A Deployable 40 kWe Lunar Fission Surface Power Concept

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<th>Team Roster</th>
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<th>Compass Team</th>
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<td>Study Lead (test driver)</td>
<td>Bill Taylor</td>
<td>Steve Oleson</td>
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<td>System Integration</td>
<td>Bill Taylor, Michael Pepen</td>
<td>Betsy Turnbull, Christy Schmid</td>
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<td>Chassis/mobility</td>
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<td>Jim Fittje</td>
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<td>Mechanical Systems</td>
<td>Vicente Suarez/Jeff Larko</td>
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<td>Tony Colozza</td>
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<td>Power:</td>
<td></td>
<td>Paul Schmitz, Brandon Klefman, Lucia Tian</td>
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<td>DV Rao</td>
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<td>Bill Taylor/Tim Schuler</td>
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<td>Cost</td>
<td>Tom Parkey</td>
<td>Natalie Weckesser, Cassandra Chang, Marissa Conway,</td>
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<td>Jon Drexler</td>
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<td>Schedule</td>
<td>Erin Wood</td>
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<td>SMA</td>
<td>Marc Gibson</td>
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40 kWe FSP Deployability Concept

• Purpose: Develop a concept for a 40 kWe Fission Surface Power (FSP) system that is deployable
  - Trade: South pole (baseline) vs Equatorial (quick one-off)
  - Trade: Stirling and (Brayton design- pushed as later work due to dissimilarity)
  - Trade: Where is the power delivered – assumed one user point

• Approach: The reactor will be deployed by a chassis common with the pressurized habitat which also needs delivered and off-loaded from the lander (this approach avoids integrating the reactor into a specific lander as well as avoids how the chassis is off-loaded)
  - Comment on impact of leaving on the system on the lander deck

• Starting Point: 6 wheel Pressurized Rover chassis
  - Mass capability ~ 8-9t – but can be exceeded for this study if necessary
  - Volume: stay in the same volume as the Pressurized Rover
    ▪ Fallback – On-lander habitat
Top Level Requirements/Design Goals

✓ 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 4 m Diameter cylinder x 6 m length
  • Maximum 6000 kg
    ✓ (design showed a ~10,000 kg landed mass required – excluding mobility system)

✓ 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)

✓ Assumed minimal crew interaction
Top Level Schematic
Launch and Parking Orbit(s) up to 5 months

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

Off-load all three elements, (2 days)

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

Rover deploys 1 km cable (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)

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

Rover deploys 1 km cable (2 days)

Empty Rover returns to lander

Deployed FSP controller package (direct Ka-Band comms to Gateway)

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

1km
Rover and FSP Envelope

Pressurized Rover (PR): Volume and Orientation

Design Constraints / Parameters
- Length: 6.23 m
- Width: 3.55 m
- Height: 3.29 m

From: HUMAN Class Cargo LUnar Lander (HCCLL) SYstem to Cargo Interface Requirements Document (IRD)
FSP 40 kW Transportability Concept
Within the Lander Envelope

3.55 m
3.29 m
6.23 m
FSP 40 kW Transportability Concept
Reactor System Deployment

Deployable Legs (Screw Drive)

Double-Sided 133.4 sq-m Reactor Radiator Deployed

Outriggers Deployed
FSP 40 kW Transportability Concept
Reactor System External Components

- Reactor Radiator (Double-Sided, 133.4 sq-m)
- Coolant Pumps
- Stirling Convertor (4 Pairs)
- Outrigger (Identical Outrigger on Opposite Side)
- Reactor and Shielding
- Cold Heat Exchanger
- Hot Heat Exchanger
- Cold Heat Exchanger
‘SPYDER’ Design: HALEU Fueled YH Moderated Heat Pipe Reactor

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

Nuclear Features
$K_{\text{eff}}$ (BOL): 1.06
Burnup: 250 kWt for 10-yr
Shielding Requirements

1. Stirling Components (1 m) n: $5 \times 10^{14}$ n/cm$^2$ (>100 keV) and Gamma: 25 MRad (Rad Si)
2. Electronics @10 m n: $5 \times 10^{11}$ n/cm$^2$ and Gamma: 25 kRad
3. Humans @ 1 km Total 5 rem/yr (gamma+neutron); 100% occupancy; 1 km wide

Power: 250 kWth
Lifetime: 10 EFPY
8 Convertor Case, 4 Strings: Dual-opposed pairs, no balancers, no single fault tolerance

8 Convertors:
- Synchronized pairs
- Not single fault tolerant
- High reliability: able to meet minimum power requirement >5 kWₑ after 3 of 4 string failures
Sky Temperature: 4 K
View Factor Assumed to be 0.5

Sunlit Surface ~ 220 K
View Factor Assumed to be 0.5

Heat Transported by the Pump Coolant Loop to the Radiator

Radiator Temperature:
- Max Sun: 395 K
- Min Shadow: 375 K

Radiating Surface Area: 133.4 m²

Solar Radiation: 1360 W/m²
FSP 40 kW Transportability Concept
Control Systems Deployment

Deployable Legs (Screw Drive)

Double-Sided 15.3 sq-m Reactor Radiator Deployed
Power System Design – Control Systems

- Stirling Cables (50m) to Stirling Controllers x 16
- 240 VAC to 400 VDC
- DC-DC Converters
- DC-DC Converters (Aux) x2
- Li-Ion Battery
- 120 VDC to Power Distr. Units
- Power Distr. Units to 400 VDC
- DC-DC Converters
- 400 VDC to 1 km ±2800 VDC Cable
- Auxiliary Loads (1000W)

To

1 km ±2800 VDC Cable
Power Transfer Spool Downconverter and Cable Design

- HabiaCable high voltage cables for electric aircraft/aeronautics
  - Design specification per Fission Surface Power (FSP) project

- Cable Design Assumptions:
  - Cable Length: 1 km
  - Cable Output Power: 43.5 kW
  - Cable Efficiency: >95% (2.2 W/m max losses)

- Selected Aluminum Bipolar Pair cable design
  - Operating voltage: +/-2800 VDC
  - Total cable mass: 73 kg
  - Cable outer diameter: 6.5 mm
  - Conductor area: 1.9 mm²

- Reference “Lunar Cables for Fission Surface Power Project (FSP)”. Adapted for 40 kW, 1 km by Christopher Barth (GRC/LET).

- Downconverter to return power to 120VDC
Power System Block Diagram

1) - Stirling Controller
- 8 controllers (redundant)
- 92.6% efficiency [1]
- (no balancer motor load req. due to synchronization)

2) - 2x line frequency energy buffering capacitors

3) - DC-DC Converter (redundant)
- 96.1% efficiency [1]

4) Power Transfer Cable
- 95% efficiency [2]
- 5,600 VDC L-L

5) - DC-DC Converter (redundant)
- 96.1% efficiency [1]

6) - Charging and Regulation
- Aux system includes redundancy
- 61.0% efficiency to aux loads [1]

7) - Power Distribution
- Li-Ion Battery
- 120 VDC

8) - PDU (redundant)
- 120 VDC

98.4% efficiency [1]

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

[1] Metcalf design models
[2] Designed efficiency
Lessons Learned

- **Increasing to a 40 kWe (from a 10 kWe) power system:**
  - Almost breaks the 12t limit for planned cargo landers
  - Cannot be landed with the mobility system (it will need to be landed with other equipment)
  - Does fit the volume limit

- **Using the pressurized rover chassis to deploy the 40 kWe system should still be possible BUT**
  - It now must be deployed as three separate pieces due to volume and mass constraints of the rover
    - A new, dedicated rover could be developed but at added cost
    - The three separate pieces add complexity, mass, and an additional trip to/from the lander

- **By laying down the reactor and placing the control electronics 50m away** directional shielding can be optimized to provide the 5 rem/year for the crew and eliminate added shielding for the control electronics.

- In the current configuration, adding distance/over the horizon between the reactor and the crew will not reduce shield mass

- **High, DC voltage found more mass efficient** (even with conversion mass/losses) for delivering power to users 1 km away

- **Modifying the design for equatorial use** requires ~60% more radiator area and different radiator configurations for all elements

- **On-Lander option:** Assuming the lander could be placed >1 km from the crew the current reactor pallet could be kept on the lander – **just the controller/cable pallet unloaded and deployed**
  - Further work to assess radiation and any interactions with the TBD lander
Lunar 40 kWe Fission Power System Demonstrator: Smart Buyer Executive 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 m² 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

**40 kWe FSP system packaged in lander envelope**

**Deployed FSP controller package**

**Deployed FSP cable/convertor package**

**Deployed 40 kWe FSP system packaged in lander envelope**

**Rover with controller and cable elements loaded (trip #2)**

**Rover with Reactor element loaded (trip #1)**

**MEL Summary: 40kW_Case 2_FSPS Deployability CD-2021-187**

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<tr>
<th>Main Subsystems</th>
<th>Fission Surface Power System</th>
<th>Control Systems</th>
<th>Cable and Spool</th>
<th>TOTAL to be carried by Lander</th>
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<td>Basic Mass (kg)</td>
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<td><strong>Element Total</strong></td>
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<td>Element Dry Mass (no prop,conam)</td>
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<td>1257.9</td>
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<td>Element Mass Growth Allowance (Aggregate)</td>
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<td>MGA Percentage</td>
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<td>System Level Mass Margin</td>
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<td>System Level Growth Percentage</td>
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<td>Element Dry Mass (Basic+MGA+Margin)</td>
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<td>Element Inert Mass (Basic+MGA+Margin)</td>
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<td><strong>Total Wet Mass (Allowable Mass)</strong></td>
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**System Level Mass Margin**

- Approximately 1 week to deploy and commission reactor and provide user power.

**System Level Growth Percentage**

- Mobility System Trip 1
- Mobility System Trip 2

- Rover with controller package
- Deployed FSP cable/convertor package
- Deployed 40 kWe FSP system packaged in lander envelope

- Mobility System Trip 1
- Mobility System Trip 2

- 1km
- 50m

- Deployed 40 kWe FSP system packaged in lander envelope

- Deployable Reactor Package: 133 m² radiator for Stirlings, sized for polar operations
- Use at equator adds 60% radiator area

- 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

- Rover: based on Pressurized rover (PR) (up to ~8 t carrying capability) and skid based off-loadable cargo concepts. Landed separately.