Space Nuclear Power

- **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)
    - Ulysses GPHS-RTG (1990)
    - Cassini GPHS-RTG (1997)
    - New Horizons GPHS-RTG (2005)

- **Fission Reactor Systems**
  - SNAP-10A (launched 1965)
  - Soviet Buk and Topaz (over 30 systems launched from 1967-1988)
  - SP-100 (1984-1993)
  - Jupiter Icy Moons Orbiter (2002-2005)
  - Fission Power Systems (present)
Why Space Fission Power?

- Abundant power to meet increasing mission demands: scalable from kilowatts to megawatts and beyond
- Potential for very high energy density and long life: significant performance advantages compared to alternatives
- Safe during all mission phases: launched cold, remains subcritical until commanded startup, low residual radiation after shutdown
- Operationally robust: high reliability with capacity for contingency operations
- Environmentally robust: eliminates dependence on sunlight, resilient under adverse environments
- Extremely flexible: can be adapted to a wide range of mission applications using common technology building blocks
- Affordable: detailed studies show development costs are competitive with alternatives
- Potential Terrestrial Spin-offs: Low power, compact, autonomous reactors? Basic technologies?
Projected Applications for Fission Power Systems

1. Planetary/Space Science
   - <1 to 10 kWe
   - 10 to 20 yr life
   - Unmanned, Autonomous
   - Above power range of interest for radioisotope systems
   - Non-Obtrusive; will not interfere with Science Objectives

2. Fission Surface Power (FSP)
   - 10 to 100 kWe
   - 5 to 10 yr Life
   - Human-rated
   - Robust and Reliable; Mass is Secondary
   - Adaptable to Multiple Missions and Environments

3. Nuclear Electric Propulsion (NEP)
   - 100 kWe to Several MWe’s
   - 5 to 15 yr Life
   - Cargo or Piloted Missions to Mars
   - Low Specific Mass (kg/kW); Must provide benefits over SEP
   - Flexible Operations: Thrust, Coast, Science, Standby

Slide courtesy Lee Mason (GRC) / Dave Poston (LANL)
Nuclear Power Performance Regimes

Radioisotope Power Systems

Fission Surface Power

Power (kWe)

Specific Mass (kg/kWe)

SNAP-10A (1965)

kW-Class Fission Power System

SMD RPS Program (Funded)

OCT Formulation Study (FTE Only)

OCT Nuclear Systems Project (Partially Funded)

Future Fission Systems (Unfunded)

Nuclear Electric Propulsion

Near Term

Mid Term

Far Term

Slide courtesy Lee Mason (GRC) / Dave Poston (LANL)
Small FPS Mission Pull

Science:
- Jupiter Europa Orbiter (5 to 6 RPS)
- Neptune Systems Explorer (9 RPS)
- Kuiper Belt Object Orbiter (9 RPS)
- Trojan Tour (6 RPS)

Exploration:
- Remote Mining Vehicles
- ISRU Demo Plants
- Site Survey Landers
- Remote Science Packages
- Comm Relay Stations

Slide courtesy Lee Mason (GRC) / Dave Poston (LANL)
Fission Power System Reference Concept

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

<table>
<thead>
<tr>
<th>Summary Data</th>
<th>Net Power ~ 40 kWe</th>
<th>Total Mass ~ 7 MT</th>
<th>Stowed Volume ~ 60 m³</th>
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</thead>
</table>


<table>
<thead>
<tr>
<th>FSPS (kg)</th>
<th>10 kWe</th>
<th>40 kWe</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power Plant (Reactor, Power Conversion, Heat Rejection, Structure)</td>
<td>1615</td>
<td>3350</td>
</tr>
<tr>
<td>Radiation Shielding</td>
<td>1310</td>
<td>3000</td>
</tr>
<tr>
<td>Transmission Cabling</td>
<td>415</td>
<td>650</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td><strong>3340</strong></td>
<td><strong>7000</strong></td>
</tr>
</tbody>
</table>

**Note:** The FSPS design includes multiple systems, each contributing to the overall mass and volume requirements.
Fission Power System Technology Project

• Current FPS Project addresses mid-range Tech Readiness Levels:
  – Sub-scale Pathfinder Component Tests
  – Full-scale Technology Demonstration Unit (TDU) Integrated System Test
  – Material & Component Irradiation Testing
  – Concept Definition to support NASA Mission Studies

• Objective is Non-Nuclear TRL6 by 2014
Completed FPS Pathfinders

- NaK Reactor Simulator
- Direct Gas-Cooled Brayton
- Electromagnetic Pump
- NaK Stirling Demo
- Full-scale NaK Pump Test
- Full-scale Radiator
- Stirling PMAD Demo
- Pin Heater Demo
- Thermodynamically-Coupled Stirling
- Titanium-Water Heat Pipes
- Alternator Radiation Test
- Reactor Control Drive
- Radiator Demonstration Unit
- High Power Dual Brayton
- Feasibility Test Loop
Fission Technology Demonstration Unit (TDU)
Government, Industry, & Academia Team Effort

- Composite Heat Pipe Radiator – GRC & Industry
- Stirling Power Conversion Unit – GRC & Sunpower
- Core Simulator – MSFC & Los Alamos National Lab
- NaK Pump – Idaho National Lab
- NaK Volume Accumulator – Oak Ridge National Lab
- Reactor Simulation – Sandia National Lab

PROTOTYPE TESTED, TDU H/W IN FAB
PROTOTYPE TESTED, TDU H/W IN FAB
PROTOTYPE TESTED, TDU H/W IN FAB
PROTOTYPE TESTED, TDU H/W COMPLETED
TDU S/W UNDERGOING BENCHMARKING TRIALS

PROTOTYPE TESTED, TDU H/W RFP IN FY11
MSFC Early Flight Fission Test Facility (EFF-TF)

- Established in 1998, the MSFC Early Flight Fission Test Facility (EFF-TF) is designed to help enable affordable development of space fission systems.

- EFF-TF can perform highly realistic thermal hydraulic, heat transfer, structural, safety, and integrated system testing of space nuclear systems using non-nuclear (electrical) heat sources. Up to 8 MWe available power.

- Designed to test with any potential coolant. Heat pipe, gas cooled, and alkali metal cooled testing performed to date.

- Licensed for testing with natural and depleted uranium.
Safe Affordable Fission Engine (SAFE)

Ultimate Goal: Perform realistic non-nuclear heated demonstrations of potential near-term space fission systems. Early focus is on core / heat exchanger.

Modular Unfueled Thermohydraulic Testing

High-Temperature SAFE Module Testing Completed in FY00.
• > 1750 K Core Module Temperature.
• > 1450 K Heat pipe Temperature.
• Direct thermal propulsion mode demonstrated.
• Fast start of heat pipe (room temp to >1400 K in < 1 hr).
• Multiple heat pipe restarts.

SAFE-30 End-to-End
• Average core temperature above 600 deg C in over 20 core tests including both vacuum and CO2 environments.
• 10 operating heat pipes with an evaporator exit temperature ~ 650 deg C, > 17 kW measured transferred to the calorimeters.
• Core and Stirling engine integrated with ion engine and tested at JPL. Testing completed Sept 2002. Demonstrated integrated system with heat generated in fuel pins converted to high specific impulse thrust.

SAFE-100
• Computationally and experimentally investigate prototypic module, core, and heat exchanger design for 100 kWt system
  • Module fabrication
  • Core support / expansion
  • Thermal performance
  • Thermal cycling effects

• Develop and utilize advanced instrumentation and power delivery system.
  • 32 radial control zones
  • Heaters match axial power profile
  • Coarse matching of fuel pin thermal conductivity

• Develop / utilize high purity liquid metal handling capability at NASA MSFC.
Direct Drive Gas Cooled Reactor (DDG)
Sandia Design, Fast-Spectrum U-235, Ex-Core Control, Be Reflected, Primary Heat Transport via Noble Gas

37-Pin, 32-kWt subscale test
- Pressure drop & flowing heat transfer code validation
- Single module stagnant He/Xe decay heat code validation

133-Pin, 100 kWt subscale test
- Pressure drop & flowing heat transfer code validation with radial power profile
- Multi-module stagnant He/Xe decay heat code validation

361-Pin, 400 kWt full-scale test
- Full system pressure drop & flowing heat transfer code validation, radial power profile
- Full system stagnant He/Xe decay heat code validation

Dynamics with 25-kWe Brayton turbomachinery and simulated nuclear temperature-dependent feedback, code validation

2 kWe BRU Test at NASA GRC
Full system dynamics with Brayton turbomachinery and simulated nuclear temperature-dependent feedback, code validation
2 kWe NaK Stirling Demonstration Test

Test Validated Reactor-Stirling Heat Transfer Approach for FSP (Stirling provided by NASA–GRC)

- 2.4 kWe at Thot=550°C, Tcold=50°C
- 32% Thermal Efficiency
- <5°C Circum. Gradient on Heater Head
- 41 Steady-State Test Points; 9 Transients
- 6 Reactivity Control Simulations
Coupled NaK Loop / Stirling Test

Cable tray providing protection from heat/NaK

Core Simulator Design by Los Alamos National Laboratory

Power Cable path to core

Integrated Stirling Test Assembly

ALIP Provided By Idaho National Laboratory
EFF-TF ALIP Test Circuit

Performance Mapping of Annular Linear Induction Pump (ALIP) provided by Idaho National Laboratory
Performance Mapping of Annular Linear Induction Pump (ALIP) provided by Idaho National Laboratory

ALIP Test Circuit (ATC)

Enhanced heating assembly ready for application of insulation

ATC ready for chamber prior to NaK fill

NaK fill

ATC Testing
EFF-TF Feasibility Test Loop

Feasibility Test Loop:
Investigate potential issues and optimizations related to pumped alkali metal systems
Fission Power System – Primary Test Circuit (FPS-PTC)
7 – Pin Reactor (Rx) Core Simulator Testing

7-Pin Rx Core Sim

37 – Pin TDU Rx Core Sim

Revised FPS-PTC layout for 7 – Pin Rx Core Sim

7 Pin Rx Core Sim installed in FPS-PTC

MSFC Designed Advanced Simulators
FPS Accomplishments

Recent Activities Focused Towards TDU Reactor Simulator

MILESTONES
Fabricate & Test : 2010-2012
Ship to GRC 2012
Fission Power Systems TDU Reactor (Rx) Simulator

Currently being tested in the MSFC EFF-TF

Rx Sim in vacuum chamber for final checkouts
Fission Power Systems TDU Reactor (Rx) Simulator

Above: FPS Project Rx Sim Test Review Board and Project Team
Below: Don Palac (GRC), FPS Project Manager is briefed by Boise Pearson, MSFC EFF-TF Team Lead

Above/Right: Rx Sim NaK Fill

Above: Rx Sim in vacuum chamber during final checkouts
Summary

• Fission power and propulsion systems can enable exciting space exploration missions. These include bases on the moon and Mars; and the exploration, development, and utilization of the solar system.

• In the near-term, fission surface power systems could provide abundant, constant, cost-effective power anywhere on the surface of the Moon or Mars, independent of available sunlight. Affordable access to Mars, the asteroid belt, or other destinations could be provided by nuclear thermal rockets.

• In the further term, high performance fission power supplies could enable both extremely high power levels on planetary surfaces and fission electric propulsion vehicles for rapid, efficient cargo and crew transfer. Advanced fission propulsion systems could eventually allow routine access to the entire solar system. Fission systems could also enable the utilization of resources within the solar system.