National Aeronautics and
Space Administration

Fission Surface Power Project (FSP)

TDM Annual Review
March 3, 2022

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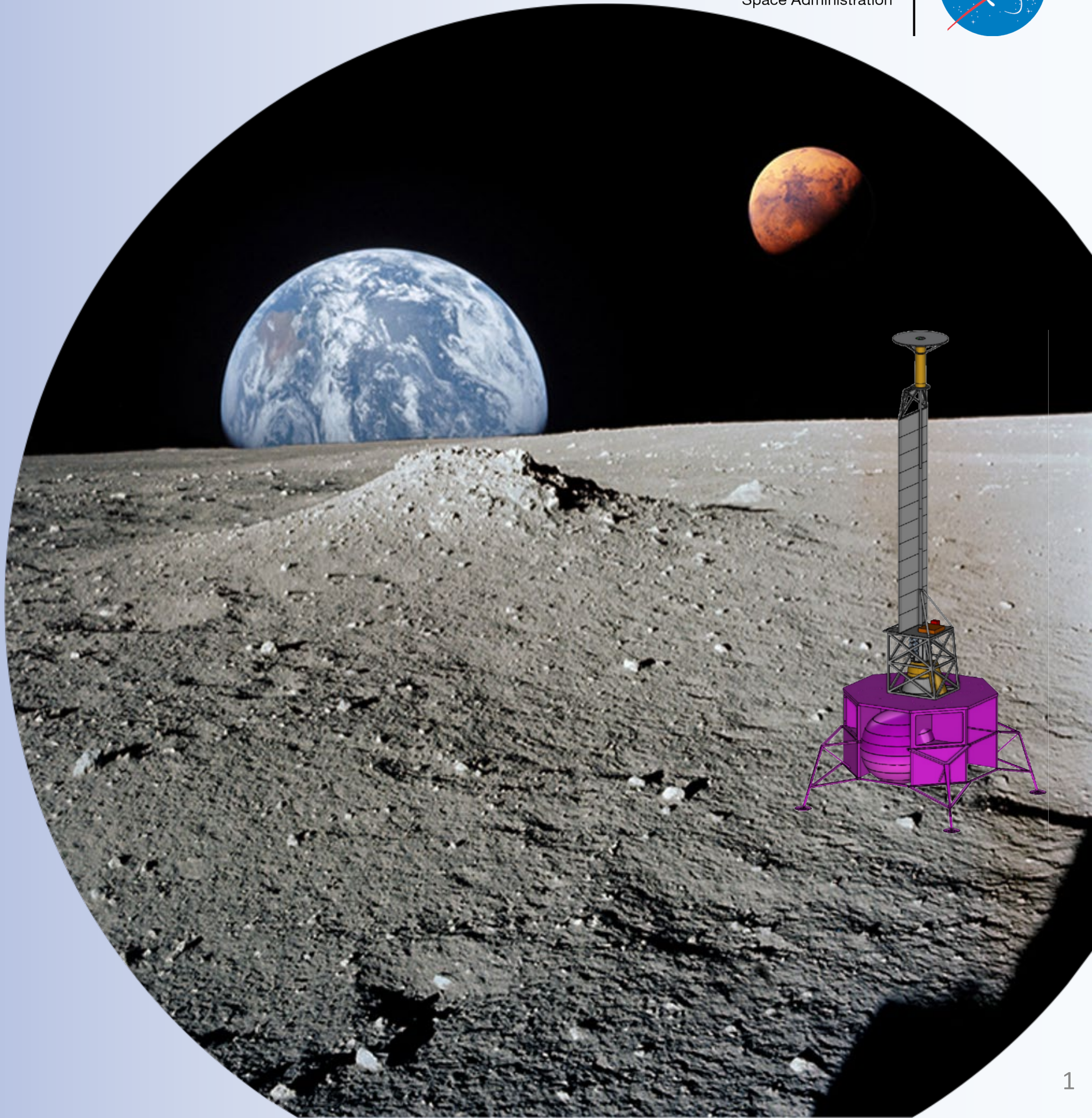

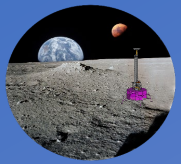

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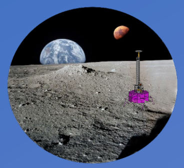
Fission Surface Power Project

NASA and DOE are Collaborating on the Development of a 40 kWe Fission Power System for a Demonstration on the Moon by late 2020s with Extensibility to Mars Missions

- Provides NASA a near-term opportunity to design, fabricate, and demonstrate a space nuclear fission system for a sustained lunar presence
- Will serve as a pathfinder for launching and operating other space fission systems
- Responsive to the 2021 STMD Strategic Technology Framework
  - "LIVE": FSP provides the capability for Sustainable Power on the Moon
- Responsive to Space Policy Directive – 6 (SPD-6) which details National Strategy for Space Nuclear Power and Propulsion Technology Development and Implementation

A Fission Surface Power System meets an identified need of the agency



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FSP Scope and Implementation

- The project's scope includes the fission power system flight hardware, cable to transmit power, user I/F voltage converter, all development hardware and a one-year demonstration
  - Develop the system for a 10-year life, support sustainable lunar operations
  - It does not include the Lander, Launch Vehicle, Rover, Cable Cart that places cable, nor Operations beyond one year
- The Project is a collaboration with DOE and their Federally Funded Research & Development Centers
  - DOE has designated Idaho National Laboratory to manage the system design and development contracts
  - Los Alamos National Laboratory provides subject matter expertise for reactor design
- The project's approach is to:
  - Utilize government subject matter experts to generate a reference design
  - Engage industry for the FSP system design and development
  - Plan and execute government-led technology maturations
- The Project is a 7120.8 technology demonstration that will transition to a 7120.5 flight project

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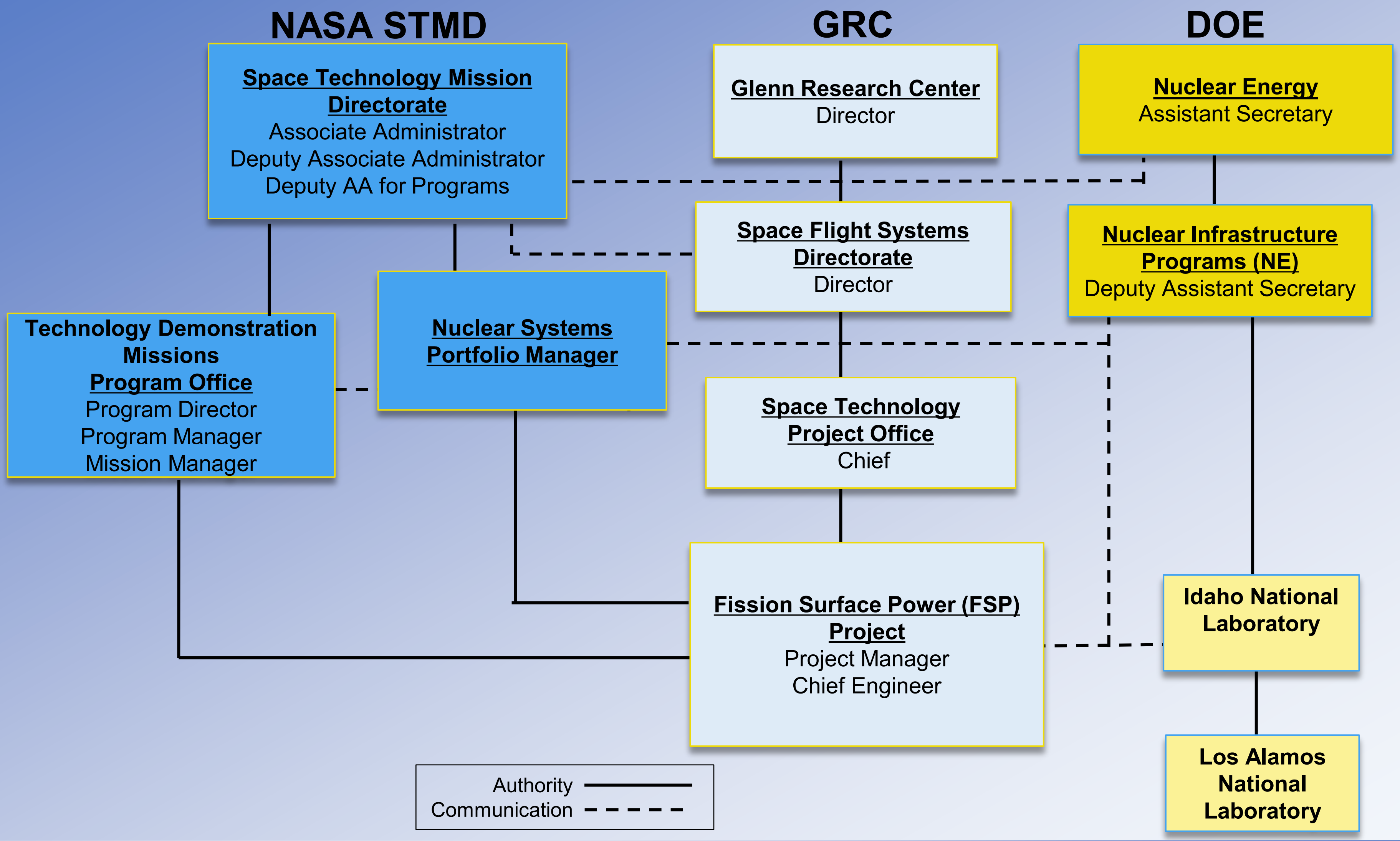
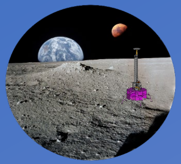
Fission Surface Power Interagency Team





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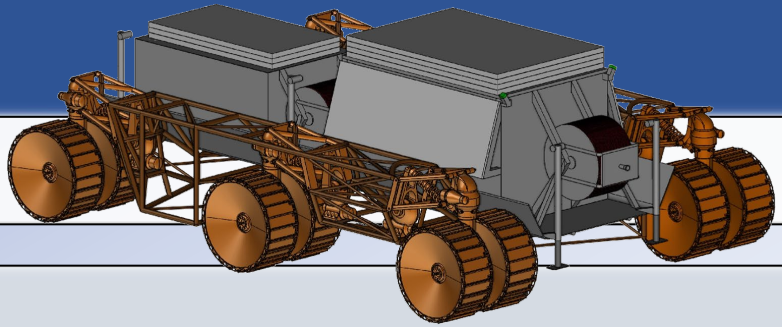
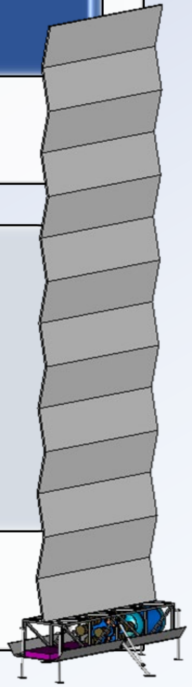
Project Accomplishments

Conducted Surface Power System Design Assessments

- 10 kWe Transportable System
- 40 kWe Transportable System
- Focused Trades and Assessments





Continued Industry Engagement

- System Design RFP
- PCS Sources Sought Notice

System Concepts & Trade Studies

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The Fission Surface Power project, GRC CPOMPASS Team, Los Alamos National Lab collaborated to complete system level trades

Objectives

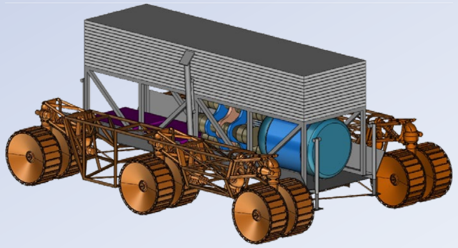
- Assess 10 kWe transportable and 40 kWe transportable system options, including reactor design, power conversion system concepts and thermal control
- Assess power transmission options; estimate reliability for various configurations

Purpose

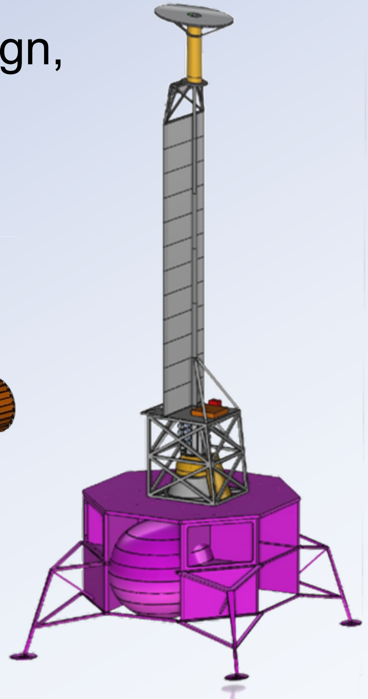
- Inform requirements feasibility and make government a smart buyer
- Provide identification of gaps, reliability drivers, and failure impacts

Driving Requirements

Power Level: 10 kWe and 40 kWe (EOL) at end user
Transportability: Operable from the lander, or removed from lander and transported
Mass Requirement: 4000 kg and 6000 kg, respectively
Launch Date: 2029



Deployable Reactor



Reference 10kWe Concept

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10 kWe Transportable Fission Power System

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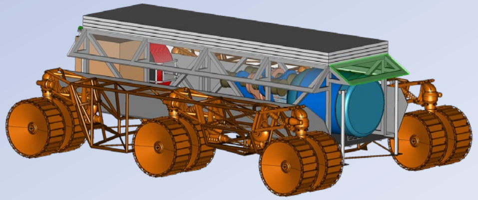
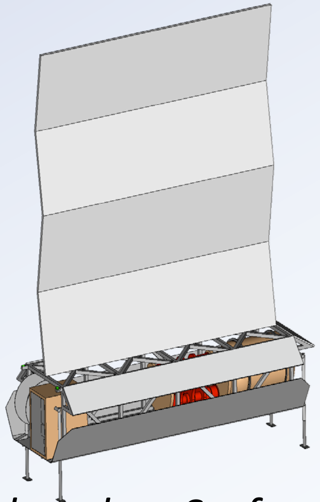
- Purpose: Develop a transportable 10 kWe Lunar Fission Surface Power System Concept
- The power system and rover are integrated and launched together; Lander deploys to the surface
- The rover is based on the pressurized rover and skid-based off-loadable cargo concepts
  - Includes two pallets: Power system, and cable with down-converter
- Operationally, use terrain to reduce radiation and shielding
- Power: 10 kWe reactor with a 3km cable to users
  - Six, 1.7 kWe Stirlings; LEU Moderated Reactor
- Thermal: Deployable radiator 40 m^2
- Mechanical: Deployable racks to lift FSP pallet off the rover
- Communications: Shielded Ka-Band link to Gateway
- Element Dry Mass (Basic + MGA + Margin) is 4200 kg (draft RFP goal was 4000 kg)



As stowed on Lander



Deployed on Surface

A 10 kWe Surface Power System is Feasible

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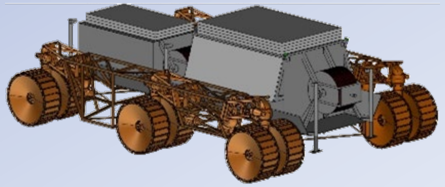
40 kWe Transportable Fission Power System

Approach:

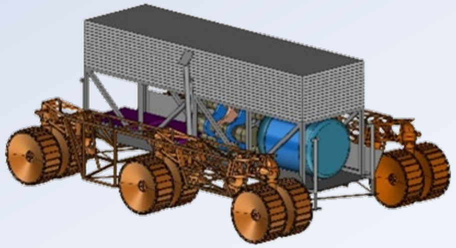
- ❑ Lander: Provides transit and delivery to lunar surface (up to 12,000 kg capability); deploys to the surface
- ❑ Transportability: Starting Point is a 6-wheel Pressurized Rover chassis



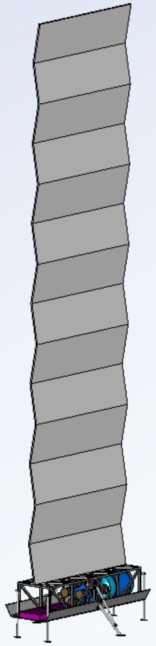
Controller and Converter Packages

Power System Concept Results (COMPASS):

- ❑ The system is separated into 3 packages: Power system, Controllers, and 120 V Converter
- ❑ Power: 40 kWe reactor with 1 km cable to users, 50m cable from reactor package to controller package
- ❑ Reactor Package:
  - Power conversion: Four - 6 kWe Stirling pairs
  - Deployable Radiators: 133 m^2 radiator for Stirlings, sized for polar operations
  - Shielded Ka-Band link; Shielded controllers and sensors for reactor
- ❑ Controller Package: Stirling controllers, spool, cable and 15 m^2 radiator
- ❑ Converter Package: High voltage to 120 Vdc converter and radiator, cable & spool
- ❑ Total FSP Mass 10,000 kg (Basic + MGA + Margin)



Reactor Package



Reactor Package

A 40 kWe Transportable System is Feasible if Mass Target is Increased

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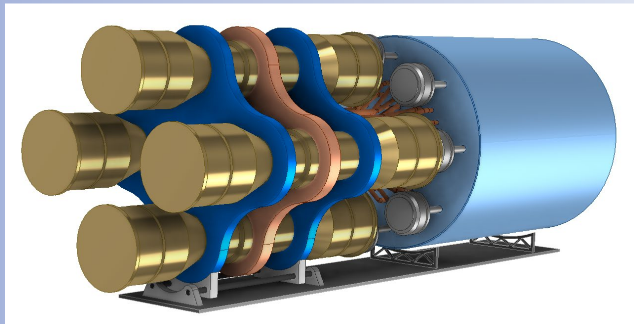
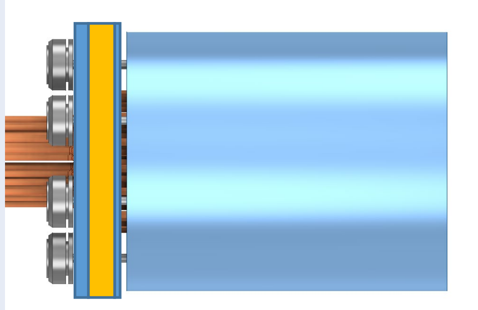
Fission Surface Power Reactor

- ❑ Reactor design concept was updated; materials, dimensions, masses were determined
- ❑ Thermal Power: 250 kWth (nominal operating power) and 500 kWth (design maximum), to be refined
- ❑ Fuel: HALEU Uranium Nitride Pellets
    - Control drums utilized; control and instrumentation recommended for maturation
- ❑ Moderator: Yttrium Hydride (YH)
    - Requires work to mature the technology
- ❑ Heat Transfer: Sodium Heat Pipe





Note: Dimensions, materials, masses, & other details deleted for this public review.

LEU Moderated Reactor Design is Feasible; Would Benefit from Technology Maturation

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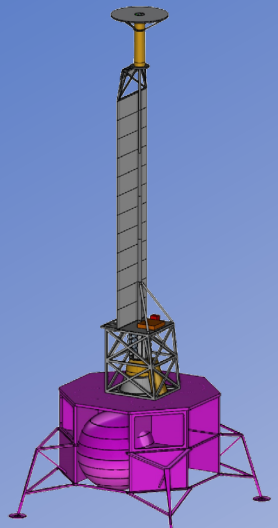
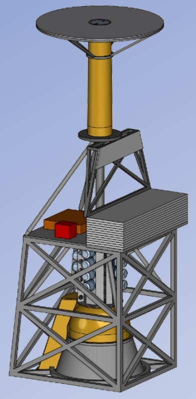
Evolution of Design Concepts

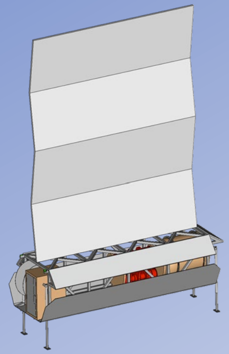
10 kWe, Stationary



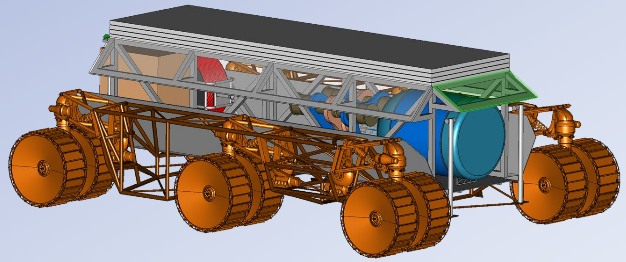
Vertical operational configuration



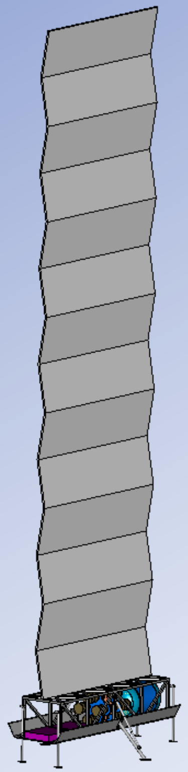
10 kWe, Transportable

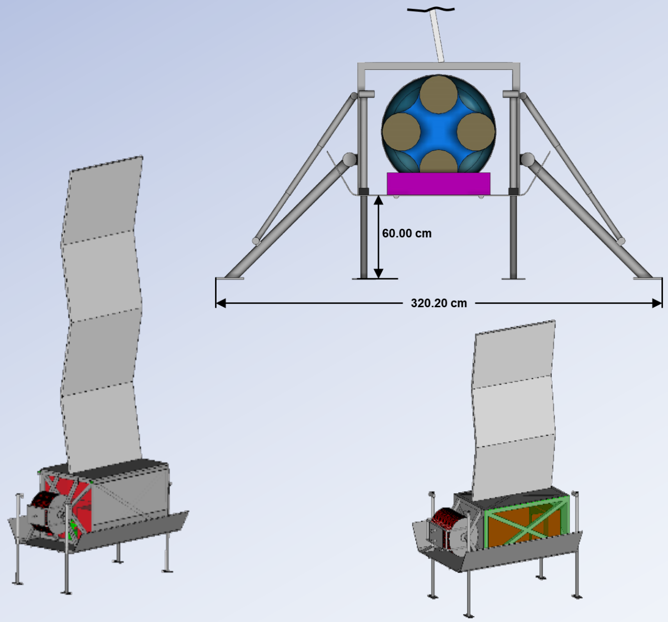


Horizontal operational configuration

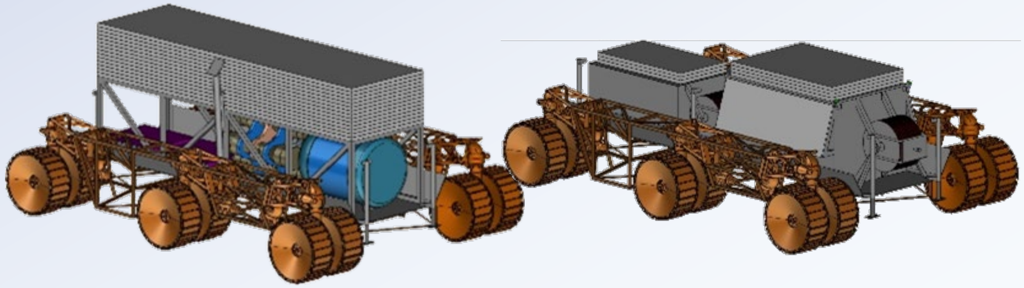


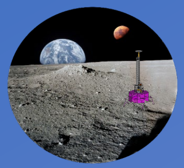
40 kWe, Transportable





Multiple horizontal packages





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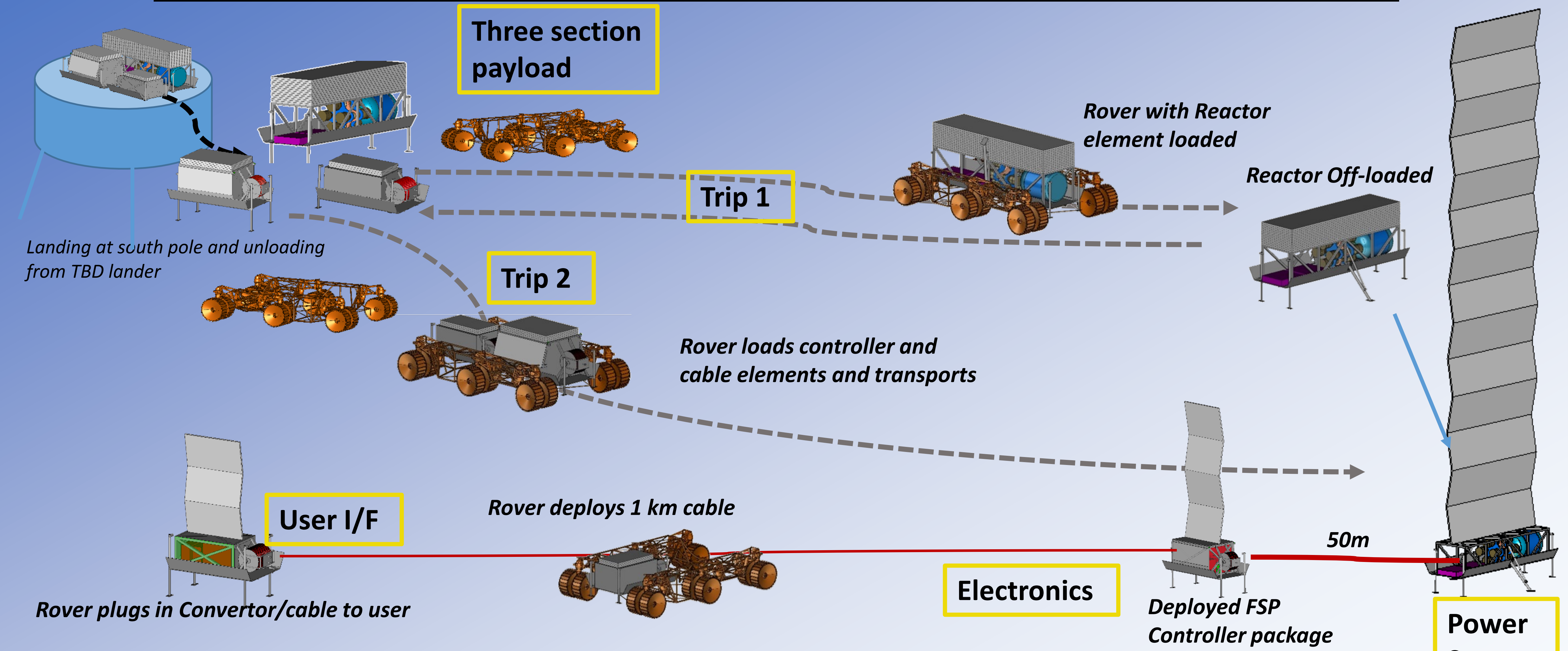
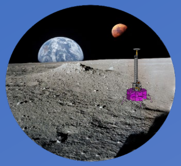
COMPASS 40 kWe Deployment Concept

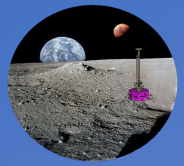


Note: The Industry Prime will determine the design and the deployment sequence



Lessons Learned – 40 kWe System

- **Increasing to a 40 kWe (from a 10 kWe) power system exceeds the mass goal**
- **Using the pressurized rover chassis to deploy the 40 kWe system should be possible BUT**
  - It now must be deployed as multiple separate pieces
  - Mass up to 9000 -10,000 kg should be ok for the rover chassis
- **Definition is needed of the lander's deployment mechanism**
- **By laying down the reactor and placing the control electronics 50m away** directional shielding can be optimized and reduce/eliminate added shielding for the control electronics
- **Modifying the design for equatorial use** requires significantly more (60%) radiator area and different radiator configurations for all elements
- **On-Lander option:** Assuming the lander could be placed >1 km from the crew, the reactor pallet could be kept on the lander with only the controller and converter pallets unloaded and deployed



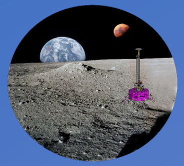
Trade Studies on Power Transmission

- **What are these trades?** – Alternates to a traditional cable were assessed for potential mass savings, operational simplicity and distance to user. Various configurations were assessed for reliability

- **10 kWe Power Transmission Medium**
  - **Power Beaming**
    - Mass efficient at low power levels or long distances; system is ~30 times the mass of insulated cable at 3 kV (400 kg)
  - **Superconducting Cables**
    - Has reliability risks; dedicated power system required for cryocoolers; significant mass penalty (~3.7x cable mass)
  - **Carbon Nanotube (CNT) Rope**
    - Lighter than copper, but conductivity is 6-10 times lower; total mass benefit is negligible
  - **Metallic conductors** - Copper / Aluminum minimize system mass
    - Cable mass dependent on transmission voltage - with elevated voltage wire, mass can be minimized

- **AC vs. DC power transfer**
  - Development of radiation hardened high-voltage switches needed for DC, still trades favorably

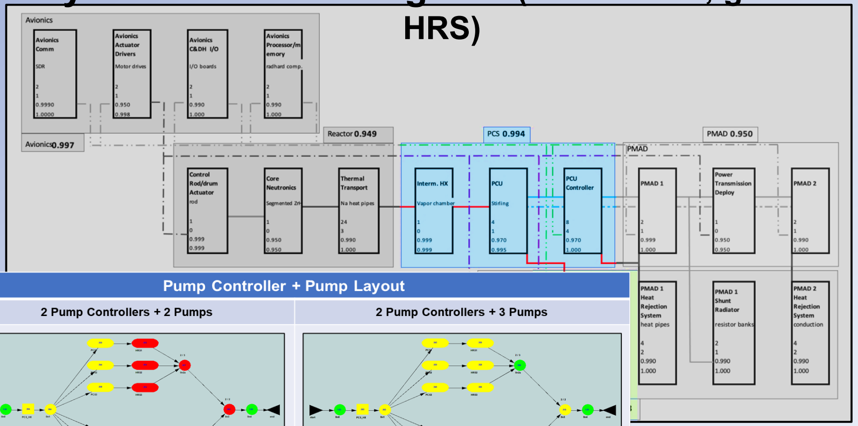
A metallic conductor cable and high DC transmission voltage trade favorably

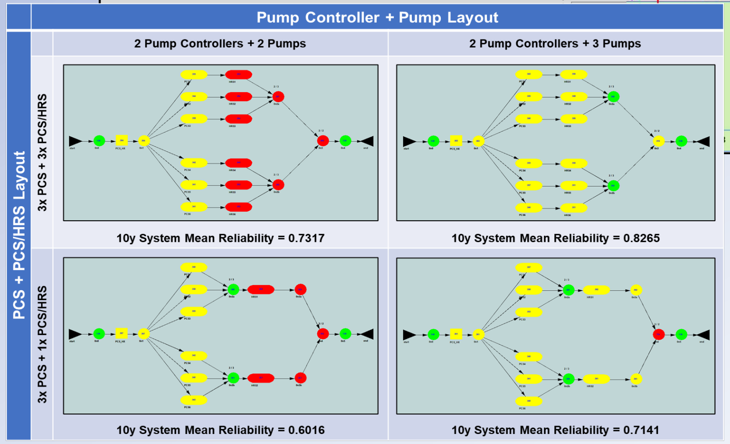


Reliability Assessment

- **Conducted a Reliability Block Diagram Configuration Study** of multiple case study options for power conversion system and heat rejection. The purpose was to assess different configurations and determine potential reliability
- **Developed System Interface Diagrams for various configurations**
- **<u>Results:</u>**
  - Multiple PCSs configurations are feasible
  - PCS: Highest Mean Reliability at 1 year is 99%
  - PCS: Highest Mean Reliability at 10 years (end of life) is 90%
  - PCS + Thermal Control: Highest Mean Reliability at 10 years (end of life) is 82%

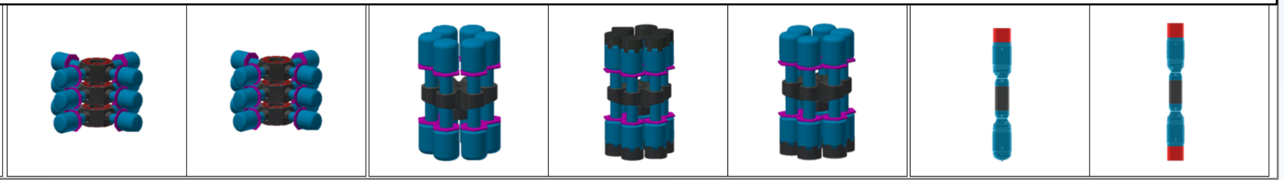
System Interface Diagram (blue is PCS; green is HRS)





PCS Case Study Options (multiple options exist and are feasible)

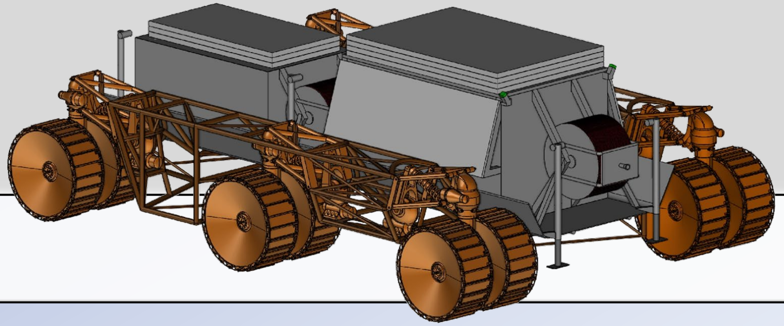
CAD Graphic



Project Accomplishments

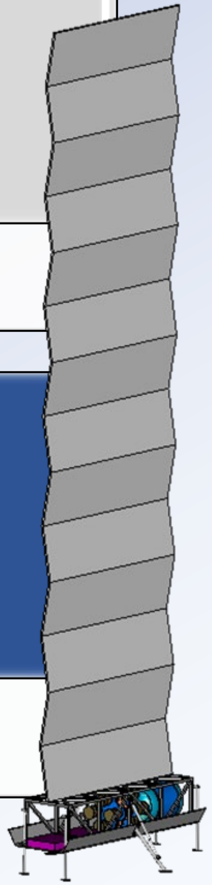
Conducted Surface Power System Design Assessments

- 10 kW Transportable System
- 40 kW Transportable System
- Focused Trades and Assessments



Continued Industry Engagement

- System Design RFP
- PCS Sources Sought Notice



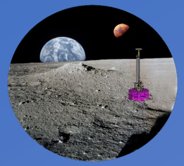
Industry Engagement

GRC - Power Conversion System (PCS) Technology Maturation Procurement

- Request for Information / Sources Sought Notice (RFI/SSN): Released for the development of a 1.2 kWe to 5 kWe Stirling-based PCS -and- Technology Readiness Level (TRL) 6 by contract end in mid-CY 2024
- Eight responses received; cost estimates significantly exceeded expectations
- Addressing high-cost estimates received; considering to focus to Stirling controller only

FSP System Design and Development

- The FSP system will be acquired via 2 major procurement phases
    - Status as of March 3rd: the project is beginning Phase 1; awaiting Phase 1 proposals
- Separate procurement Phases will accomplish integration with the lander, and lunar operation



Solicitation Efforts for the FSP System

PHASE 1 → Award Industry Contracts for initial System designs; managed by Idaho National Lab

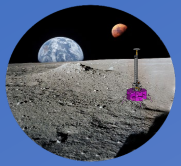
- Proposals due March 4th: Three contracts; 12-month period of performance, $5M max each
- Objective: Provide a system point design, estimate costs, schedule, and challenges for the flight design, build and test (Phase 2). Show there are viable design options and inform Phase 2 procurement
- Deliverables include: Design Document, System and Subsystem Requirements and Verification, Interface Requirements, Mass Properties Report, System and Subsystem Drawing Package, Technology Readiness Assessment, Cost and Schedule Estimate for Phase 2

PHASE 2 → One INL-managed Contract → Estimated start in Q2 FY24

- Objective: Design, build, development units and flight unit. Perform nuclear ground testing of non-flight FSP unit; Build & Deliver space-qualified FSP Flight System
- The Phase 2 Industry contract will be new and independent from the Phase 1 contracts
- Hold a NASA Mission Concept Review/System Requirements Review and an Acquisition Strategy Meeting prior to releasing RFP 2

PHASE 3 and beyond → NASA-managed Contract

- Industry contract for integration & testing the FSP system with the Lander
- Launch support
- 1-year Demonstration on the Moon



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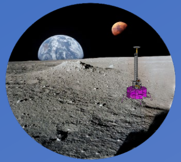
FY22 Look-Ahead

- ❑ Initiate design contracts for a 40 kWe system (Summer 2022)
- ❑ Initiate nuclear technology maturation (Summer 2022)
  - The following are design-neutral, low-TRL components that have no heritage or relevant industry expertise:
    - Moderator and Core Materials Testing, Evaluation and Maturation
    - Instrumentation and Control System
    - Shielding Materials and Architectures
- ❑ Power Conversion System Technology Maturation Fall (2022)
  - Focus on Stirling-based systems
- ❑ Refine government concepts and perform trades (2022)
  - Refine the reactor (including shielding) and power conversion design, re-assess Brayton
  - Explore different heat transport and radiator deployment options



Significant Issues/Risks to the Project

- **<u>Ship to Launch Site in 2028 is Aggressive</u>** *(Project Risk 14)*

  Current plan gives Phase 2 Flight Hardware contractor less than 5 years, includes: Completing nuclear & PCS tech mat, nuclear ground test unit development and test campaign, flight hardware development, acceptance testing

  - ***NASA will receive Industry's initial, order of magnitude estimates after Phase 1 is completed <u>in Q3 FY23</u>***

- **<u>Required Nuclear Test Facilities Unknown</u> – Potential Cost & Schedule Impacts** *(Project Risk 10)*

  Ground nuclear tests/demo are required. There is uncertainty if existing facilities are adequate for assembly and test. May include facilities at the launch site. Project team is assessing facilities capability

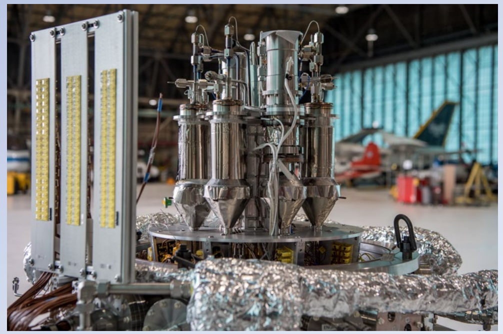
- **<u>Nuclear-related Project Risks</u>** *(Project Risk 14)*

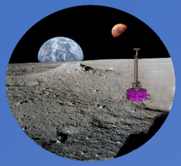
  Risk #17: Control Instrumentation for Reactors – identified as critical gap, even per RFI responses; Nuclear Tech Maturation on critical path of notional project schedule

  Risk #19: Immature Hydride Moderator Technology – numerous physical & mechanical data identified as critical needs, even per RFI responses; Nuclear Tech Maturation on critical path of notional Project Schedule

Transition into TDM

- **The Kilopower project was part of the Game Changing Development program**
- **Kilowatt Reactor Using Stirling Technology (KRUSTY), was part of NASA's larger Kilopower project**
  - KRUSTY was designed to test a 1 kWe prototype fission reactor coupled to Stirling engines
  - KRUSTY employed an HEU, fast spectrum design
  - A 28-hour full-power nuclear experiment performed in March 2018
  - Demonstrated Stirling engine performance and production of electrical power from eight heat pipes embedded in the core
- **The team simulated power reduction, failed engines and failed heat pipes, showing that the system could continue to operate and successfully handle multiple failures**
- **Very successful test!**





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Transition/Infusion Plans

Technology Maturation

- ❑ Make data available to Phase 2 contractor; they determine potential applicability to their design

Flight Hardware

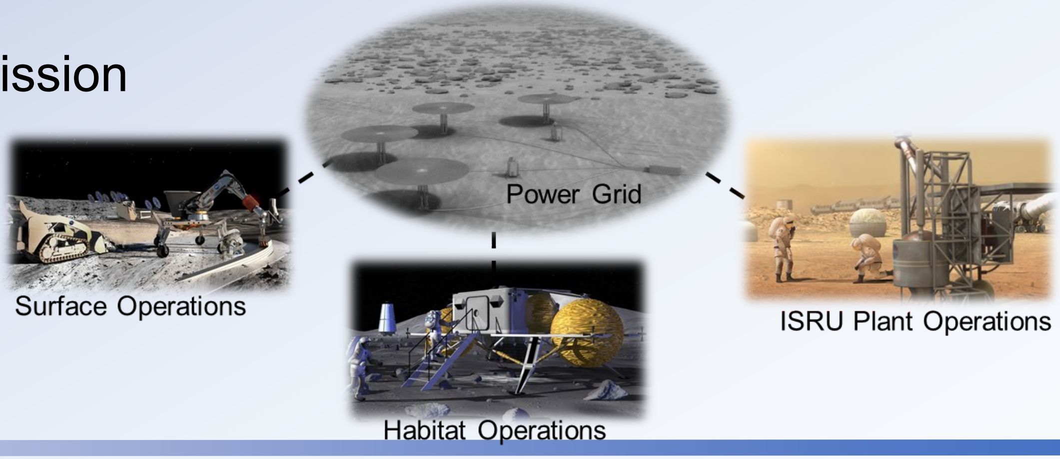
- ❑ 2029 Mission to the Moon for 1 year demonstration; validate functionality & reliability
  - Project team communicates with Lunar Architecture Team

Artemis

- ❑ Operate on the Moon for 10 years; support surface operations, ISRU operations

Mars

- ❑ Adjust design for new environment, and build for Mars mission
  - Project team communicates with Mars Architecture Team



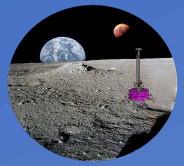
Summary

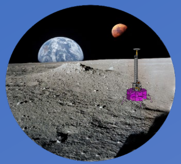
- ✓ Completed a government 10 kWe transportable Fission Surface Power Assessment → **Stirlings traded favorably, and reactor solutions meet system and operational requirements**

- ✓ Completed a government 40 kWe Fission Surface Power Assessment → **Concept requires multiple pallets on a lander to meet rover mass capacity and volume**

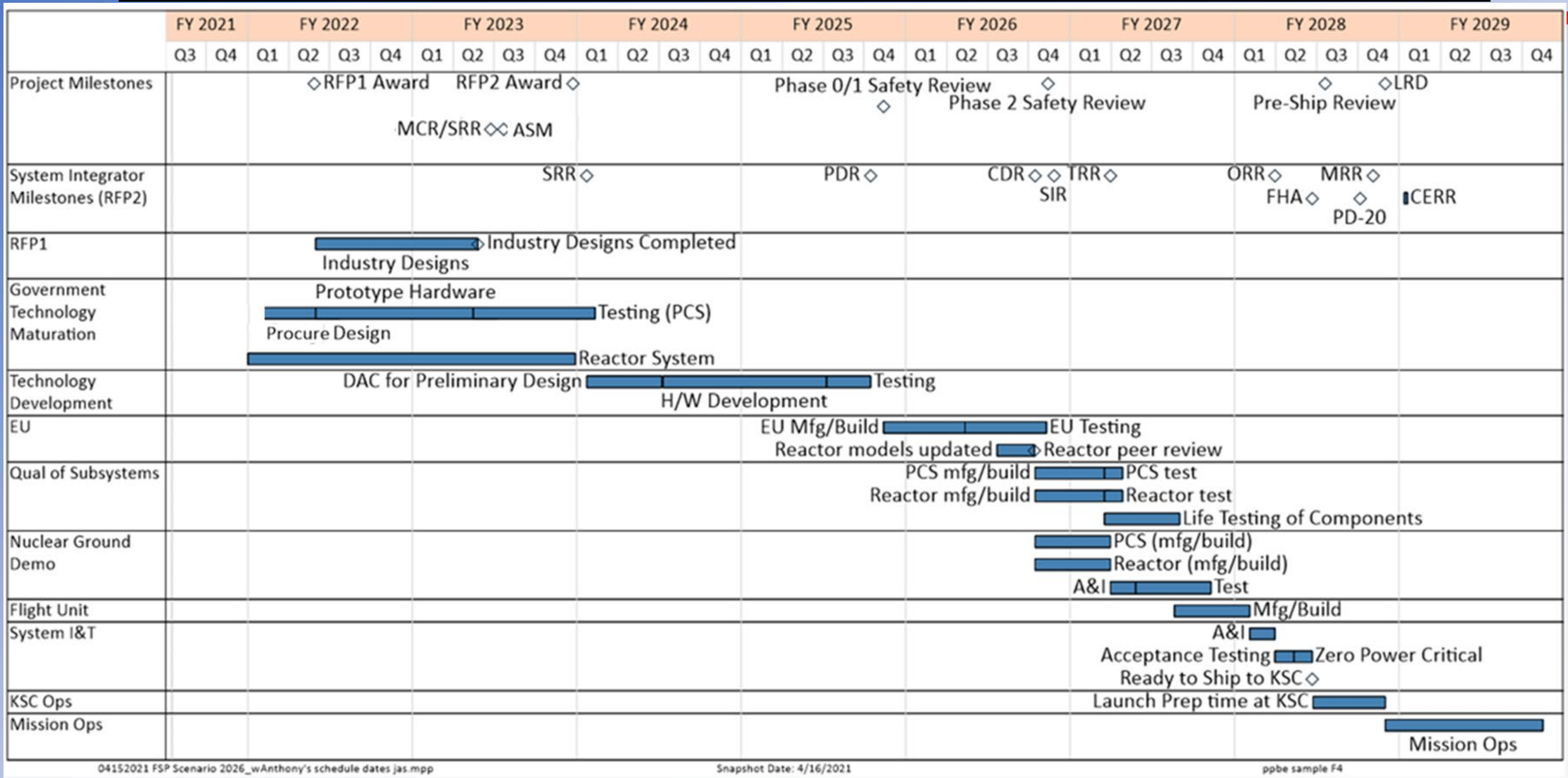
- ✓ Released RFP and awaiting proposals for three competing initial system designs→ **The designs will inform Phase 2 solicitation documents**

Project's Priority is to Move Forward with Industry Contracts for 40 kWe Fission Surface Power System Designs





FSP Project – Notional Schedule for a 2029 Launch



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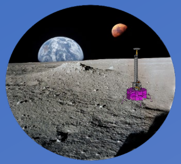

National Aeronautics and Space Administration

Requirements and Goals

	Title	Requirement Details
DR-1	**Power**	The FSP shall be designed to operate at a minimum end-of-life 40 kW_E continuous power output for at least 10 years in the lunar environment as detailed in Attachment A. Higher power ratings are desirable provided remaining DRs are satisfied.
DR-2	**Launch & Landing Loads**	The FSP shall be designed to withstand structural loads as detailed in Attachment B.
DR-3	**Radiation Protection**	The FSP shall be designed to limit radiation exposure at a user interface location 1 km away to a baseline value of 5 rem per year above lunar background.

DG-	Title	Goal Details
DG-1	**Volume**	The FSP should fit within a 4 m diameter cylinder, 6 m in length in the stowed launch configuration.
DG-2	**Mass**	The total mass of the FSP should not exceed 6,000 kg which includes mass growth allowance and margin.
DG-3	**Power Cycles**	As a safety feature, the FSP should be capable of multiple commanded and autonomous on/off power cycling.
DG-4	**User Load**	The FSP should be capable of supporting user loads from zero to 100% power at the user interface
DG-5	**Fault Detection & Tolerance**	The FSP should minimize single-point failure modes, should be capable of detecting and responding to system faults, and have the capability to continue providing no less than 5 kW_E under faulted conditions.
DG-6	**System Transport ability**	The FSP should be capable of operating from the deck of a lunar lander or be removed from the lander and placed on a separately provided mobile system and transported to another lunar site for operation.

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