Lunar Surface Innovation Consortium

Dr. Anthony Calomino | NASA Space Nuclear Technology Portfolio Manager | January 27, 2022
Space Nuclear Technologies: Fission Surface Power

• Fission surface power is the Agency’s top nuclear priority
• Reliable energy production is essential to human and scientific exploration missions
• Nuclear enables higher energy systems that operate continuously in extreme environments
• NASA seeks synergy and collaboration with industry, other government agencies, and academia

Benefits:

✓ Space Leadership
✓ National Security
✓ Global Competition
✓ Domestic Economy
✓ Green Energy
Nuclear Power for the Moon and Mars

Nuclear power systems will enable robust exploration of Moon and Mars

• Fission power systems can provide abundant and continuous surface power in all environmental conditions on Moon and Mars:
  – Lunar night is 14.5 Earth days long and permanently shadowed regions may contain water ice, thus surface nuclear power is required for a sustainable lunar presence
  – Mars has recurring planet-wide dust storms that can last for weeks or months

• A fission system designed for a capability demonstration on the Moon will be directly applicable to human Mars exploration

• Recent analyses indicate that a Mars fission surface power system is likely to enable 2-3x less mass to be flown to space and be significantly more reliable than a comparable solar power system in the 10 to 40 kWe class
Nuclear Power Technologies Enable Sustained Surface Operations

Fission Power Systems

SNAP-10: 500 W HEU NaK loop - thermoelectric TRL-9
KRUSTY (Kilopower Reactor Using Sterling Technology) 5 kW HEU NaK loop - Sterling
FSP (Fission Surface Power) 40 kWe HA-LEU design (industry contracts ~ 3 QTR/22)

Terrestrial
Non-radiative cooled
Non-space environment

Surface Operations
Habitat Operations
ISRU Plant Operations
Power Grid
Systems Test of Krusty
Lunar Fission Surface Power
Federal Policy and Processes

NSPM-20
Updates launch approval process and establishes quantified risk levels

OSTP/NSTC
Integrated implementation of SPD-6 and EO 13972 with integrated interagency roadmap

SPD-6
Defines national strategy for use of space nuclear power and propulsion systems

EO 13972
Directs NASA to utilize common nuclear systems for exploration missions through 2040

 Defines:

- Agency launch authority
- Interagency reviews (INSRB)
- Use of HEU for SNPP
- Commercial launch process
- Process for interagency roadmap
Fission Surface Power Requirements

- **Power:** 40 kWe with technology extensible to higher power
- **Mobility:** Capable of being transported on a rover
- **Size:** Capable of fitting on a large lander
- **Mass:** Capable of fitting on a large lander
- **Fuel:** DOE reactor study completed in March 2020 identified LEU reactor solutions in same mass class as HEU system
Metallic hydrides (zirconium and yttrium hydride) minimize critical reactor geometries, beryllium compounds (beryllium, beryllium carbide, and beryllium oxide) are capable of higher operating temperatures.

Ref: K. Palomares, NETS 2021
Two Recommended Reactor Concepts

All DOE reactor configurations were deemed feasible, however they all carry varying technical risk.

High Enriched Uranium (HEU)-Fast

- Reactor technology and performance simple and straightforward
- Needs DOE facilities for processing and fabricating core
- Limited industry infrastructure

High Assay Low Enriched Uranium (HALEU)-Segmented

- Requires more development effort than the Fast configurations
- Aligns with several ongoing industry commercial and DoD initiatives
- Industry infrastructure is high
- Design is especially compatible with all fuel forms, including TRISO, at higher power level
### HEU and HALEU Reactor Advantages and Disadvantages

<table>
<thead>
<tr>
<th>Reactor Configuration</th>
<th>HEU Fast</th>
<th>HALEU Fast</th>
<th>HALEU-YH</th>
<th>HALEU-ZrH</th>
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<tbody>
<tr>
<td><strong>Configuration</strong></td>
<td>Simplest reactor design using a cylindrical core of U-Mo alloy surrounded by a BeO$_2$ reflector Heritage: Russian BUK and NASA Kilopower</td>
<td>Homogeneous neutronic and thermal YH moderated has reduced design complexity Heritage: SNAP</td>
<td>Cooled and thermally insulated ZrH moderator block provides higher maturity with increased design complexity Heritage: NERVA and TOPAZ</td>
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<td><strong>Auxiliary Systems</strong></td>
<td>All require similar auxiliary systems, neutron reflector, B$_4$C control rods, radiation shields, power conversion system, and waste heat rejection radiators. Sterling and Brayton cycle engines primary space application</td>
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<td><strong>Mass Impact (10 kWe)</strong></td>
<td>Lowest mass</td>
<td>Heaviest mass (~60% more than HEU fast)</td>
<td>Moderated reactors can be competitive with HEU fast at &lt;20% mass increase</td>
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<td><strong>Nuclear Technology Readiness</strong></td>
<td>High TRL 5 with simple design approach, fission fuel maturity, and available data from heritage systems</td>
<td>Lowest TRL 3 related to YH moderator material performance and design experience</td>
<td>TRL of 4 based on higher maturity for ZrH and previous nuclear reactor and vacuum testing</td>
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<td><strong>Non-nuclear Technology Readiness</strong></td>
<td>TRL varies between 3 and 5 depending on reactor configuration. Development needs include reactor controls, thermal-power loop heat transfer, lightweight radiation shielding, space-rated power conversion system, and thermal management schemes</td>
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Ref: Internal NASA DOE Report, 2019
Fission Surface Power Acquisition Strategy

FSP Project Concerns
• Budget profile constraints may limit actual development and delivery schedule
• COVID quarantine restricted facility (laboratory and test facility access)

FSP industry solicitation released November 19, 2021
Two phase acquisition strategy for industry solutions:
• Phase 1: Three 12-month efforts for a preliminary design (planned completion 3QTR/FY23
• Phase 2: System design, build, test, and demonstration hardware delivery (~2028)
Fission Surface Power: Notional System Overview

Mechanical Power Conversion System (PCS)  
Brayton/Stirling

Radiation shielding

Electrical Power
System located 10 m from reactor assembly

1 km power cable

Heating Sodium to PCS via heat pipes

Heated Sodium to reactor

Cooled Sodium to reactor

Excess Heat

Thermal Control System (TCS)
Heat Pipes, Heat Exchangers, Radiators

Nuclear Heat Source

Reactor shielding

Reactor core design & reactor shielding not in scope

Heat rejection to environment

Surfam Element Power System/Storage (not in scope)

$T_{\text{hot}}$ (temperature at “hot side” of converter)

$T_{\text{cold}}$ (temperature at “cold side” of converter)
Critical Aspects of a Power Conversion Systems for a Lunar Demonstration

FSP Power Conversion System

- Reliable, robust, low degradation (sufficient power at end of mission)
- High specific power, high efficiency (low system mass)
- Ease of use (minimize complexity of design and operations)
- Flexible (multi-mission capable, extensible to Mars)
- Low power variation (during Lunar day/nigh cycles)
- Maturity (support the near-term planned missions)
Heat Rejection System

High temperature, high efficiency thermal radiators can increase conversion efficiency and reduce system mass (reactor)
FSP Technology Maturation

• Advance moderated HALEU reactor design TRL (3/4-6)
  ‒ Technology developments are related to the moderator life testing and qualification

• Advance dynamic power converters (TRL 4–6)
  ‒ NASA has been advancing a 1 kW class converter and controller

• Ancillary non-nuclear sub-systems (TRL 3-5)

Challenges

• Enhance alignment with industry capabilities and interests
• Maintain stable funding profiles and support
• Address operational reliability needs
• Design for growth to accommodate future needs (ISRU and NEP)
Fission Surface Power Summary

2021 Accomplishments

- Established a HA-LEU government reference design to guide technology and design decisions
- Completed power conversion system and power transmission studies
- Released Phase I request for proposal to industry for industry-led designs
- Completed power conversion technology maturation SOW with planned release in early 2022

Summary

- NASA is working with other government agencies to establish a common technology development roadmap that leverage priorities and resources for advancing space nuclear energy technology
- NASA priority focus remains on designing, building, and demonstrating a low enriched uranium fission surface power system that is directly applicable for Moon and Mars, scalable to power levels above 100 kWe, and has potential to advance NEP system needs
- NASA will continue to be closely engaged with industry to seek innovative, unique design approached for fission surface power systems
- NASA will continue to support inter-agency missions and other nuclear technology development efforts
Interagency Collaborations

Leverage Commonality:

- Reactor Designs
- Fuel Production
- Reactor Materials
- Launch Regulations
Interagency Engagements

DOD/SCO – Mobile Terrestrial Power Plant
   Partnered support to establish commercial source for coated fission fuel forms and participation in mobile reactor design advancements

USSF – Space Nuclear Systems Capabilities
   Joint meetings to provide insight on space power investment initiatives, planned capabilities, development strategy

DIU – Low Kilowatt In Space Nuclear Power
   Shared subject matter expertise supporting proposal evaluations, space nuclear electric propulsion technology, and small fission reactor development investments

DOE – Organic Authority and Nuclear Energy Expertise
   Integrated technology development teams are maturing moderated LEU fission reactor designs and materials, design database development, digital modeling, and advancing nuclear test capabilities for space systems

DARPA – DRACO NTP Flight Demonstration
   Program and technical teams provide support to proposal evaluations, contract management, cryogenic thermal management, fission reactor technology, and turbine machinery design
Background
FSP PCS Overview

Power conversion system converts heat to usable electrical power

1. **Free-Piston Stirling** – 39/40 successful Stirling flight cryocoolers (TRL 9); 40+ space design engines ground tested (TRL4-5)
   - Flight gas bearing Stirling cryocooler operated successfully on the RHESSI solar flare observatory for 21.1 years
   - Longest operating flexure power producing Stirling over 14 years, ongoing
   - Longest operating gas bearing Stirling convertor over 10 years, ongoing
   - Demonstrated space design power levels: 35 W and 12.5 kW by multiple vendors

2. **Closed-Cycle Turbo-Brayton** – Space cryocoolers flown (TRL 9)
   - Flight Brayton cryocooler operated successfully on the Hubble Space Telescope
   - 10+ space engines ground tested (TRL3-4)
   - Mini-Brayton Rotating Unit (BRU) multiple units (1974-1978) tested (BIPS version tested for 1,000 hours)

3. **Thermoelectrics** – numerous successful missions in space environments
   - 28 flight Radioisotope Power System (RPS) missions over past 50 years (TRL 9)
   - Recent flights: Mars Curiosity and Perseverance use a Multi-Mission Radioisotope Thermoelectric Generator (MMRTG)
   - Advanced thermoelectrics in development for future missions beyond 2030
Nuclear Legacy Systems

Thousands of reactors at various power levels

1938: Fission Discovered
1943: X-10 Reactor (ORNL), 3500 kWt
1944: B-Reactor (Hanford), 250,000 kWt

Small research reactors
University Research/TRIGA reactors

Advanced, high-power research reactors, associated facilities:
US Fast Flux Test, EBR-II, ATR, HFIR

Commercial Light Water Reactors
1,371,000 kWe (3,800,000 kWt)

Space power reactors
SNAP-10A: 42 kWt / 0.6 kWe
Soviet reactors typically 100 kWt 3kWe
(some systems >150 kWt)
Cost is design-dependent

Space Propulsion
RoverNERVA 100MWt – 5000MWt