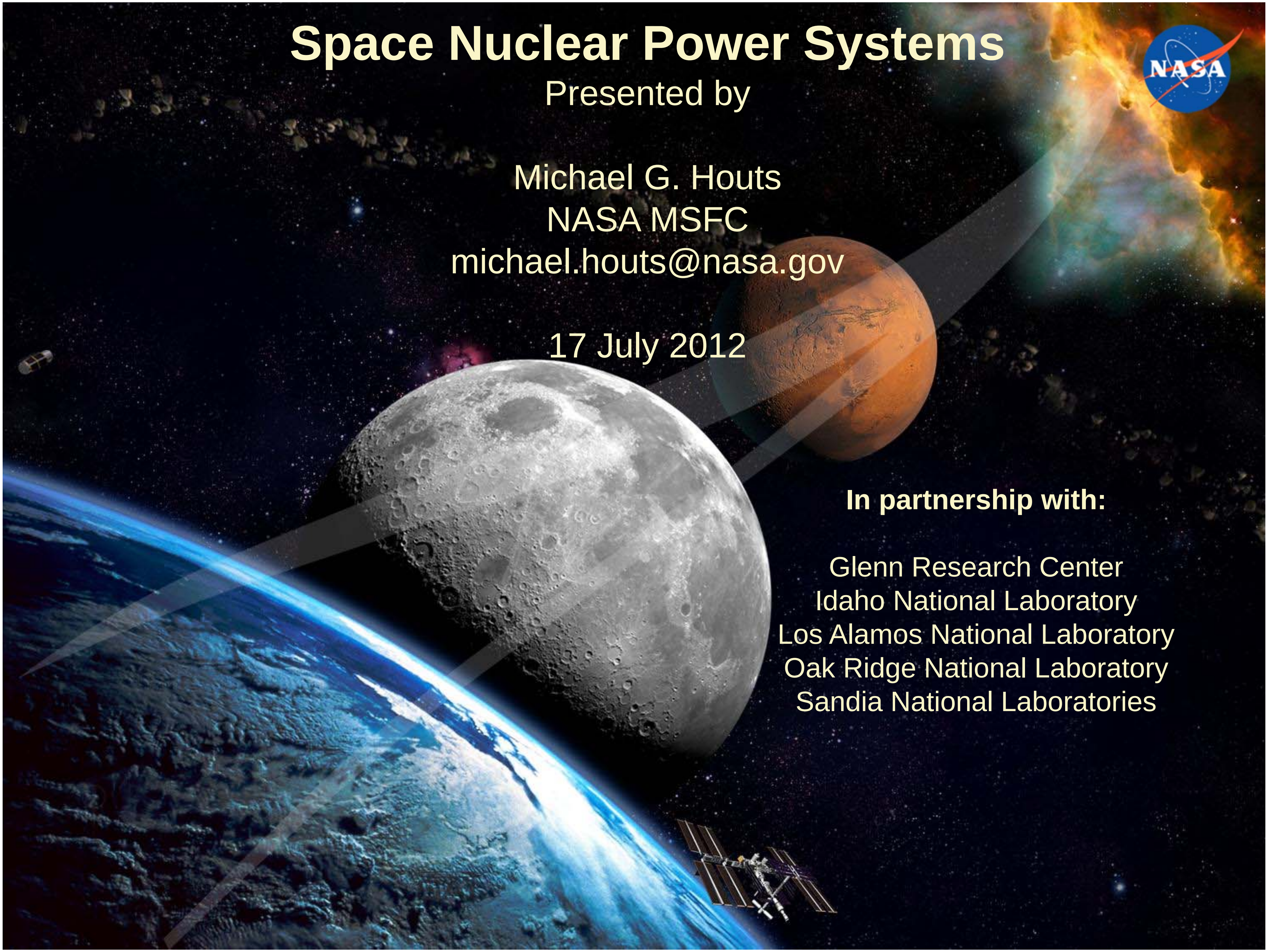


Space Nuclear Power Systems

Presented by

Michael G. Houts
NASA MSFC
michael.houts@nasa.gov

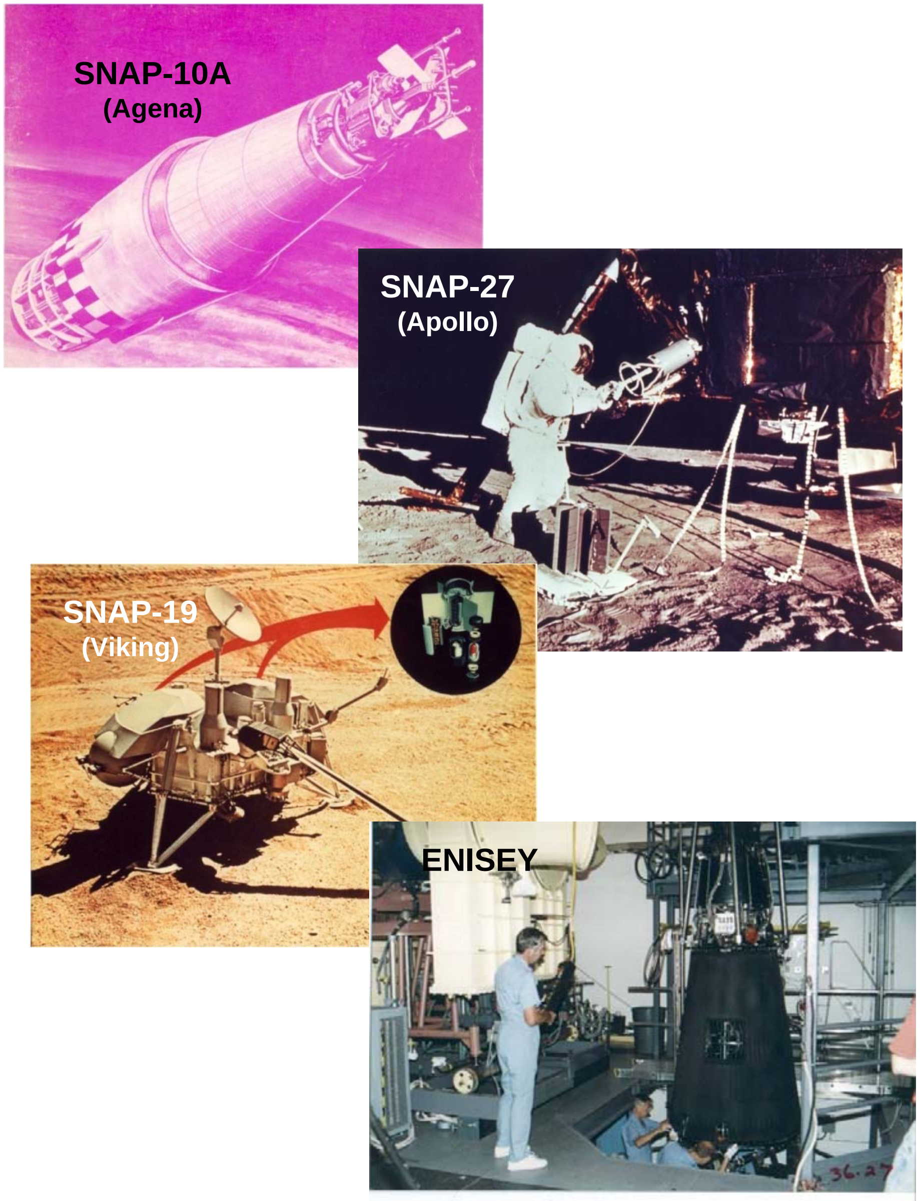
17 July 2012

In partnership with:

Glenn Research Center
Idaho National Laboratory
Los Alamos National Laboratory
Oak Ridge National Laboratory
Sandia National Laboratories

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)

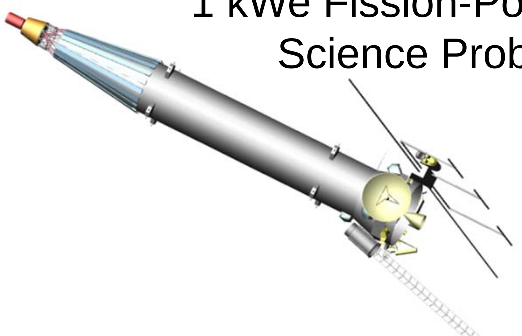


Why Space Fission Power?

- **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?

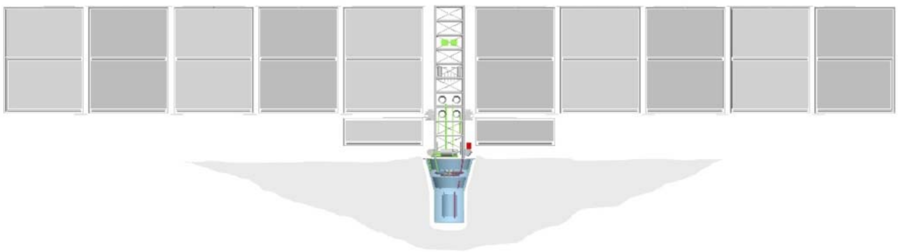
Projected Applications for Fission Power Systems

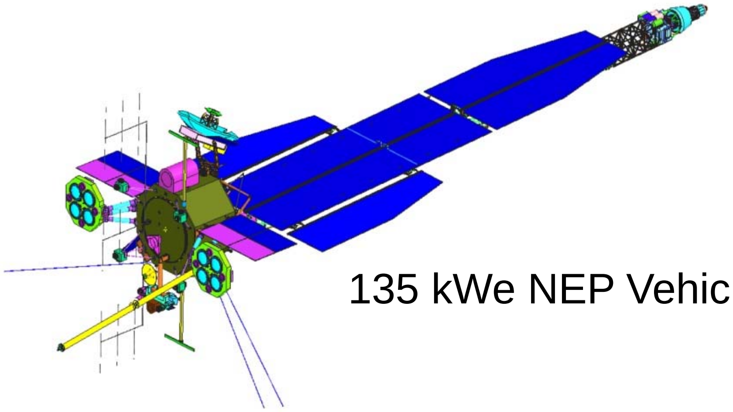
1. **Planetary/Space Science**
   - <1 to 10 kWe
   - 10 to 20 yr life
   - Unmanned, Autonomous
   - Above power range of interest for radioisotope systems
   - Non-Obtrusive; will not interfere with Science Objectives
2. **Fission Surface Power (FSP)**
   - 10 to 100 kWe
   - 5 to 10 yr Life
   - Human-rated
   - 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



1 kWe Fission-Powered Science Probe

40 kWe FSP System

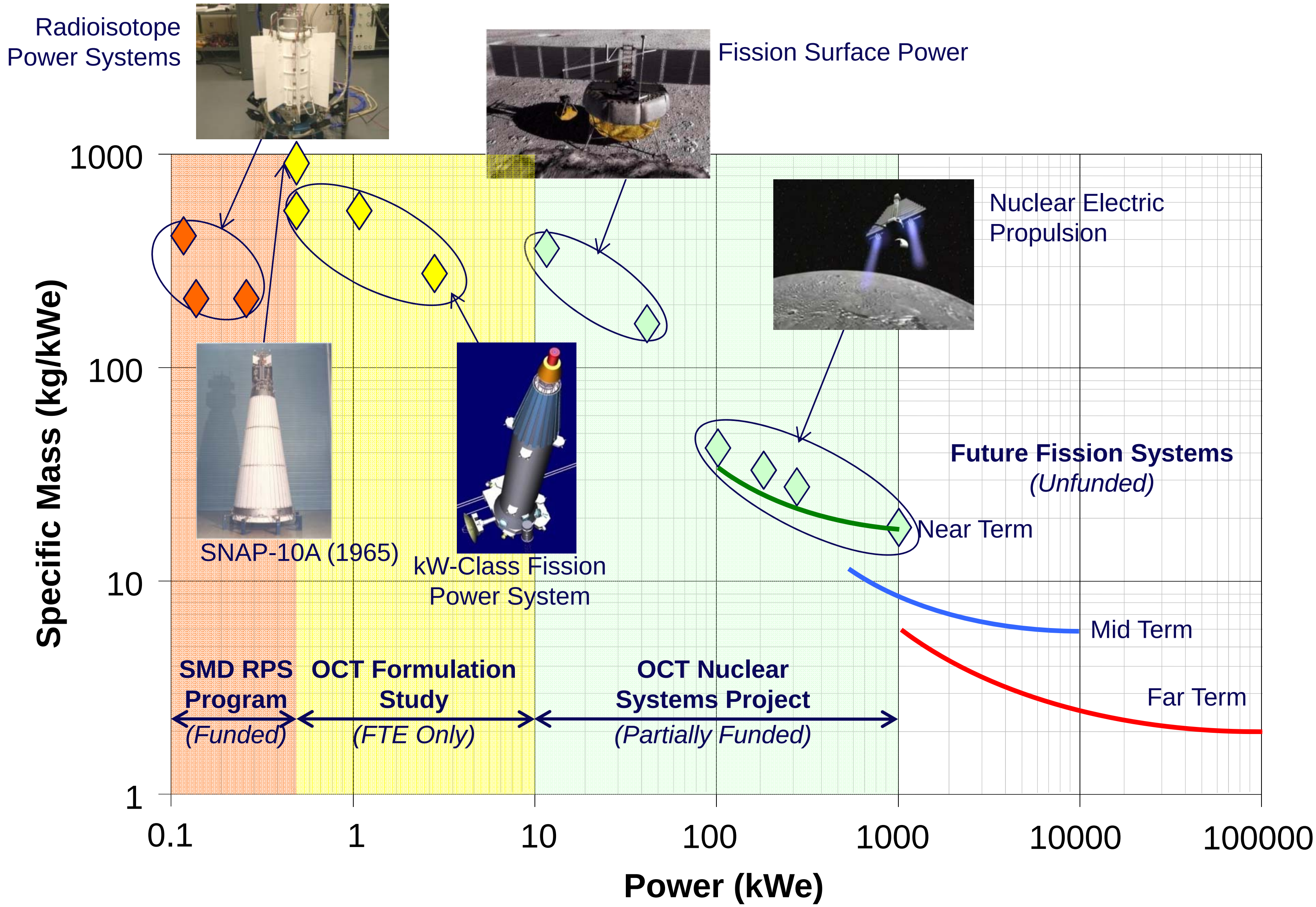




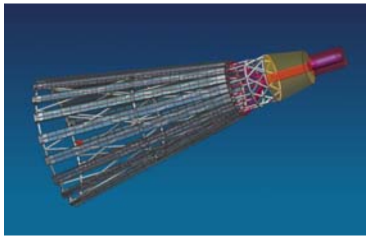
135 kWe NEP Vehicle

Slide courtesy Lee Mason (GRC) / Dave Poston (LANL)

Nuclear Power Performance Regimes

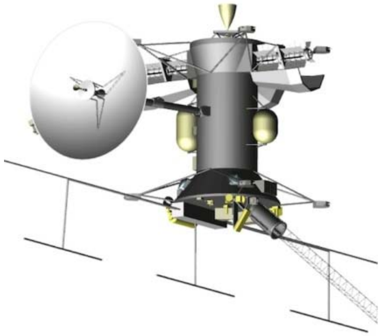


Slide courtesy Lee Mason (GRC) / Dave Poston (LANL)

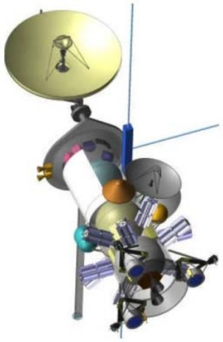


Small FPS Mission Pull

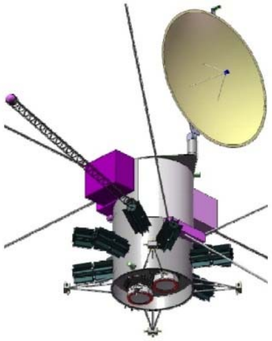
Science:



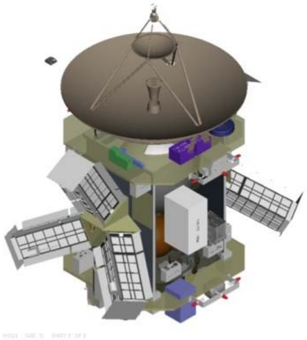
Jupiter Europa Orbiter
(5 to 6 RPS)



Neptune Systems Explorer
(9 RPS)



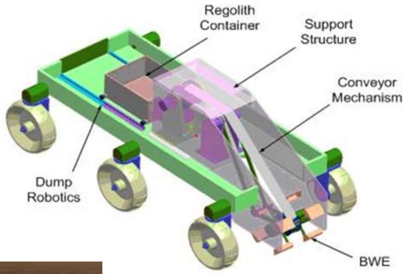
Kuiper Belt Object Orbiter
(9 RPS)

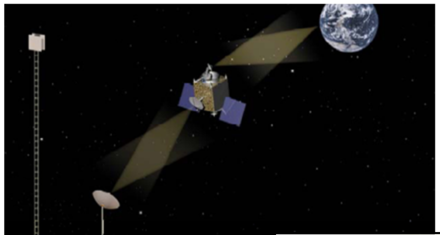


Trojan Tour
(6 RPS)

Exploration:

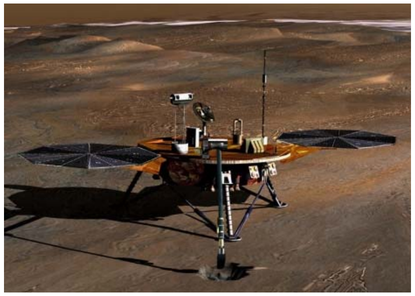
Remote Mining
Vehicles



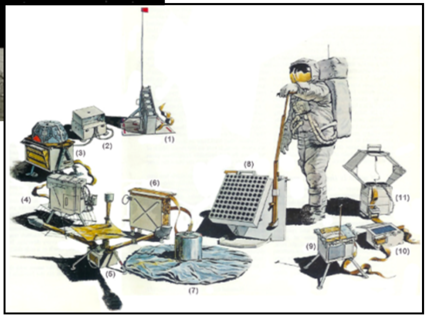


Comm Relay
Stations

ISRU Demo
Plants



Site Survey
Landers

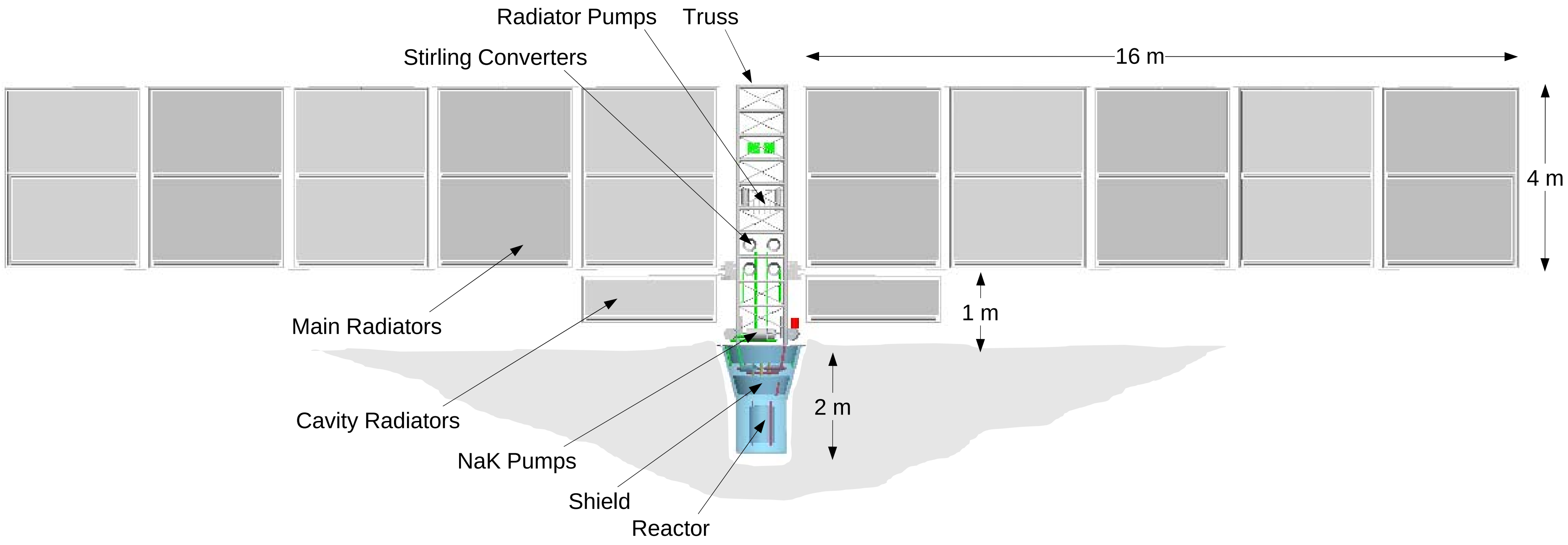


Remote Science
Packages

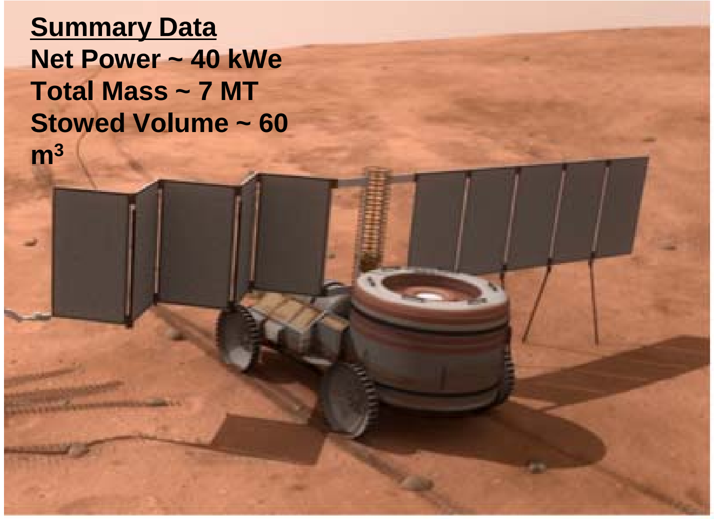
Slide courtesy Lee Mason (GRC) / Dave Poston (LANL)

Fission Power System Reference Concept

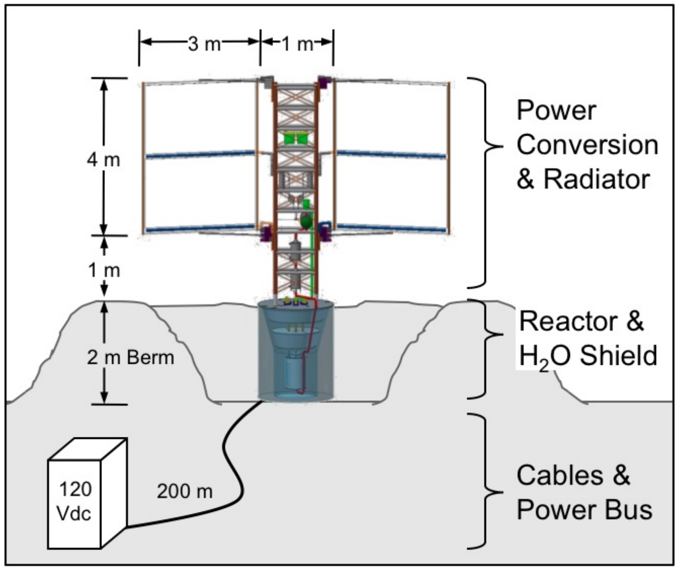
- Modular 40 kWe system with 8-year design life suitable for (global) lunar and Mars surface applications
- Emplaced configuration with regolith shielding augmentation permits near-outpost siting (<5 rem/yr at 100 m separation)
- Low temperature, low development risk, liquid-metal (NaK) cooled reactor with UO_2 fuel and stainless steel construction



Mars Fission Surface Power System (FSPS)



Summary Data
Net Power ~ 40 kWe
Total Mass ~ 7 MT
Stowed Volume ~ 60 m^3

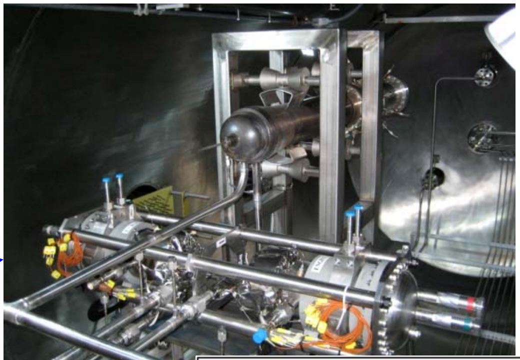


FSPS (kg)	10 kWe	40 kWe
Power Plant (Reactor, Power Conversion, Heat Rejection, Structure)	1615	3350
Radiation Shielding	1310	3000
Transmission Cabling	415	650
TOTAL	**3340**	**7000**

Reference: L.S. Mason and D.I. Poston, “A Summary of NASA Architecture Studies Utilizing Fission Surface Power Technology,” NASA/TM-2011-216819, April 2011.

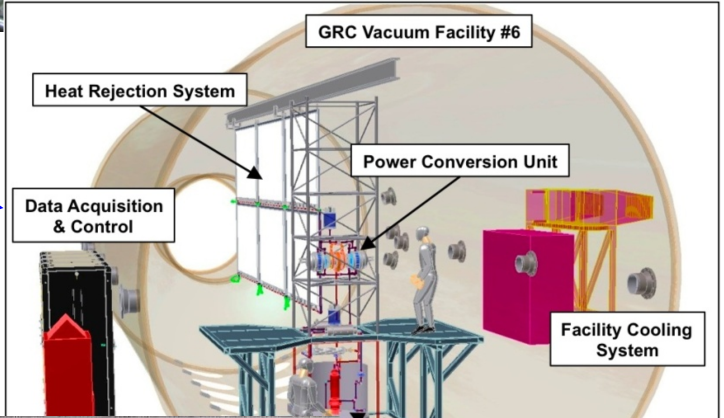
Fission Power System Technology Project

- 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



2 kWe NaK-Stirling Demo

TDU System Test



LSS Scenario 5: Lander-Integrated FSP System

Completed FPS Pathfinders


NaK Reactor Simulator


NaK Stirling Demo


Full-scale Radiator


Electromagnetic Pump

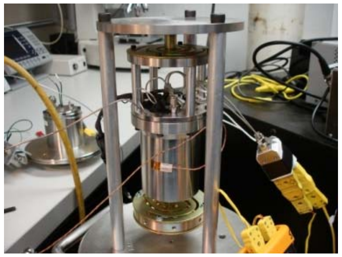

Direct Gas-Cooled Brayton

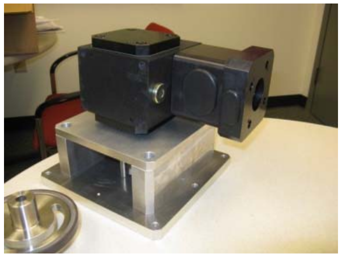

Full-scale NaK Pump Test

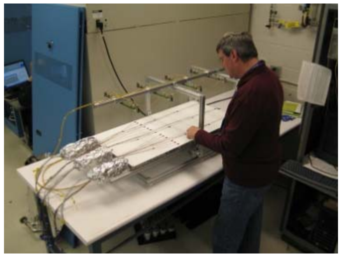

Pin Heater Demo


Titanium-Water Heat Pipes

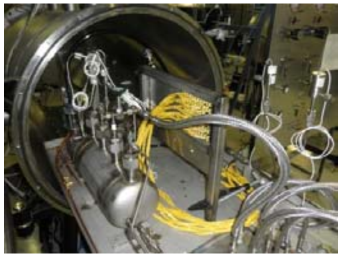

Stirling PMAD Demo

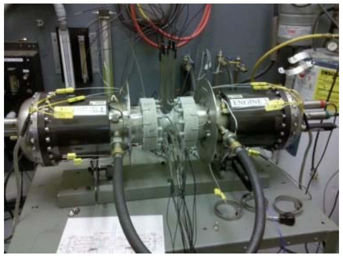

Alternator Radiation Test


Reactor Control Drive


Radiator Demonstration Unit


High Power Dual Brayton

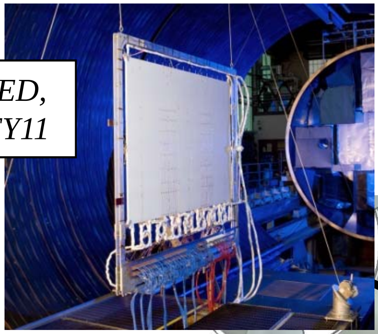

Feasibility Test Loop


Thermodynamically-Coupled Stirling

Fission Technology Demonstration Unit (TDU)

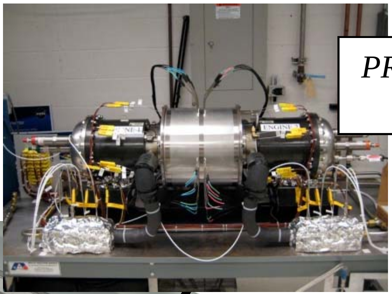
Government, Industry, & Academia Team Effort

Composite Heat Pipe Radiator – GRC & Industry



PROTOTYPE TESTED,
TDU H/W RFP IN FY11

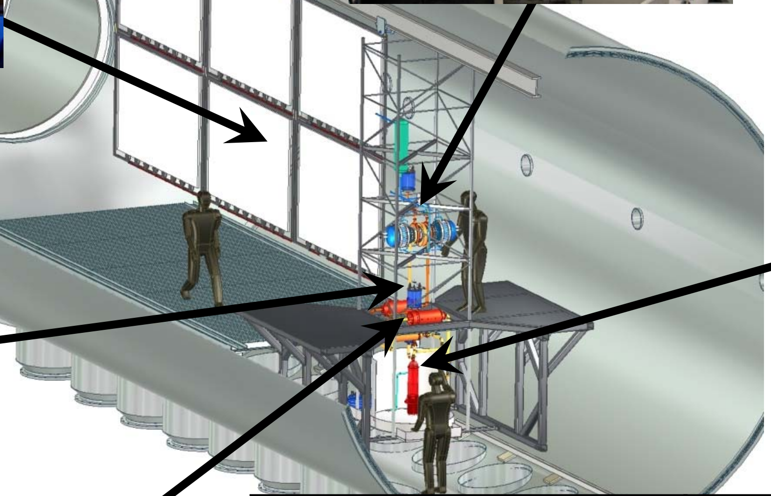
Stirling Power Conversion Unit – GRC & Sunpower



PROTOTYPE TESTED,
TDU H/W IN FAB

Core Simulator – MSFC & Los Alamos National Lab

PROTOTYPE TESTED,
TDU H/W COMPLETED



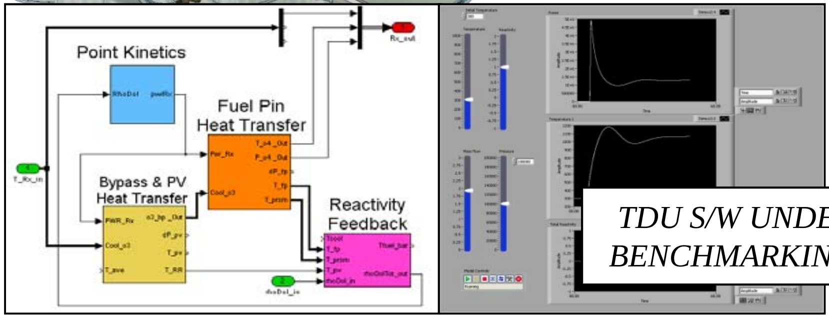
NaK Volume Accumulator – OaK Ridge National Lab

PROTOTYPE TESTED,
TDU H/W IN FAB

NaK Pump – Idaho National Lab

PROTOTYPE TESTED,
TDU H/W IN FAB

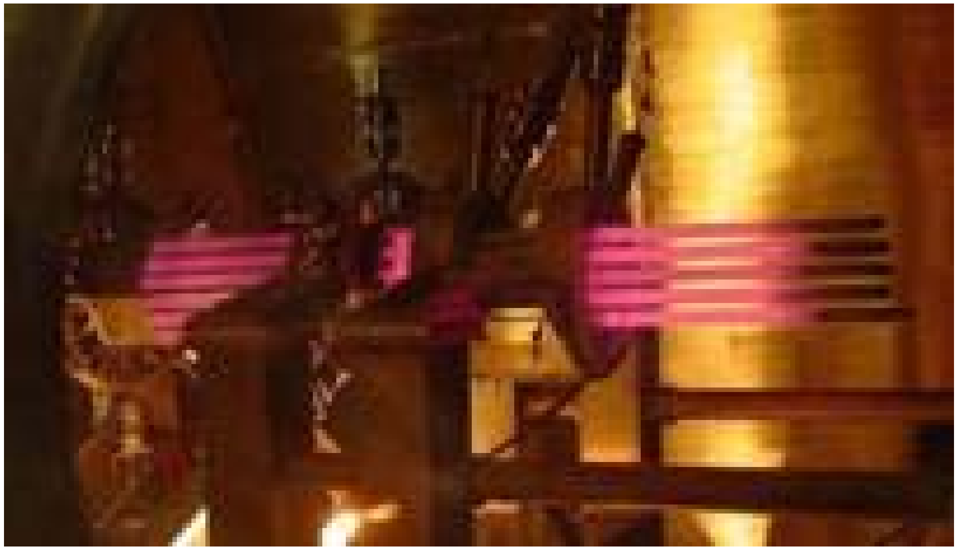
Reactor Simulation – Sandia National Lab



TDU S/W UNDERGOING
BENCHMARKING TRIALS

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.

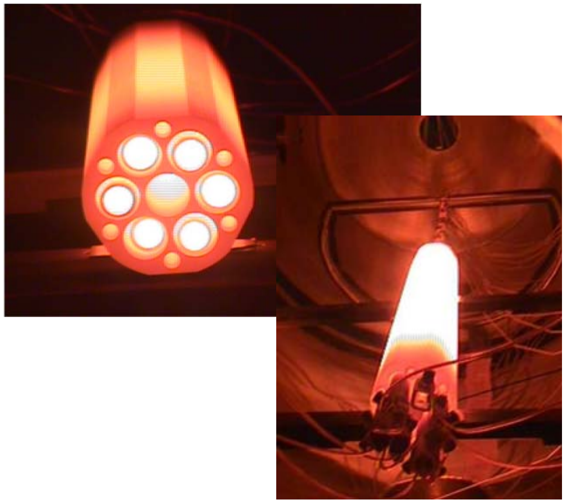


Safe Affordable Fission Engine (SAFE)

LANL Design, Fast-Spectrum U-235, Ex-Core Control, Be Reflected, Primary Heat Transport via Heat Pipes

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

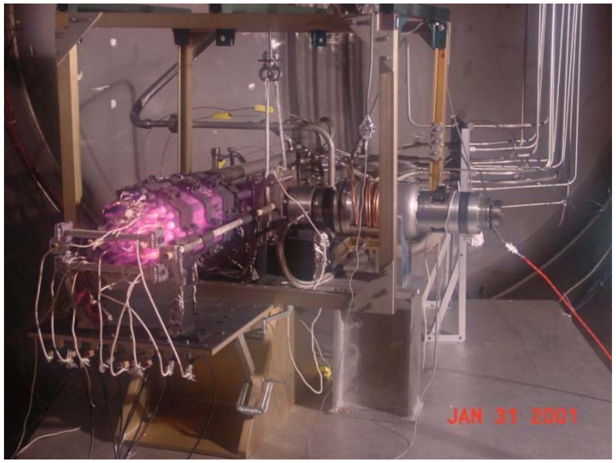


High-Temperature SAFE Module Testing Completed in FY00.

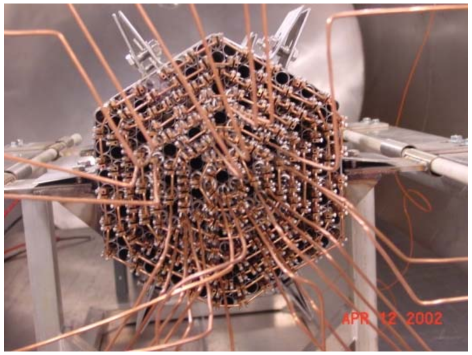
- > 1750 K Core Module Temperature.
- > 1450 K Heat pipe Temperature.
- Direct thermal propulsion mode demonstrated.
- Fast start of heat pipe (room temp to >1400 K in < 1 hr).
- Multiple heat pipe restarts.

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

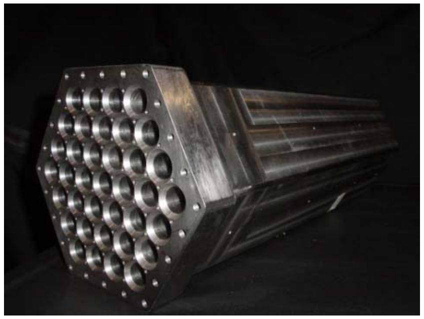


- Computationally and experimentally investigate prototypic module, core, and heat exchanger design for 100 kWt system
    - Module fabrication
    - Core support / expansion
    - Thermal performance
    - Thermal cycling effects
- Develop and utilize advanced instrumentation and power delivery system.
    - 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

Single-Channel Flow Test → **Pressure drop & flowing heat transfer, Testability**



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** → **Dynamics with 25-kWe Brayton turbomachinery and simulated nuclear temperature-dependent feedback, code validation**
- **Multi-module stagnant He/Xe decay heat code validation**

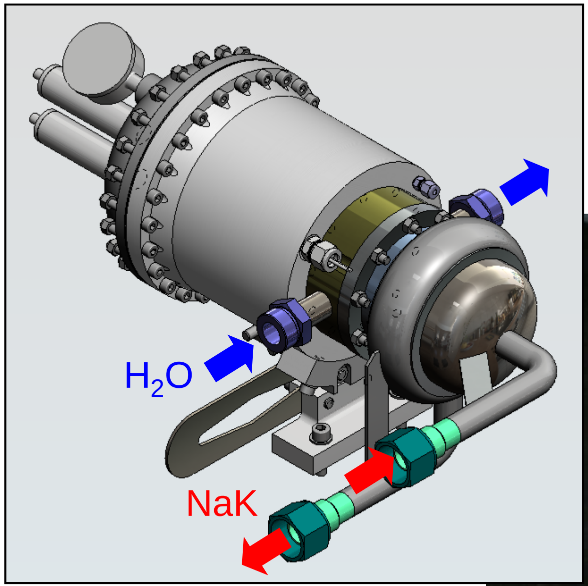
2 kWe BRU Test at NASA GRC

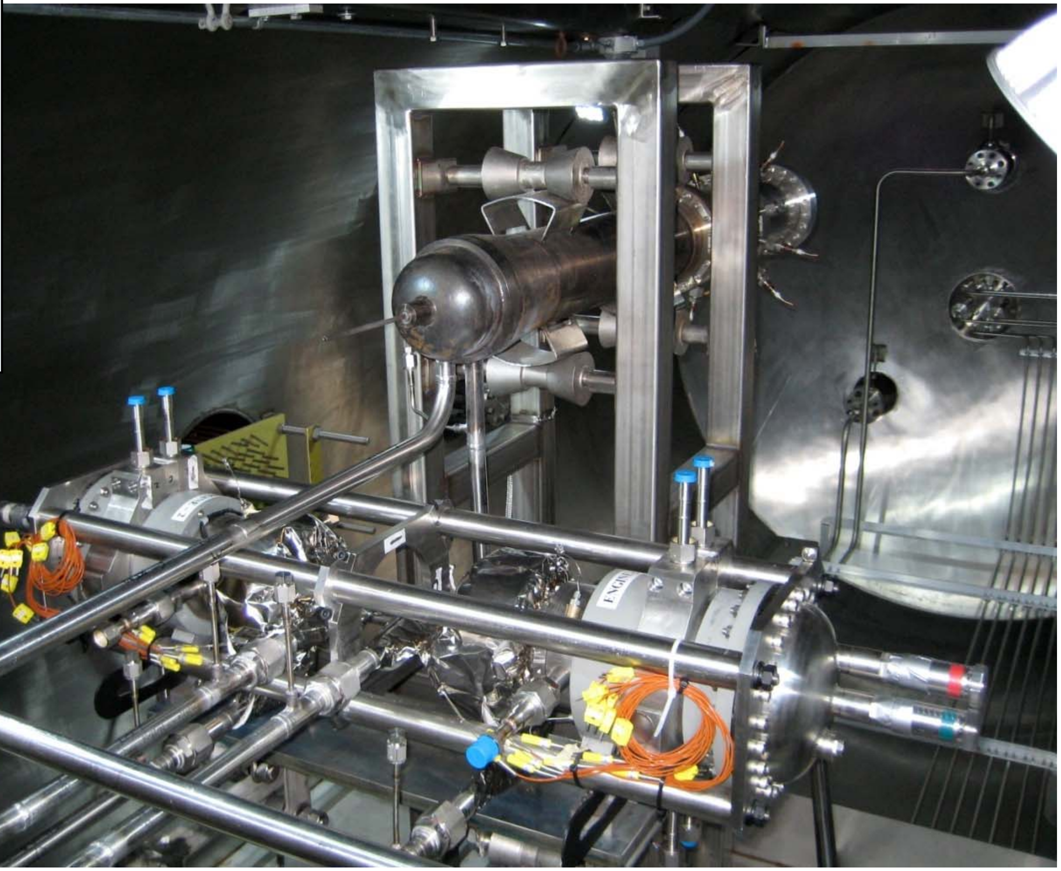
361-Pin, 400 kWt full-scale test

- **Full system pressure drop & flowing heat transfer code validation, radial power profile** → **Full system dynamics with Brayton turbomachinery and simulated nuclear temperature-dependent feedback, code validation**
- **Full system stagnant He/Xe decay heat code validation**

2 kWe NaK Stirling Demonstration Test

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

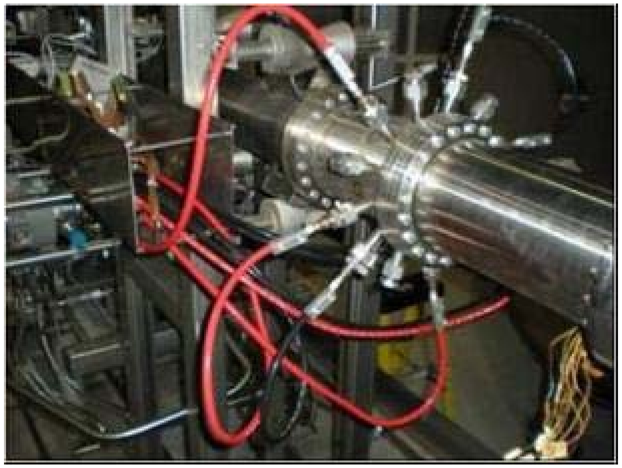




- 2.4 kWe at Thot=550ºC, Tcold=50ºC
- 32% Thermal Efficiency
- <5ºC Circum. Gradient on Heater Head
- 41 Steady-State Test Points; 9 Transients
- 6 Reactivity Control Simulations

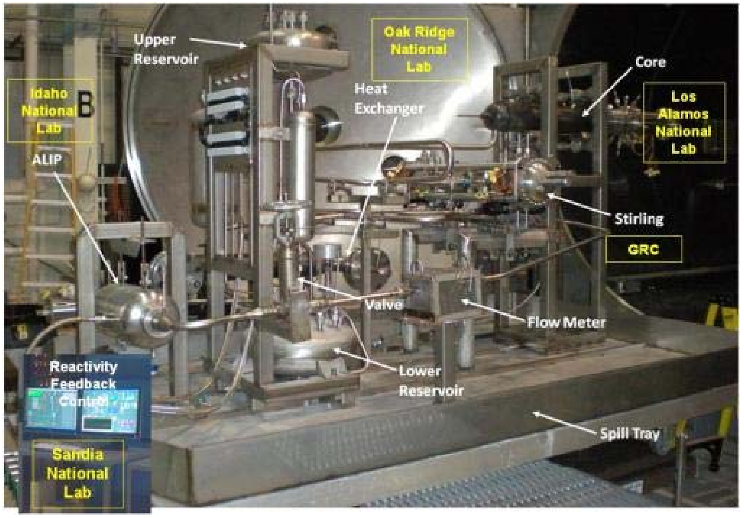
Coupled NaK Loop / Stirling Test

Cable tray providing protection from heat/NaK



Core Simulator Design by Los Alamos National Laboratory

Power Cable path to core

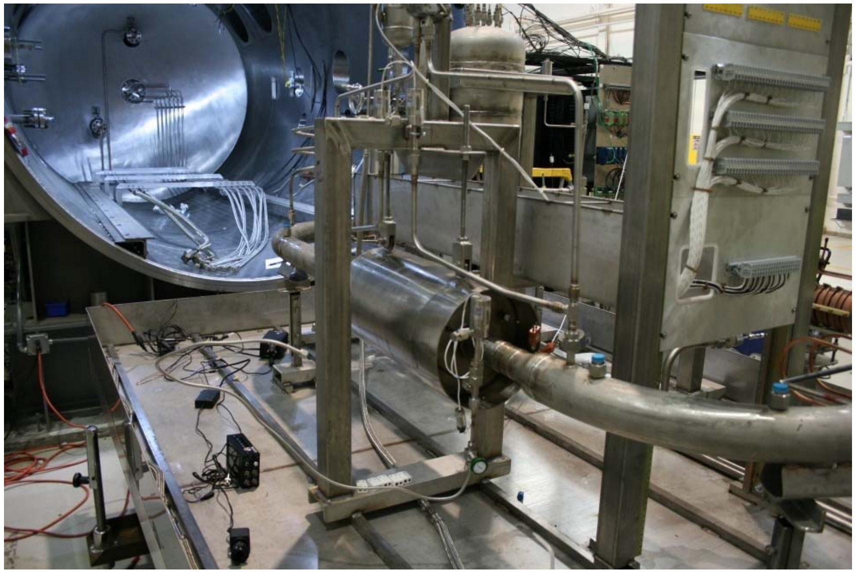


Integrated Stirling Test Assembly

ALIP Provided By Idaho National Laboratory

EFF-TF ALIP Test Circuit

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



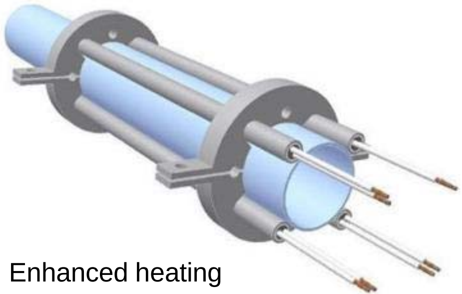
Performance Mapping of Annular Linear Induction Pump (ALIP) provided by Idaho National Laboratory

ALIP Test Circuit (ATC)

ALIP

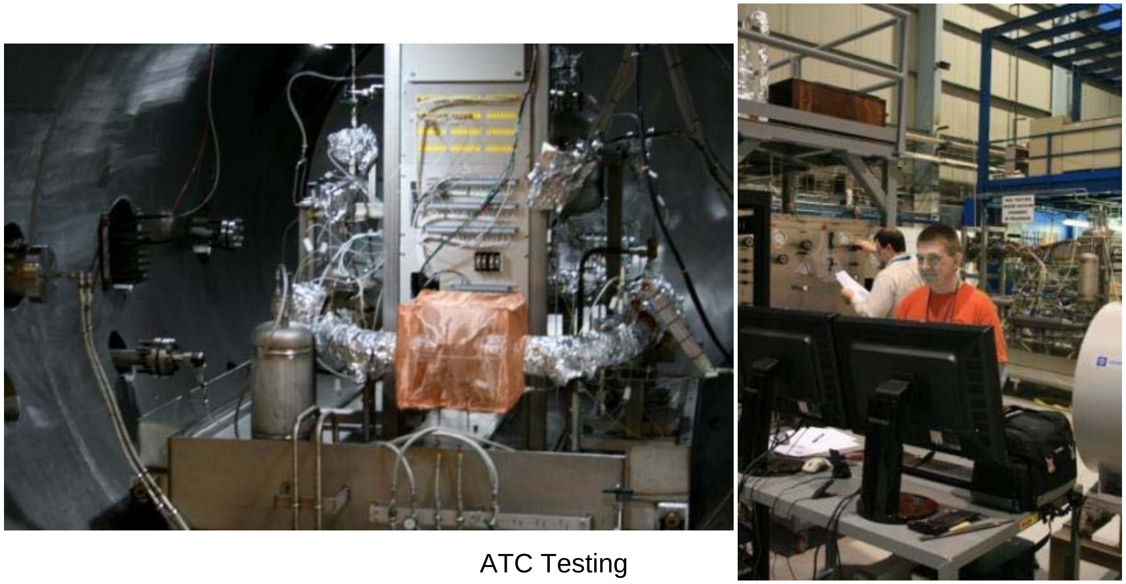
ATC ready for chamber prior to NaK fill

NaK fill



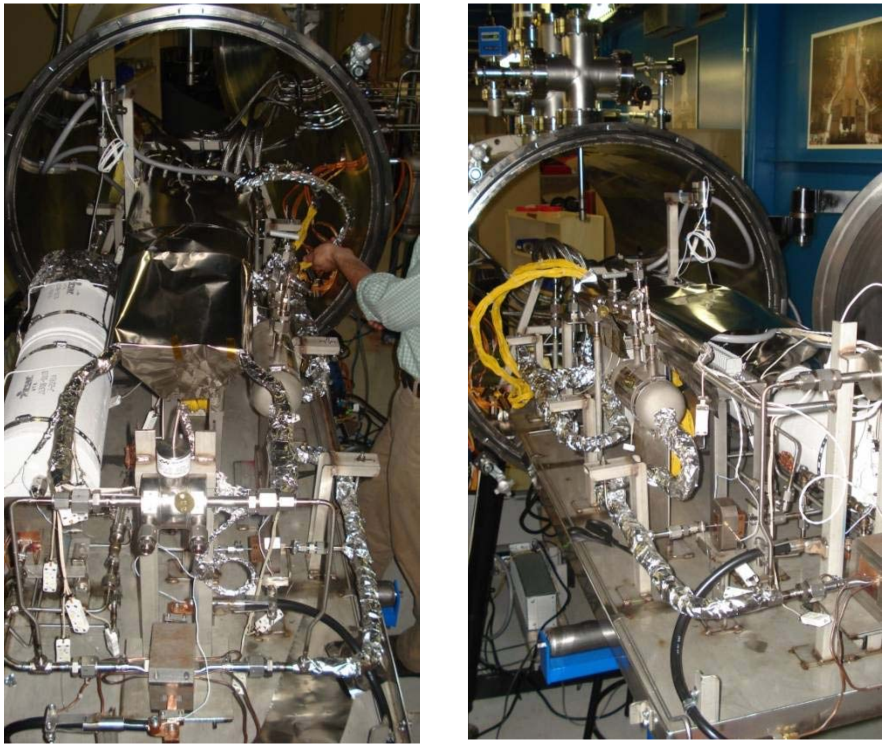
Enhanced heating assembly

Enhanced heating assembly ready for application of insulation



ATC Testing

EFF-TF Feasibility Test Loop



Feasibility Test Loop:

Investigate potential issues and optimizations related to pumped alkali metal systems

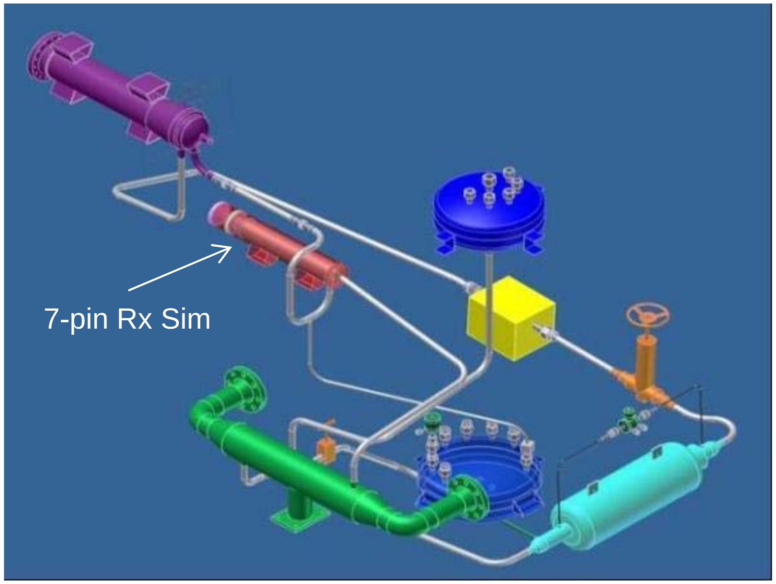
Fission Power System – Primary Test Circuit (FPS-PTC)
7 – Pin Reactor (Rx) Core Simulator Testing

MSFC
Designed
Advanced
Simulators

7 – Pin Rx Core Sim Rendering

7-Pin Rx
Core Sim

37 – Pin TDU Rx Core Sim



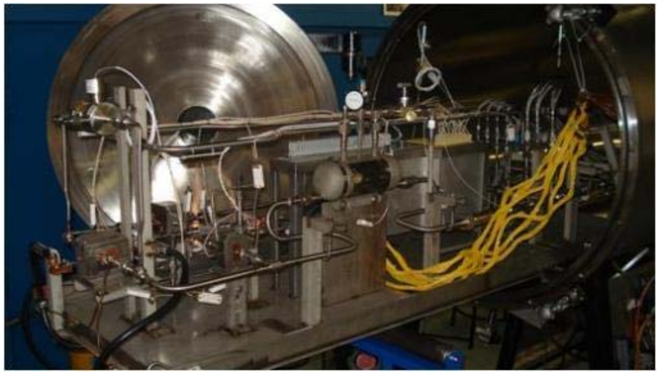
Revised FPS-PTC layout for 7 – Pin Rx Core Sim

7 Pin Rx Core Sim installed in FPS-PTC

FPS Accomplishments

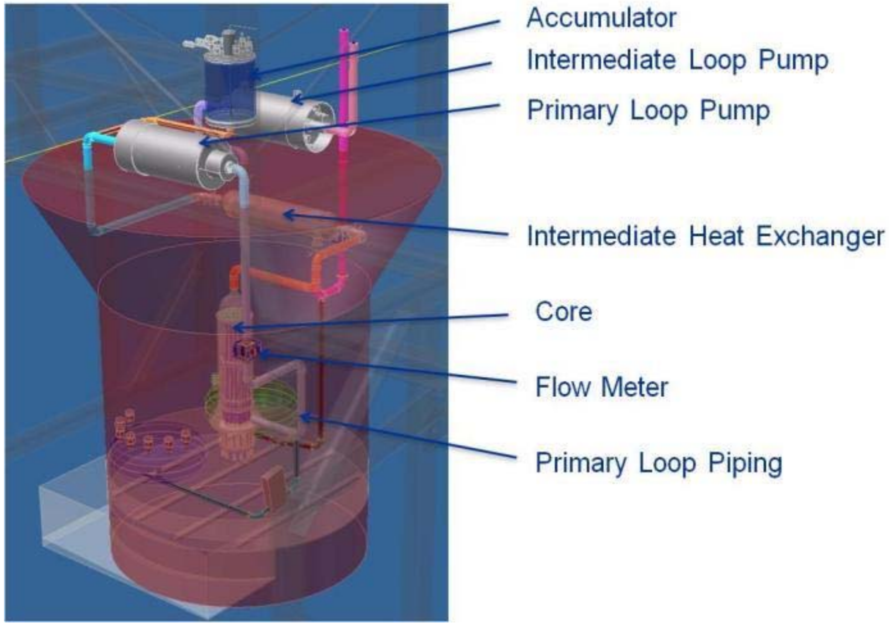
FPS-PTC
Stirling &
7 Pin Rx Core
Sim
Testing

ATC
Testing



FTL
Testing

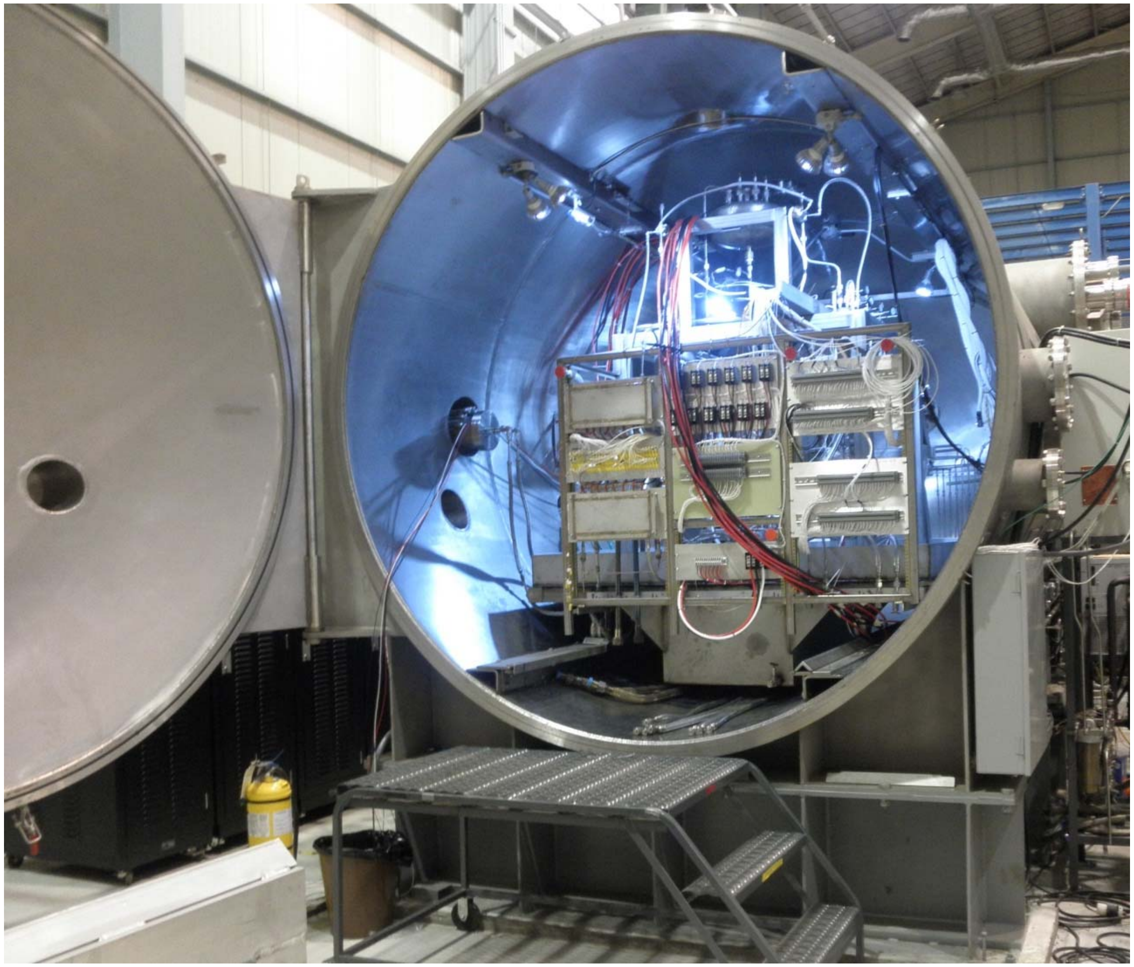
Recent Activities Focused Towards TDU Reactor Simulator



MSFC Designed Reactor Simulator in TDU
(top view close up)

MILESTONES
Fabricate & Test : 2010-2012
Ship to GRC 2012

Fission Power Systems TDU Reactor (Rx) Simulator



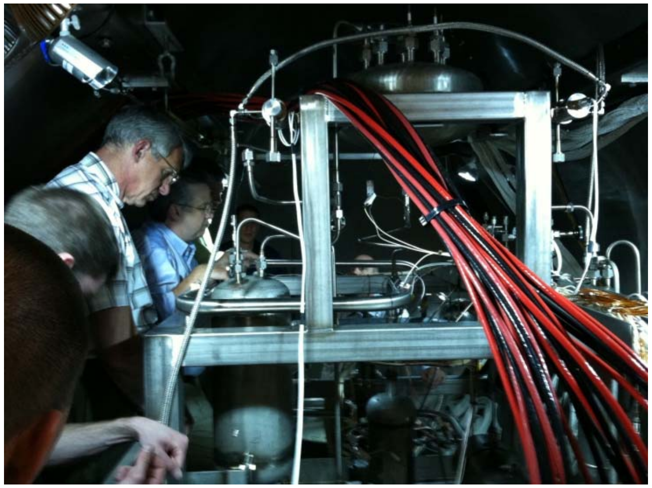
Rx Sim in vacuum chamber for final checkouts

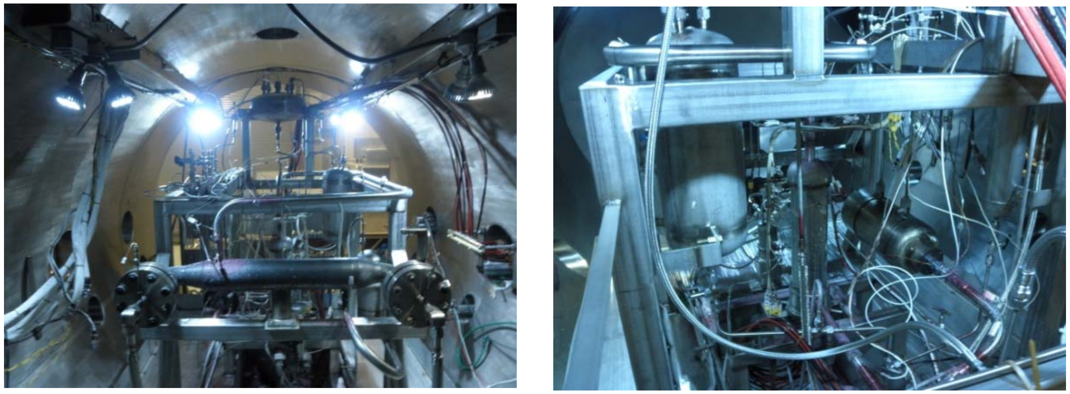
Currently being tested in the MSFC EFF-TF

Fission Power Systems TDU Reactor (Rx) Simulator

Above/Right: Rx Sim
NaK Fill

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: 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.