NON-NUCLEAR TESTING OF SPACE NUCLEAR SYSTEMS AT NASA MSFC

Michael G. Houts, J. Boise Pearson, Kenneth C. Aschenbrenner, David E. Bradley, Ricky E. Dickens, William J. Emrich, Anne E. Garber, Thomas J. Godfroy, Roger T. Harper, Jim J. Martin, Kurt A. Polzin, Michael P. Schoenfeld, Kenneth L. Webster

NASA Marshall Space Flight Center: MSFC / VP33, MSFC, AL, 35812, michael.houts@nasa.gov

ABSTRACT

Highly realistic non-nuclear testing can be used to investigate and resolve potential issues with space nuclear power and propulsion systems. Non-nuclear testing is particularly useful for systems designed with fuels and materials operating within their demonstrated nuclear performance envelope. Non-nuclear testing allows thermal hydraulic, heat transfer, structural, integration, safety, operational, performance, and other potential issues to be investigated and resolved with a greater degree of flexibility and at reduced cost and schedule compared to nuclear testing. The primary limit of non-nuclear testing is that nuclear characteristics and potential nuclear issues cannot be directly investigated. However, non-nuclear testing can be used to augment the potential benefit from any nuclear testing that may be required for space nuclear system design and development. This paper describes previous and ongoing non-nuclear testing related to space nuclear systems at NASA's Marshall Space Flight Center (MSFC).

INTRODUCTION

Space nuclear power and propulsion systems have many potential applications. For example, fission surface power (FSP) systems could be used to provide power anytime, anywhere on the surface of the Moon or Mars. FSP systems could be used at lunar polar locations, at locations away from the poles, or in permanently shaded regions, with excellent performance at all sites. FSP systems could also be designed to be readily extensible for use anywhere on the surface of Mars, and to be resistant to Mars environmental conditions including global dust storms.

In-space fission electric systems could be used to provide power to robotic or crewed spacecraft as well as power for advanced, high efficiency electric propulsion systems. Power levels ranging from 500 We to over 10 MWe could potentially be useful.

Nuclear Thermal Propulsion (NTP) systems could enable the sustainable exploration, development, and utilization of the moon, Mars, and other areas of the solar system. NTP systems are attractive because they can provide high thrust at a specific impulse approximately twice that of the best chemical systems.

Radioisotope (Pu-238) powered systems have enabled robotic exploration throughout the solar system, and have also powered experiments deployed on the Apollo moon landings and by the Mars Viking landers. Radioisotope-powered systems remain vital to a robust space program.

Effective, realistic non-nuclear testing is important to the development of any nuclear system, including those designed for use in space. Beginning in 1998, a facility has been developed at NASA MSFC that is optimized for reducing the development cost and schedule associated with potential space nuclear systems through the use of highly realistic non-nuclear testing. The Early Flight Fission Test Facility (EFF-TF) is capable of performing research related to both surface and in-space fission electric systems as well as nuclear thermal propulsion systems and radioisotope power systems. When used in conjunction with facilities at other NASA centers and at Department of Energy (DOE) National Laboratories, the EFF-TF could help enable affordable space nuclear systems for a variety of applications. The EFF-TF also helps facilitate a close working relationship between NASA and the DOE in the area of space nuclear power and propulsion.

FISSION SURFACE POWER TECHNOLOGY TESTING

Under the NASA Exploration Technology Development Program (ETDP), NASA and the DOE have begun long-lead technology development for integrated Fission Surface Power (FSP) systems. The project is led by NASA GRC, and involves multiple NASA centers and DOE national laboratories. The primary customer for this technology is the NASA Constellation Program which is responsible for the development of surface systems to support human exploration on the moon and Mars. The objectives of the FSP technology project are:

1) Develop FSP concepts that meet expected surface power requirements at reasonable cost with added benefits over other options.
2) Establish a hardware-based technical foundation for FSP design concepts and reduce overall development risk.
3) Reduce the cost uncertainties for FSP and establish greater credibility for flight system cost estimates.
4) Generate the key products to allow Agency decision-makers to consider FSP as a viable option for flight development.

To be mass efficient, FSP systems must operate at higher coolant temperatures and use different types of power conversion than typical terrestrial systems. The primary reason is the difficulty in rejecting excess heat to space. Although many options exist, the NASA/DOE team has devised a potential reference FSP system that uses a fast spectrum, pumped-NaK cooled reactor coupled to a Stirling power conversion subsystem. The reference system uses technology with significant terrestrial heritage while still providing excellent performance on the surface of the moon or Mars. The reference system (used to guide technology development) is designed to produce 40 kWe and to be cost-competitive with alternatives while providing more power for less mass anywhere on the lunar surface. The reference FSP system (FSPS) is also readily extensible for use on Mars. At Mars the system would be capable of operating through global dust storms and providing year-round power at any Martian latitude.

Recent non-nuclear testing at NASA MSFC's Early Flight Fission Test Facility (EFF-TF) has helped assess the viability of the reference FSP system, and has helped evaluate methods for system integration. In June, 2009, a representative pumped NaK loop (provided by Marshall Space Flight Center) was coupled to a Stirling power converter (provided by Glenn Research Center) and tested at various conditions representative of those that would be seen during actual FSP system operation. The test used a pump provided by Idaho National Laboratory (INL) to circulate the NaK, a core simulator designed with extensive assistance from Los Alamos National Laboratory (LANL), an instrumentation and control systems designed in coordination with Sandia National Laboratories (SNL) and Oak Ridge National Laboratory (ORNL), and other components developed or obtained through work within the NASA/DOE team. In all areas, performance of the integrated system exceeded project goals. Significant results from the coupled pumped NaK loop / Stirling power converter testing include a demonstrated thermal to electrical efficiency of 32% at a hot side temperature of 825K and a cold side temperature of 325 K; a very low (<5ºC) circumferential temperature gradient on the Stirling heater head; and a total power production (2.4 kWe) significantly higher than the test goal. Testing included 41 steady-state test points, 9 transients, and 6 reactivity control simulations. Integrated pumped NaK loop / Stirling test hardware is shown in Figure 1. Additional details related to Integrated pumped NaK loop / Stirling testing are provided in [1].

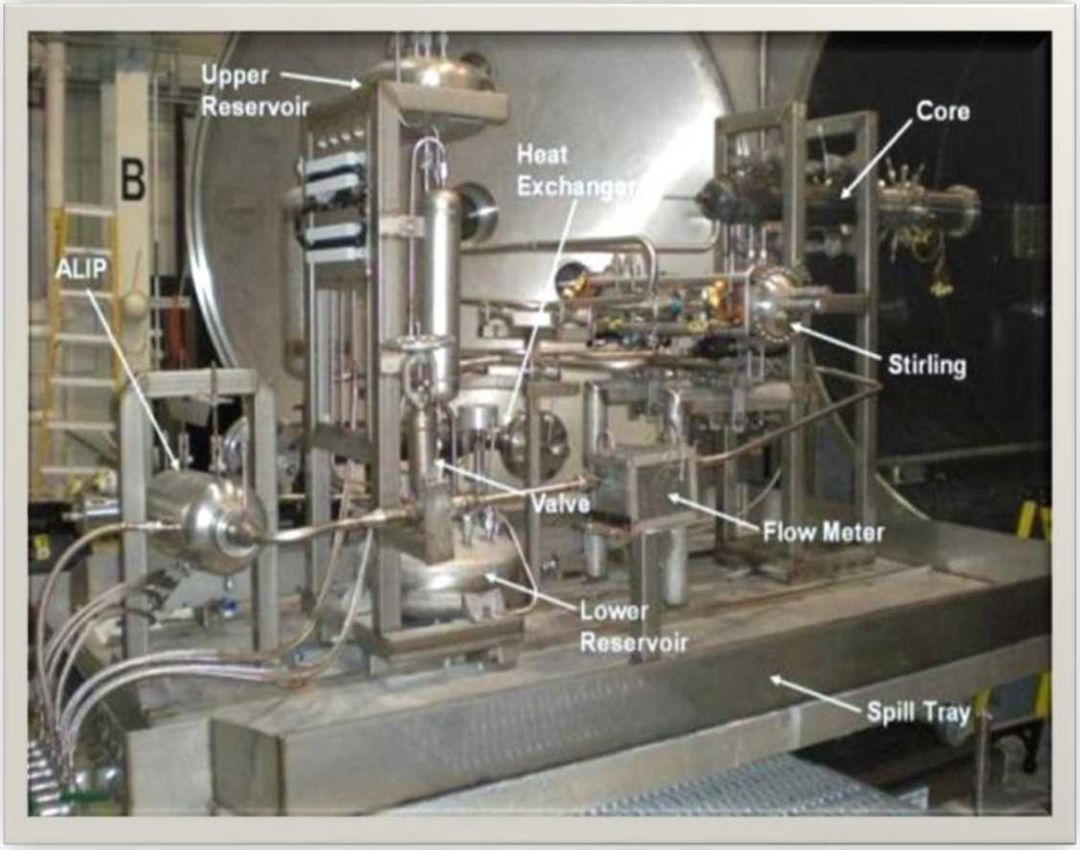

Figure 1. Integrated pumped NaK loop / Stirling test hardware

High-temperature NaK pump testing has also been performed at the EFF-TF, as has testing of methods for providing long-duration NaK purity. Pump testing completed in January, 2010 demonstrated the feasibility of using an Annular Linear Induction Pump (ALIP) to circulate NaK in the reference FSP system. ALIP testing demonstrated the fundamental feasibility of using an ALIP in a potential FSP flight system, and provided data useful for optimizing efficiency, operating frequency, operating voltage, and other parameters in future ALIP designs. Testing also helped identify potential improvements in ALIP manufacturing techniques and specifications. Additional details related to ALIP testing are provided in [1].

To ensure adequate lifetime in pumped NaK systems operating at temperatures up to ~900 K, it is desirable to maintain purity levels such that oxide concentration in the NaK is <20 ppm. Additionally, although pumped NaK systems are designed to launch with the NaK liquid and for the NaK to remain throughout the duration of the mission, contingencies should be developed in case the NaK were to inadvertently freeze.

To help assess potential operational and lifetime issues associated with the use of NaK coolant, bench-scale Feasibility Test Loops (FTLs) are being operated as part of the EFF-TF. Results to date have partially demonstrated methods for ensuring NaK purity on initial loading, measuring NaK purity within an operating system, and purifying NaK (if needed) without requiring system shutdown. Additional testing is slated to be performed in technologies related to the use of pumped NaK coolant for long-life space nuclear power systems.

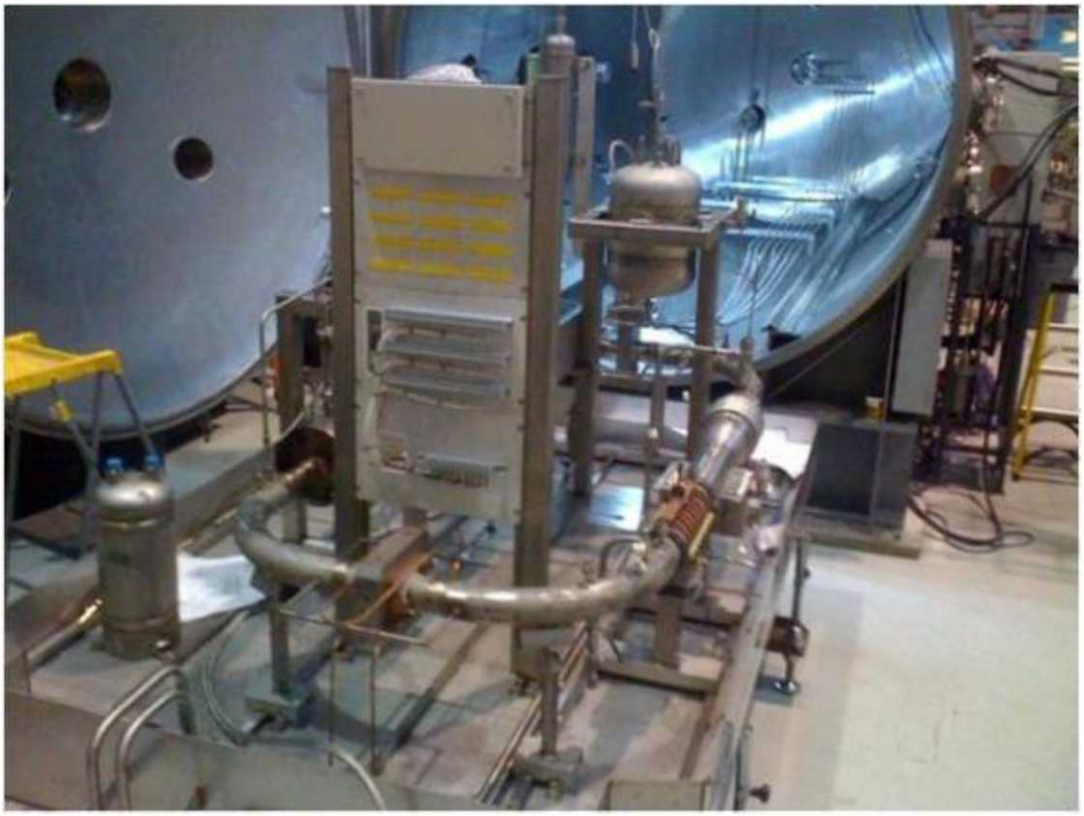

Figure 2. Annular Linear Induction Pump (ALIP) Test Circuit

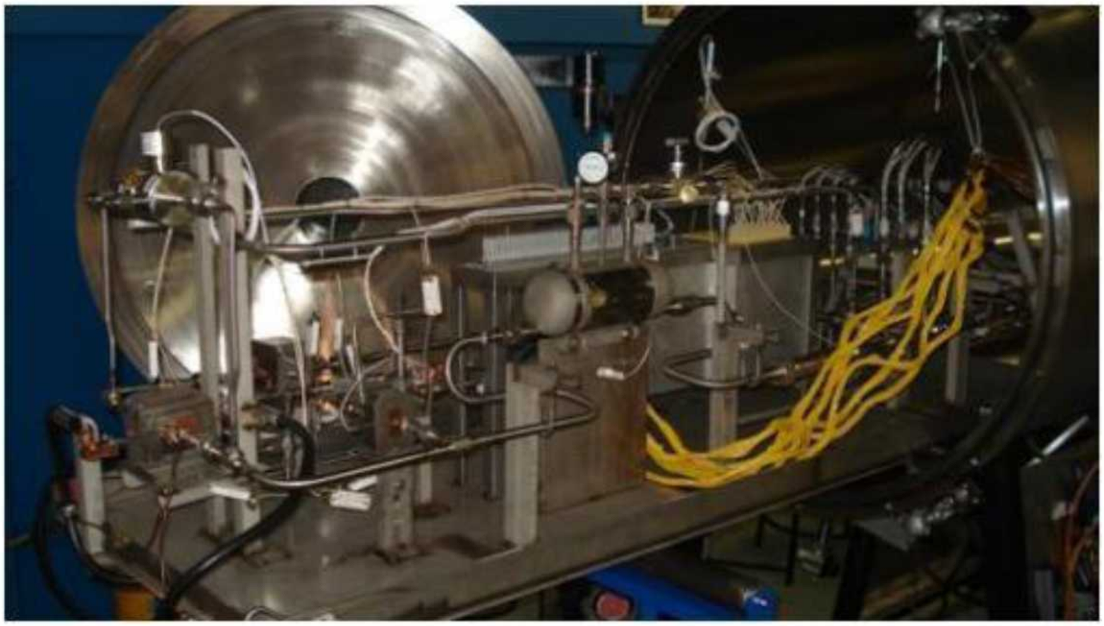

Figure 3. Feasibility Test Loop (FTL) NaK Loading and Verification

IN-SPACE FISSION POWER SYSTEM TESTING

From 1999-2006 testing related to in-space fission electric power systems was performed at the EFF-TF. Testing related to both low and moderate power systems was performed.

The focus of the low power system testing was on heat pipe cooled systems capable of delivering up to 400 kWt to a power conversion subsystem. In 2001, testing centered on a system that used 10 active heat pipes to transfer power from a simulated core with dimensions and materials that would enable an operational reactor if uranium dioxide fuel and a neutron reflector were added. The testing was successful, with a maximum power of 19.2 kW transferred from the core at representative heat pipe operating temperatures. Tests were also performed to demonstrate rapid startup, thermal cycling, and thermal coupling from the heat pipes to a Stirling engine. The Stirling engine (obtained with the assistance of NASA GRC) operated at full power and performed as expected. Figure 4 shows testing of the heat pipe cooled reactor core coupled to the Stirling engine. Although electrically heated thermal simulators were used to mimic heat from fission, the core used in these tests was designed to match the axial and radial power profiles of an actual operating reactor.

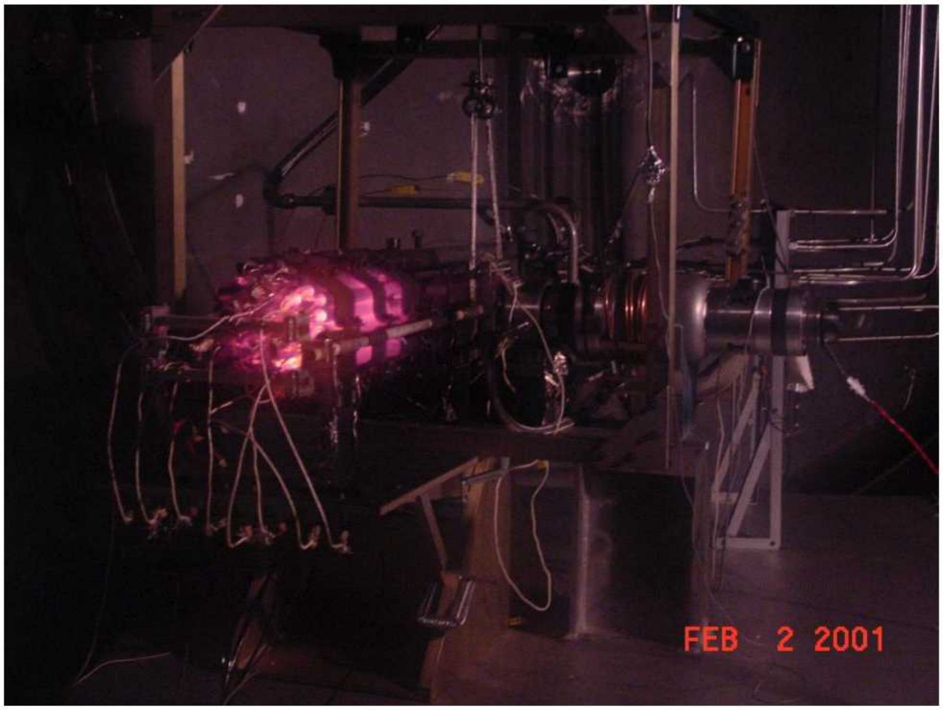

Figure 4. Heat Pipe Cooled Simulated Reactor Core Coupled to Stirling Engine

NUCLEAR THERMAL ROCKET FUELS TESTING

Nuclear thermal rocket (NTR) fuels testing has been identified by the National Research Council as an important technology development area [2]. MSFC's Nuclear Thermal Rocket Element Environmental Simulator (NTREES) is capable of performing realistic non-nuclear testing of potential NTR fuel elements. NTREES can achieve fuel temperature of 3000 K in a flowing hydrogen environment at high power densities. NTREES is licensed to test elements containing depleted uranium, and has diagnostics for measuring real-time erosion and corrosion. NTREES capability would be important to early technology development work associated with nuclear thermal propulsion systems. A picture of the NTREES is shown in Figure 5.

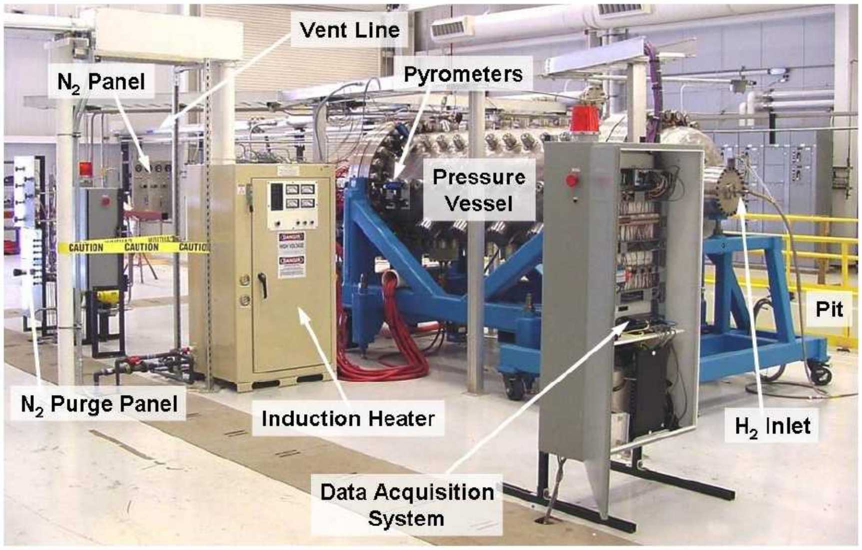

Figure 5. Nuclear Thermal Rocket Element Environmental Simulator (NTREES)

RADIOISOTOPE POWER SYSTEM (RPS) THERMAL SIMULATORS

Future radioisotope systems may use a different GPHS module configuration than current systems. In addition, the potential for using isotopes other than Pu-238 is occasionally considered. To facilitate the initial evaluation of these systems, MSFC has developed GPHS module thermal simulators that have the flexibility to test any desired module configuration and to simulate any potential isotope using the standard iridium clad. These simulators could be of use to future radioisotope system development programs.

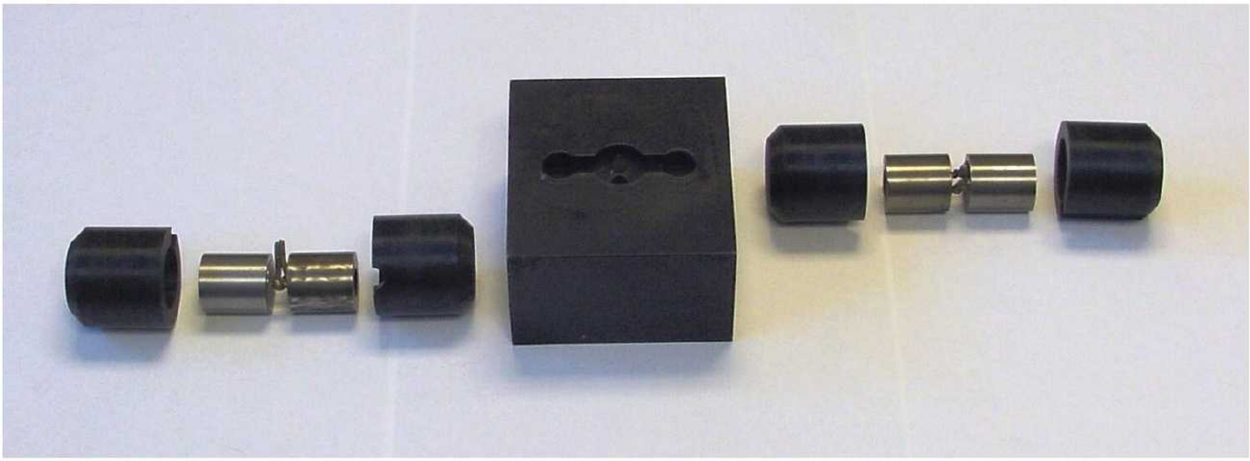

Figure 5. General Purpose Heat Source (GPHS) Module Thermal Simulator

CONCLUSIONS

Space nuclear power and propulsion systems have numerous potential applications. Highly realistic non-nuclear testing can be used to investigate and resolve potential issues with space nuclear power and propulsion systems. Beginning in 1998, a facility has been developed at NASA MSFC that is optimized to reduce the development cost and schedule associated with potential space nuclear systems through the use of highly realistic non-nuclear testing. The Early Flight Fission Test Facility (EFF-TF) is capable of performing research related to both surface and in-space fission electric systems as well as nuclear thermal propulsion systems and radioisotope power systems. When used in conjunction with facilities at other NASA centers and at Department of Energy (DOE) National Laboratories, the EFF-TF could help enable affordable space nuclear systems for a variety of applications. The EFF-TF also helps facilitate a close working relationship between NASA and the DOE in the area of space nuclear power and propulsion.

REFERENCES

[1] K. Polzin, et al. “Testing of Liquid Metal Components for Nuclear Surface Power Systems”, JANNAF paper 1394, May, 2010.

[2] National Research Council “A Constrained Space Exploration Technology Development Program”, National Academies Press, 2008, ISBN 13: 978-0-309-12583-3

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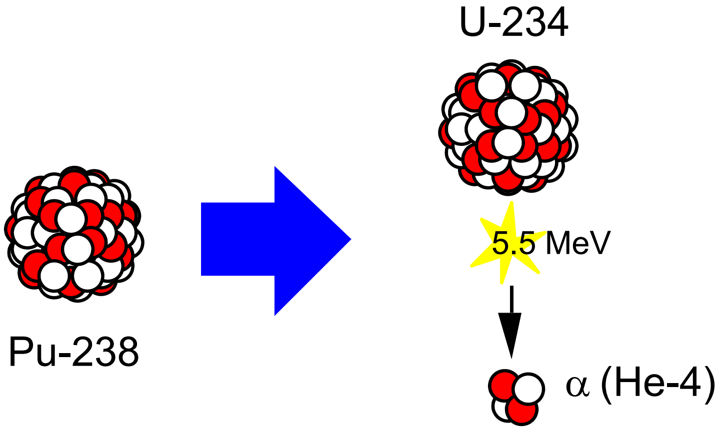
michael.houts@nasa.gov

Two Types of Space Nuclear Systems

Radioisotope Decay (Pu-238)

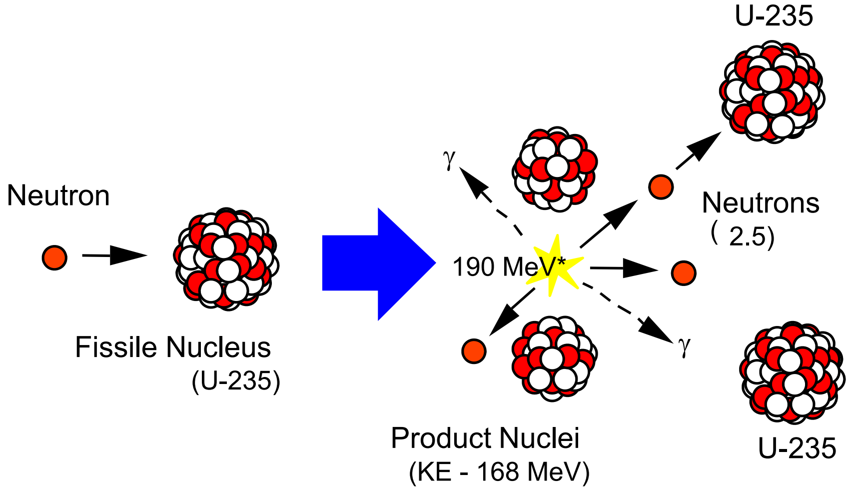


Heat Energy = 0.023 MeV/nucleon (0.558 W/g Pu-238)

Natural decay rate (87.7-year half-life)

- **Long history of use on Apollo and space science missions**
  - 44 RTGs and hundreds of RHUs launched by U.S. during past 4 decades
- **Heat produced from natural alpha (α) particle decay of Plutonium (Pu-238)**
- **Used for both thermal management and electricity production**

Fission (U-235)



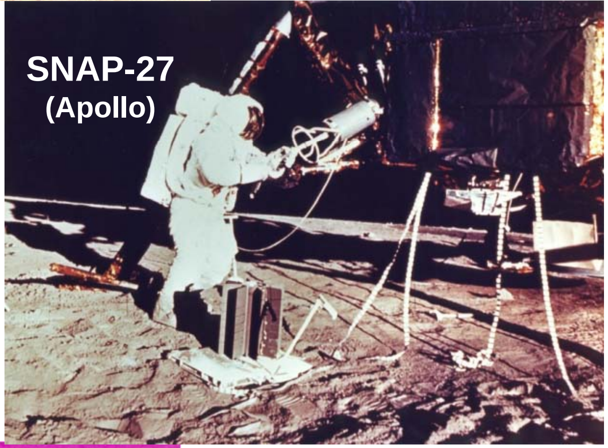
Heat Energy = 0.851 MeV/nucleon

Controllable reaction rate (variable power levels)

- **Used terrestrially for over 65 years**
  - Fissioning 1 kg of uranium yields as much energy as burning 2,700,000 kg of coal
- **Heat produced from neutron-induced splitting of a nucleus (e.g. U-235)**
  - At steady-state, 1 of the 2 to 3 neutrons released causes a subsequent fission in a “chain reaction”
- **Heat converted to electricity, or used directly to heat a propellant**

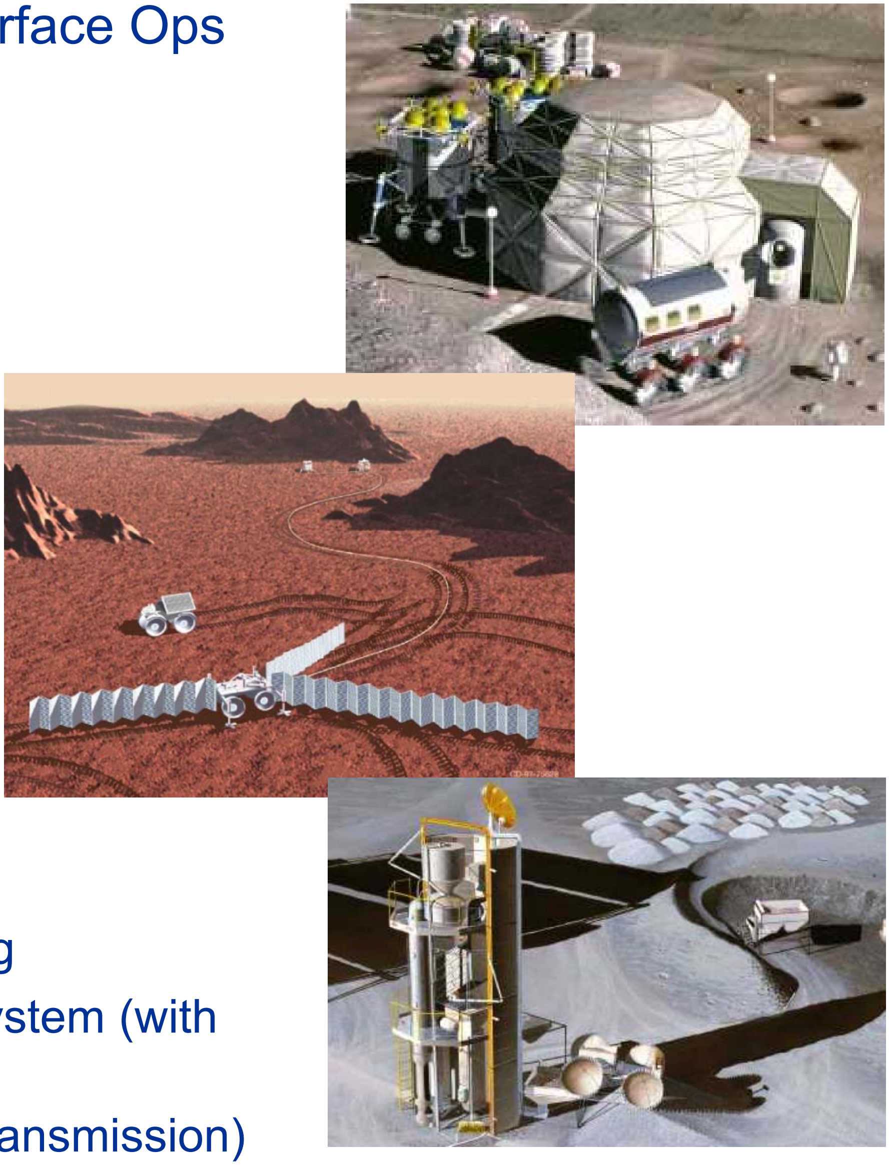
Two Types of Space Nuclear Systems

- Radioisotope Power Systems
  - 44 Successful U.S. Radioisotope Thermoelectric Generators (RTGs) 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)
- Fission Reactor Systems
  - SNAP-10A (launched 1965)
  - SP-100 (concept / cancelled 1992)
  - Jupiter Icy Moons Orbiter (concept / cancelled 2005)
  - Fission Surface Power (concept / ongoing technology development)



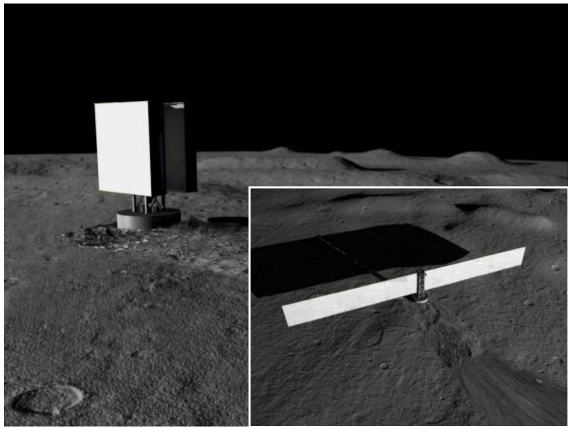
Recent Interest in Fission Surface Power (FSP) to Support Moon / Mars Exploration

- Continuous Day/Night Power for Robust Surface Ops
- Same Technology for Moon and Mars
- Suitable for any Surface Location
  - Lunar Equatorial or Polar Sites
  - Permanently Shaded Craters
  - Mars Equatorial or High Latitudes
- Environmentally Robust
  - Lunar Day/Night Thermal Transients
  - Mars Dust Storms
- Operationally Robust
  - Multiple-Failure Tolerant
  - Long Life without Maintenance
- Highly Flexible Configurations
  - Excavation Shield Permits Near-Habitat Siting
  - Option for Above-Grade System or Mobile System (with shield mass penalty)
  - Option for Remote Siting (with high voltage transmission)
  - Option for Process Heat Source (for ISRU or habitat)



Recent Interest in Fission Surface Power (FSP) to Support Moon / Mars Exploration

- Safe During All Mission Phases
  - Launched Cold, No Radiation Until Startup
  - Safe during Operation with Excavation or Landed Shield
  - Safe after Shutdown with Negligible Residual Radiation
- Scalable to Higher Power Levels (kWs to MWs)
- Performance Advantages Compared to PV/RFC
  - Significant Mass & Volume Savings for Moon
  - Significant Mass & Deployed Area Savings for Mars
- Competitive Cost with PV/RFC
  - Detailed, 12-month “Affordable” Fission Surface Power System Cost Study Performed by NASA & DOE
  - LAT2 FSP and PV/RFC Options had Similar Overall Cost
  - Modest Unit Cost Enables Multiple Units and/or Multiple Sites
- Technology Primed for Development
  - Terrestrial Reactor Design Basis
  - No Material Breakthroughs Required
  - Lineage to RPS Systems (e.g. Stirling) and ISS (e.g. Radiators, Electrical Power Distribution)

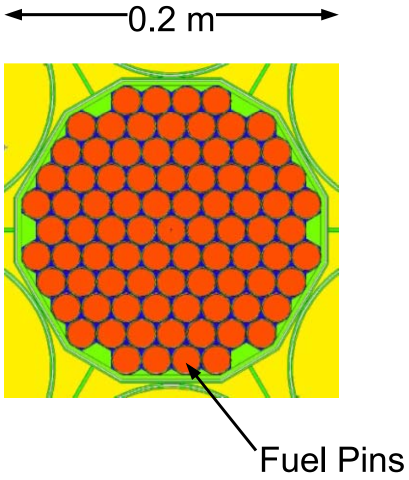


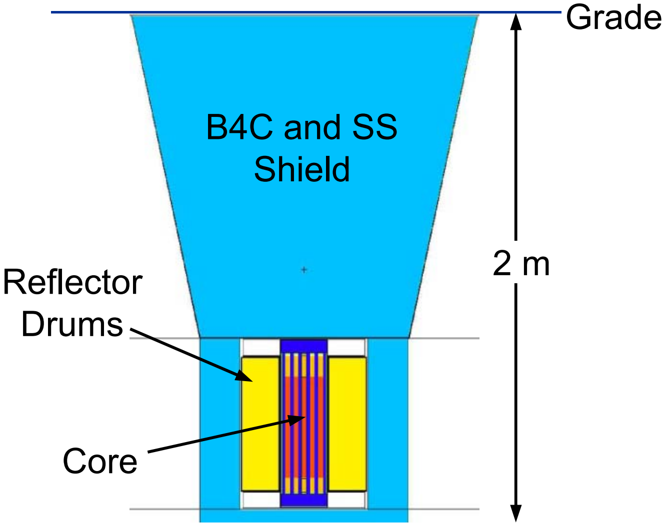
Fission Surface Power Design Philosophy

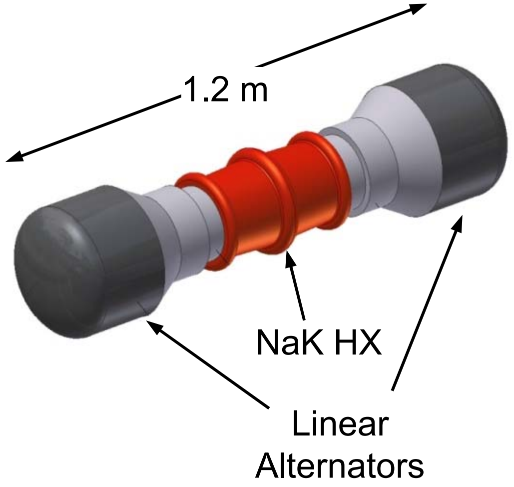
- **Conservative**
  - Low Temperature
  - Known Materials and Fluids
  - Generous Margins
  - Large Safety Factors
  - Terrestrial Design Basis
- **Simple**
  - Modest Power & Life Requirements
  - Simple Controls
    - Negative Temperature Reactivity Feedback: assures safe response to reactor temperature 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 Test-able Configurations
- **Robust**
  - High Redundancy
  - Fault Tolerance… including ability to recover from severe conditions such as:
    - Loss of Reactor Cooling
    - Stuck Reflector Drums
    - Power Conversion Unit Failure
    - Radiator Pump Failure
    - Loss of Radiator Coolant
    - Loss of Electrical Load
  - High TRL Components
  - Hardware-Rich Test Program
  - Multiple Design Cycles

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

Key Design Features







Reactor Core:

- Well-known UO$_2$ fuel and SS-316 cladding at moderate temperature (<900K)
- Low power (<200 kWt), low fuel burn-up (~1%)
- Fluence levels well below material thresholds
- NaK coolant: low freeze temp (262K), extensive space & terrestrial technology base
- Simple and safe, negative temperature feedback control

Reactor Module:

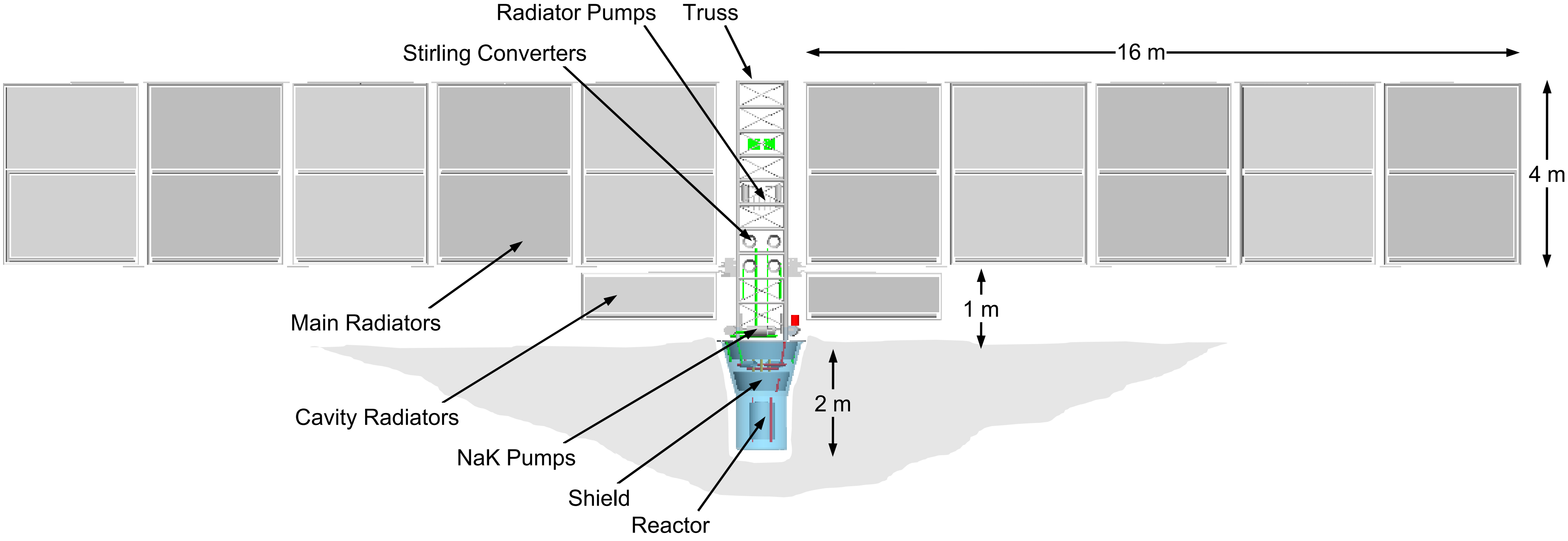
- Fault-tolerant, radial Be reflector control drums
- Low-risk B4C and SS shielding with regolith augmentation
- <2 Mrad and 1x10^{14} n/cm^2 at power conversion; <5 rem/yr at outpost (100 m)
- SS-316 primary & intermediate coolant loops with redundant EM pumps
- Cavity cooling with surface-mounted radiators

Stirling Power Conversion:

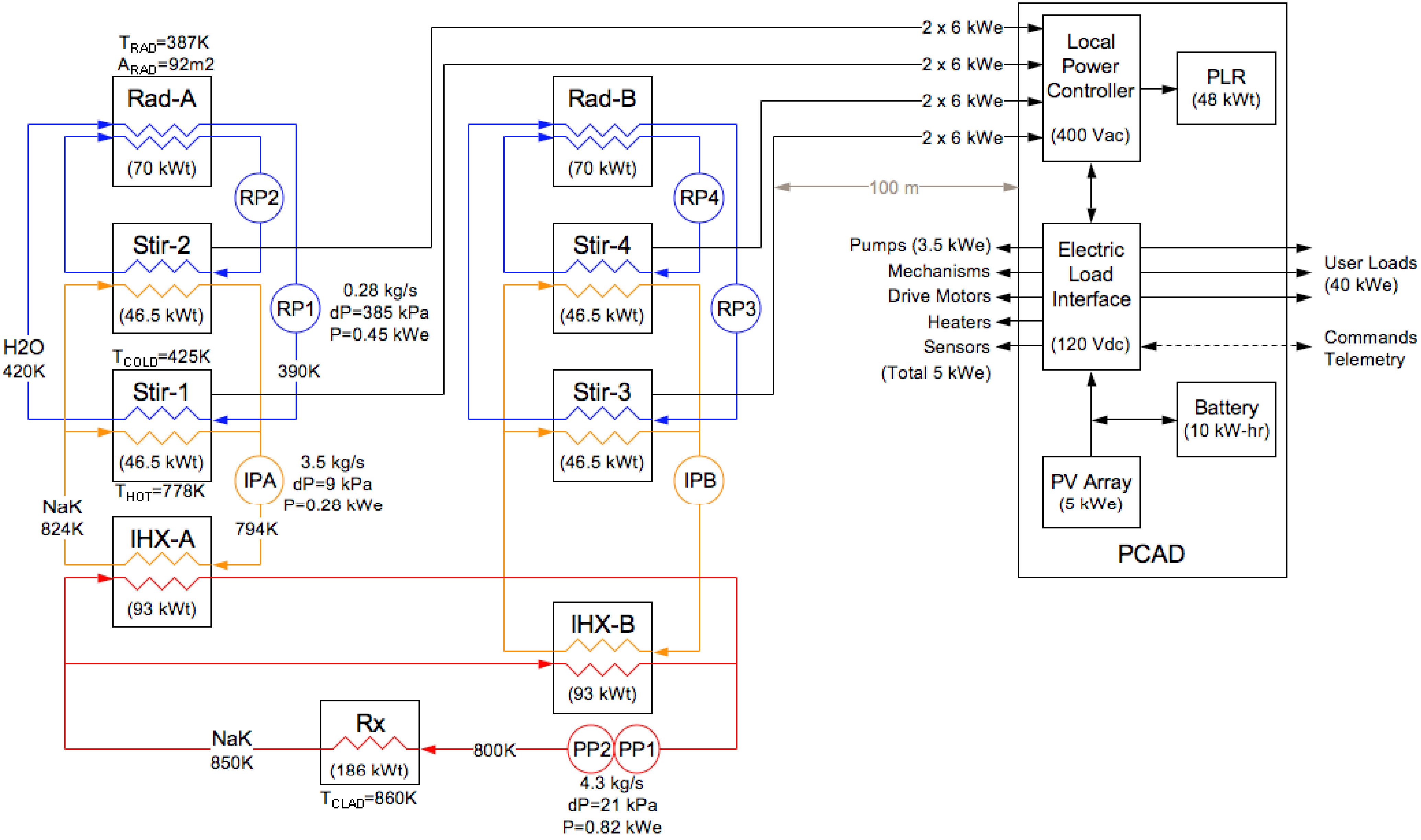
- High efficiency (>25%) at low hot-end temperature (830K)
- Pumped-water cooling (400K)
- Smallest radiator size among PC options
- 4 dual opposed engines, 8 linear alternators
- 400 Vac power distribution
- Demonstrated technology at 25 kW size in 1980's
- Potential to leverage current RPS program

FSP Reference Concept

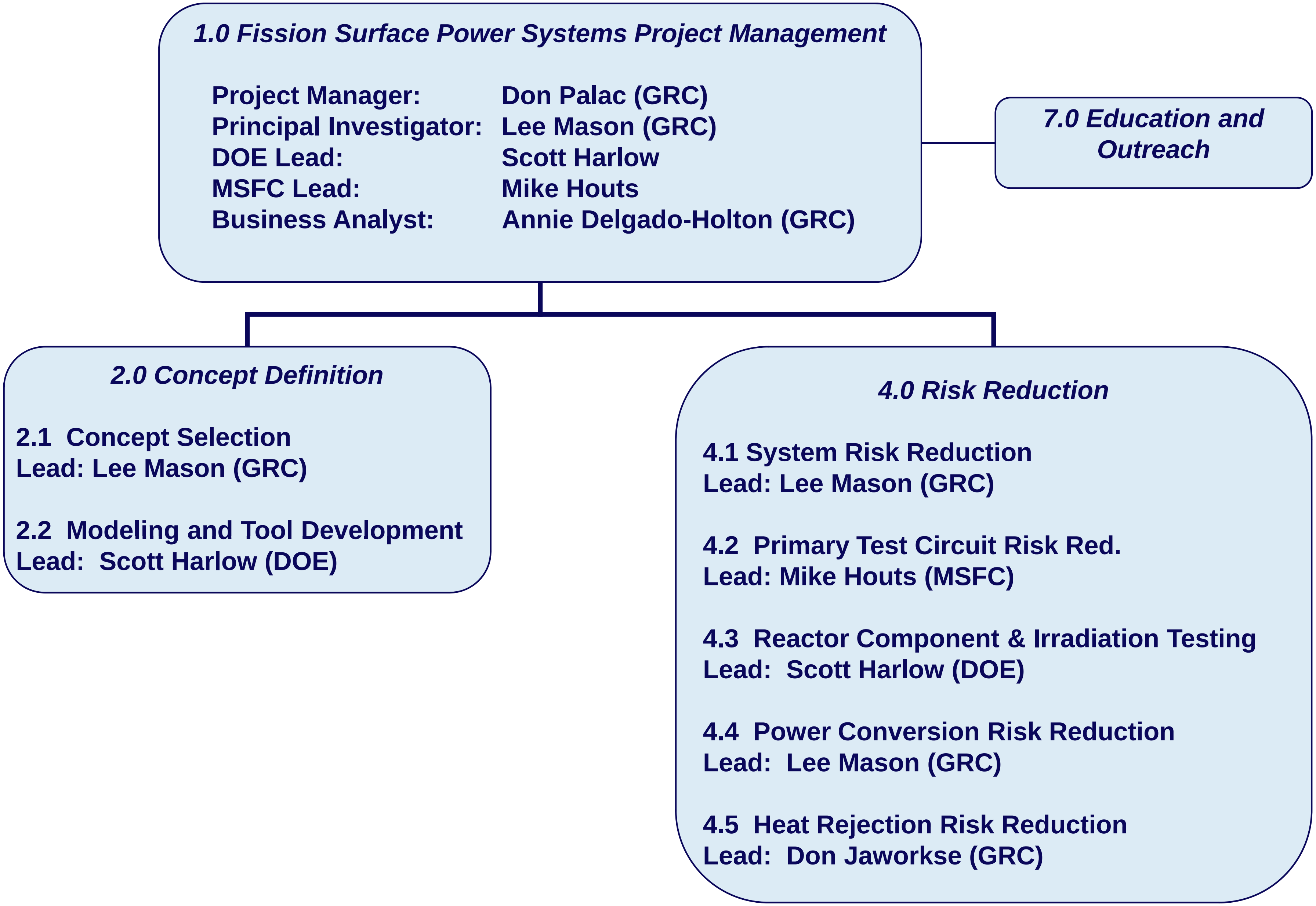
- Modular 40 kWe System with 8-Year Design Life suitable for (Global) Lunar and Mars Surface Applications
- Emplaced Configuration with Regolith Shielding Augmentation Permits Near-Outpost Siting (<5 rem/yr at 100 m Separation)
- Low Temperature, Low Development Risk, Liquid-Metal (NaK) Cooled Reactor with UO_2 Fuel and Stainless Steel Construction



FSP Reference Concept



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**
Business Analyst:	**Annie Delgado-Holton (GRC)**

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)

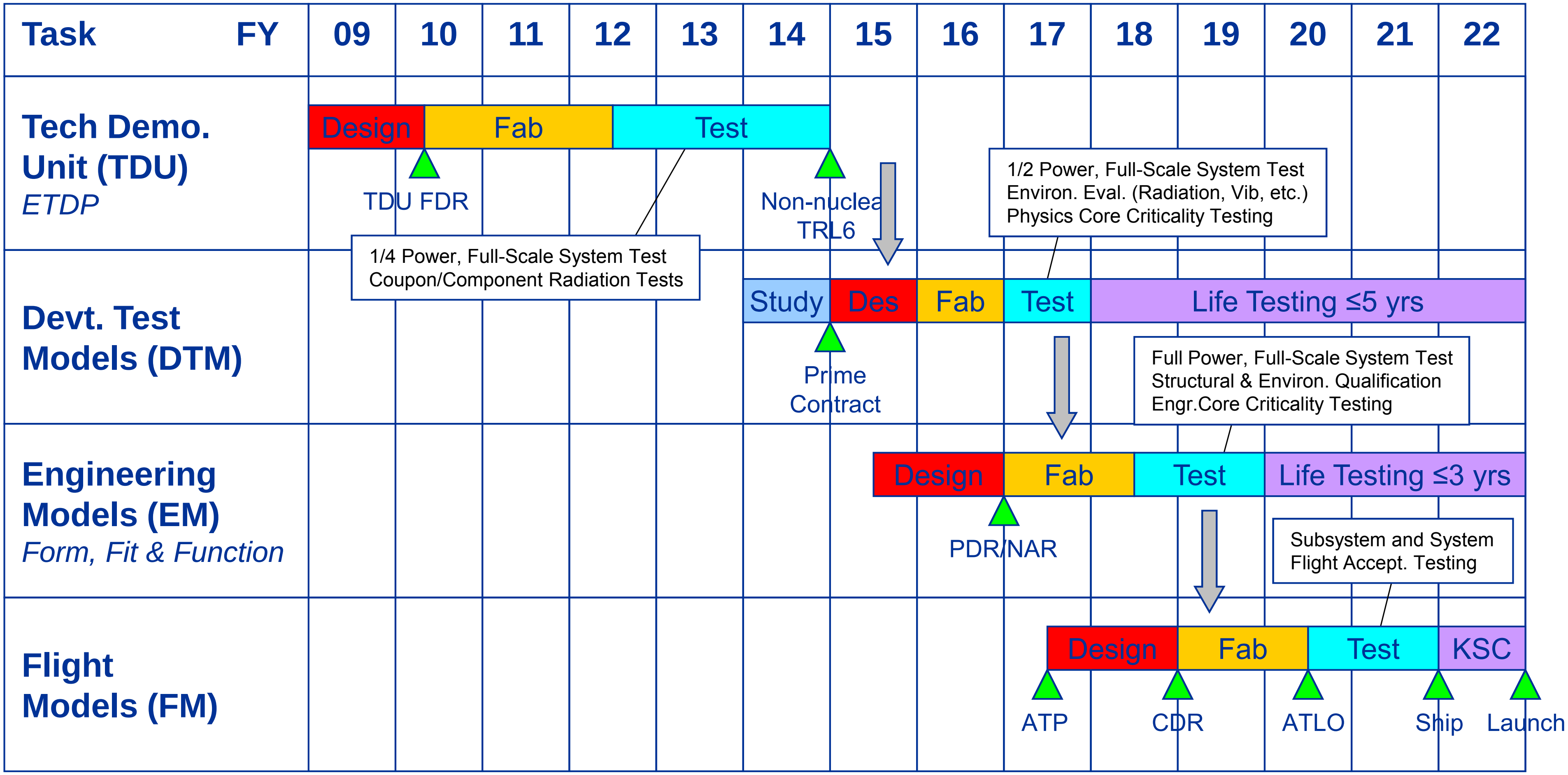
4.2 Primary Test Circuit Risk Red.
Lead: Mike Houts (MSFC)

4.3 Reactor Component & 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)

Notional FSP Flight Development Schedule



Task FY 09 10 11 12 13 14 15 16 17 18 19 20 21 22

Tech Demo. Unit (TDU)
ETDP

Design Fab Test

TDU FDR

Non-nuclear TRL6

1/4 Power, Full-Scale System Test
Coupon/Component Radiation Tests

1/2 Power, Full-Scale System Test
Environ. Eval. (Radiation, Vib, etc.)
Physics Core Criticality Testing

Devt. Test Models (DTM)

Study Des Fab Test Life Testing ≤5 yrs

Prime Contract

Full Power, Full-Scale System Test
Structural & Environ. Qualification
Engr.Core Criticality Testing

Engineering Models (EM)
Form, Fit & Function

Design Fab Test Life Testing ≤3 yrs

PDR/NAR

Subsystem and System
Flight Accept. Testing

Flight Models (FM)

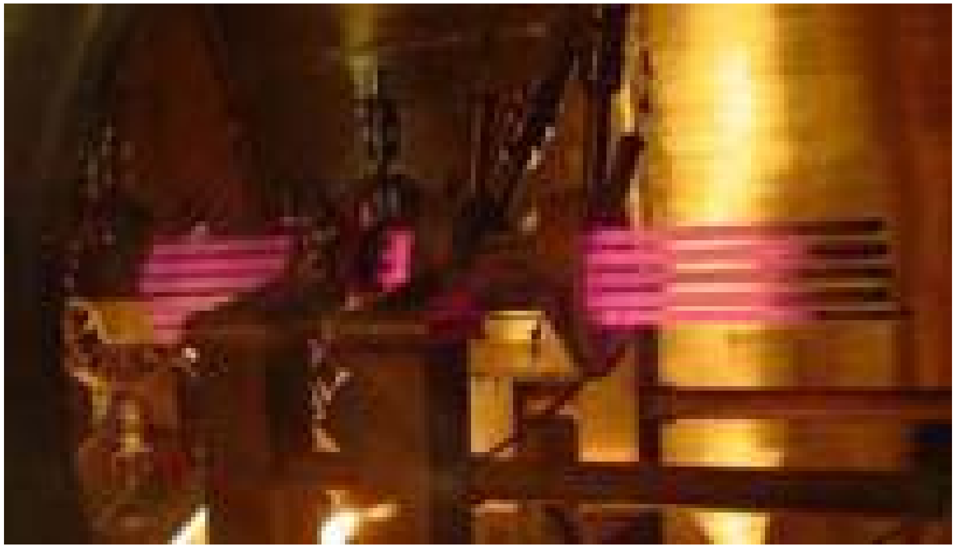
Design Fab Test KSC

ATP CDR ATLO Ship Launch

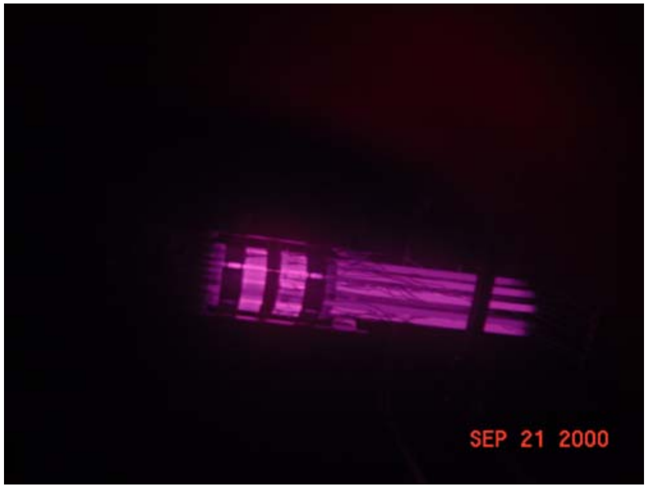
Revised 8/5/09

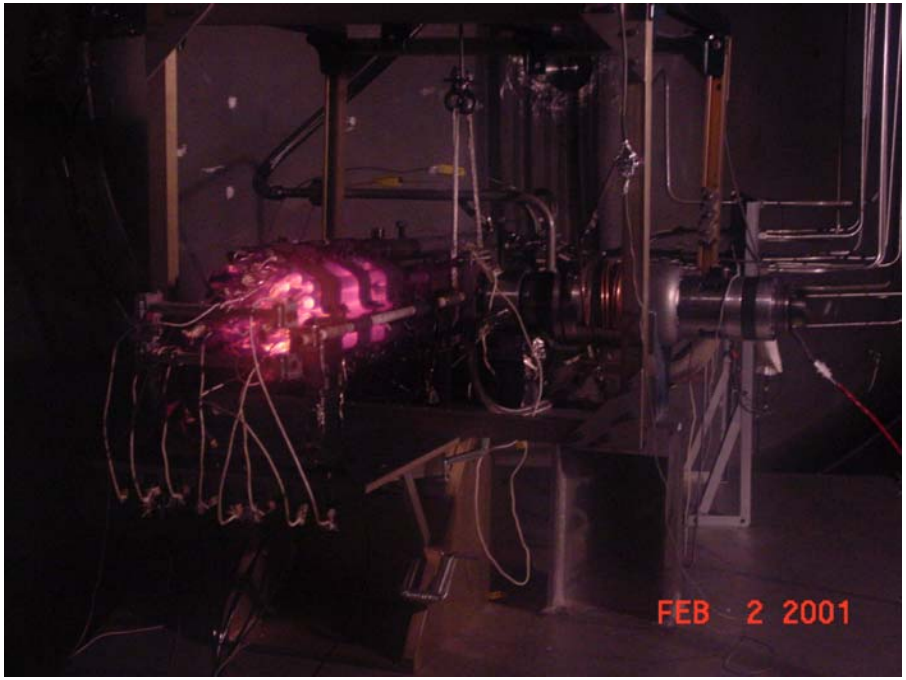
MSFC Early Flight Fission Test Facility (EFF-TF)

- 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
- Applicable to both surface and in-space fission systems
- Heat pipe, gas cooled, and alkali metal cooled testing performed to date



Initial Emphasis on Heat Pipe Cooled Systems





SAFE-30 (2000 - 2002)

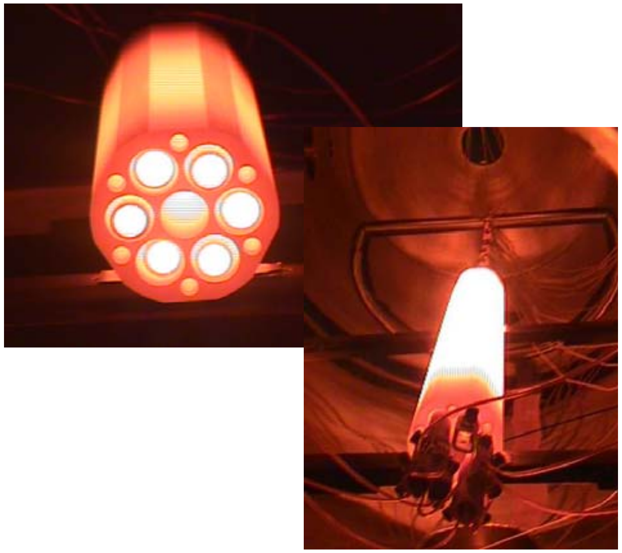
- Isothermal heatpipe operation. Moderate power (17.6 kW) at high temperature (>900 K). Demonstrated high-temperature CO_2 compatibility.
- Heaters developed in-house (Ricky Dickens).
- Fifteen restarts as of February, 2001.
- Remaining tests include direct thermal propulsion.
- Utilizes materials and geometry required for fission system core / primary heat transport.
- First realistic full-core / primary heat transport test of US space fission system since 1969.

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

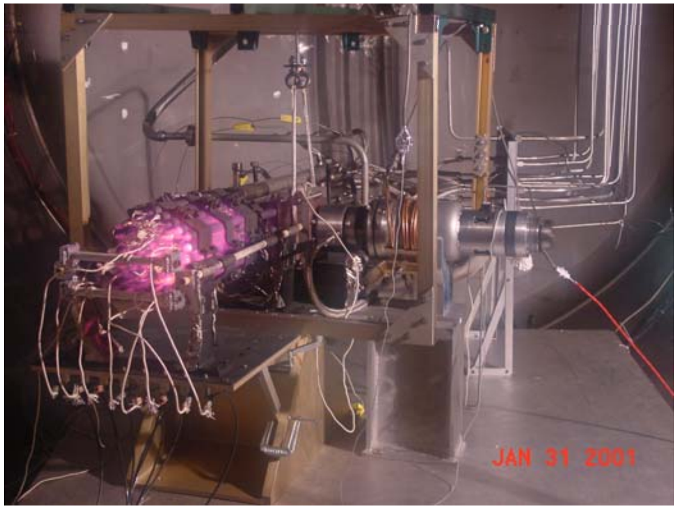


High-Temperature SAFE Module Testing Completed in FY00.

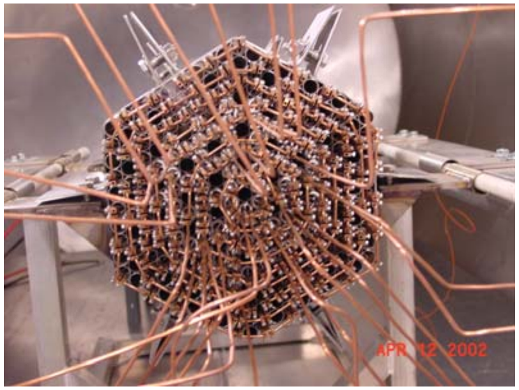
- > 1750 K Core Module Temperature.
- > 1450 K Heat pipe Temperature.
- Direct thermal propulsion mode demonstrated.
- Fast start of heat pipe (room temp to >1400 K in < 1 hr).
- Multiple heat pipe restarts.

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

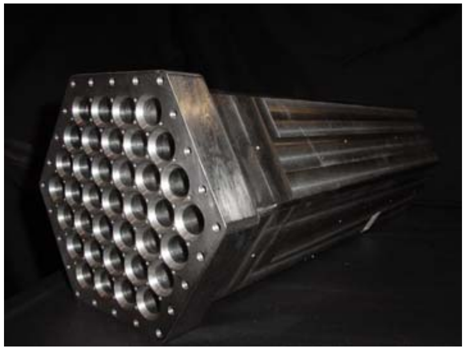


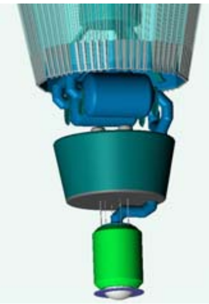
- Computationally and experimentally investigate prototypic module, core, and heat exchanger design for 100 kWt system
  - Module fabrication
  - Core support / expansion
  - Thermal performance
  - Thermal cycling effects
- Develop and utilize advanced instrumentation and power delivery system.
  -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

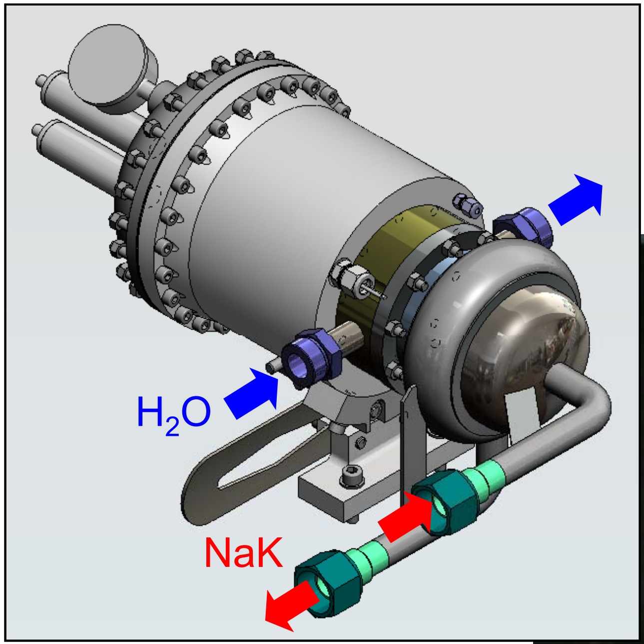
133-Pin, 100 kWt subscale test
- Pressure drop & flowing heat transfer code validation with radial power profile → Dynamics with 25-kWe Brayton turbomachinery and simulated nuclear temperature-dependent feedback, code validation
- Multi-module stagnant He/Xe decay heat code validation

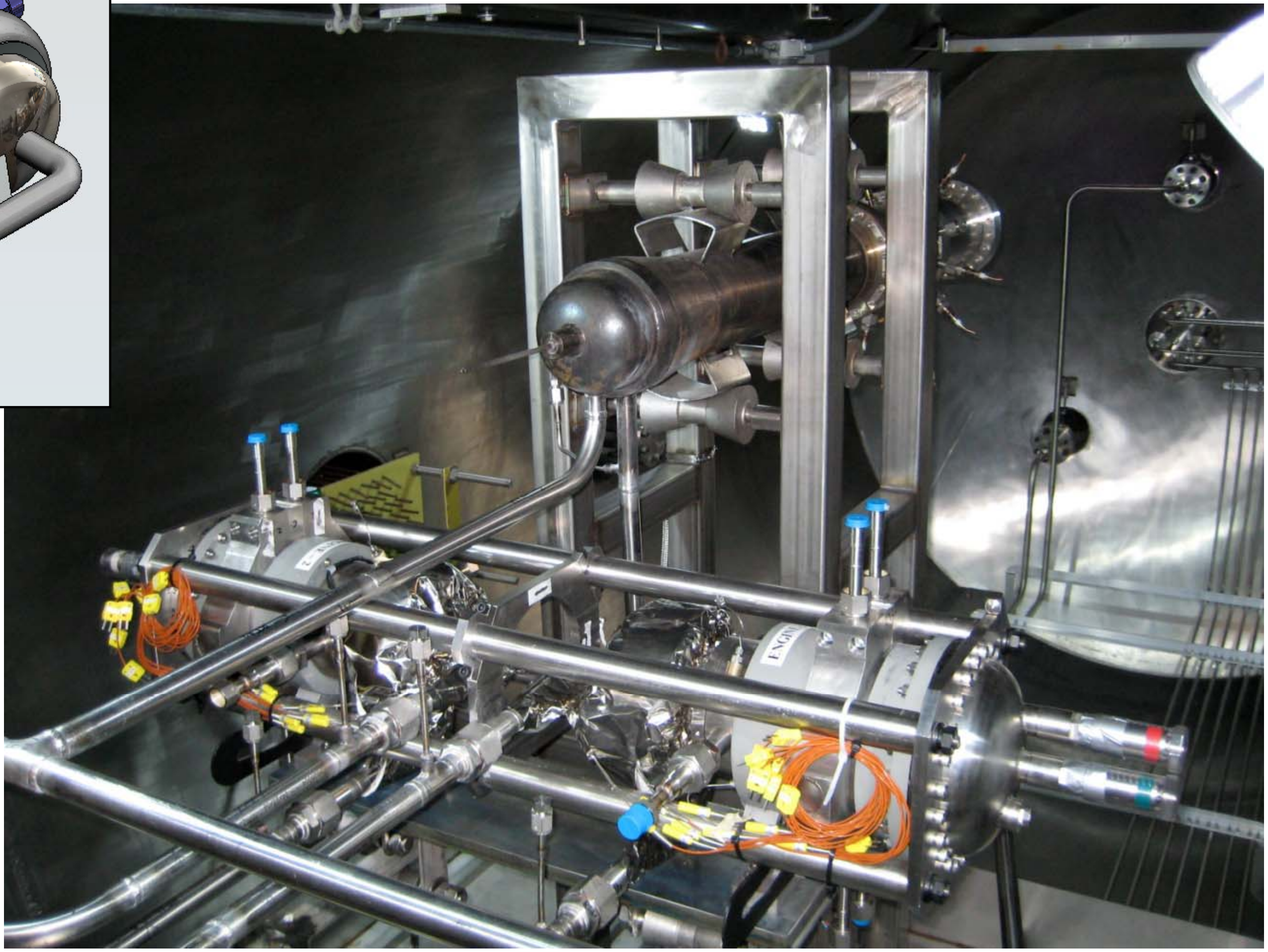
2 kWe BRU Test at NASA GRC

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)

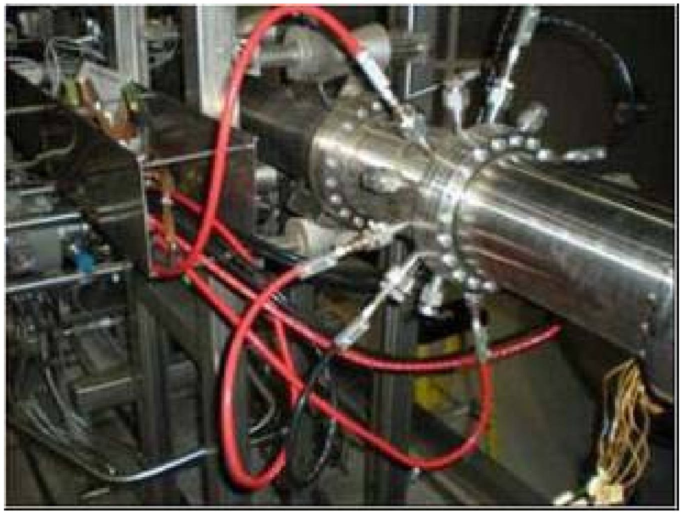




- 2.4 kWe at Thot=550ºC, Tcold=50ºC
- 32% Thermal Efficiency
- <5ºC Circum. Gradient on Heater Head
- 41 Steady-State Test Points; 9 Transients
- 6 Reactivity Control Simulations

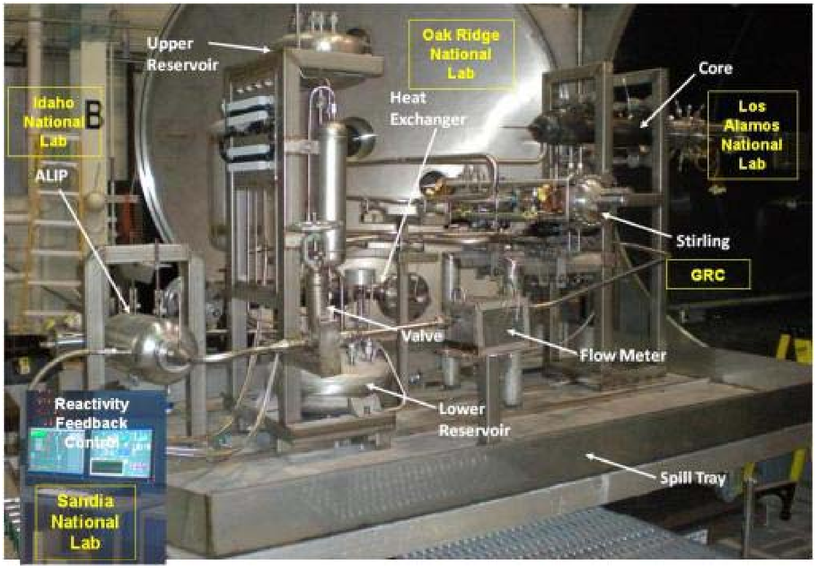
Coupled NaK Loop / Stirling Test

Cable tray providing protection from heat/NaK



Core Simulator Design by Los Alamos National Laboratory

Power Cable path to core

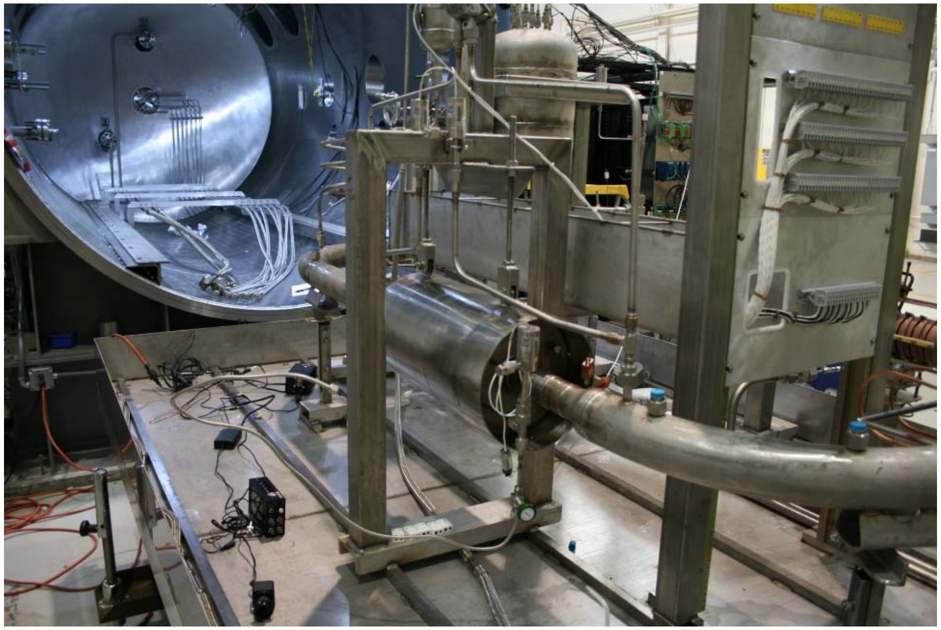


Integrated Stirling Test Assembly

ALIP Provided By Idaho National Laboratory

EFF-TF ALIP Test Circuit

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



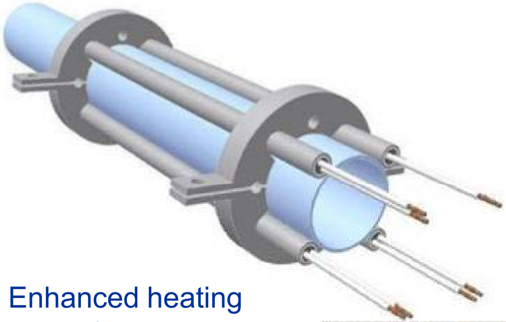
Performance Mapping of Annular Linear Induction Pump (ALIP) provided by Idaho National Laboratory

ALIP Test Circuit (ATC)

ALIP

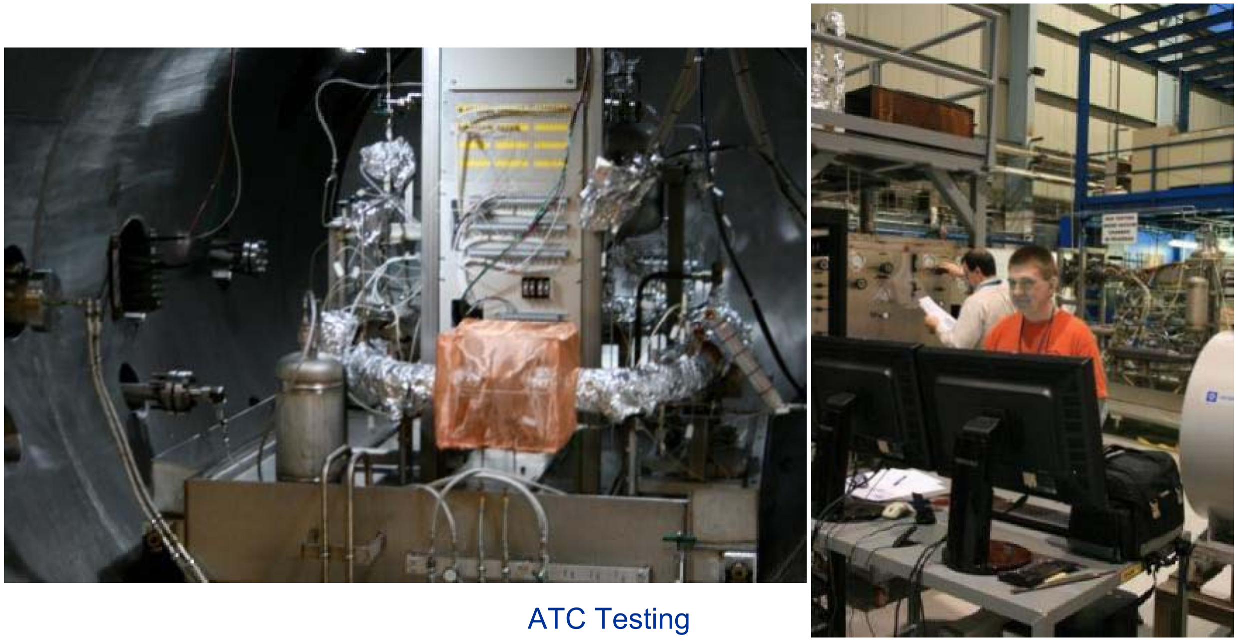
ATC ready for chamber prior to NaK fill

NaK fill



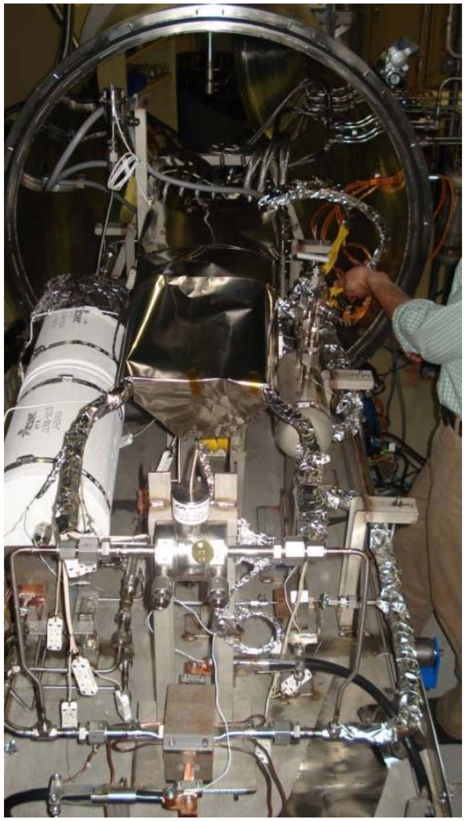
Enhanced heating assembly

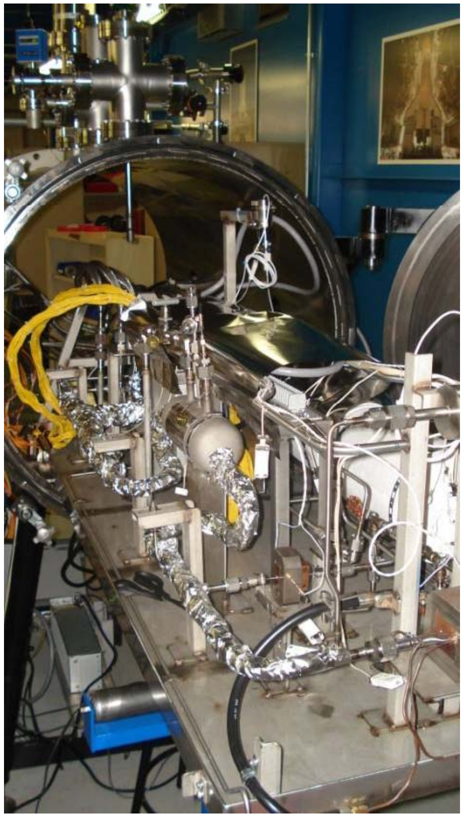
Enhanced heating assembly ready for application of insulation

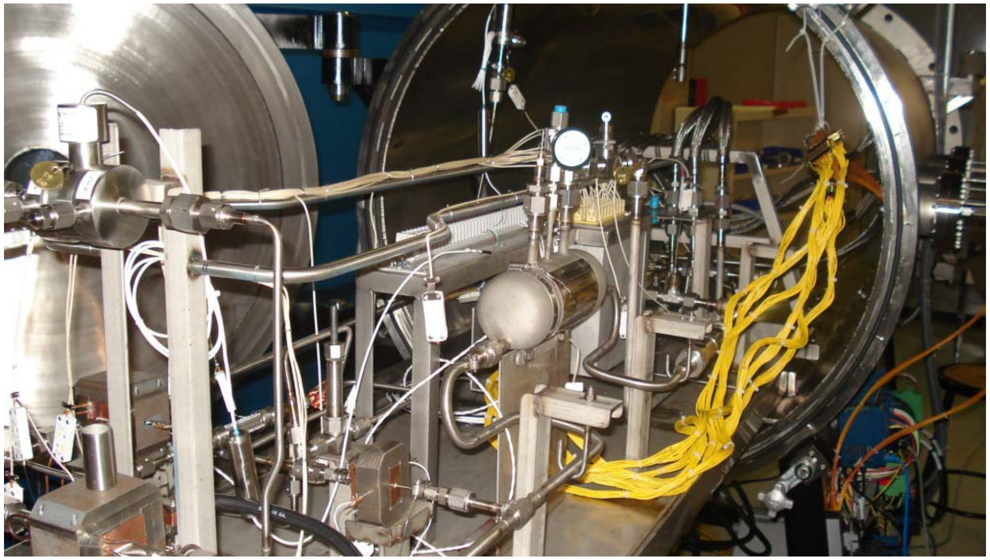


ATC Testing

EFF-TF Feasibility Test Loop







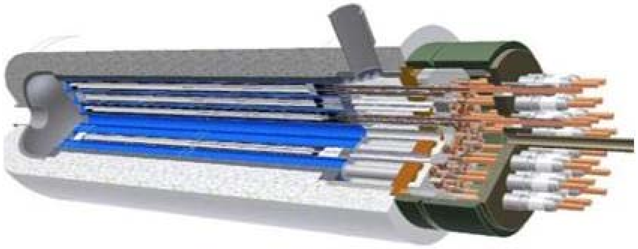
Feasibility Test Loop:

Investigate potential issues and optimizations related to pumped alkali metal systems

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

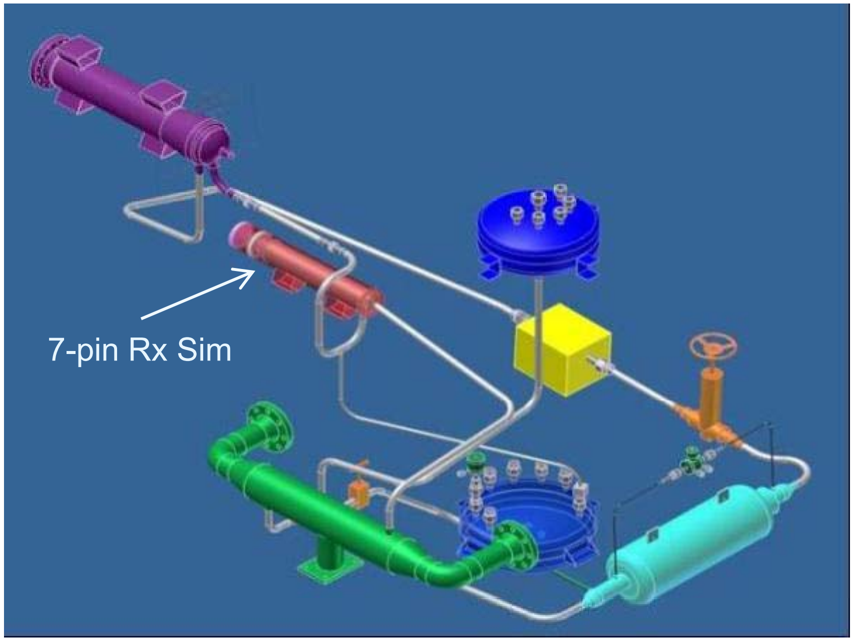
MSFC
Designed
Advanced
Simulators

7-Pin Rx
Core Sim



37 – Pin TDU Rx Core Sim

7 – Pin Rx Core Sim Rendering



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

7 Pin Rx Core Sim installed in FSP-PTC

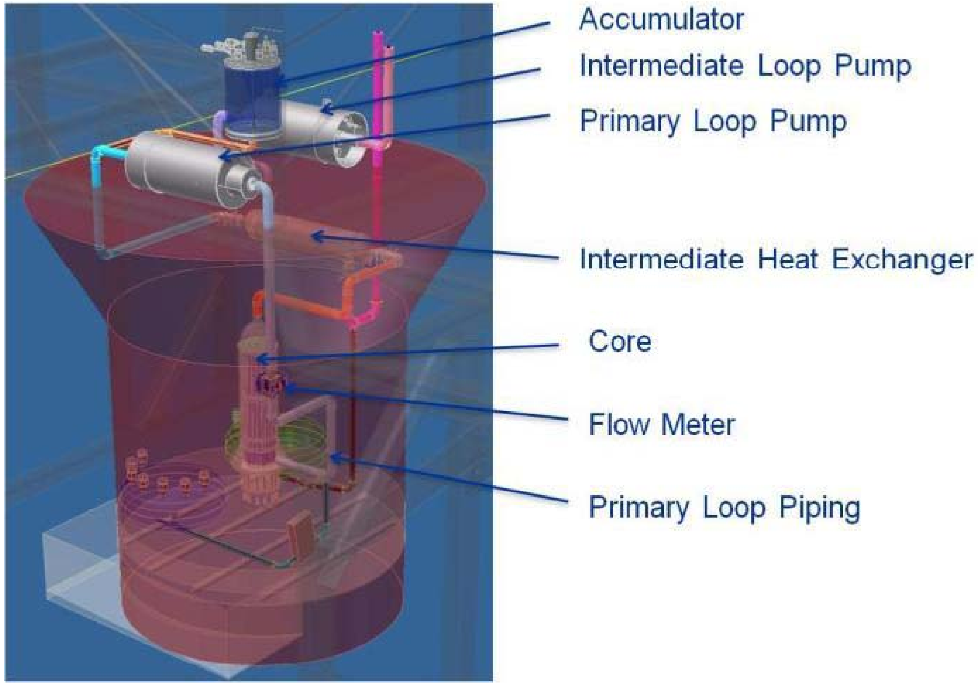
FSPS Accomplishments

FSP-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 : 2010-2011
Ship to GRC 2012

Ongoing Program Focused on FSP

- FSP has many advantages
  - Very cost competitive with solar
  - Day/night power
  - Location independence
  - Environment tolerance
  - Moon/Mars commonality
  - High power, low mass
- Mission integration options are plentiful
  - Buried or Landed, Early or Later, With or without PV
  - Minimal impact on crew
  - Major impact on surface capabilities
- Conservative, Simple, Robust
  - Selected well established liquid metal reactor concept
    - Rich terrestrial heritage
    - Extensive fab/operating experience
    - Vast database
  - Known materials, generous margins including safety
  - Modest requirements
  - Self-regulating controls
  - Fault tolerant, designed to recover from anomalies
  - Hardware-rich test program
  - Low development risk, accept mass penalties if necessary
  - Design to minimize nuclear testing and new facilities needs

Numerous Additional Space Fission Applications