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Fission Surface Power Technology Development Update

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Abstract

Power is a critical consideration in planning exploration of the surfaces of the Moon, Mars, and places beyond. Nuclear power is an important option, especially for locations in the solar system where sunlight is limited or environmental conditions are challenging (e.g., extreme cold, dust storms). NASA and the Department of Energy are maintaining the option for fission surface power for the Moon and Mars by developing and demonstrating technology for a fission surface power system.

The Fission Surface Power Systems project has focused on subscale component and subsystem demonstrations to address the feasibility of a low-risk, low-cost approach to space nuclear power for surface missions. Laboratory demonstrations of the liquid metal pump, reactor control drum drive, power conversion, heat rejection, and power management and distribution technologies have validated that the fundamental characteristics and performance of these components and subsystems are consistent with a Fission Surface Power preliminary reference concept. In addition, subscale versions of a non-nuclear reactor simulator, using electric resistance heating in place of the reactor fuel, have been built and operated with liquid metal sodium-potassium and helium/xenon gas heat transfer loops, demonstrating the viability of establishing system-level performance and characteristics of fission surface power technologies without requiring a nuclear reactor. While some component and subsystem testing will continue through 2011 and beyond, the results to date provide sufficient confidence to proceed with system level technology readiness demonstration.

To demonstrate the system level readiness of fission surface power in an operationally relevant environment (the primary goal of the Fission Surface Power Systems project), a full scale, 1/4 power Technology Demonstration Unit (TDU) is under development. The TDU will consist of a non-nuclear reactor simulator, a sodium-potassium heat transfer loop, a power conversion unit with electrical controls, and a heat rejection system with a multi-panel radiator assembly. Testing is planned at the Glenn Research Center Vacuum Facility 6 starting in 2012, with vacuum and liquid-nitrogen cold walls to provide simulation of operationally relevant environments. A nominal two-year test campaign is planned including a Phase 1 reactor simulator and power conversion test followed by a Phase 2 integrated system test with radiator panel heat rejection. The testing is expected to demonstrate the readiness and availability of fission surface power as a viable power system option for NASA's exploration needs. In addition to surface power, technology development work within this project is also directly applicable to in-space fission power and propulsion systems.

Nomenclature

DAS	Data Acquisition System
DOE	Department of Energy
ELS	Electric Load Simulator
FCS	Facility Cooling System
FSP	Fission Surface Power
FSPS	Fission Surface Power System
GRC	Glenn Research Center
HR	Heat Rejection
HRS	Heat Rejection System
HX	Heat Exchanger
I&C	Instrumentation and Controls
IHX	Intermediate Heat Exchanger
INL	Idaho National Laboratory
IP	Intermediate Pump
IVA	Intermediate Volume Accumulator
kg	kilogram
kW	kilowatts
kWe	kilowatts (electric)
kWt	kilowatts (thermal)
LaNL	Los Alamos National Laboratory
LN_2	Liquid Nitrogen
m	meter
MSFC	Marshall Space Flight Center
NaK	Sodium/Potassium mixture
NASA	National Aeronautics and Space Administration
ORNL	Oak Ridge National Laboratory
PC	Power Conversion
PCU	Power Conversion Unit
PMAD	Power Management and Distribution
PP	Primary Pump
PVA	Primary Volume Accumulator
RDU	Radiator Demonstration Unit
rem	Roentgen Equivalent Man
RP	Radiator Pump
RVA	Radiator Volume Accumulator
Rx	Reactor
Rx Sim	Reactor Simulator
SNL	Sandia National Laboratory
TDU	Technology Demonstration Unit
TRL	Technology Readiness Level
yr	year

Introduction

The Fission Surface Power Systems (FSPS) project was initiated in 2007 to develop system level technology that provides the option for fission surface power for the U.S. Space Exploration Policy. The project key goals are to:

- Develop an FSPS concept that meets surface power requirements at reasonable cost with added benefits over competitive options, and that is safe during all mission phases
- Establish a hardware-based technical foundation for FSPS design concepts and reduce risk
- Reduce the cost uncertainties for FSPS and establish greater credibility for flight system cost estimates
- Generate the key gate products that would allow Agency decision-makers to consider FSPS as a viable option to proceed to flight development

Key to accomplishment of these goals is demonstration of fission surface power technology at the system level in an operationally relevant environment, defined by NASA as Technology Readiness Level 6 (Ref. 1).

Initiation of the FSPS project was contingent on successful demonstration that a fission surface power system could be developed affordably. In 2007, NASA and DOE performed a rigorous assessment of fission surface power cost elements, and approaches to minimize them while meeting expected mission requirements (Ref. 2). Key principles of an affordable approach were found to include: (1) selection of component performance goals well within envelopes of existing experience and demonstrated capabilities where possible; (2) avoidance of component technology development (especially in the reactor) to the extent practical; and (3) selection of component and system solutions with lower risk and complexity, even at the expense of higher mass. The resultant themes of simplicity, robustness, and conservatism were key to an affordable approach to fission surface power (Ref. 3). These findings were applied to development of a preliminary FSP concept, which was then used to determine the minimum set of component technologies that would require development prior to initiation of a system-level FSP technology demonstration.

From 2008 to 2010, the FSPS project emphasized concept definition and "Pathfinder" technology development. Concept definition refined the trade studies and development of a reference concept to guide technology development and demonstration. The FSPS reference concept for the lunar surface (with applicability to Mars) is shown in Figure 1. The FSP system is defined by four major elements: (1) Reactor Module, (2) Power Conversion Module, (3) Heat Rejection Module, and (4) Power Management and Distribution (PMAD) Module. The reactor generates the nuclear heat through fission. Thermal power is transferred from the reactor to the power conversion and waste heat is transferred from the power conversion to the heat rejection. Electrical power generated by the power conversion is processed through the PMAD to the user loads. The PMAD supplies electric power for power conversion startup and for auxiliary loads associated with the reactor and heat rejection. The PMAD also provides the primary communications link for command, telemetry, and health monitoring of the FSP system. The reactor core is located at the bottom of an approximate 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. More information on the FSP reference concept can be found in NASA/TM—2010-216772 (Ref. 4).

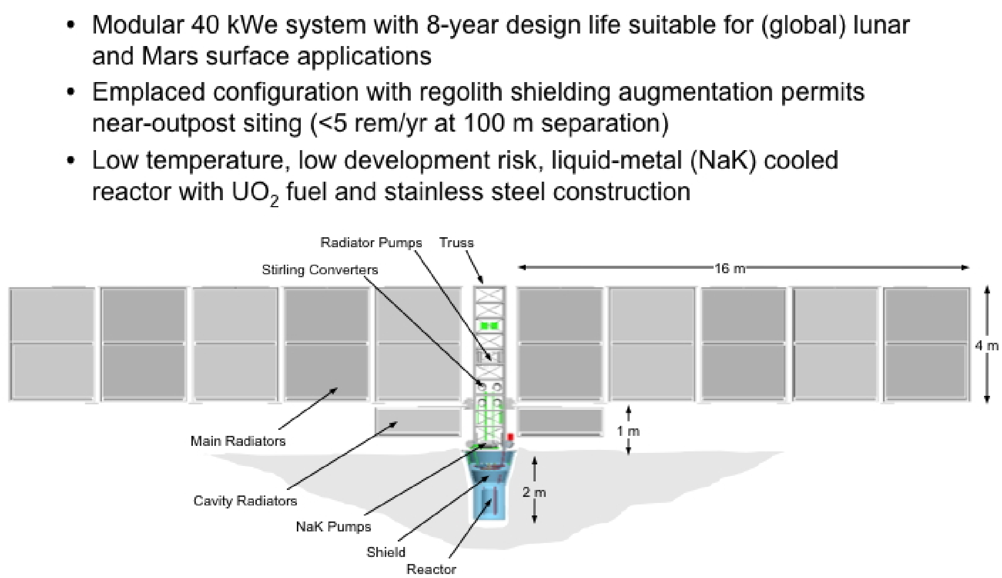

Figure 1.—FSP reference concept.

FSP “Pathfinder” technology development included component research as well as component and subsystem demonstrations needed prior to designing, fabricating, and testing of a full-scale system technology demonstration. Areas of Pathfinder technology development and demonstration included reactor simulation (including an electrical heat source and the liquid metal heat transfer loops), liquid metal electromagnetic pumps, power conversion units, heat rejection radiators, and integrated reactor simulator/power conversion tests. Prior publications provide more information on this phase of FSP technology development (Refs. 5 to 8). Successful completion of a majority of the milestones in this phase of testing has provided sufficient confidence to proceed with the design of the full scale system level Technology Demonstration Unit.

FSP Technology Demonstration Unit Overview

The TDU is an end-to-end system test of a reactor simulator (Rx Sim), Power Conversion Unit (PCU), and Heat Rejection System (HRS) in thermal-vacuum as shown in Figure 2. The TDU is intended to demonstrate the major elements of a notional Fission Surface Power System (FSPS) using a non-nuclear heat source. The Rx Sim includes an electrical resistance heat source and two liquid metal (sodium potassium or NaK) heat transport loops. It simulates the reactor thermal interface and expected dynamic response. The PCU generates electric power utilizing the heated liquid metal and rejects waste heat to the HRS. The HRS includes a pumped water cooling loop coupled to vertical radiator panels suspended in the thermal-vacuum facility. An intermediate test configuration, prior to the installation of the HRS, includes a Facility Cooling System (FCS) to reject PCU waste heat utilizing an external heat exchanger. The data acquisition and control, and power management and distribution equipment would be external to the vacuum facility and provide prototypic functionality using commercially available, rack-mounted components.

TDU Objectives

The primary objective of the TDU is to demonstrate the technology readiness of the integrated FSP system using a non-nuclear heat source. Upon completion of the testing, FSP technology will achieve Technology Readiness Level 6 (system demonstration in an operational and relevant environment). This is based on the use of high-fidelity hardware and prototypic software tested under realistic conditions and correlated with analytical predictions. The nuclear aspects of the system will not be demonstrated in the

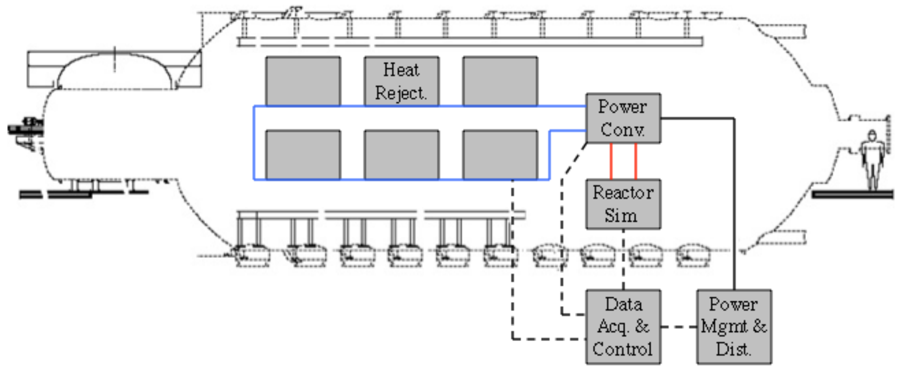

Figure 2.—TDU test layout.

TDU, but those are considered fairly mature based on terrestrial reactor technology. Some nuclear-related technology development will be conducted in parallel with the TDU including reflector control drive testing, shield development, and material/component irradiation testing. If FSP technology were to be selected for an exploration power application, the FSP reactor would be developed and qualified as part of a subsequent mission flight development program. Further, the TDU will not demonstrate system lifetime or launch/landing survivability, since both of those items are better addressed in a flight program when the requirements are better defined and the design is more mature.

Some of the major challenges that the TDU testing will address are the liquid metal heat transport, electric power generation, and waste heat removal. The basic test plan is to subject the system to realistic operating conditions and gather data to better understand performance sensitivity, control stability, and response characteristics. A more comprehensive set of TDU objectives is enumerated in Table 1.

TDU Block Diagram

The TDU Block Diagram is shown in Figure 3. The Rx Sim includes a Core Simulator, a primary NaK heat transport loop, a NaK-to-NaK intermediate heat exchanger (IHX), and an intermediate NaK heat transport loop. The Core Simulator includes a series of pin-type electrical resistance heating elements arranged to represent the reactor fuel pin bundle. The two NaK loops each include an electromagnetic pump and volume accumulator. A NaK Fill & Drain system provides the capability for charging and discharging the two NaK loops. A Rx Sim Controller collects data, relays command signals, and supplies electric power for the Rx Sim components. The Rx Sim controller provides the means to control core simulator NaK outlet temperature and NaK flow rate in both loops. It also would include the software to simulate the expected temperature-reactivity feedback dynamics of a FSPS reactor.

The PCU consists of the Power Converter, PCU Controller, and Gas Fill & Drain system. The Power Converter includes a NaK-to-gas heat exchanger for heat input and a gas-to-water heat exchanger for waste heat removal. Two power conversion technologies are currently under consideration: Brayton and Stirling. The Brayton option would utilize a single heat engine with a rotating turbine-alternator-compressor and gas-to-gas recuperator. The Stirling option would utilize two free-piston heat engines with integral regenerators and linear alternators in an opposed configuration to balance motion. The Gas Fill & Drain system provides the capability for charging and discharging the converter’s working fluid, either CO_2 for the Brayton option or helium for the Stirling option. The PCU Controller collects data, relays command signals, and supplies startup electric power for the converter. It also processes the electric output of the converter providing AC-DC conversion, parasitic load control, and voltage regulation.

TABLE 1.—TDU OBJECTIVES

1. Reduce FSP Development Risk	• Build non-nuclear components that are representative of possible flight components to provide a hardware basis for the initial flight design
2. Verify System-Level Performance in Realistic Environment	• Achieve TRL6 by operating the integrated (non-nuclear) system in thermal-vacuum • Measure power output of the integrated system and compare to predictions • Use measured parameters to determine system energy balance and efficiency and compare to predictions • Demonstrate the functionality of the integrated system over a wide range of conditions without failure
3. Characterize Component Performance in a System Context	• Measure component interface parameters including temperature, pressure, and flow rate and compare to predictions • Demonstrate the functionality of the components over a wide range of conditions without failure
4. Obtain Operational Data under Steady-State and Transient Conditions	• Instrument the system to permit measurement of all pertinent operating parameters • Collect steady-state data at various operating set-points (e.g., full power, part power, low reactor temp, low/high radiator temp, etc.) • Collect transient data during startup, set-point changes, environmental changes, simulated faults, shutdown, and restart
5. Develop System Control Methods	• Demonstrate electrical controls that isolate the thermal system from electrical transients (e.g., user load fluctuations, over-load, short circuit) • Demonstrate that the system can respond to environmental changes (e.g., lunar day/night cycle) and simulated faults (e.g., loss of reactor flow, loss of radiator flow, power conversion unit shutdown) without failure • Perform tests to optimize system response to operating changes and implement automated algorithms that perform those functions
6. Benchmark Analytical Codes	• Generate pre-test performance predictions for planned test sequences and compare with measurements • Modify codes as necessary to accurately represent test conditions • Use test-validated codes to assist in flight system concept development
7. Gain System Operations Experience for the NASA/DOE Team	• Establish a team of personnel across NASA, DOE, and industry that is familiar with the operation of the integrated (non-nuclear) system and its components • Collect 100’s of hours of system operations data
8. Expand Industrial Infrastructure for Component Design and Fabrication	• Provide opportunities for industry to design and build FSP components including power conversion units, heat exchangers, radiators, pumps, accumulators, piping, insulation, sensors, and controllers
9. Obtain As-Built Mass and Cost Data	• Document the mass and cost of the various components to support future flight system estimates • Document the cost of system integration and test to support future test cost estimates
10. Provide Tangible and Measurable Technology Milestone	• Complete an activity that clearly demonstrates the technical readiness of FSP to proceed into flight development

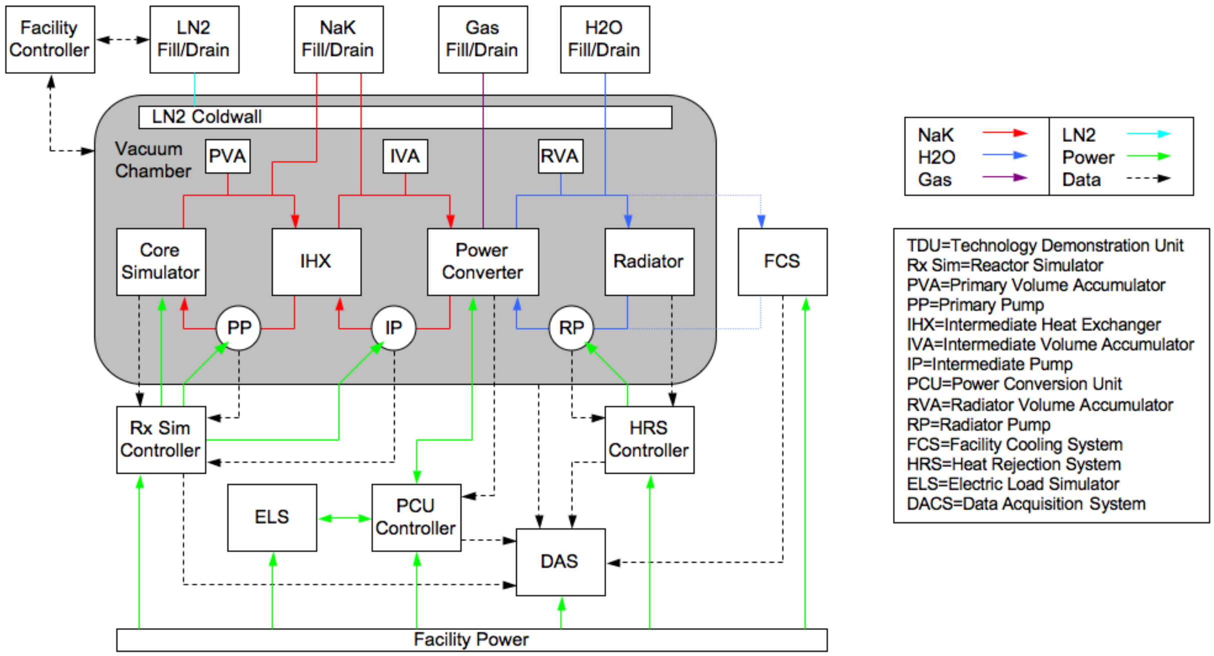

Figure 3.—TDU block diagram.

The HRS consists of a radiator, pumped water heat transport loop, and HRS controller. The radiators are two-sided vertical panels with embedded titanium-water heat pipes. The radiator panels include a manifold with heat exchangers to transfer heat from the pumped water loop to the heat pipe evaporators. The heat pipes transfer the heat to the condenser section and then to the panel surface where it is radiated to the walls of the thermal-vacuum chamber. The water heat transport loop provides direct cooling of the Power Converter and includes a pump and volume accumulator. The HRS controller collects data, relays command signals, controls the pump flow rate, and supplies pump power.

Prior to the HRS installation, the FCS will provide waste heat removal for the Power Converter. The FCS will also utilize water coolant and will include all of the equipment to circulate the water and remove the waste heat using a commercial heat exchanger located outside the vacuum chamber. The H_2O Fill & Drain provides the capability for charging and discharging the water loop with either the HRS or FCS-based test configuration.

The balance of the test system is associated with the facility. The facility includes the Vacuum Chamber (Vacuum Facility #6), Liquid Nitrogen (LN_2) cold wall, LN_2 Fill & Drain system, Facility Controller, Facility Power, Electric Load Simulator (ELS), and Data Acquisition System (DAS). The Vacuum Chamber is a 21 m long by 7.6 m diameter horizontal cylindrical tank with cryogenic pumps. The LN_2 cold wall extends along the center 16.2 m of the chamber length and covers all but the bottom 60° of the circumference as shown in Figure 3. The LN_2 sections would operate at liquid nitrogen temperature (77 K) while the bottom and end-cap sections would be at ambient temperature (300 K). The LN_2 Fill & Drain provides the capability for charging and discharging the cold wall. The Facility Controller provides the operations interface for the Vacuum Chamber and LN_2 cold wall. The Facility Power supplies electric power for the TDU components with availability of 110, 220, 440, and 208 V service.

The ELS receives the regulated electric power from the PCU controller and provides a user interface for switching typical loads. The ELS also provides the power bus for starting the Power Converter. The DAS provides a central data collection node for the Rx Sim, PCU, and HRS Controllers as well as facility instrumentation. A communication network is envisioned that will permit the transfer of data between the various controllers and the DAS.

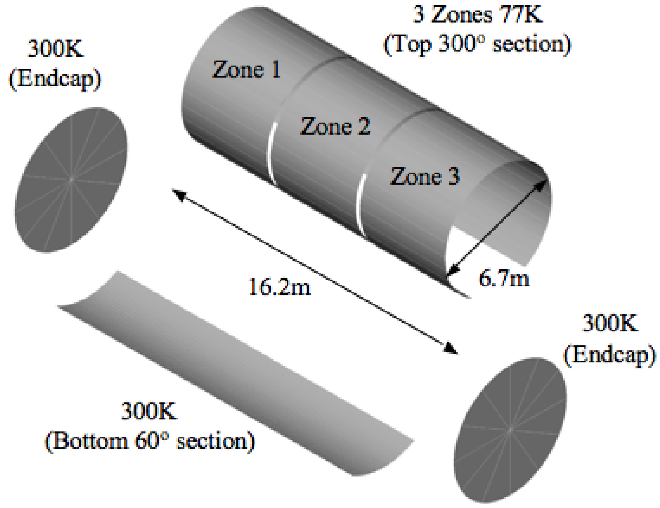

Figure 4.—LN_2 cold wall arrangement.

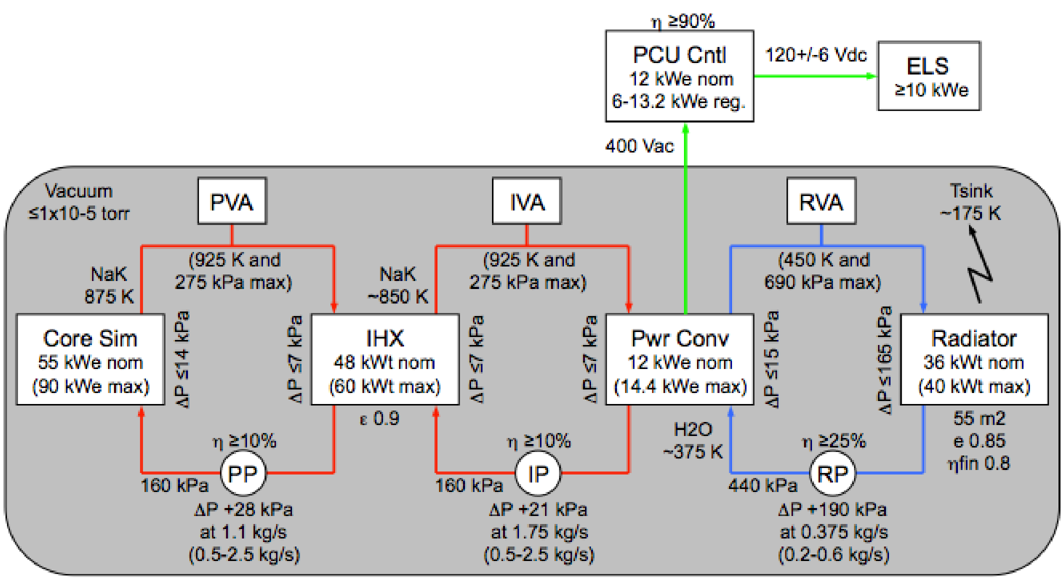

Figure 5.—Key performance requirements.

A summary of the key TDU performance requirements with a Stirling PCU is shown in Figure 5. The Core Simulator nominal input power is 55 kWe producing a primary NaK outlet temperature of 875 K. The IHX transfers about 48 kWt to the intermediate loop with a NaK outlet temperature of 850 K. The Stirling PCU generates 12 kWe and transfers 36 kWt to the water cooling loop with an inlet temperature of 375 K. A 55 m^2 radiator with an outlet temperature of 375 K rejects the 36 kWt to the thermal-vacuum chamber cold sink of 175 K. The 400 Vac Stirling alternator output power is processed in an electrical controller that delivers 10 kWe to the ELS at 120 Vdc. The TDU system is intended to function over a wide range of operating points and transient conditions, representative of what could occur in a lunar or Mars surface mission. The primary test variables are core simulator power, primary and intermediate NaK flow rate, Stirling piston amplitude, water flow rate, sink temperature, and user load demand.

Preliminary TDU Test Planning

The TDU test program will be defined in detail at the Test Readiness Review prior to starting the initial test phase. A preliminary test plan has been developed to guide the design process and identify operational expectations for the test hardware. The overall test philosophy is to start simple and introduce greater complexity as operations experience is gained. The testing is expected to occur in two major phases: Reactor-Power Conversion Test and Integrated System Test. The Reactor-Power Conversion Test will include the Rx Sim and PCU with the external FCS providing waste heat rejection. The Integrated System Test will replace the FCS with the HRS including the internal radiator panels. Within each phase, there will be a number of test sequences, and each sequence will have a specific test objective. A test sequence will produce a number of steady-state test points and answer the key technical issues related to the test objective. The basic test plan is to subject the system to realistic operating conditions and gather data to better understand FSP system performance sensitivity, control stability, and response characteristics.

A pre-test analytical simulation will be generated to guide the test sequence and assure that the system is operated within prescribed limits. Test sequences will be conducted on a 24 hour per day operation schedule and could last from several days to over a week in duration. At the conclusion of a test sequence, the system will be shutdown and the test team would thoroughly review the data. The test data will be used to update the analytical model and provide improved accuracy for the next test sequence.

FSP Technology Demonstration Unit Status and Outlook

The TDU System Requirements Review was held in December 2008 at which time a draft TDU System Specification was generated to guide the design process. In February 2009, the TDU Preliminary Design Review formally kicked off the development of the FSP TDU. An independent review panel evaluated the readiness of the TDU system and component designs to proceed to final design, consistent with the TDU objectives listed in Table 1 and the requirements shown in Figure 5. In May 2009, an independent panel reviewed the final designs and fabrication readiness of the main TDU components: Core Simulator, NaK Pump, NaK Accumulator, Intermediate Heat Exchanger, and Power Conversion Unit. An additional product of the May review was a final management-approved TDU System Specification. The design formulation process culminated with the TDU System Final Design Review in October 2009 where a third independent panel evaluated the system design readiness and recommended that the project proceed. All major components of the TDU are now in development, and test facility modifications are in process. One exception is the TDU intermediate heat exchanger, shown in Figure 6, which was completed by ORNL and delivered to MSFC in April 2010.

Figure 6.—TDU intermediate heat exchanger.

Another major milestone in TDU development was the initiation of the PCU fabrication contract. Sunpower, Incorporated was selected to fabricate and test a 12 kWe PCU consisting of two 6 kWe Stirling engines, and began work in March 2010. Figure 7 shows the design for the thermodynamically-coupled pair of engines with interfaces for the liquid metal heat input from the reactor simulator (central pipes and manifold), and the pumped water waste heat rejection (two outer pipe sets and manifolds). The PCU is expected to have a thermal-to-electric efficiency of approximately 27 percent with a NaK inlet temperature of 850 K and a water inlet temperature of 375 K. A prototype with two electrically-heated 1 kWe Stirling engines that share a common expansion space will be tested at GRC in 2010.

Work is also proceeding on the core simulator. MSFC has completed the design and initial testing of the graphite heating elements that will be used to represent the reactor fuel pins. There are 36 heating elements in the TDU core simulator, each measuring about 1.5 cm diameter by 43 cm long. The graphite heaters are contained in a stainless steel sleeve that is in direct contact with the flowing NaK. Testing has confirmed that the heater elements can be operated up to 2.5 kWe each, indicating a total core simulator power capability of 90 kWe. This provides margin relative to the 55 kWe required for nominal system performance and operational flexibility for off-design and transient testing. A 7-tube heater bundle test apparatus, shown in Figure 8, was fabricated at MSFC to demonstrate multi-heater performance in a TDU-like configuration. Testing was performed in 2010 over a range of power levels, temperatures, and NaK flow rates representative of the requirements imposed on the TDU core simulator.

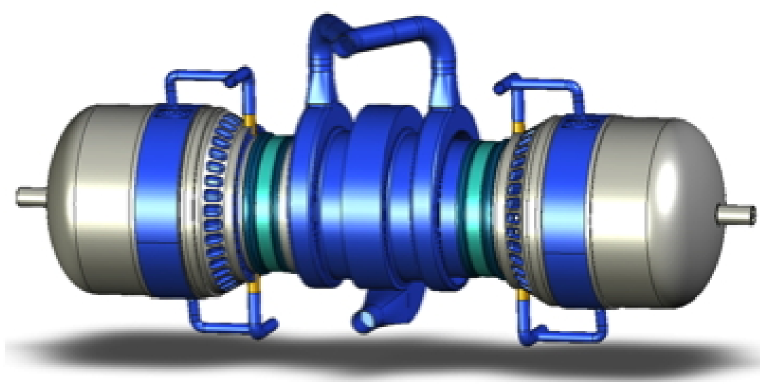

Figure 7.—12 kWe dual-opposed PCU.

Figure 8.—7-tube heater bundle test.

Conclusions

The TDU is a crucial step in demonstrating the readiness of fission technology for future space applications. The FSPS Project has completed concept definition studies and Pathfinder tests to help guide the TDU development effort. The TDU design process has included a System Requirements Review, Preliminary Design Review, and System Final Design Review with multiple independent review panels providing a confirmation of the approach and content. The various hardware elements are now in the fabrication stage with checkout testing slated to begin in 2011. The TDU test will occur in two phases. During the first phase, the reactor simulator and power conversion unit will be assembled and tested in thermal-vacuum. An external facility cooling system will provide the PCU heat rejection using a commercial water-to-air heat exchanger. Phase 1 hardware checkout testing is scheduled to begin in 2012. Also during the first phase, the heat rejection system design and fabrication will be completed. After the phase 1 testing, the HRS will be integrated into the TDU. Phase 2 testing of the fully integrated system is scheduled for completion during 2014, establishing system-level technology readiness of fission power for exploration applications.

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13. SUPPLEMENTARY NOTES

14. ABSTRACT
Power is a critical consideration in planning exploration of the surfaces of the Moon, Mars, and places beyond. Nuclear power is an important option, especially for locations in the solar system where sunlight is limited or environmental conditions are challenging (e.g., extreme cold, dust storms). NASA and the Department of Energy are maintaining the option for fission surface power for the Moon and Mars by developing and demonstrating technology for a fission surface power system. The Fission Surface Power Systems project has focused on subscale component and subsystem demonstrations to address the feasibility of a low-risk, low-cost approach to space nuclear power for surface missions. Laboratory demonstrations of the liquid metal pump, reactor control drum drive, power conversion, heat rejection, and power management and distribution technologies have validated that the fundamental characteristics and performance of these components and subsystems are consistent with a Fission Surface Power preliminary reference concept. In addition, subscale versions of a non-nuclear reactor simulator, using electric resistance heating in place of the reactor fuel, have been built and operated with liquid metal sodium-potassium and helium/xenon gas heat transfer loops, demonstrating the viability of establishing system-level performance and characteristics of fission surface power technologies without requiring a nuclear reactor. While some component and subsystem testing will continue through 2011 and beyond, the results to date provide sufficient confidence to proceed with system level technology readiness demonstration. To demonstrate the system level readiness of fission surface power in an operationally relevant environment (the primary goal of the Fission Surface Power Systems project), a full scale, 1/4 power Technology Demonstration Unit (TDU) is under development. The TDU will consist of a non-nuclear reactor simulator, a sodium-potassium heat transfer loop, a power conversion unit with electrical controls, and a heat rejection system with a multi-panel radiator assembly. Testing is planned at the Glenn Research Center Vacuum Facility 6 starting in 2012, with vacuum and liquid-nitrogen cold walls to provide simulation of operationally relevant environments. A nominal two-year test campaign is planned including a Phase 1 reactor simulator and power conversion test followed by a Phase 2 integrated system test with radiator panel heat rejection. The testing is expected to demonstrate the readiness and availability of fission surface power as a viable power system option for NASA's exploration needs. In addition to surface power, technology development work within this project is also directly applicable to in-space fission power and propulsion systems.

15. SUBJECT TERMS
Nuclear electric power generation

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