NON-NUCLEAR TESTING OF FISSION TECHNOLOGIES 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

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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 also provides an excellent way for screening potential advanced fuels and materials prior to nuclear testing, and for investigating innovative geometries and operating regimes. 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 power systems (FPS) could be used to provide power anytime, anywhere on the surface of the Moon or Mars. FPS could be used at lunar polar locations, at locations away from the poles, or in permanently shaded regions, with excellent performance at all sites. FPS 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.

FPS could be used in space 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. NTP systems developed and tested during the Rover/NERVA program (1955-1973) demonstrated the potential for high thrust-to-weight operation at a specific impulse of ~900 s [1]. Modern fuels, materials, flow geometries, and engine cycles could enable NTP systems with specific impulses in excess of 1000 s. NASA has initiated a significant project in fiscal year 2012 (the Nuclear Cryogenic Propulsion Stage project, or "NCPS") to demonstrate the affordability and viability of a modern NTP system.

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 POWER SYSTEM TECHNOLOGY TESTING

Under the NASA Exploration Technology Development Program (ETDP), NASA and the DOE began long-lead technology development for integrated FPS. The project is currently funded through NASA's Office of Chief Technologist (OCT), is led by NASA GRC, and involves multiple NASA centers and DOE national laboratories. The technology being developed by the project could support both human and robotic missions. The objectives of the FPS technology project are:

1) Develop FPS concepts that meet expected surface power requirements at reasonable cost with added benefits over other options.
2) Establish a hardware-based technical foundation for FPS design concepts and reduce overall development risk.
3) Reduce the cost uncertainties for FPS and establish greater credibility for flight system cost estimates.
4) Generate the key products to allow Agency decision-makers to consider FPS as a viable option for flight development.
5) Provide a foundation for the development of other space fission systems, including advanced power systems, nuclear electric propulsion systems, and nuclear thermal propulsion systems.

To be mass efficient, FPS 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 FPS 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 FPS 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. Derivatives of the FPS could also be used to provide power for In-Situ Resource Utilization (ISRU) at asteroids, Phobos or Deimos, or other objects throughout the solar system. The use of a FPS to provide in-space power for a human Mars mission is also being assessed under the NCPS project.

Recent non-nuclear testing at NASA MSFC's Early Flight Fission Test Facility (EFF-TF) has helped assess the viability of the reference FPS 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 FPS 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. Annular Linear Induction Pumps (ALIPs, provided by Idaho National Laboratory) were tested in 2010 and 2011 to help assess pump performance and verify suitability for use in a10 kWe technology demonstration unit (TDU). In April, 2012 testing of an integrated reactor simulator for use with the TDU will begin. Integrated TDU testing will begin at GRC in 2013. Previous testing at the EFF-TF has included the thermal and mechanical coupling of a pumped NaK loop to Stirling engines (provided by GRC). Testing related to heat pipe cooled systems, gas cooled systems, heat exchangers, and other technologies has also been performed. 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].

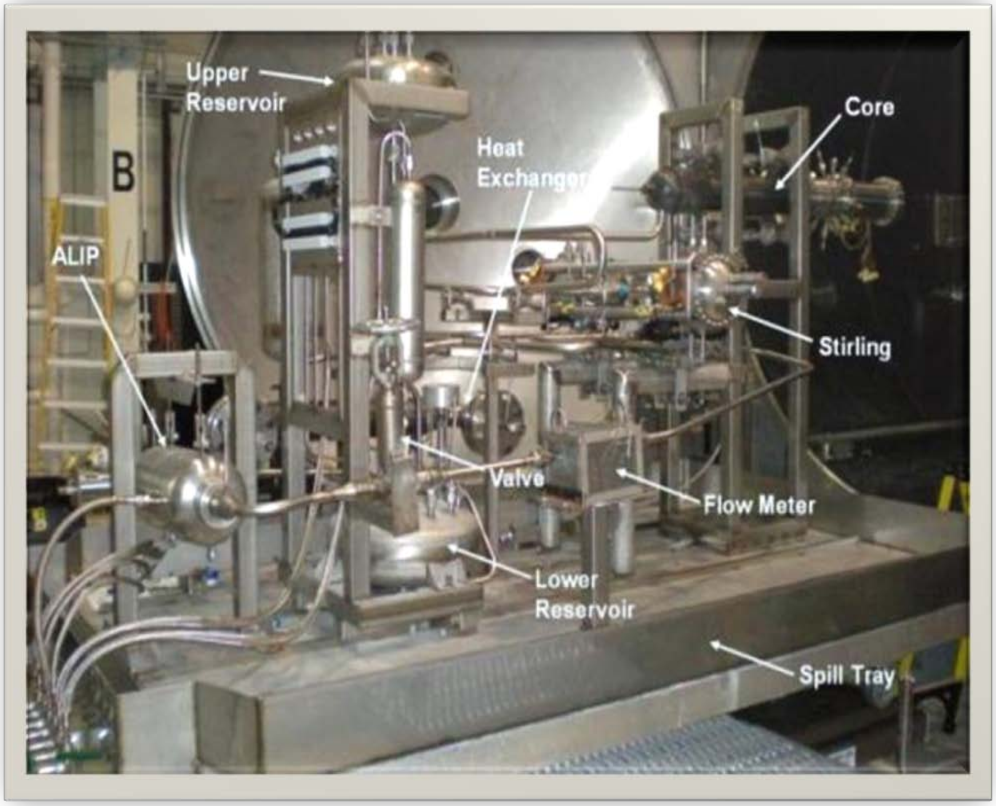

Figure 1. Integrated pumped NaK loop / Stirling test hardware

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 FPS system. ALIP testing demonstrated the fundamental feasibility of using an ALIP in a potential FPS 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

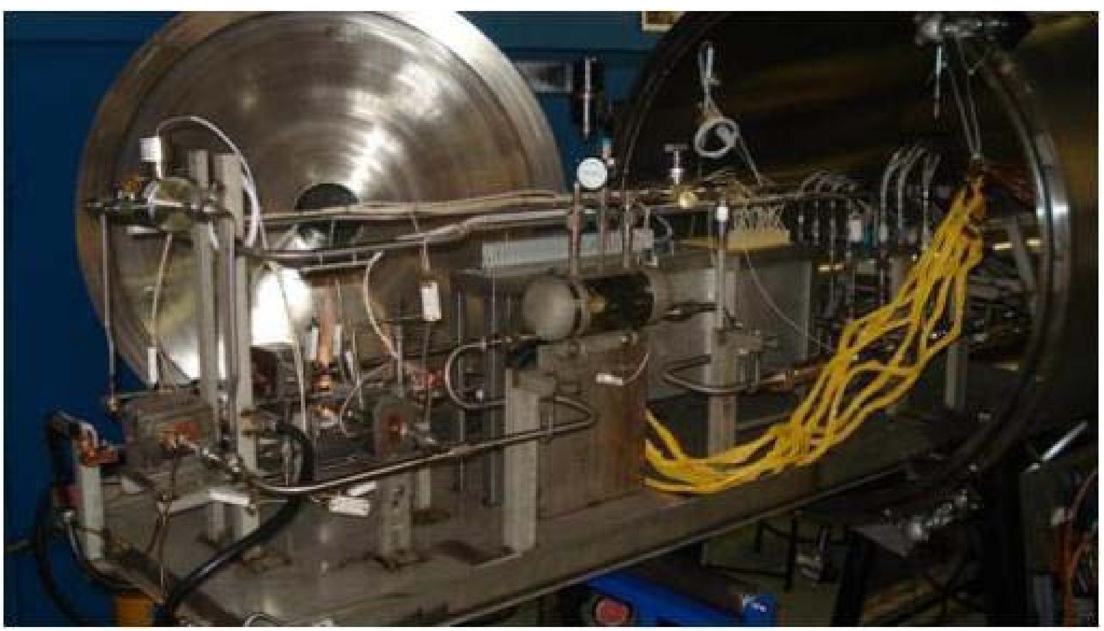

Figure 3. Feasibility Test Loop (FTL) NaK Loading and Verification

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.

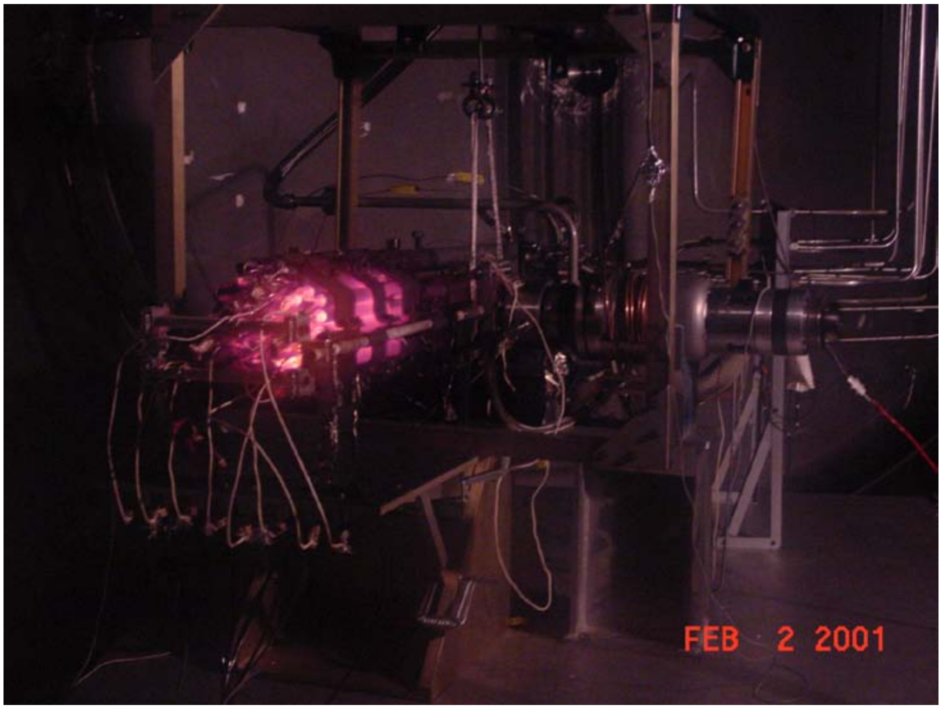

Figure 4. Heat Pipe Cooled Simulated Reactor Core Coupled to Stirling Engine

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 [3]. 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.

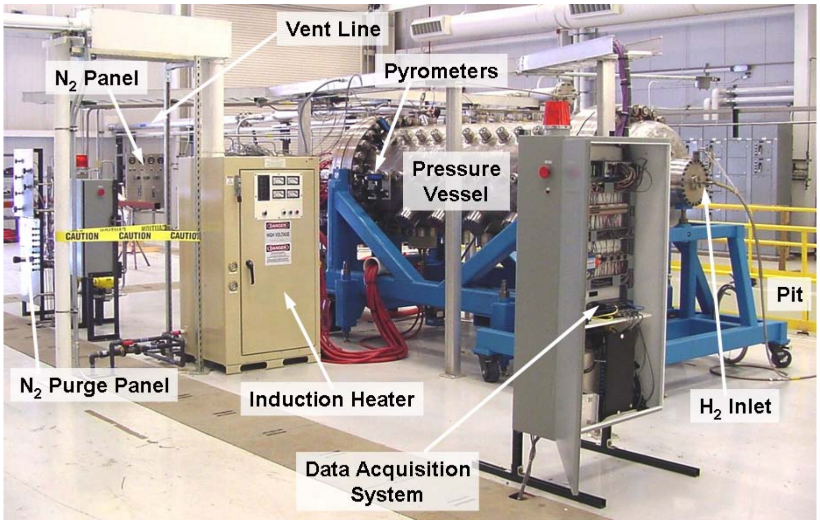

Figure 5. Nuclear Thermal Rocket Element Environmental Simulator (NTREES)

The viability and affordability of modern NTR systems is dependent on the availability of suitable fuels. Because of this, potential modern NTR fuels will be fabricated under the NCPS project. An initial assessment of these fuels will then be performed using the NTREES. Leading candidates include bead-loaded graphite fuels (developed and tested extensively under the Rover/NERVA program), composite fuels (developed/tested under the Rover/NERVA program), cermet fuels (developed/tested under the GE-710 program) and carbide fuels (developed/tested in the former Soviet Union, also some development under the Rover/NERVA program).

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 (Fig 6). In addition, the GPHS module thermal simulators can be used to develop related technologies, such as multi-layer insulation needed for specific radioisotope power system configurations. These simulators could be of use to future radioisotope system development programs.

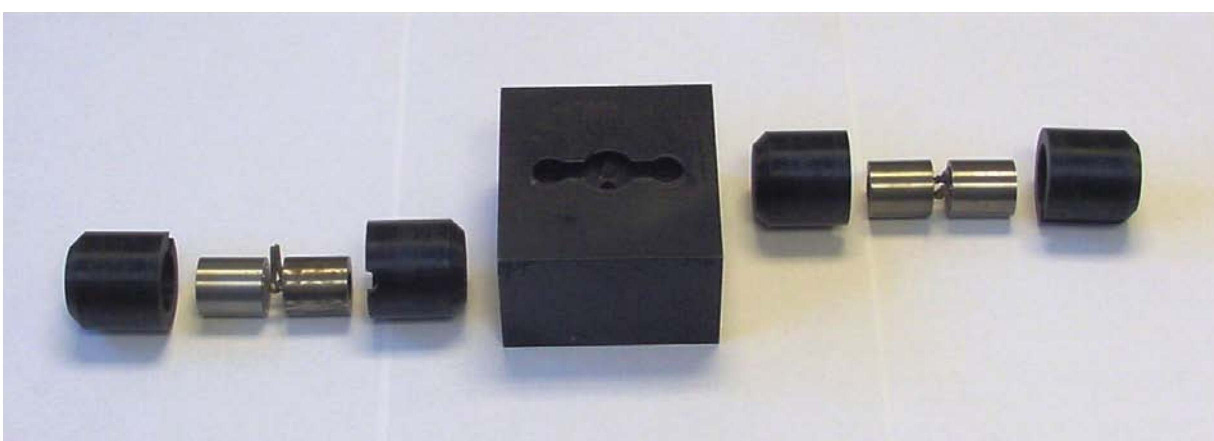

Figure 6. General Purpose Heat Source (GPHS) Module Thermal Simulator

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] D. Koenig “Experience Gained from the Space Nuclear Rocket Program (Rover),” LA-10062-H, Los Alamos National Laboratory, Los Alamos, NM, May 1986.

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

[3] 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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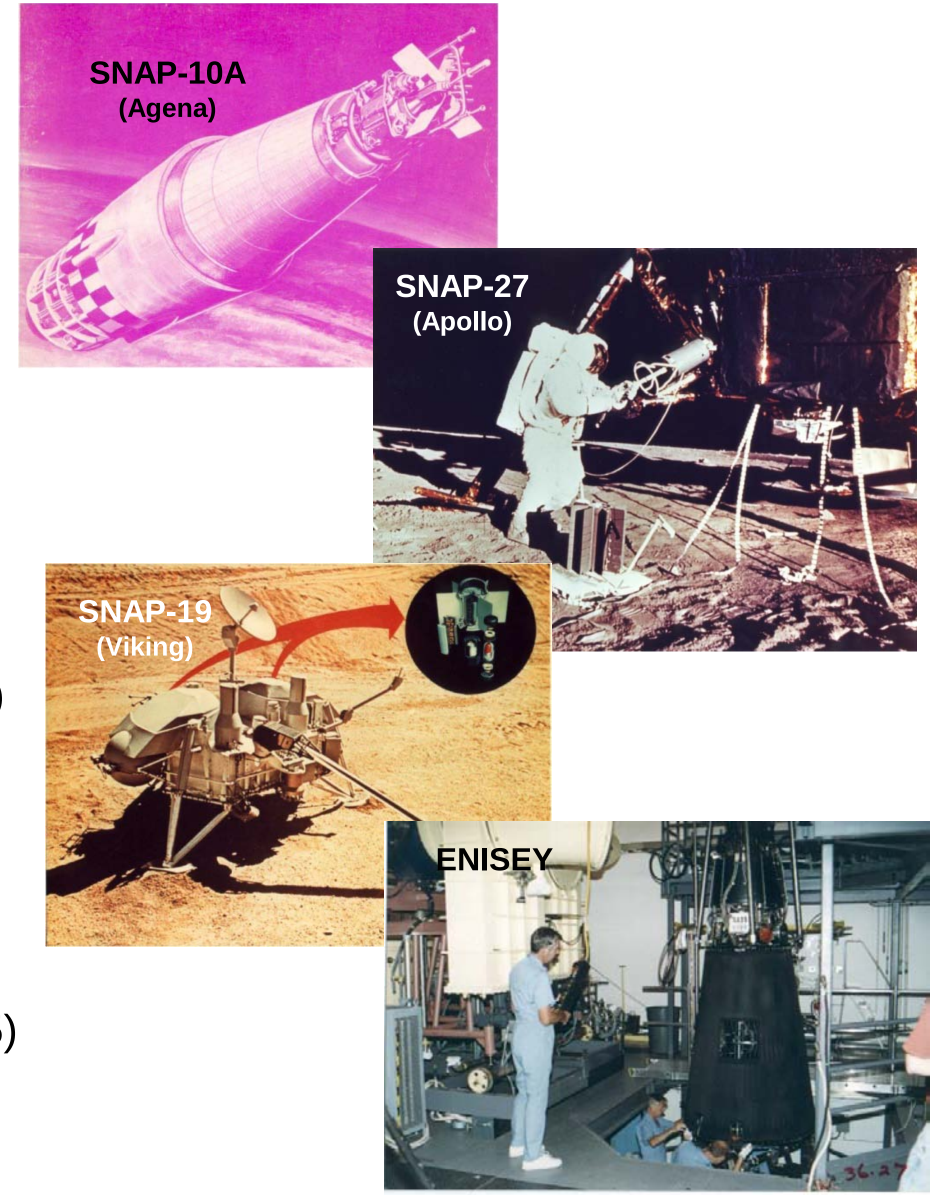
NASA MSFC

In partnership with:

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

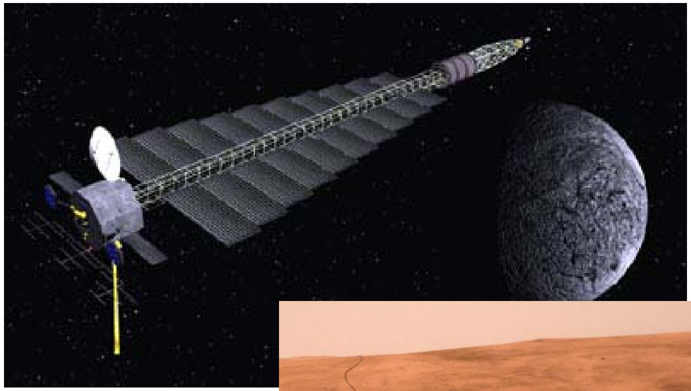
Space Nuclear Power

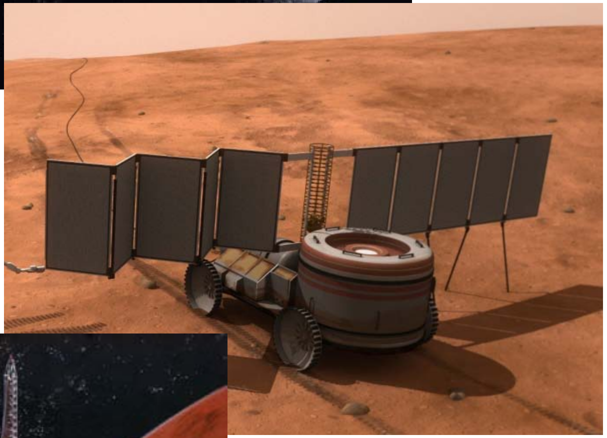
- Radioisotope Power Systems
  - 44 Successful U.S. Radioisotope Thermoelectric Generators (RTG) Flown Since 1961
  - Some Examples:
    - » Apollo SNAP-27 (1969-72)
    - » Viking SNAP-19 (1975)
    - » Voyager MHW-RTG (1977)
    - » Galileo GPHS-RTG (1989)
    - » Ulysses GPHS-RTG (1990)
    - » Cassini 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?



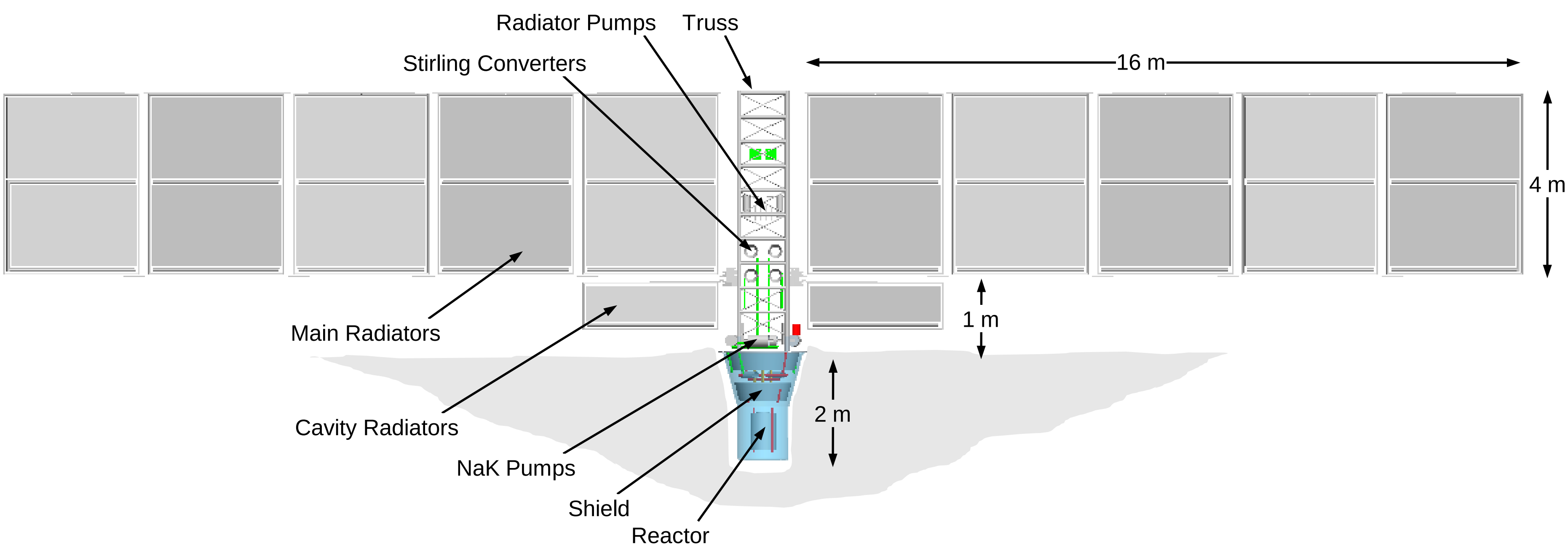


MSFC Early Flight Fission Test Facility (EFF-TF)

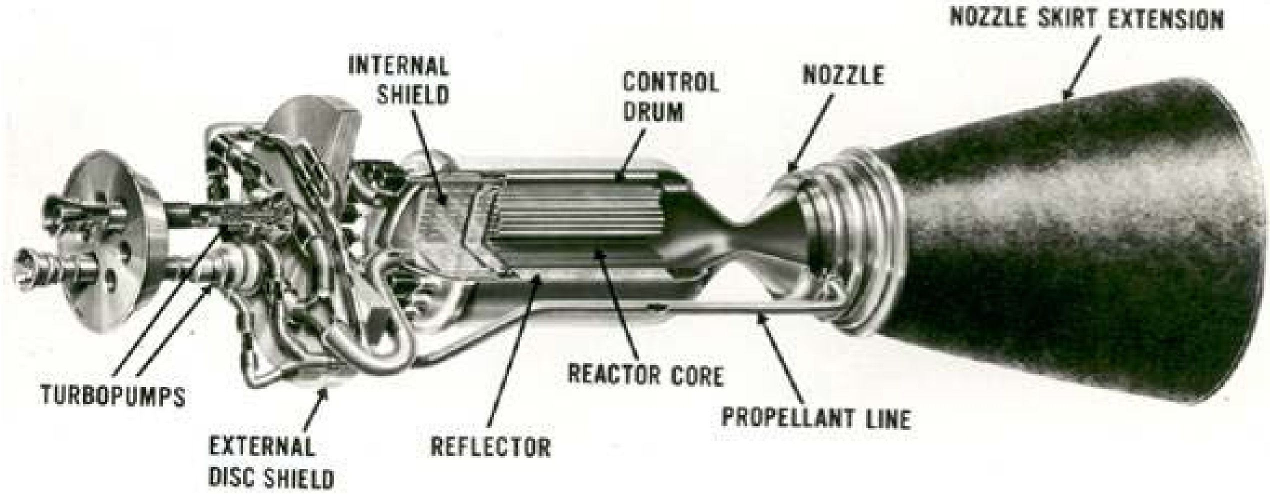
- Established in 1998, the MSFC Early Flight Fission Test Facility (EFF-TF) is designed to help enable affordable development of space fission systems.
- EFF-TF can perform highly realistic thermal hydraulic, heat transfer, structural, safety, and integrated system testing of space nuclear systems using 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.

Fission Surface Power Reference Concept

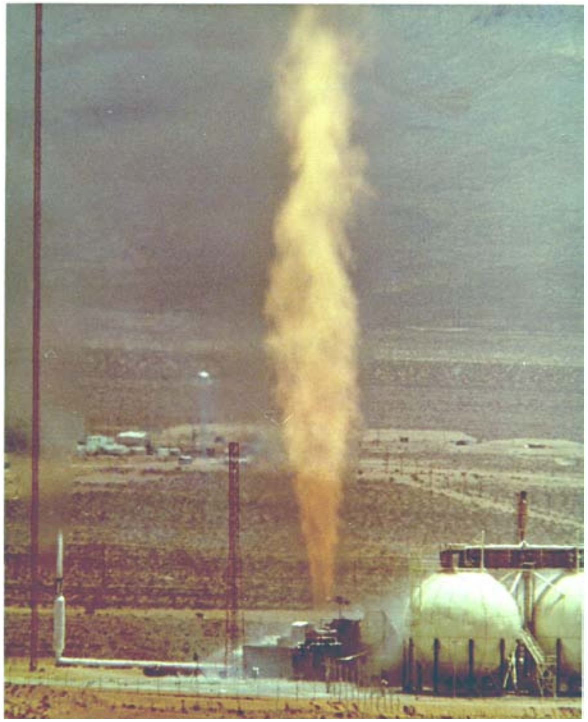
- Modular 40 kWe system with 8-year design life suitable for (global) lunar and Mars surface applications
- Emplaced configuration with regolith shielding augmentation permits near-outpost siting (<5 rem/yr at 100 m separation)
- Low temperature, low development risk, liquid-metal (NaK) cooled reactor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



Nuclear Thermal Propulsion

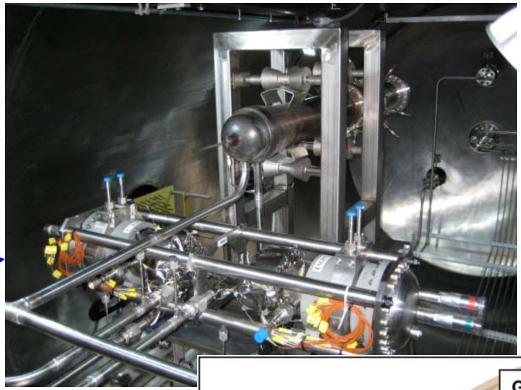


- Hydrogen from propellant tank (not shown) directly heated by reactor and expanded through nozzle to provide thrust.
- ~850 second Isp demonstrated in ground tests at high thrust/weight.
- Potential for > 900 s Isp with advanced fuel forms and cycles.
- Potential Applications
  - Rapid robotic exploration missions throughout solar system
  - Piloted missions to moon, Mars, inner solar system



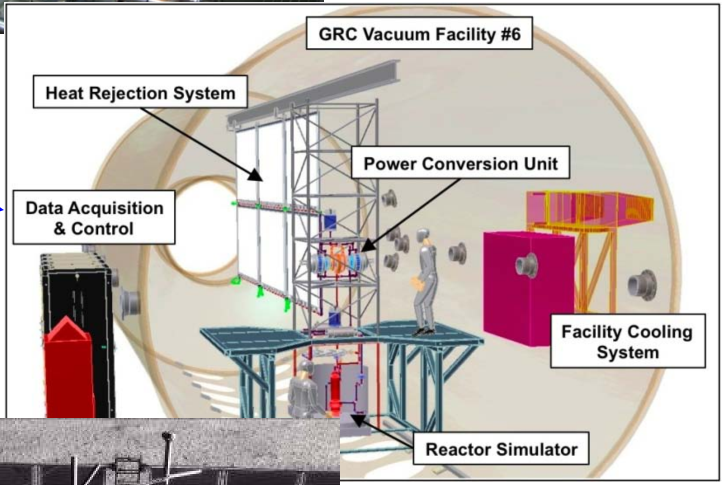
Fission Power System Technology Project

- 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

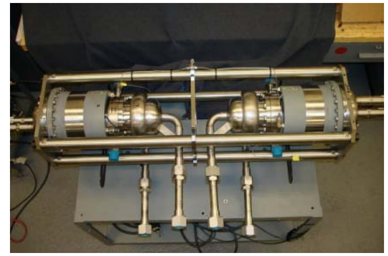
TDU System Test



LSS Scenario 5: Lander-Integrated FSP System

Completed FPS Pathfinders

NaK Reactor Simulator



NaK Stirling Demo

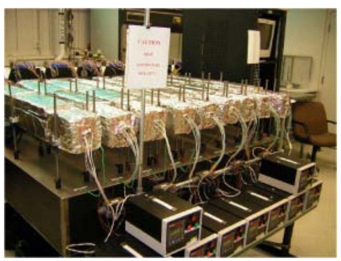
Full-scale Radiator

Electromagnetic Pump

Direct Gas-Cooled Brayton

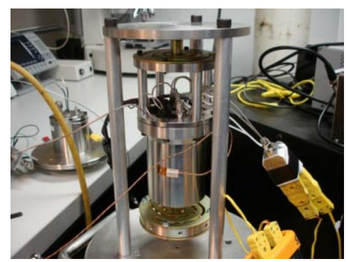
Full-scale NaK Pump Test

Pin Heater Demo

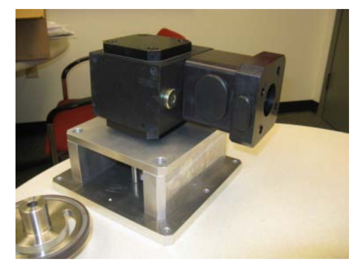


Titanium-Water Heat Pipes

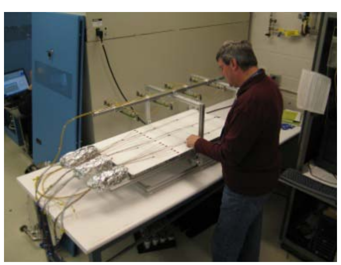
Stirling PMAD Demo



Alternator Radiation Test



Reactor Control Drive



Radiator Demonstration Unit

High Power Dual Brayton

Feasibility Test Loop

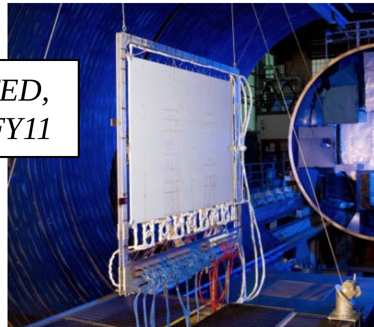
Thermodynamically-Coupled Stirling

Fission Technology Demonstration Unit

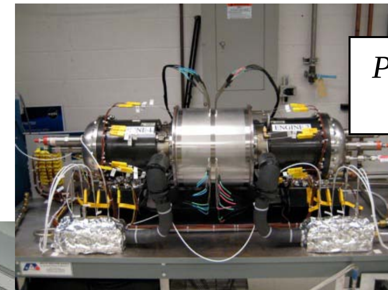
Government, Industry, & Academia Team Effort

Composite Heat Pipe Radiator – GRC & Industry

PROTOTYPE TESTED, TDU H/W RFP IN FY11



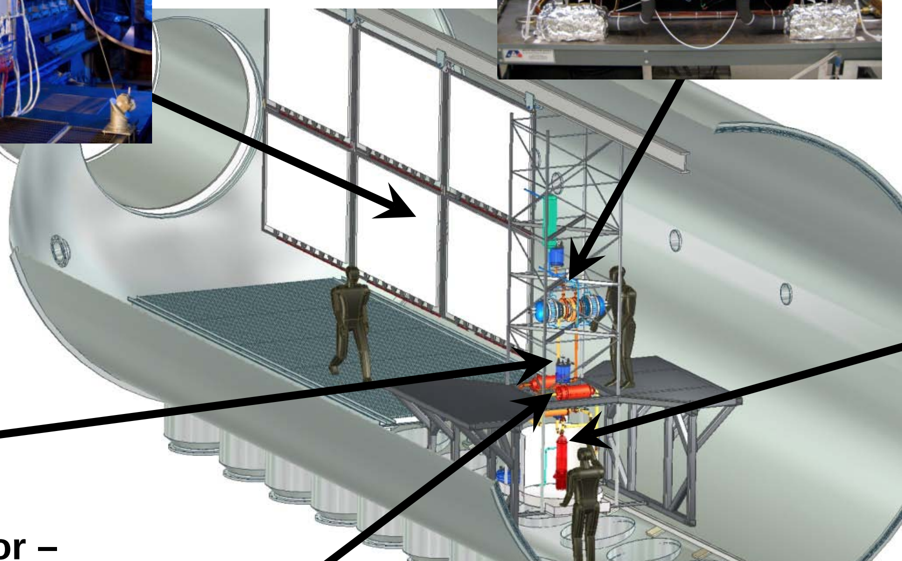
Stirling Power Conversion Unit – GRC & Sunpower



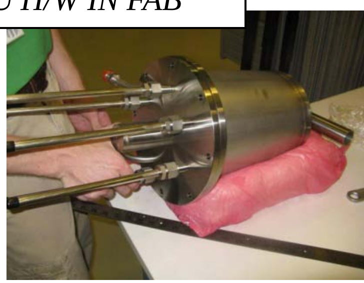
PROTOTYPE TESTED, TDU H/W IN FAB

Core Simulator – MSFC & Los Alamos National Lab

PROTOTYPE TESTED, TDU H/W COMPLETED



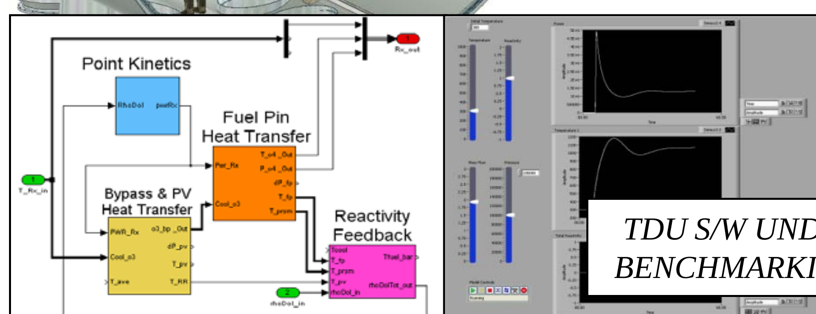
PROTOTYPE TESTED, TDU H/W IN FAB



NaK Volume Accumulator – OaK Ridge National Lab

PROTOTYPE TESTED, TDU H/W IN FAB

NaK Pump – Idaho National Lab



TDU S/W UNDERGOING BENCHMARKING TRIALS

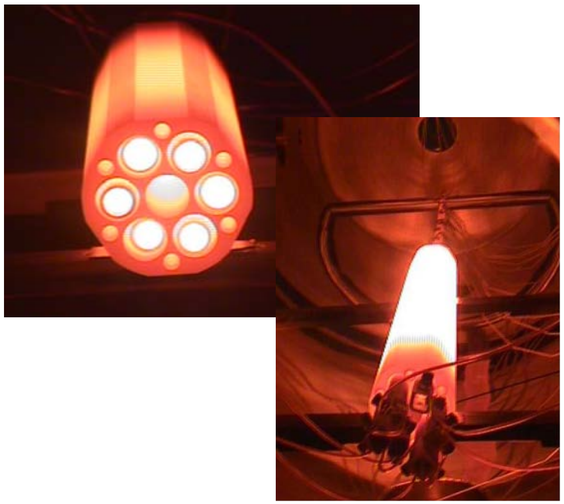
Reactor Simulation – Sandia National Lab

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

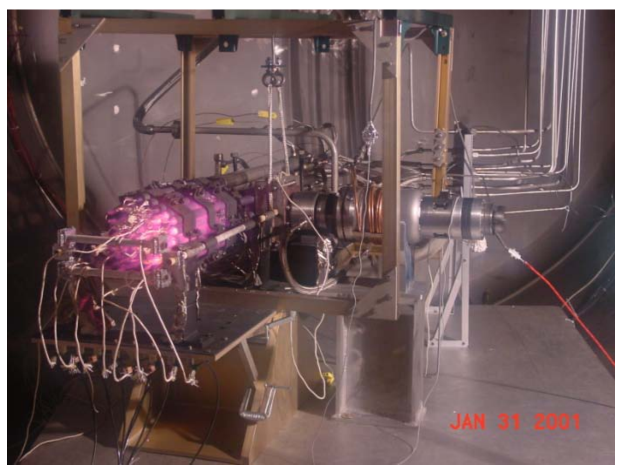


High-Temperature SAFE Module Testing Completed in FY00.

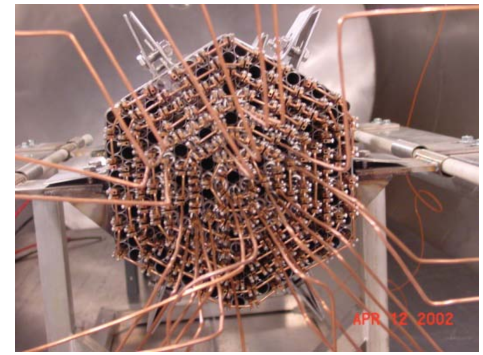
- > 1750 K Core Module Temperature.
- > 1450 K Heat pipe Temperature.
- Direct thermal propulsion mode demonstrated.
- Fast start of heat pipe (room temp to >1400 K in < 1 hr).
- Multiple heat pipe restarts.

SAFE-30 End-to-End

- Average core temperature above 600 deg C in over 20 core tests including both vacuum and CO_2 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

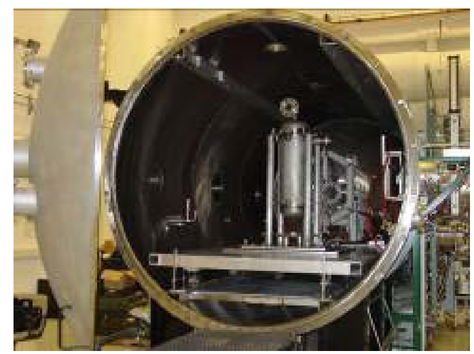
Single-Channel Flow Test → **Pressure drop & flowing heat transfer, Testability**

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**

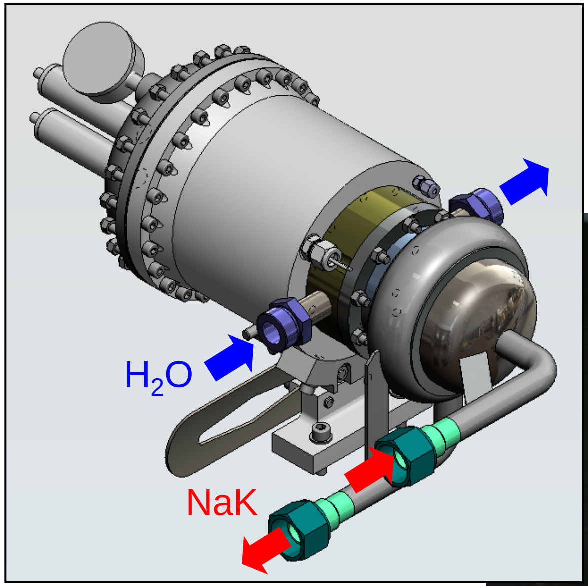


2 kWe BRU Test at NASA GRC

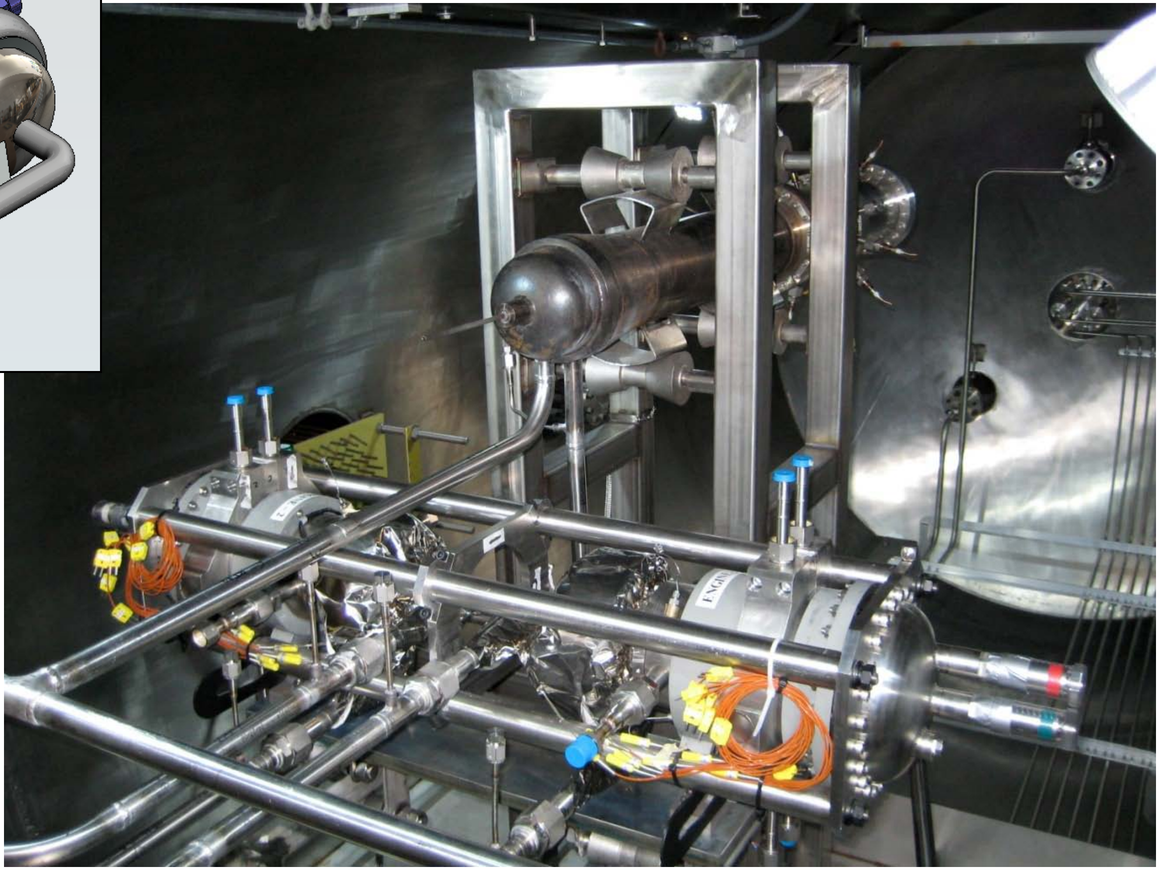
361-Pin, 400 kWt full-scale test

- → **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



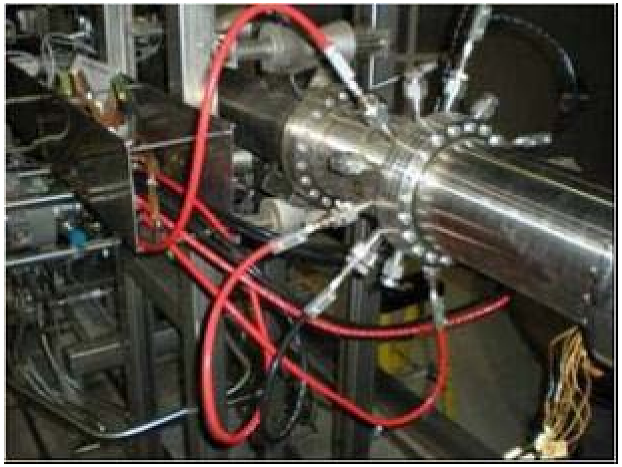
Test Validated Reactor-Stirling Heat Transfer Approach for FSP (Stirling provided by NASA–GRC)



- 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

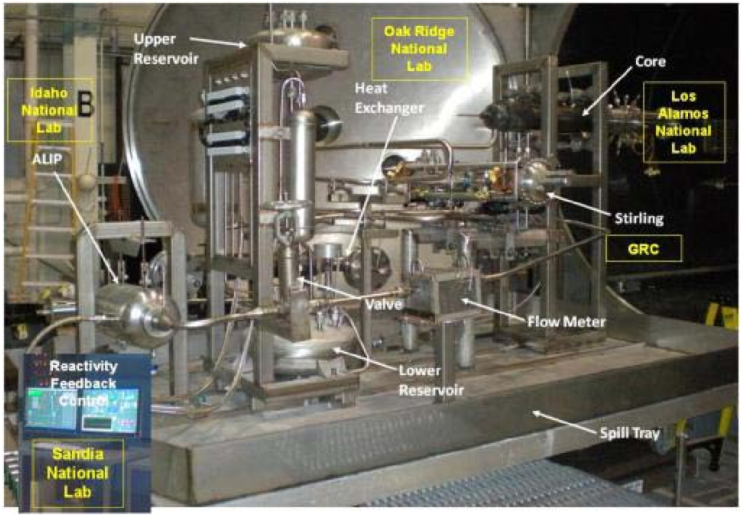
Coupled NaK Loop / Stirling Test

Cable tray providing protection from heat/NaK



Core Simulator Design by Los Alamos National Laboratory

Power Cable path to core

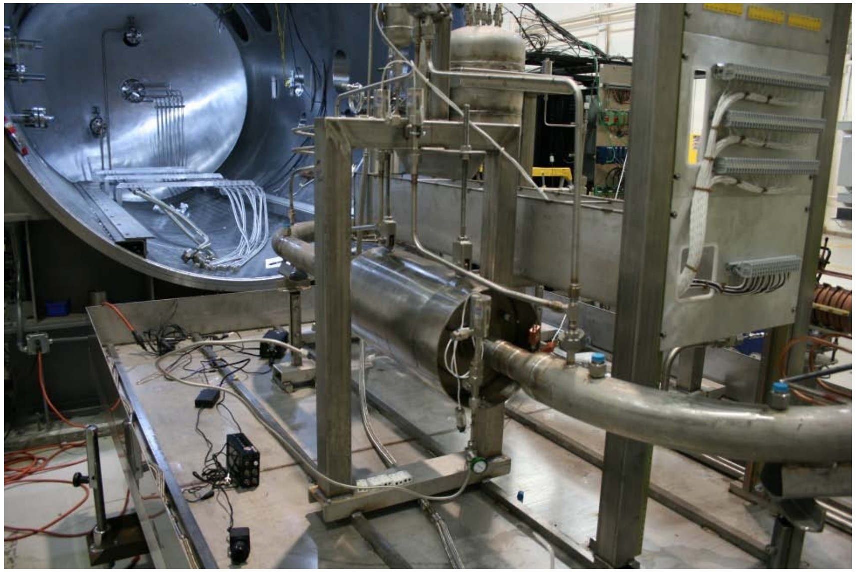


Integrated Stirling Test Assembly

ALIP Provided By Idaho National Laboratory

EFF-TF ALIP Test Circuit

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



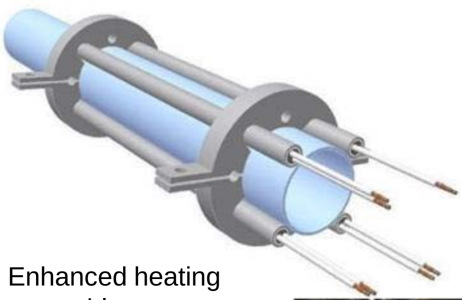
Performance Mapping of Annular Linear Induction Pump (ALIP) provided by Idaho National Laboratory

ALIP Test Circuit (ATC)

ALIP

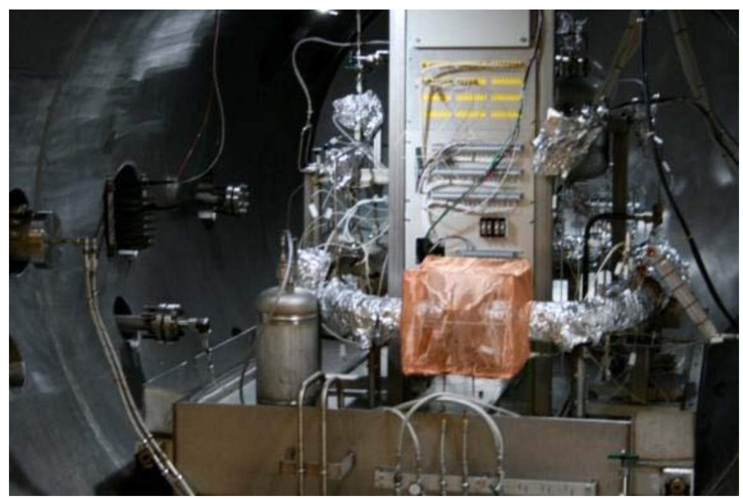
ATC ready for chamber prior to NaK fill

NaK fill



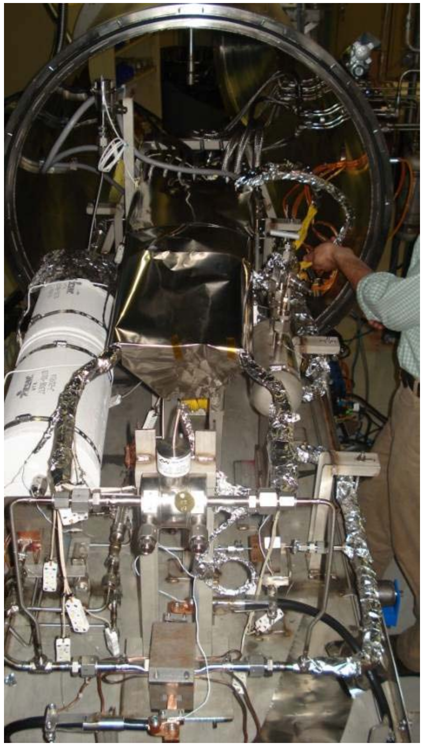
Enhanced heating assembly

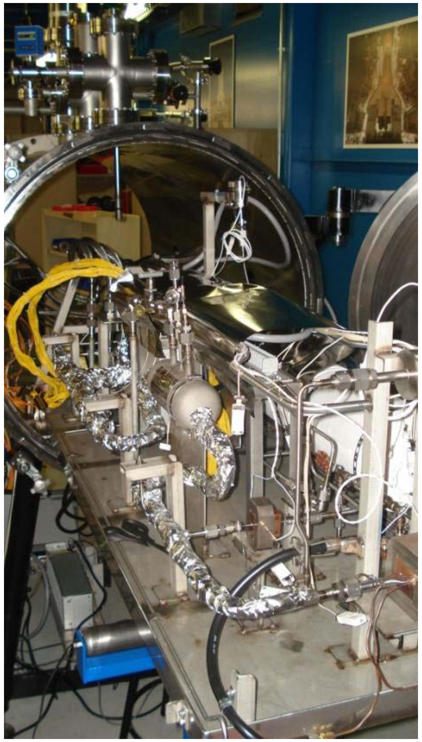
Enhanced heating assembly ready for application of insulation

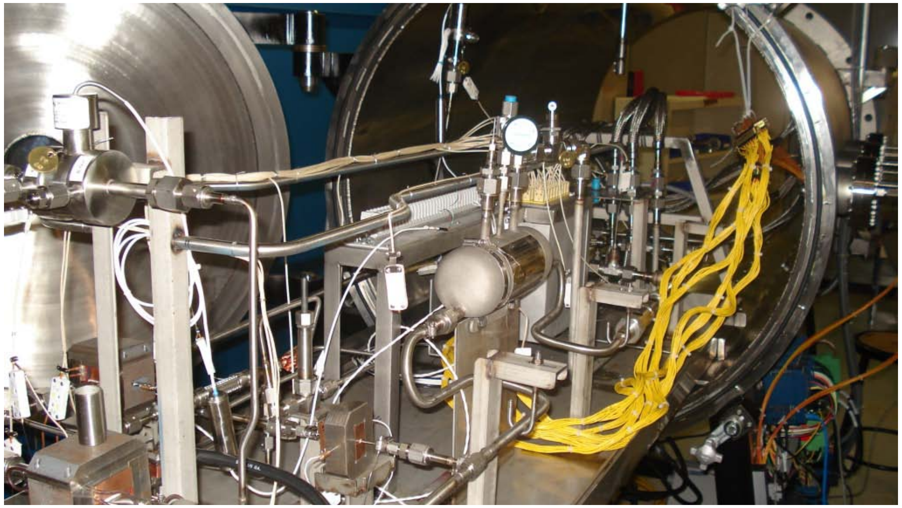


ATC Testing

EFF-TF Feasibility Test Loop







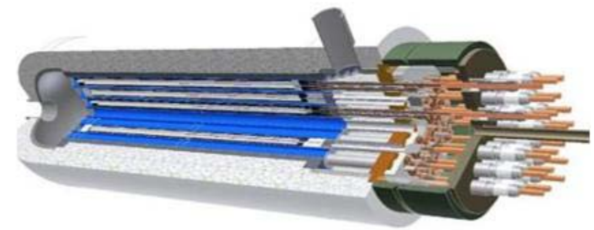
Feasibility Test Loop:

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

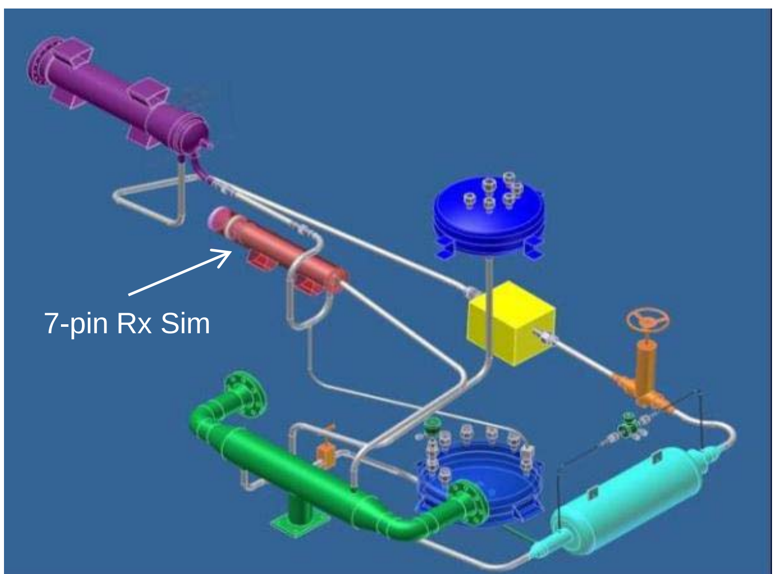
MSFC Designed Advanced Simulators

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

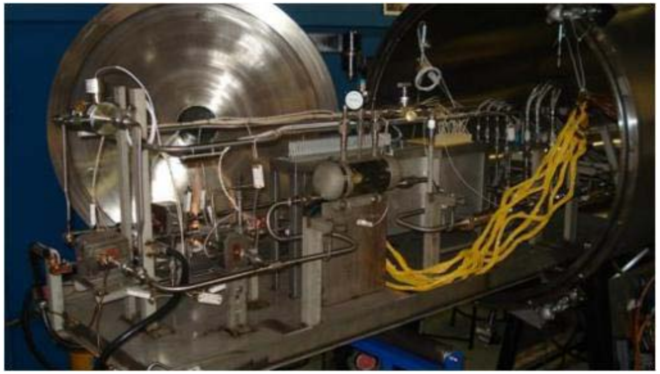
7 Pin Rx Core Sim installed in FSP-PTC

Reactor (RX) Simulator Primary Loop Assembly

FSPS Accomplishments

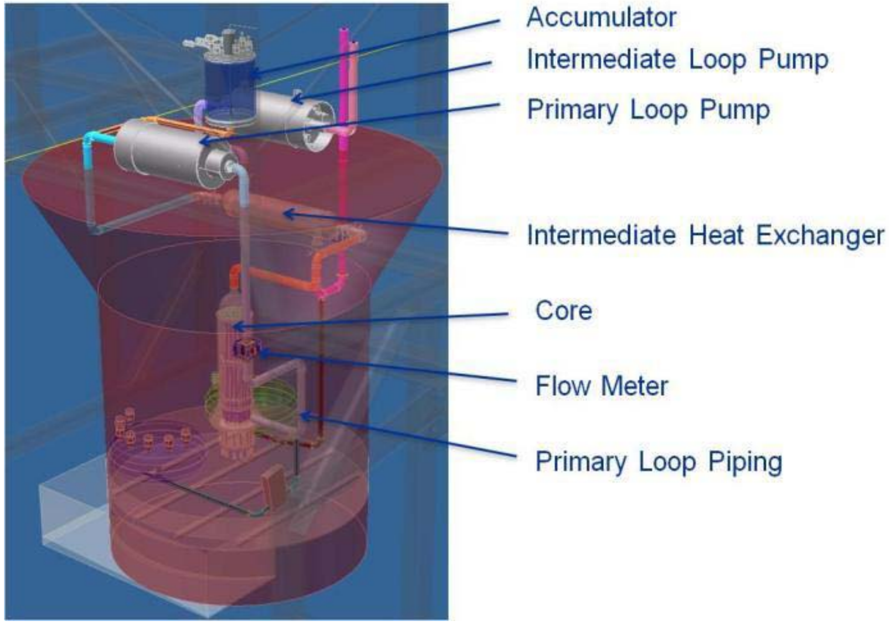
FSP-PTC Stirling & 7 Pin Rx Core Sim Testing

ATC Testing



FTL Testing

Recent Activities Focused Towards TDU Reactor Simulator

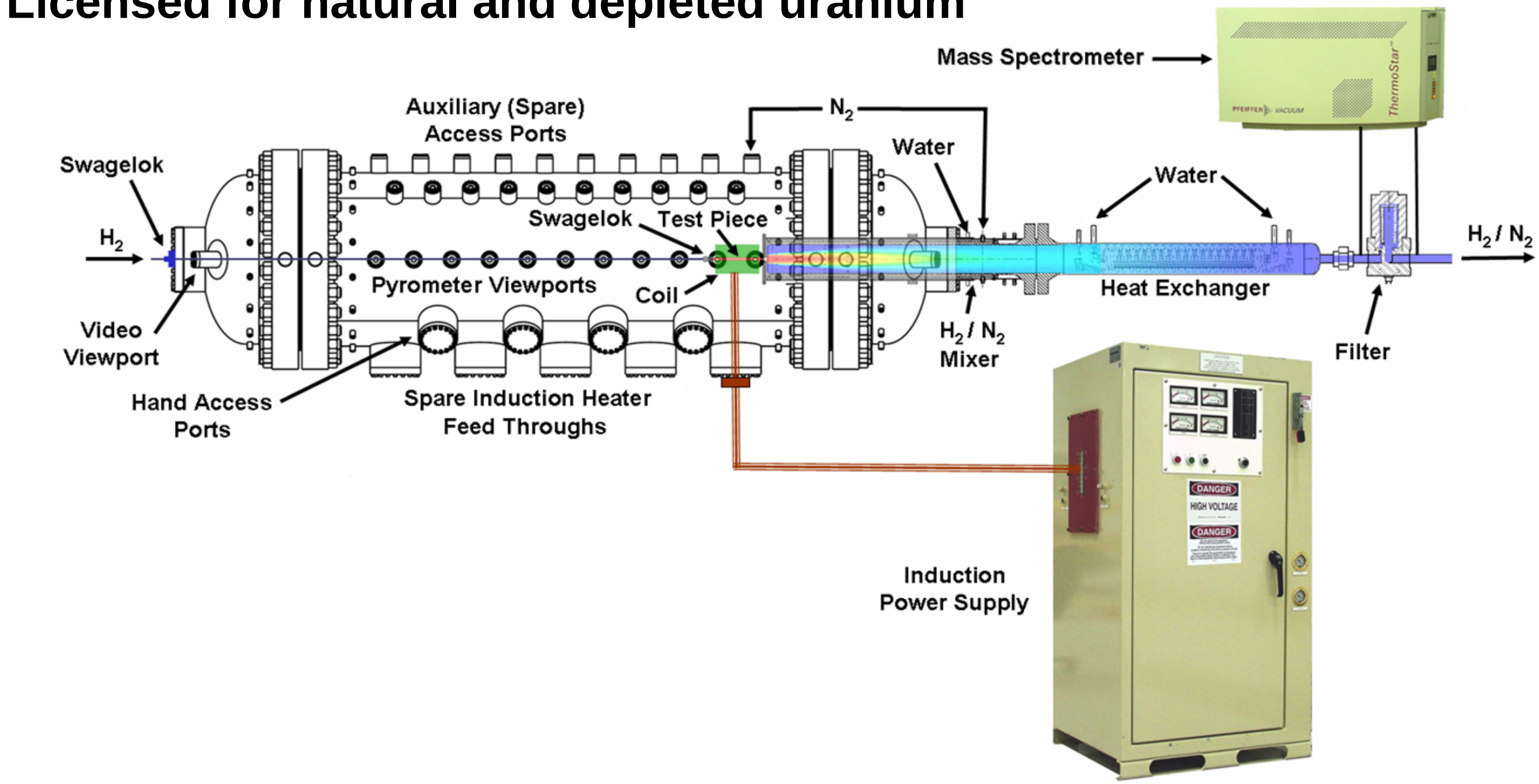


MSFC Designed Reactor Simulator in TDU
(top view close up)

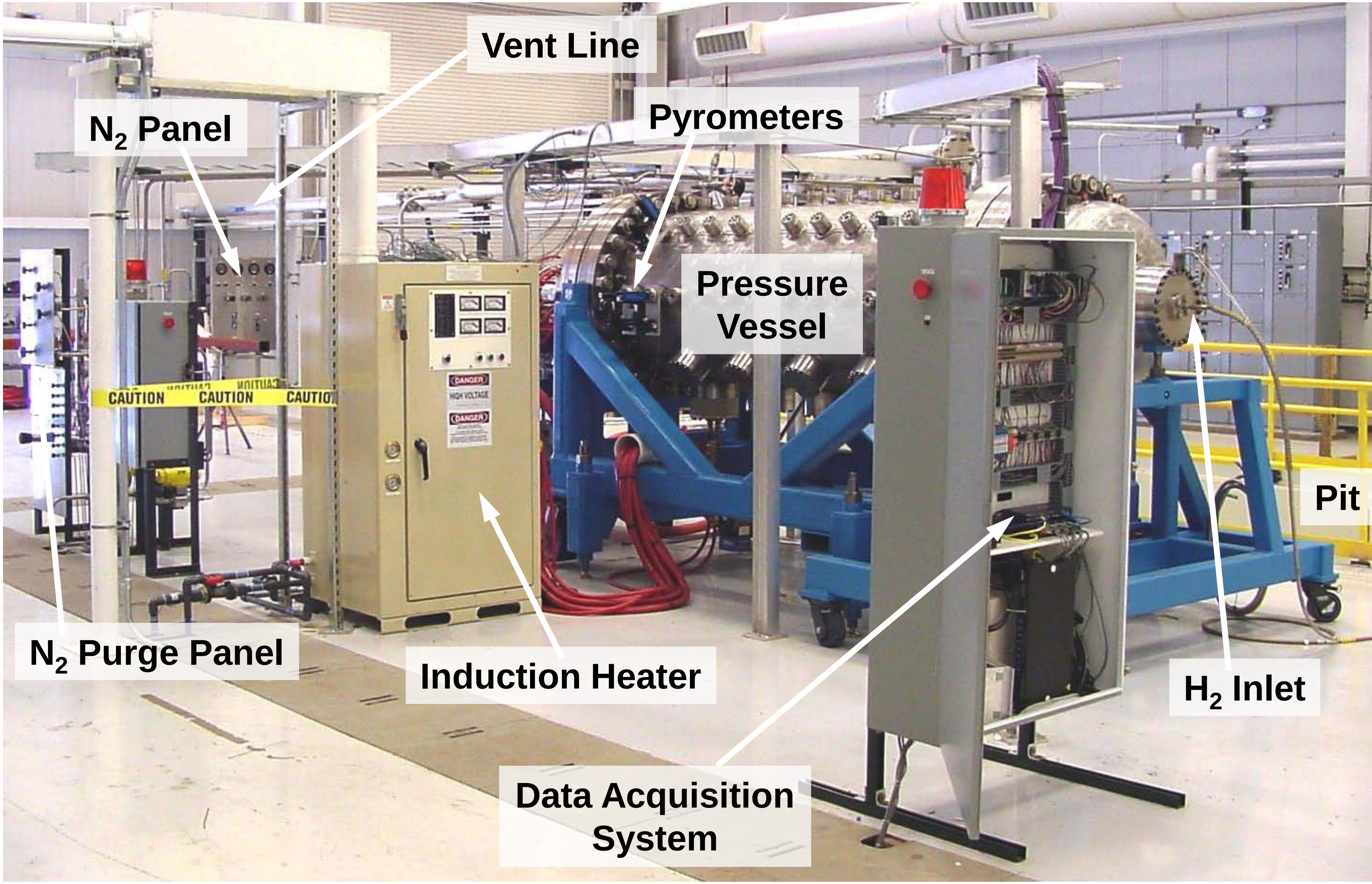
MILESTONES
Fabricate & Test : 2010-2012
Ship to GRC 2012

Nuclear Thermal Rocket Element Environmental Simulator (NTREES)

- 50 kW RF power supply (NTREES is sized to accommodate up to 5 MW of RF power)
- Exhaust mixer system and heat exchanger to cool and dilute hot hydrogen flow
- Backpressure control instrumentation, valves, and filters
- Mass spectrometer on vent gas system
- Pyrometers to measure test specimen surface temperatures
- Licensed for natural and depleted uranium



NTREES Facility



NTREES Type Testing: Advantages & Disadvantages

Advantages

- **Relatively easy to study behavior of fuel under conditions similar to that which would be encountered during actual engine operation**
- **Inexpensive (Thousands of $/test)**
- **Quick turn around between tests (Days between tests)**
- **Many different fuel configurations may be tested**
- **Fuel is non-radioactive after test so fuel examination can be performed directly without special protective equipment**

Disadvantages

- **Fuel is tested under similar, but not the exact conditions it will encounter during operation**
- **Simultaneous radiation, thermo-chemical, and thermal-hydraulic effects on fuel behavior will not be achieved**
- **Can only study one fuel element (or perhaps a small cluster of fuel elements) at a time**

Fuel Element Under Test in NTREES

Near-Term Plans

- Complete Fission Power System (FPS) Technology Demonstration Unit (TDU) Component testing.
- Ship integrated TDU reactor simulator to GRC.
- Complete TDU testing at GRC.
- Complete NTREES upgrade to 1 MW.
- Complete NTREES testing of representative samples.
- Continue to investigate potential terrestrial spinoffs / applications of space nuclear power and propulsion technologies and test facilities.