Fission Surface Power Systems (FSPS) Project Final Report for the Exploration Technology Development Program (ETDP)
Fission Surface Power, Transition Face to Face

Donald T. Palac
Glenn Research Center, Cleveland, Ohio

January 2011
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Abstract

The Fission Surface Power Systems Project became part of the ETDP on October 1, 2008. Its goal was to demonstrate fission power system technology readiness in an operationally relevant environment, while providing data on fission system characteristics pertinent to the use of a fission power system on planetary surfaces. During fiscal years 08 to 10, the FSPS project activities were dominated by hardware demonstrations of component technologies, to verify their readiness for inclusion in the fission surface power system. These Pathfinders demonstrated multi-kWe Stirling power conversion operating with heat delivered via liquid metal NaK, composite Ti/H₂O heat pipe radiator panel operations at 400 K input water temperature, no-moving-part electromagnetic liquid metal pump operation with NaK at flight-like temperatures, and subscale performance of an electric resistance reactor simulator capable of reproducing characteristics of a nuclear reactor for the purpose of system-level testing, and a longer list of component technologies included in the attached report. Based on the successful conclusion of Pathfinder testing, work began in 2010 on design and development of the Technology Demonstration Unit (TDU), a full-scale 1/4 power system-level non-nuclear assembly of a reactor simulator, power conversion, heat rejection, instrumentation and controls, and power management and distribution. The TDU will be developed and fabricated during fiscal years 11 and 12, culminating in initial testing with water cooling replacing the heat rejection system in 2012, and complete testing of the full TDU by the end of 2014. Due to its importance for Mars exploration, potential applicability to missions preceding Mars missions, and readiness for an early system-level demonstration, the Enabling Technology Development and Demonstration program is currently planning to continue the project as the Fission Power Systems project, including emphasis on the TDU completion and testing.
Topics to Be Covered

• Project Background and Overview
• Summary of accomplishments over the project lifetime with emphasis on the expected FY10 accomplishments
• Project progression on Key Performance Parameters (show how the KPP has progressed over the lifetime of the project leading to current status)
• Disposition of Project Risks including the expectation of where these risks will be by the end of FY10
• Project’s assessment of the TRL (per NPR 7120.8 Appendix J) at the end of FY10; if technology is not going to be at TRL 6 by the end of FY10 what will it take to mature the technology including technical, budget, and schedule
• Close-out plans for the project including what remains to be accomplished in FY10 prior to entering into ETDP close-out
• Lessons learned including both technical and programmatic

Background and Overview

Fission Surface Power Systems (FSPS)
Space Nuclear Power

• Fission Reactor Systems
  – SNAP-10A (launched 1965)
  – Soviet Buk and Topaz (over 30 systems flown from 1976-1988)
  – SP-100 (cancelled 1992)
  – Jupiter Icy Moons Orbiter (cancelled 2005)
  – Fission Surface Power (present)

• Radioisotope Power Systems
  – 44 Successful U.S. Radioisotope Thermoelectric Generators (RTG) Flown Since 1961
  – Some Examples:
    » Apollo SNAP-27 (1969-72)
    » Viking SNAP-19 (1975)
    » Voyager MHW-RTG (1977)
    » Galileo GPHS-RTG (1989)
    » New Horizons GPHS-RTG (2005)

Why Fission Surface Power?

• Flexibility
  – Suitable for any surface location
  – Same technology for Moon and Mars
  – Highly flexible configurations
  – Scalable to higher power levels

• Robustness
  – Continuous day/night power for robust surface operations
  – Environmentally robust
  – Operationally robust
  – Safe during all mission phases

• Cost effectiveness
  – Performance advantages compared to alternatives
  – Cost competitive with alternatives

• Synergy with other technology development activities
Recent Recognition of the Need for Space Nuclear Power

• “This is a critical enabling technology for human exploration of the Moon and Mars.” National Research Council review of ETDP, 2008

• “LSS categorizes Fission Surface Power as critical for near-term technology investment.” From Jonette Stecklein, Cx/Lunar Surface Systems Technology Integration Lead, e-mail to Al Conde, Cx Technology Integration Manager, April, 2009

• Fission Surface Power was deemed critical to Mars exploration by the Mars Architecture Team in the 2008 Cx Technology Prioritization Process

Fission Surface Power Reference Concept

• Modular 40 kWe system with 8-year design life suitable for (global) lunar and Mars surface applications
• Emplaced configuration with regolith shielding augmentation permits near-outpost siting (<5 rem/yr at 100 m separation)
• Low temperature, low development risk, liquid-metal (NaK) cooled reactor with UO₂ fuel and stainless steel construction
Fission Surface Power System

Design Philosophy

- **Conservative**
  - Moderate temperature (<900 K)
  - Known materials and fluids
  - Generous margins
  - Large safety factors
  - Terrestrial design basis

- **Simple**
  - Simple Controls
    - Negative Temperature Reactivity Feedback: assures safe response to reactor temperature excursions
    - Parasitic Load Control: maintains constant power draw regardless of electrical loads and allows thermal system to remain near steady-state
  - Slow thermal response
  - Conventional design practices
  - Established manufacturing methods
  - Modular and testable configurations
  - Modest power and life requirements

- **Robust**
  - High redundancy
  - Fault tolerance...including ability to recover from conditions such as:
    - Temporary loss of reactor cooling
    - Stuck reflector drums
    - Power conversion unit failure
    - Radiator pump failure
    - Loss of radiator coolant
    - Loss of electrical load
  - High technology readiness components
  - Hardware-rich test program
  - Multiple design cycles

Minimize Cost by Reducing Risk -- Accept Mass Penalties if Needed

Fission Surface Power Project

1.0 Fission Surface Power Systems Project Management
- Project Manager: Don Palac (GRC)
- Principal Investigator: Lee Mason (GRC)
- DOE Lead: Scott Harlow
- MSFC Lead: Mike Houts

2.0 Concept Definition
  - 2.1 Concept Selection
    - Lead: Lee Mason (GRC)
  - 2.2 Modeling and Tool Development
    - Lead: Scott Harlow (DOE)

4.0 Risk Reduction
  - 4.1 System Risk Reduction
    - Lead: Lee Mason (GRC)
  - 4.2 Primary Test Circuit Risk Red.
    - Lead: Mike Houts (MSFC)
  - 4.3 Reactor Component and Irradiation Testing
    - Lead: Scott Harlow (DOE)
  - 4.4 Power Conversion Risk Reduction
    - Lead: Lee Mason (GRC)
  - 4.5 Heat Rejection Risk Reduction
    - Lead: Don Jaworkse (GRC)

7.0 Education and Outreach
Summary of Accomplishments
(See FY10 Accomplishment Section)

Fission Surface Power Systems (FSPS)

Key FSPP Milestones

ETDP: Accomplished

'07 Affordable Fission Surface Power System Study
'08 High Efficiency Power Conversion Demo [2008 APG]
'08 FSP Reference Concept Selection
'09 Sub-scale Liquid Metal Heated Power Conversion Demo
'09 Full-scale Radiator Panel Demo [2009 APG]
'10 Full-scale Liquid Metal Pump Demo [2010 APG]
'10 Reactor Instrumentation and Control Demo

ETDP: Planned

'11 TDU Primary Loop Verification Test
'12 Detailed Dynamic System Performance Model
'12 Full-scale Power Conversion Unit Fabrication
'12 Liquid Metal Cooled Reactor Simulator Fabrication
'13 Full-scale Heat Rejection System Fabrication
'14 End-to-end Technology Demonstration Unit System Test
'14 Experimentally-benchmarked Dynamic System Model
FSP Technology Project: Concept Definition

- Reactor Heat Transport Loop Integration
- Stirling Convertor Concept
- Stirling CFD Modeling
- Radiator Model Validation
- Fission Surface Power Systems (FSPS)
- Reactor Core Modeling
- Radiator and Deployment System

Architecture Study Support

- **Lunar Architecture Team:** Option 6
  - Based on FSP Reference Concept (buried reactor)
  - Detailed Concept-of-Operations generated
- **Mars Architecture Team:** Design Reference Architecture 5.0
  - System pre-deployed with ISRU plant prior to crew departure from Earth
  - Alternative wheeled-cart deployment concept developed
- **Constellation Architecture Team and Lunar Surface Systems:** Scenario 5
  - System delivered on 1st cargo lander to support expanded operations
  - Alternative lander-integrated system concept developed
  - Detailed shielding analyses and mass vs. separation distance trade studies
- **International Architecture Working Group:** Global Point of Departure
  - Alternative low power (10 kWe) Mobile Fission Power System (MFPS) concept developed
  - Capable of being operated, shut-down, moved to new location, and re-started to support mobility-based architectures

NASA/TM—2011-216975
Example: LSS Scenario 5

- Two FSP options selected for LSS Scenario 5
  1) FSPS off-loaded and buried
  2) FSPS remains on lander

- Common features to both options:
  - FSPS delivered on 1st cargo lander
  - Central power distribution node at outpost
  - Orion solar array and battery for startup/backup
  - On-board shielding is augmented with regolith to limit reactor radiation contribution to <3 mrem/hr at specified distance

- Off-Loaded and Buried (5.0.2)
  - Lowest mass FSPS (~5800 kg)
  - Reactor can be located close to outpost (100 m)
  - Requires 2.3 m deep hole
  - ATHLETE digs hole; moves FSPS to site; places FSPS in hole

- Remains on Lander (5.1)
  - Greater separation (400 m) to achieve same radiation level
  - Additional on-board shielding and power cabling results in greater system mass (~6600 kg)
  - Requires regolith fill in lander cavity surrounding reactor core
  - Bladed rover collects regolith near lander; Crane scoops regolith and fills cavity

Scenario 5 Shielding Options

A) FSPS Off-Loaded and Reactor Buried

B) FSPS Off-Loaded and Placed in Berm

C) FSPS Stays on Lander as Delivered

D) FSPS Stays on Lander with Regolith Augmentation
Example: Mobile Fission Power System

- Deliver 10 kWe movable fission system on Malapert cargo lander
  - 2000 kg dry mass includes reactor, water shield vessel, power conversion, radiator, power cabling, and bus
  - 1300 kg water to be added to shield vessel prior to system startup
  - Water could be delivered separately or scavenged from fuel cells
- System would be off-loaded, placed on surface, and surrounded with berm
- Reactor located ~200 m from crew hab
  - Cabling connects reactor to 120 Vdc power bus at crew hab area
- Shield vessel filled with water and system started in approx. 24 hr
- System can be operated for any duration, shut-down, and relocated
  - Post-operation radiation levels would be very manageable
  - Water could be drained or left in shield vessel for movement
  - Setup would be repeated at new location

FSP Technology Project: Risk Reduction

2006
- Low Power NaK Reactor Simulator Design & Fabrication (LANL/MSFC)
- Ti-H₂O Heat Pipe Life Test (GRC)
2007
- 25 kWth Dual Capstone Closed Brayton Loop Test (GRC)
- EBR-II NaK Pump Refurbishment & Test (INL/MSFC)
- Sub-scale Radiator Demonstration Unit Panel Tests (GRC)
2008
- Stirling High Power Linear Alternator Test Rig (GRC)
- 2 kWth Direct Drive Gas Brayton Reactivity Feedback Test (GRC/MSFC)
- Heat Pipe Thermal Interface Evaluation Rig (GRC)
2009
- 2 kWth NaK Stirling Demonstration Test (MSFC/GRC)
- Full-scale Radiator Demonstration Unit Fabrication & Test (GRC)
- Stirling Alternator Radiation Test Article (GRC/SNL)
- Stirling Polymer Coupon Irradiation Testing (GRC/ORNL)
- FET-Based Stirling PMAD Module & Regulated User Load Bus (GRC)
- NaK Feasibility Test Loop: Impurities & Mass Transport (MSFC)
2010
- Full-scale Annular Linear Induction Pump Fabrication & Test (INL/MSFC)
- Reactor Control Drive Mechanism Test (ORNL)
- Reactor Simulator 7-Pin Heater Bundle Test (MSFC)
- IGBT-Based Stirling PMAD Module (GRC)
- NaK-to-NaK Intermediate Heat Exchanger Fabrication & Test (ORNL)
- Thermodynamically-Coupled, Dual-Opposed Stirling Demonstration (GRC)
Sampling of Hardware Progression Toward System Level Demonstration

- NaK Reactor Simulator
- Electromagnetic Pump
- Gas Brayton Test
- NaK Stirling Test
- Composite Radiator
- Full-Scale Radiator
- Full-Scale NaK Pump
- Fission Surface Power Systems (FSPS)
- Stirling Irradiation Test
- Heat Pipe Life Test
- 7-Pin Bundle Test

Example: NaK Stirling Demonstration Test

- Electrically-Heated Test at GRC
  - Sunpower P2A with GRC-developed NaK HX
  - Hardware Procurement
  - Laboratory Setup
  - Engine Performance Mapping:
    » 400 to 550 °C hot-end
    » 30 to 70 °C cold-end
    » 5 to 11 mm piston amplitude
  - Testing:
    » 41 steady-state + 9 transient test points
    » 6 reactivity feedback simulations
    » Model validation

- NaK-Heated Test at MSFC
  - Facility Integration
  - NaK Fill & Checkout
  - System Performance Testing:
    » 41 steady-state + 9 transient test points
    » 6 reactivity feedback simulations
    » Model validation

Test Validates Reactor-Stirling Heat Transfer Concept for FSP
Example: 2nd Gen. Radiator Demonstration Unit

Test Verifies Radiator Manufacturing and Environmental Performance

Composite Radiator provides 2X Mass Improvement over SOA Aluminum
- Full-scale panel: 2.7 x 1.7 m
- Over 6 kWt Rejected at Tin = 400 K, Tsink = 180 K
- Over 150 Steady-State Test Points
- Over 250 hr of Operation
- Heat Pipe & Fluid Loop Frozen Restart
- Lunar & Martian Gravity Simulation
- Cold Soak Survivability

GRC Vacuum Facility #6

Fission Surface Power Systems (FSPS)

FSP Technology Demonstration Unit

TDU Components:
- 850 K Reactor Core Simulator
- Pumped Primary & Intermediate NaK Loops
- NaK-to-NaK Intermediate Heat Exchanger
- 12 kWe Power Conversion Unit
- 400 Vac-to-120 Vdc Power Mgmt & Distribution
- 375 K H₂O Heat Rejection System

GRC Vacuum Facility #6

Fission Surface Power Systems (FSPS)
**Initial Test Configuration (2012)**

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**TDU Accomplishments to Date**

- TDU Facility Requirements Document – Feb ‘08
- Full-scale Power Conversion Unit Contract Awards – May ‘08
- Preliminary Hazards Analysis – Sep ‘08
- Initial Release of TDU System Specification – Dec ‘08
- TDU System Requirements Review – Dec ‘08
- Initial Version of TDU Dynamic System Model – Jan ‘09
- TDU Preliminary Design Review – Feb ‘09
- Initial Release of TDU Piping & Instrumentation Diagram – Mar ‘09
- Full-scale PCU Contract Final Design Reviews – Apr ‘09
- Signed-Version of TDU System Specification – Apr ‘09
- Full-scale PCU Fabrication Contract RFP – Jun ‘09
- Full-scale PCU Contract Award – Mar ‘10
FSP Technology Schedule


- NASA News Release “NASA Developing Fission Surface Power Technology” Katherine Martin (9/10/08)
  - Picked up by Dozens of Internet Sites including SpaceRef and Science Daily
  - 100’s of Blogs... mostly supportive and positive

- DiscoveryChannel.com “NASA Eyes Nuclear Reactor for Moon Base” Irene Klotz (9/15/08)

- Space.com “NASA Eyes Nuclear Power for Moon Base” Jeremy Hsu (9/17/08)

- Popular Science Magazine “Gone Fission” Dawn Stover (Dec 2008 Issue)

- Space.com “NASA Steps Closer to Nuclear Power for Moon Base” Targ Malik (8/6/09)

- MIT Technology Review “A Lunar Nuclear Reactor” Brittany Sauser (8/17/09)
Progress on Key Performance Parameters

Key Performance Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>SOA</th>
<th>Goal</th>
<th>Threshold</th>
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</thead>
<tbody>
<tr>
<td>System Power Level (kWe)</td>
<td>0.5</td>
<td>13x10^6</td>
<td>40</td>
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<tr>
<td>System Specific Mass (kg/kWe)</td>
<td>870</td>
<td>125</td>
<td>200</td>
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<tr>
<td>System Design Life (yrs)</td>
<td>1</td>
<td>30</td>
<td>8</td>
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<tr>
<td>Reactor Outlet Temperature (K)</td>
<td>900</td>
<td>900</td>
<td>800</td>
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<tr>
<td>Reactor Fuel Burnup</td>
<td>10%</td>
<td>1.5%</td>
<td>1%</td>
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<tr>
<td>Reactor Material Fluence (n/cm²)</td>
<td>1x10^22</td>
<td>1x10^22</td>
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<td>Aux-Shield Material Fluence (n/cm²)</td>
<td>1x10^13</td>
<td>1x10^14</td>
<td>1x10^13</td>
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<tr>
<td>Electromagnetic Pump Efficiency</td>
<td>30%</td>
<td>15%</td>
<td>10%</td>
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<td>Power Conversion Unit Power (kWe)</td>
<td>2</td>
<td>12</td>
<td>6</td>
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<tr>
<td>Power Conversion Hot-End (K)</td>
<td>825</td>
<td>825</td>
<td>750</td>
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<td>Power Conversion Efficiency</td>
<td>25%</td>
<td>25%</td>
<td>20%</td>
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<td>Power Conversion Output Voltage (Vac)</td>
<td>240</td>
<td>400</td>
<td>300</td>
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<tr>
<td>Power Distribution Voltage (Vdc)</td>
<td>120</td>
<td>270</td>
<td>120</td>
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<tr>
<td>Effective Radiator Temperature (K)</td>
<td>300</td>
<td>450</td>
<td>400</td>
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<tr>
<td>Heat Rejection Areal Density (kg/m²)</td>
<td>8.5</td>
<td>3.5</td>
<td>5</td>
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### Progress on Key Performance Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>How?</th>
<th>When?</th>
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<tbody>
<tr>
<td>System Power Level (kWe)</td>
<td>TDU</td>
<td>2014</td>
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<tr>
<td>System Mass (kg/kWe)</td>
<td>TDU</td>
<td>2014</td>
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<tr>
<td>System Design Life (yrs)</td>
<td>Flight OTMs and EMs</td>
<td>2021</td>
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<tr>
<td>Reactor Outlet Temperature (K)</td>
<td>Primary Test Circuit</td>
<td>2009</td>
</tr>
<tr>
<td>Reactor Fuel Burnup</td>
<td>Existing Database, Confirmatory Testing as Needed</td>
<td>TBD</td>
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<tr>
<td>Reactor Material Fluence (n/cm²)</td>
<td>Existing Database, Confirmatory Testing as Needed</td>
<td>TBD</td>
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<td>Aft-Shield Material Fluence (n/cm²)</td>
<td>Component Irradiations</td>
<td>2011</td>
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<td>Electromagnetic Pump Efficiency</td>
<td>Primary Test Circuit</td>
<td>2009</td>
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<tr>
<td>Power Conversion Unit Power (kWe)</td>
<td>TDU Power Convertor</td>
<td>2012</td>
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<tr>
<td>Power Conversion Hot-End (K)</td>
<td>PTC Stirling Test</td>
<td>2009</td>
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<td>Power Conversion Efficiency</td>
<td>TDU Power Convertor</td>
<td>2012</td>
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<tr>
<td>Power Conversion Output Voltage (Vac)</td>
<td>Stirling Alternator Rig</td>
<td>2008</td>
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<tr>
<td>Power Distribution Voltage (Vdc)</td>
<td>Stirling Alternator Rig</td>
<td>2008</td>
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<tr>
<td>Effective Radiator Temperature (K)</td>
<td>2nd Gen RDU</td>
<td>2009</td>
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<tr>
<td>Heat Rejection Areal Density (kg/m²)</td>
<td>2nd Gen RDU</td>
<td>2009</td>
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### Key Performance Parameters

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<tr>
<td>System Power Level (kWe)</td>
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<td>20</td>
<td>Holding goal level¹</td>
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<tr>
<td>System Mass (kg/kWe)</td>
<td>125</td>
<td>200</td>
<td>Holding goal level²</td>
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<tr>
<td>System Design Life (yrs)</td>
<td>8</td>
<td>5</td>
<td>Holding goal level¹</td>
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<tr>
<td>Reactor Outlet Temperature (K)</td>
<td>900</td>
<td>800</td>
<td>875</td>
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<tr>
<td>Reactor Fuel Burnup</td>
<td>1.5%</td>
<td>1%</td>
<td>Holding goal level²</td>
</tr>
<tr>
<td>Reactor Material Fluence (n/cm²)</td>
<td>1X10¹²</td>
<td>5X10¹²</td>
<td>Holding goal level²</td>
</tr>
<tr>
<td>Aft-Shield Material Fluence (n/cm²)</td>
<td>1X10¹⁴</td>
<td>1X10¹³</td>
<td>Holding goal level²</td>
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<tr>
<td>Electromagnetic Pump Efficiency</td>
<td>15%</td>
<td>10%</td>
<td>4% (increase planned)</td>
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<tr>
<td>Power Conversion Unit Power (kWe)</td>
<td>12</td>
<td>6</td>
<td>2 (increase planned)</td>
</tr>
<tr>
<td>Power Conversion Hot-End (K)</td>
<td>825</td>
<td>750</td>
<td>825</td>
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<tr>
<td>Power Conversion Efficiency</td>
<td>25%</td>
<td>20%</td>
<td>28% at 2 kWe</td>
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<tr>
<td>Power Conversion Output Voltage (Vac)</td>
<td>400</td>
<td>300</td>
<td>270 at 2 kWe (increase planned)</td>
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<tr>
<td>Power Distribution Voltage (Vdc)</td>
<td>270</td>
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<td>120</td>
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<tr>
<td>Effective Radiator Temperature (K)</td>
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<td>Heat Rejection Areal Density (kg/m²)</td>
<td>3.5</td>
<td>5</td>
<td>3.2 (radiation only)</td>
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</table>

¹Test and analysis to date indicate Goal level is achievable, but will be further validated by TDU testing.

²Test and analysis to date indicate Goal level is achievable, but will be further validated by post-project nuclear criticals testing (criticals testing was originally planned to be part of FSPS prior to budget reductions).
<table>
<thead>
<tr>
<th>Deliverable</th>
<th>Due/Need Date</th>
<th>Description</th>
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<tr>
<td>Power Conversion Unit Final Design Reviews</td>
<td>March 2009</td>
<td>Demonstration of design feasibility and readiness of full scale power conversion options</td>
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<tr>
<td>Reactor Simulator Final Design Review</td>
<td>May 2009</td>
<td>Demonstration of reactor simulator design feasibility and readiness</td>
</tr>
<tr>
<td>Fabrication of Full Scale Radiator Demonstration Test Unit Complete</td>
<td>September 2009</td>
<td>Demonstrated readiness of radiator hardware for full scale testing</td>
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<tr>
<td>Concept Definition Update Based on Design &amp; Test Data To Date</td>
<td>Cx LSS LSCR, June 2010</td>
<td>Minimal update of FSP baseline reference concept incorporating results of component Pathfinder (subscale) test and full scale hardware design and fabrication</td>
</tr>
<tr>
<td>Fabrication of Full Scale Power Conversion Unit Complete</td>
<td>March 2012</td>
<td>Demonstrated readiness of power conversion hardware for full scale testing</td>
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<tr>
<td>Heat Rejection System Final Design Review</td>
<td>June 2012</td>
<td>Demonstration of heat rejection ( radiator and heat exchangers) design feasibility and readiness</td>
</tr>
<tr>
<td>Fabrication of Full Scale Reactor Simulator Complete</td>
<td>June 2012</td>
<td>Demonstrated readiness of reactor simulator hardware for full scale testing</td>
</tr>
<tr>
<td>Concept Definition Update Based on Design &amp; Test Data To Date</td>
<td>LSS SRR, July 2012</td>
<td>Update of FSP baseline reference concept incorporating results of component full scale hardware design, fabrication, and testing</td>
</tr>
<tr>
<td>Pre-Conceptual Design Review</td>
<td>LSS SDR, March 2013</td>
<td>Customer review of FSP concept characteristics &amp; performance against requirements; timed to support LSS Systems Design Review</td>
</tr>
<tr>
<td>Fabrication of Full Scale Heat Rejection Module Complete</td>
<td>April 2013</td>
<td>Demonstrated readiness of heat rejection hardware for full scale testing</td>
</tr>
<tr>
<td>Complete Initial Testing of Reactor Simulator + Power Conversion Unit</td>
<td>LSS Tech. Inf., September 2013</td>
<td>Demonstration of technology readiness of power conversion coupled to reactor (in non-nuclear simulation)</td>
</tr>
<tr>
<td>System-Level Verification of FSP Full Scale Test Hardware in Operational Environment (TRL-6)</td>
<td>LSS Tech. Inf., September 2014</td>
<td>Verification of FSP system technology readiness sufficient to support a decision to proceed with FSP system development</td>
</tr>
<tr>
<td>Concept Definition Update Based on TRL-6 Test Data</td>
<td>LSS PDR, March 2015</td>
<td>Update of FSP baseline reference concept incorporating results of component full scale hardware testing in operational environment</td>
</tr>
</tbody>
</table>

**Disposition of Project Risks**

- Major LSS Milestone
- Unfunded but planned
- Completed
### Fission Surface Power Systems Project Programmatic Risk Assessment

<table>
<thead>
<tr>
<th>Rank</th>
<th>Description</th>
<th>Likelihood (L), Consequence (C)</th>
<th>Risk Management Approach</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1. Stable Project Budget Authority</td>
<td>Cost growth of near-term Cx programs represent challenges for Lunar Surface Systems technologies</td>
<td>Continue support to Cx LSS project, maintain high project performance on milestones and deliverables</td>
</tr>
<tr>
<td>2</td>
<td>2. Uncertain Customer Schedule</td>
<td>Cx LSS need dates dependent on current Cx program progress and budget, and currently undefined</td>
<td>Maintain strong communications with Cx LSS staff via Power Element lead</td>
</tr>
<tr>
<td>3</td>
<td>3. Undefined Customer Requirements</td>
<td>Maturation of Cx requirements may impact technology needs</td>
<td>Maintain close communications with LSS, adjust requirements as needed, maintain FSPS applicability to broad range of Lunar &amp; Mars surface expected requirements</td>
</tr>
</tbody>
</table>

#### Criticality
- **High**
- **Med**
- **Low**

#### L x C Trend
- Decreasing (Improving)
- Increasing (Worsening)
- Unchanged
- New since last month

### Fission Surface Power Systems Project Technical Risk Assessment

<table>
<thead>
<tr>
<th>Rank</th>
<th>Description</th>
<th>Likelihood (L), Consequence (C)</th>
<th>Risk Management Approach</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Given that funding and progress on space-nuclear power has not been even in the past decade, fission surface system technology development may suffer unexpected problems</td>
<td>L of 3 due to affordable approach which rests on large database of terrestrial and prior space fission power experience. C of 3 due to variability in unexpected problems</td>
<td>Maintain affordable FSPS approach, low-temp reactor, non-refractory materials, within existing database</td>
</tr>
<tr>
<td>2</td>
<td>Given that Stirling power conversion technology was last developed for 10’s of kilowatts for space power in the early 1980’s. Stirling technology development has to meet performance, mass, cost objectives</td>
<td>L of 2 due to prior Stirling space power conversion experience, including laboratory demonstrations of Multi-kilowatt Stirling Space Engine Demonstrator. C of 2 due to increased radiator mass needed for engine other than Stirling</td>
<td>Maintain affordable FSPS approach, low-temp reactor, non-refractory materials, within existing database</td>
</tr>
<tr>
<td>3</td>
<td>Given that the lunar surface presents a unique environment for space habitats, and that a fission surface power system heat rejection system may face unexpected challenges</td>
<td>L of 2 due to large database of space radiator development, including the ISS and Orion service modules. C of 2 due to increase of system weight if radiator mass and performance goals are not met. Other technology design is proceeding in parallel to Stirling design as back-up</td>
<td>The Jupiter Icy Moons Orbiter mission began light weight high temperature radiator technology development that FSPS has benefits of. FSHP heat rejection technology development subsequently began early in the FSPS program, and a technology demonstrator design has already been successfully completed</td>
</tr>
</tbody>
</table>

#### Criticality
- **High**
- **Med**
- **Low**

#### L x C Trend
- Decreasing (Improving)
- Increasing (Worsening)
- Unchanged
- New since last month

---

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TRL Assessment

Fission Surface Power Systems (FSPS)
**FPS PPBE-12 Budget**

<table>
<thead>
<tr>
<th>Cost Element Description</th>
<th>FY11</th>
<th>FY12</th>
<th>FY13</th>
<th>FY14</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Core Simulator</td>
<td>6.0</td>
<td>6.8</td>
<td>5.5</td>
<td>3.0</td>
<td>21.3</td>
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<tr>
<td>NaK Fluid System</td>
<td>1.1</td>
<td>1.5</td>
<td>1.1</td>
<td>0.8</td>
<td>4.5</td>
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<tr>
<td>Power Conversion Unit</td>
<td>3.1</td>
<td>1.8</td>
<td>0.8</td>
<td>0.8</td>
<td>6.5</td>
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<tr>
<td>Heat Rejection System</td>
<td>0.7</td>
<td>2.2</td>
<td>2.7</td>
<td>1.2</td>
<td>6.8</td>
</tr>
<tr>
<td>System Engr &amp; Integration</td>
<td>2.9</td>
<td>5.1</td>
<td>5.4</td>
<td>4.8</td>
<td>18.2</td>
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<tr>
<td>Data Acquisition &amp; Controls</td>
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<td>0.8</td>
<td>0.5</td>
<td>0.4</td>
<td>2.2</td>
</tr>
<tr>
<td>Test Support Equipment</td>
<td>0.7</td>
<td>0.6</td>
<td>0.6</td>
<td>0.4</td>
<td>2.3</td>
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<tr>
<td>Test Planning &amp; Operations</td>
<td>0.6</td>
<td>1.5</td>
<td>1.6</td>
<td>1.6</td>
<td>5.3</td>
</tr>
<tr>
<td>Facility Consumables &amp; Maint.</td>
<td>0.3</td>
<td>0.5</td>
<td>0.8</td>
<td>0.6</td>
<td>2.1</td>
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<tr>
<td>Data Analysis &amp; Model Valid.</td>
<td>0.7</td>
<td>1.7</td>
<td>1.9</td>
<td>1.9</td>
<td>6.2</td>
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<tr>
<td>Separate Effects Testing</td>
<td>0.6</td>
<td>0.8</td>
<td>1.6</td>
<td>3.0</td>
<td>6.9</td>
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<tr>
<td>Project Mgmt/Travel/Other</td>
<td>0.9</td>
<td>1.0</td>
<td>1.1</td>
<td>1.0</td>
<td>4.0</td>
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<tr>
<td>Total</td>
<td>10.6</td>
<td>13.7</td>
<td>13.6</td>
<td>12.4</td>
<td>50.3</td>
</tr>
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</table>

Note: in last PPBE cycle, $1M of FY11 budget was included as overguideline, and $200K was moved from FPS to HESPS

**Cost Element Descriptions**

<table>
<thead>
<tr>
<th>Cost Element</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Core Simulator</td>
<td>46 kW nominal, 90 kW max electric heater with 36 pin resistor elements arranged in bundle that simulates reactor core</td>
</tr>
<tr>
<td>NaK Fluid System</td>
<td>875 K NaK heat transport loop including two pumps, two volume accumulators, intermediate heat exchanger, piping, fill/drain system, and argon pressurant</td>
</tr>
<tr>
<td>Power Conversion Unit</td>
<td>12 kW dual, opposed free-piston Stirling converter, NaK hot-end heat exchanger, H₂O cold-end heat exchanger, 400 Vac-to-120 Vdc power controller, helium gas fill/drain</td>
</tr>
<tr>
<td>Heat Rejection System</td>
<td>3kW, 6 panel composite heat pipe radiator assembly, 375 K H₂O heat transport loop including pump and accumulator</td>
</tr>
<tr>
<td>Data Acquisition &amp; Controls</td>
<td>Instrumentation, cables, feedthroughs, signal conditioning, calibration, power supplies, auxiliary heating, computers, software, data racks</td>
</tr>
<tr>
<td>Test Support Equipment</td>
<td>Test support structure, facility interface structure, facility cooling system (pre-HRS), electric load simulator, water fill/drain, thermal insulation</td>
</tr>
<tr>
<td>Test Planning &amp; Operations</td>
<td>Systems engineering, test plan development, hazards analysis, safety permit process, checksheets/procedures, test limits, performance predictions, test operations</td>
</tr>
<tr>
<td>Facility Consumables &amp; Maintenance</td>
<td>Facility prep, vacuum, coldwall, liquid nitrogen, electrical service, uninterruptible power system, facility upgrades (e.g., CO₂), equipment spares</td>
</tr>
<tr>
<td>Data Analysis &amp; Model Validation</td>
<td>System performance model, reactivity feedback model, fluid and material properties, data processing and interpretation, test reports, model refinements, model extrapolation to flight system designs</td>
</tr>
<tr>
<td>Separate Effects Testing</td>
<td>Coupon and component irradiation testing, reactor control drive testing, reflector and shielding materials, reactor cavity cooling, lunar/Mars regolith interactions</td>
</tr>
<tr>
<td>Project Mgmt/Travel/Other</td>
<td>Management, reporting, budget, travel, indirect costs</td>
</tr>
</tbody>
</table>

**Fission Surface Power Systems (FSPS)**

NASA/TM—2011-216975
Close-out Plans

FY10 To-Dos

- Complete reactor simulator 7-pin bundle subscale test
- Initiate vacuum testing of reactor control drive assembly
- Complete thermodynamically-coupled Stirling test
- Complete TDU primary NaK pump fabrication
- Complete required ETDP documentation
- Complete ETDD transition documentation
- Continue progress toward TDU development, assembly, and test
Alternative Missions

• The technology being developed under the FSP project is NOT limited to surface missions
  – Hardware tests (Pathfinders, TDU) and analytical models are relevant to surface or space systems

• Fission technology is broadly applicable for a wide range of exploration missions, especially when...
  – Power requirements are high (e.g., in-situ resource utilization, cryogenic propellant storage, electric propulsion)
  – Mission duration is long (e.g., Mars transfer vehicles, orbiting telescopes)
  – Environmental conditions are challenging (e.g., reduced or intermittent sunlight, extreme temperatures, dust storms)
  – Reliability is paramount (e.g., human life support)

• Fission technology is a basic building block for expanding human presence beyond Earth orbit
  – FSP provides the only practical power solution for crewed Mars base
  – FSP provides a crucial foundation for higher power NEP systems
Relationship to Foundational Domain

- Fission team members can support architecture and concept design studies in related domain projects including:
  - Fission systems for EP demos
  - Alternative surface power configurations for ISRU demos

- Fission team members can support the definition and planning of a follow-on ground-based nuclear demonstration
  - System development plans generated under the ETDP project identified the benefits of critical nuclear experiments as confirmatory tests of the FSP reactor design
  - Initial contact was made with the DOE’s Device Assembly Facility (DAF) at the Nevada Test Site
  - DAF personnel have reviewed the notional requirements for space reactor critical experiments and have concluded that they are feasible under the current facility ground rules
  - The next step is to develop a test plan and identify the possible test materials

Summary

- Pathfinder tests have demonstrated feasibility of Fission Surface Power component technologies
- Technology Demonstration Unit (TDU) integrated system test is planned to begin in 2012 using non-nuclear reactor simulator and full-scale components to demonstrate technology readiness
- Fission Surface Power concept development has focused on minimizing development risks and costs to provide and preserve a key option for Lunar/Mars surface power
- The Fission Surface Power Systems Project is maintaining progress toward a system demonstration of technology readiness through a measured-risk approach
Lessons Learned

- NASA desperately needs a user-friendly secure web server
  - Windchill is not a good example
- ETDPO’s willingness to take on the hard work of adapting to multiple project formats for reporting reflected emphasis on technical progress
  - *Our successful completion of our “Pathfinder” testing at minimal cost reflects streamlined and flexible management oversight – thank you!*
  - I observed no sign that this streamlined, flexible approach came at a cost of management effectiveness – in fact, it may have contributed to ETDPO’s effectiveness at focusing on the bigger picture
    » Establishing and maintaining a credible technology program
    » Keeping a focus on technical accomplishment
- ETDPO’s communications ramped up during times of struggle
  - We were informed on challenges and how to address them – and ETDP was more of a team when times got tough
  - This helped immensely in communicating patience and understanding to our technical teams – we had the information to explain even adverse decisions
More Lessons Learned

- An affordable fission power option exists that minimizes development risk and operational complexity
- Development and demonstration of fission power system in a relevant environment is the key challenge remaining for application of nuclear systems to space, and can best be accomplished by a non-nuclear demonstration
  - Adaptation of power conversion and heat rejection technologies allow application of existing reactor technology to achieve required system performance
- The use of existing (terrestrial-based) reactor technology significantly reduces development risk, provides margin for safety and performance, and provides a vast foundation for predicting and analyzing demonstration results
- Fission power systems can be highly adaptable to meet a wide range of missions and requirements
- The most productive means to develop a fission power capability is through an integrated team approach that combines the space systems expertise of NASA and the nuclear expertise of DOE
- The existing national competency for developing space fission power systems is eroding and must be maintained if NASA is ever to implement this technology

Accomplishments
Support to Lunar Surface Systems
Scenario 5 Definition

Objective:  Constellation Lunar Surface Systems (LSS) is defining architectures for lunar exploration in support of architecture analysis and down-selection. Prompted by the Fission Surface Power Systems workshop in May 2008, LSS initiated development of a FSPS – focused scenario to allow comparison of the use of FSPS to other power system architectures.

Key Accomplishment/Deliverable/Milestone:  LSS defined two emplacement configurations of FSPS that represent the breadth of variations in lunar outpost accommodation of FSPS: 1) burying of the FSP system in a hole so that lunar regolith provides some reactor shielding, and 2) integration of the FSPS system with an Altair cargo lander, and the lander structure is used to support regolith collection for shielding. The FSPS team provided shielding analysis, and electrical and structural integration definition in support of the Scenario 5 concept definition.

Significance:  The conceptual foundation for Scenario 5 will support LSS architecture features comparison.

Power Conversion Unit (PCU)
Final Design Review (FDR) Completion

Objective:  A key to the affordable approach to Fission Surface Power for lunar and Mars exploration is the high energy density of nuclear power combined with the high efficiency of dynamic power conversion. Demonstrating a FSP laboratory system, including power conversion, in an operational environment is the ultimate goal of the FSPS project. The design of two candidate power conversion options was completed in the spring of 2009, paving the way to selection and fabrication of a power conversion unit for the FSP system Technology Demonstration Unit.

Key Accomplishment/Deliverable/Milestone:  April 21-22, 2009
• In May 2008, the Fission Surface Power (FSP) project awarded two parallel contracts for the design and analysis of a full-scale 12 kWe Power Conversion Unit (PCU) for the end-to-end, non-nuclear Technology Demonstration Unit (TDU) test. The contracts were awarded to Sunpower, Inc. of Athens Ohio and Barber Nichols, Inc. of Arvada Colorado. Final design reviews of both designs were successfully completed. No major design challenges were identified.

Significance:  Successful completion of the PCU FDRs paves the way for selection of PCU design to be fabricated. The PCU will later be combined with a non-nuclear reactor simulator, a liquid metal heat transfer loop, and a heat rejection system to make up the TDU, which will validate FSP system technology readiness when tested in an operational environment.
Completion of Fouling, Oxidation, and Additives Study

Objective: Water is the planned working fluid in the FSP heat rejection system, both for transfer of waste heat from the power conversion system to the radiator, and as the radiator heat pipe working fluid. A fouling, oxidation, and additives study was undertaken to address the use of water in a heat rejection system on the lunar surface, with an eye toward unattended operation for 10 years. The concern is a marked decrease in thermal performance brought about by fouling and/or oxidation over such a long duration.

Key Accomplishment/Deliverable/Milestone:
- April 23, 2009
  - A literature search indicates that a combination of water treatments such as distillation, reverse osmosis, degassing, and sterilization can prevent contaminants that would affect water thermal performance in a FSP heat rejection system. In addition, there exist a broad range of chemical additives that are suitable for suppression of deposits for the conditions and lifetimes expected for a FSP system.

Significance: The versatility and capabilities of water as a heat transfer fluid are accompanied by its capabilities as a solvent and a host for organisms. This study shows that these properties can be controlled by a variety of mature processes and technologies. It will be up to the FSP flight system developers to define the right suite for the final requirements.

Shown: Effectiveness of Several Polymers in Preventing Deposits

Delivery of Liquid Metal Electromagnetic Annular Linear Induction Pump (ALIP)

Objective: Electromagnetic (EM) pump technology has been used in prior space nuclear power technology demonstrations and in terrestrial reactors, but no new EM pumps suitable for FSP requirements have been built for decades. Development, fabrication, and testing of an annular linear induction pump in a liquid metal NaK loop will reestablish the feasibility of applying this technology in an FSP system.

Key Accomplishment/Deliverable/Milestone:
- May 1, 2009
  - An annular linear induction pump was built by Pacific Northwest and Idaho National Laboratories as a “Pathfinder” technology demonstrator for FSP expected requirements. The pump will provide a delta p of 58 to 68 kPa at a flow rate of 4 to 4.3 kg/s. It will be tested in a liquid metal NaK test loop at MSFC with electrically heated NaK.

Significance: Laboratory demonstration of component feasibility of this critical no-moving-part highly reliable pump for transfer of heat from a FSP reactor to the power conversion system will pave the way for development of the FSP Technology Demonstration Unit ALIP.

Shown: Annular Linear Induction Pump Delivered by Idaho and Pacific Northwest National Laboratories
**Second Generation RDU Completes Thermal Vacuum Testing**

**Objective:** The Second Generation RDU is a full-scale radiator comparable in design, size and performance to a radiator for lunar and Martian power applications. Testing in a thermal vacuum chamber simulates conditions on the Moon. The radiator was tested with varying water flow rates, water temperatures, operating manifolds and sink temperatures to develop a full performance map. In addition, freeze-thaw survivability and start-up were demonstrated.

**Key Accomplishment/Deliverable/Milestone:**
- July 31, 2009
- Completed thermal vacuum testing and collected approximately 42 million data points for performance analysis and use in validating the models developed of the Second Generation Radiator Demonstration Unit (RDU).
- Demonstrated that the radiator assembly could undergo repeated and numerous freeze-thaw cycles with minimal damage and could be started from a frozen state.
- Will provide data for a full performance map for this and similar radiator designs.

**Significance:**
- This is the first full-scale radiator panel and manifold system that has demonstrated heat rejection technology for a Fission Surface Power System. This technology will be used as the basis for the heat rejection subsystem in the FSPS Technology Demonstration Unit, and potentially for future lunar and Martian power systems.

**Initial Primary Test Circuit Stirling Test Results**

**Objective:** Prior to fabrication of full scale power conversion demonstrators, Pathfinder test articles were developed to demonstrate the feasibility of application of power conversion technologies to the expected Fission Surface Power System requirements. In addition to providing sub-scale, relatively low cost feasibility demonstrations, these Pathfinders inform the design and fabrication of full scale demonstrators to follow.

**Key Accomplishment/Deliverable Milestone:**
- June 11, 2009
- Completed initial tests on a pair of 1 kWe Stirling Power Convertors in the Marshall Space Flight Center pumped primary test circuit. The Stirling Convertors were built by Sunpower, Inc., and modified by Glenn Research Center with a unique NaK heat exchanger. During the week of June 6-11, 2009, the engine pair produced 2.4 kWe of alternate current power output at their design temperature ratio of 2.55 (Thot = 550 °C, Tcold = 50 °C). Testing will continue through early July.

**Significance:**
- This is the first-ever attempt at powering a free-piston Stirling engine with a pumped liquid metal heat source, a major milestone towards demonstrating technical feasibility. It is in time to inform the detailed design of the full-scale Technology Demonstration Unit Power Conversion Unit.
Fabricate a Full Scale 7-Pin Thermal Simulator Bundle

**Objective:** Fabricate a full scale 7-pin thermal simulator bundle to validate and improve the design of the 37-pin Technology Demonstration Unit (TDU) core thermal simulator, as well as future thermal simulators. Assess manufacturability, assembly, performance, and cost.

**Key Accomplishment/Deliverable Milestone:**
- June 30, 2009
- Demonstrated an affordable approach for manufacturing and assembling a core thermal simulator that meets performance and schedule requirements. Resolved potential issues with simulator power leads. Resolved potential issues with NaK heat transfer fluid plenum pressure drop. Resolved potential issues with maintaining desired straightness and NaK flow channel dimensions.

**Significance:**
- The core thermal simulator allows realistic fission surface power component and integrated system testing to be performed without requiring nuclear heat. The core thermal simulator can closely mimic heat from fission, and will be used to provide power to the NaK working fluid. The TDU core thermal simulator will be built based on experience from the 7-pin thermal simulator bundle fabrication and test, and is required for the TDU to achieve all test objectives.

Feasibility Test Loops FY09 Demonstrate Methods for Measuring NaK Impurities Complete

**Objective:** All 34 reactors launched to date (1 US, 33 Soviet) have been cooled by a pumped sodium-potassium (NaK) coolant. The systems operated for up to a year in space with excellent performance. For Fission Surface Power (FSP) systems, lifetimes of 8 years or more may be desired. To help ensure extremely long life, NaK purity must be accurately measured and controlled. Feasibility Test Loops (FTLs) are being used to measure and control NaK impurities, to evaluate the potential for on-line NaK purification, and to assess NaK loop transport concerns.

**Key Accomplishment/Deliverable Milestone:**
- July 31, 2009
- Successfully completed initial NaK on-line purification tests through FTL plugging loop to characterize operations and provide experimental estimate of impurity level. Completed all modifications to FTL hardware based on earlier testing. New components include unique MSFC designed flowmeter (patent submitted) and in-house heaters for chamber. Completed initial tests to validate RF heater controls and fine tune the instrumentation temperature control algorithm. Impurity measurement is accomplished through accurate determination of impurity precipitation temperature.

**Significance:**
- FTLs help resolve potential technology issues associated with pumped alkali metal FSP systems. FY08 work helped resolve potential issues associated with freeze/thaw and maintaining required coolant purity. Current tests refine and validate methods for measuring NaK impurities.
**Objective:** Fabricate a NaK-to-NaK Intermediate Heat Exchanger. In a Fission Surface Power System, the heat from the reactor will be transferred in a primary liquid metal NaK loop to an intermediate heat exchanger, which allows transfer of heat to a secondary NaK loop connected to the Stirling power converters. A Pathfinder heat exchanger test article demonstrates the readiness of liquid metal heat exchanger technology to meet FSPS needs.

**Key Accomplishment/Deliverable Milestone:**
- August 31, 2009
- Mahan's completed fabrication of a 64-tube tube-and-shell heat exchanger capable of transferring the heat required to operate the TDU Stirlings from the primary heat transfer loop to the intermediate heat transfer loop.

**Significance:**
- This demonstrates the ability to design and fabricate small heat exchangers capable of meeting FSPS mission requirements. This heat exchanger will be performance tested to determine our ability to predict heat transfer and pressure drop in heat exchangers of this size.

---

**Objective:** The transfer of heat from NaK liquid metal working fluid to the Stirling helium working fluid is critical to Stirling application in a Fission Surface Power System. Various heat exchanger configurations are being considered, one of which depends on joining of 316L stainless steel (SS316L) to Inconel 718 (IN718). The objective of this task was to demonstrate the capability to join SS316L to IN718 for FSPS Stirling heat exchanger expected requirements.

**Key Accomplishment/Deliverable Milestone:**
- September 30, 2009
- Dr. Ivan Locci (GRC) worked collaboratively with the American Brazing company to prepare 316SS to IN718 joint samples with representative tubular geometry and Nioro braze alloy based on NASA GRC in-house brazing research development. The effort examined both paste and foil brazing materials using either 3 or 4 in. diameter concentric tube samples. Brazing using paste and foil produced good joints after trials to develop procedures, and brazing methods to produce successful results were documented.

**Significance:**
- Identification of successful and industry-accepted methods of joining IN718 and SS316L provides a credible foundation for Stirling heat exchanger design trades that make use of IN718 and SS316L joints.
Objective: To develop the parametric and transient systems models and risk assessment tools needed for the AFSPS project. This is a task to develop an initial Relap5 reference concept model of the Fission Surface Power System.

Key Accomplishment/Deliverable Milestone:

• September 30, 2009

• Updated an FSP Relap5 model to improve heat transfer correlations and core neutronics values. Also ran some benchmark calculations. Based on information provided by LANL, INL updated a Relap5 model of the reactor system for steady state and transient performance comparison and assess model differences.

• Significance:

  • This is an interim step in developing the needed modeling and analytical tools need to aid in the design and adequately predict the Fission Surface Power System performance using a code that is widely accepted within the nuclear community for reactor design and steady state and transient performance models. A Relap5 model built by Oak Ridge was modified to use reactor kinetics based on neutron lifetime and kinetics coefficients computed with the MCNP neutron transport code. Additional modifications were done to use the Stirling engine hot structures. The working fluid for the primary and secondary sides is NaK and helium for the Stirling engine hot structures.

Completion of Low Delta-P Thermal Interface Evaluation (TIE) Heat Exchanger Testing

Objective: Heat exchange between a closed loop heat source and the evaporators of heat pipes in a radiator panel is critical to rejection of Fission Surface Power System (FSPS) excess heat. Experiments were conducted to examine alternatives for heat transfer from the FSPS excess heat water loop to radiator heat pipes, while minimizing the pressure drop in the water loop. A major consideration in this interface design is accommodation of thermal expansion and contraction of heat rejection system components during operation.

Key Accomplishment/Deliverable/Milestone:

• November 18, 2009

• A Poco graphite heat exchanger bonded to a titanium-water heat pipe utilizing silver-filled epoxy fillets allowed heat to move from dual titanium manifolds, through the graphite matrix, to a single heat pipe evaporator. A Thermal Interface Evaluation (TIE) facility was utilized to measure heat flow between the closed loop heat source and the heat pipe via gas gap calorimetry to calculate thermal resistance.

Significance: Experimental testing has provided data to indicate that “sandwiching” the evaporator end of a heat pipe between two water loop manifolds provides heat transfer competitive with alternatives, while minimizing pressure drop in the water loop.
**FSPS Control Drum Control Drive Assembly Testing**

**Objective:** Assemble and perform initial performance characterizations on a prototypic reactor control drive assembly. Hardware demonstration of the FSPS reactor control method will validate the feasibility of the FSPS reactor control approach and provide information for FSP reactor control system design.

**Key Accomplishment/Deliverable Milestone:**
- December 30, 2009. Performance testing of combined stepper motor controller, stepper motor, and control drive gear reduction sufficient to rotate reactor control drums to increase or decrease reactivity for all expected FSP operating conditions.

**Significance:**
- Prototypic stepper motor controller, stepper motor, and control drive gear reduction were tested to evaluate power consumption and thermal effects in air. This information provides baseline data for future testing with the assembly under load and in different operational environments.

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**Develop FSP System Model Validation Plan**

**Objective:** Define a consensus approach to building an analytical model of the FSP system, and validation of the system model with historical data and ultimately the FSP Technology Demonstration Unit (TDU) test data.

**Date of Accomplishment:** December, 2009

**Key Accomplishment/Deliverable/Milestone:**
- Several analytical models of FSP components have been developed, but not integrated into a system model
- A strategy has been developed for a FSP power system model and how its configuration will be managed. The model will be verified using historical data and validated with TDU test data
- During the TDU test program, the model will be used for predicting test performance. If test predictions indicate test limits may be violated, the test plan will be adjusted accordingly.

**Significance:**
- This plan outlines the path forward for FSP code development that will lead to a modeling tool that can effectively be used to operate the FSP TDSU system in an operationally relevant environment (NASA TRL 6)
**Complete Initial Fission Surface Power (FSP) System Concept Definition**

**Objectives:** Generate the initial reference concept to guide FSP development and support Lunar Surface System (LSS) architecture studies by providing credible and timely FSP design information.

**Key Accomplishment/Deliverable/Milestone:**
- February, 2010
  - Complete narrative documentation of FSP Preliminary Reference Concept design including reactor, power conversion, heat rejection, and PMAD
  - Includes the results of trade studies to define an initial FSP concept consistent with expected lunar and Mars surface outpost requirements, and FSP goals of low development risk and cost
  - Contributions from NASA, DOE, space reactor experts, and industry were integrated into single document that will be published as NASA TM
  - Concept alignment with LSS customer needs confirmed via LSS Workshop and various interactive architecture studies

**Significance:**
- Concept will guide the configuration and test objectives for the system-level demonstration of FSP technology readiness in an operationally relevant environment (TRL6) to start in FY2012

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**Award Power Conversion Unit Fabrication Contract**

**Objectives:** Secure a contractor to finalize the design and complete the fabrication and assembly of a full-scale Power Conversion Unit (PCU) for use in the FSP Technology Demonstration Unit (TDU) test.

**Date of Accomplishment:** March, 2010

**Key Accomplishment/Deliverable/Milestone:**
- Competitive Phase I Design contracts completed by Sunpower and Barber Nichols in May 2009
- Phase II Fabrication and Test Proposals received in August 2009; Source Evaluation Committee completed review and Source Selection Official made selection in March 2010
- Sunpower design provides high efficiency, low risk, and straightforward path to flight

**Significance:**
- This award adds a crucial industry partner to the FSP government team that is capable of delivering the power conversion hardware required for system technology validation
- The timing of the award provides confidence that the TDU system test can be completed on-schedule

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*Shown: 40 kWe FSP Initial Concept*  
*• Reactor emplaced in pre-dug hole uses lunar regolith shielding properties*  
*• Power conversion and coolant systems on central truss*  
*• Heat rejection via deployable radiators*  
*• Not shown: FSP power electronics and control interface at outpost habitat*

*12 kWe Dual-Opposed, Free-Piston Stirling Power Conversion Unit*
Annular Linear Induction Pump (ALIP) Test Report

**Objectives:** A key FSP technology is the liquid-metal pump. The pump must be compatible with liquid NaK coolant at high temperature (800 K) and have adequate performance to enable a viable flight system. An annular linear induction pump (ALIP) was designed to the reference mission requirements and tested at representative operating conditions to serve as a “pathfinder” for the FSP Technology Demonstration Unit (TDU).

**Date of Accomplishment:** March, 2010

**Key Accomplishment/Deliverable/Milestone:**
- Successfully completed ALIP Test Circuit (ATC) test matrix
- Achieved full range of NaK temperatures 25 °C to peak temperature of 525 °C.
- Ran at nominal operating frequency (design point) - 36 Hz.
- Obtained data for pump operating on variable frequency drive-supplied three-phase power at 33, 36, 39, and 60 Hz, and also on standard AC wall power at 60 Hz.
- Operated at voltages ranging from 5 to 120 VAC at the nominal frequency (36 Hz), and over smaller voltage ranges at other frequencies.
- Submitted test report for technical memorandum (TM)

**Significance:**
- Test report details the design and fabrication of the ALIP Test Circuit and performance testing of a prototypic ALIP with NaK liquid metal at operating temperatures and flow rates that are relevant to a future 40 kw fission surface power system.
- Demonstrated viability of ALIP for use with FSP. Demonstrated cost-effective testing over wide range operating conditions.

Demonstrate Thermodynamically-Coupled Stirling Pair

**Objectives:** Demonstrate the functionality and control of high power Stirling convertors that share a common expansion space.

**Date of Accomplishment:** March, 2010

**Key Accomplishment/Deliverable/Milestone:**
- A pair of existing 1 kWm Stirling convertors were reconfigured by Sunpower to utilize a common expansion space
- The two units were connected at the heater head domes via a joining ring and weldment
- The design was verified by operating the Stirling engines as coolers via electrical-motorizing of the linear alternators

**Significance:**
- The reference FSP concept assumes coupled Stirling units as a means to simplify the mechanical and electrical integration
- Demonstration of the coupled configuration allows work to proceed on the electrical-resistance heat source integration for power operations and eventual delivery to SRC for performance testing
Deliver TDU Intermediate Heat Exchanger to MSFC

**Objective:** Design and fabricate a liquid metal NaK to NaK heat exchanger for the FSPS Technology Demonstration Unit (TDU)

**Date of Accomplishment:** April, 2010 (2 months early)

**Key Accomplishment/Deliverable/Milestone:**
- The FSPS conceptual reference design delivers heat from the reactor to the Stirling power conversion system via a primary liquid metal NaK loop, through intermediate heat exchangers, to a second set of NaK loops for redundancy and separation of Stirling NaK flow from reactor NaK flow.
- A reduced scale FSP TDU intermediate heat exchanger that incorporates joining technology considered to be flight system ready was designed and fabricated. This unit will demonstrate system-level readiness of space nuclear power in an operationally relevant environment during the TDU.

**Significance**
- First full-scale TDU component to be delivered.
- Clears the way to begin build-up of TDU assembly.

Refine Operations Concept for FSP Systems

**Objective:** Provide greater definition of the operations concepts associated with fission-based power systems including launch, delivery, installation, startup, and shutdown based on the most recent design configurations and mission architectures.

**Date of Accomplishment:** June, 2010

**Key Accomplishment/Deliverable/Milestone:**
- Interaction with the International Architecture Working Group has resulted in a new implementation approach for FSP technology.
- To support the International Global Point of Departure architecture, a low power (10 kWe) “movable” FSP concept was developed.
  - Intended for mobility-based architectures when surface assets are relocated to accommodate different crew landing sites.
  - System can be deployed, operated, shut down, moved to new location, and restarted as needed.
  - Design layout, mass summary, and full “ops concept” description provided to IAIWG Campaign Integration Team.
- System enables full eclipse operations at non-polar GPoD mission sites previously not possible with solar-based power systems.

**Significance**
- Continued interaction with surface mission planners has increased awareness of new requirements.
- FSP technology has been shown to be very adaptable to changing mission needs.
- Technology demonstration as planned by the FSPS project fully supports latest requirements.
Objective: Demonstrate the technology to simulate the FSP reactor in non-nuclear testing by using electrical heating to heat molten NaK in a "pathfinder" partial heater bundle that represents one portion of an FSP Technology Demonstration Unit (TDU) reactor simulator.

Date of Accomplishment: June, 2010

Key Accomplishment/Deliverable/Milestone:
- A key part of a low-cost approach to FSP technology demonstration is using an electrically-heated reactor simulator in place of a nuclear reactor for system-level technology demonstration.
- A reactor simulator must deliver heat in a small package and be able to transfer it efficiently to the liquid metal working fluid as would a nuclear core.
- Prior to building a full-size 37-pin TDU reactor simulator, a partial "pathfinder" bundle of seven heater-element pins was assembled and tested to validate the simulator technology.
- Testing was initiated on June 3, 2010.
- Preliminary results indicated nominal performance.

Significance:
- Testing will be completed in the summer of 2010.
- Continued consistent results will allow initiation of build-up of TDU reactor simulator.

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4.3.2 Irradiation Testing

- Complete MC Neutron Irradiation Test Report ORNL 9/30/2010

4.3.4 Shielding

- Shielding work deferred

4.3.7 Thermal Simulator Development: Heater Bundles

- Integrate 7-Pin Bundle into Primary Test Circuit MSFC 2/28/2010 Monthly Mgt Review - Feb 10

4.4 Power Conversion Risk Reduction

4.4.1 Stirling Power Conversion Risk Reduction

- Complete Thermodynamically-Coupled Stirling Test GRC 8/30/2010
- Demonstrate IGBT-Based Stirling Controller GRC 8/31/2010

4.4.3 Power Conversion Materials

- Deliver Alternator Materials for Neutron Irradiation Test report Dec09 Alternator Mats Neutron Irrad.docx
- Develop Stirling Radiation Specification GRC 7/31/2010 IECC Paper Mireles IECC paper submit to Don.doc

4.5 Heat Rejection Risk Reduction

4.5.1 Radiator Panel Technology

- Evaluate SBR Developed Ultra-light Panel Radiator Panel Technology GRC 4/30/2010

4.5.2 Heat Pipe Technology

- Complete 3 yr Life Testing of T-H2O Heat Pipes Radiator Panel Technology GRC 1/31/2010 MRR Report
- Complete Analysis of ACT Phase III Heat Pipe Li Radiator Panel Technology GRC 9/30/2010
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4.5.5 Heat Rejection Materials

- HR Materials work deferred

4.5.3 Heat Pipe Technology

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4.5.4 Thermal Interface Evaluation

The Fission Surface Power Systems Project became part of the ETDP on October 1, 2008. Its goal was to demonstrate fission power system technology readiness in an operationally relevant environment, while providing data on fission system characteristics pertinent to the use of a fission power system on planetary surfaces. During fiscal years 08 to 10, the FSPS project activities were dominated by hardware demonstrations of component technologies, to verify their readiness for inclusion in the fission surface power system. These Pathfinders demonstrated multi-kWe Stirling power conversion operating with heat delivered via liquid metal NaK, composite Ti/H$_2$O heat pipe radiator panel operations at 400 K input water temperature, no-moving-part electromagnetic liquid metal pump operation with NaK at flight-like temperatures, and subscale performance of an electric resistance reactor simulator capable of reproducing characteristics of a nuclear reactor for the purpose of system-level testing, and a longer list of component technologies included in the attached report. Based on the successful conclusion of Pathfinder testing, work began in 2010 on design and development of the Technology Demonstration Unit (TDU), a full-scale 1/4 power system-level non-nuclear assembly of a reactor simulator, power conversion, heat rejection, instrumentation and controls, and power management and distribution. The TDU will be developed and fabricated during fiscal years 11 and 12, culminating in initial testing with water cooling replacing the heat rejection system in 2012, and complete testing of the full TDU by the end of 2014. Due to its importance for Mars exploration, potential applicability to missions preceding Mars missions, and readiness for an early system-level demonstration, the Enabling Technology Development and Demonstration program is currently planning to continue the project as the Fission Power Systems project, including emphasis on the TDU completion and testing.