JOHNS HOPKINS
APPLIED PHYSICS LABORATORY

LSIC Surface Power Telecon

January 27, 2022

Begins at 11:03

Lunar Surface Innovation
CONSORTIUM

Wesley T. Fuhrman, PhD
Johns Hopkins Applied Physics Laboratory
Space Exploration Sector

Wesley.Fuhrman@jhuapl.edu

Confluence Discussion:
https://lsic-wiki.jhuapl.edu/display/SP/27+January+2022

LSIC | Agenda

- Community Updates
- Technical Discussion
    - Anthony Calomino – Fission Surface Power
- Open discussion (time permitting, or extending as warranted)
    - What we want to do this year, including our second annual goal

LSIC | Working Group: MOSA

- **Lead: James Mastandrea**

- **LSIC Modular Open System Approach (MOSA) Working Group**
  - Goal:
    - Document community feedback on recommended lunar MOSA activities
      - Compile existing efforts and identify overlap
      - List systems that could benefit from MOSA
      - Perform system decompositions to find critical interfaces & what requirements are needed to ensure interoperability
  - Plan
    - Each LSIC focus group is participating
    - Cross focus group participation is encouraged
    - Surface power MOSA subgroup will meet after the surface power monthly telecons starting in February 2022.

LSIC | Upcoming Meetings and Workshops

- LSIC Spring Meeting:
  - https://app.sli.do/event/9WJnFKk98qzPZ1zL1sX8Sw/live/polls
  - (Pause to collect community input)

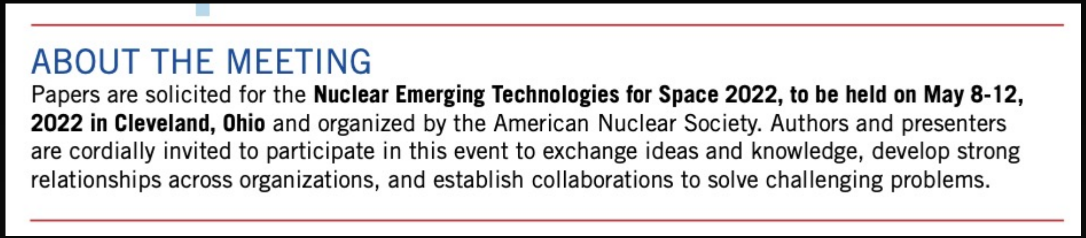
- ISRU and E&C
  - Regolith to Rebar Feb 23 (https://lsic.jhuapl.edu/Events/Agenda/index.php?id=177)
  - Prospecting Campaign

- Nuclear and Emerging Technologies for Space (NETS)
  - https://www.ans.org/meetings/nets2022/
  - Track on “To the Moon to Stay”

ANS®

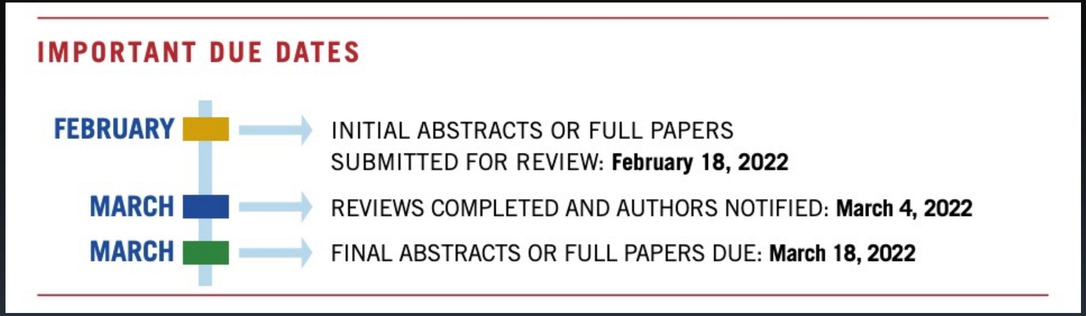
Nuclear Emerging Technologies for Space 2022 (NETS 2022)

May 8-12, 2022 | Cleveland, OH | The Westin Cleveland Downtown



ABOUT THE MEETING

Papers are solicited for the **Nuclear Emerging Technologies for Space 2022, to be held on May 8-12, 2022 in Cleveland, Ohio** and organized by the American Nuclear Society. Authors and presenters are cordially invited to participate in this event to exchange ideas and knowledge, develop strong relationships across organizations, and establish collaborations to solve challenging problems.



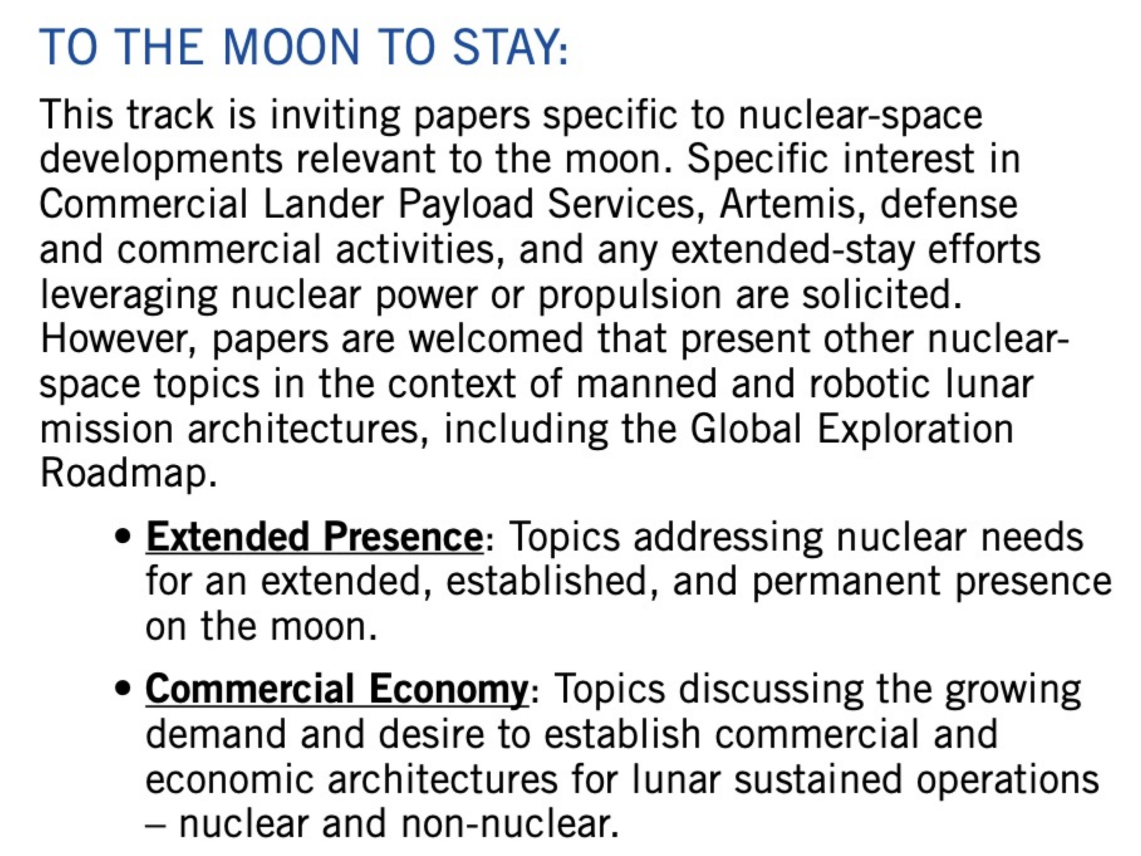
IMPORTANT DUE DATES

FEBRUARY → INITIAL ABSTRACTS OR FULL PAPERS SUBMITTED FOR REVIEW: **February 18, 2022**

MARCH → REVIEWS COMPLETED AND AUTHORS NOTIFIED: **March 4, 2022**

MARCH → FINAL ABSTRACTS OR FULL PAPERS DUE: **March 18, 2022**

www.ans.org/meetings/nets2022



TO THE MOON TO STAY:

This track is inviting papers specific to nuclear-space developments relevant to the moon. Specific interest in Commercial Lander Payload Services, Artemis, defense and commercial activities, and any extended-stay efforts leveraging nuclear power or propulsion are solicited. However, papers are welcomed that present other nuclear-space topics in the context of manned and robotic lunar mission architectures, including the Global Exploration Roadmap.

- **Extended Presence**: Topics addressing nuclear needs for an extended, established, and permanent presence on the moon.
- **Commercial Economy**: Topics discussing the growing demand and desire to establish commercial and economic architectures for lunar sustained operations – nuclear and non-nuclear.

LSIC | Solicitations

- DARPA RFI on Rad-hard electronics:
  - **New Approaches to Qualifying Electronics in a High Radiation Environment Request for Information (RFI)**
  - https://sam.gov/opp/c2075bf4d79841b6bd3e666261a97798/view

- Space Tech Solicitations (**https://www.nasa.gov/directorates/spacetech/solicitations**)

  - **NASA Innovative Advanced Concepts (NIAC) 2022 Phase III solicitation**
    Mandatory Preliminary Proposals due: January 28, 2022
  - **NASA Small Business Innovation Research (SBIR) / Small Business Technology Transfer (STTR) 2022 Phase I solicitation**
    Proposals due: March 9, 2022
  - **Fission Surface Power System Design Solicitation (released by the U.S. Department of Energy)**
    Proposals due: February 17, 2022
    - **Anthony Calomino, NASA**

EXPLORE SPACE TECH
TECHNOLOGY DRIVES EXPLORATION

Lunar Surface Innovation Consortium

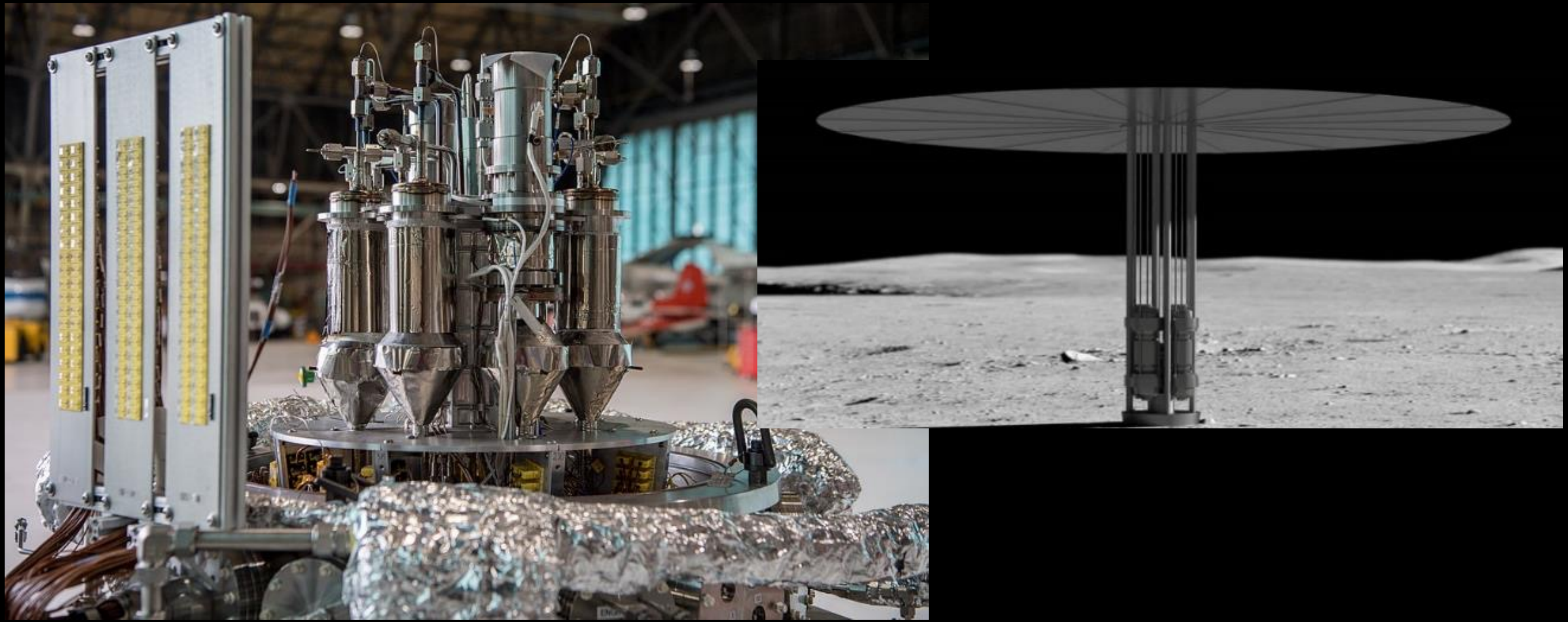
Dr. Anthony Calomino | NASA Space Nuclear Technology Portfolio Manager | January 27, 2022

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:

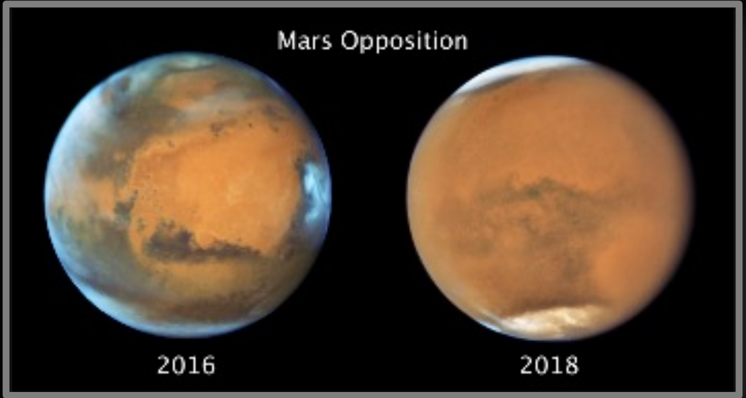
- ✓ Space Leadership
- ✓ National Security
- ✓ Global Competition
- ✓ Domestic Economy
- ✓ Green Energy



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

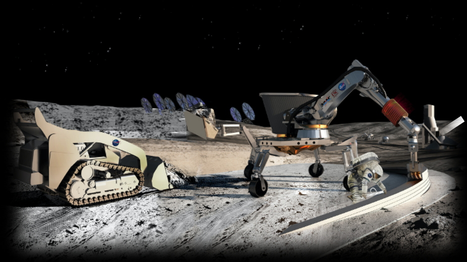
SNAP-10: 500 W HEU NaK loop - thermoelectric TRL-9
KRUSTY (Kilopower Reactor Using Sterling Technology) 5 kW HEU NaK loop - Sterling
FSP (Fission Surface Power) 40 kWe HA-LEU design (industry contracts ~ 3 QTR/22)

Terrestrial

Non-radiative cooled
Non-space environment

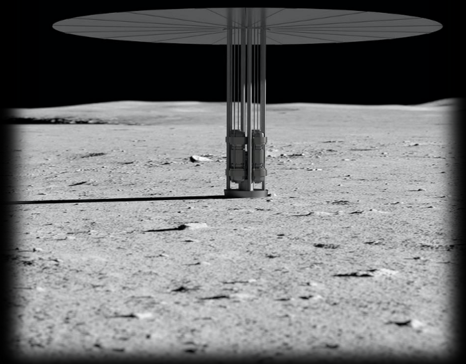
Power Grid

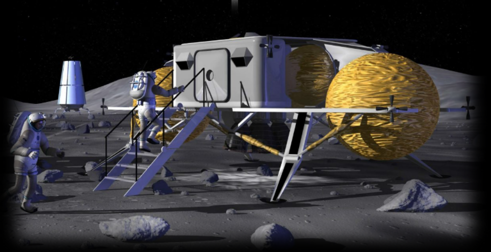
Systems Test of Krusty



Surface Operations

ISRU Plant Operations





Habitat Operations

Lunar Fission Surface Power

Federal Policy and Processes

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

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

Nuclear Regulatory Commission

Department Of Transportation

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

Defines:

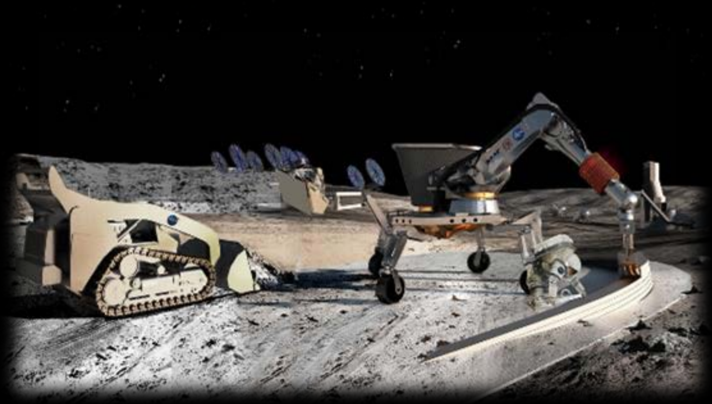
- ✓ Agency launch authority
- ✓ Interagency reviews (INSRB)
- ✓ Use of HEU for SNPP
- ✓ Commercial launch process
- ✓ Process for interagency roadmap

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

Fission Surface Power Requirements

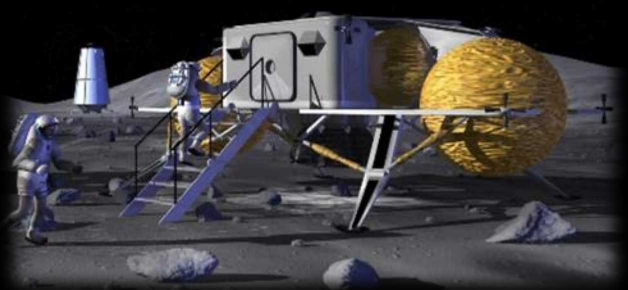
- Power: 40 kWe with technology extensible to higher power
- Mobility: Capable of being transported on a rover
- Size: Capable of fitting on a large lander
- Mass: Capable of fitting on a large lander
- Fuel: DOE reactor study completed in March 2020 identified LEU reactor solutions in same mass class as HEU system

Surface Operations

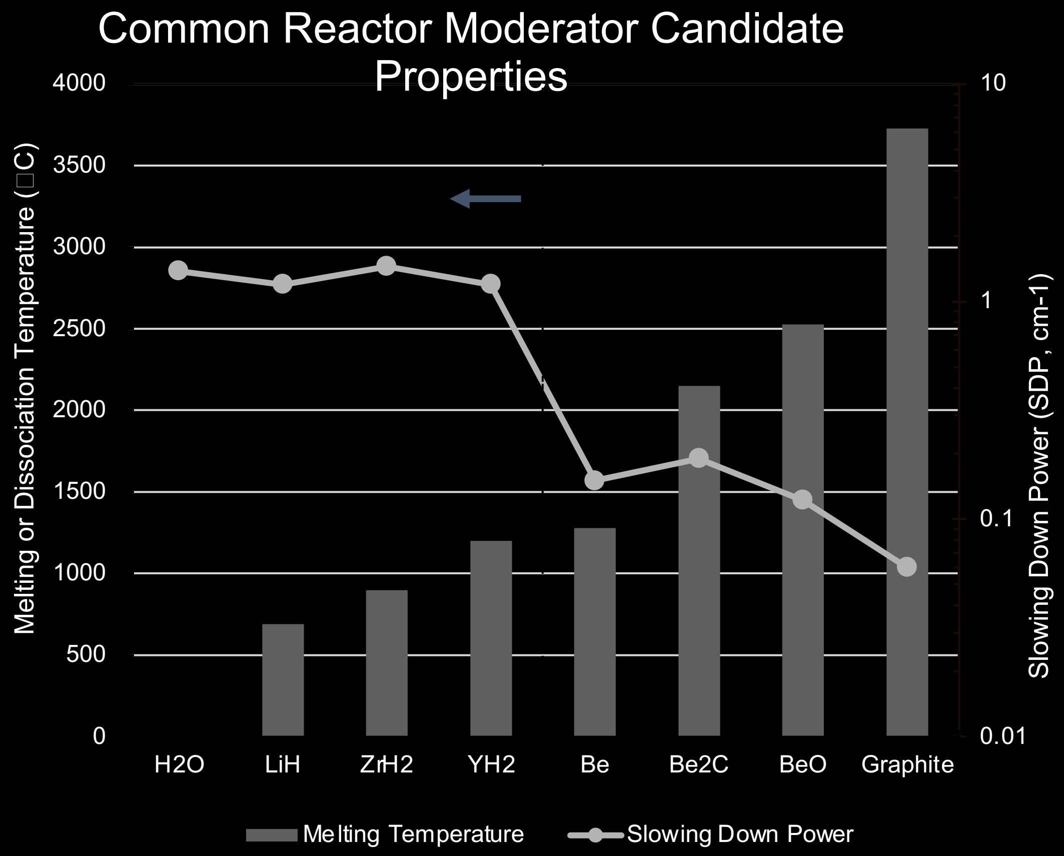


ISRU Operations

Habitat Operations



Moderator Comparison


Common Reactor Moderator Candidate Properties

Material	Melting / Maximum Operating Temperature	Density (g/cm³)	SDP (cm⁻¹)	ξ	Moderating Ratio	H2 Stability	Vacuum Stability	CO₂ Compatibility
H_2	-	8.988×10^{-5}	5×10^{-4}	1	61.45	-	-	-
H_2O	100	0.997	1.38	0.7066	62.11	-	-	-
$ZrH_{2.0}$	900	5.56	1.66	0.6739	37.45	Compatible	Poor	Incompatible
$YH_{2.0}$	1200	4.28	1.22	0.6741	17.32	Compatible	Poor	Incompatible
Be	1287	1.85	0.17	0.2066	133.99	Compatible		< 550 °C
BeO	2527	2.85	0.13	0.1633	173.99	< 2200 °C	<1930 °C	< 2200 °C
Be_2C	2150	2.44	0.19	0.1903	149.15	unknown	Poor	unknown
Graphite	3727	2.266	0.07	0.1578	202.3	< 700 °C	< 2800 °C	< 600 °C

Metallic hydrides (zirconium and yttrium hydride) minimize critical reactor geometries, beryllium compounds (beryllium, beryllium carbide, and beryllium oxide) are capable of higher operating temperatures.

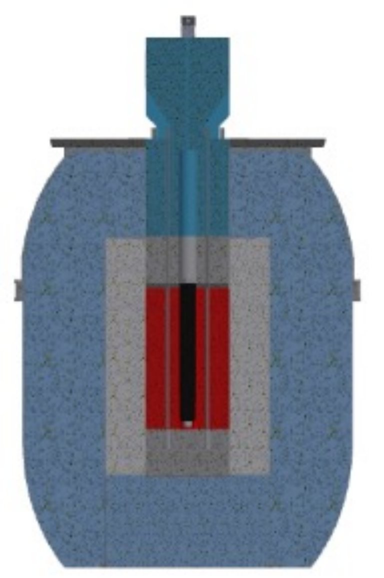
Ref: K. Palomares, NETS 2021

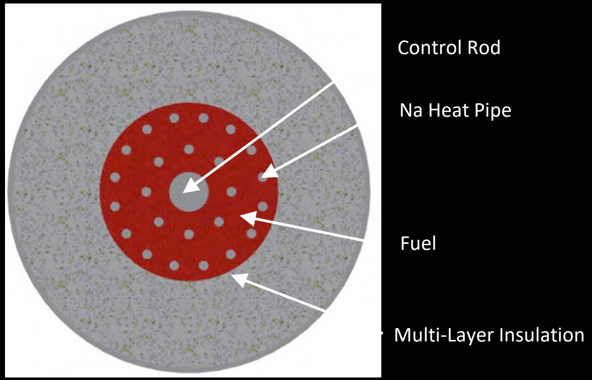
Two Recommended Reactor Concepts

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

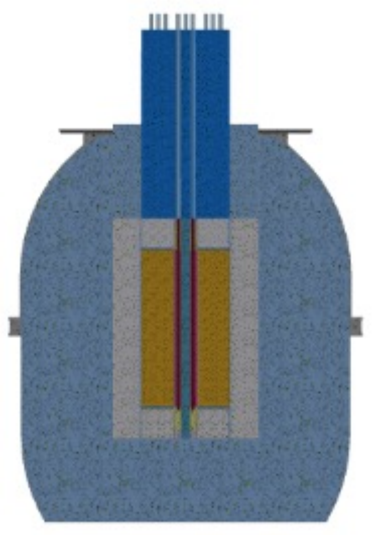
High Enriched Uranium (HEU)-Fast

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

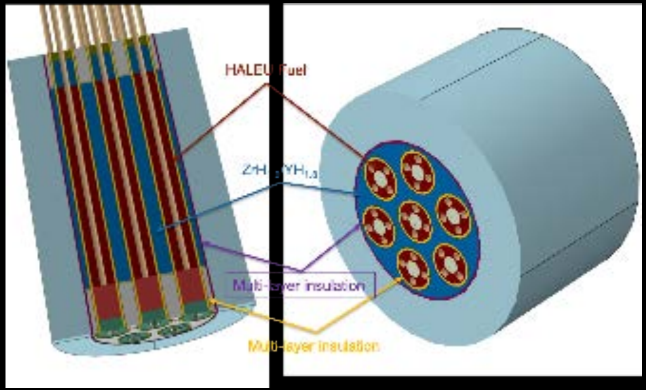




High Assay Low Enriched Uranium (HALEU)-Segmented



- 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

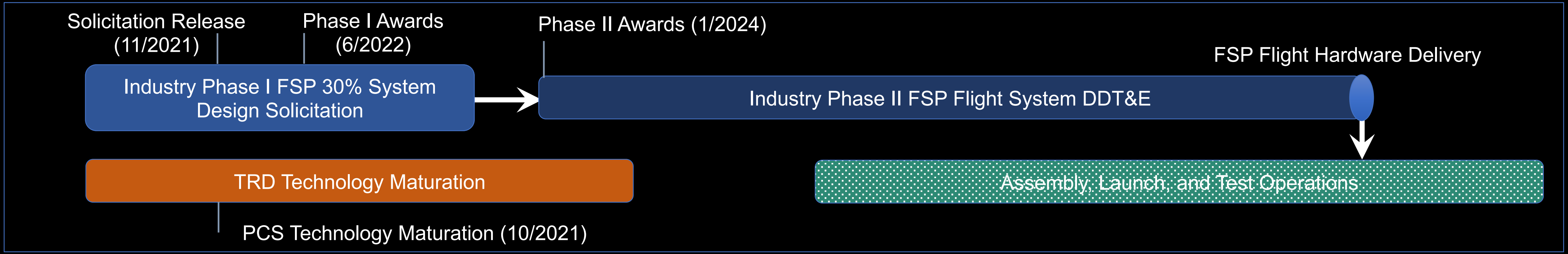


HEU and HALEU Reactor Advantages and Disadvantages

	HEU Fast	HALEU Fast	HALEU-YH	HALEU-ZrH
Reactor Configuration	Simplest reactor design using a cylindrical core of U-Mo alloy surrounded by a BeO$_2$ reflector Heritage: Russian BUK and NASA Kilopower		Homogeneous neutronic and thermal YH moderated has reduced design complexity Heritage: SNAP	Cooled and thermally insulated ZrH moderator block provides higher maturity with increased design complexity Heritage: NERVA and TOPAZ
Auxiliary Systems	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			
Mass Impact (10 kWe)	Lowest mass	Heaviest mass (~60 % more than HEU fast)	Moderated reactors can be competitive with HEU fast at <20% mass increase	
Nuclear Technology Readiness	High TRL 5 with simple design approach, fission fuel maturity, and available data from heritage systems		Lowest TRL 3 related to YH moderator material performance and design experience	TRL of 4 based on higher maturity for ZrH and previous nuclear reactor and vacuum testing
Non-nuclear Technology Readiness	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			

Ref: Internal NASA DOE Report, 2019

Fission Surface Power Acquisition Strategy

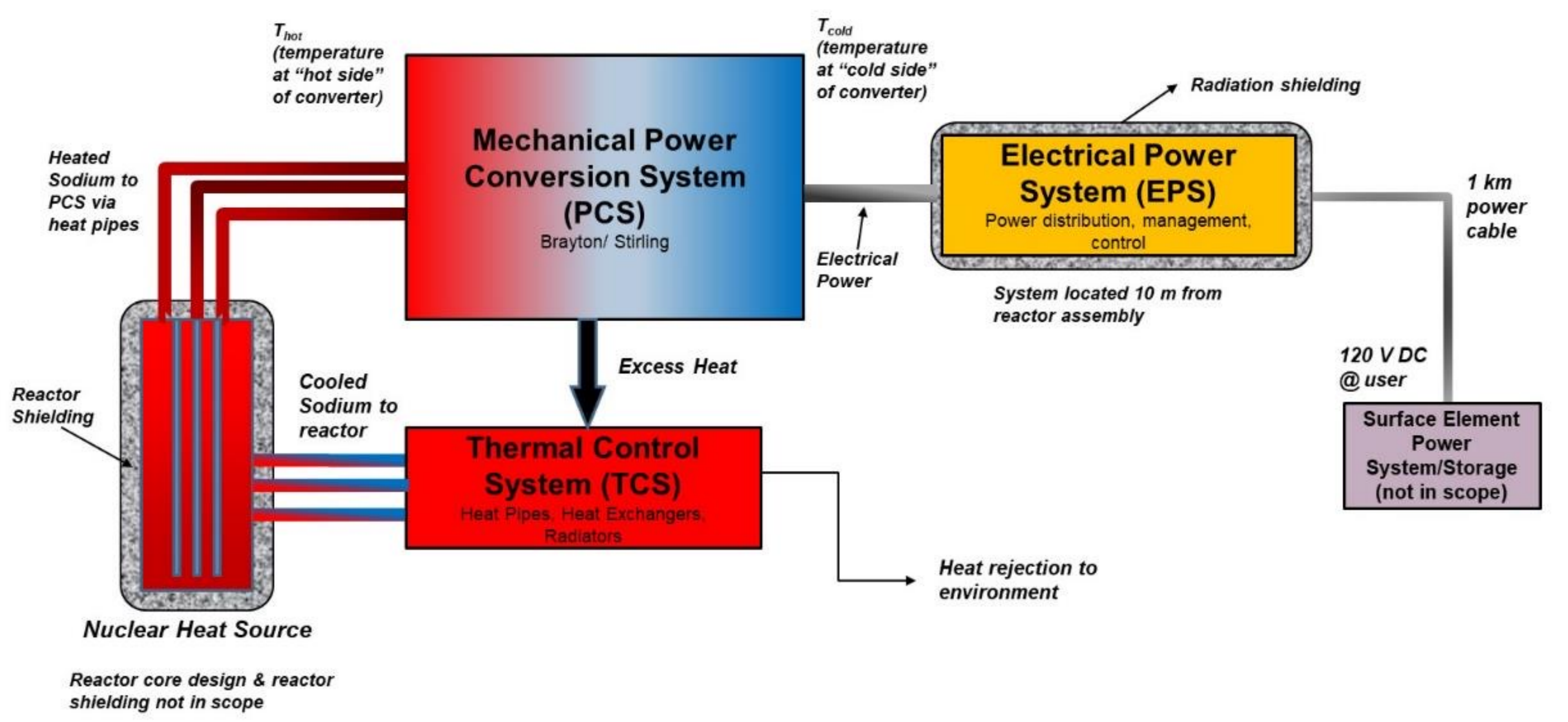


FSP Project Concerns
- Budget profile constraints may limit actual development and delivery schedule
- COVID quarantine restricted facility (laboratory and test facility access)

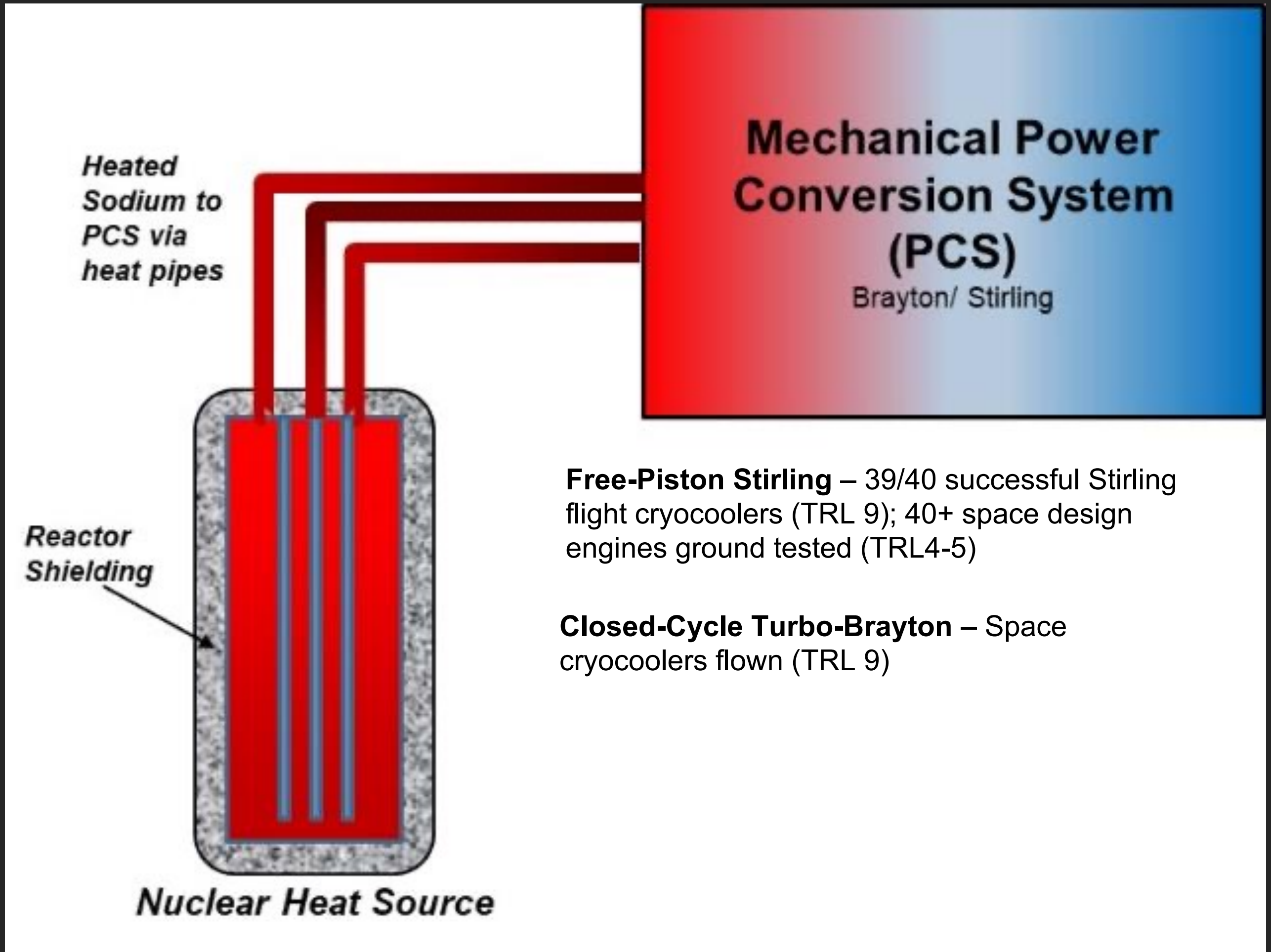
FSP industry solicitation released November 19, 2021

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



Critical Aspects of a Power Conversion Systems for a Lunar Demonstration

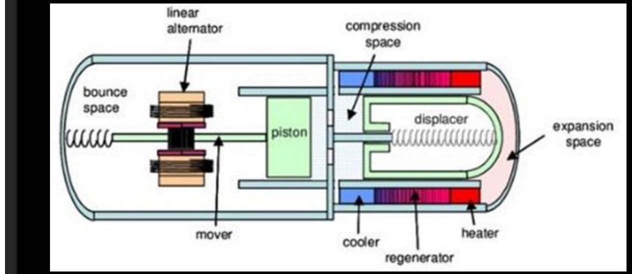


Free-Piston Stirling – 39/40 successful Stirling flight cryocoolers (TRL 9); 40+ space design engines ground tested (TRL4-5)

Closed-Cycle Turbo-Brayton – Space cryocoolers flown (TRL 9)

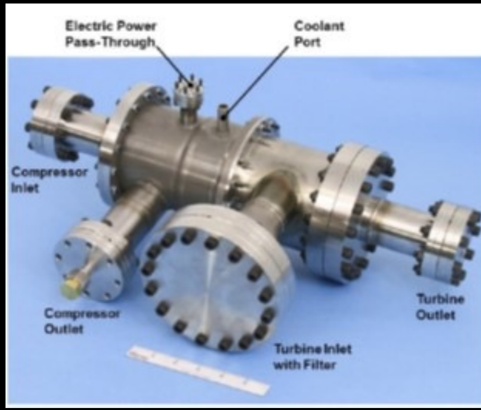
FSP Power Conversion System

- 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/night cycles)
- Maturity (support the near-term planned missions)



Free Piston Stirling Architecture

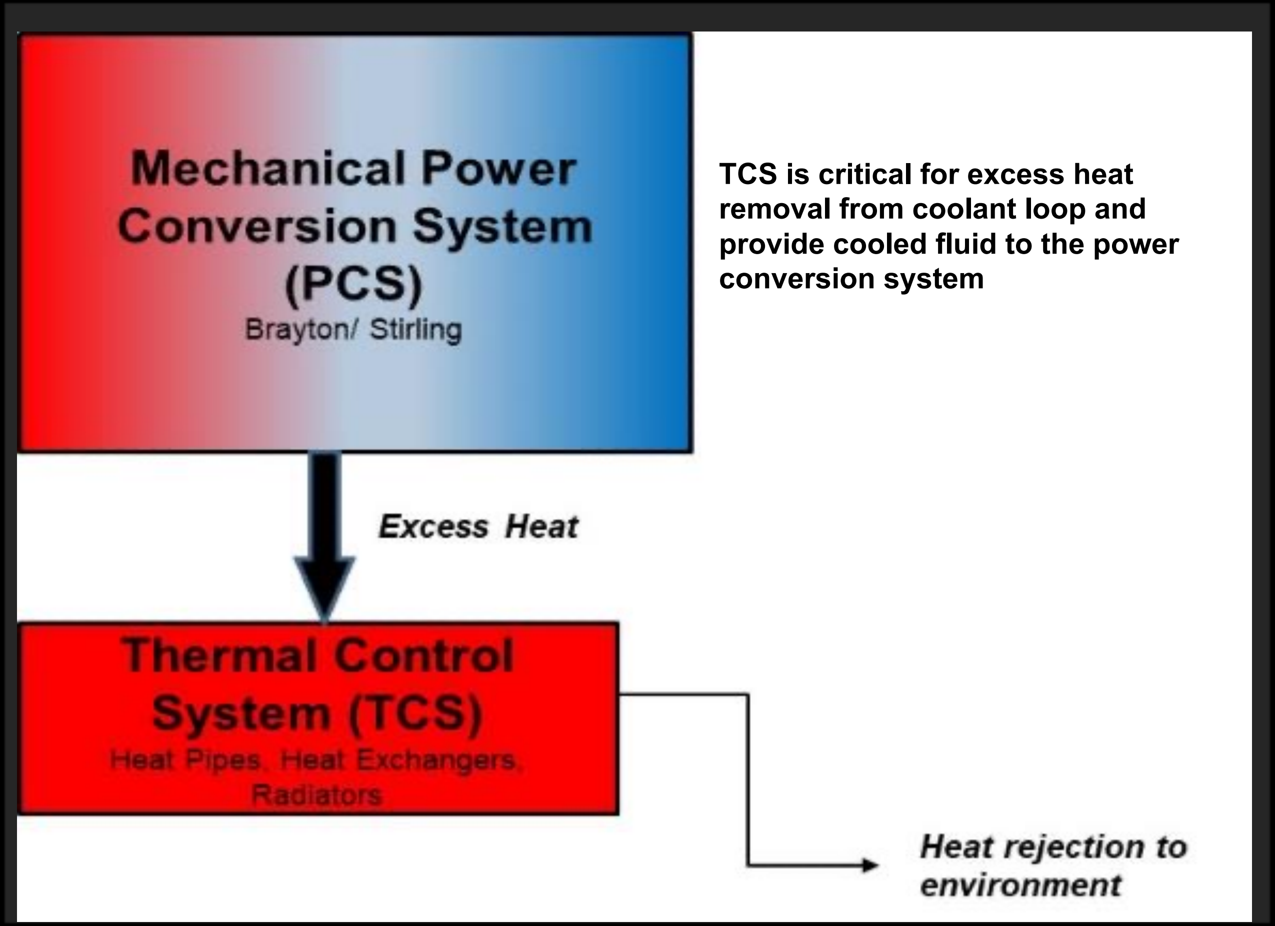
1.8 kWe generator: Two 1 kWe Stirling convertors mounted dual-opposed (Army Research Lab)



1 kWe Brayton SBIR

Heat Rejection System

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



Mechanical Power Conversion System (PCS)

Brayton/ Stirling

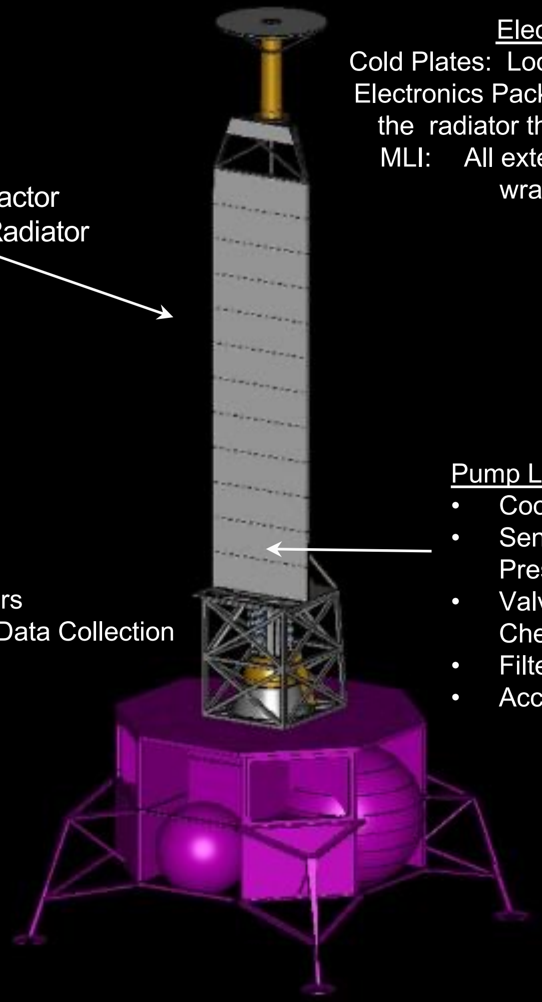
TCS is critical for excess heat removal from coolant loop and provide cooled fluid to the power conversion system

Excess Heat

Thermal Control System (TCS)

Heat Pipes, Heat Exchangers, Radiators

Heat rejection to environment



Electronics

Cold Plates: Located Beneath Each Electronics Package - connected to the radiator through heat pipes

MLI: All exterior surfaces are wrapped with MLI

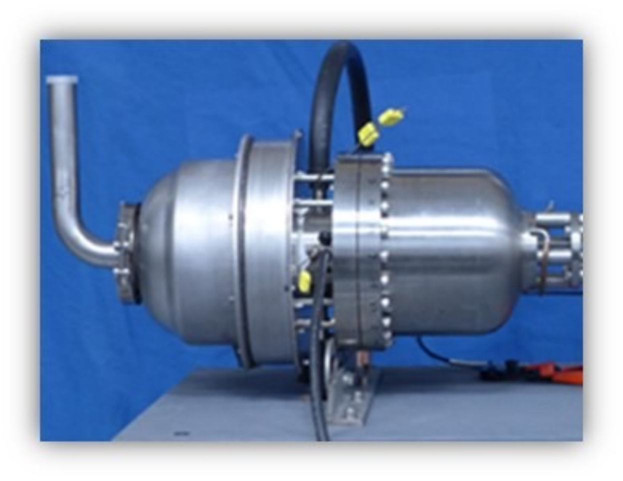
Fission Reactor Deployable Radiator

Additional Items:
- Heaters
- Thermal Sensors
- Controller and Data Collection
- Switches

Pump Loop Coolant System:
- Coolant Pumps
- Sensors: Temperature, Pressure & Flow
- Valves: Flow Control, Check, Pressure Relief
- Filters
- Accumulators

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
- Anciliary non-nuclear sub-systems (TRL 3-5)



1,000 watt Stirling

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

Coordination

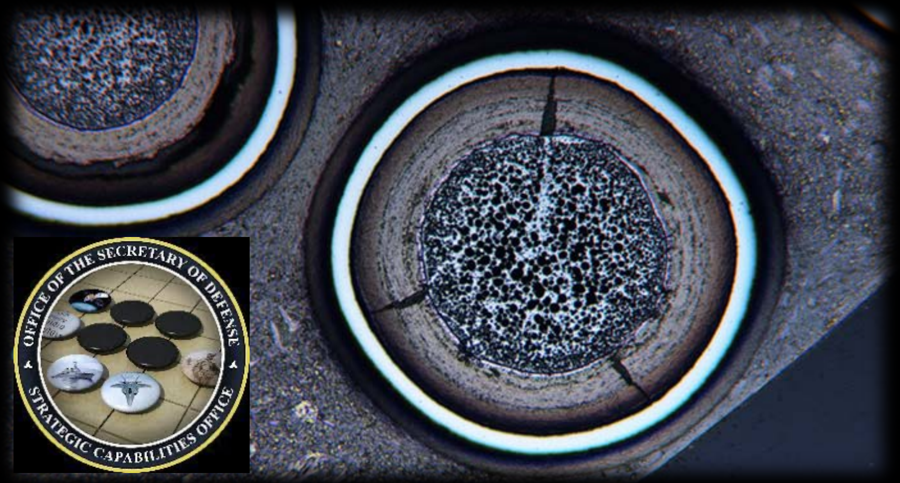
UNITED STATES SPACE FORCE
DEPARTMENT OF THE AIR FORCE
MMXIX

DEFENSE
INNOVATION UNIT

Leverage Commonality:

- ✓ Reactor Designs
- ✓ Fuel Production
- ✓ Reactor Materials
- ✓ Launch Regulations

Fuel



OFFICE OF THE SECRETARY OF DEFENSE
STRATEGIC CAPABILITIES OFFICE

Facilities

U.S. DEPARTMENT OF
ENERGY

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

Kilopower KRUSTY used 80 We Stirlings

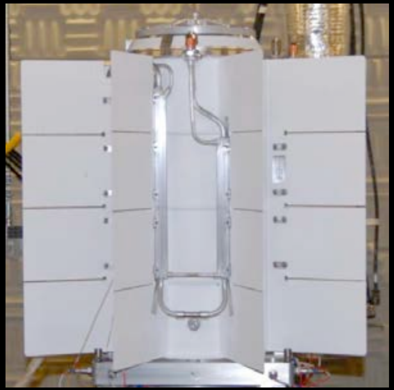
2. Closed-Cycle Turbo-Brayton – Space cryocoolers flown (TRL 9)

- 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)

2kW Mini-BRU power conversion unit

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

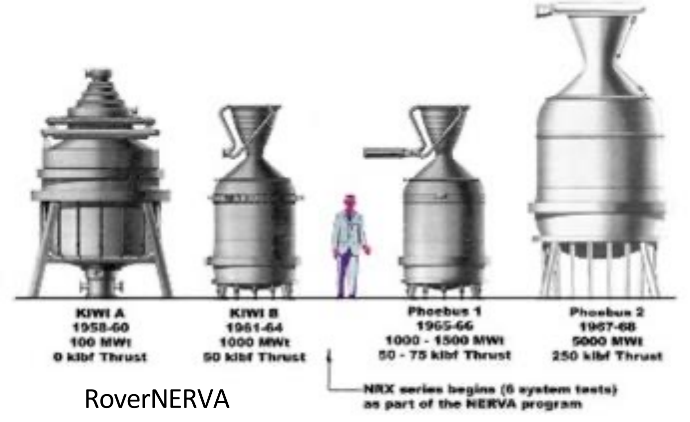


MMRTG

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



RoverNERVA

Small research reactors
University Research/TRIGA reactors

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

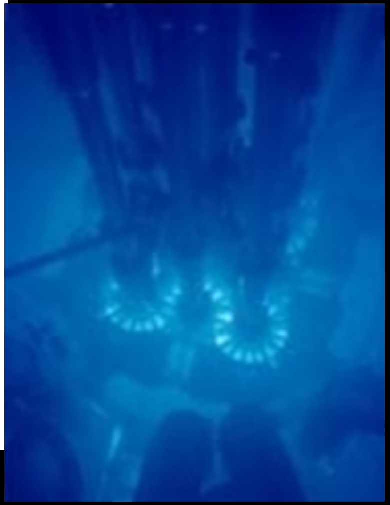
Commercial Light Water Reactors
1,371,000 kWe (3,800,000 kWt)

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

Research Reactors



SNAP 10A

Russian TOPAZ

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