INL/MIS-23-75022-Revision-0

Space Reactor Seminar 2023

October 2023

Changing the World's Energy Future

Sebastian Carmine Corbisiero

Idaho National Laboratory

INL is a U.S. Department of Energy National Laboratory operated by Battelle Energy Alliance, LLC

INL/MIS-23-75022-Revision-0

Space Reactor Seminar 2023

Sebastian Carmine Corbisiero

October 2023

Idaho National Laboratory
Idaho Falls, Idaho 83415

http://www.inl.gov

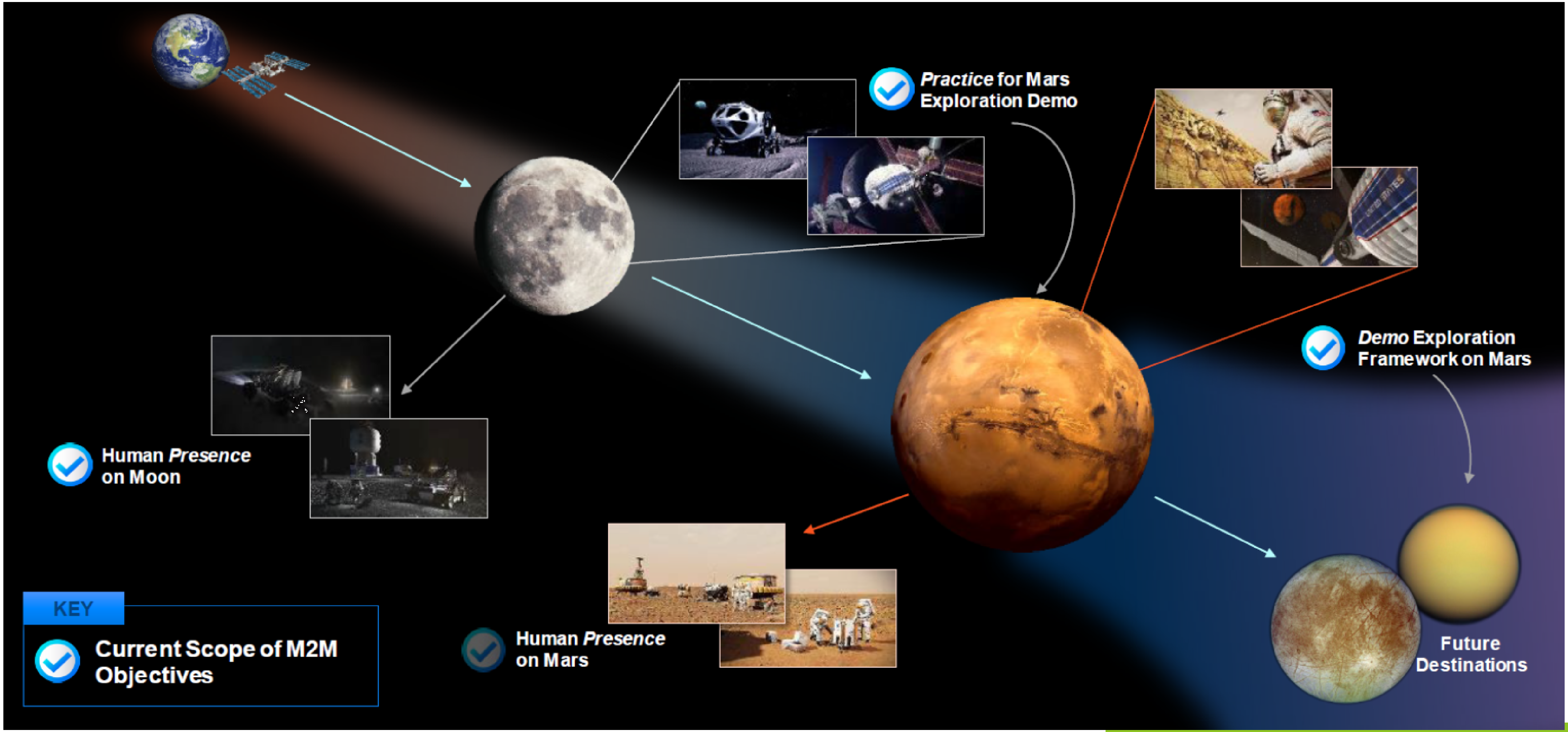
Prepared for the
U.S. Department of Energy
Under DOE Idaho Operations Office
Contract DE-AC07-05ID14517

Space Fission Reactors

Sebastian Corbisiero
Program Manager, Space Fission Reactors
Fission Surface Power Project Lead, INL

Idaho National Laboratory

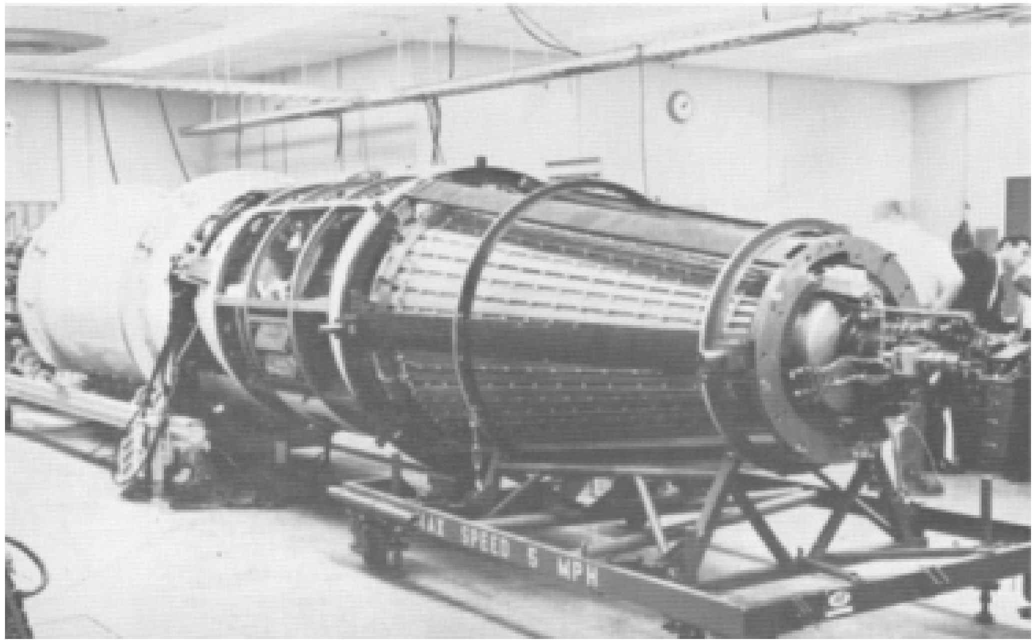
NASA Moon2Mars: Current Scope

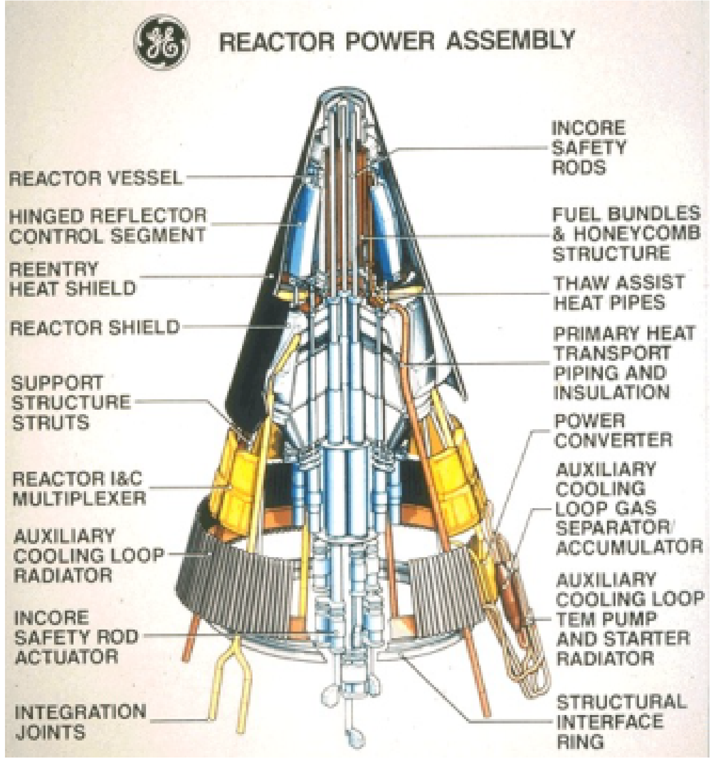


Space Fission Reactors are needed for NASA' s mission

Space Reactor History

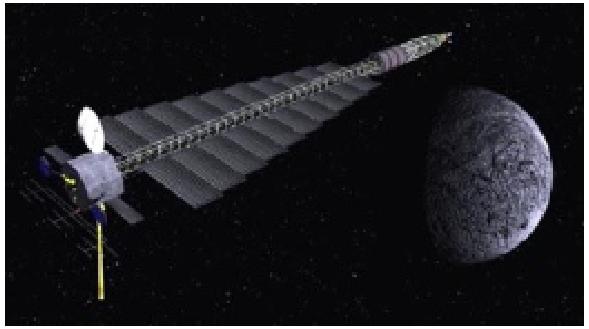
- Only U.S. flight reactor, **SNAP-10A (1960s)**
  - HEU UZrH fuel, 790K NaK cooling, and SiGe thermoelectrics to produce 0.5 kWe at 1.4% efficiency
  - Flight test ended after 43 days due to spacecraft electronics anomaly not related to reactor





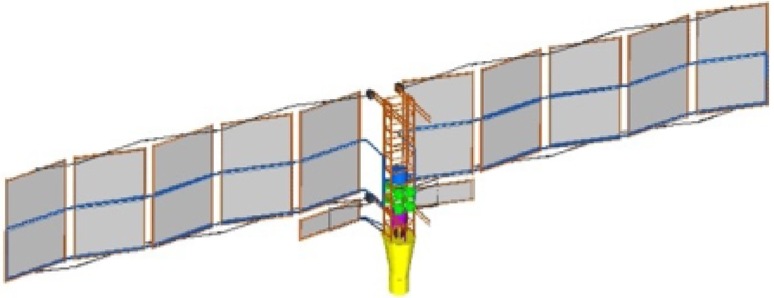
- **SP-100 (1980s)**
  - HEU UN fuel, 1350K Li cooling, and SiGe thermoelectrics to produce 100 kW_e at 4% efficiency
  - Growth versions considered both Stirling and Brayton to produce 500–800 kW_e with the same reactor, with major emphasis on lunar surface power
  - Considerable advancements made on the UN fuel, but project was canceled before flight.

Space Reactor History



- **Prometheus/JIMO (early 2000s)** studied both Li-cooled and HeXe-cooled highly enriched uranium (HEU) reactors using 1150K Brayton for 100–200 kWe systems
  - Major products included down-select study and numerous Brayton and heat rejection technology development tests

- **Constellation/FSP (early 2010s)** was directed to reduce the reactor cost and risk and responded with HEU UO2 reactor, 875K NaK cooling, and Stirling to produce 40kWe at 22% efficiency
  - Non-nuclear system test including full-scale Stirling and full-scale composite radiator

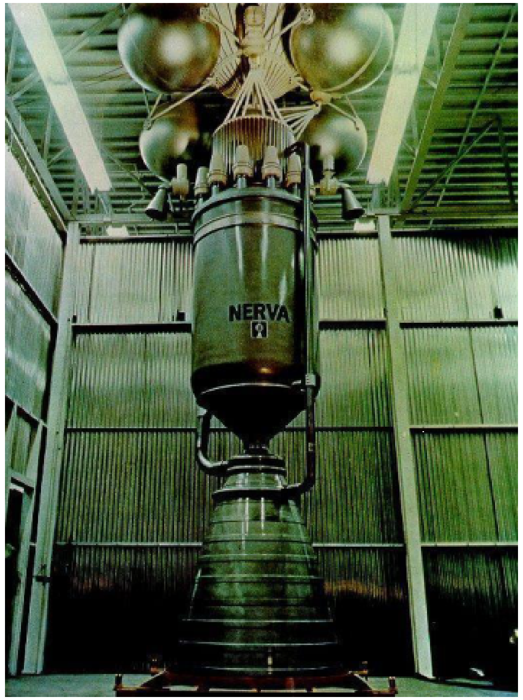


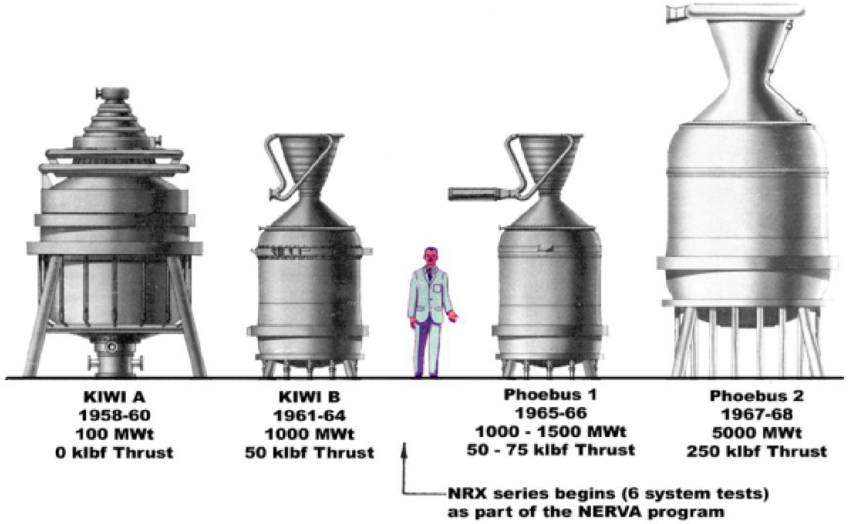
- **Kilopower/KRUSTY (late 2010s)** primary goal was to provide proof that a real space reactor could be built and tested with today's technology
  - 3-year project culminated in successful reactor prototype test at Nevada Test Site
  - 1kWe HEU fueled, Sodium heat-pipe cooled, w/ Stirling power conversion

NASA/TM—2018-219941

Space Propulsion Reactor History

- ~23 nuclear ground test rockets
  - Liquid H propellent & HEU fuel of various types
- The Rover/NERVA Program (1959–1972)
  - Pewee
    - Operated at 503 MW for 40 minutes at 2550K with a peak to 2750K





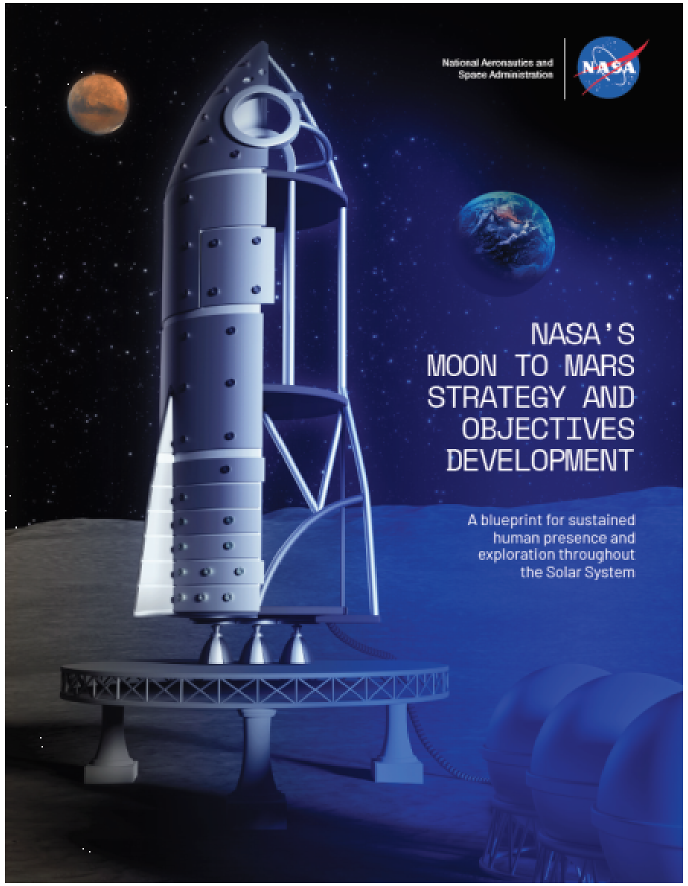

Phoebus-2A

Space Reactor Programs Today

- NASA, the Department of Energy (DOE), and INL partnered to develop Space Reactors with the commercial industry
- Nuclear Thermal Propulsion (NTP)
  - Establish a conceptual design for an NTP low-enriched uranium (LEU) engine in the thrust range of interest for a human Mars mission
  - Design, build, and test prototypic fuel element segments based on the conceptual design
  - Establish robust production manufacturing methods for an LEU fuel element /reactor core
  - Demonstrate the feasibility of exhaust capture as a method of nuclear rocket engine testing
- Nuclear Electric Propulsion (NEP)
  - Reactor generates electricity used for propulsion
- Fission Surface Power (FSP)
  - A power system for the moon

Fission Surface Power

- National Aeronautics and Space Administration (NASA) Moon 2 Mars Architecture
  - Develop an incremental lunar power generation and distribution system that is evolvable to support continuous robotic/human operation and is capable of scaling to global power utilization and industrial power levels

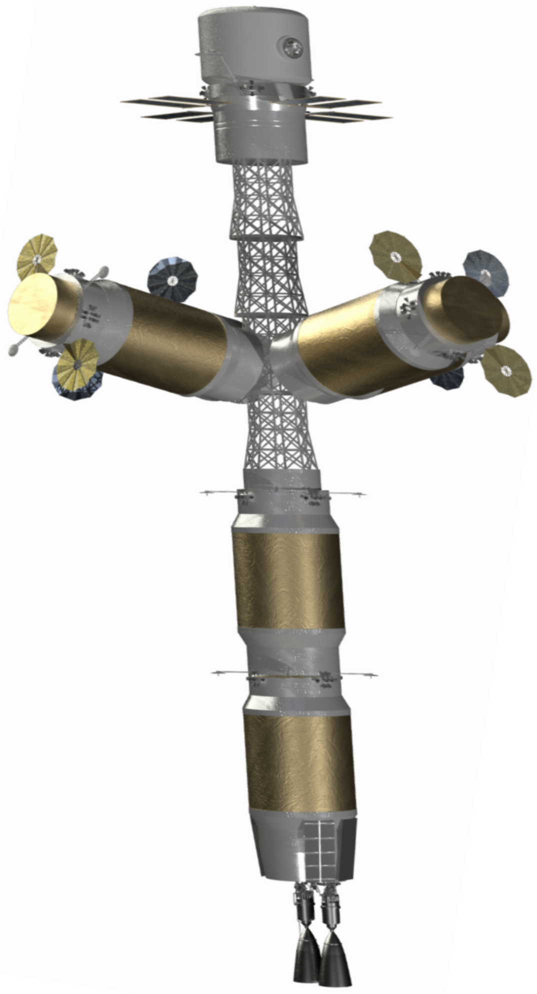


- Fission Surface Power (FSP)
  - A technology demonstration mission to deploy a small fission reactor to the surface of the moon in the early 2030s

- Long range Moon 2 Mars goals
  - Sustained human presence on the moon and Mars will require sun-independent power
  - In situ resource utilization:
    - water, oxygen, etc.

Space Nuclear Propulsion

- Space fission propulsion systems are game changing technologies for space exploration and cis-lunar mobility.
- First generation Nuclear Thermal Propulsion (NTP) systems provide significant benefits to sustained human Mars exploration and other missions.
  - Vision:
    - Earth-Mars transit times of 120 days
    - 540-day total Mars mission times
    - reduced crew health effects from cosmic radiation and exposure to microgravity
    - robust architectures including abort capability.
- Advanced space fission power and propulsion systems will enable extremely ambitious space exploration and development.



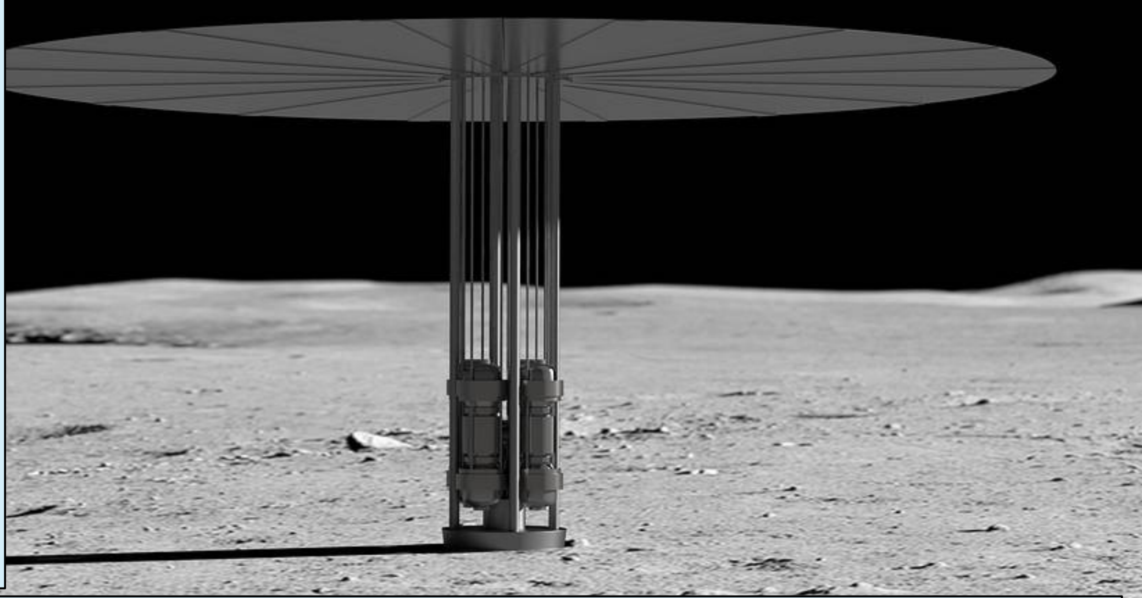
National Laboratory Roles

- What do the national labs do for space reactors?
  - Technical expertise and oversight of the industry design efforts
  - Work with NASA on requirements development
  - Test bed and testing infrastructure
  - Develop key technologies and processes that to be transferred to industry.
    - Such as fuel, moderator, instrumentation & control

Provide constructive support and guidance

Fission Surface Power Overview

- **Phase 1: Key Requirements & Goals**
  - $40kW_E$ for 10 years
  - Withstand launch and landing loads
  - Radiation protection: <5rem/year above lunar background at user interface location
  - <6000kg, fit within 4m × 6m cylinder
  - Fault detection and tolerance, transportable (pre-start-up), variable user load



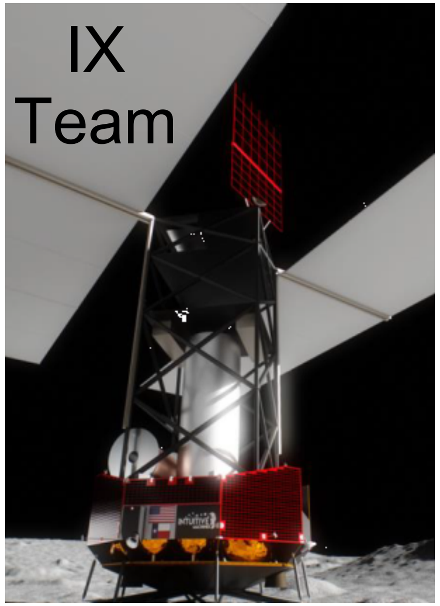
- Phase 1 teams led by:
  - IX
  - Westinghouse
  - Lockheed Martin

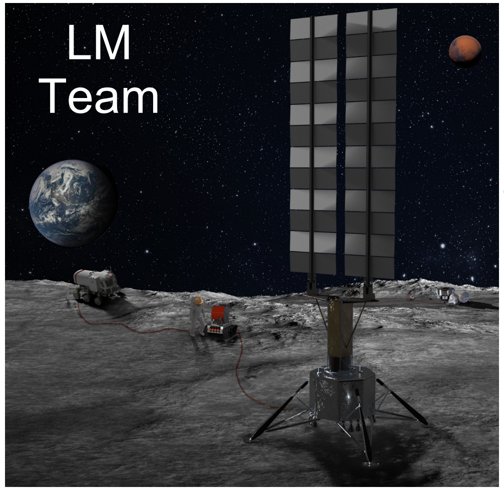
- **Phase 1: Key Deliverables**
  - System/subsystem requirements, drawings, and interfaces
  - Mass properties
  - Technical readiness assessment
  - Cost/schedule projection for Phase 2

Fission Surface Power - Design Challenges

- FSP Reactor is "Criticality Limited"
  - 40kWe for 10 years – total energy is only 146 MW_e-days – very little fuel depletion

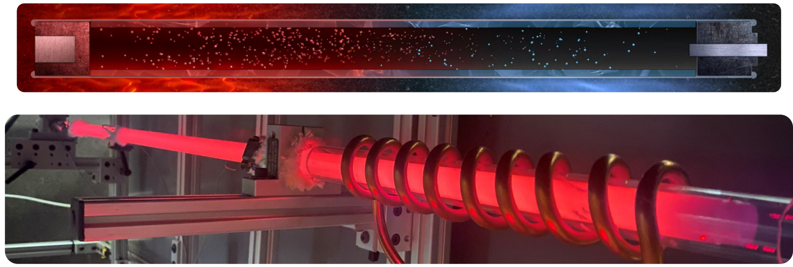
If having enough fuel to go critical is the limiting factor – why not just design to produce more power or last longer?





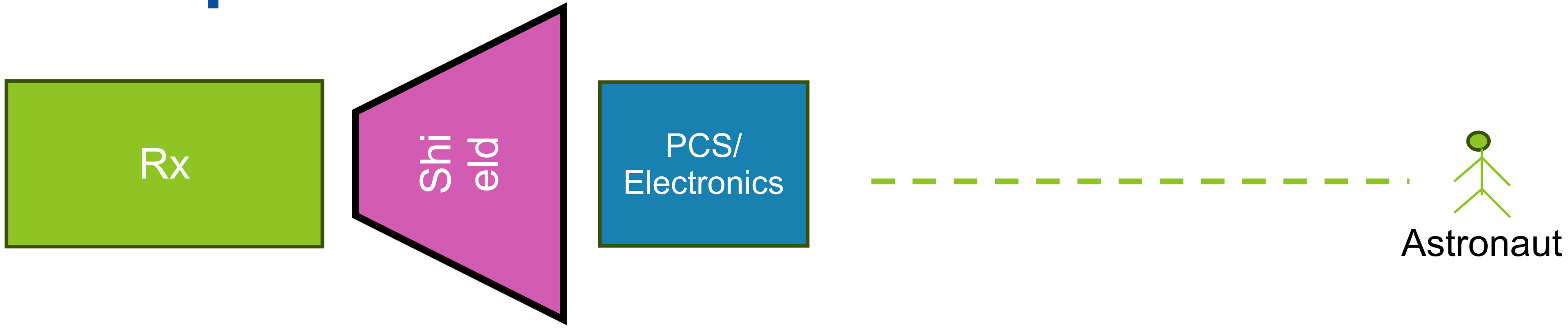
- Terrestrial reactors are designed to maximize profit, a space reactor ***needs to minimize mass***
  - How much does it cost to put a payload on the moon?
    - ~$1.8M per kg
- Besides volume and mass restrictions, what are the key differences between a terrestrial and lunar space reactor?
  - Heat rejection in Space/Moon
  - Dose to equipment and astronauts
  - Reliability
  - Vacuum (specialized equipment, also no attenuation)
  - Lunar night

Westinghouse High temperature, high performance heat pipe

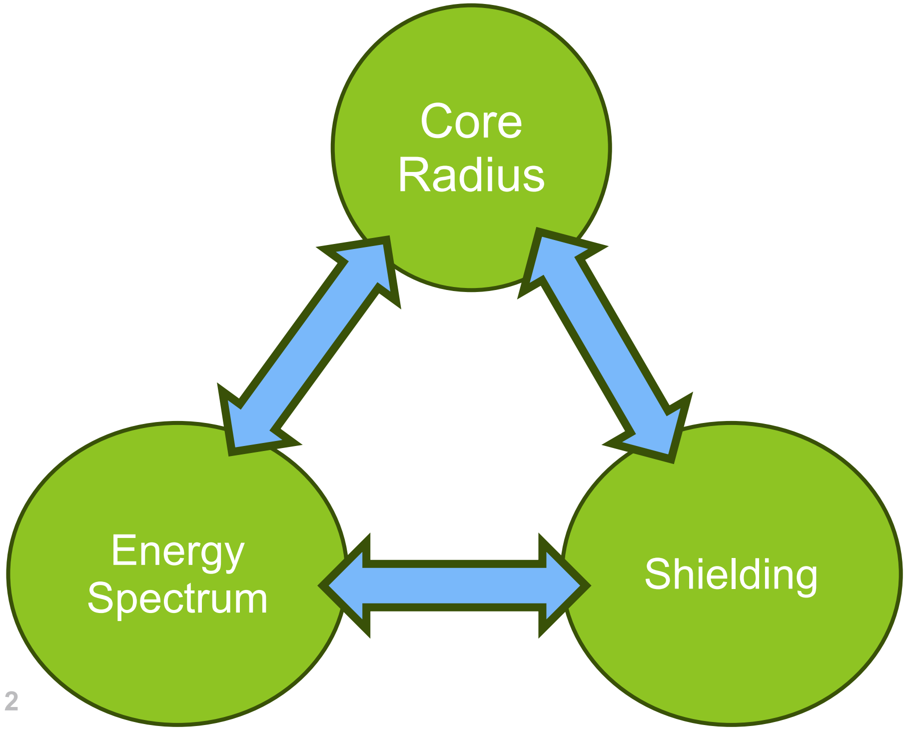


How do you make the lightest core possible?
And what are the key driving factors?

Fission Surface Power Design Challenges – Trade Study Example



Example FSP Configuration



- Design Trade: Energy Spectrum
  - Harder spectrum: More fuel (fuel is heavy), but smaller radius (reduces structural masses and shield size)
    - But harder spectrum means higher energy neutrons -> need more neutron shielding
  - Softer spectrum: More moderator/less fuel, larger core radius/shield radius

Technology Maturation Overview

- National laboratory - Nuclear Technology Maturation
  - Design agnostic
  - Technology under development is for industry consideration (i.e., implementation not required)
  - Industry engagement

Areas currently being pursued…

Solid Moderator/Metal-Hydride

In a high-assay low-enriched uranium (HALEU) space reactor, a thermal spectrum is generally viewed to be more mass-effective than fast spectrum

Ideally, the moderator needs to:

- Withstand high temperature to enable power conversion efficiency
- Maximize moderator effectiveness per unit mass
- Retain H sufficiently over the life of the reactor

Shielding

FSP shielding must protect equipment and satisfy human dose requirements at the power interface. Expected to have significant mass.

Are there materials or design techniques that could reduce shield mass?

Parametric evaluation of:

- Gamma & neutron shield materials
- Shield design/layers
- Localized component shielding options

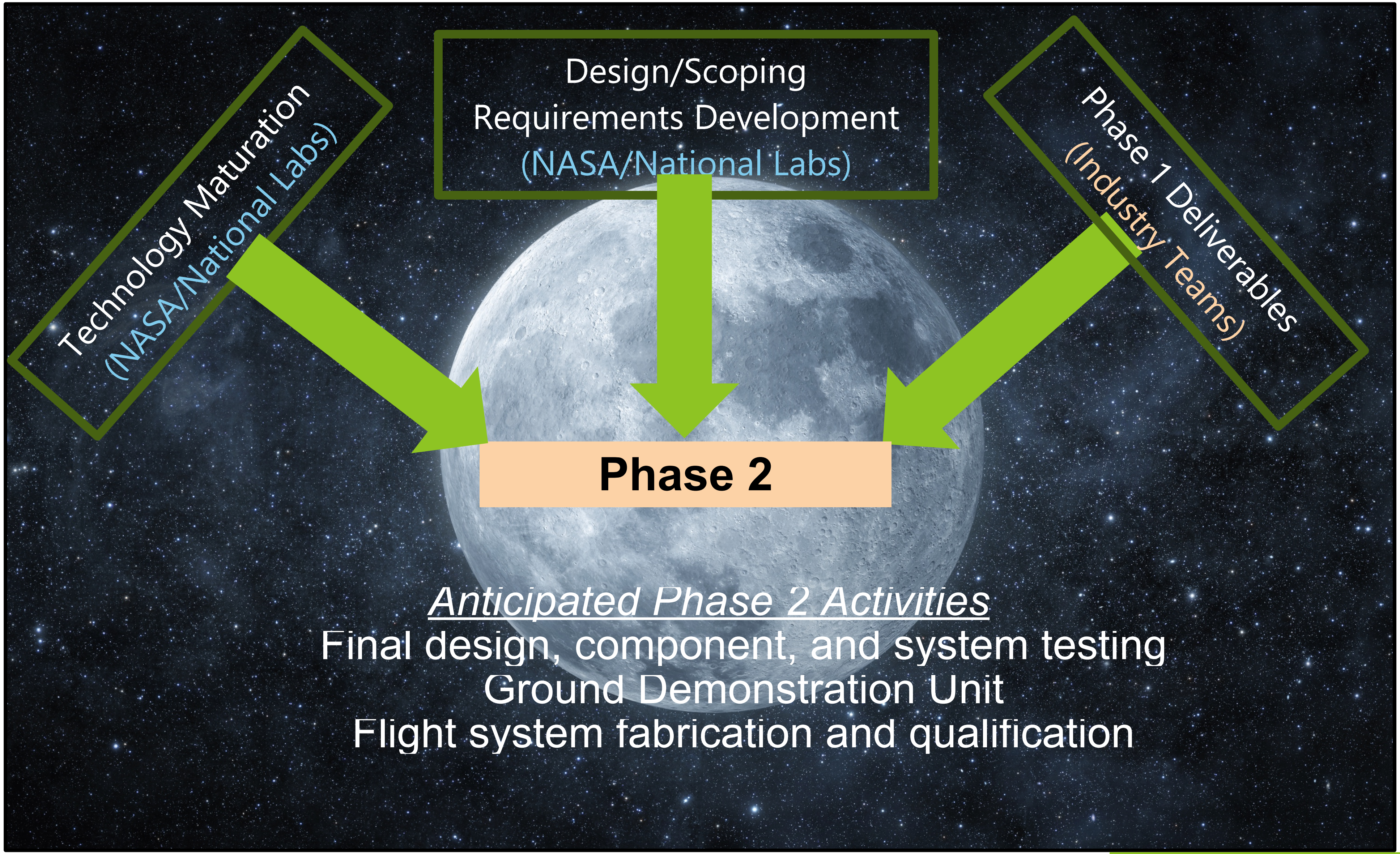
Instrumentation & Control (I&C) Systems

FSP will require an I&C system that can withstand both nuclear reactor conditions and the environmental conditions of space simultaneously for 10 years without intervention.

Gap Assessment

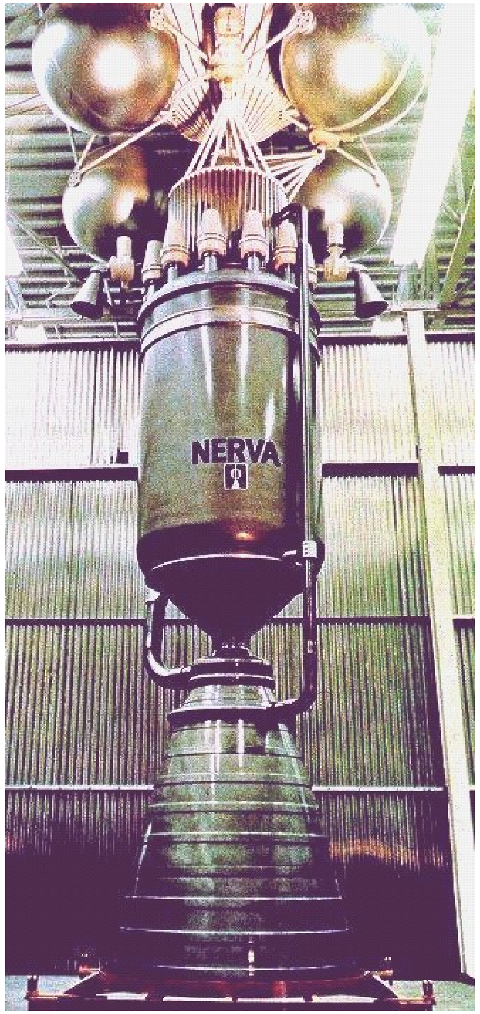
- Radiation detectors, temperature and pressure sensors
- Motors and actuators, switches, position indicators
- Electronics, cabling
- Instrumentation & control system architecture
- Digital twin solutions

Fission Surface Power Next Steps



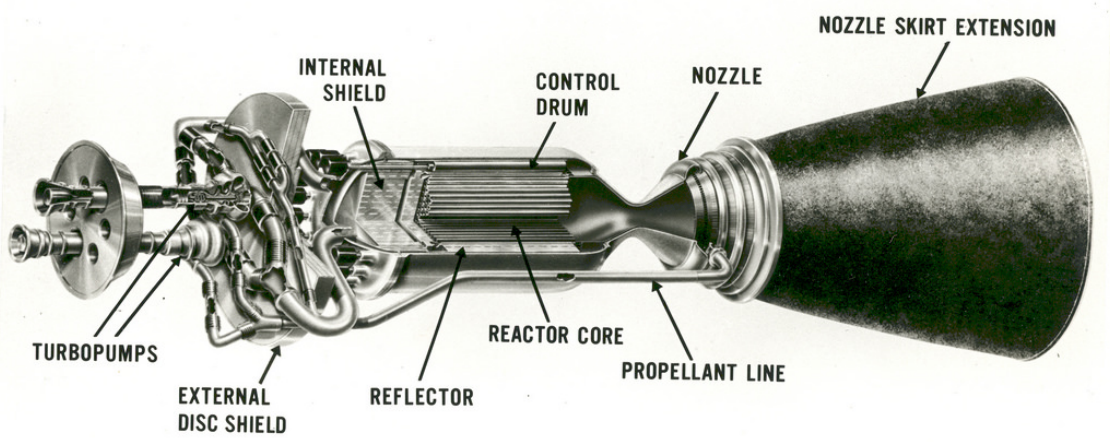
Nuclear Thermal Propulsion
How does it work?

- Propellant heated directly by a nuclear reactor and thermally expanded/accelerated through a nozzle (Low molecular weight propellant – typically hydrogen)
- Thrust directly related to thermal power of reactor: 100,000 N (22.5 klb_f) ≈ 450 MW_{th} at 900 sec I_{sp}
- Specific Impulse directly related to exhaust temperature: 830–1000 sec (2300–3100K)
- Specific impulse improvement over chemical rockets due to lower molecular weight of propellant (exhaust stream of O_2/H_2 engine runs much hotter than NTP)



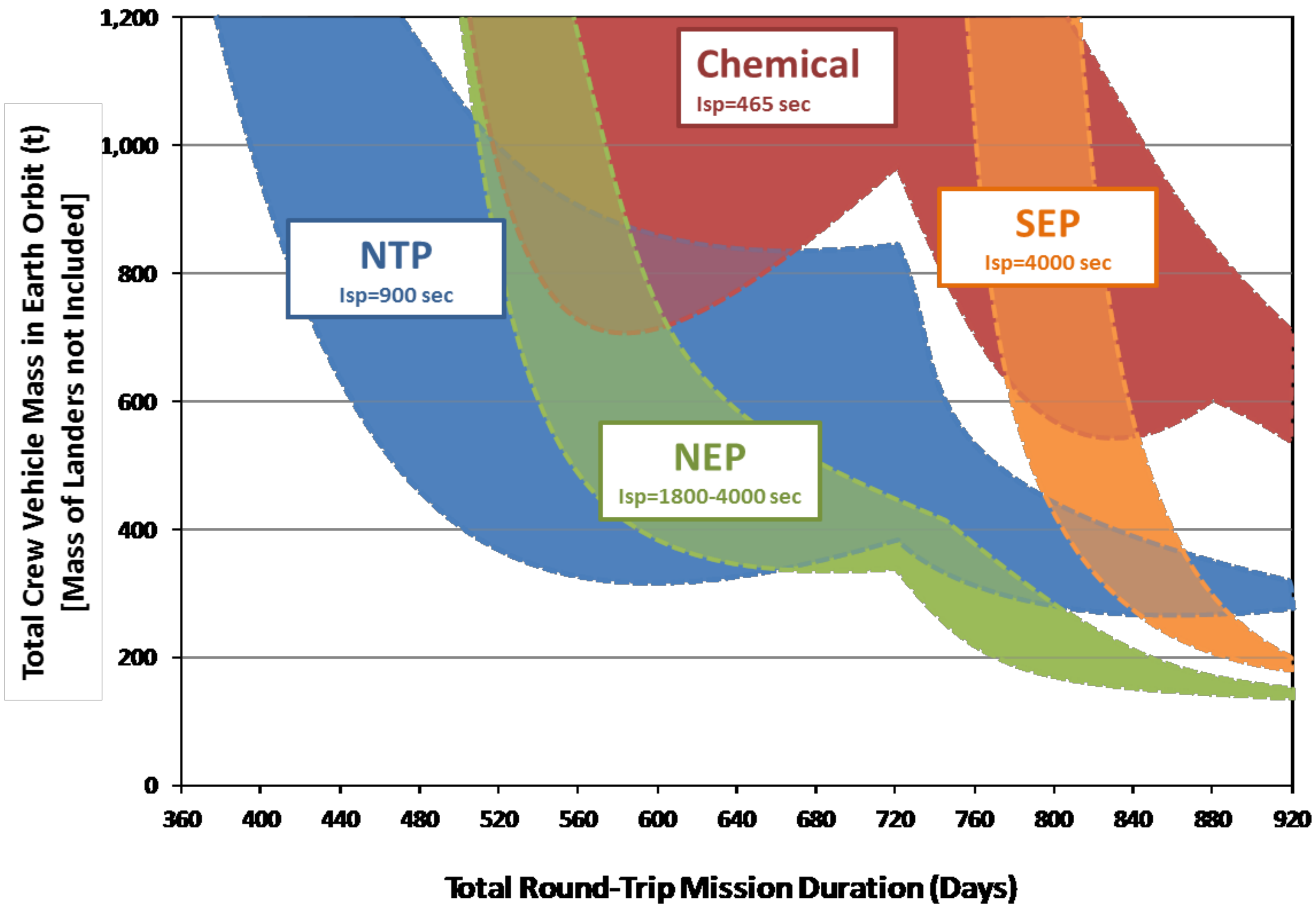
NERVA Nuclear Thermal Rocket Prototype

Major Elements of a Nuclear Thermal Rocket



Why Nuclear Propulsion?

- High Delta V capability → potential shorter trip time (reduce exposure to galactic cosmic radiation and zero-g)
- Mission robustness and potential abort scenarios
- Fewer rocket launches → save time and $$$



Technical Challenges

High Temperatures

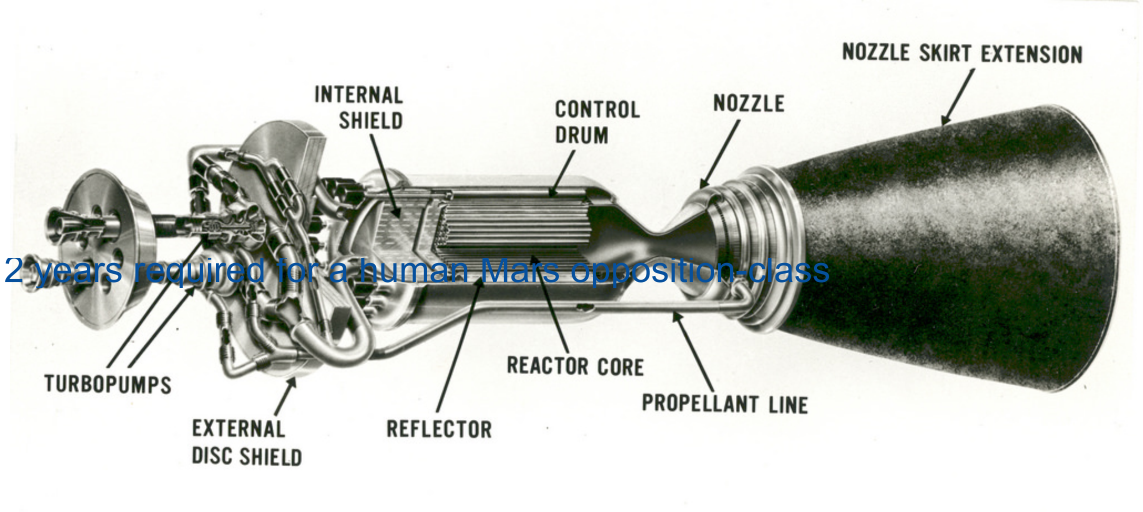
- To achieve 900 s I_{sp}, propellant must be heated from cryo-temperatures to at least 2700 K (2427°C)
- This leads to a required uranium fuel temperature of *at least* 2850 K
  - Well beyond the temperatures in terrestrial power reactors
  - Power Density: 5000W/cc versus 100wcc in commercial power
- Near or above the melting point for some uranium alloys
  - Unlike in a chemical rocket, the propellant is not the hottest part of the system.
- Neutron moderators have significantly lower temperature limits
  - Can use propellant (to some extent) as a coolant for the moderator and reactor containment shell

Structural

- High ΔT both radially and axially
  - Different coefficients of thermal expansion
- Hot hydrogen is chemically very reactive/corrosive

Operational

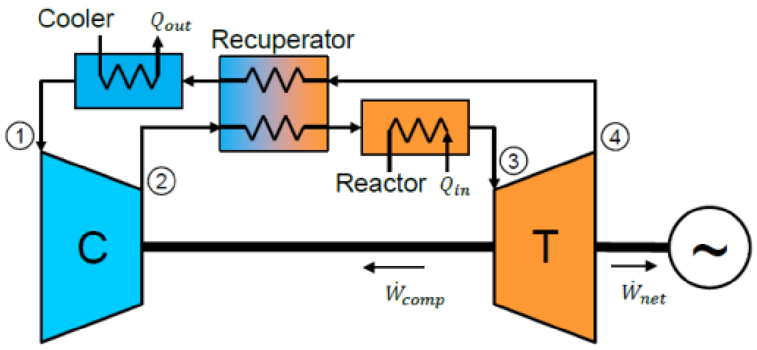
  - Start QUICKLY – why?
  - Multiple restarts with operation for 30 minutes to several hours over 2 years required for a human Mars opposition-class mission (plus flow during cool-down for decay heat removal)



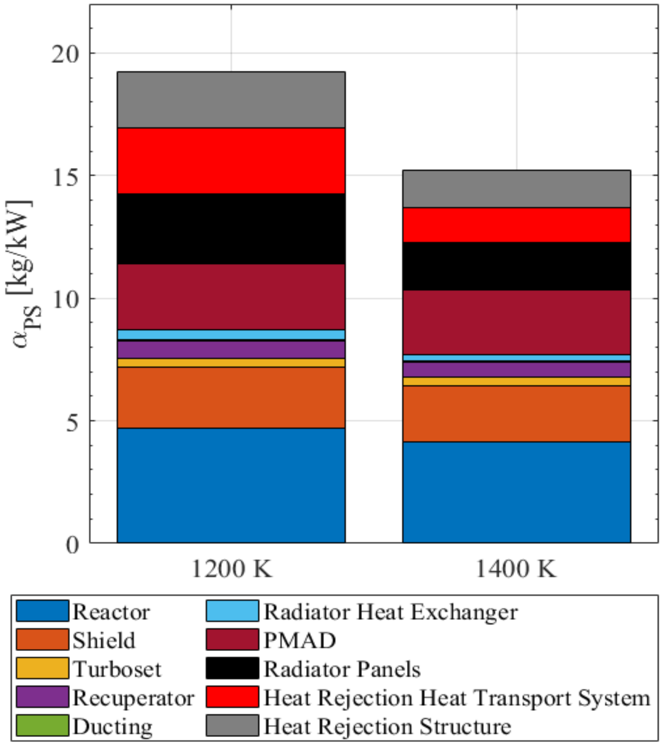
Nuclear Electric Propulsion

≥ 25,000 hours of continuous operation

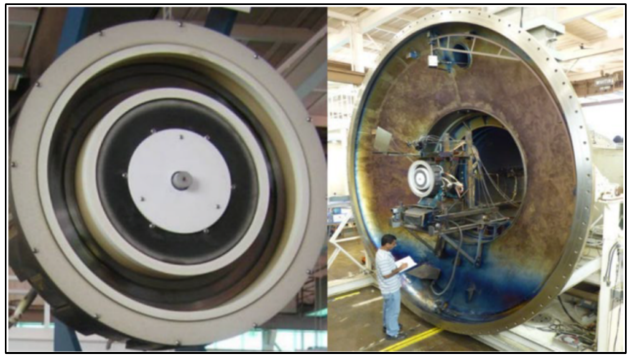
- Reactor
  - Similar to terrestrial, but **hotter**
    - But lower temperatures than nuclear thermal propulsion
  - Potentially higher power than FSP
- Hall Thruster
  - Xe fed
- Power Conversion
  - Closed cycle, hot inlet
  - Do not want highest possible efficiency
- Heat Rejection (Radiators)
  - Want lightweight radiator at high temperature and emissivity



Closed Brayton Cycle Power Generation System



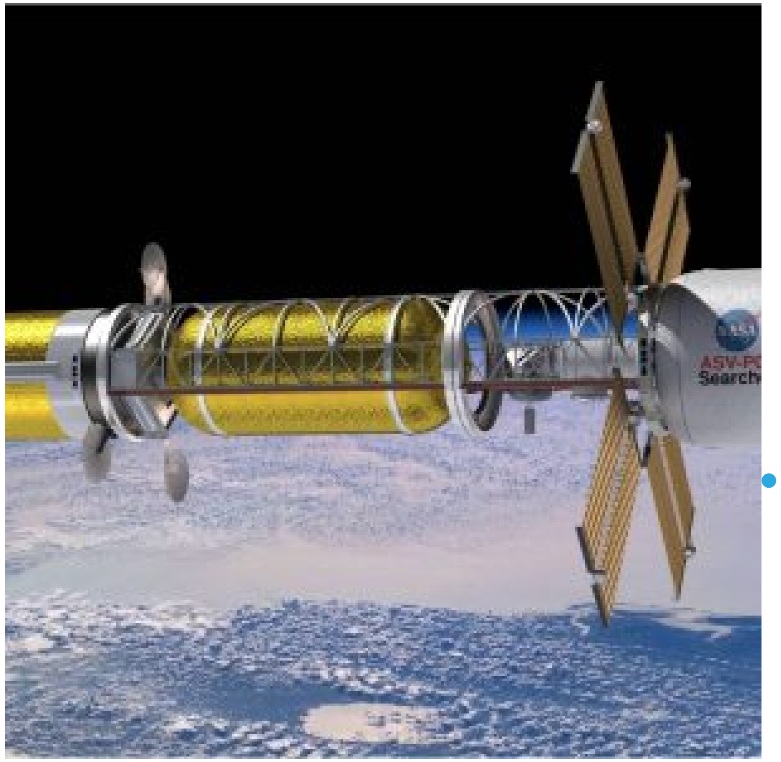
2 MW_e gas-cooled reactor mass breakdown for PCIT of 1200 and 1400 K

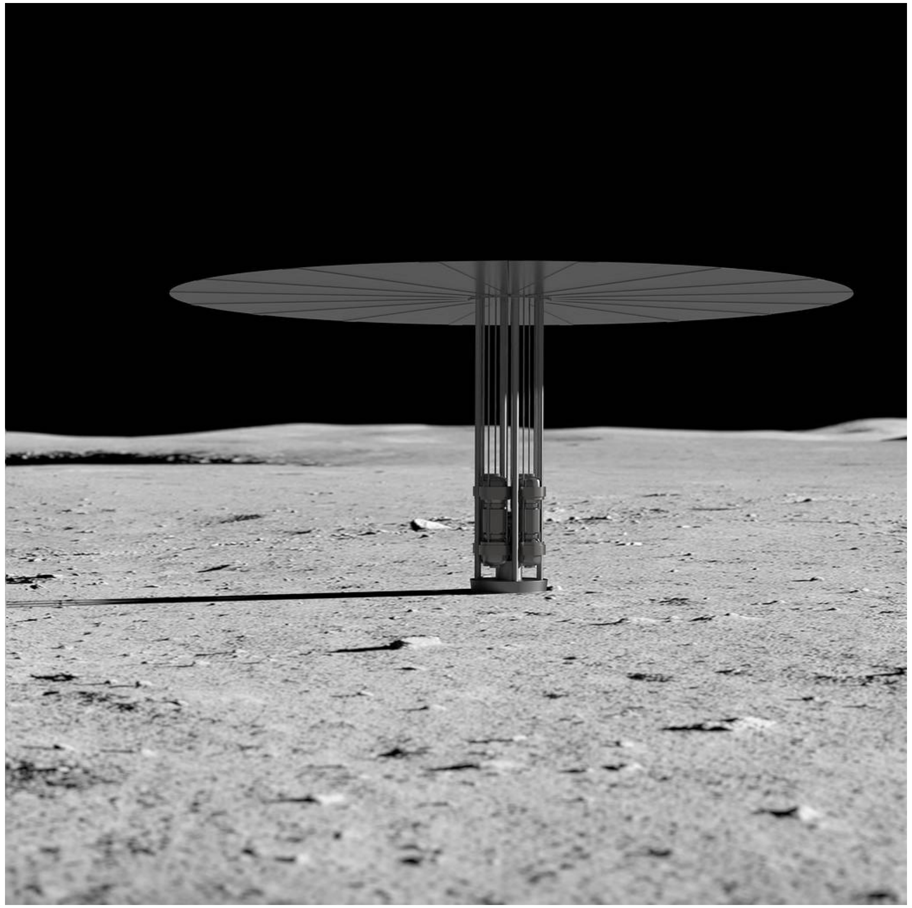

NASA-457 v2 Hall Thruster

Summary

- Fission reactors used for both propulsion and generator electricity are key to space exploration

- Space reactors have a long history





- NASA and the DOE National Laboratories are currently working together with the space and nuclear commercial industry

Idaho National Laboratory

Battelle Energy Alliance manages INL for the U.S. Department of Energy's Office of Nuclear Energy. INL is the nation's center for nuclear energy research and development, and also performs research in each of DOE's strategic goal areas: energy, national security, science and the environment.