NASA/TM—2011-216975

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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Level of Review: This material has been technically reviewed by technical management.

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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/H_2O 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

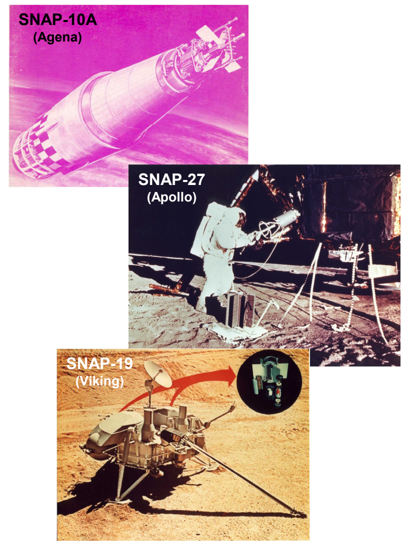
Fission Surface Power Systems (FSPS)

Background and Overview

Fission Surface Power Systems (FSPS)

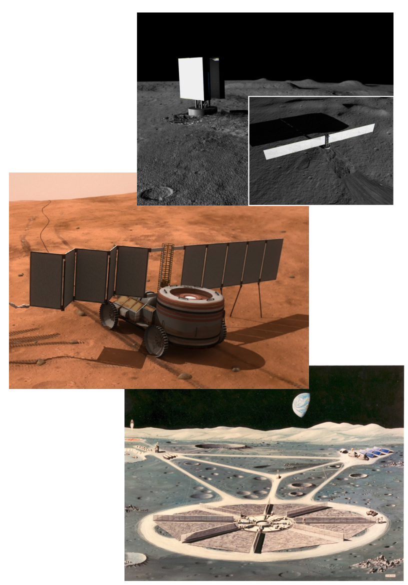
Space Nuclear Power

- 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



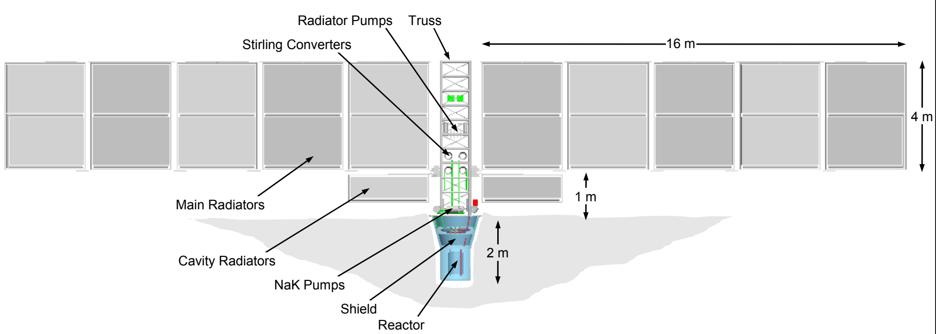
Recent Recognition of the Need for Space Nuclear Power

- "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 Systems (FSPS)

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 UO_2 fuel and stainless steel construction



Fission Surface Power Systems (FSPS)

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 Systems (FSPS)

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

7.0 Education and Outreach

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)

Fission Surface Power Systems (FSPS)

Summary of Accomplishments

(See FY10 Accomplishment Section)

Fission Surface Power Systems (FSPS)

Predecisional: For Planning Purposes Only

Key FSPS Milestones

ETDP: Accomplished

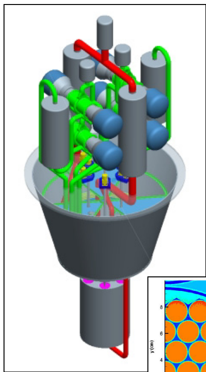
‘07	Affordable Fission Surface Power System Study
‘08	High Efficiency Power Conversion Demo [*2008 APG*]
‘08	FSP Reference Concept Selection
‘09	Sub-scale Liquid Metal Heated Power Conversion Demo
‘09	Full-scale Radiator Panel Demo [*2009 APG*]
‘10	Full-scale Liquid Metal Pump Demo [*2010 APG*]
‘10	Reactor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

ETDP: Planned

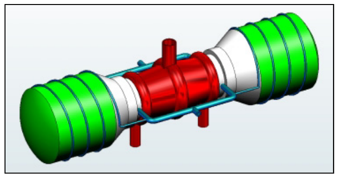
’11	TDU Primary Loop Verification Test
‘12	Detailed Dynamic System Performance Model
‘12	Full-scale Power Conversion Unit Fabrication
‘12	Liquid Metal Cooled Reactor Simulator Fabrication
‘13	Full-scale Heat Rejection System Fabrication
‘14	End-to-end Technology Demonstration Unit System Test
‘14	Experimentally-benchmarked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

Fission Surface Power Systems (FSPS)

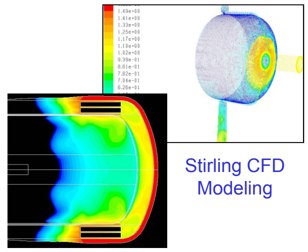
FSP Technology Project: Concept Definition



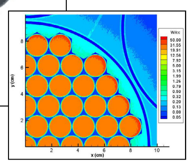
Reactor Heat Transport Loop Integration



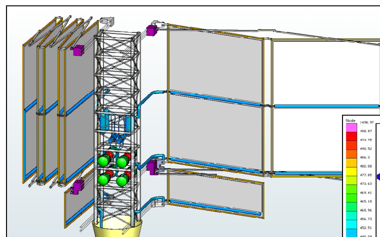
Stirling Convertor Concept



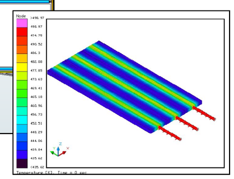
Stirling CFD Modeling



Reactor Core Modeling



Radiator and Deployment System



Radiator Model Validation

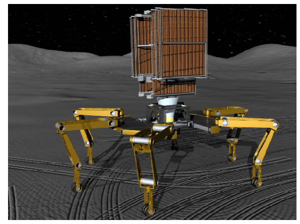
Architecture Study Support

- 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

Example: LSS Scenario 5

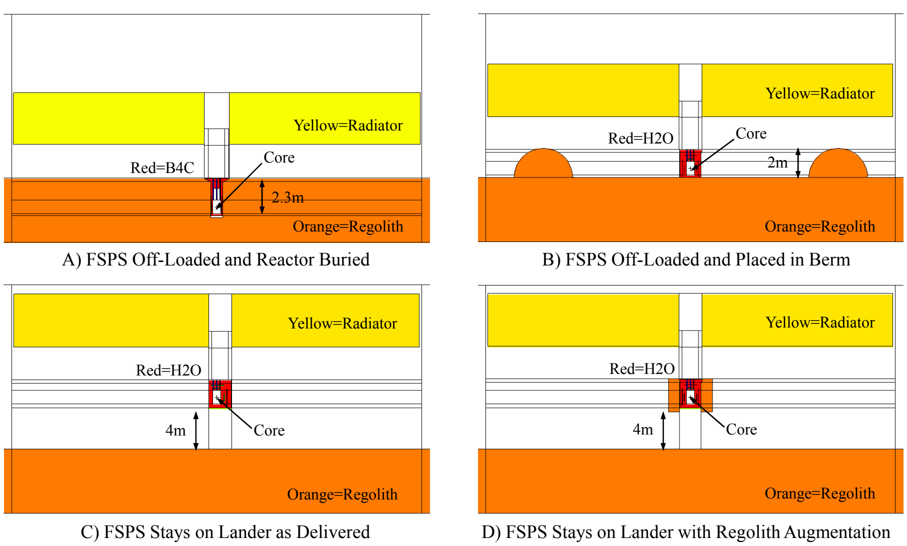
- Two FSP options selected for LSS Scenario 5
  1) FSPS off-loaded and buried
  2) FSPS remains on lander
- Common features to both options:
  - FSPS delivered on 1st cargo lander
  - Central power distribution node at outpost
  - Orion solar array and battery for startup/backup
  - On-board shielding 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

5.0.2 Off-Loaded and Buried



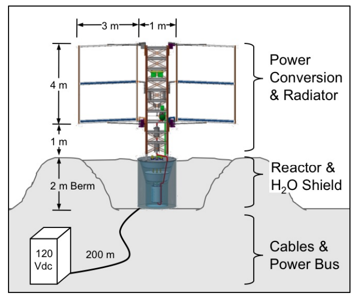
5.1 Remains on Lander

Scenario 5 Shielding Options



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



Movable system provides an excellent demo for future higher power unit

FSP Technology Project: Risk Reduction

2006
- Low Power NaK Reactor Simulator Design & Fabrication (LANL/MSFC)
- Ti-H_2O Heat Pipe Life Test (GRC)

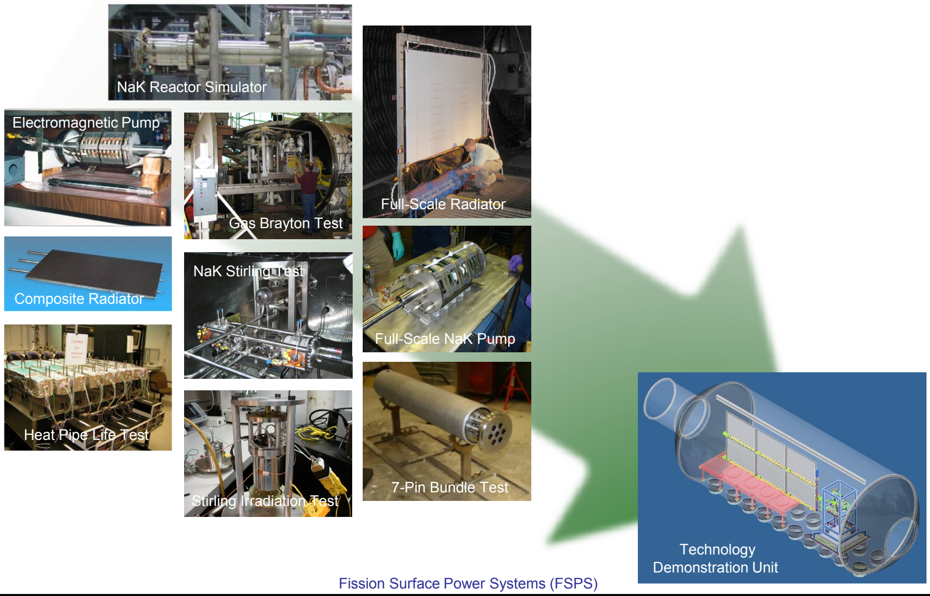
2007
- 25 kWe Dual Capstone Closed Brayton Loop Test (GRC)
- EBR-II NaK Pump Refurbishment & Test (INL/MSFC)
- Sub-scale Radiator Demonstration Unit Panel Tests (GRC)

2008
- Stirling High Power Linear Alternator Test Rig (GRC)
- 2 kWe Direct Drive Gas Brayton Reactivity Feedback Test (GRC/MSFC)
- Heat Pipe Thermal Interface Evaluation Rig (GRC)

2009
- 2 kWe 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)

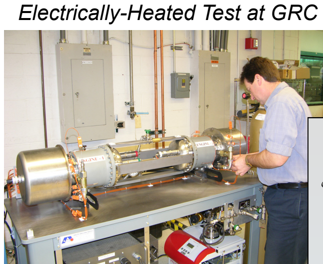
Sampling of Hardware Progression Toward System Level Demonstration



Fission Surface Power Systems (FSPS)

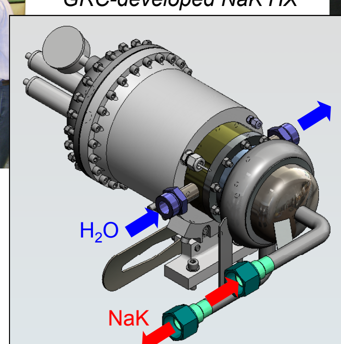
Example: NaK Stirling Demonstration Test

Electrically-Heated Test at GRC



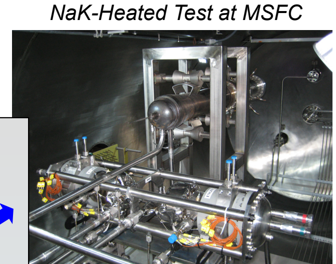
- Hardware Procurement
- Laboratory Setup
- Engine Performance Mapping:
  - » 400 to 550 °C hot-end
  - » 30 to 70 °C cold-end
  - » 5 to 11 mm piston amplitude

Sunpower P2A with GRC-developed NaK HX



2.4 kWe and 32% Thermal Efficiency at T_{HOT}=550 °C, T_{COLD}=50 °C

NaK-Heated Test at MSFC



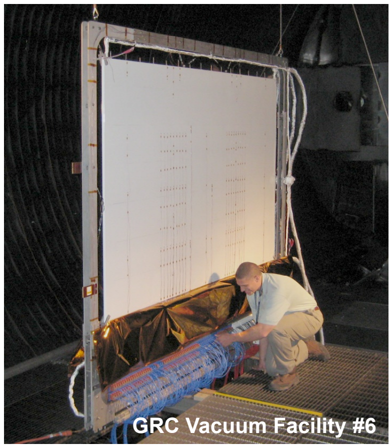
- Facility Integration
- NaK Fill & Checkout
- System Performance Testing:
  - » 41 steady-state + 9 transient test points
  - » 6 reactivity feedback simulations
  - » Model validation

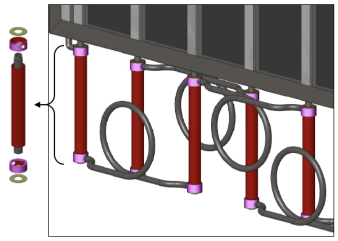
Test Validates Reactor-Stirling Heat Transfer Concept for FSP

Fission Surface Power Systems (FSPS)

Example: 2nd Gen. Radiator Demonstration Unit

Test Verifies Radiator Manufacturing and Environmental Performance

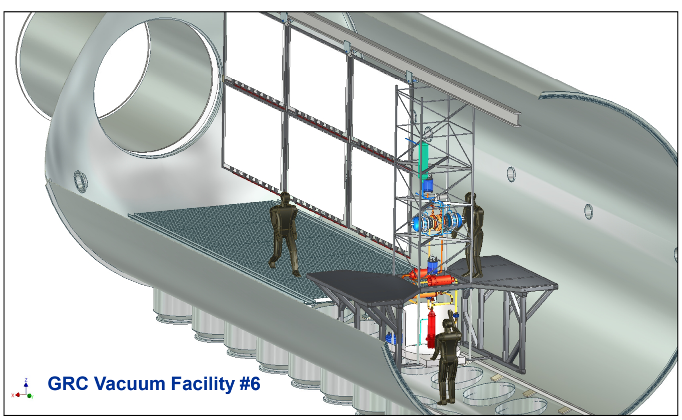




Composite Radiator provides 2X Mass Improvement over SOA Aluminum

- 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

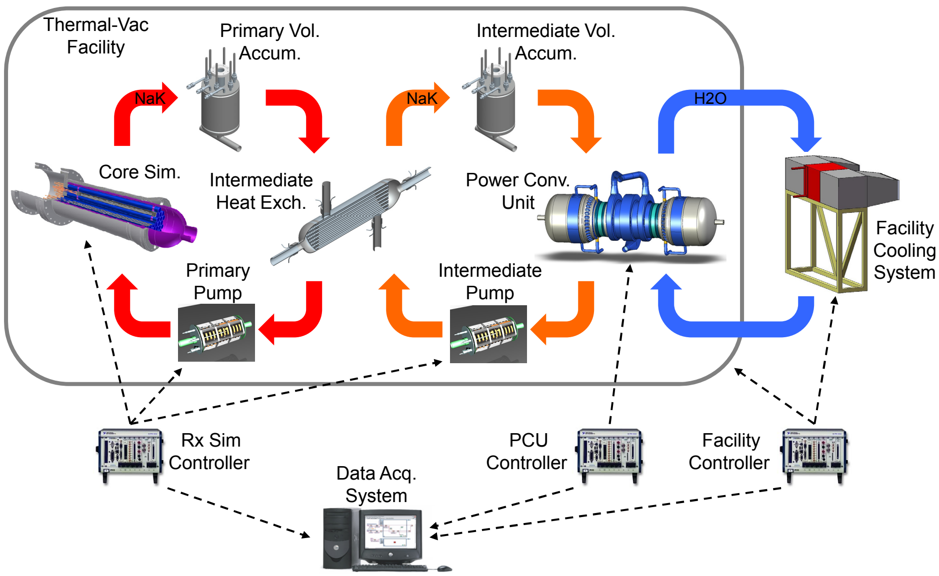
FSP Technology Demonstration Unit



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 H_2O Heat Rejection System

Initial Test Configuration (2012)



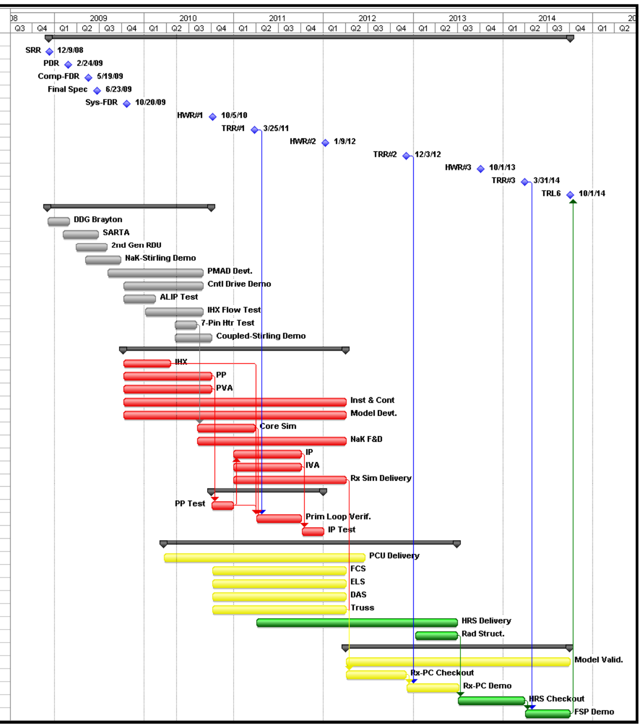
Fission Surface Power Systems (FSPS)

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
- TDU Component Final Design Review with Independent Review Panel – May '09
- Full-scale PCU Fabrication Contract RFP – Jun '09
- TDU System Final Design Review with Independent Review Panel – Oct '09
- Full-scale PCU Contract Award – Mar '10

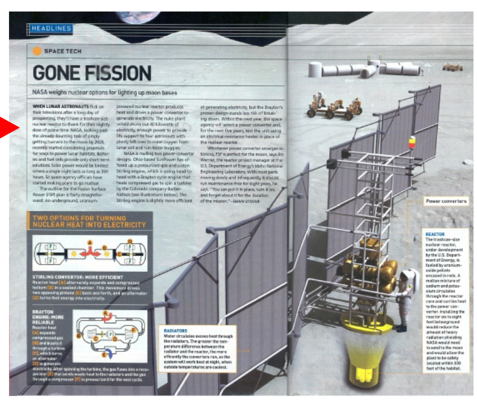
Fission Surface Power Systems (FSPS)

ID	Task Name	Contact	Start	Finish
1	**Key Events**		**Tue 12/9/08**	**Wed 10/1/14**
2	System Reqmts Review	Mason	Tue 12/9/08	Tue 12/9/08
3	Prelim Design Review	Mason	Tue 2/24/09	Tue 2/24/09
4	Comp Final Design Review	Mason	Tue 5/19/09	Tue 5/19/09
5	Final System Spec	Mason	Tue 6/23/09	Tue 6/23/09
6	System Final Design Review	Mason	Tue 10/20/09	Tue 10/20/09
7	Hardware Review	Mason	Tue 10/5/10	Tue 10/5/10
8	Test Readiness Review	Houts	Fri 3/25/11	Fri 3/25/11
9	Hardware Review	Mason	Mon 1/9/12	Mon 1/9/12
10	Test Readiness Review	Mason	Mon 12/3/12	Mon 12/3/12
11	Hardware Review	Mason	Tue 10/1/13	Tue 10/1/13
12	Test Readiness Review	Mason	Mon 3/31/14	Mon 3/31/14
13	Non-nuclear TRL6	Mason	Wed 10/1/14	Wed 10/1/14
14	**Pathfinder Testing**		**Mon 12/1/08**	**Thu 9/30/10**
15	Direct Drive Gas Brayton	Hervol	Mon 12/1/08	Fri 2/27/09
16	Stirling Alt Rad Test Article	Bowman	Mon 2/2/09	Fri 6/26/09
17	Full-scale Radiator	Ellis	Fri 3/27/09	Fri 7/31/09
18	NaK-Heated Stirling	Geng	Mon 5/4/09	Fri 9/25/09
19	Stirling PMAD Devt	Hervol	Mon 8/3/09	Fri 8/27/10
20	Rx Control Drive Ass'y	Qualls	Tue 10/6/09	Fri 8/27/10
21	Full-scale ALIP	Houts	Tue 10/6/09	Fri 2/12/10
22	IHX Prototype	Qualls	Mon 1/4/10	Fri 8/27/10
23	7-Pin Heater Bundle	Houts	Mon 5/3/10	Fri 7/30/10
24	Coupled-Stirling	Geng	Mon 5/3/10	Thu 9/30/10
25	**Reactor Simulator**		**Tue 10/6/09**	**Fri 3/30/12**
26	Intermediate Heat Exch	Qualls	Tue 10/6/09	Fri 4/16/10
27	Primary Pump	Werner	Tue 10/6/09	Thu 9/30/10
28	Primary Vol Accum	Qualls	Tue 10/6/09	Thu 9/30/10
29	Rx Sim Controller	Qualls	Tue 10/6/09	Fri 3/30/12
30	RPCSIM System Model	Radel	Tue 10/6/09	Fri 3/30/12
31	Core Simulator	Houts	Mon 8/2/10	Fri 3/25/11
32	NaK Fill & Drain	Houts	Mon 8/2/10	Fri 3/30/12
33	Intermediate Pump	Werner	Wed 12/29/10	Fri 9/30/11
34	Intermediate Vol Accum	Qualls	Wed 12/29/10	Fri 9/30/11
35	Rx Sim Assembly	Houts	Wed 12/29/10	Fri 3/30/12
36	**Rx Sim Testing**		**Fri 10/1/10**	**Fri 12/30/11**
37	Primary Pump	Houts	Fri 10/1/10	Tue 12/28/10
38	Primary Loop	Houts	Fri 4/1/11	Fri 9/30/11
39	Intermediate Pump	Houts	Mon 10/3/11	Fri 12/30/11
40	**Balance of Plant**		**Mon 3/22/10**	**Fri 6/28/13**
41	Power Conv Unit	Wood	Mon 3/22/10	Fri 6/15/12
42	Facility Cooling System	Hervol	Mon 10/4/10	Fri 3/30/12
43	Elect Load Simulator	Hervol	Mon 10/4/10	Fri 3/30/12
44	Data Acq System	Gibson	Mon 10/4/10	Fri 3/30/12
45	Truss Assembly	Gibson	Mon 10/4/10	Fri 3/30/12
46	Heat Reject System	TBD	Fri 4/1/11	Fri 6/28/13
47	HRS Assembly	Gibson	Mon 1/7/13	Fri 6/28/13
48	**System Testing**		**Mon 4/2/12**	**Tue 9/30/14**
49	RPCSIM Benchmarking	Radel	Mon 4/2/12	Tue 9/30/14
50	Rx-PC Integration	Gibson	Mon 4/2/12	Fri 11/30/12
51	Rx-PC Demo	Mason	Tue 12/4/12	Wed 7/3/13
52	HRS Integration	Gibson	Mon 7/1/13	Fri 3/28/14
53	Integrated System Demo	Mason	Tue 4/1/14	Tue 9/30/14



Positive Press

- 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" Tarig Malik (8/6/09)
- MIT Technology Review "A Lunar Nuclear Reactor" Brittany Sauser (8/17/09)



Fission Surface Power Systems (FSPS)

Progress on Key Performance Parameters

Fission Surface Power Systems (FSPS)

Key Performance Parameters

Parameter	SOA		Goal	Threshold
System Power Level (kWe)	0.5	13x10^5	40	20
System Specific Mass (kg/kWe)	870		125	200
System Design Life (yrs)	1	30	8	5
Reactor Outlet Temperature (K)	900		900	800
Reactor Fuel Burnup	10%		1.5%	1%
Reactor Material Fluence (n/cm^2)	1x10^{23}		1x10^{22}	5x10^{22}
Aft-Shield Material Fluence (n/cm^2)	1x10^{13}		1x10^{14}	1x10^{13}
Electromagnetic Pump Efficiency	30%		15%	10%
Power Conversion Unit Power (kWe)	2		12	6
Power Conversion Hot-End (K)	825		825	750
Power Conversion Efficiency	25%		25%	20%
Power Conversion Output Voltage (Vac)	240		400	300
Power Distribution Voltage (Vdc)	120		270	120
Effective Radiator Temperature (K)	300		450	400
Heat Rejection Areal Density (kg/m^2)	8.5		3.5	5

SNAP-10A (yellow) | Terrestrial Nuclear (green) | Laboratory Test Unit (blue) | ISS (purple)

Fission Surface Power Systems (FSPS)

Progress on Key Performance Parameters

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

Fission Surface Power Systems (FSPS)

Predecisional: For Planning Purposes Only

Key Performance Parameters Status at Close-Out

Parameter	Goal	Threshold	Close-Out Status
System Power Level (kWe)	40	20	Holding goal level[1]
System Mass (kg/kWe)	125	200	Holding goal level[1]
System Design Life (yrs)	8	5	Holding goal level[1]
Reactor Outlet Temperature (K)	900	800	875
Reactor Fuel Burnup	1.5%	1%	Holding goal level[2]
Reactor Material Fluence (n/cm^2)	$1X10^{22}$	$5X10^{22}$	Holding goal level[2]
Aft-Shield Material Fluence (n/cm^2)	$1X10^{14}$	$1X10^{13}$	Holding goal level[2]
Electromagnetic Pump Efficiency	15%	10%	4% (increase planned)
Power Conversion Unit Power (kWe)	12	6	2 (increase planned)
Power Conversion Hot-End (K)	825	750	825
Power Conversion Efficiency	25%	20%	28% at 2 kWe
Power Conversion Output Voltage (Vac)	400	300	270 at 2 kWe (increase planned)
Power Distribution Voltage (Vdc)	270	120	120
Effective Radiator Temperature (K)	450	400	430
Heat Rejection Areal Density (kg/m^2)	3.5	5	3.2 (radiator only)

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

[2]Test 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)

Fission Surface Power Systems (FSPS)

CSA Deliverables

Deliverable	Due/Need Date	Description
Power Conversion Unit Final Design Reviews	March 2009	Demonstration of design feasibility and readiness of full scale power conversion options
Reactor Simulator Final Design Review	May 2009	Demonstration of reactor simulator design feasibility and readiness
Fabrication of Full Scale Radiator Demonstration Test Unit Complete	September 2009	Demonstrated readiness of radiator hardware for full scale testing
Concept Definition Update Based on Design & Test Data To Date	Cx LSS LSCR, June 2010	Minimal update of FSP baseline reference concept incorporating results of component Pathfinder (subscale) test and full scale hardware design and fabrication
Fabrication of Full Scale Power Conversion Unit Complete	March 2012	Demonstrated readiness of power conversion hardware for full scale testing
Heat Rejection System Final Design Review	June 2012	Demonstration of heat rejection (radiator and heat exchangers) design feasibility and readiness
Fabrication of Full Scale Reactor Simulator Complete	June 2012	Demonstrated readiness of reactor simulator hardware for full scale testing
Concept Definition Update Based on Design & Test Data To Date	LSS SRR July 2012	Update of FSP baseline reference concept incorporating results of component full scale hardware design, fabrication, and testing
Pre-Conceptual Design Review	LSS SDR March 2013	Customer review of FSP concept characteristics & performance against requirements; timed to support LSS Systems Design Review
Fabrication of Full Scale Heat Rejection Module Complete	April 2013	Demonstrated readiness of heat rejection hardware for full scale testing
Complete Initial Testing of Reactor Simulator + Power Conversion Unit	LSS Tech. Inf. September 2013	Demonstration of technology readiness of power conversion coupled to reactor (in non-nuclear simulation)
System-Level Verification of FSP Full Scale Test Hardware in Operational Environment (TRL-6)	LSS Tech. Inf. September 2014	Verification of FSP system technology readiness sufficient to support a decision to proceed with FSP system development
Concept Definition Update Based on TRL-6 Test Data	LSS PDR March 2015	Update of FSP baseline reference concept incorporating results of component full scale hardware testing in operational environment

Major LSS Milestone

Unfunded but planned

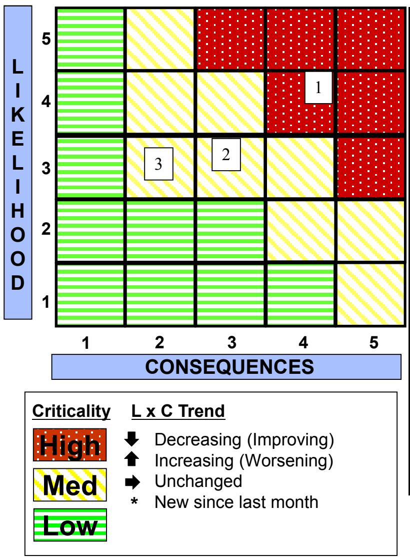
Completed

Fission Surface Power Systems (FSPS)

Disposition of Project Risks

Fission Surface Power Systems (FSPS)

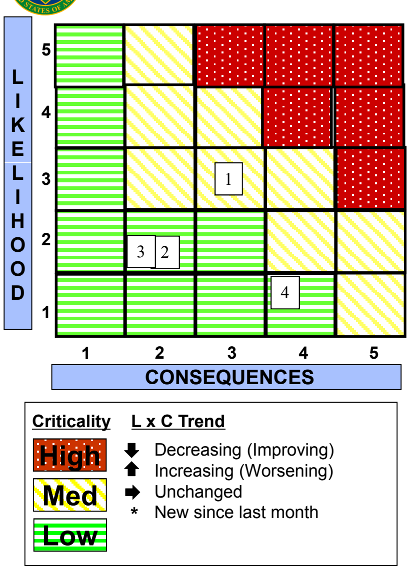
Fission Surface Power Systems
Project Programmatic Risk Assessment



Rank, Trend	Description	Likelihood, Consequence (e.g. $, weeks of slip, technical)	Risk Management Approach
1 ➡	1. Stable Project Budget Authority	Cost growth of near-term Cx programs represent challenges for Lunar Surface Systems technologies	Continue support to Cx LSS project Maintain high project performance on milestones and deliverables
2 ➡	2. Uncertain Customer Schedule	Cx LSS need dates dependent on current Cx program progress and budget, and currently undefined	Maintain strong communications with Cx LSS staff via Power Element lead
3 ➡	3. Undefined Customer Requirements	Maturation of Cx requirements may impact technology needs	Maintain close communications with LSS Adjust requirements as needed Maintain FSPS applicability to broad range of Lunar & Mars surface expected requirements

Fission Surface Power Systems (FSPS)

Fission Surface Power Systems Project
Technical Risk Assessment



Rank, Trend	Description	Likelihood (L), Consequence (C)	Risk Management Approach
1 ➡	Given that funding and progress on space nuclear power has not been even in the past decade, fission surface system technology development may suffer unanticipated problems	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 uncertainty in magnitude of unexpected problems	Maintain affordable FSPS approach • Low temp reactor • Non-refractory materials • Within existing database
2 ➡	Given that Stirling power conversion technology was last developed for 10's of kilowatts for space power more than a decade ago, Stirling technology development fails to meet performance, mass, or cost objectives	L of 2 due to prior Stirling space power conversion experience, including laboratory demonstrations of 25 kW Stirling Space Power Demonstrator Engine in 1980's. C of 2 due to increased radiator size needed for options other than Stirling	Multi-kilowatt Stirling engine technology demonstrator designs were conducted in parallel by two major Stirling engine vendors Brayton cycle technology demonstrator engine design is proceeding in parallel to Stirling design as back-up
3 ➡	Given that the lunar surface presents a unique environment for space radiators, and that a fission power system rejects heat at higher temperature than is common to most space radiator designs, development of a light weight fission surface power heat rejection system may face unexpected challenges	L of 2 due to large database of space radiator development, including the ISS and Orion service module. C of 2 due to increase of system weight if radiator mass and performance goals are not met (likelihood was reassessed due to better understanding of likelihood level definitions)	The Jupiter Icy Moons Orbiter mission began light weight high temperature radiator development that FSPS has leveraged FSPS heat rejection technology development subsequently began early in the FSPS project, and a technology demonstrator design has already been successfully completed
4 ➡	Given that a space reactor has not been flown by the U.S. for decades, recovery of space reactor design knowledge may be incomplete and require redevelopment	L of 1 due to affordable FSPS approach that is based on well known reactor technology. C of 4 due to costs of redeveloping space nuclear reactor technology	Continue affordable FSPS approach that has at its basis the avoidance of new reactor technology development

Fission Surface Power Systems (FSPS)

TRL Assessment

Fission Surface Power Systems (FSPS)

ID	Task Name	Contact	Start	Finish
1	**Key Events**		**Tue 12/9/08**	**Wed 10/1/14**
2	System Reqmts Review	Mason	Tue 12/9/08	Tue 12/9/08
3	Prelim Design Review	Mason	Tue 2/24/09	Tue 2/24/09
4	Comp Final Design Review	Mason	Tue 5/19/09	Tue 5/19/09
5	Final System Spec	Mason	Tue 6/23/09	Tue 6/23/09
6	System Final Design Review	Mason	Tue 10/20/09	Tue 10/20/09
7	Hardware Review	Mason	Tue 10/5/10	Tue 10/5/10
8	Test Readiness Review	Houts	Fri 3/25/11	Fri 3/25/11
9	Hardware Review	Mason	Mon 1/9/12	Mon 1/9/12
10	Test Readiness Review	Mason	Mon 12/3/12	Mon 12/3/12
11	Hardware Review	Mason	Tue 10/1/13	Tue 10/1/13
12	Test Readiness Review	Mason	Mon 3/31/14	Mon 3/31/14
13	Non-nuclear TRL6	Mason	Wed 10/1/14	Wed 10/1/14
14	**Pathfinder Testing**		**Mon 12/1/08**	**Thu 9/30/10**
15	Direct Drive Gas Brayton	Hervol	Mon 12/1/08	Fri 2/27/09
16	Stirling Alt Rad Test Article	Bowman	Mon 2/2/09	Fri 6/26/09
17	Full-scale Radiator	Ellis	Fri 3/27/09	Fri 7/31/09
18	NaK-Heated Stirling	Geng	Mon 5/4/09	Fri 9/25/09
19	Stirling PMAD Devt	Hervol	Mon 8/3/09	Fri 8/27/10
20	Rx Control Drive Ass'y	Qualls	Tue 10/6/09	Fri 8/27/10
21	Full-scale ALIP	Houts	Tue 10/6/09	Fri 2/12/10
22	IHX Prototype	Qualls	Mon 1/4/10	Fri 8/27/10
23	7-Pin Heater Bundle	Houts	Mon 5/3/10	Fri 7/30/10
24	Coupled-Stirling	Geng	Mon 5/3/10	Thu 9/30/10
25	**Reactor Simulator**		**Tue 10/6/09**	**Fri 3/30/12**
26	Intermediate Heat Exch	Qualls	Tue 10/6/09	Fri 4/16/10
27	Primary Pump	Werner	Tue 10/6/09	Thu 9/30/10
28	Primary Vol Accum	Qualls	Tue 10/6/09	Thu 9/30/10
29	Rx Sim Controller	Qualls	Tue 10/6/09	Fri 3/30/12
30	RPCSIM System Model	Radel	Tue 10/6/09	Fri 3/30/12
31	Core Simulator	Houts	Mon 8/2/10	Fri 3/25/11
32	NaK Fill & Drain	Houts	Mon 8/2/10	Fri 3/30/12
33	Intermediate Pump	Werner	Wed 12/29/10	Fri 9/30/11
34	Intermediate Vol Accum	Qualls	Wed 12/29/10	Fri 9/30/11
35	Rx Sim Assembly	Houts	Wed 12/29/10	Fri 3/30/12
36	**Rx Sim Testing**		**Fri 10/1/10**	**Fri 12/30/11**
37	Primary Pump	Houts	Fri 10/1/10	Tue 12/28/10
38	Primary Loop	Houts	Fri 4/1/11	Fri 9/30/11
39	Intermediate Pump	Houts	Mon 10/3/11	Fri 12/30/11
40	**Balance of Plant**		**Mon 3/22/10**	**Fri 6/28/13**
41	Power Conv Unit	Wood	Mon 3/22/10	Fri 6/15/12
42	Facility Cooling System	Hervol	Mon 10/4/10	Fri 3/30/12
43	Elect Load Simulator	Hervol	Mon 10/4/10	Fri 3/30/12
44	Data Acq System	Gibson	Mon 10/4/10	Fri 3/30/12
45	Truss Assembly	Gibson	Mon 10/4/10	Fri 3/30/12
46	Heat Reject System	TBD	Fri 4/1/11	Fri 6/28/13
47	HRS Assembly	Gibson	Mon 1/7/13	Fri 6/28/13
48	**System Testing**		**Mon 4/2/12**	**Tue 9/30/14**
49	RPCSIM Benchmarking	Radel	Mon 4/2/12	Tue 9/30/14
50	Rx-PC Integration	Gibson	Mon 4/2/12	Fri 11/30/12
51	Rx-PC Demo	Mason	Tue 12/4/12	Wed 7/3/13
52	HRS Integration	Gibson	Mon 7/1/13	Fri 3/28/14
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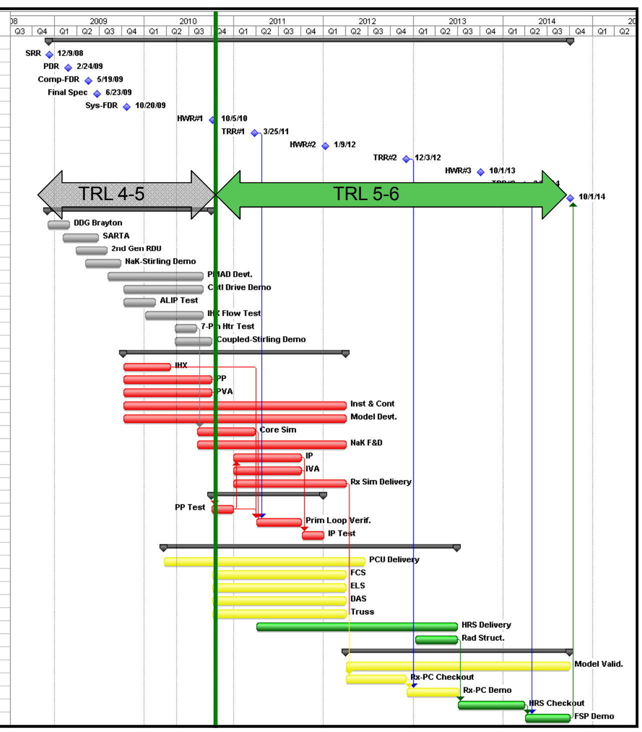


FPS PPBE-12 Budget

Element	FY11	FY12	FY13	FY14	Total
Component Development/Fab	6.0	6.8	5.5	3.0	21.3
Core Simulator	1.1	1.5	1.1	0.8	4.5
NaK Fluid System	1.2	1.4	0.9	0.6	3.9
Power Conversion Unit	3.1	1.8	0.8	0.4	6.1
Heat Rejection System	0.7	2.2	2.7	1.2	6.8
System Engr & Integration	2.9	5.1	5.4	4.8	18.2
Data Acquisition & Controls	0.7	0.8	0.5	0.4	2.3
Test Support Equipment	0.7	0.6	0.6	0.4	2.3
Test Planning & Operations	0.6	1.5	1.6	1.6	5.3
Facility Consumables & Maint.	0.3	0.5	0.8	0.6	2.1
Data Analysis & Model Valid.	0.7	1.7	1.9	1.9	6.2
Separate Effects Testing	0.8	0.8	1.6	3.6	6.9
Project Mgmt/Travel/Other	0.9	1.0	1.1	1.0	4.0
Total	10.6	13.7	13.6	12.4	50.3

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

Cost Element Descriptions

Cost Element	Description
Core Simulator	48 kWt nominal, 90 kWt max electric heater with 36 pin resistor elements arranged in bundle that simulates reactor core
NaK Fluid System	875 K NaK heat transport loop including two pumps, two volume accumulators, intermediate heat exchanger, piping, fill/drain system, and argon pressurant
Power Conversion Unit	12 kWe dual, opposed free-piston Stirling converter, NaK hot-end heat exchanger, H_2O cold-end heat exchanger, 400 Vac-to-120 Vdc power controller, helium gas fill/drain
Heat Rejection System	36 kWt, 6 panel composite heat pipe radiator assembly, 375 K H_2O heat transport loop including pump and accumulator
Data Acquisition & Controls	Instrumentation, cables, feedthroughs, signal conditioning, calibration, power supplies, auxiliary heating, computers, software, data racks
Test Support Equipment	Test support structure, facility interface structure, facility cooling system (pre-HRS), electric load simulator, water fill/drain, thermal insulation
Test Planning & Operations	Systems engineering, test plan development, hazards analysis, safety permit process, checksheets/procedures, test limits, performance predictions, test operations
Facility Consumables & Maintenance	Facility prep, vacuum, coldwall, liquid nitrogen, electrical service, uninterruptible power system, facility upgrades (e.g., CO_2), equipment spares
Data Analysis & Model Validation	System performance model, reactivity feedback model, fluid and material properties, data processing and interpretation, test reports, model refinements, model extrapolation to flight system designs
Separate Effects Testing	Coupon and component irradiation testing, reactor control drive testing, reflector and shielding materials, reactor cavity cooling, lunar/Mars regolith interactions
Project Mgmt/Travel/Other	Management, reporting, budget, travel, indirect costs

Close-out Plans

Fission Surface Power Systems (FSPS)

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

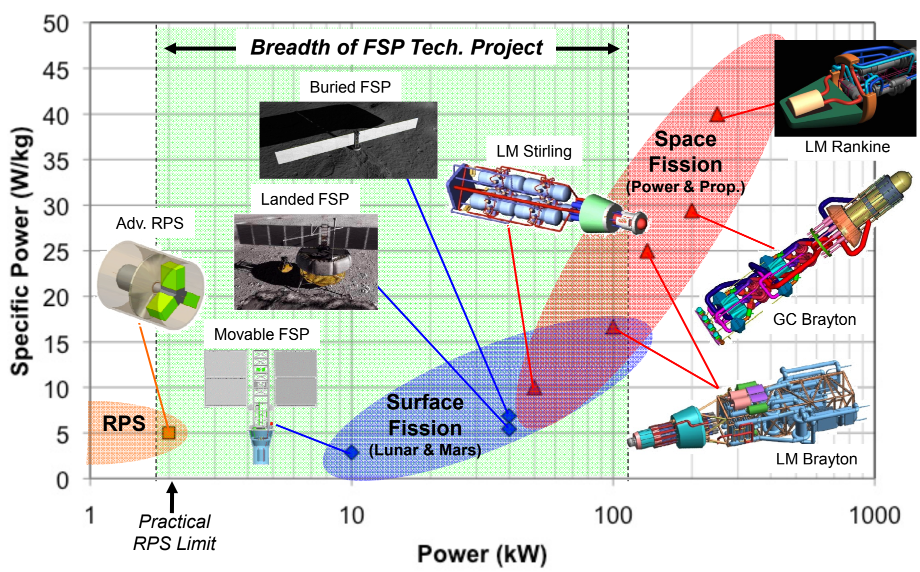
Fission Surface Power Systems (FSPS)

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

Fission Surface Power Systems (FSPS)

FSP Technology Relevance



Fission Surface Power Systems (FSPS)

Relationship to Foundational Domain

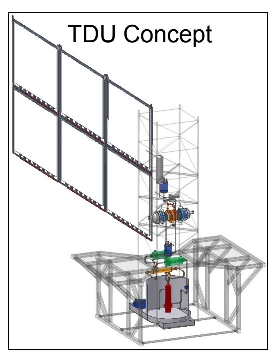
- Fission team members can support architecture and concept design studies in related domain projects including:
  - Fission systems for EP demos
  - Alternative surface power configurations for ISRU demos

- 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

Fission Surface Power Systems (FSPS)

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



Fission Surface Power Systems (FSPS)

Lessons Learned

Fission Surface Power Systems (FSPS)

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

Fission Surface Power Systems (FSPS)

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

PT: Fission Surface Power Systems
PM: Don Palac
PI: Lee Mason

Objective: ***Completion Date: Dec. 2008***

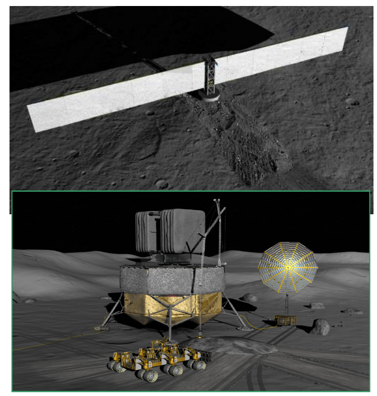
Constellation Lunar Surface Systems (LSS) is defining architectures for lunar exploration in support of architecture analysis and down-selection. Prompted by the Fission Surface Power Systems workshop in May 2008, LSS initiated development of a FSPS – focused scenario to allow comparison of the use of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



Shown: LSS Scenario 5 buried FSPS and lander-integrated FSPS concepts

NON-PROPRIETARY ***Comp. Rpt. File Name:*** FSP for Jan F2F rev1.ppt **Reporting Period: December 2008**

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

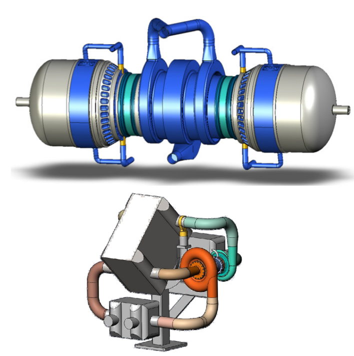
PT: Fission Surface Power Systems
PM: Don Palac
PI: Lee Mason

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.



Shown: Stirling (top) and Brayton Power Conversion Unit Final Designs (not to scale)

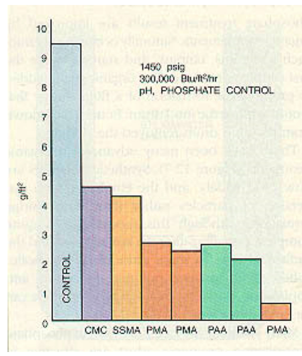
Completion of Fouling, Oxidation, and Additives Study

PT: Fission Surface Power Systems
PM: Don Palac
PI: Dave Ellis/Don Jaworske/Jim Sanzi

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

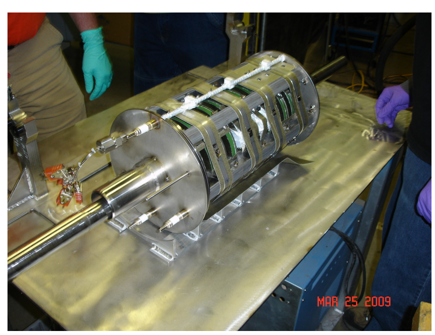
Delivery of Liquid Metal Electromagnetic Annular Linear Induction Pump (ALIP)

PT: Fission Surface Power Systems
PM: Don Palac
PI: Jim Werner/Idaho Nat'l Lab

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

PT: Fission Surface Power Systems
PM: Don Palac
PI: Lee Mason/Dave Ellis

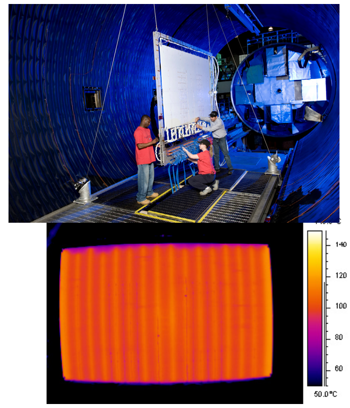
Objective: The Second Generation RDU is a full-scale radiator comparable in design, size and performance to a radiator for lunar and Martian power applications. Testing in a thermal vacuum chamber simulates conditions on the Moon. The radiator was tested with varying water flow rates, water temperatures, 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.



Shown: The Second Generation RDU in Vacuum Facility #6 and an infrared camera image of the radiator showing temperature distribution.

Initial Primary Test Circuit Stirling Test Results

PT: Fission Surface Power Systems
PM: Don Palac
PI: Lee Mason/Mike Houts

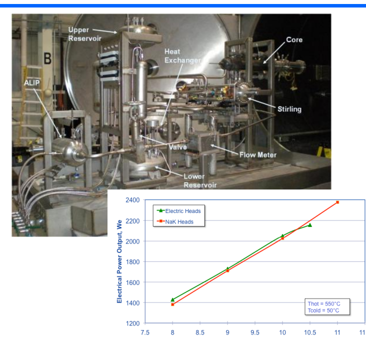
Objective: Prior to fabrication of full scale power conversion demonstrators, Pathfinder test articles were developed to demonstrate the feasibility of application of power conversion technologies to the expected Fission Surface Power System requirements. In addition to providing sub-scale, relatively 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.



Shown: Picture of Primary Test Circuit with Reactor Core Simulator, Liquid Metal NaK Heat Transfer, and Stirling Power Conversion. Graph Showing Match of Stirling Output to Data from Prior Electrically Heated Test

Fabricate a Full Scale 7-Pin Thermal Simulator Bundle

PT: Fission Surface Power Systems
PM: Don Palac
PI: Lee Mason/Mike Houts

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.

Shown: Assembled Bundle (top); Bundle grid plate, pin simulators, and core body (left); neck-down region of pin simulator (center); pin simulators, core body, downcomer, and outer pipe (right).

Feasibility Test Loops FY09 Demonstrate Methods for Measuring NaK Impurities Complete

PT: Fission Surface Power Systems
PM: Don Palac
PI: Lee Mason/Mike Houts

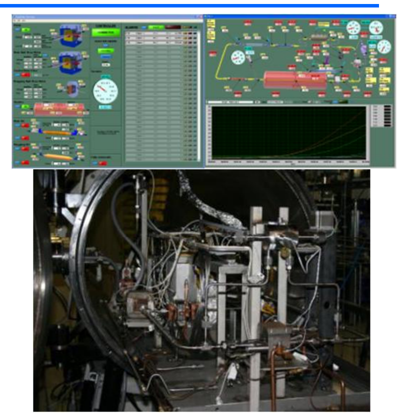
Objective: All 34 reactors launched to date (1 US, 33 Soviet) have been cooled by a pumped sodium-potassium (NaK) coolant. The systems operated for up to a year in space with excellent performance. For Fission Surface Power (FSP) systems, lifetimes of 8 years or more may be desired. To help ensure extremely 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.



Shown: Top:- FTL instrumentation during testing; Bottom - FTL prior to insertion into chamber for NaK impurities testing

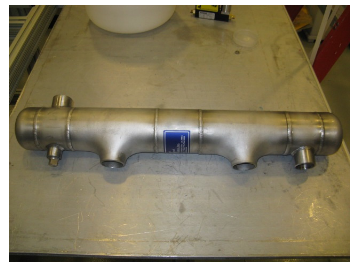
NaK to NaK Heat Exchanger Fabrication

PT: Fission Surface Power Systems
PM: Don Palac
PI: Lee Mason/Lou Qualls

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 convertors. 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.



Shown: Fission Surface Power NaK to NaK intermediate heat exchanger demonstration unit

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.

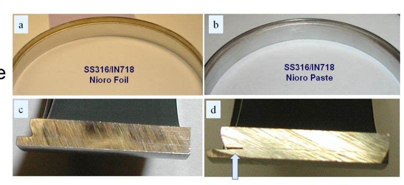
Evaluate Prototypic Stirling Heat Exchanger Joint

PT: Fission Surface Power Systems
PM: Don Palac
PI: Ivan Locci/Lee Mason

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.



Shown: a) and (b) examples of foil and paste filler material used to braze dissimilar rings; (c) and (d) Transverse sections contrasting completely filled brazed region versus a region revealing an unfilled gap at the top of the ring where the braze was originally dispensed

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.

RELAP FSPS Model Development

PT: Fission Surface Power Systems
PM: Don Palac
PI: James Werner (INL)/Lee Mason (GRC)

Objective: To develop the parametric and transient systems models and risk assessment tools needed for the AFSPS project. This is a task is to develop an initial Relap5 reference concept model of the Fission Surface Power System.

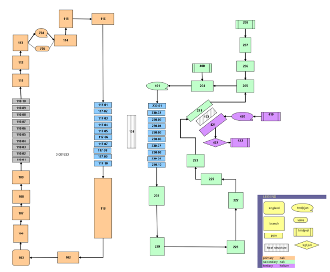
Key Accomplishment/Deliverable Milestone:

• 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.



Shown: Graphical Representation of Relap5 Lunar Reactor Model

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

PT: Fission Surface Power Systems
PM: Don Palac
PI: Don Jaworske/Jim Sanzi/ Lee Mason

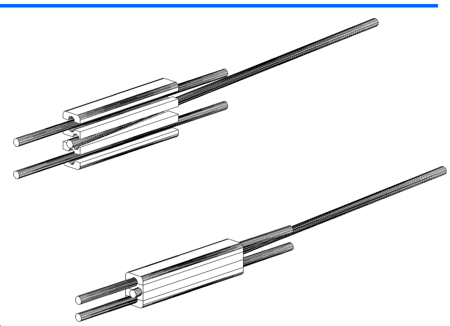
Objective: Heat exchange between a closed loop heat source and the evaporators of heat pipes in a radiator panel is critical to rejection of Fission Surface Power System (FSPS) excess heat. Experiments were conducted to examine alternatives for heat transfer from the FSPS excess heat water loop to radiator 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.



Novel Geometry of a Poco Graphite Heat Exchanger With Dual Titanium Manifolds and a Single Heat Pipe Located Across the Center

FSPS Control Drum Control Drive Assembly Testing

PT: Fission Surface Power Systems
PM: Don Palac
PI: Lee Mason/Lou Qualls

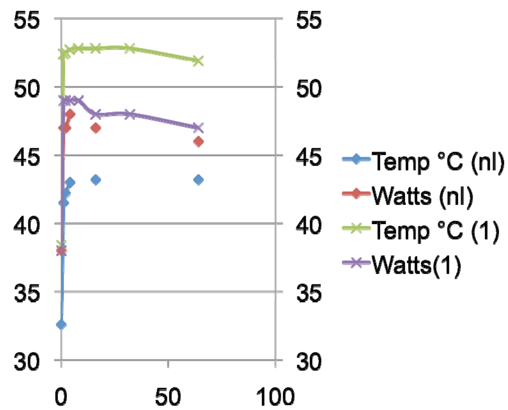
Objective: Assemble and perform initial performance characterizations on a prototypic reactor control drive assembly. Hardware demonstration of the FSPS reactor control method will validate the feasibility of the FSPS reactor control approach and provide information for FSP reactor control system design.

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.



Shown: Controller consumption and motor surface temperature as a function of rotation rate and configuration under no load and with a single 30 to 1 reducer. Power consumption was not affected by gear reduction, however the operating temperature is higher due to different thermal sink.

Develop FSP System Model Validation Plan

PT: Fission Surface Power Systems
PM: Don Palac
PI: Jim Werner/Mike Houts/Lee Mason

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

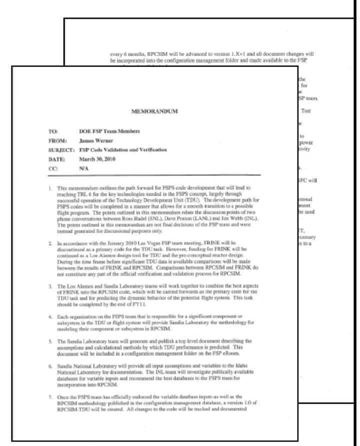
Date of Accomplishment: December, 2009

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 use to operate the FSP TDSU system in an operationally relevant environment (NASA TRL 6)


MEMORANDUM

TO: DOE FSP Team Members
FROM: James Werner
SUBJECT: FSP Code Validation and Verification
DATE: March 30, 2010
CC: N/A

Model Validation Plan

Complete Initial Fission Surface Power (FSP) System Concept Definition

PT: Fission Surface Power Systems
PM: Don Palac
PI: Lee Mason

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

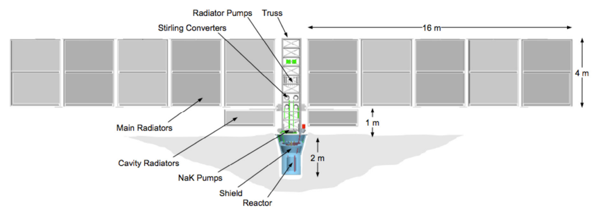
•Includes the results of trade studies to define an initial FSP concept consistent with expected lunar and Mars surface outpost requirements, and FSP goals of low development risk and cost

•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



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

Award Power Conversion Unit Fabrication Contract

PT: Fission Surface Power Systems
PM: Don Palac
PI: Lee Mason

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

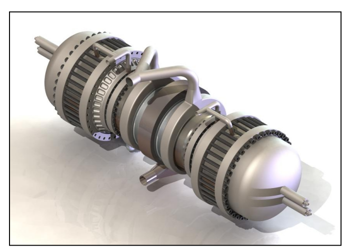
– Phase II Fabrication and Test Proposals received in August 2009; Source Evaluation Committee completed review and Source Selection Official made selection in March 2010

– 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



12 kWe Dual-Opposed, Free-Piston Stirling Power Conversion Unit

Annular Linear Induction Pump (ALIP) Test Report

PT: Fission Surface Power Systems
PM: Don Palac
PI: Mike Houts/Jim Werner

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.

Above: ALIP mounted in the ALIP Test Circuit (ATC)
Below: ATC prior to insertion in chamber and test

Demonstrate Thermodynamically-Coupled Stirling Pair

PT: Fission Surface Power Systems
PM: Don Palac
PI: Lee Mason

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

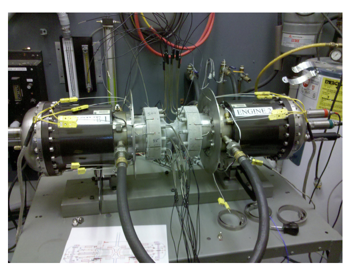
Date of Accomplishment: March, 2010

Key Accomplishment/Deliverable/Milestone:

- A pair of existing 1 kWe 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-motoring 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 GRC for performance testing



2 kWe Thermodynamically-Coupled Stirling Assembly during Cold-Motor Demonstration Test

Deliver TDU Intermediate Heat Exchanger to MSFC

PT: Fission Surface Power Systems
PM: Don Palac
PI: Lou Qualls

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

Completed TDU Intermediate Heat Exchanger

Refine Operations Concept for FSP Systems

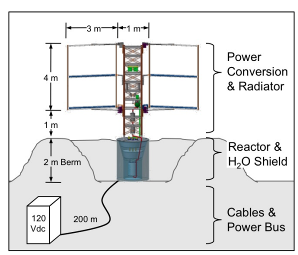
PT: Fission Surface Power Systems
PM: Don Palac
PI: Lee Mason

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 re-started as needed
  • Design layout, mass summary, and full "ops concept" description provided to IAWG Campaign Integration Team
  • System enables full eclipse operations at non-polar GPoD mission sites previously not possible with solar-based power systems
- Findings documented in conference paper for International Energy Conversion Engineering Conference, July 26-28 Nashville Tennessee



Movable FSP Concept for Global Point of Departure Architecture

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

Initiate Testing of 7-Pin Bundle

PT: Fission Surface Power Systems
PM: Don Palac
PI: Mike Houts/Lee Mason

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

7-Pin Bundle in MSFC Primary Test Circuit

Publications

Author	Title	Meeting/Journal	Report Number
McGuire, M.L., et al.	USE OF HIGH-POWER BRAYTON NUCLEAR ELECTRIC PROPULSION (NEP) FOR A 2033 MARS ROUND-TRIP MISSION	SPACE TECHNOLOGY & APPLICATIONS INTERNATIONAL FORUM (STAIF-2006) - Albuquerque, New Mexico	TM-214106
Mason, L.	A PRACTICAL APPROACH TO STARTING FISSIO SURFACE POWER DEVELOPMENT	2006 INTERNATIONAL CONGRESS ON ADVANCES IN NUCLEAR POWER PLANTS (ICAPP) - Reno, Nevada	TM-214366
Siamidis, J.	HEAT REJECTION CONCEPTS FOR LUNAR FISSION SURFACE POWER APPLICATIONS	FOURTH INTERNATIONAL ENERGY CONVERSION ENGINEERING CONFERENCE AND EXHIBIT (IECEC) - San Diego, California	CR-214388
Johnson, P.K., et al.	PERFORMANCE AND OPERATIONAL CHARACTERISTICS FOR A DUAL BRAYTON SPACE POWER SYSTEM WITH COMMON GAS INVENTORY	FOURTH INTERNATIONAL ENERGY CONVERSION ENGINEERING CONFERENCE AND EXHIBIT (IECEC) - San Diego, California	TM-214393
Johnson, P.K.	A METHOD FOR CALCULATING VISCOSITY AND THERMAL CONDUCTIVITY OF A HELIUM-XENON GAS MIXTURE	N/A	CR-214394
Birchenough, A., et al.	OPERATIONAL RESULTS FROM A HIGH POWER ALTERNATOR TEST BED	SPACE TECHNOLOGY AND APPLICATIONS INTERNATIONAL FORUM (STAIF-2007) - Albuquerque, New Mexico	TM-214708
Sanzi, J.L.	THERMAL PERFORMANCE OF HIGH TEMPERATURE TITANIUM - WATER HEAT PIPES BY MULTIPLE HEAT PIPE MANUFACTURERS	SPACE TECHNOLOGY AND APPLICATIONS INTERNATIONAL FORUM (STAIF-2007) - Albuquerque, New Mexico	CR-214820
Ellis, D.L.	EFFECTS OF LONG-TERM THERMAL EXPOSURE ON CHEMICALLY PURE (CP) TITANIUM GRADE 2 ROOM TEMPERATURE TENSILE PROPERTIES AND MICROSTRUCTURE	N/A	TM-214968
Juhasz, A.J.	HEAT TRANSFER ANALYSIS OF A CLOSED BRAYTON CYCLE SPACE RADIATOR	FIFTH INTERNATIONAL ENERGY CONVERSION ENGINEERING CONFERENCE AND EXHIBIT (IECEC) - St. Louis, Missouri	TM-215003
Birchenough, A., et al.	TEST RESULTS FROM A SIMULATED HIGH VOLTAGE LUNAR POWER TRANSMISSION LINE	SPACE TECHNOLOGY AND APPLICATIONS INTERNATIONAL FORUM (STAIF-2008) - Albuquerque, New Mexico	TM- 215164

Publications

Author	Title	Meeting/Journal	Report Number
Mason, L.S., et al.	SYSTEM CONCEPTS FOR AFFORDABLE FISSION SURFACE POWER	SPACE TECHNOLOGY AND APPLICATIONS INTERNATIONAL FORUM (STAIF-2008) - Albuquerque, New Mexico	TM-215166
Jaworske, D.A., et al.	REVIEW OF END-OF-LIFE THERMAL CONTROL COATING PERFORMANCE	N/A	TM-215173
Jaworske, D.A., et al.	OPTICAL PROPERTIES OF THERMAL CONTROL COATINGS AFTER WEATHERING, SIMULATED ASCENT HEATING, AND SIMULATED SPACE RADIATION EXPOSURE	CENTRAL REGIONAL MEETING OF THE AMERICAN CHEMICAL SOCIETY - Columbus, Ohio	TM-215259
Dyson, R.W., et al.	INVESTIGATION OF LIQUID METAL HEAT EXCHANGER DESIGNS FOR FISSION SURFACE POWER	SIXTH INTERNATIONAL ENERGY CONVERSION ENGINEERING CONFERENCE (IECEC) - Cleveland, Ohio	TM-215505
Ellis, D.L., et al.	EFFECTS OF LONG THERMAL EXPOSURE ON CHEMICALLY PURE (CP) TITANIUM GRADE 2 ELEVATED TEMPERATURE TENSILE PROPERTIES	N/A	TM-215484
Briggs, M.H., et al.	SUMMARY OF TEXT RESULTS FROM A 1KWE-CLASS FREE-PISTON STIRLING POWER CONVERTOR INTEGRATED WITH A PUMPED NAK LOOP	EIGTH INTERNATIONAL ENERGY CONVERSION ENGINEERING CONFERENCE (IECEC) - Nashville, Tennessee	TM-216934
Birchenough, A., et al.	TEST RESULTS FROM A HIGH POWER LINEAR ALTERNATOR TEST RIG	EIGTH INTERNATIONAL ENERGY CONVERSION ENGINEERING CONFERENCE (IECEC) - Nashville, Tennessee	TM-216910
Mason, L.S., et al.	A SUMMARY OF NASA ARCHITECTURE STUDIES UTILIZING FISSION SURFACE POWER TECHNOLOGY	EIGTH INTERNATIONAL ENERGY CONVERSION ENGINEERING CONFERENCE (IECEC) - Nashville, Tennessee	TM-216819

Publications

Author	Title	Meeting/Journal	Report Number
Bragg-Sitton, S.M. and Webster, K.L	APPLICATION OF SIMULATED REACTIVITY FEEDBACK IN NONNUCLEAR TESTING OF A DIRECT-DRIVE GAS-COOLED REACTOR	NA	NASA/TM-2007-214959
Butler, C. and Albright, D	CORE PHYSICS AND KINETICS CALCULATIONS FOR THE FISSIONING PLASMA CORE REACTOR	NA	NASA/CR-2007–214724
Reid, R.S. and Martin, J.J. and Yocum, D.J. and Stewart, E.T	HEAT TRANSFER AND PRESSURE DROP IN CONCENTRIC ANNULAR FLOWS OF BINARY INERT GAS MIXTURES	NA	NASA/TM-2007-215135
Polzin, K.A. and Markusic, T.E. and Stanojev, B.J.,	LIQUID BISMUTH PROPELLANT MANAGEMENT SYSTEM FOR THE VERY HIGH SPECIFIC IMPULSE THRUSTER WITH ANODE LAYER	53RD JANNAF PROPULSION MEETING / 2ND LIQUID PROPULSION / 1ST SPACECRAFT PROPULSION SUBCOMMITTEE JOINT MEETING, Monterey, CA 29TH INTERNATIONAL ELECTRIC PROPULSION CONFERENCE, Princeton, NJ, 42ND AIAA/ASME/SAE/ASEE JOINT PROPULSION CONFERENCE, Sacramento, CA JOURNAL OF PROPULSION AND POWER, Vol. 23, No. 6, pp. 1285-1290, Nov.-Dec. 2007.	NASA/TM-2007-214958
Polzin, K.A	LIQUID-METAL PUMP TECHNOLOGIES FOR NUCLEAR SURFACE POWER	SPACE NUCLEAR CONFERENCE 2007, Boston, MA	NASA/TM-2007-214851
Kazeminezhad, F. and Anghaie, S	EXPERIMENTAL PLANS FOR SUBSYSTEMS OF A SHOCK WAVE DRIVEN GAS CORE REACTOR	N/A	NASA/CR-2008-215412
Kazeminezhad, F. and Anghaie, S	GAS CORE REACTOR NUMERICAL SIMULATION USING A COUPLED MHD-MCNP MODEL	N/A	NASA/CR-2008-215408
Bragg-Sitton, S.M. and Dickens, R.E. et. al	HEATER DEVELOPMENT, FABRICATION, AND TESTING: ANALYSIS OF FABRICATED HEATERS	AMERICAN NUCLEAR SOCIETY: 2007 ANNUAL MEETING, Boston, MA SPACE TECHNOLOGY & APPLICATIONS INTERNATIONAL FORUM (STAIF-2008) - Albuquerque, New Mexico	NASA/TM-2008-215466

Publications

Author	Title	Meeting/Journal	Report Number
Hickman, R.R. and Martin, J.J. et al.	COST ESTIMATE FOR MOLYBDENUM AND TANTALUM REFRACTORY METAL ALLOY FLOW CIRCUIT CONCEPTS	NA	NASA_TM_2010_216431
Martin, James and Reid, R.S. and Bragg-Sitton, S.M	DESIGN OF REFRACTORY METAL LIFE TEST HEAT PIPE AND CALORIMETER	2006 INTERNATIONAL CONGRESS ON ADVANCES IN NUCLEAR POWER PLANTS (ICAPP) - Reno, Nevada SPACE TECHNOLOGY & APPLICATIONS INTERNATIONAL FORUM (STAIF-2006) - Albuquerque, New Mexico	NASA/TP—2010–216435
Godfroy, T.J. and Martin, J.J. et al.	DOCUMENTATION OF STAINLESS STEEL LITHIUM CIRCUIT TEST SECTION DESIGN,	SPACE TECHNOLOGY & APPLICATIONS INTERNATIONAL FORUM (STAIF-2006) - Albuquerque, New Mexico	NASA_TP_2010_216437
Polzin, K.A. and Pearson, J.B. et al.	PERFORMANCE TESTING OF A PROTOTYPIC ANNULAR LINEAR INDUCTION PUMP FOR FISSION SURFACE POWER	57TH JANNAF PROPULSION MEETING/5TH LIQUID PROPULSION/4TH SPACECRAFT PROPULSION SUBCOMMITTEE JOINT MEETING, Colorado Springs, CO, 8TH INTERNATIONAL ENERGY CONVERSION ENGINEERING CONFERENCE, Nashville, TN	NASA_TP_2010_216430
Garber, Anne et al.	Performance Testing of a 7-Pin Bundle in the Fission Surface Power-Primary Test Circuit		In work
Bradley, David et al.	Performance Testing of Subscale Fission Surface Power Components as Part of the Feasibility Test Loop		In work

eRoom Summary Report Location: Fission Surface Power > FSP Project Management > Project Management > Milestone Reporting

		Milestone Title (red or blue = reportable)	Resp. Org.	Completion Date	Description	File Name	Report Number	ETDP Summary?
FY09								
1.0	Project Mgt	Support PPBE-11 Budget Cycle	GRC	Apr-09	PPBE-11 Input	FSPS FY11 PPBE INGUIDE_4_24_09.xls		
		Prepare Integrated Baseline Review Package	GRC	Sep-09	Project Plan, EVM, & assoc. docs.	10_5_09_FSP_Proj Pln accept.doc		
2.1.1	Concept Studies	Complete Reference Concept Trade Studies	LANL	Jan-09	ANS Paper	NETS09-208589-FSPSReactor_final.pdf	NETS09-208589	
		Complete Initial Concept Definition	GRC	Feb-10	Final Concept Definition Doc.	Initial Concept Definition 021710.doc		
2.1.2	Architecture Studies	Support FSP-Lander Integration Studies	GRC/LANL	Oct-08	Presentation to LSS Face to Face	FSP for Jan F2F rev1.ppt		
		Support LSS Scenario 5 Definition	GRC	Jan-09	Presentation to LSS Face to Face	FSP for Jan F2F rev1.ppt		Y
2.2.3	System Modeling	Update System Model with Components	LANL	Feb-09		Superceded by FY10 milestone		
		Update RPCSIM Model of Reference Concept	SNL	Jul-09	Deliverable Letter from SNL	SD_02_02 Deliverable Letter-Palac		
		Develop Initial RELAP Reference Concept Model	INL	Oct-09	Summary Report of FSP RELAP	Lunar Reactor Report.doc		Y
		Complete Fully Functional Dynamic System Moc	LANL	Jan-10	Source code	SystemModel-Jan09-dip.pptx		
4.1.1	Reactor Simulator	Complete RPCSIM Model of TDU	SNL	Jan-09	Deliverable Letter from SNL	Palac Ltr Mar 09.pdf		
		Complete Reactor Simulator Design Package	LANL/MSFC	Sep-09		Included in FY10 Initial Concept Def. Report in 10		
		Complete Reactor Simulator Controller Concept	ORNL	Sep-09	Milestone 1-page summary	fspscontrolstrategysummary.docx		
		Complete Reactor Simulator Accept. Test Plan	MSFC/LANL	Feb-10	LANL/SNL Reports	TDU Control Strategy Plan-v1.doc		
4.1.2	Full Scale PCU	Complete PCU Final Design Reviews	GRC	Apr-09	Milestone 1-page summary	FSPS_PCU_FDR_Milestone_4_09.ppt		Y
		Issue Phase 2 Request For Proposal	GRC	Jun-09	Copy of Synopsis	NNC09ZRP001R.pdf		
		Award Phase 2 Fabrication Contract	GRC	Mar-10	Copy of contract	Attac001.PDF		Y
		Complete Phase 2 Work Plan	GRC	May-10	Work Plan			
4.1.4	TDU Facility Integ.	Develop TDU Data Acquisition Plan	GRC	Mar-09	PDR Presentation	Data Acquisition System.ppt		
		Complete Facility Cooling System Concept	MSFC	Oct-09	FDR Presentation	FCS_Hervol_System_ FDR_FINAL.ppt		
4.2.1	Heat Exchangers	Evaluate NaK-to-NaK HX Technology Options	ORNL	Mar-09	PDR Presentation	fspscdrihxquallsfinal.pptx		
		Fabricate a NaK-to-NaK Heat Exchanger	ORNL	Aug-09	Milestone 1-page summary	FSPS_NaKtoNaKHeatExchanger_8_09a.ppt		Y
4.2.2	Feasibility Test Loops	Complete On-Line Purification Test Report	MSFC	Aug-09	White paper	20091215 Summary of FTL Activities.doc edit		
		Demonstrate Methods for Measuring NaK Impur	MSFC	Jul-09	Milestone 1-page summary	FSPS_PTC_NaK_Impurities_Milestone_7_09MGH.ppt		Y
		Initiate Mass Transport Measurement Test	MSFC	Sep-09	White paper	20091215 Summary of FTL Activities.doc edit		
4.2.3	Volume Accumulator	Evaluate Volume Accumulator Technology Optic	ORNL	May-09	Component FDR Presentation			
		Fabricate a NaK Volume Accumulator	ORNL	Sep-09	Milestone 1-page summary	VolumeAccumulatorFab.ppt		
4.2.4	Liq. Metal Pump	Develop ALIP Test Plan	INL	Dec-08	Test Plan	EM pump test plan HA Rev 3.doc		
		Deliver ALIP to MSFC	INL	Apr-09	Milestone 1-page summary	FSPS_ALIP_Milestone_4_09.ppt		Y
		Complete ALIP Integration and Checkout	MSFC/INL	Nov-09	Test Readiness Review Report	ATC TRR ER24 memo full (2).doc		
		Complete ALIP Test Report	MSFC/INL	Dec-09	ALIP Test Report Received			Y
4.3.2	Irradiation Testing	Complete Gamma Irradiation Test Report (HFIR	ORNL/SNL	Jul-09	Milestone 1-page summary	FSPS_HFIR_GIF_Milestone_8_09 EES input_r1.ppt		Y
		Estimate Stirling and I&C Radiation Tolerance	ORNL	Sep-09	Milestone 1-page summary	FSPS Estimate of Stirling Rad Toler.ppt		
4.3.3	Instr. & Control	Complete Control Drive Controller Design Repor	ORNL	Apr-09	Component FDR Presentation	FSPS tdu control ORNL_report 2.docx		
		Define I&C Requirements and Design Events	SNL	Mar-09	Component FDR Presentation	fspscdropsquallsfinal.pptx		
		Fabricate a Control Drive Mechanism Assembly	ORNL	Aug-09	Milestone 1-page summary	Control Drive Assembly Fab.ppt		
		Complete Testing of Control Drive Mechanism	ORNL	Dec-09	Milestone 1-page summary	FSPS control drive test complete.pptx		Y
		Complete I&C Design Report	ORNL	Sep-09	Milestone 1-page summary	CompleteI&CDesignReport.ppt		
4.3.4	Shielding	Complete Shield Design Report	ORNL	Sep-09	Milestone 1-page summary	Shieding Design Report.ppt		
4.3.7	Thermal Simulators	Fabricate a Full-scale Pin Heater Bundle	MSFC	Jun-09	Milestone 1-page summary	FSPS_Pin_Heater_Bundle_Milestone_7_17_09.ppt		Y
4.4.1	Stirling	Complete Auburn 5 kWe Stirling Test Report	GRC	Jun-09	Auburn Final Report	Monthly report for June 2009.doc		
		Complete NaK-Stirling Test Report	MSFC/GRC	Sep-09	Conference Report	NaK Stirling Test FINAL REPORT 10_19_09 (compressed)-1.doc		
		Demonstrate Regulated PMAD User Bus	GRC	Aug-09	MMR Charts	Demonstrate_Regulated_PMAD_bus.ppt		
		Demonstrate Thermodynamically-Coupled Stirli	GRC	Mar-10	MMR Charts			Y
4.4.2	Brayton	Complete DDG-Brayton Test Report	GRC	Apr-09	ANS Conference Paper	NETS09 Paper 208198 Bragg-Sitton	NETS09-208198	
4.4.3	PC Materials	Deliver Alternator to DOE for Gamma Irradiatio	GRC	Apr-09	White paper	Dec09 PCMat milestone summary.docx		
		Compare Joining Methods for SS316 to IN718	GRC	May-09	MMR Charts	SARTA_Delivery.ppt		
		Evaluate Prototypic Stirling HX Joint	GRC	Sep-09	Final report	2009-FSP-Milestone-Prototypic-Stirling-Joint-11-9-09dp.doc		Y
4.5.1	Radiators	Deliver 2nd Generation RDU to GRC	GRC	Mar-09	MMR Charts	2ndGendRDUDelivery.ppt		
		Complete Evaluation of SBIR-Developed Panel	GRC	Jul-09	White paper	SBIRPanelMilestoneReport072109.docx		
		Complete 2nd Generation RDU Performance Tes	GRC	Jun-09	Milestone 1-page summary	FSPS_Second Generation RDU Milestone Report.ppt		Y
4.5.2	Heat Pipes	Complete 2 yr Life Testing of Ti-H2O Heat Pipes	GRC	Jan-09	White paper	Two Year Life Test Results of High Temperature Titanium A.doc		
		Complete Low delta-P TIE Heat Exchanger Testi	GRC	Nov-09	IECEC Abstract (paper coming)	Jaworske112409_TIE_LowDeltaP.pdf		Y
		Complete ACT Phase III Heat Pipe Life Test	GRC	Sep-09	MMR Charts	Complete ACT Phase III Heat Pipe Test.ppt		
4.5.3	HR Materials	Complete Fouling, Oxidation, and Additives Stu	GRC	Apr-09	Milestone 1-page summary	FSPS_FoulingOxidationAdditives_Milestone_4_09.ppt		Y
		Complete Thermal Coatings Characterization	GRC	Aug-09	MMR Charts	SBIR Panel & Thermal Coatings 7_09.ppt		
FY10								
1.0	**Project Management**	**Project and Business Management**						
		Support PPBE-12 Budget Cycle	GRC	4/30/2010	Budget Presentation	ETDD FY10 PPBE Presentation-FPS_6_1_10.pptx		
		Prepare Integrated Baseline Review Package	GRC	9/30/2010				
2.0	**Concept Develepment**							
2.1	**Concept Definition**							
2.1.1	System Concept Definition	**Concept Studies**						
2.1.1	System Concept Definition	Refine Ops Concept for FSP Systems	GRC	6/30/2010	TM	TM-2010-216772_DRAFT.pdf	TM-2010-216772	
		Update FSP Shielding Strategies	LANL	9/30/2010	DOE Report	Assessment of Shield and Reflector Materials for Fission Surface Power Syste		
2.1.2	Architecture Studies	**Architecture Studies**						
		Develop FSP Option for Global Point of Departure	GRC	6/30/2010	TM	TM-2010-216772_DRAFT.pdf	TM-2010-216772	
2.2	**Modeling and Tools**							
2.2.1	PC Modeling & Tools	**Stirling Modeling**						
		Add Controller to 6 kWe Stirling Dynamic Model	GRC	12/31/2009	Task Report	Dec09 Stirling Controller Model.doc		
2.2.2	HR Modeling & Tools	**2nd Generation RDU Modeling**						
		Complete Report on 2nd Gen RDU Model Validat	GRC	3/31/2010		2nd GEN RDU Thermal Analysis Report 6-3-2010.pdf		
2.2.3	System Modeling	**FSP System Model Validation**						
2.2.3	System Modeling	Develop FSP System Model Validation Plan	DOE/MSFC	2/28/2010	Memorandum	FSP Code Validation Plan.pdf		Y
2.6	**System Engineering**	**Update to Reactor Element Schedule**						
4.0	**Technology Development**							
4.1	**System Risk Reduction**							
4.1.1	Reactor Simulator	**TDU Reactor Simulator**						
		Develop Core Simulator Acceptance Test Plan	DOE	2/28/2010	Test Plan	Jan10-TDURxSimAcceptanceTestPlan.docx		
		Complete Fabrication of TDU ALIP	INL	8/30/2010				
4.1.1	Reactor Simulator	Deliver TDU Intermediate Heat Exchanger to MSI	ORNL	6/30/2010	Milestone Report	4.1.1_Deliver TDU Intermediate Heat Exchangeralq .ppt		Y
		Initate Testing of TDU ALIP	MSFC	9/30/2010				
		Deliver TDU Primary Volume Accumulator to MSI	ORNL	9/30/2010				
		Fabricate Components of 37 Pin TDU Core Simul	MSFC	9/30/2010				
4.1.1	Reactor Simulator	Demonstrate Heater Control Algorithm	MSFC	11/30/2010				
4.1.2	Technology Demonstration Unit D	**Full Scale Power Conversion Unit**						
		Complete PCU Fabrication Drawing Package	GRC	3/31/2010				
		Complete PCU Interface Requirements Documen	GRC	6/30/2010				
4.1.3	TDU Heat Rejection System	**Initiation of Heat Rejection System Acquisitior**	GRC					
4.1.3	TDU Heat Rejection System	Issue TDU HRS Contract Request for Proposal	GRC	8/31/2010	Deferred to FY11			
4.1.4	Tech Demo Unit Facilities	**TDU Facility Integration**						
		Perform NaK Vacuum Leak Detection Experiment	GRC	3/31/2010	White paper	NaK Leak Detection Experiment_summary.docx		
		Finalize TDU Integration Structure for VF6	GRC	7/31/2010	CAD output	TBD		
		Complete Facility Cooling System Purchase Spec	GRC	9/30/2010				
4.1.5	TDU System	**TDU Systems Integration**						
		Conduct TDU System Final Design Review	GRC	10/31/2009	Presentations from FDR	Various		
		Issue Report on TDU Model Results vs. PTC Data	SNL/LANL	2/28/2010				
		Develop System Control Requirements Documen	ORNL/SNL	6/30/2010	DOE Report	FSPScontroldrive_ORNL_report.pdf		
		Conduct TDU Hardware Review	GRC	10/30/2010				
4.2	**Primary Test Circuit Risk Reduction**							
4.2.1	Annular Linear Induction Integ. &	**In FY10, all ALIP I&T effort is in support of the TDU**						
4.2.2	Pumped Alkali Metal Loop Testin	**PTC Feasibility Test Loops**						
		Complete Report on NaK Loading & Verification	MSFC	8/31/2010				
4.2.3	Accumulator Technololgy	***All Accumulator Work in FY10 is in support of TDU***						
4.2.4	Liquid Metal Pump Technology	**Liquid Metal Pump Technology**						
		Issue Report on ALIP Design Tools	INL	2/26/2010	INL Report	Design of an Annular Linear Induction Pump fc	INL/EXT-10-17950	
		Verify ALIP Design Tools Based on Test Results	INL	5/31/2010		NASA_TP_2010_216430_small.pdf		

4.3	**Reactor Components and Irradiation Testing**					
4.3.2	Irradiation Testing	**Irradiation Testing**				
		Initiate Neutron Irradiation of I&C Materials at HFI	ORNL	3/31/2010	MMR Report	To be superceded by final test report
		Complete I&C Neutron Irradiation Test Report	ORNL	9/30/2010		
4.3.3	Instrumentation & Controls	**Instrumentation & Control Technology**				
		Initate Environment Testing of Control Drive Asse	ORNL	3/31/2010		Superceded by test report (see 4.1.5)
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	
4.3.7	Thermal Simulator Development (	Initiate Testing of 7-Pin Bundle	MSFC	4/30/2010	Monthly Mgt Review - June 10	
		Issue Test Report	MSFC	6/30/2010		
4.4	**Power Conversion Risk Reduction**					
4.4.1	Stirling Power Conversion Risk R	**Stirling Technology**				
4.4.1	Stirling Power Conversion Risk R	Complete Thermodynamically-Coupled Stirling Te	GRC	6/30/2010		
		Demonstrate IGBT-Based Stirling Controller	GRC	8/31/2010		
		Issue Report on Thermodynamically-Coupled Stir	GRC	10/30/2010		
4.4.2	Brayton Power Conversion Risk I	**Brayton work deferred**				
4.4.3	Power Conversion Materials	**PC Materials Evaluation**				
		Deliver Alternator Materials for Neutron Irradiatior	GRC	12/31/2009	Test report	Dec09 Alternator Matls Neutron Irrad.docx
		Develop Stirling Radiation Specification	GRC	7/31/2010	IECEC Paper	Mireles IECEC paper submit to Don.doc
		Evaluate Externally Reinforced Stirling Heater He	GRC	9/30/2010		
4.5	**Heat Rejection Risk Reduction**					
4.5.2	Radiator Panel Technology	**Radiator Panel Technolgy**				
4.5.2	Radiator Panel Technology	Evaluate SBIR-Developed Ultra-light Panel	GRC	4/30/2010		
4.5.3	Heat Pipe Technology	**Heat Pipe Technology**				
		Complete 3 yr Life Testing of Ti-H2O Heat Pipes	GRC	1/31/2010	MMR Report	
		Complete Rack Hardware for Heat Pipe Flight Te:	GRC	5/31/2010	MMR Report	
		Complete Analysis of ACT Phase III Heat Pipe Li	GRC	9/30/2010		
		Deliver Ti-H20 Heat Pipes to DOE for Radiation T	GRC	9/30/2010		
4.5.4	Thermal Interface Evaluation	**AlSiC & Simulated 1/6 g Testing**				
		Complete AlSiC TIE Heat Exchanger Testing	GRC	2/28/2010	IECEC Paper	IECEC060710a.doc
		Evaluate Heat Pipe Performance in Simulated 1/6	GRC	9/30/2010	Test report	Titanium-Square Heat Pipe Test Report 7-13-10.doc
4.5.5	Heat Rejection Materials	**HR Materials work deferred**				

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13. SUPPLEMENTARY NOTES

14. 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/H_2O 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.

15. SUBJECT TERMS
Spacecraft power supplies

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