Micro-grid for Future Planetary Surface Needs

Jeffrey Csank and James Soeder
NASA Glenn Research Center
Cleveland, OH
In LEO
Commercial & International partnerships

In Cislunar Space
A return to the moon for long-term exploration

On Mars
Research to inform future crewed missions
The Moon

Size:
- Equatorial radius of 1,738.1 km ~ 0.2725 of Earth
  - 5th largest moon in our solar system
  - Largest moon in solar system relative to size of the planet

Orbit period / length of day
- 27 days
- Earth and moon are tidally-locked
  - Earth will only see one side of the moon

Exploration
- More than 105 robotic spacecraft missions
- Only celestial body beyond Earth visited by Humans
Human Lunar Exploration

Future Human Lunar Missions

- Focused on testing and demonstrating technologies for sustained Lunar presence and Mars
- Potential sites & environmental concerns
  - Equatorial Regions
    - Eclipse: 14 day (336 hours)
    - Temperature: -170°C to 125°C mean -80°C
  - Polar Regions
    - Eclipse: 65 to 122 hours
    - Temperature: -230°C to -80°C mean -170°C (NP)
    - “Definitive evidence” of water-ice on the lunar surface*
      » August 2018 – Moon Mineralogy Mapper, M3
      » May contain volatiles

*Definitive evidence* of water-ice on the lunar surface.
Impact crater at the South Pole

Named after Antarctic Explorer Ernest Shackleton

Size:
- 21 km (13 mi) in diameter and 4.2 km (2.6 mi) deep

Rims are in almost continuous sunlight

Interior is perpetually in shadow (eternal darkness)
- Average temperature -183 °C (90 K)
- Temperature never exceeds -173 °C (100K / -280 °F)
- Any water vapor that arrived at the lunar surface from comets or meteorites would have been trapped

Electrical Power for the Lunar Surface

- Long Term Vision for Lunar Surface Power
- Evolution of Power on the Lunar Surface
- Grid Challenges and Requirements
- Technologies
  - Power Generation
  - Distribution
  - Micro-grids
  - Interfaces
Sustainable Presence Lunar Surface Activities

Lunar Surface Operation Power Needs

- Manufacture propellant
  - Fuel landers for round trips between the Lunar surface and Gateway at a rate of four flights per year
  - Mining/excavation regolith
  - In-Situ Resource Utilization (ISRU)
- Support a crew / crew operations
  - Crew of four for at least 30 days stay four times per year
  - Possible human 45 day Moon exploration missions
- Lunar science and technology demonstrations

A sustainable Lunar presence will require electrical power that is highly reliable and available (similar to Earth’s Electric Grid)

Evolution of Lunar Activities

Artemis I: First human spacecraft to the Moon in the 21st century

Artemis II: First humans to orbit the Moon in the 21st century

Artemis Support Mission: First high-power Solar Electric Propulsion (SEP) system

Artemis Support Mission: First pressurized module delivered to Gateway

Artemis Support Mission: Human Landing System delivered to Gateway

Artemis III: Crewed mission to Gateway and lunar surface

Commercial Lunar Payload Services
- CLPS-delivered science and technology payloads

Early South Pole Mission(s)
- First robotic landing on eventual human lunar return and In-Situ Resource Utilization (ISRU) site
- First ground truth of polar crater volatiles

Large-Scale Cargo Lander
- Increased capabilities for science and technology payloads

Humans on the Moon - 21st Century
First crew leverages infrastructure left behind by previous missions
Lunar Surface Sustainable Power Challenges

**Lunar surface power needs/uses will grow and evolve over time.**
- Power strategy (generation / energy storage) will need to evolve over time.
  - PMAD system must also be able to grow from a point to point distribution system to and integrated micro-grid
- Maintainability/reusability is a key feature, especially for early science missions/payloads.

**Ability to continue lunar surface operations regardless of time of lunar day.**
- Requires a complex power generation and energy storage strategy to provide continuous power.
  - Most likely cannot rely on just batteries/fuel cells to provide all power during lunar night.

**Highly distributed power system.**
- Power sources (generation & storage) and loads will need to be separated by large distances.
  - Physical constraints
    - Engine blast radius to minimize dust contamination
    - Nuclear radiation exclusion.
  - Operational constraints
    - Placement of solar arrays to maximize power generations.
    - Providing power into cold traps for water-ice excavation.
Lunar Surface Sustainable Power Challenges

Autonomous operation for extended periods
- Lunar surface operations will occur without Astronauts being on the surface
  - Routine procedures (excavation, mining, etc.) and construction / build-up

Robotically deployable PMAD / power systems
- Need ability for the systems to be assembled / repaired robotically
  - Majority of the time the lunar surface will be unmanned.

Mass minimization
- Finite number of landers/flights with mass restrictions.
- Have to include mass of the spares, etc.
  - Modularity / maintainability / reusability can help reduce # of parts and overall mass

Able to survive the lunar environment
- Cold temperatures
- Lunar dust (good electrical insulator and low thermal conductivity)
- Radiation hardening from cosmic rays
## Power Users

<table>
<thead>
<tr>
<th></th>
<th>Nominal Power, W</th>
<th>Survival Power, W</th>
<th>Battery Storage, Whr</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>CLPS</td>
<td>~100-500</td>
<td>~75</td>
<td>?</td>
<td>• Likely Solar design; Notional Estimates only</td>
</tr>
<tr>
<td>Lunar Terrain Vehicle</td>
<td>1750</td>
<td>300</td>
<td>15,000</td>
<td>• Solar/battery design</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>• Energy storage limited by CLPS payload capacity (500kg)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>• Requires extra 20,000 W-hr prior to Habitable Mobility Platform arrival for 4 day eclipse survival</td>
</tr>
<tr>
<td>Foundational Habitat</td>
<td>10,000</td>
<td>2,000</td>
<td>?</td>
<td>• Solar design</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>• Entire survival energy storage not desired in landed payload due to lander limits</td>
</tr>
<tr>
<td>Habitable Mobility Platform</td>
<td>3500</td>
<td>500</td>
<td>70,000</td>
<td>• Solar/battery design</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>• No extra energy storage required for 4 day survival period</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>• Extra water thermal heat available</td>
</tr>
<tr>
<td>ISRU Plants</td>
<td>8,000-37,000</td>
<td>400</td>
<td>?</td>
<td>• Design dependent: a mix of nuclear reactors and/or solar electric and solar electric/solar thermal/RFC</td>
</tr>
<tr>
<td>HLS</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>• Power sources selected for in-space operation &amp; &lt;30 day surface stay in sunlight only &amp; independent operation</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>• Power level/designs contractor dependent</td>
</tr>
</tbody>
</table>

*J. Fincannon, Lunar Surface Power Architecture, 5/4/2020*
## Power Generation

### Solar Power (Arrays)
- Lunar south pole has peaks of eternal light (85%+ of the time)
- Sun is low on the horizon
  - To maximize power arrays need to be tilted
  - Requires additional arrays to cover the horizon or be movable
- Still need power during eclipse (<15% of the time)

### Primary Fuel Cell
- Produce constant power regardless of conditions (sunlight)
- Heat & water byproducts
- No flight hardware
- Lower TRL

---

*Recent ground demo of a new PEM fuel cell for space*
**Power Generation**

### Nuclear Fission
- Produce constant power regardless of conditions (sunlight)
- Protective shielding is very heavy
  - Alternatively nuclear sources can be placed a safe distance from Lunar operations (1+ km)
- Current design produces low frequency (~60 Hz) AC power
  - Traditional space power is DC
- Technology is still at a lower TRL

### Radioisotope
- Produce constant power regardless of conditions (sunlight)
  - Low power 0.1 to 1.0 kW
- Low radiation
- Higher TRL (already in use in many applications)
- Fuel availability is limited

1kW Nuclear Fission Power
2018 Ground Demo

125W Multi-mission RTG (MMRTG)
### Energy Storage

#### Batteries
- Energy stored in electrochemical cells
- High maturity, low cost, high reliability and efficient
- Low energy density and intolerant to extreme temperatures

#### Regenerative Fuel Cells
- Insolation (charge): Electrolyzer splits water into H2 and O2
- Eclipse (discharge): Create electricity + water + heat
- High energy density
- Complex and lower TRL

#### Advanced Concepts
- Flywheel: mechanical energy storage
- Superconducting Magnetic Energy Storage (SMES)
Lunar Micro-grid

- Ability to integrate dissimilar power sources
  - Allows for sharing power between sources (generation/storage)
  - Increase overall reliability and availability of power
- Adds redundancy (distribution / generation)
- Evolvable / scalable / reconfigurable
  - Allows for evolution from a point to point – on power source per load to integrated system of multiple power sources serving multiple loads
  - Allows for consumers to grow and change over time.
- Micro-grid challenges
  - Standard interface for both power producers and consumers
  - System stability / power quality
  - Design parameters (voltage, etc) to maximize efficiency
  - Accommodates long term unattended operation
**Wired Power Transmission**

- High efficiency
- Inductive power coupling could mitigate robotic connector & dust issues
- Not limited by line-of-sight (allows for reactor to be hidden by ridge)
- Requires robotic deployment of cable and connectors
- Standard connectors will need to be dust tolerant
- High voltage transmission for space applications is low TRL

**Wireless Power Transmission**

- Convert source electricity to laser or microwave energy & transmit wirelessly (beam)
- No need for robotic deployment of cables and connectors
- Effective distance is line-of-sight with no degradation in power
  - Allows for exploration/operations in difficult terrain
- Requires active tracking for acceptable performance
- Low end-to-end efficiency (~25%) results in increase power source
- Components and systems are low maturity
Universal Modular Interface Converter (UMIC)

UMIC

- Standardize interface to connect stationary power sources – Solar Arrays / Fission to mission loads through the micro-grid
  - Power Source to micro-grid
  - Micro-grid to loads
- Modular Converter to service loads and sources at different power levels
  - Source Voltage to Micro-grid voltage
  - Micro-grid voltage to Load voltage
  - Be power scalable based on the size of the source / load
  - Minimized spare mass (hardware can be scavenged & repurposed)
- Must incorporate a connector that:
  - Can survive the harsh lunar environment (cold, dust)
  - EVA/EVR capable
Leverage early science mission payloads to increase the power generation / energy storage capability of the Lunar Surface power system.
STMD Collaboration Opportunities

https://www.nasa.gov/directorates/spacetech/solicitations

Open Solicitations
- NASA Space Technology Graduate Research Opportunities - Fall 2021 (NSTGRO21) (Nov 2, 2020)
- Lunar Vertical Solar Array Technology (Nov 16, 2020)

Recently Closed Solicitations
- Lunar Surface Technology Research (LuSTR) Opportunities

Upcoming Solicitations
- Nuclear Thermal Propulsion Industry Solicitation (DOE) – September/October 2020
- Fission Surface Power System Design Solicitation (DOE) – October 2020
- 2021 SBIR/STTR Phase I solicitation – November 2020
- 2021 Early Career Faculty solicitation – February 2021
- 2021 Early Stage Innovations solicitation – April 2021
Summary

NASA has an increasing focus on returning to the Moon to test and demonstrate technology for Mars

- Major step towards getting humans on Mars (Moon2Mars)

Sustainable power for the Lunar surface has some very unique challenges.

- Ability for the lunar surface power system to grow and evolve over time.
- Ability to survive the lunar environment

Key features of the Lunar surface power system will include:

- Dissimilar power sources to deliver the required power
- Growth from a point-to-point system to a Lunar power utility
- Robotically deployable, modular, and reconfigurable power systems
- A highly distributive design that spans large distances
  - Allow for Lunar activities to occur where needed:

To deliver will require an investment in power related technologies

- Autonomous control, robotics, and Autonomous power management
- Modular power systems
- Power source devices, such as Nuclear Fission and Fuel Cell
Thank you!!
Any Questions?
Power Electronics (PMAD)

**Modular (AMPS / MUSTANG)**
- Small suite of common component replaceable power system building blocks
- Reduced time development time and cost
- Minimized spare mass (hardware can be scavenged & re-purposed)
- Higher initial mass/volume
- Medium TRL
- Standards & industry adoption is ongoing

**Custom / Dedicated**
- Current standard for space components
- Lowest initial mass
- Highest performance & maturity
- Higher development cost
- Higher total system mass for crewed missions