirements were understood, in part, to be different than the DUFF requirements, but much was to be learned in their similarities for this proof-of-concept demonstration.

Mechanical Integration

Hardware integration required the heat pipe and thermal interfaces to conform to the Flattop geometry built in 1951. Flattop had a specific purpose concerning reactor criticality experiments and had never been configured to accept a heat pipe for the purpose of extracting thermal power. The uniqueness of the DUFF experiment required both the LANL and Glenn Research Center teams to investigate numerous designs to ensure that the experiment would be successful. Figure 2 shows the Flattop geometry and provides dimensional details for the assembly.

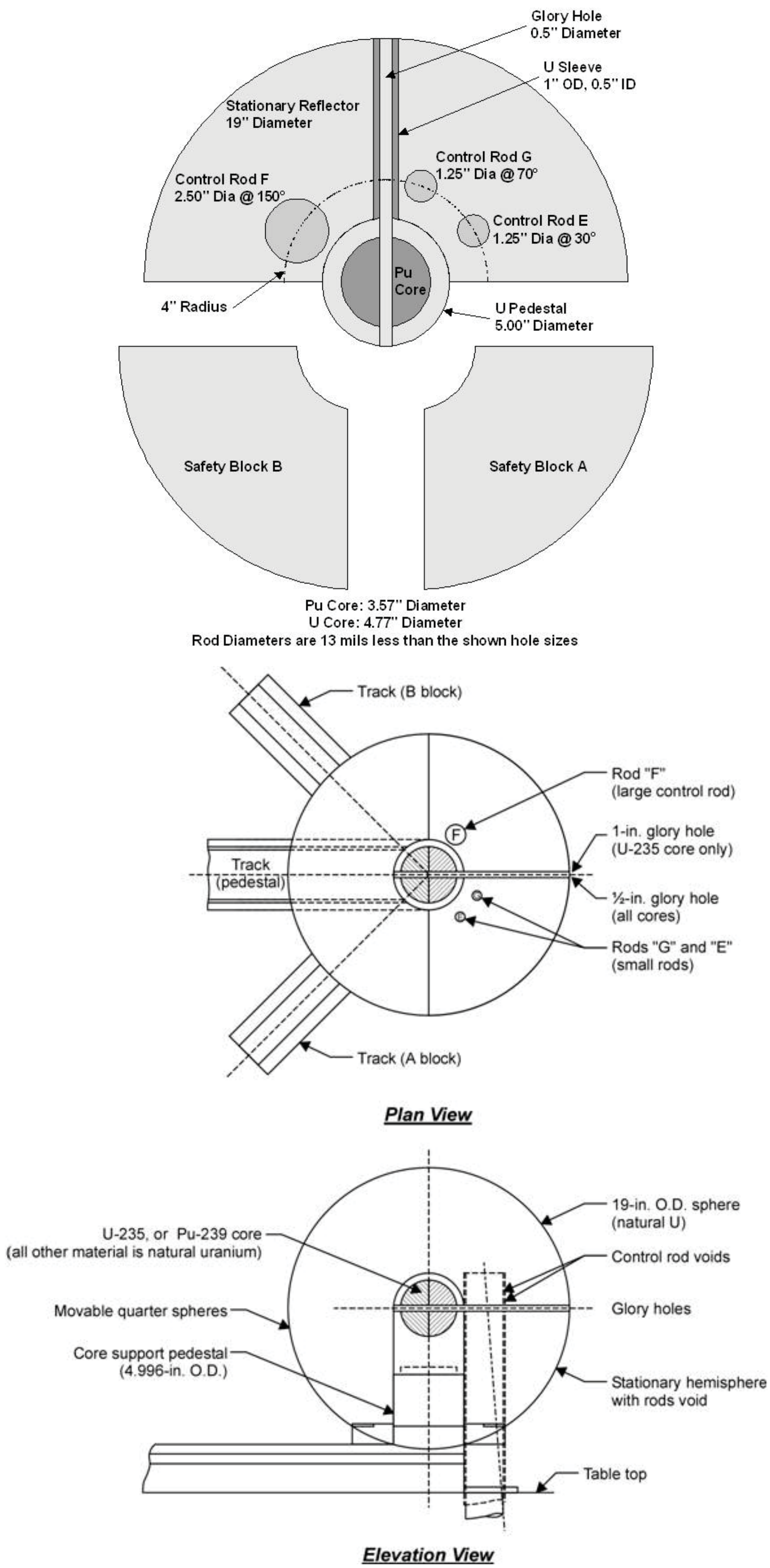

Figure 2.—Flattop reactor diagrams depicting internal structure and glory hole used for heat pipe placement.

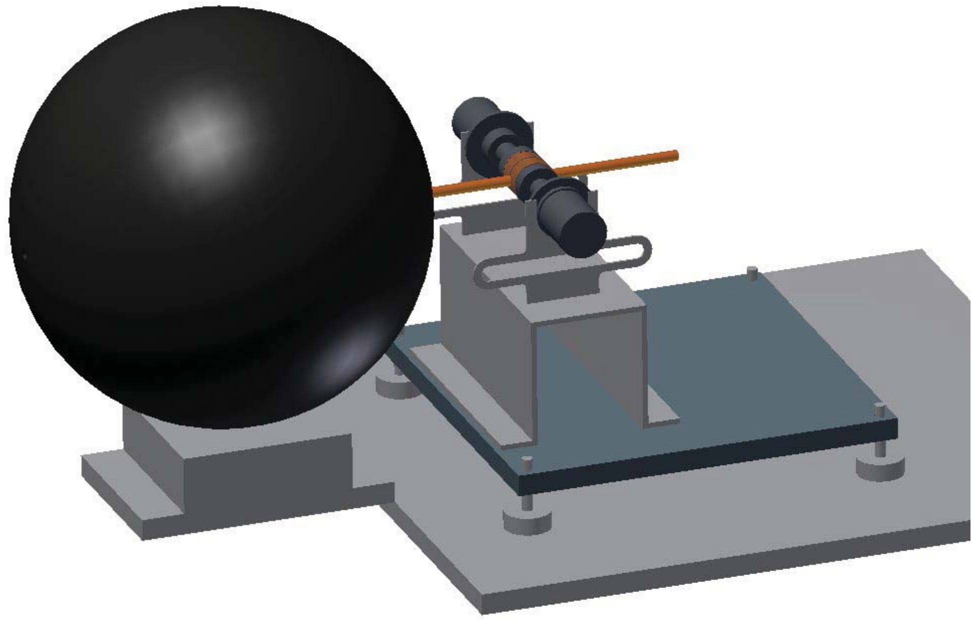

Figure 3.—Test configuration model showing 19-in. reflector sphere, heat pipe, convertors, and test fixturing.

The heat pipe would be inserted through the 19-in.-diameter stationary reflector and into the 5.0-in.-diameter uranium core, both having a 0.505-in. hole. The evaporator would have, at most, 4.75 in. of heat transfer length but concerns about excess reactivity could potentially decrease the available space with the addition of fuel plugs. Special requirements were established between the heat pipe and uranium core to ensure that the fuel would not get damaged or that the heat pipe would not become lodged in the fuel. This requirement allowed a graphite lubricant to be used between the heat pipe and fuel but would not allow any type of thermal grease or other products that could potentially react with the uranium metal. The temperature drops associated with the lubricant and radial gap would need to be tested for expected thermal performance during Glenn laboratory testing.

Mechanically coupled to the backside of the core and pedestal was the hemispherical reflector that housed a 1.0-in. outer diameter (O.D.) by 0.5-in. inner diameter (I.D.) uranium sleeve. In order for the heat pipe vapor to reach the Stirling convertors, it was necessary that this 7.0-in. section of heat pipe be as adiabatic as possible, minimizing the heat transfer to the reflector assembly. To meet this requirement, the uranium sleeve would need to be replaced with a new alumina or stainless steel sleeve with a larger I.D. The new sleeve would provide an air gap between the heat pipe and reflector thus minimizing large amounts of heat transfer from leaving the heat pipe assembly. Both alumina and stainless steel sleeves were made and either could be used depending on reactivity affects.

Once outside the reflector, the heat pipe would have the freedom to attach to the Stirling convertors as long as the engine assembly and test fixturing did not interfere with the reflector and was confined inside the edges of the table. The Glenn convertor test assembly would lie on the Flattop table and adjustments to align the centerlines of the heat pipe, reflector sleeve, and glory hole would be modified through adjustments of leveling feet. A generic model of the DUFF test assembly can be seen in Figure 3.

Thermal Requirements

Flattop is typically configured for two temperature measurements of the uranium core: one at the outer surface positioned in the core pedestal, and the other attached to a probe positioned in the glory hole. The DUFF heat pipe would replace the glory hole probe, leaving only the outside surface measurement of the fuel at the pedestal mount. The configuration changes with the internal uranium plugs, reflector sleeve, and heat pipe insertion had never been tested and would leave reactivity levels to be modeled computationally. The LANL team modeled a number of Flattop free run scenarios and compared against Flattop test data to verify model predictions. Once the Flattop model had been verified it was modified to incorporate the DUFF test configuration and used to predict expected performance. The Glenn team would eventually use the DUFF model predictions as inputs for the electrically simulated testing, and provide the heat pipe and conversion data back to LANL for model improvements. The initial DUFF model estimated that a 30 cent insertion could deliver up to 700 W of thermal power to the evaporator, ramping the glory hole temperature from 23 °C up to 300 °C in 2 min. The time period between reaching the peak fuel temperature and reactor scram was not specified but was estimated to be approximately 10 min. This scenario was defined by the Glenn team as the maximum transient condition that the heat pipe and conversion system would have to endure. A steady-state scenario was also examined using a 10 min ramp from room temperature up to a steady-state glory hole temperature of 200 °C that would be held for 10 min. The heat pipe and conversion system would have to make power in both scenarios.

Heat Pipe Design

The heat pipe design was driven by the transient and steady-state thermal requirements described above as well as the horizontal orientation while in Flattop. The major concern with the initial design was to minimize thermal resistance through the heat pipe knowing that reactor run times and temperatures were not well defined. The expected temperatures were somewhat troublesome as few heat pipe fluids are known to perform well in the range between 200 and 300 °C. Dowtherm A and water were tested to determine which fluid would ultimately provide the best performance for the DUFF heat pipe. Water is typically used up to 200 °C but extending the operation to 300 °C would require additional analysis with pressures exceeding 1200 psi. Dowtherm A would operate at a much lower pressure (35 psi at 300 °C), allowing a thinner wall section, but had inferior heat transfer properties to water. The horizontal heat pipe orientation, which is often used for zero-gravity simulations for space flight articles, would require the heat pipe to have significant pumping capacity in the wick structure to handle the high heat flux transient requirements. These constraints would require the heat pipe wick to have superior qualities in all major categories; capillary pumping, thermal conductivity, and permeability. A Glenn-designed heat pipe model was used to predict the performance of several wick designs using both water and Dowtherm as the working fluid. Figure 4 shows the expected performance of the heat pipe using the final design configuration and the two working fluids.

After a detailed analysis was completed, it was determined that a nickel sintered wick with integral arteries would provide the best performance given the design requirements and short schedule. Three sizes of nickel particles, 100-, 200-, and 325-mesh, were prepared for the wick structure to establish a range of capillary performance. Stainless steel (316L) was chosen as the heat pipe material to allow sintering of the nickel wick and provide strength at the operating temperatures. The fact that these heat pipes were only intended for the DUFF test, as opposed to a flight design, relaxed the weight constraints, allowing use of the heavier stainless and nickel materials. Grade 2 titanium was also considered, but lacked the strength needed to contain the water pressures during the higher temperature operations as well as the uncertainty of its compatibility with Dowtherm. Details regarding the heat pipe design can be seen in Figure 5.

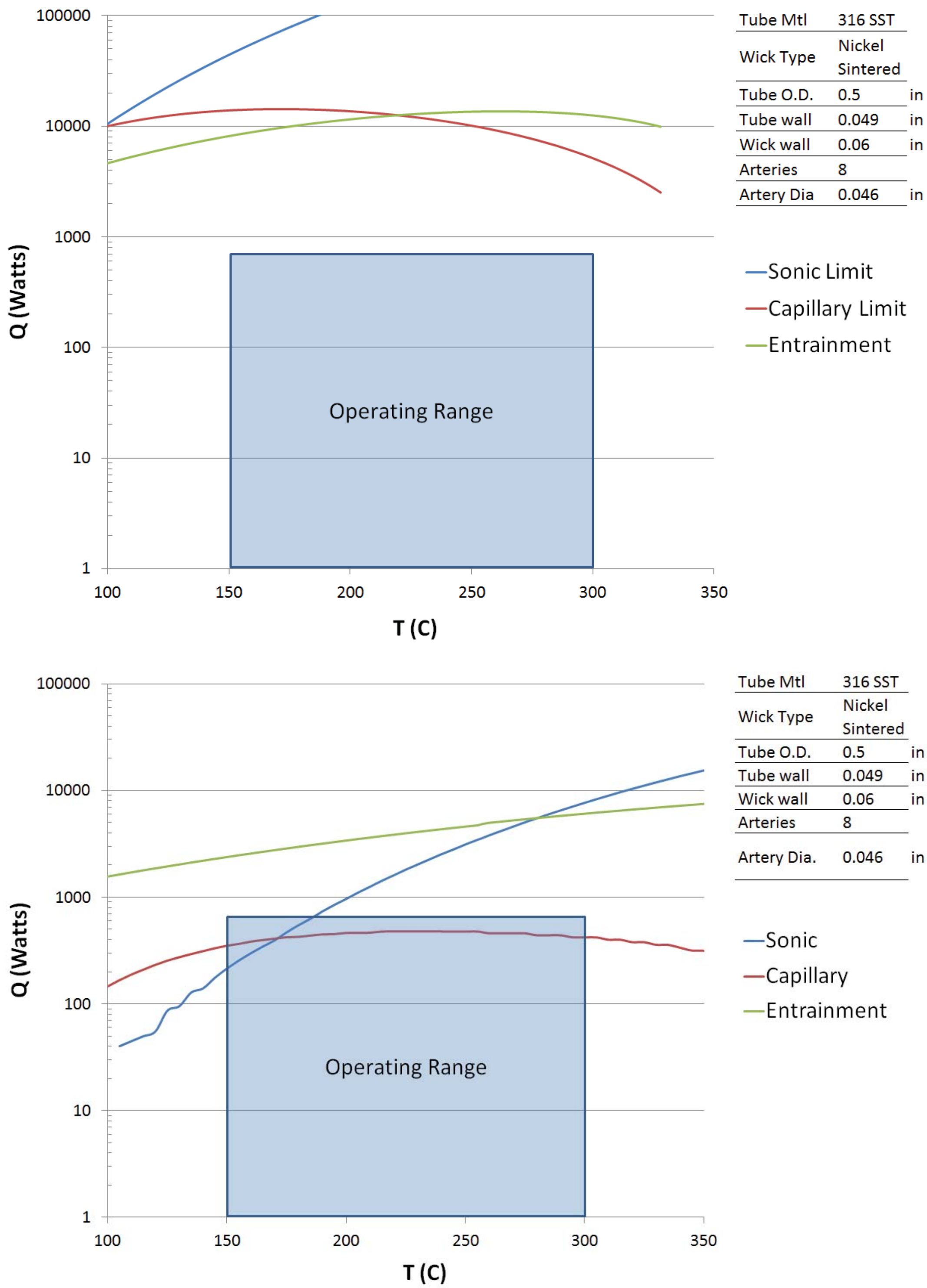

Figure 4.—Predicted heat pipe performance using water, left, and Dowtherm A, right.

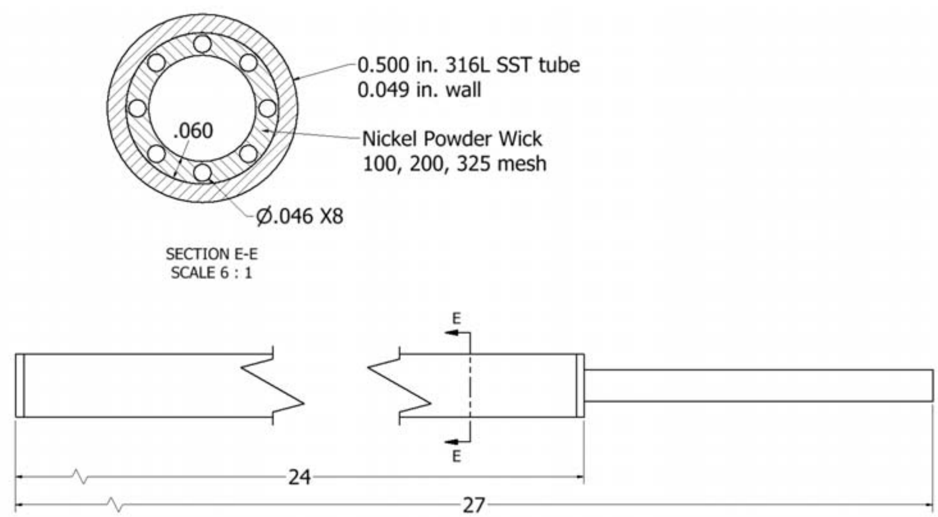

Figure 5.—DUFF heat pipe schematic, dimensions in inches.

Three DUFF heat pipes were fabricated for initial Glenn checkout testing, each with a different particle size. The 325-mesh heat pipe was tested first with Dowtherm A as the working fluid. The initial testing quickly showed that the heat pipe was not performing as predicted and the temperature drops were more significant than anticipated. It was quickly determined that the Dowtherm fluid was not going to function as expected for the DUFF testing. It is presumed that insufficient wetting between the fluid and wick material affected the pumping capacity and artery priming ability. This translated into a decreased capacity in the thermal power and would not suffice the DUFF requirements.

The second 200-mesh heat pipe was charged with water as the working fluid and tested over a wide range of temperatures and power throughputs. The water heat pipe worked as predicted and was able to carry the expected power to the Stirling convertors over numerous transient and steady-state test scenarios. The water also provided a much earlier startup temperature (50 °C) than the Dowtherm, which gave the heat pipe more time to heat up the Stirling convertors as the fuel temperature was rising. The only downfall of the water was the pressures that were produced at 300 °C which required additional testing and analysis. To ensure that the stainless tube would not rupture during testing, the heat pipe assembly was hydrostatically tested to 4000 psi as well as operated at above nominal conditions up to 350 °C. Performance characteristics of the DUFF heat pipe and convertors can be seen in the testing section of this paper.

Stirling Power Conversion

Fabrication of an ASC-like convertor with a heat pipe thermal interface was outside the budget and time constraints of this project. Therefore, the DUFF convertor had to be chosen from the existing stock of RPS-style convertors. Since neither the Flattop reactor nor any of the candidate convertors were designed to transfer heat through a heat pipe, temperature drops across the thermal interfaces were uncertain and expected to be rather large. On the reactor side, this was caused by the 5-mil radial gap and the inability to use thermal interface materials. On the convertor side, this was caused by the heat collector design of all candidate convertors, which required low surface area in the heat pipe condenser section and relatively large temperature drops. Allowing for margin on both the maximum fuel temperature and the temperature drop across the suboptimal thermal interfaces, the convertor had to produce power at a worst-case hot-end temperature of 150 °C. Most of the Stirling convertors that have been designed for space applications (both RPS and FPS) operate at a nominal hot-end temperature between 550 to 850 °C, and do not produce power below 200 °C. The one exception was an early predecessor of the ASC, called the Buzz convertors which had been modified for low-temperature operation (Figure 6).

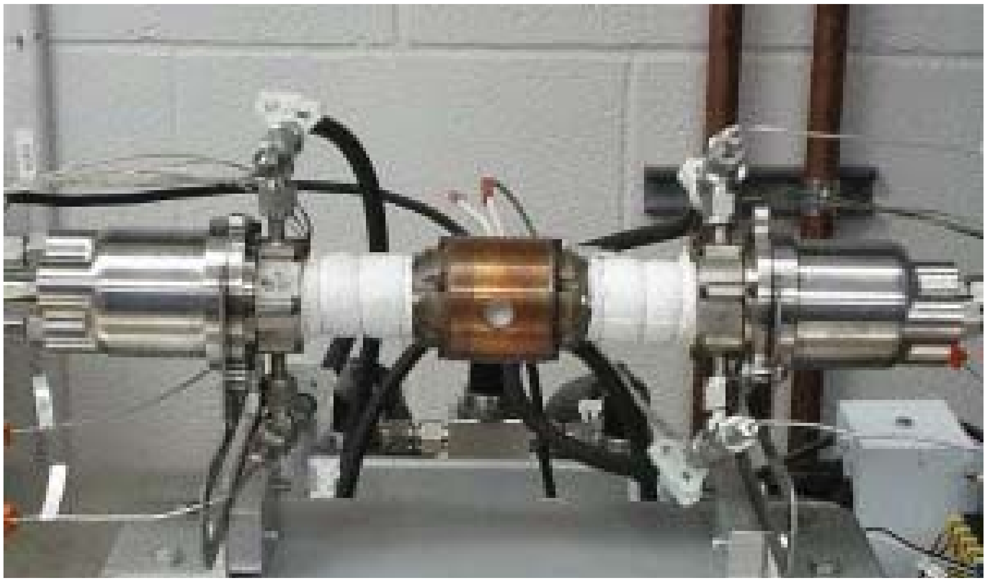

Figure 6.—Buzz convertors mounted being built up at Glenn.

When these convertors were run at the minimum coolant temperature of –50 °C, the convertor pressure vessel gas temperature reached 0 °C. For an expected hot-end temperature between 150 and 250 °C, the temperature ratio ranges between 1.55 and 1.92, which was enough for the convertors to produce power. Although the Buzz convertors do not represent the state of the art in Stirling design and performance, they were affordable, available, and compatible with the DUFF test constraints, making them the best choice for this proof-of-concept test.

Final Preparation and Testing

Several steady-state and transient tests were run at Glenn using electrical heaters prior to nuclear testing at DAF. Steady-state performance maps were used to verify temperature drop estimates across thermal interfaces and verify that the Buzz convertors produced power at the required temperatures. An electrically heated core simulator was manufactured to match the hole dimensions of the Flattop fuel so that measured temperature drops and heat fluxes accurately reflected those that would be experienced during nuclear testing. Figure 7 shows temperature drop data taken from electrically heated testing at Glenn. The data showed that the fuel to hot-end temperature drop ranged from 50 to 100 °C over the expected convertor operating range, depending on the heat draw from the convertors. Approximately half of this temperature drop occurred across the thermal interface between the fuel simulator and the heat pipe. The other half is attributed to thermal resistance through the copper adapter interfaces, and along the axial length of the Stirling heat collector. The convertor produced power at each of these conditions, including the worst-case fuel temperature condition of 200 °C, corresponding to a convertor hot-end temperature of 150 °C.

Transient tests were run to verify operation and performance under the most strenuous conditions and to validate modeling efforts. Figure 8 shows a maximum power startup transient, in which the heater delivered its maximum power of 750 W for just under 3 min and was then set to lower power operation to maintain the fuel simulator temperature. The initial transient represented the highest heat flux condition for the heat pipe, and thus carried the highest risk of evaporator dryout. However, this test demonstrated that the heat pipe was able to handle the heat load and successfully transfer heat to the Stirling hot end. This test was also used to estimate the minimum required startup time for DUFF testing and to validate the balance of plant portion of the nuclear system model developed by LANL.

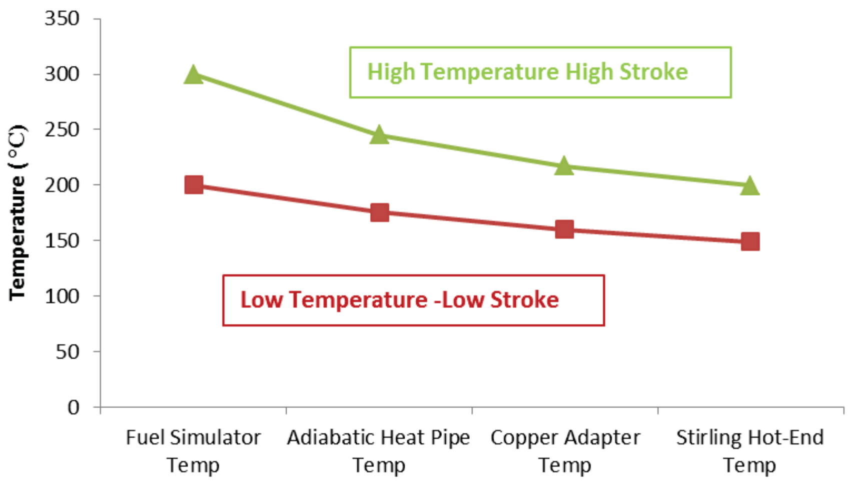

Figure 7.—Steady-state temperature data taken during electrically heated testing at Glenn.

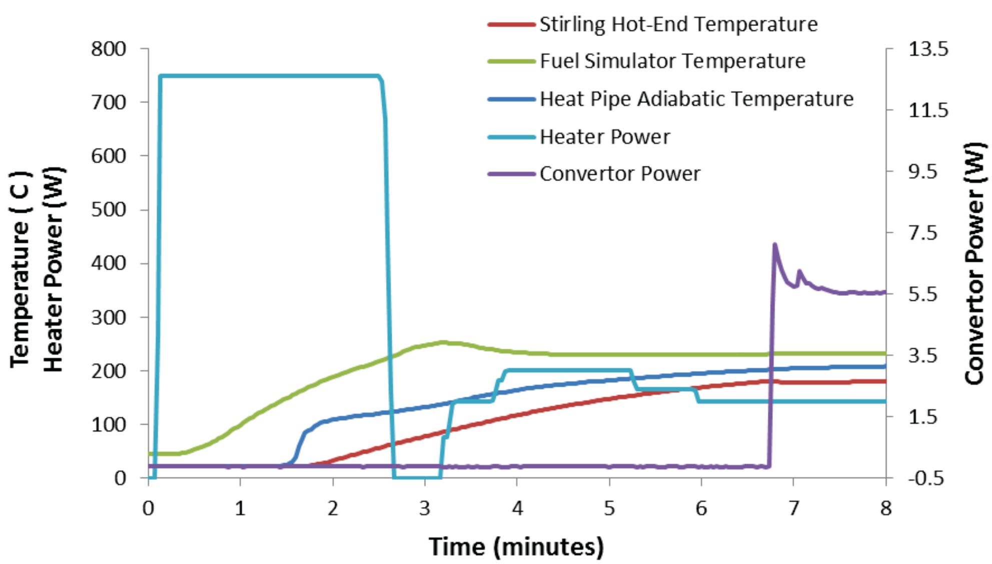

Figure 8.—Electrically heated simulation of a Flattop 30 cent insertion.

Conclusion

Small fission power systems (FPSs) are capable of providing new mission-enabling options for power-rich science missions and human exploration precursor missions in the 1- to 10-kWe range. Currently, this power level is absent from NASA's nuclear power portfolio with a low-power (<300 W) flight-qualified Radioisotope Power System (RPS) on the low end and numerous nonflight-qualified higher power (>10-kWe) FPS on the high end. Since the Systems Nuclear Auxiliary Power (SNAP) program, FPS have made significant nonnuclear technology advancements but have been unsuccessful in achieving flight status due, in part, to the flight development cost and its uncertainty. The systems are at a point where nuclear testing is essential to maturing the technology beyond its current state, both technically and programmatically. The Demonstration Using Flattop Fission (DUFF) test was a first step in addressing nuclear testing of FPS and maturing the technology beyond electrically simulated testing. In a few short months, the Glenn team performed the electrically simulated system test using a stainless steel water heat pipe and a pair of Stirling convertors, which were delivered to LANL for a successful DUFF test, proving that heat-pipe-cooled reactors are a viable option for Kilopower FPS.

References

1. Mason, Lee; Poston, David; and Qualls, Louis: System Concepts for Affordable Fission Surface Power. NASA/TM—2008-215166, 2008.
2. Mason, Lee, et al.: A Small Fission Power System for NASA Planetary Science Missions. Proceedings of Nuclear and Emerging Technologies for Space 2011, Albuquerque, NM, 2011.

Bibliography

Mason, Lee S.; Palac, Donald T.; and Harlow, Scott: Fission Surface Power Technology Development Status. NASA/TM—2010-216249, 2009.