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Recent Advances in Power Conversion and Heat Rejection Technology for Fission Surface Power

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July 2010

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Abstract

Under the Exploration Technology Development Program, the National Aeronautics and Space Administration (NASA) and the Department of Energy (DOE) are jointly developing Fission Surface Power (FSP) technology for possible use in human missions to the Moon and Mars. A preliminary reference concept was generated to guide FSP technology development. The concept consists of a liquid-metal-cooled reactor, Stirling power conversion, and water heat rejection, with Brayton power conversion as a backup option. The FSP project has begun risk reduction activities on some key components with the eventual goal of conducting an end-to-end, non-nuclear, integrated system test. Several power conversion and heat rejection hardware prototypes have been built and tested. These include multi-kilowatt Stirling and Brayton power conversion units, titanium-water heat pipes, and composite radiator panels.

Introduction

Nuclear Fission Surface Power (FSP) is a candidate power technology for human exploration missions to the Moon and Mars. FSP offers the potential to provide abundant power during the day and night with long service life. With the proper design approach, FSP can also be made to be affordable (Ref. 1).

Fission Surface Power Concept

The National Aeronautics and Space Administration (NASA) and the Department of Energy (DOE) have developed a preliminary reference FSP system concept that includes a liquid-metal-cooled, fast-neutron reactor with Stirling power conversion and water-based heat rejection (Ref. 1). The reactor uses UO_2 fuel pins in a cylindrical core with external drum reflectors. Heat is transferred to the Stirling power convertors by a pumped sodium-potassium (NaK) coolant loop. The core structure and coolant piping is constructed of stainless steel to reduce cost and development risk. The Stirling convertors generate single-phase alternating current (ac) output that is converted to direct current (dc) for user loads. Stirling waste heat is removed by a pumped water coolant loop that is coupled to a series of two-sided, vertical radiator panels. The radiator panels are composed of titanium-water heat pipes in a composite facesheet sandwich. The FSP concept is designed to produce a net power of 40 kWe with a full-power service life of 8 years. This same design could be used for missions at essentially any location (equator to poles) on the lunar or Mars surface.

The reactor core is located at the bottom of a 2 m deep excavation with an upper plug shield to protect the equipment above from direct radiation. The NaK pumps, Stirling convertors, and water pumps are mounted on a 5-m-tall truss structure that attaches to the top face of the shield. Two symmetric radiator wings are deployed via a scissor mechanism from the truss. Each radiator wing is approximately 4 m tall by 16 m long and is suspended 1 m above the lunar surface. In its stowed configuration, the FSP system is approximately 3 by 3 by 7 m tall.

The preliminary reference system schematic is shown in Figure 1. The use of redundant components and parallel fluid loops allows the system to produce partial power in the event of unexpected failures. The schematic shows the system energy balance and the anticipated temperatures, pressures, and flow rates at some of the key interfaces.

The reactor produces approximately 186 kWt with a peak fuel pin clad temperature of 860 K. It delivers heated NaK at 850 K to a pair of intermediate heat exchangers (IHX) using two fully-redundant electromagnetic primary pumps. The IHX is a NaK-to-NaK heat exchanger that provides a buffer between the primary NaK and the Stirling convertors, and a means to adjust the NaK flow rate and resulting temperature drop across the Stirling convertors separately from the reactor flow and temperature drop. Each intermediate NaK loop services two Stirling convertors at a supply temperature of 824 K. The effective Stirling hot-end temperature is 778 K. The secondary NaK loops include an intermediate pump of similar design to the primary NaK pump.

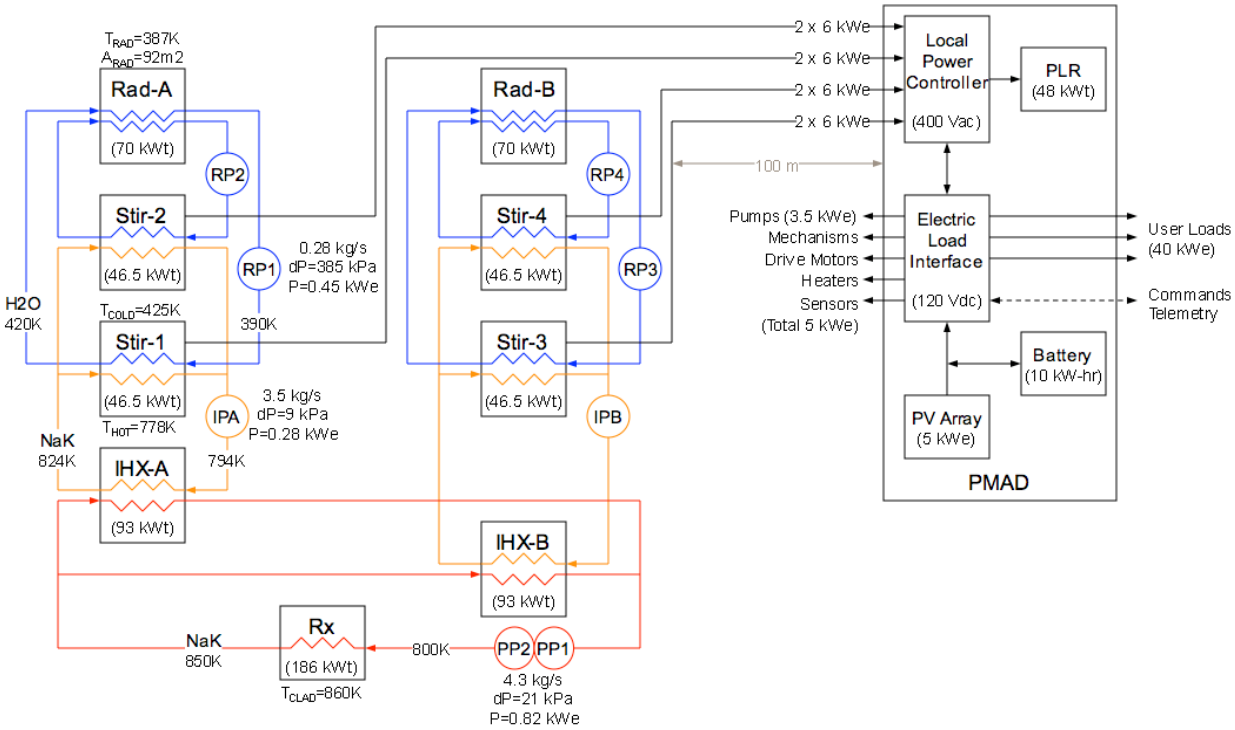

Figure 1.—FSP preliminary reference concept schematic. Reactor is Rx, intermediate heat exchanger is IHX, primary pump is PP, intermediate pump is IP, Stirling convertor is Stir, radiator is Rad, parasitic load radiator is PLR.

Each Stirling convertor is composed of two axially opposed Stirling heat engines and two linear alternators. Power conversion efficiency is estimated at 26 percent. The alternators deliver 6 kWe each at 400 Vac and 75 Hz to a Power Management and Distribution (PMAD) subsystem. A Local Power Controller (LPC), located approximately 100 m from the reactor, converts the 400 Vac to 120 Vdc for distribution to the Electrical Load Interface (ELI). The 48 kWe gross Stirling output power provides sufficient capacity to account for electrical losses (~3 kWe) and system parasitic loads (~5 kWe) and still deliver 40 kWe net for user loads. A Parasitic Load Radiator (PLR) dissipates electric power that is not required by the user loads, and allows the system to be operated at constant power thus eliminating the complexity of thermal system load following. The ELI serves as the primary power bus and system interface for commands and telemetry. A 5 kWe photovoltaic (PV) array and a 10 kW-hr battery are included with the FSP PMAD for startup and backup power.

The heat rejection subsystem is composed of four water heat transport loops and two radiator wings (two loops per wing). The radiator wing receives heated water at 420 K from the Stirling convertors and returns the water at 390 K using a mechanical radiator pump (RP), while rejecting approximately 35 kWt per loop. The resulting Stirling cold-end temperature is 425 K. The total heat load is approximately 140 kWt and the total two-sided FSP system radiator area is 184 m^2 assuming a 250 K effective sink temperature and 10 percent area margin. Each radiator wing includes 10 subpanels, each measuring approximately 2.7 m wide by 1.7 m tall.

The FSP preliminary reference concept provides a guide for technology development. The unit power levels, temperatures, pressures, flow rates, and efficiencies become notional requirements for early hardware prototypes. Some of the key component technologies to be developed under FSP include NaK pumps, heat exchangers, multi-kilowatt power conversion units, and water radiator panels (Ref. 2). One of the major goals of the FSP technology development project is to show that the components can be assembled and operated as an integrated system. To support this goal, an end-to-end integrated Technology Demonstration Unit (TDU) using full-scale components and a non-nuclear reactor simulator is planned.

The ensuing sections describe some of the current efforts in power conversion and heat rejection technology development related to FSP. Reactor-related technology development for FSP is the responsibility of DOE. NASA and DOE share responsibility for system-level technology development and demonstration (Ref. 2).

Power Conversion Technology

NASA has initiated development of several power conversion technologies to support FSP. A key objective is to develop a high-power and high-efficiency power conversion unit that is compatible with the 900 K NaK reactor heat source. NASA Glenn Research Center (GRC) is evaluating both free-piston Stirling and closed Brayton cycle options. Both technologies provide a feasible path to meet the power, efficiency, and lifetime goals for FSP (Ref. 3). Stirling appears to offer the highest efficiency and lowest system radiator area. The main challenges include convertor scaling and system integration. Brayton may provide lower development risk given the large industrial base for terrestrial microturbines, making it an attractive backup option. However, Brayton would still require development to address FSP system integration issues.

Free-Piston Stirling

There are three separate but coordinated free-piston Stirling efforts under FSP: 1) NaK Stirling demonstration test, 2) Stirling PMAD development, and 3) Stirling radiation testing. Here, the underlying goal is to improve the understanding of the various Stirling interfaces and learn how they may influence the design of a Stirling-based FSP system.

The NaK Stirling test will attempt to demonstrate Stirling convertor electrical power generation using a pumped liquid-metal heat source under thermal conditions that represent the FSP reactor. In 2007, GRC procured a pair of commercial 1-kWe Stirling convertors from Sunpower Incorporated. The convertors were tested at GRC in a dual-opposed configuration with electrical resistance heating to generate a performance map under varied hot-end temperature, cold-end temperature, and piston amplitude. The pair produced over 2 kWe at the design operating temperatures of 823 K hot-end and 323 K cold-end with thermal-to-electric efficiency of nearly 30 percent. In parallel, GRC developed a NaK shell heat exchanger design that could be readily integrated with the existing Stirling heater head (Ref. 4).

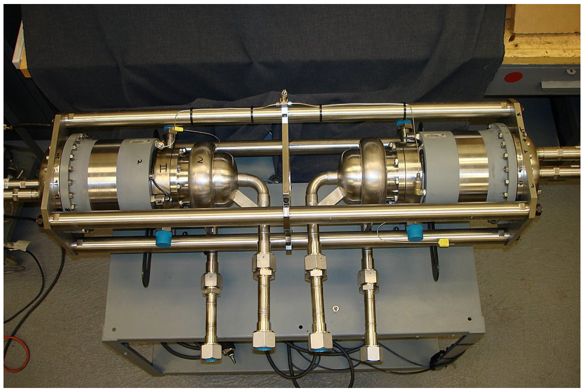

Figure 2.—NaK Stirling test assembly.

The resulting NaK Stirling test assembly is shown in Figure 2. The heat exchanger allows NaK to enter axially, flow over the Stirling heat acceptor, and discharge radially from a toroidal manifold. This assembly has been delivered to Marshall Space Flight Center (MSFC) and has been integrated with their NaK Primary Test Circuit. Both steady-state and transient testing will be performed at MSFC in 2009 with the goal of replicating the GRC performance map and demonstrating efficient heat transfer from the liquid metal to the Stirling heater head.

Figure 3.—High power linear alternator test rig.

The second FSP Stirling activity is meant to address the PMAD electrical interface using a High Power Linear Alternator Test Rig (HPLATR). The HPLATR includes two opposed 5-kWe linear alternators driven by two pressure wave generators that simulate the Stirling heat engine interface. The test rig, shown in Figure 3, was procured by GRC from the Clever Fellows Innovative Consortium. It provides an accurate representation of the Stirling alternator dynamics to allow focused PMAD technology development (Ref. 4).

Initial testing was performed in 2008 using a GRC-developed 600-W Field Effect Transistor (FET)-based module. The module processed the single-phase 300-Vac alternator output and delivered regulated 120 Vdc power. The testing successfully demonstrated ac-to-dc rectification, power factor correction, parasitic load control, and voltage regulation with overall efficiency greater than 90 percent. In 2009, a second module was developed and operated in parallel with the first at power levels up to 1500 W demonstrating channelized power sharing that could improve PMAD reliability. Future versions are planned that will use Insulated-Gate Bipolar Transistor (IGBT)-based electronics to perform the same functions and accommodate even higher power levels.

The third FSP Stirling effort is focused on the radiation tolerance of Stirling convertor materials and subcomponents. Two separate test articles have been developed by GRC. The first is an array of material coupons that will be gamma irradiated at Oak Ridge National Laboratory in the High Flux Isotope Reactor (HFIR) spent fuel pool. The materials to be tested include polymer adhesives, elastomers, tribological coatings, and wiring insulation. The coupons will be irradiated

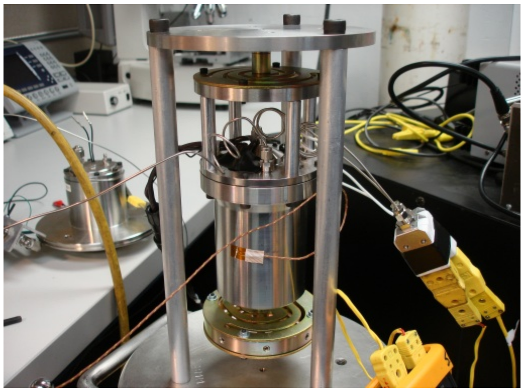

Figure 4.—Stirling alternator radiation test article.

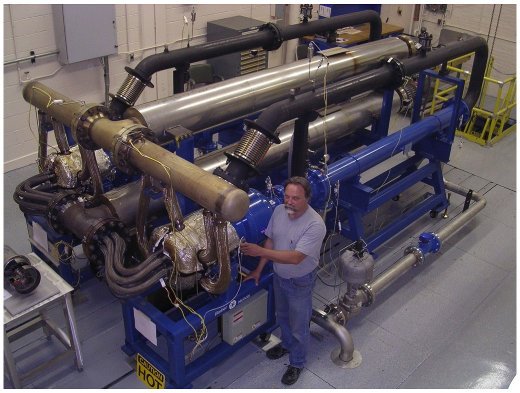

Figure 5.—Dual Brayton test loop.

under prototypic conditions in an inert gas environment with heaters for temperature control. Post-irradiation characterization of the polymer chemistry and mechanical properties will be performed to evaluate radiation-induced degradation.

A second test article, the Stirling Alternator Radiation Test Article (SARTA), will be tested at the Sandia National Laboratories Gamma Irradiation Facility (GIF). Shown in Figure 4, the SARTA is an 80-W linear alternator fabricated by Sunpower Incorporated. It will be electrically motored while being exposed to gamma irradiation from a cobalt-60 source. The alternator will be operated at representative pressure and temperature and monitored for performance changes. Testing will be conducted at gamma dose levels that are relevant to both FSP and Radioisotope Power System (RPS) mission applications. The Oak Ridge and Sandia irradiation tests are expected to begin in 2009.

Closed Brayton Cycle

There are two main Brayton-related efforts under the FSP project: 1) dual Brayton test loop and 2) direct drive gas Brayton test. These efforts are intended to demonstrate Brayton performance under various FSP-derived operating scenarios.

The dual Brayton test loop is shown in Figure 5. It includes two turbine generators that utilize a common nitrogen working fluid inventory and a shared electrical-resistance heat source. The test system was designed and built by Barber Nichols Incorporated in 2007. The turbine generators are commercial open-cycle units with annular recuperators that were modified for closed-cycle operation. Waste heat rejection is provided by two separate pumped-water cooling loops. The main test objective was to investigate interactions that may occur between redundant Brayton units in a common gas loop. A secondary objective was to validate analytical models.

The system was installed at GRC and testing was completed in 2008 (Ref. 5). The system produced up to 22 kWe at a turbine inlet of 950 K, compressor inlet of 300 K, and shaft speed of 90 000 rpm. Performance mapping was completed for a range of turbine inlet temperatures and shaft speeds. In addition, testing was conducted to evaluate the performance impacts of operating at unequal shaft speeds and the operational differences for staggered and simultaneous turbine startup. Results showed that imbalanced shaft speed operation led to undesirable working gas redistribution from the higher-speed unit to the lower-speed unit and system performance penalties. For the same heater input power, staggered turbine startup required less total motoring energy than the simultaneous startup, but took longer to reach system break-even power.

Figure 6.—Direct drive gas Brayton test system.

The second Brayton effort is a joint activity with MSFC to test a space-configured 2-kWe Brayton unit with a direct drive gas (DDG) reactor simulator. Figure 6 shows the test system installed at GRC's Vacuum Facility #6. The GRC Brayton unit was assembled in the 1990s for the Solar Dynamic Flight Demonstrator Project. The MSFC reactor simulator includes an array of pin-type electrical-resistance heating elements arranged in a bundle similar to a reactor core. The gas inlet and outlet ducts are coupled to the Brayton unit as they would be in a direct gas-cooled reactor system. The working fluid is a mixture of helium and xenon.

Testing was completed in 2009 (Ref. 6). The main objective was to demonstrate stable and controllable operation of the integrated system. Test variables included heater power and shaft speed. Nominal operating conditions were 850 K turbine inlet, 285 K compressor inlet, and 46 000 rpm shaft speed. A portion of the testing was dedicated to reactivity control simulation. Two types of test series were performed. In the first series, the reactivity feedback controller simulated the response to a step change in Brayton shaft speed. Testing showed that shaft speed perturbations resulted in stable and predictable heater response. In the second series, a control drum maneuver was replicated by commanding the reactivity controller to simulate insertion of positive or negative reactivity. A simulated negative reactivity insertion produced a stable but lower heater exit temperature and a corresponding reduction in Brayton output power as expected.

Full-Scale Power Conversion Unit

These individual Stirling and Brayton hardware activities are "pathfinders" toward the development of a full-scale 12-kWe Power Conversion Unit (PCU) for the FSP Technology Demonstration Unit (TDU). In 2008, GRC initiated a procurement and awarded parallel contracts to Sunpower and Barber Nichols. Sunpower is developing a free-piston Stirling design employing two opposed 6-kWe engines. Barber Nichols is developing a single 12-kWe recuperated Brayton unit. Both designs include the requisite heat exchangers to operate with an 850 K NaK heat source and a 375 K water cooling supply, representative of the anticipated FSP reactor and radiator interfaces. Both designs also include the appropriate PMAD to convert the ac output power and deliver 120 Vdc to a bus. A single contract down-select for fabrication and test is expected in 2010. Once exercised, that contract would deliver a 12-kWe unit for the TDU test in the 2012 timeframe.

Heat Rejection Technology

FSP heat rejection technology development is focused on titanium-water heat pipes and composite radiators. The objective is to develop efficient and reliable heat rejection systems that are compatible with the power conversion cold-end temperature (approximately 400 K) and heat load (up to 140 kWt). The current FSP heat rejection concept utilizes a pumped water cooling loop coupled to radiator panels with embedded heat pipes.

Heat Pipes

Heat pipes provide an efficient method for spreading heat and also reducing the potential for single-point failure by segmenting the radiator surface. GRC began titanium-water (Ti-H_2O) heat pipe development during the Jupiter Icy Moons Orbiter (JIMO) Program to address the need for 500 K radiators. Ti-H_2O heat pipes are well suited for operating temperatures between 350 and 500 K. This temperature range has very limited heat pipe fluid choices.

Figure 7.—Titanium-water heat pipe life test.

An initial step in developing high-temperature water heat pipes was the evaluation of performance, life, and manufacturing capability (Ref. 7). To that end, GRC established a heat pipe lab and populated it with nine Ti-H_2O heat pipes as shown in Figure 7. The heat pipes were provided by three different vendors—Advanced Cooling Technologies (ACT), Swales, and Thermacore—each utilizing a different wick structure. All nine heat pipes share common design features of 500 K operating temperature, 25-cm evaporator, 90-cm condenser, 1.27-cm outside diameter, and CP–2 titanium envelope. After initial testing verified performance expectations, the heat pipes were placed on life-test in December 2006 and have accumulated over 2 years of operation at 500 K with minimal performance change observed.

Another key issue for implementing heat pipe radiators with the FSP system is the efficient transfer of waste heat from the pumped water loop to the heat pipe evaporators. The temperature drop from the pumped water loop to the radiator has a significant impact on the radiator area and mass. GRC built a test rig to evaluate various heat exchanger options. In 2008, testing was completed on a myriad of heat exchanger geometries based on an immersed evaporator configuration (convectively coupled). Testing showed that heat pipes with abraded evaporator surface outperformed those that were plain or enhanced with fins. In 2009, the test rig will be modified for testing conductively coupled heat pipe evaporators. The conductive interface places the evaporator on the outside of the coolant channel. This approach results in a larger temperature drop, but much less cooling loop pressure drop resulting in lower pumping power.

Radiator Panels

With respect to radiator panels, GRC has two ongoing technology development activities: 1) subscale Radiator Demonstration Units (RDU), and 2) full-scale Second Generation RDU.

These main activities are complemented by a number of Small Business Innovative Research (SBIR) efforts addressing FSP radiator concepts. Composite panels are favored in the FSP application due to their low mass and high heat transfer effectiveness. The underlying objectives for panel development are to verify fabrication methods and demonstrate performance under realistic conditions.

The subscale RDU activity started with a GRC contract to ACT for the design and fabrication of three different 0.5-m-wide by 1-m-tall radiator assemblies. Each assembly contains three 1.9-cm-diameter Ti-H_2O heat pipes sandwiched between two Polymer Matrix Composite (PMC) facesheets. The heat pipe condensers are encased in individual graphite thermal saddles to allow effective bonding to the facesheets, and aluminum-honeycomb is added as a filler material between heat pipes. The facesheets use K13D2U graphite fibers and three different resin binders, the main discriminator among the panels.

Initial thermal-vacuum testing of the RDUs completed at GRC in 2007 showed the panels to exhibit similar performance and reject about 1 kWt each (Ref. 8). In 2008, the vacuum facility was outfitted with quartz lamps to simulate lunar insolation. The RDU panels were subjected to a cold-soak startup with frozen heat pipes similar to what would be expected after delivery and setup of the FSP system at the Moon. Test results revealed that the heat pipes could be reliably started with a combination of simulated sunlight and evaporator heat input as envisioned for the FSP application (Ref. 9). In 2009, two of the RDU panels will be coated with a high-emissivity, low-absorptivity thermal coating and some of the performance tests will be repeated. A photo of an RDU panel coated with white emissive paint is shown in Figure 8.

The Second Generation RDU, shown in Figure 9, is a full-scale radiator assembly measuring 2.7-m-wide by 1.7-m-tall. It is similar in size to one of 10 subpanels that would be needed in a FSP radiator wing. The test hardware was designed and fabricated by Material Innovations Incorporated. The panel assembly builds on lessons learned from the initial RDUs, including construction materials and manufacturing techniques. A major addition is a titanium manifold that transfers heat from a pumped water loop to the heat pipes using individual immersion heat exchangers connected in series. The heat exchangers are configured for annular water flow over the heat pipe evaporators with consideration given to minimizing the water pressure drop.

The Second Generation RDU has 16 Ti-H_2O heat pipes. There are two independent water flow channels each contacting eight heat pipes in an alternating arrangement. The heat pipes have a 25-cm-long evaporator and a 170-cm-long condenser. Like the previous RDUs, the heat pipe condensers are encased in graphite saddles that are bonded to PMC facesheets. A composite c-channel edge surrounds the panel for stiffness in lieu of the honeycomb filler. The panel is designed to reject 6 kWt with a water supply temperature of 400 K and total flow rate of 0.5 kg/s. Thermal-vacuum testing of the Second Generation RDU will begin at GRC's Vacuum Facility #6 in 2009. The Second Generation RDU is a prototype of a future Heat Rejection System (HRS) radiator panel that would be used in the system-level TDU test.

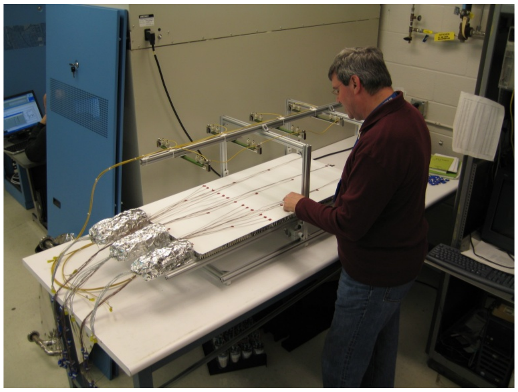

Figure 8.—Radiator demonstration unit.

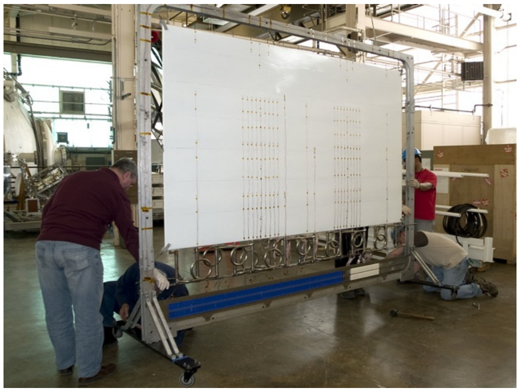

Figure 9.—Second generation RDU.

Technology Demonstration Unit

The basic TDU test plan is to subject the system to realistic operating conditions and gather data to better understand performance sensitivity, control stability, and response characteristics. The TDU reactor simulator is planned to include a core simulator with electrical pin-heaters and a NaK heat transport system, representative of the FSP concept. The reactor simulator would be coupled to the 12 kWe Power Conversion Unit (PCU) discussed earlier. The TDU HRS would reject the PCU waste heat using a pumped-water cooling loop and multiple 2.7-m-wide by 1.7-m-tall radiator panels connected in a series. The Stirling-based PCU is estimated to require six panels while the Brayton-based PCU would require approximately eight panels. Under the current plan, the TDU HRS would be implemented after an initial test phase that includes a DOE/MSFC-developed reactor simulator with the full-scale PCU and an external Facility Cooling System (FCS). The HRS procurement is expected to begin in 2010 or 2011. A notional test layout for the TDU with the six-panel HRS is shown in Figure 10.

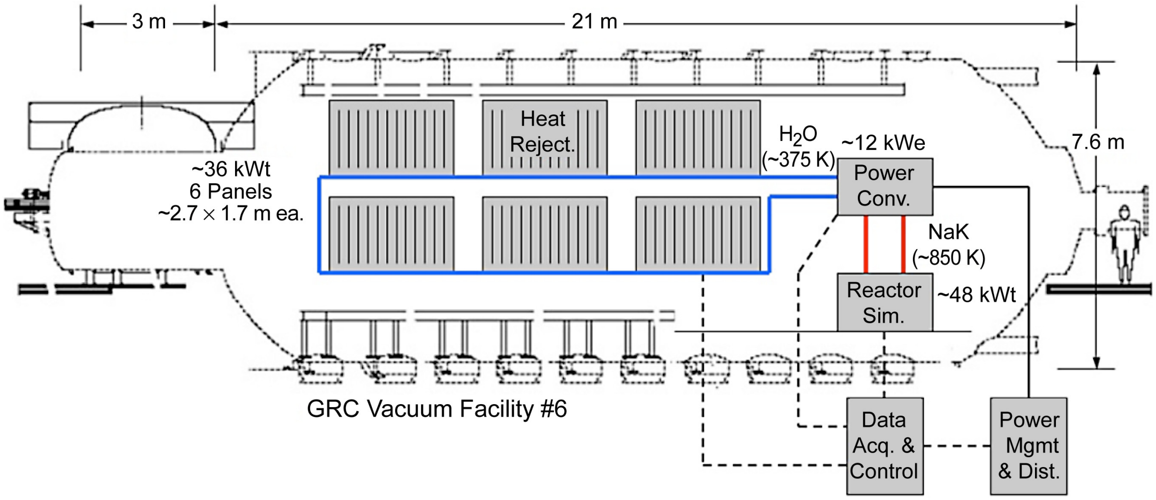

Figure 10.—Technology demonstration unit test layout.

Conclusions

Fission Surface Power (FSP) systems are currently being studied by NASA as an option for future human exploration missions to the Moon and Mars. NASA and the Department of Energy have partnered to help mature FSP technology so that it may be considered for future flight development. The FSP team has generated a preliminary FSP reference concept to help guide technology development. A portion of the FSP project is focused on designing, building, and testing some of the key FSP components in order to demonstrate technology readiness. This paper discusses some of the progress being made in power conversion and heat rejection technology. Under power conversion technology, multi-kilowatt Stirling and Brayton "pathfinder" tests are underway to improve our understanding of system integration issues. In heat rejection technology, the focus has been on titanium-water heat pipes and composite radiators with the goal of developing sound fabrication methods and demonstrating performance under realistic operating conditions. Ultimately, the FSP project plans to assemble and test an end-to-end system-level Technology Demonstration Unit (TDU) using full-scale components and a non-nuclear reactor simulator.

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13. SUPPLEMENTARY NOTES

14. ABSTRACT

Under the Exploration Technology Development Program, the National Aeronautics and Space Administration (NASA) and the Department of Energy (DOE) are jointly developing Fission Surface Power (FSP) technology for possible use in human missions to the Moon and Mars. A preliminary reference concept was generated to guide FSP technology development. The concept consists of a liquid-metal-cooled reactor, Stirling power conversion, and water heat rejection, with Brayton power conversion as a backup option. The FSP project has begun risk reduction activities on some key components with the eventual goal of conducting an end-to-end, non-nuclear, integrated system test. Several power conversion and heat rejection hardware prototypes have been built and tested. These include multi-kilowatt Stirling and Brayton power conversion units, titanium-water heat pipes, and composite radiator panels.

15. SUBJECT TERMS
Fission surface power; Liquid-metal cooled reactor; Power conversion technology

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