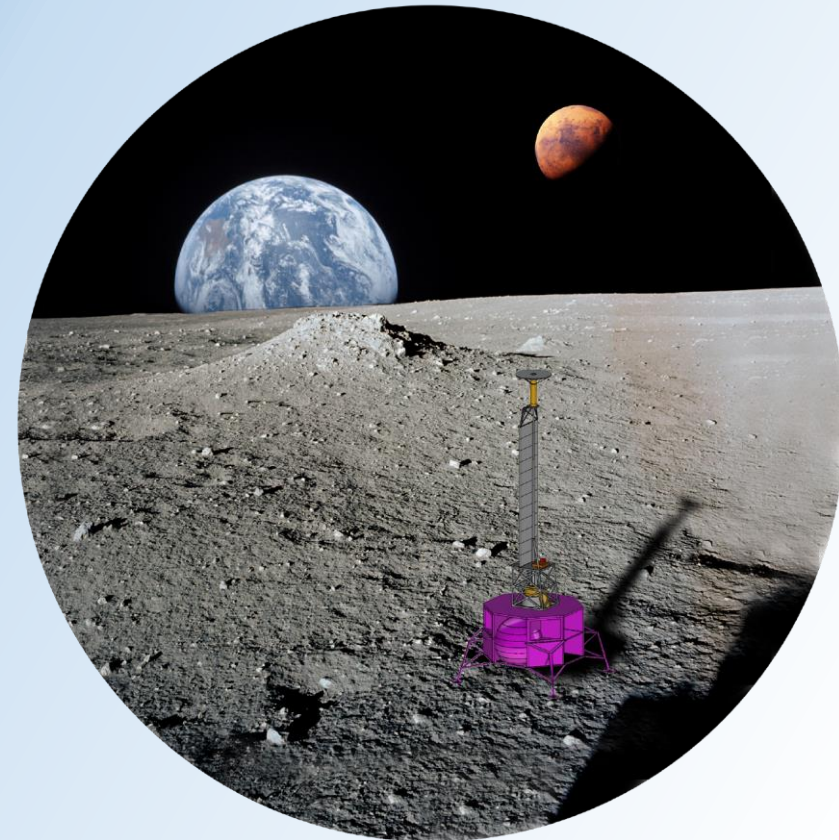


# Fission Surface Power (FSP) Project update

Interagency Advanced Power Group  
Annual Meeting

**August 23rd – 25th, 2022**

Christopher Barth, PhD (Presenter), David Pike,  
Steve Oleson, NASA Glenn Fission Surface Power and COMPASS Teams  
NASA Glenn Research Center, Cleveland, OH , 44135





## ❑ Project Overview

- Project goal
- Scope, implementation, and team structure

## ❑ System Studies

- Goals and history
- Review of 40 kW mobile reactor concept
- Power transmission

## ❑ Supporting SBIRs in progress

- ThermAvant Technologies, LLC - High temperature heat rejection
- Peregrine Falcon Corporation - Consolidation of heat pipes within a U-8Mo Core
- Creare - Brayton converter for nuclear electric propulsion
- Sigma Technologies – NanoLam capacitors

## ❑ In-house technical activities at GRC

- Integrated heat pipe-Stirling convertor test
- Simplified Stirling control
- Stirling simulators



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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**

- 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**

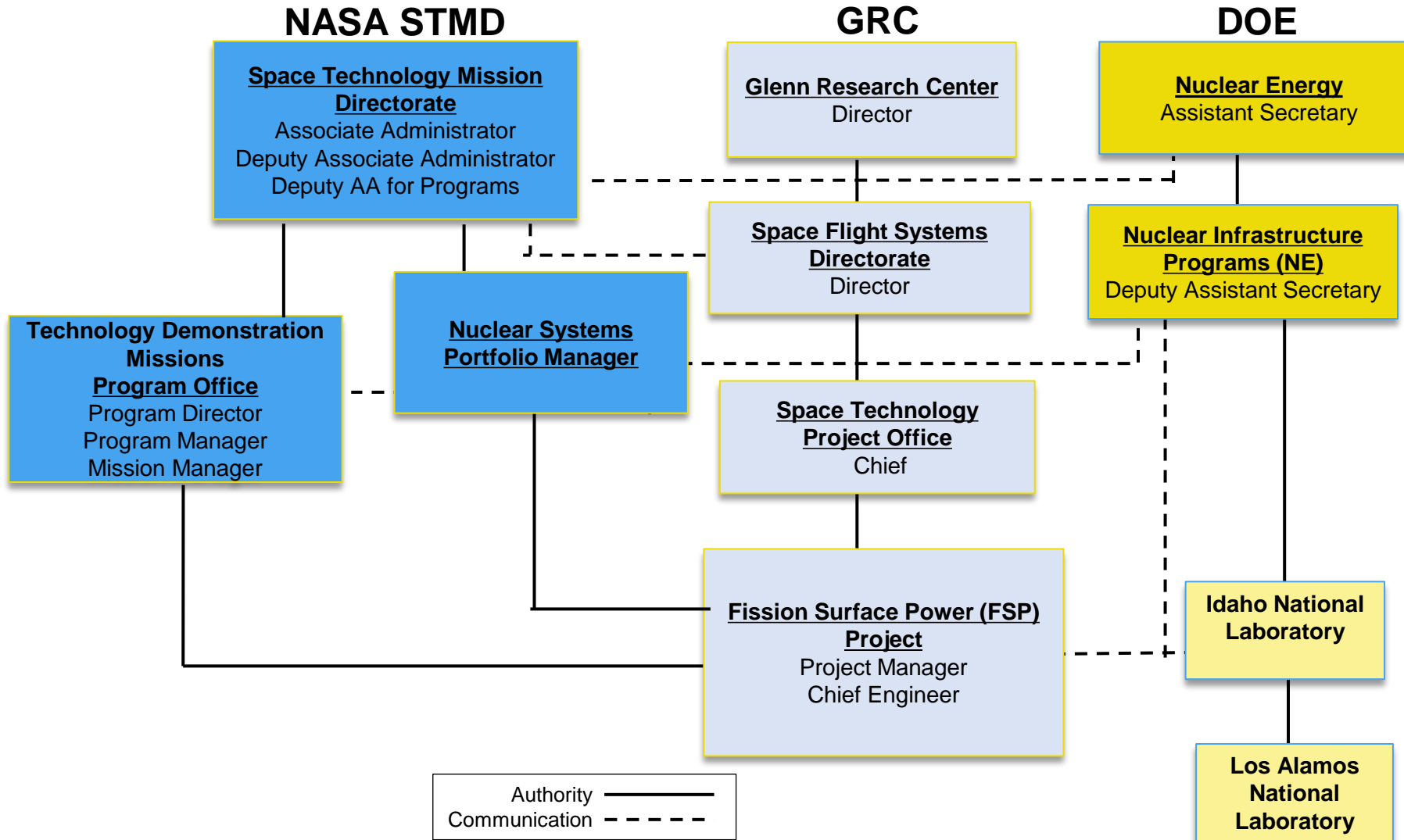
# FSP Scope and Implementation

---



- ❑ **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
  - Plan and execute government-led technology maturation
  - Engage industry for the FSP system design and development
  
- ❑ **The Project is a 7120.8 technology demonstration that will transition to a 7120.5 flight project**

# Fission Surface Power Interagency Team



Authority ———  
Communication - - - -



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# System Concepts & Trade Studies



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

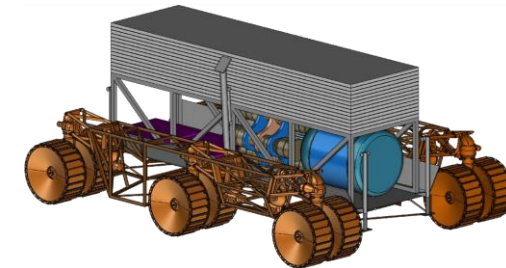
## Driving Requirements

**Power Level:** 10 kWe and 40 kWe (EOL) at end user

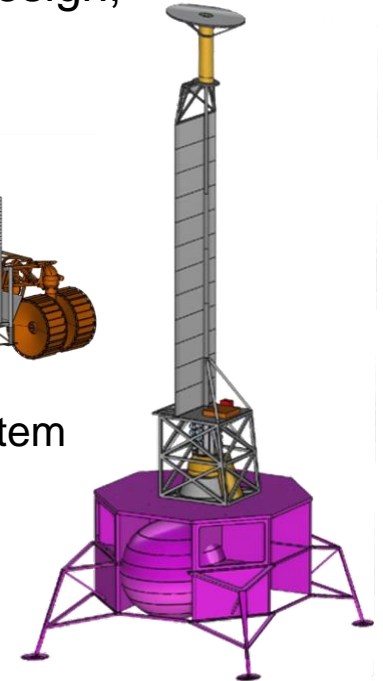
**Transportability:** Operable from the lander, or removed from lander and transported

**Mass Goal:** 4000 kg and 6000 kg, respectively

**Launch Date:** 2029



Transportable System



Reference 10kWe Concept

# GRD Top Level Requirements/Design Goals

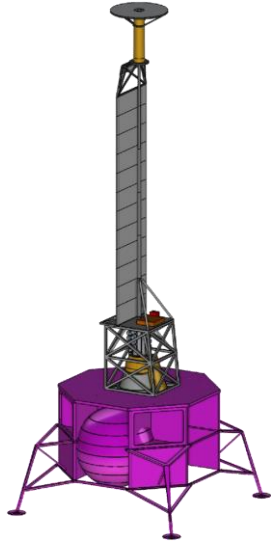
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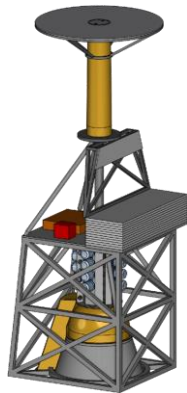
- ✓ 40 kWe for 10 years on Lunar South Pole
  - ✓ *Low Enriched Uranium (LEU) reactor includes shielding to keep radiation to 5 Rem/year at 1 km*
  - ✓ *Stow in cylinder, 4m diameter x 6m length*
  - ✓ *Approximately 10,000 kg landed mass required – (Exceeds mass allocation)*
  - ✓ *Commanded and autonomous on/off*
  - ✓ *Up to 100% shunting of power*
  - ✓ *Single fault tolerant with a minimum provided power of 5 kWe*
  - ✓ *Operable from lander deck OR be removed and transported by a separate mobile system (focus of study)*
- 
- “Fission Surface Power (FSP) Project Statement of Work (SOW) No. 18960 Revision ID: 0,” sam.gov (2021).
  - S. Oleson, et al. “A Deployable 40 kWe Lunar Fission Surface Power Concept,” Nuclear and Emerging Technologies for Space (NETS), Cleveland, OH, May 8-12, 2022

# Evolution of Design Concepts

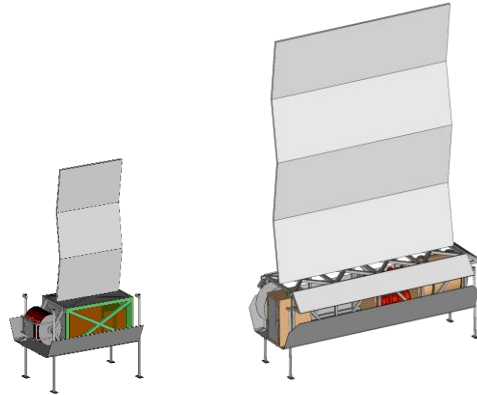
## 10 kWe, Stationary



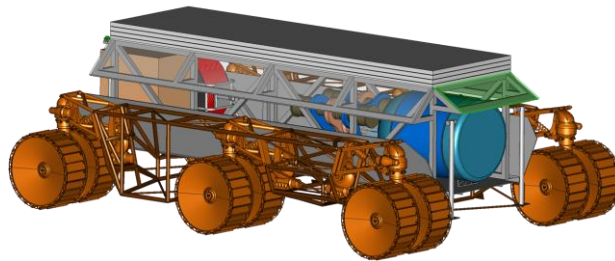
Vertical operational configuration



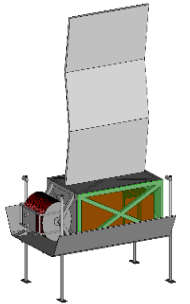
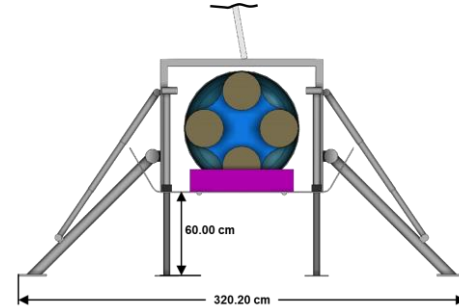
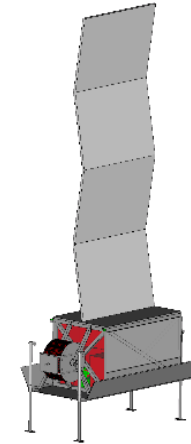
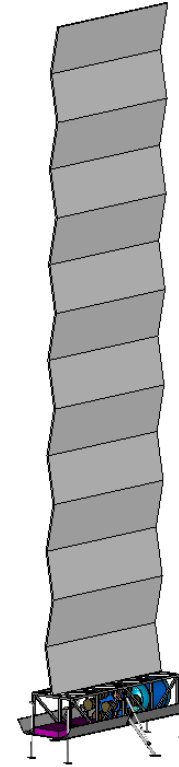
## 10 kWe, Transportable



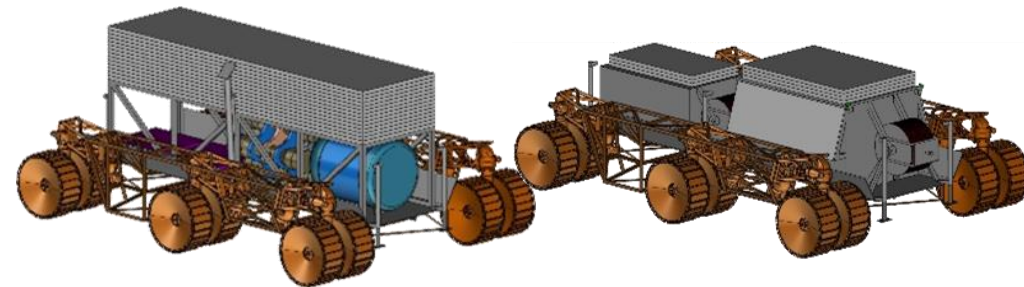
Horizontal operational configuration



## 40 kWe, Transportable



Multiple horizontal packages



# Space Exploration Vehicle Concept

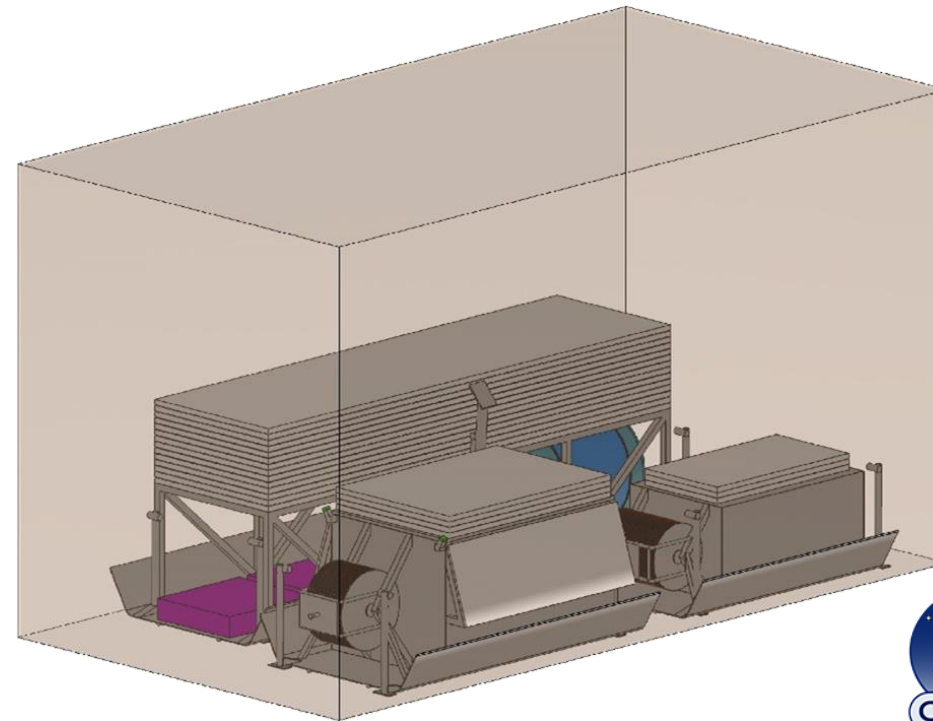
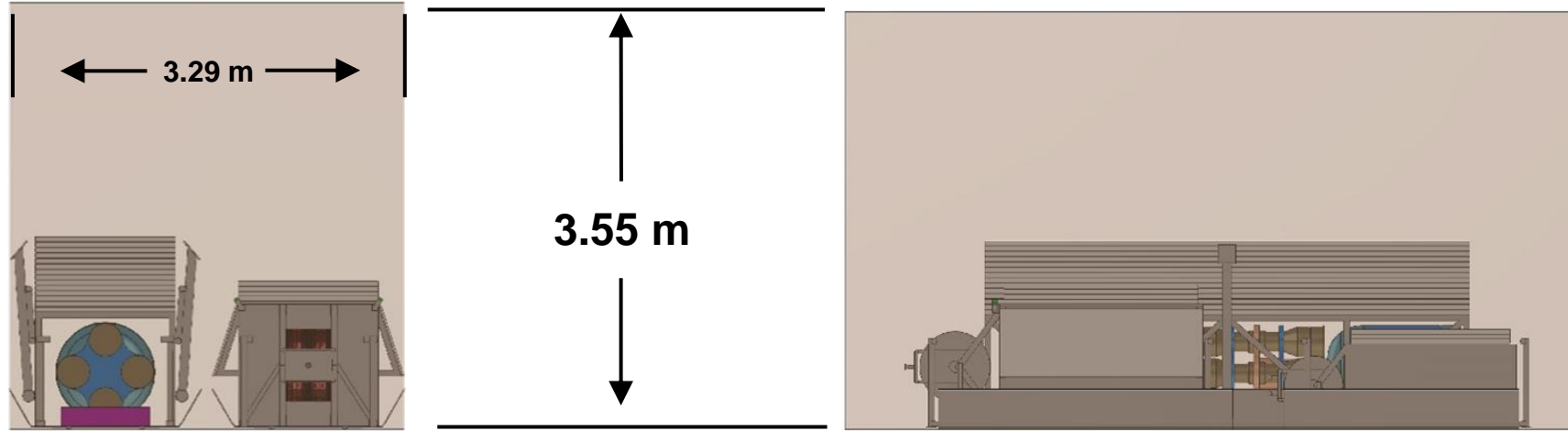
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*This government reference design is based on the premise of reactor mobility and the use of the proposed Space Exploration Vehicle (SEV).*



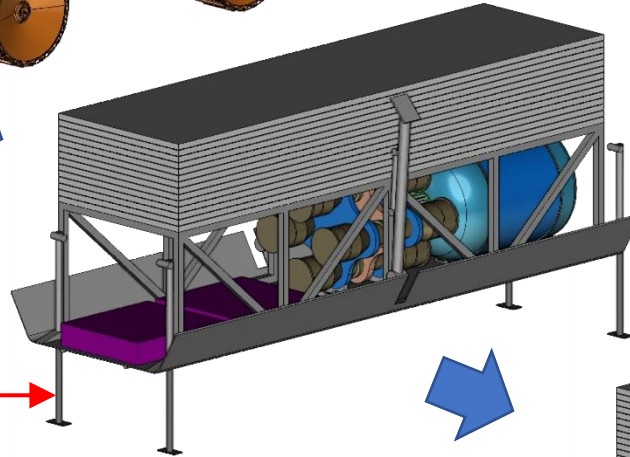
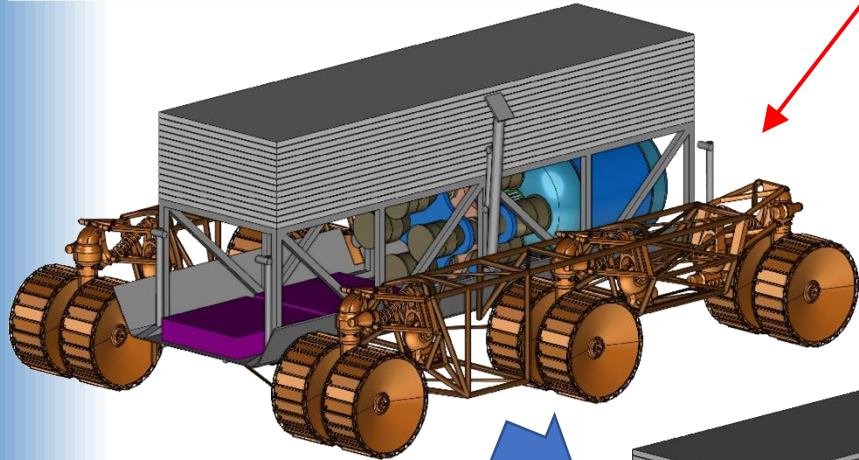
# FSP 40 kW Concept in Lander Envelope



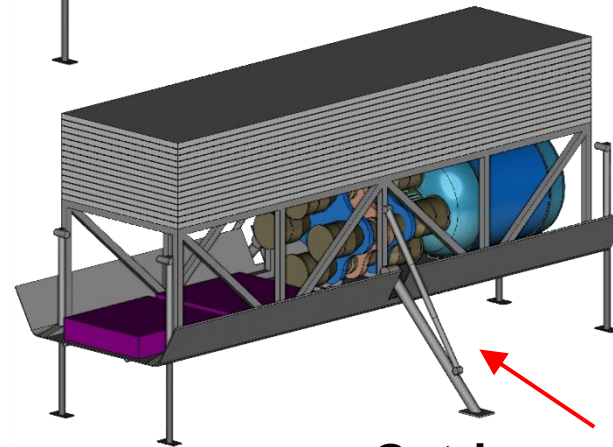
# Reactor System Deployment



NASA Space Exploration Vehicle (SEV) Pressurized Rover chassis

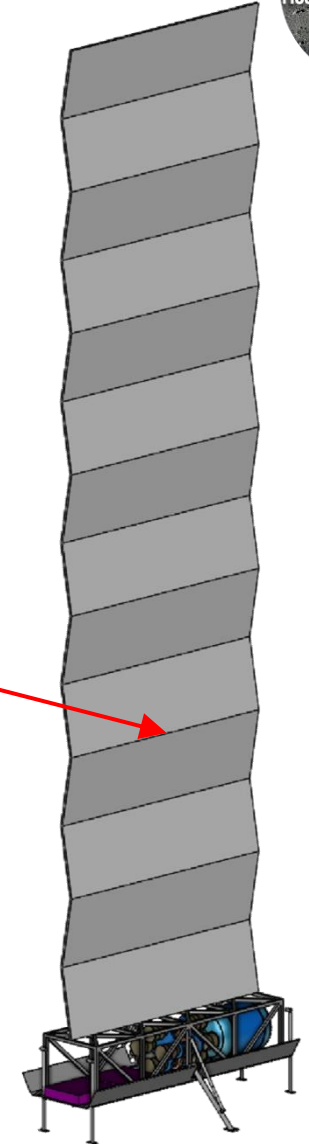


Deployable Legs (Screw Drive)

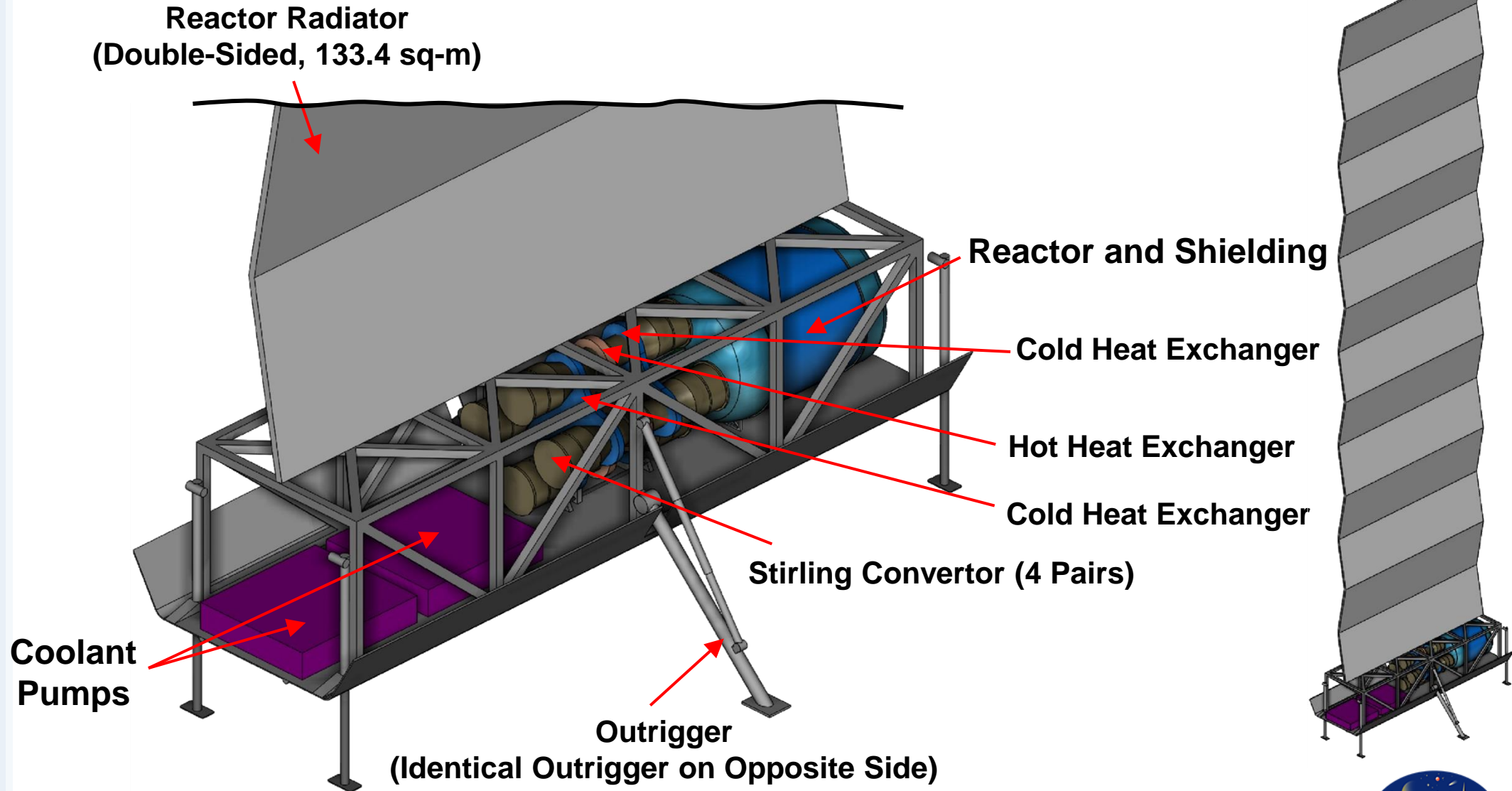


Outriggers Deployed

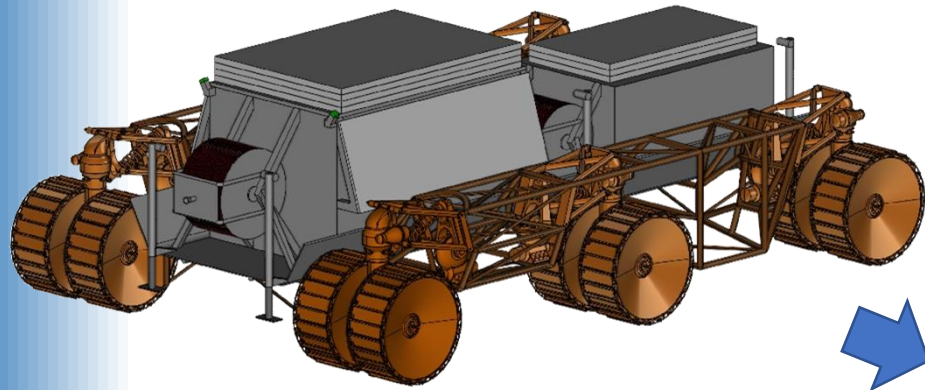
Double-Sided 133.4 sq-m Reactor Radiator Deployed



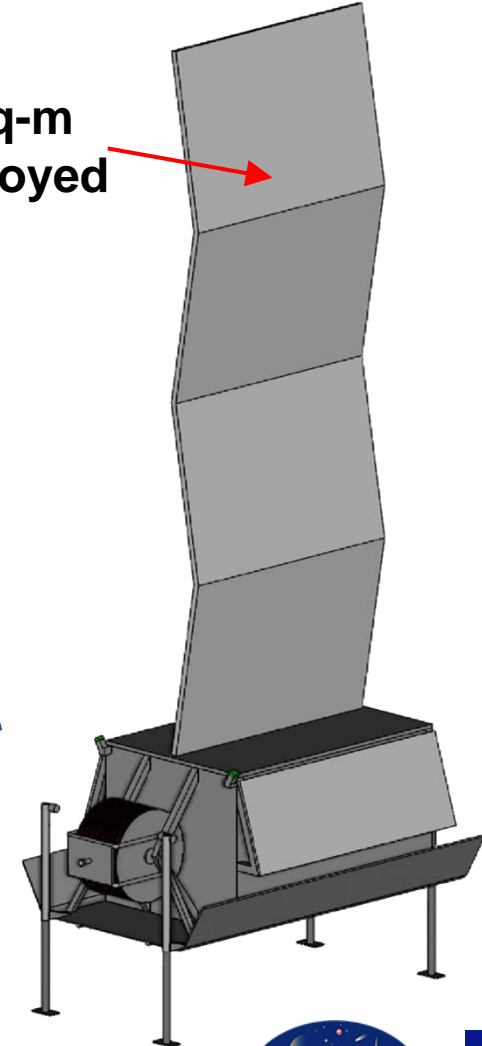
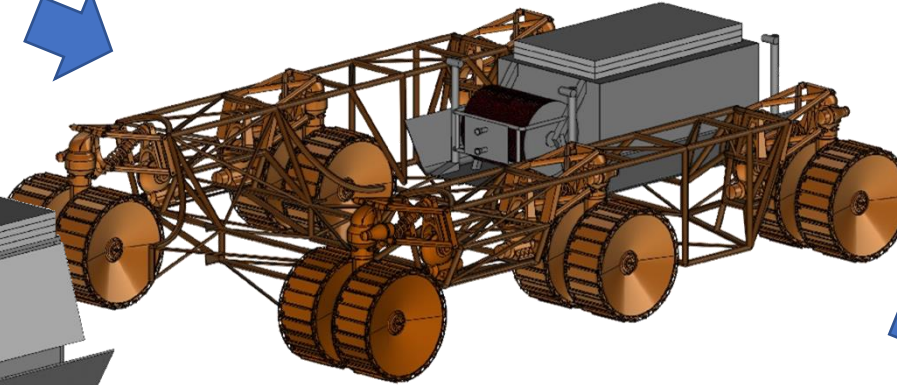
# Reactor System External Components



# Control Systems Deployment



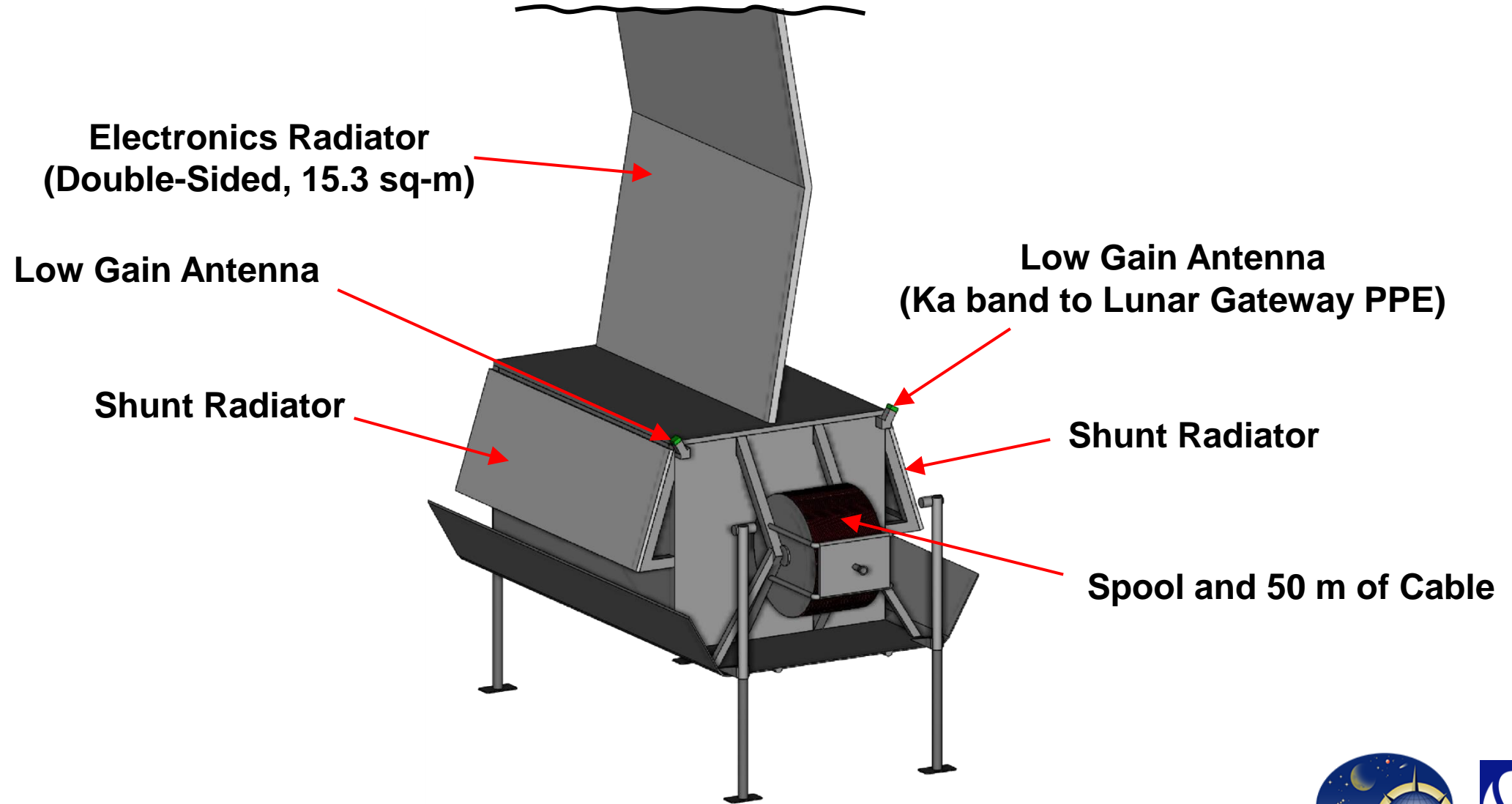
Double-Sided 15.3 sq-m  
Reactor Radiator Deployed



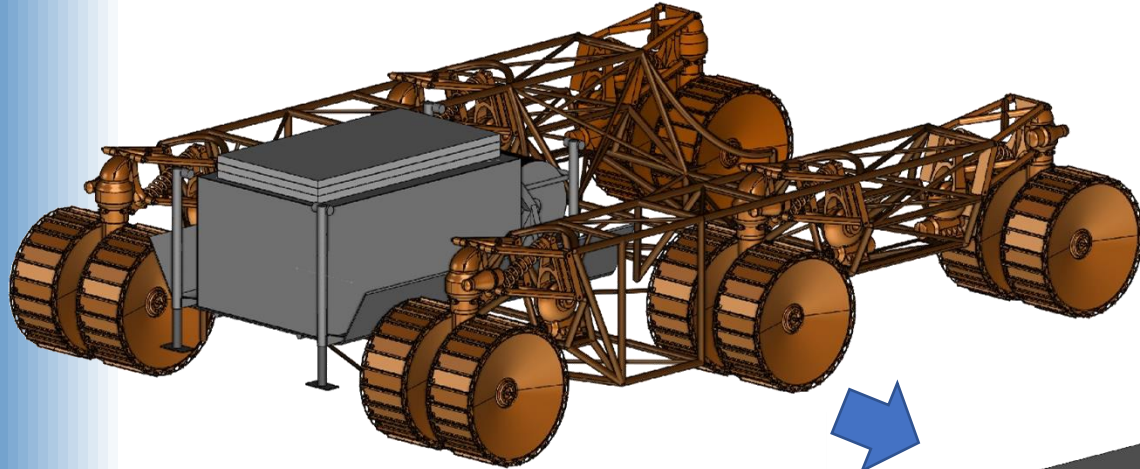
Deployable Legs  
(Screw Drive)



# Control Systems External Components



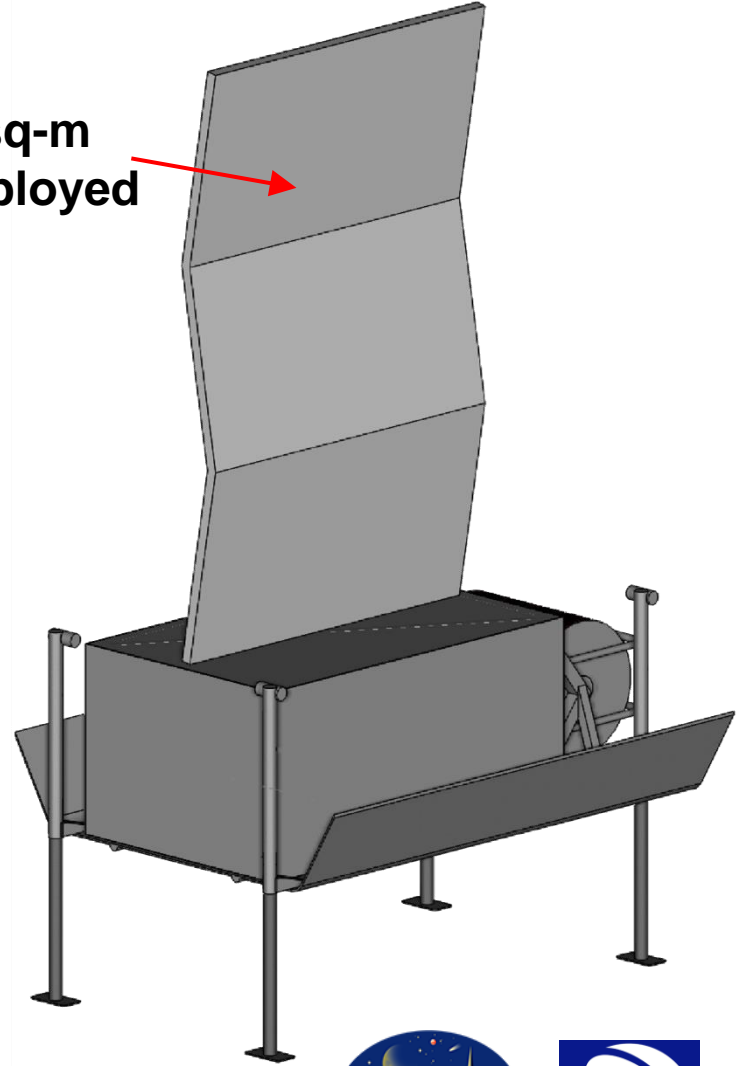
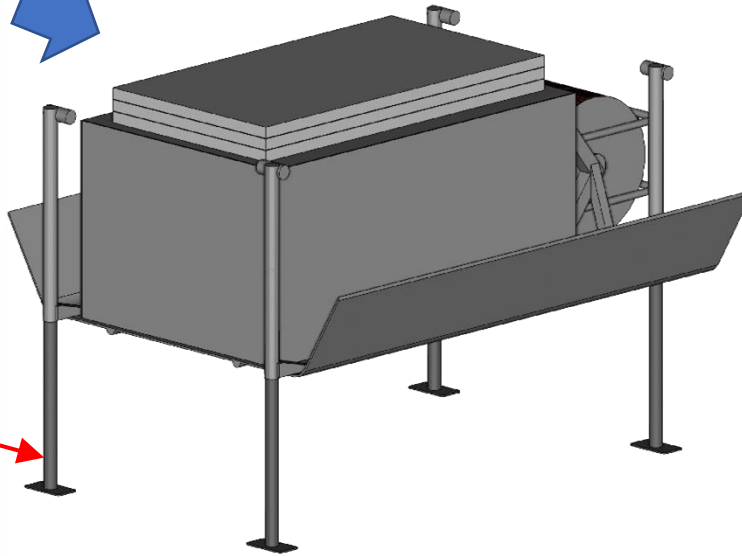
# Cable and Spool System Deployment



Double-Sided 6.0 sq-m  
Reactor Radiator Deployed



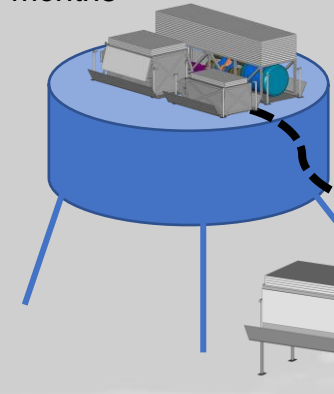
Deployable Legs  
(Screw Drive)



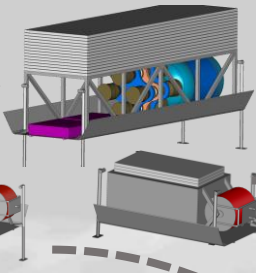
# System Deployment Process



Launch and Parking  
Orbit(s) up to 5  
months



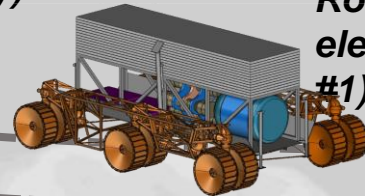
Off-load all three elements, (2 days)



Rover (delivered by  
separate lander)

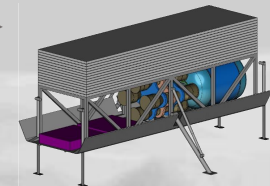


Rover loads and delivers the  
Power Generation Pallet  
(reactor) to operations site (1  
day)

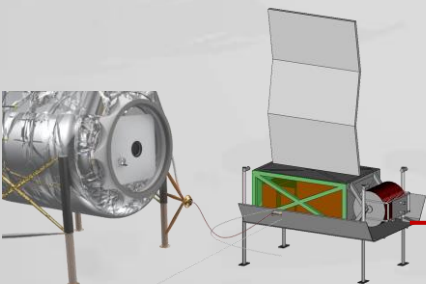


Rover with Reactor  
element loaded (trip  
#1)

Reactor Off-loaded

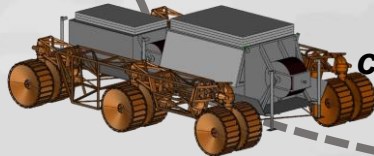


Landing at south pole and  
unloading from TBD lander (<2  
days, 2 kW supplied by lander) in  
sunlight



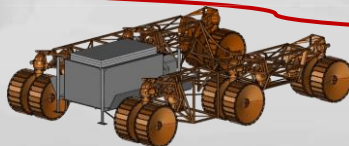
Empty Rover returns to lander

Rover loads controller and  
cable elements and transports  
(8 hours) (trip #2)



Controller plugged in, deployed  
50m (2 hours), Reactor/controller  
radiators deployed and reactor  
started (8 hours)

Rover deploys 1 km cable (2 days)



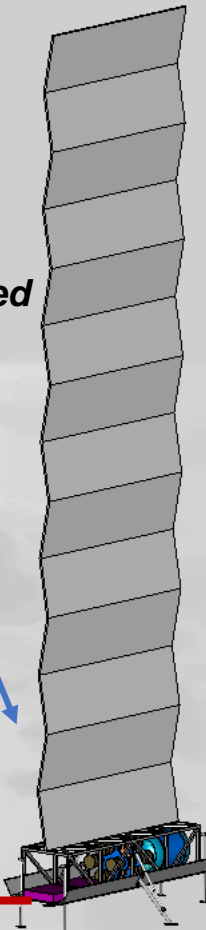
Rover plugs in convertor/cable to user,  
deploys pallet, returns to other duties

1km



Deployed FSP controller package  
(direct Ka-Band comms to Gatew

50m



# 'SPYDER' - HALEU Fueled YH Moderated Heat Pipe Reactor

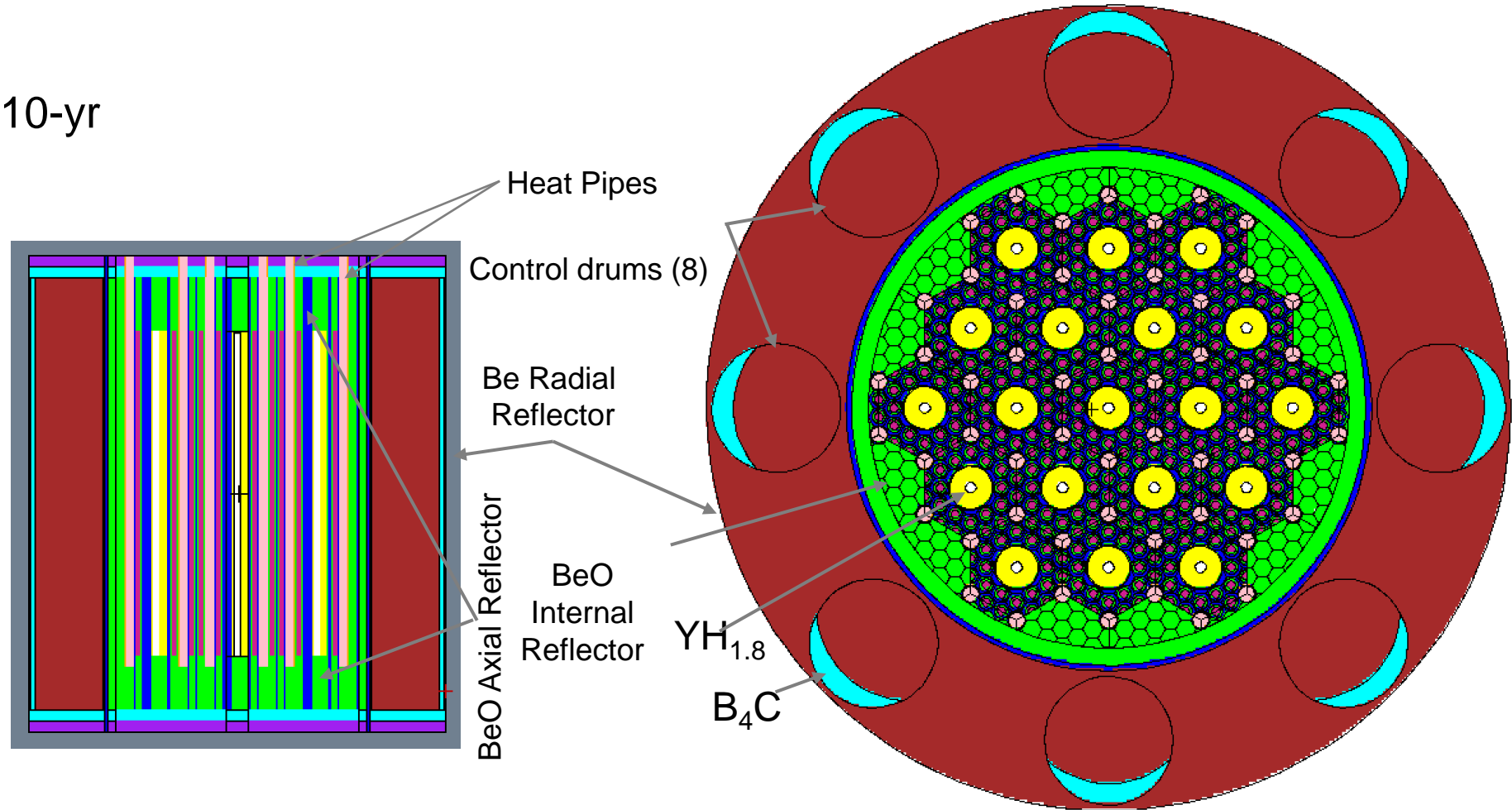


## Nuclear Features

$K_{\text{eff}}$  (BOL): 1.06

Burnup: 250 kWt for 10-yr

Fuel: UN pellets  
Enrichment: 19.75%  
Monolith: Graphite  
Heat Pipes: Na-Mo  
Moderator:  $\text{YH}_{1.8}$



System Architecture Concept

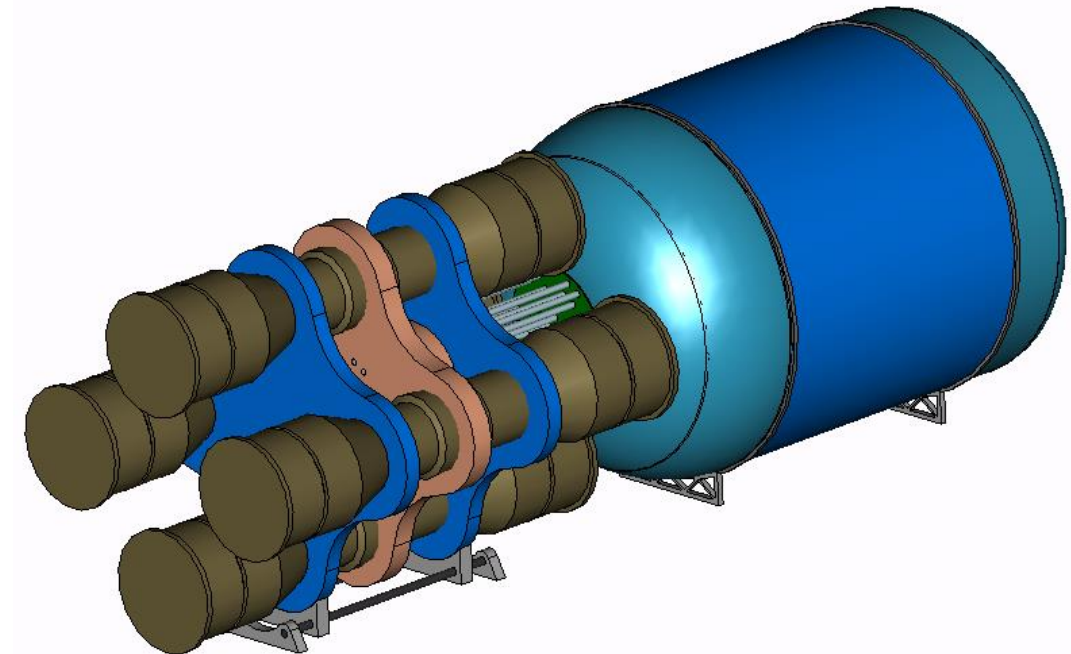
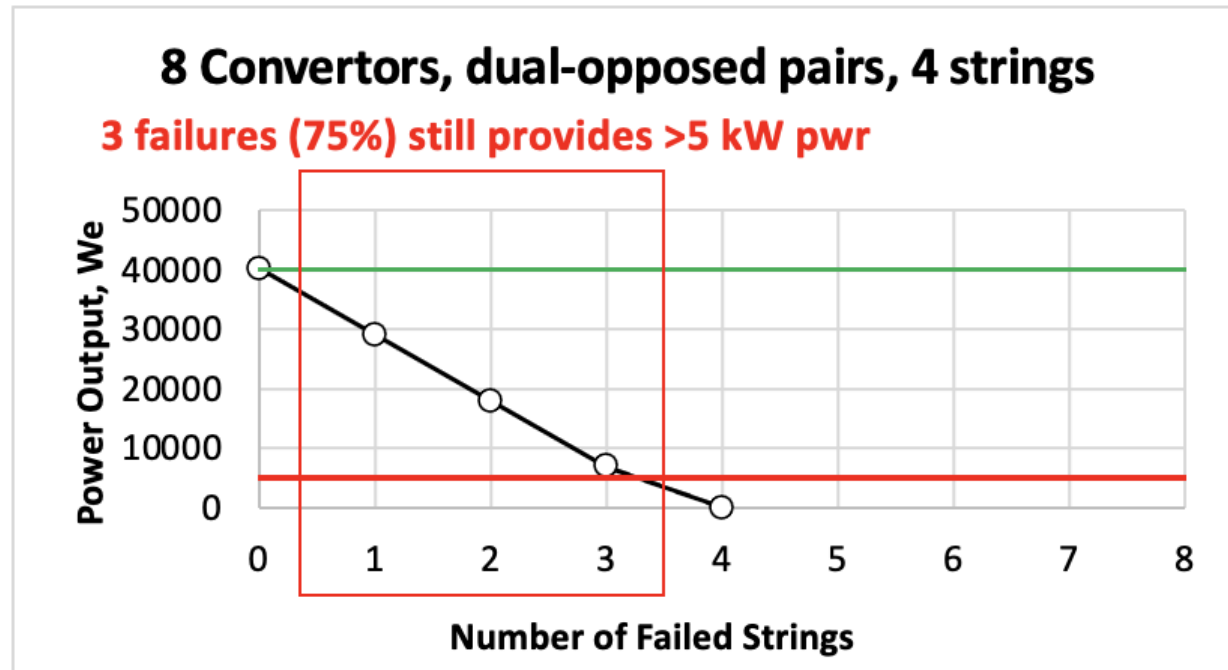
# Stirling-Based Power Conversion System



## 8 Convertors:

- Synchronized pairs
- System-level failure tolerance instead of engine-level
- High reliability: able to meet minimum power requirement  $>5 \text{ kW}_e$  after 3 of 4 string failures

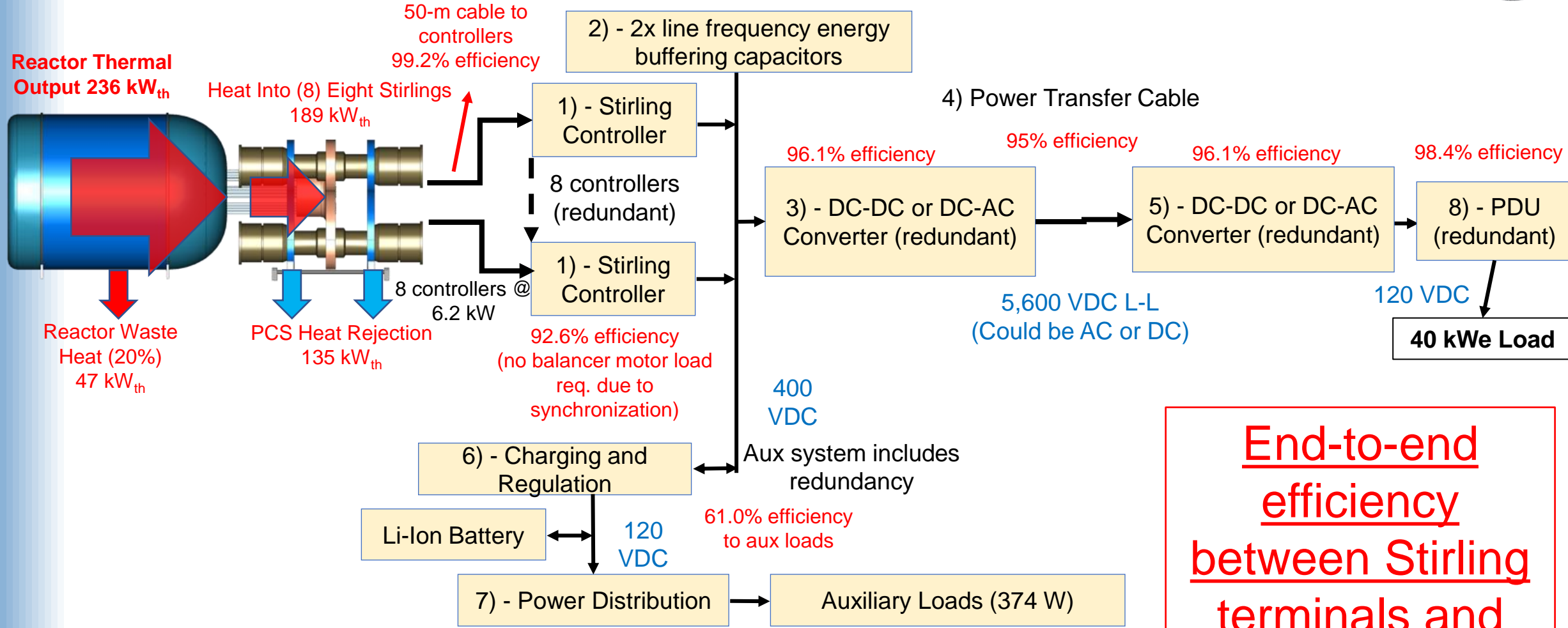
## 8 Convertor Case, 4 Strings: Dual-opposed pairs, no balancers



# Proposed Fission Generation System Architecture



Stirling Output: ~51,000 W, 240 VAC @ 50 Hz



System Architecture Concept

**End-to-end efficiency between Stirling terminals and load is ~78%**

# Lunar 40 kWe Fission Power System Demonstrator Summary



- ❑ Purpose: Develop a deployable 40 kWe Lunar Fission Surface Power System Concept
- ❑ Users: Human lander, Night-time survival, Science, ISRU, communications
- ❑ Total FSP Mass ~ 10,000 kg (~2t rover not included)
- ❑ Power: 40 kWe reactor 1km cable to users
  - Eight, 6 kWe Stirlings ensure ~ 5kWe at 10 years
  - Radiation tolerance set to 100 krad in controller
  - Radiation at Stirlings set to 25 Mrad
  - <5 mrem/hr at >1 km from habitat
  - Utilize same rover to deploy 1km, +/- 2800VDC cable
- ❑ Lander:
  - Provides transit and delivery to lunar surface (up to 12,000 kg capability)
  - Provides structure for mounting FSP and carrier rover
  - Deploys FPS/Rover to surface in the same was as the PR
- ❑ Rover: based on Pressurized rover (PR) (up to ~8 t carrying capability) and skid based off-loadable cargo concepts. Landed separately.
- ❑ Comms: Reactor Package: shielded Ka-Band link to 70,000 km Gateway (almost continuous commlink)
- ❑ C&DH: Reactor Package: Shielded controllers for reactor and Stirlings, interface to Gateway
- ❑ Thermal:
  - Deployable Reactor Package: 133 m<sup>2</sup> radiator for Stirlings, sized for polar operations
    - Use at equator adds 60% radiator area
- ❑ Mechanical:
  - Deployable jacks to lift FSP pallets off of rover
  - Deployable radiators
  - 50m 240VAC (@50Hz) and 1 km 3000 VDC cable/spools
  - Stability legs for reactor element

MEL Summary: 40kW_Case 2_FSPS Deployability CD-2021-187	Fission Surface Power System	Control Systems	Cable and Spool	TOTAL to be carried by Lander
Main Subsystems	Basic Mass (kg)	Basic Mass (kg)	Basic Mass (kg)	Total Basic Mass(kg)
Fission Power System	3969	0.0	0.0	3969.1
Command & Data Handling	0.0	46.4	0.0	46.4
Communications and Tracking	0.0	25.6	0.0	25.6
Electrical Power Subsystem	0.0	733.4	357.0	1090.3
Thermal Control (Non-Propellant)	1100.6	183.8	68.1	1352.6
Structures and Mechanisms	520.4	268.7	172.3	961.5
<b>Element Total</b>	<b>5590.2</b>	<b>1257.9</b>	<b>597.4</b>	<b>7445.5</b>
<b>Element Dry Mass (no prop,consum)</b>	5590.2	1257.9	597.4	7445.5
<b>Element Mass Growth Allowance (Aggregate)</b>	905.4	401.1	176.9	1483.4
<b>MGA Percentage</b>	16%	32%	30%	20%
<b>Predicted Mass (Basic + MGA)</b>	6495.6	1659.1	774.3	8928.9
<b>System Level Mass Margin</b>	838.5	188.7	89.6	1116.8
<b>System Level Growth Percentage</b>	15%	15%	15%	15%
<b>Element Dry Mass (Basic+MGA+Margin)</b>	7334.1	1847.8	863.9	10045.8
<b>Element Inert Mass (Basic+MGA+Margin)</b>	7334.1	1847.8	863.9	10045.8
<b>Total Wet Mass (Allowable Mass)</b>	<b>7334.1</b>	<b>1847.8</b>	<b>863.9</b>	<b>10045.8</b>
	Mobility System Trip 1	Mobility System Trip 2		

# Power Transmission Strategies



- ❑ Alternative power transmission strategies have been proposed for fission power transmission
- ❑ Fission power system mass is dominated by generation mass and the most efficient system will be the lightest
- ❑ Transmission technology trade changes at low power and long distance

Transmission	End-to-End Efficiency	Additional Generation	Increased FSP mass (efficiency penalty) <u>(Neglecting beaming hardware mass)</u>	
Beamed - $\mu\text{m}$	26%-27%	110 kW	30,000 kg	
Beamed - mm	13%-18%	220 kW	60,000 kg	
Beamed - Laser	14%-18%	210 kW	57,000 kg	
Superconducting	42%	55 kW	15,000 kg	
Carbon Nanotube Rope	~75%	~12 kW	~3,200 kg	Comparable mass to copper but low TRL
<b>Copper Wire System</b>	<b>77%</b>	<b>12 kW</b>	<b>3,200 kg</b>	

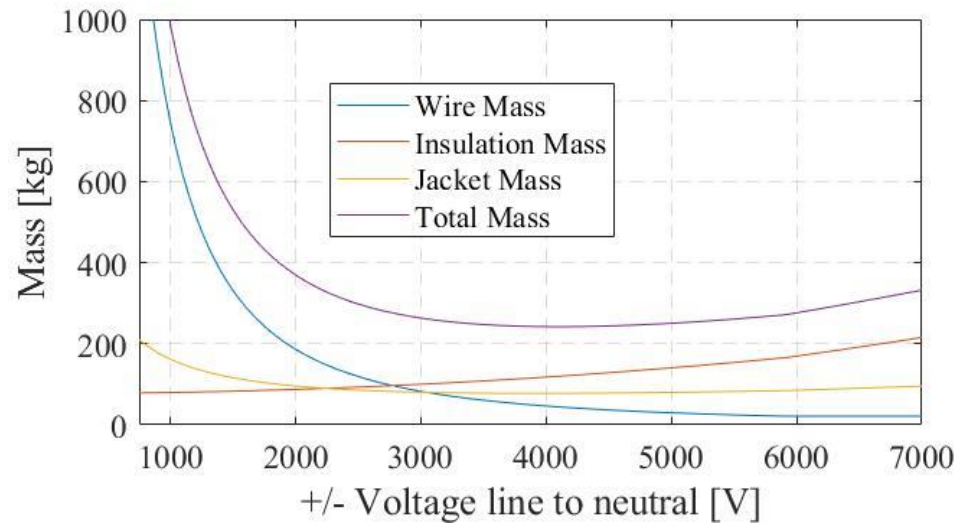
Comparison of bulk power transmission strategies

Reference: [29]

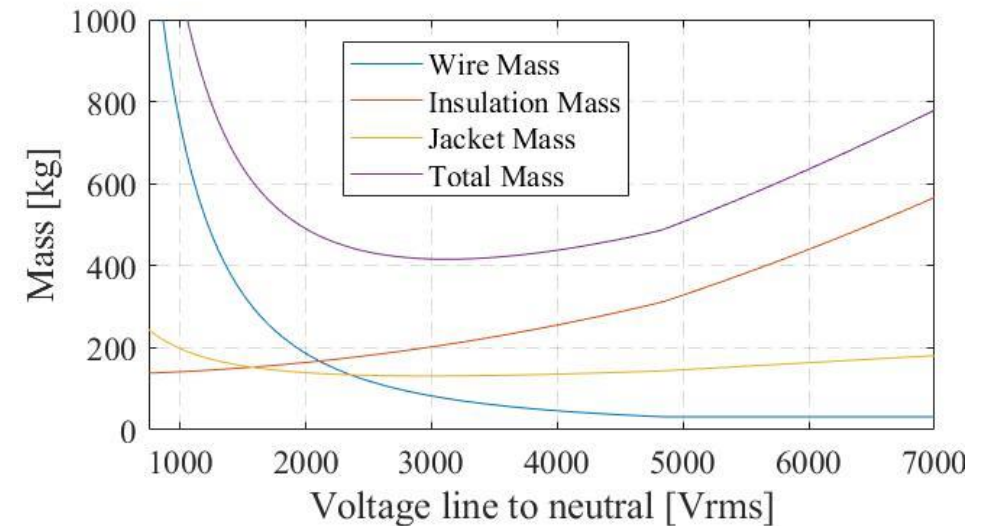
# Power Transmission Strategies



- ❑ Metallic conductor technology well understood and minimizes program risk
  - Cable mass dependent on transmission voltage
- ❑ Assumptions:
  - Cable sized for transmission of 43 kW and a distance of 3 km with 95% efficiency [29]
  - Cable power loss limited to 0.7 W/m



DC cable system



AC cable system



## □ Project Overview

- Project goal
- Scope, implementation, and team structure

## □ System Studies

- Goals and history
- Review of 40 kW mobile reactor concept
- Power transmission

## □ Supporting SBIRs in progress

- ThermAvant Technologies, LLC - High temperature heat rejection
- Peregrine Falcon Corporation - Consolidation of heat pipes within a U-8Mo Core
- Creare - Brayton converter for nuclear electric propulsion
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## □ In-house technical activities at GRC

- Integrated heat pipe-Stirling convertor test
- Simplified Stirling control
- Stirling simulators



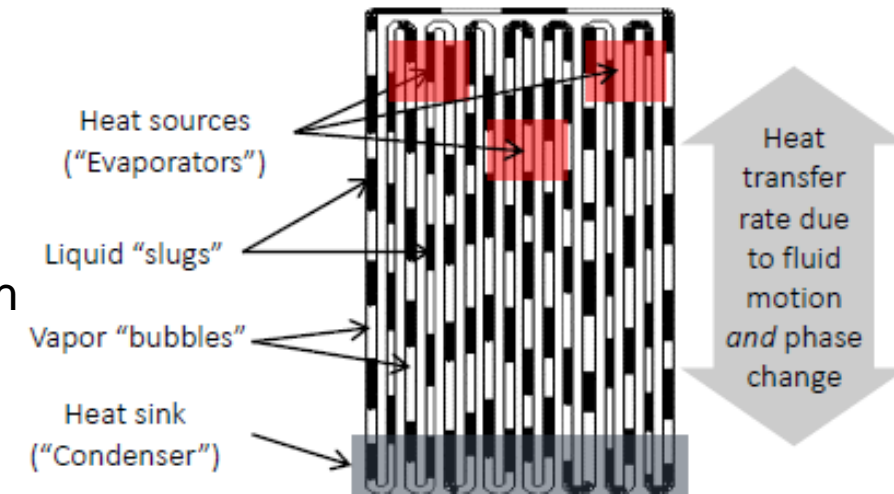
## ❑ ThermAvant specializes in Oscillating Heat Pipe (OHP) technologies

### ❑ SBIR Phase I outcomes

- Performed studies comparing OHP concepts against titanium water Variable Conductance Heat Pipes with carbon fin and showed an increased rejection capacity
- Tested an OHP panel operating with a 110 C PFL heat source, with a conductance of 80 W/K and rejection power of > 800 W on a 0.5 m<sup>2</sup> panel.

### ❑ Phase II objectives

- Optimize an OHP radiator panel to operate at 175C for FSP application
- Improve predictive modeling of OHPs
- Verify fluid and envelope material compatibility
- Study working fluids for a broad temperature range (100-300 C)
- Elevate TRL of OHP radiator panels
- Develop multiple manufacturing processes for making large OHP radiators



Example of how OHP technology



SBIR Contract # 80NSSC21C0545

# **Peregrine Falcon Corporation - Consolidation of Heat Pipes within a U-8Mo Core**



- ❑ **Phase II Sequential SBIR to develop process for consolidating the joint between heat pipe(s) and DU core**
  - ❑ Consolidated joint provides overall lower losses in heat transfer from the core
- ❑ **SBIR Phase I and II outcomes**
  - Phase I
    - Developed a process to join flat coupons of Haynes 230 and DU
    - Demonstrated material compatibility and a strong metallurgical joint
  - Phase II
    - Successfully joined Haynes 230 with surrogate core material using axial force
- ❑ **Phase II Sequential objectives**
  - Develop process (pressure, temperature, time, etc.) to join cylindrical coupons of Haynes 230 and DU using axial force
  - Test and identify the shear strength of the consolidated joint



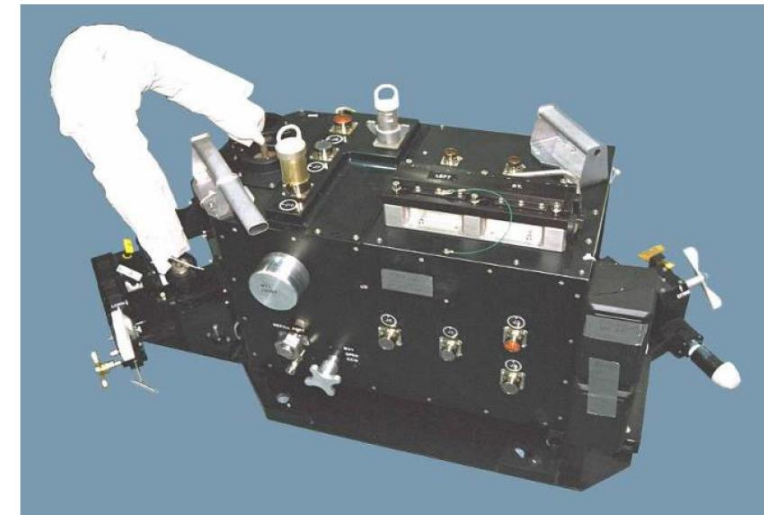
**PEREGRINE**  
AGILE · ADEPT

SBIR Contract # 80NSSC21C0007

# Creare - Brayton Converter for Nuclear Electric Propulsion



- ❑ Creare is an established provider of turbo-Brayton refrigerators and turbo-molecular vacuum pumps for space
- ❑ Phase I SBIR covered paper design of 500 kWe Supercritical Brayton Converter
  - Study evaluated
    - Working fluid
    - Turbine inlet temperature
    - Compressor inlet temperature
    - Compressor inlet pressure
    - Pressure ratio
    - Recuperator thermal effectiveness
    - Alternator efficiency
  - Improved alternator cooling strategies evaluated experimentally
  - SBIR Contract #80NSSC21C0090
- ❑ Phase II SBIR focusing on fabrication of 500 kWe turbomachine assembly

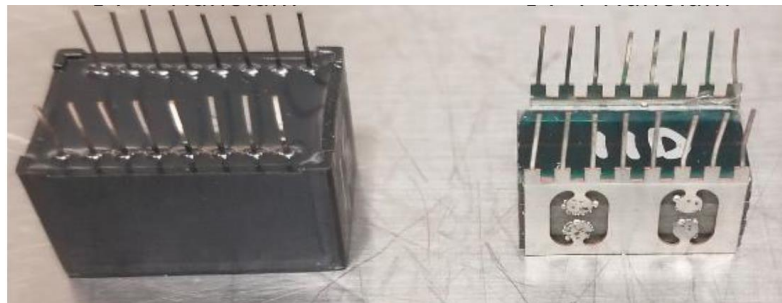


Creare Brayton cryocooler for Hubble Space telescope

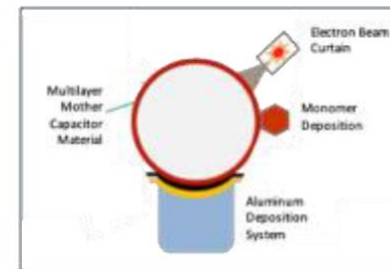
# Sigma Technologies – NanoLam capacitors



- ❑ Polymer-multilayer (NanoLam) capacitors offer game-changing energy storage
  - Thermoset polymer
- ❑ Compares favorably to ceramics
  - Lower dissipation factor and cost
  - Comparable energy density to nominal value of ceramics without bias dependence or fragility
  - 6.3J/cc demonstrated in 140uF/2200V medical application
- ❑ **Roughly 50X density improvement over MIL-PRF-39022/12 devices**
- ❑ Radiation tolerant (Polypropylene capacitors are susceptible to radiation)
- ❑ Lower dissipation factor and cost than ceramics without fragility or bias-dependance
- ❑ Self-healing, fail-open safety
- ❑ Stable up to 200 °C
- ❑ Low ESL and ESR



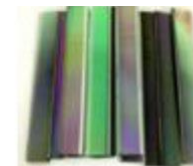
14 uF, 300 VDC capacitors for NASA PPUs (2019 Phase II)



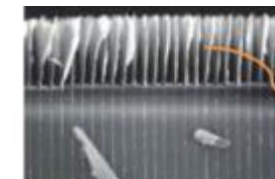
PML Capacitor Process Schematic



Segmented Mother Capacitor Material



Individual Capacitor Elements



Aluminum Electrodes



Arc Sprayed Termination

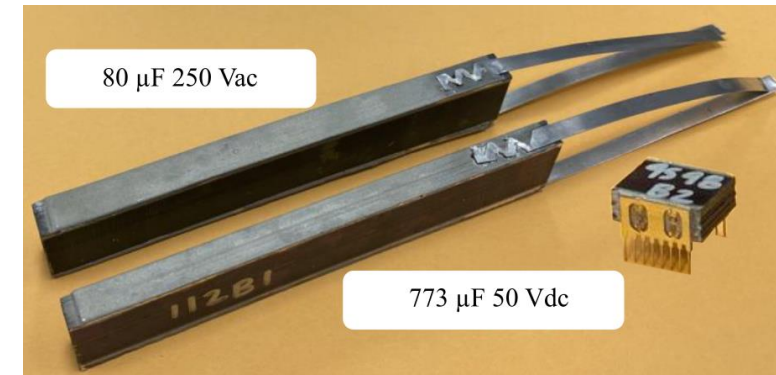
# Sigma Technologies – NanoLam capacitors



- ❑ **Objective: Adopt NanoLam technology for,**
  - DC link capacitor in Dynamic Radioisotope Power Systems (DRPS)
    - 50 Vdc, 750  $\mu$ F
    - Lessons learned directly apply to the mild hybrid automotive market (48 Vdc).
  - AC power factor correction for kilowatt-class Stirling engines (250 Vac, 71  $\mu$ F)
    - Previously developed capacitors were only for dc applications.

- ❑ **Phase I Outcome:**

- DC link capacitors: 50 Vdc, 750  $\mu$ F
- AC PFC capacitors: 250 Vac, 80  $\mu$ F (Proof of concept)
- Breakdown voltage (2.6x safety factor)
- Short-term life tests (900 hrs)



- ❑ **Phase II SBIR and evaluation of NanoLam devices by NASA Electronic Parts and Packaging (NEPP) group in progress**

- FY 2023 NEPP funding
- SBIR Contract #80NSSC21C0492



## □ Project Overview

- Project goal
- Scope, implementation, and team structure

## □ System Studies

- Goals and history
- Review of 40 kW mobile reactor concept
- Power transmission

## □ Supporting SBIRs in progress

- ThermAvant Technologies, LLC - High temperature heat rejection
- Peregrine Falcon Corporation - Consolidation of heat pipes within a U-8Mo Core
- Create - Brayton converter for nuclear electric propulsion
- Sigma Technologies – NanoLam capacitors

## □ In-house technical activities at GRC

- Integrated heat pipe-Stirling convertor test
- Simplified Stirling control
- Stirling simulators

# Integrated Heat Pipe-Stirling Converter Test – GRC



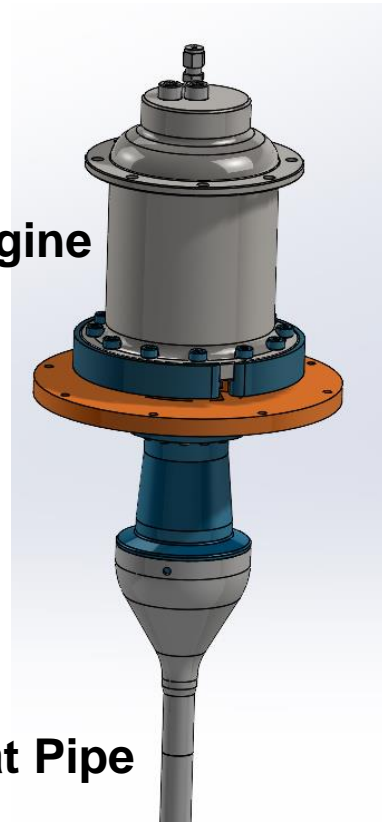
## ❑ Integrated interface between the heat pipe and a Stirling engine

- Sodium heat pipe integrated into Stirling heater head
- Welded joint provides improved heat transfer and lower temperature drop across interface, compared to KRUSTY clamped-plate design

## ❑ Test Plans

- In-air testing
  - Characterize & compare thermal performance of integrated joint/system
  - Verify contractor data of Stirling engine and controller functionality
  - Identify gaps in controller design
  - Provide baseline performance data for comparison during future vacuum testing
- Vacuum testing
  - Extended operation in vacuum environment in vertical orientation to demonstrate performance/reliability of heat pipe, heater head welded interface, and breadboard controller

Stirling Engine



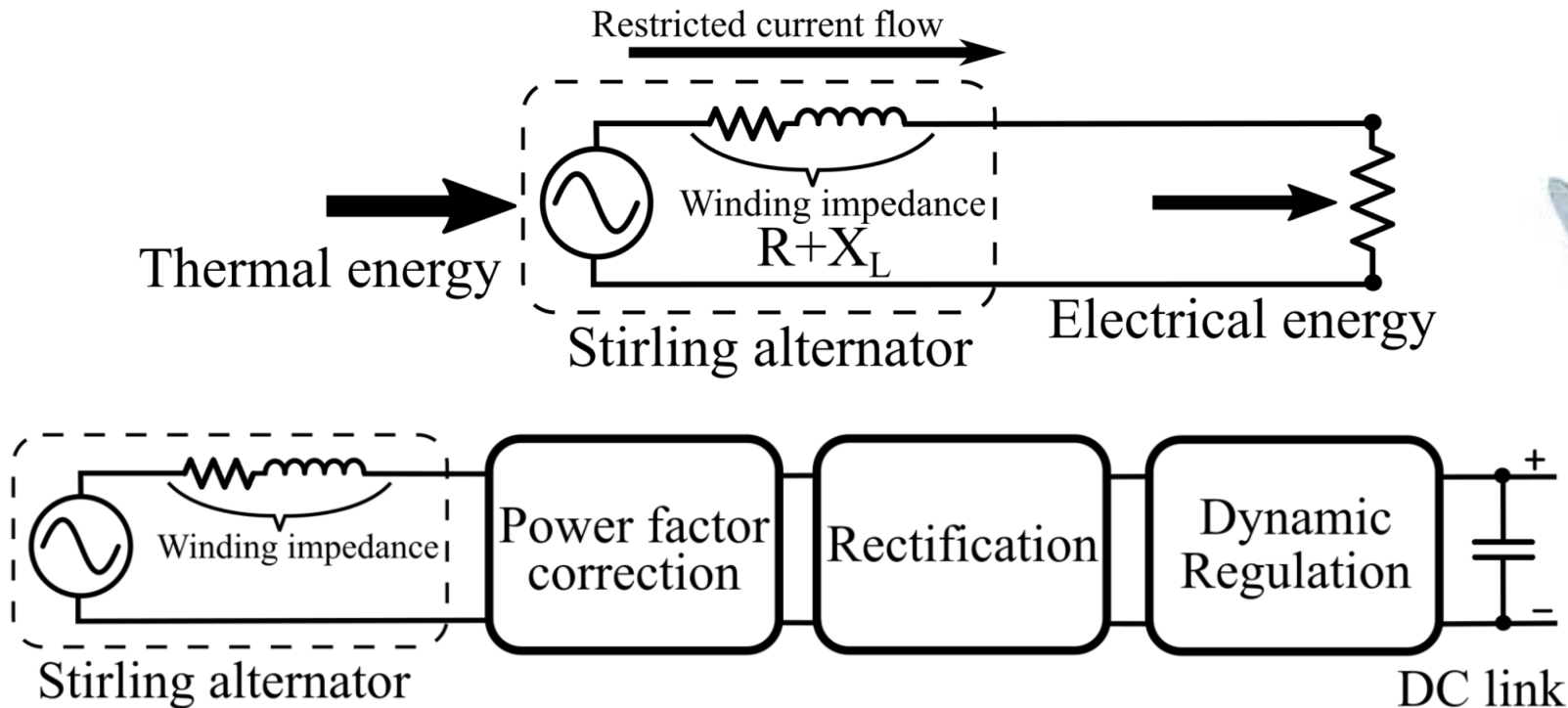
Heat Pipe

# Need for Stirling Controllers



## □ Stirling engines require control to maintain stable operation

- Thermal energy flowing into engine is constant
- Energy must be extracted to limit piston motion
- Stirling alternator inductance limits power flow from alternator\*.
- Energy accumulation in the piston results in overstroke.

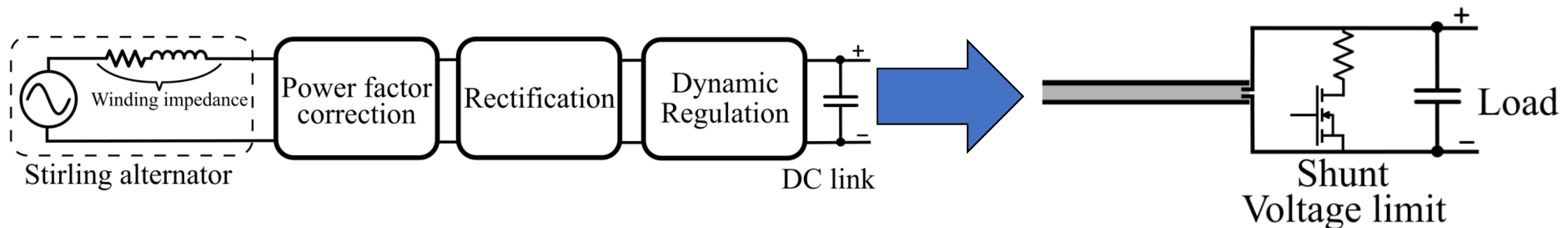
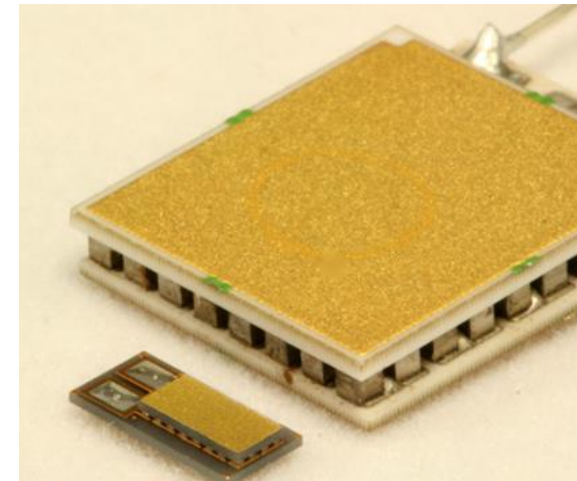


# Simplified Stirling Control



- ❑ Stirling control has historically sought to meet reliability and performance requirements through complex digital control with sensing and fault response
- ❑ Additional complexity dramatically increases development and validation costs as well as potential failure rate due to increased component count

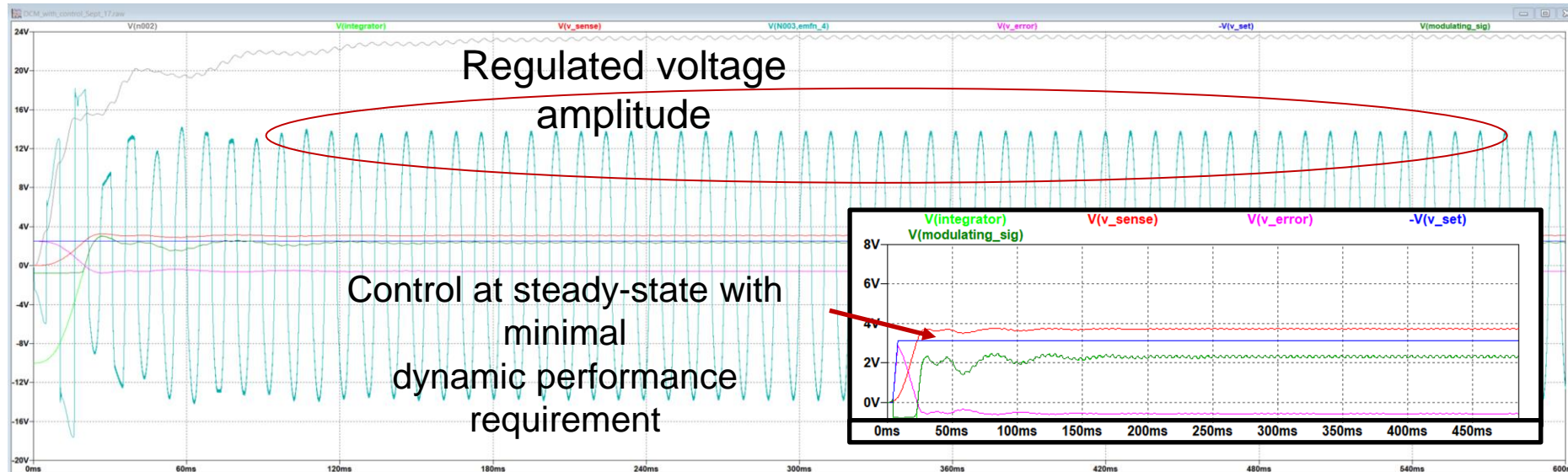
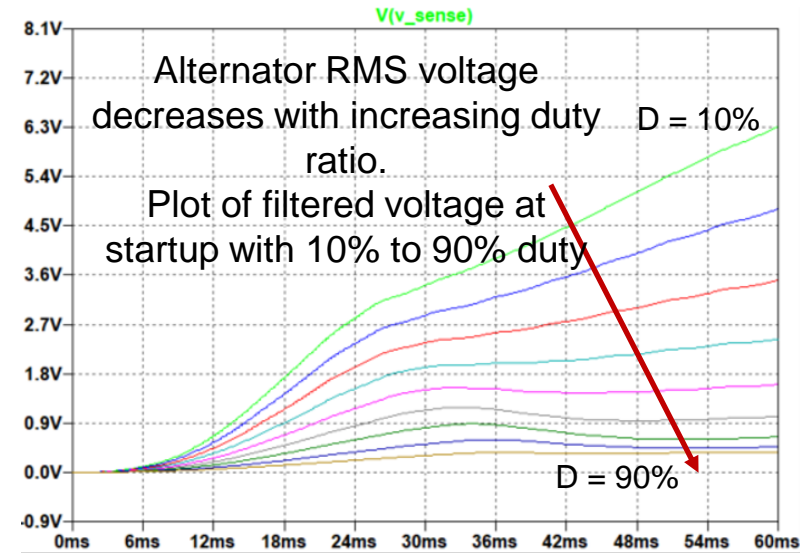
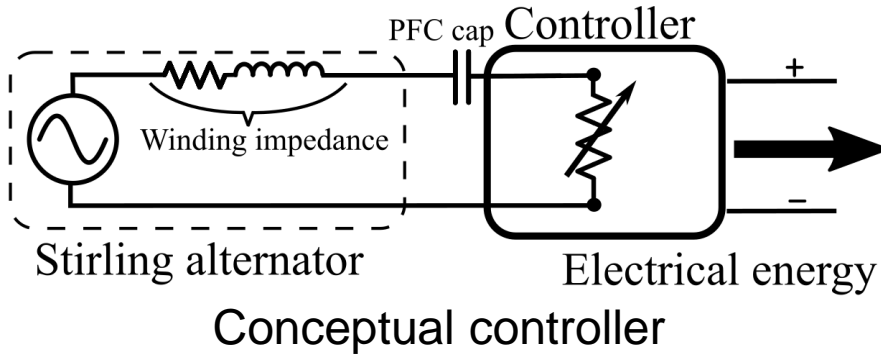
How can Stirling systems be simplified in fission applications?



# Simplified Stirling Control



## □ Average amplitude Stirling control



C. B. Barth, D. M. Yang and M. F. Chaiken, "Design of a 1 kW, simplified Stirling controller using capacitor-based power factor correction," in *Nuclear and Emerging Technologies for Space (NETS)*, Oak Ridge, TN, 2021.

# Stirling simulators as a Tool for Controller Development



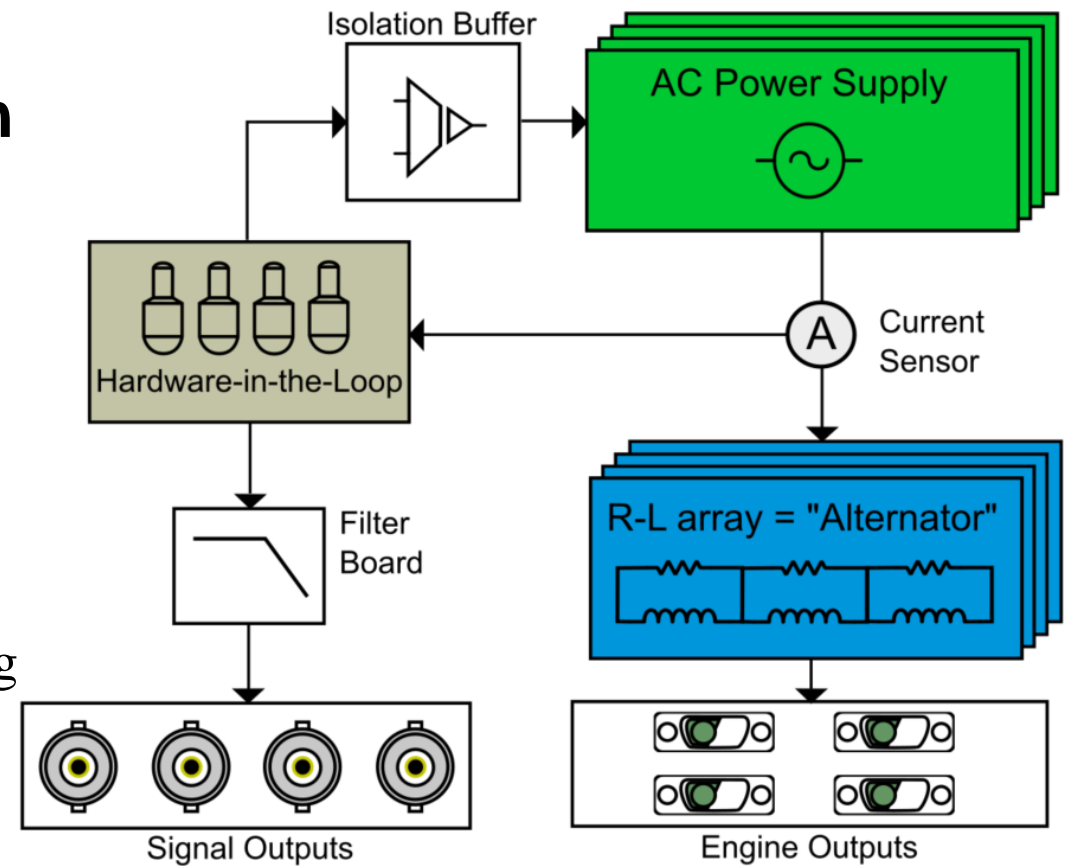
- ❑ Most Stirling Controller concepts utilize power factor correcting (PFC) boost rectifiers
- ❑ Power electronics development requires a testing and validation which risks engine damage
- ❑ Stirling simulators emulate engine characteristics for controller validation

- **Purpose**

- Test controller functionality prior to operating with an actual convertor.

- **Benefits**

- Identifies unexpected controller issues and prevents potential convertor damage
- Reduces the start-up time required for operating convertors



Simulator block diagram

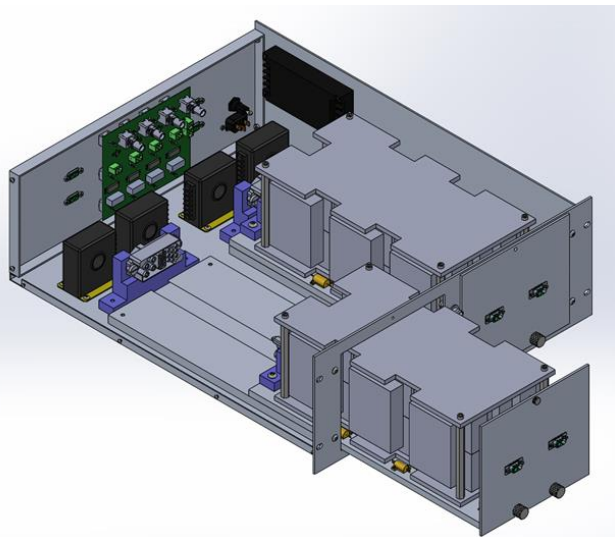
# Stirling simulators as a Tool for Controller Development



## ❑ Hardware

- Linearized convertor model implementation
  - dSPACE MicroLabBox
- Convertor alternator equivalent circuits
  - Designed to emulate the frequency response of the actual alternator up to 1MHz
- Current Sensors
  - American Aerospace Controls S273-25-B ( $\pm 25A$ )
- AC power supplies
  - Chroma 61602; 2-quadrant switched-mode power supply

## ❑ Currently configured for up to four engines



Physical inductor assembly  
interchangeable for  
simulating different engines



dSPACE unit

Chroma power  
supplies

GRC reconfigurable simulator



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# Questions and discussion



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