LSIC Surface Power Telecon

June 22nd, 2023
Begins at 11:03

Dr. Sean Young, Dr. Matt Clement
Sam Andrade, Julie Peck, Dr. Joseph Kozak
Johns Hopkins Applied Physics Laboratory
Space Exploration Sector

LSIC Surface Power Facilitator POC: matt.clement@jhuapl.edu
LSIC | Agenda

• Community Updates
  • Solicitations and Awards
  • Conferences/Workshops/Telecons
    • July 12-13: LSIC Lunar Proving Grounds Workshop
    • July 26-27: LSIC Surface Power Reliability Workshop

• Confluence Tour

• Lunar Surface Habitats
  • Paul Kessler (NASA, Surface Habitat Lead Architect)
  • Professor Ali Bazzi (University of Connecticut)
  • Professor Marshall Porterfield (Purdue University)

• Q&A
LSIC | Solicitations and Awards

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

NIAC 2024 Phase I Proposals
Proposals Due: June 28, 2023

Early Stage Innovation Solicitation
Proposals Due: July 6, 2023

Lunar Terrain Vehicle (LTV) Services
Proposals Due: July 10, 2023

University Smallsat Technology Partnership (USTP)
Full Proposals Due: July 18, 2023

TechFlights Solicitation
Final Proposals Due: October 4, 2023

Space Technology Research Institutes (STRI)
Solicitation release coming in 2024
Lunar Terrain Vehicle Services (LTVS) Procurement

- Solicitation Released: May 26th
- Proposals Due: July 10th
- Contract awards begin: November 2023

  - LTV will functionally be a cross between an Apollo-style crewed rover and a Mars-style autonomous vehicle (e.g. Curiosity, Perseverance).
  - The awardee will provide end-to-end (development, delivery and execution) of LTV services.
  - NASA intends to utilize an LTV for crewed operations on Artemis V around 2029.
LSIC | Upcoming Meetings and Workshops

LSIC Lunar Proving Grounds Workshop
July 12-13, HYBRID: Laurel, MD and Virtual

LSIC Surface Power Reliability Workshop
July 26-27, Virtual

PI Launchpad: Developing Your First Mission Proposal
July 24-27, Ann Arbor, MI

LSIC Autonomy Workshop (Joint E&C-EA)
August 21-22, Virtual

2023 LSIC Fall Meeting & Transition to Industry Workshop
October 10-12, Pittsburg, PA

More complete calendar on LSIC website, email with additional events!
Summary:

- The topic of facilities needed for testing hardware destined for the Moon and the need for Earth-based ‘Lunar Proving Grounds’ for testing systems has come up across all six Focus Areas of LSIC. While facilities exist for component- and instrument-level technology maturation (e.g., up to system/subsystem demo in relevant environments), and there are potential flight opportunities for component maturation to flight-qualified and even flight-proved systems, the Artemis Program vision for a sustained presence and transition to industry (e.g., the Moon to Mars Objectives and the LSIC “Path to an Enduring Lunar Presence” white paper) suggests an architecture of integrated systems and systems of systems more complex than Apollo or the International Space Station.

Objectives:

1. Define the role of a lunar proving ground on the Earth (and potentially on the Moon).
2. Collect/define needs, attributes, and performance capabilities of Lunar Proving Grounds from technology developer’s perspective.
3. Identify the programmatics and logistics required to implement the Lunar Proving Ground.
LSIC | Surface Power Reliability Workshop

- Date: July 26-27
- Time: 11:00AM – 3:30 PM ET
- Location: Virtual via Zoom
- Abstracts Due: 30 June
- Registration Closes: 7 July

REGISTRATION AND ABSTRACT SUBMISSION ARE OPEN

- How do we approach reliability from the system/grid level and how should this affect the early-TRL development at the component level?

John Scott (NASA)
Principal Technologist
Power & Energy Storage

Clay Smith (APL)
ISS Probabilistic Risk Assessment Creator

David McGlone (NAVSEA)
Director
Submarine Safety Program

Joe Miller (NSF)
Antarctic Facilities Program Manager

Jim Soeder (NASA, ret.)
Senior Power Technologist (08-21)
Power Development Chief (87-08)

Roger Boyer (NASA)
Artemis Probabilistic Risk Assessment Lead

Blanca Lara (NASA)
JSC EHP Lunar Power Lead

Bill Anderson (NAVFAC)
Director of Utilities and Energy Management
We hope to see you all at our next telecon, which will take place on Thursday August 24\textsuperscript{th}, 2023 at 11:00AM ET.

**Topic:** A High Temperature Heat Rejection System for Fission Power Generation

**Speakers:** Alex Miller (ThermAvant Technologies)

**Description:** ThermAvant Technologies (ThermAvant) has used a NASA Phase II SBIR to develop of an intermediate temperature, large format, high-capacity Oscillating Heat Pipe (OHP) embedded radiator panel to significantly improve the size, weight and power density of a future kilowatt class Fission Power Systems (FPS). More specifically, their work aims to construct thin profile radiator panels, (>1 m\textsuperscript{2} scale and 2-3mm thick), to reject waste heat from the reactor system, and get the technology positioned for implementation.
Objective: The goal of this workshop is to gather the Lunar community to exchange ideas on autonomy, as well as identify technology gaps and use cases for establishing a sustainable presence on the Moon and Mars.

Day 1:
- Morning - Autonomous Systems, Situational and Self Awareness, Reasoning and Acting
- Afternoon - Collaborative Systems

Day 2:
- Morning - Applications in Autonomy on Lunar Surface - Current Champions (e.g. Autonomous Construction & Assembly)
- Afternoon - Challenges in Autonomy (Test & Evaluation, Cybersecurity, Dynamic Reasoning Models, Environmental Considerations)
Surface Power Home

Created by Andrea Harman, last modified by Matt Clement on Mar 27, 2023

Surface Power

Vision Statement:

NASA needs power systems which can survive the lunar night and enable exploration. The overarching goal of the surface power focus group is to provide specific recommendations to NASA for rapidly achieving appropriate-scale power-related technologies needed to enable sustained presence and exploration.

What We Will Do:

The Surface Power focus area will develop and mature technologies and systems to supply continuous power throughout the day and night for lunar surface missions. In the short-term, our interdisciplinary community that includes members from industry, government, academia, and non-profits is pursuing solutions to provide power for near-term lunar missions and the development of a lunar grid. It is crucial that this initial grid is also scalable in order to support the much larger power demands of initial production-scale ISRU operations in the 2030s. The primary multi-kW power generation technologies being investigated within the LSIC Surface Power community are Fission Surface Power (FSP) and Vertical Solar Array Technologies (VSAT). It is highly likely that a combination of both of these types of units will ultimately form the foundation of the initial lunar grid.

At the sub-kW power scale, the LSIC community concentrates on radioisotope power sources (RPS) and low-temperature batteries. Additionally, power distribution (cables and beamed power), large-scale energy storage (e.g., Regenerative Fuel Cells), and radiation-tolerant electronics represent key technology gaps that the Surface Power team and our collaborators focus on.

The group will conduct a phased, system level assessment of possible power architecture solutions for the planned Artemis missions to the lunar surface missions and beyond. To work towards this, we connect power experts to their potential user base, framed by the economic and institutional drivers that set the scale of power demand. This approach enables us to identify near-term needs for immediate prioritization, and long-term goals that impact early architectural decisions.

Recent Accomplishments:

- Led a Low-Temperature Power and Energy-Storage Workshop in July of 2022 to discuss novel solutions for surviving the extreme conditions of the 14-day lunar night, and better connect industry and academic community members working on cutting-edge battery and thermal management technologies with NASA engineers, technologists, and policy makers.
- Hosted all three NASA FSP Phase I awardees (Lockheed Martin, Westinghouse, and X-Energy) for an extended January 2023 telecon that included presentations and a panel discussion. The event illuminated the current state of the blossoming space nuclear industry, and also highlighted a number of potential challenges requiring imminent attention.
- Continued to broaden the LSIC Surface Power Community by hosting new industry members working on power beaming and radiation testing of space electronics as speakers for the February and March 2023 telecons, respectively.

Current Efforts

- Hosting all three NASA VSAT Phase II awardees (Astrobotic, Honeybee, and Lockheed Martin) for an extended telecon and panel discussion on May 25, 2023.
- Planning a 2-day Power System Reliability Workshop (July 26-27, 2023) to better characterize what “reliability” means for lunar systems and explore methods for assessing the reliability of multi-kW power systems. The workshop will feature a mix of presentations, technical panel discussions, and small group discussions to provide a forum for community members to exchange ideas and experiences related to power system reliability.
Surface Power meetings usually occur on the fourth Thursday of the month at 11:00AM eastern time.

Past Meeting Pages:
- 2020 SP Telecons
- 2021 SP Telecons
- 2022 SP Telecons
- 2023 SP Telecons

Meeting Information
https://jhuapl.zoomgov.com/j/1617206812?pwd=ZWhaW5XRURtRmxLcWo4b1ZceFFwUT09

Meeting ID: 161 720 6812
Password: 655310
One tap mobile
+16692545252, +1617206812# US (San Jose)
+16468287666, +1617206812# US (New York)
Dial by your location

Upcoming Telecons:

June 22 2023:
- Power requirements for Lunar Habitats:
  - Paul Kessler (NASA, Surface Habitat Lead Architect)
  - Ali Bazzi (University of Connecticut)
  - Marshall Porterfield (Purdue, Pulsar)

August 24 2023:
- Alex Miller (ThermAvant Technologies)

September 28 2023:
- Eric Maxeiner (Rolls Royce)
16 March 2023

On March 16th at 11:00AM ET, the Surface Power Focus Group will host a Rad-Hard Electronics-themed telecon. We will hear from Akin Akturk (CoolCAD Electronics) about heavy ion, gamma and neutron testing methodologies.

Speaker: Akin Akturk

Abstract: CoolCAD has extensive experience in performing a variety of radiation experiments required for space (gammas, x-rays, electrons, protons, heavy ions) and terrestrial (wide energy spectrum neutrons) qualifications. Of particular interest are several ionizing dose, single event effects, and displacement damage tests we performed for space applications, as well as atmospheric neutron tests we performed for terrestrial applications, using silicon carbide low and high voltage devices that we fabricate and also are commercially available. In this talk, we will mainly focus on SiC high voltage power MOSFETs, and give a brief summary of the response of these devices to various stimuli. Additionally, at CoolCAD, we work on improving radiation tolerance of silicon carbide power devices. As part of this effort, we test heavy ion single event effects in silicon carbide devices we design and fabricate. We will also present some of the new data from our newly fabricated devices that are radiation tolerant.

Agenda:
- Intro and Community Updates
- Akin Akturk Presentation
- Question and Answer

Zoom Recording

Speaker’s slides

Speaker’s abstract
Go to Surface power page under “Our Work”

Click on “Past Meetings”

Slides and Zoom recordings
Useful papers, publications, articles and slides organized by SP's various technology focus areas.
• Speaker: Paul Kessler
• NASA, Surface Habitat Lead Architect
• Speaker: Ali Bazzi
• University of Connecticut
• Charles H. Knapp Associate Professor of Electrical Engineering
Speaker: Marshall Porterfield

Purdue University

Professor of Agricultural & Biological Engineering
Lunar Surface Power Assessment for Habitation

Paul Kessler, Surface Habitat Lead Architect
LSIC 6/22/2023
Background

• **Energy Storage Challenges for Habitation**
  – Initial allocations for shadow period survival challenges delivery capability
  – **Mass**: Habitable elements often struggle meeting vehicle delivery performance
  – **Volume**: Smaller habitable elements struggle to fit energy storage within volume envelopes

• **Potential architectural shifts to include multi-regional exploration**
  – Driven by desire for significant surface exploration
  – Leverages relocatable/mobile habitable elements

• **NASA Lunar Power Sub-Architecture Trade requires habitation perspective**

• **Emerging external power system investments (i.e., Vertical Solar Array Technology (VSAT))**
  – May change habitation power architecture
  – Fission Surface Power excluded in initial study

• **Differing element energy storage requirements necessitate closer investigation of energy storage assumptions**
  – Surface Habitat (SH) concept protects 100 hr darkness, necessitating optimal placement in few locations
  – Multi-purpose Habitat (MPH) and mobile elements protect 150 hr darkness
Goal and Objectives

GOAL:
Arrive at a government reference, optimized power architecture for scalable lunar surface habitation, considering possible external power integration and mobile assets.

- Define scope of lunar surface habitation power needs
- Summarize previous lunar power architecture studies & assumptions
- Assess current and near-future power generation & energy storage technologies
- Better quantify maximum expected terrain shadowing periods & variability for lunar south pole
- Determine the effects of mobility on power architectures (Element and/or external power system mobility)
The Lunar Habitat Energy Trade Space

**Power System Technology Trade Space**
- Solar Arrays/Photovoltaics
- Fuel Cells/Regenerative Fuel Cells (RFC)
- Heat Engines
- Phase Change Materials (PCM)
- Nuclear Systems

**Energy Storage**
- Batteries
- Reactants

**Future scope**

**Power Integration Trade Space**
- Notional Surface Habitat

**Standalone Power**
- Power systems integral to habitation element

**External Power**
- Power systems externally connected with habitation element

**Shared Power**
- Power systems shared with attached habitation element (i.e., mobility chassis)

Future scope

Notional Relocatable Habitat

Paired technologies
Surface Habitat Reference Concept

NASA’s surface habitat concept serves as a central hub for building & initial sustainment of Artemis’ Foundation Exploration activities

Key Surface Habitat functions:
- Power generation & energy storage (100 hrs)
- Open/Regenerative Environmental Control & Life Support (ECLS)
- Extravehicular Activity (EVA) support & suit maintenance
- Communications & data relay
- Medical support

Surface Habitat Concept Design Characteristics

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
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<tbody>
<tr>
<td>Crew Size</td>
<td>2 crew (nominal) – 4 crew (surge*)</td>
</tr>
<tr>
<td>Mission Duration</td>
<td>~30 days (initial) – 60 days (extended)</td>
</tr>
<tr>
<td>Lifetime</td>
<td>15 years</td>
</tr>
<tr>
<td>Mass Target</td>
<td>12 mt (goal)</td>
</tr>
<tr>
<td>Max Power</td>
<td>15 KWe</td>
</tr>
<tr>
<td>Pressurized Volume</td>
<td>~190 m³</td>
</tr>
<tr>
<td>Operating Pressure</td>
<td>8.2 – 10.2 psia (70.3 – 56.5 kPa)</td>
</tr>
<tr>
<td>Oxygen Composition</td>
<td>34-26.5% (limits for 8.2-10.2 psia)</td>
</tr>
</tbody>
</table>

*Surge capacity when other elements present

### Power System Technology Trade Space

**Assessment Processes**

1. Capture near-term power generation & storage options
2. Establish Figures of Merit (FOMs)
3. Gather state-of-the-art quantitative FOMs for each option
4. Quantify South Pole lighting availability
5. Capture & discuss qualitative FOMs
6. Assess each option against incremental power generation & energy storage levels
   - Power generation increments of 2 kW ranging 2-20 kW
   - Energy storage increments supporting 80-340 hrs of darkness and 2-20 kW power loads
   - Intent is to identify if preferred solution changes at given power or energy storage levels
7. Capture future power generation & storage options

### Power Integration Trade Space

**Power System Technology Assessment**

1. Capture near-term power generation & storage options
2. Establish Figures of Merit (FOMs)
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   - Intent is to identify if preferred solution changes at given power or energy storage levels
7. Capture future power generation & storage options

**Power Integration Assessment**

1. Identify MPH & SH power loads for minimal crewed mission functionality
2. Identify MPH & SH power loads for maximum crewed mission functionality
3. Identify potential external power solutions
   - Outline planned development timeframes & highlight developmental risks
4. Identify possible mass/volume savings with external power
5. Assess opportunities for power sharing with other elements
Assessment Ground Rules & Assumptions

• Assume lunar south pole region (~>83°S) and associated illumination considerations
  – Region of focus for initial Artemis missions, with notional exploration regions aligning with Artemis III candidate landing sites

• Power architecture will support habitat lifetime of 10 yrs
  – This may not be achievable with some systems, requiring logistical replacement/refurbishment which should be captured

• Assume crewed operations do not nominally occur during darkness periods
  – May be considered as a future capability with augmentation

• Power architecture will consider average/nominal power loads
  – Peak & variable loading should be analyzed as a future assessment through modeling & simulation

• Energy storage will be sized for uncrewed operational power loads during darkness

• Supplementary external power may be considered
  – Minimum standalone power generation and energy storage needs will be integrated with habitation element

• Ability to scale the power architecture supporting habitation should be considered
  – Accommodates evolving mission needs (i.e., future inclusion of regenerative environmental control and life support systems (ECLSS))

• Highlight technologies likely to support 2029-2030 delivery to lunar surface
  – Some technologies may carry higher development risk, which should be captured
Habitation Power/Energy Considerations

- Long duration survival through shadowed periods
- Energy storage and regeneration for habitat relocation
- Lander delivery performance and human-rated battery mass
- Regenerative Fuel Cell (RFC) volumetric requirements
- RFC development schedule
- Lunar environment impact to power system degradation
- Surface power/energy storage augmentation availability to habitation
Questions
Modeling and Operation of Microgrids for Deep Space Habitats Under Environmental Disturbances

Ali Bazzi
University of Connecticut
06/22/2023
Resilient Extraterrestrial Habitats Institute

- RETHi is a NASA Space Technologies Research Institute (STRI) that is focused on topics beyond habitat design to achieve habitat resilience
- Fourth year annual review concluded yesterday, one more year to go.
- Member institutions:
  - Purdue University (Lead, PI: Prof. Shirley Dyke)
  - University of Connecticut (Institutional PI: Prof. Ali Bazzi)
  - Harvard University (Institutional PI: Dr. Justin Werfel)
  - University of Texas at San Antonio (Institutional PI: Prof. Arturo Montoya)
At UConn, we focus on: Power systems and microgrids, structural health monitoring, communication systems, and robotics.

**Two testbeds that UConn is co-developing:**

- Modular coupled virtual testbed (MCVT): a full habitat simulation in Simulink with many system models.
- Cyber-physical testbed (CPT): UConn has a power hardware-in-the-loop testbed with coupling to a structure (pressure box), structural health monitoring, full communication and sensing network, power sources and loads, and a robotic arm to perform repairs.
Work Contribution

- Review the state-of-the-art of the space microgrid for long-term space exploration and human presence in space.

- Presents many aspects of extraterrestrial electrical power system.

- Studies the challenges of extraterrestrial microgrids, possible microgrid failures, and their effects on the functionality of the space habitat.

- Presents simulation results of different disruption scenarios and microgrid failures using a modular space habitat model.
Proposed Extraterrestrial Microgrid

Power Subsystem

- Monitoring loads
- Solar PV generator
- Energy storage system
- Nuclear generator
- Agent
- Smart Power Distribution (SPD)
- Management, control, and communication system

Other space habitats loads
Critical loads

- Power transmission (Physical)
- Communication signal (Cyber)
- Intervention
- Disruption

Disturbances:
- Sensor failure
- Dust
- Meteorite
- Fire
- Moongale

Funded by the National Aeronautics and Space Administration
Proposed Extraterrestrial Microgrid

Electrical loads

- Power transmission (Physical)
- Communication signal (Cyber)
- Intervention
- Disruption

Power Subsystem

- Smart Power Distribution (SPD)
- Solar PV generator
- Energy storage system
- Nuclear generator

- Monitoring loads
- Other space habitats loads
- Critical loads

Disturbances
- Sensor failure
- Dust
- Meteorite

Fire
Moonquake

Funded by the National Aeronautics and Space Administration
Electrical loads in extraterrestrial habitats vary in criticality and profile.

- **Life support**
  - Heating
  - Cooling
  - Pressure
  - Air quality

- **Monitoring loads**
  - Lighting
  - Sensors
  - FDD equipment

- **Other habitat loads**
  - Housekeeping
  - Scientific instruments
  - Rovers and EV chargers
Proposed Extraterrestrial Microgrid

Power generation

- Monitoring loads
- Other space habitats loads
- Critical loads
- Smart Power Distribution (SPD) Management, control, and communication system
- Solar PV generator
- Energy storage system
- Nuclear generator

Power transmission (Physical)
Communication signal (Cyber)
Intervention
Disruption

Funded by the National Aeronautics and Space Administration
Proposed Extraterrestrial Microgrid

Power generation

Nontraditional energy generation technologies are suggested due to the:

- Extreme environmental conditions in space
- Criticality of some electrical loads
- Complexity of the system
- Limited resources
- Other logistical requirements
  - Size of the equipment
  - Weight of the equipment
Proposed Extraterrestrial Microgrid

Power generation

Multi-junction PV cells
- Superior solar energy efficiency
- Mature manufacturing processes
- Radiation hardness
- Low temperature coefficient
- High specific power
- Time and location dependency

Kilowatt nuclear fission
- Scalable power range
- Small size
- Reliable, resilient, and stable
- Location and time independent
- High specific power
- Time and location dependency

Fuel cells
- High specific energy
- Low technology readiness level
- Limited resources in space
Proposed Extraterrestrial Microgrid

Energy storage
Energy storage system is the only solution to support the habitat during critical situations, disturbances, and failures.

- **Nickel Cobalt Aluminum Oxides (NCA)** batteries are commonly used in space:
  - Operational capabilities in shallow temperatures of less than −40°C
  - High specific energy (more than 250Wh/kg)
  - Long calendar life (more than five years)
  - Long cycle life
  - Radiation tolerance
Proposed Extraterrestrial Microgrid
Smart power distribution

Power Subsystem

- Monitoring loads
- Other space habitats loads
- Critical loads
- Smart Power Distribution (SPD)
- Energy storage system
- Solar PV generator
- Nuclear generator

Disturbances:
- Sensor failure
- Dust
- Meteorite
- Fire
- Moongrave

- Power transmission (Physical)
- Communication signal (Cyber)
- Intervention
- Disruption

Funded by the National Aeronautics and Space Administration
The control and operation management system of space microgrids involves:

- Scheduling resources
- Planning the loads and their operating modes

Load prioritization and distribution model
The proposed smart power distribution system has 3 modes of operations:

- **Mode 1:** 
  \[ \text{Load} \leq \text{Nuclear} \rightarrow \text{The power demand is supplied from the nuclear power only (ES is not needed, charged if needed)} \]

- **Mode 2:** 
  \[ \text{Nuclear} < \text{Load} \leq \text{Nuclear} + \text{Solar PV} \rightarrow \text{The power demand is supplied from the nuclear and solar power (ES is not needed, charged if needed)} \]

- **Mode 3:** 
  \[ \text{Nuclear} + \text{Solar PV} < \text{Load} \rightarrow \text{The power demand is supplied from the nuclear, solar and ES (ES is needed)} \]
Load prioritization, management, and distribution are identified based on the system phase of operation and mission type.

Example – crewed system:

The distribution operating conditions after a fault occurs could be:

1. Supply all the loads
2. Supply critical loads and monitoring loads
3. Supply Critical and FDD loads
4. Supply critical loads only
5. No load supply

Note: In case there is excess of power, energy storage system is charged

Ex: \( P_{\text{critical}} < P_{\text{GB}} < P_{\text{critical}} + P_{\text{FDD}} \)

\[ P_{\text{charging}} = P_{\text{GB}} - P_{\text{critical}} \]
DC power distribution system is recommended:
- Higher efficiency and reliability
- Ease of maintenance
- It is employed in permanently crewed space installations – International Space Station (ISSS)

Proposed based on the:
- Ratings of the power generating units
- Electrical requirements of the loads in the ISS
- Electrical systems ratings used for aeronautic applications
Environmental Challenges of Extraterrestrial Microgrid

- Monitoring loads
- Power transmission (Physical)
- Communication signal (Cyber)
- Intervention
- Disruption
- Other space habitats loads
- Energy storage system
- Nuclear generator
- Agent
- Sensor failure
- Dust
- Meteorite
- Fire
- Moonglare
Extraterrestrial electrical power system environmental threats include:

- Temperature extremes; e.g. −193.15°C to 122.78°C on the lunar surface
- Space debris, micrometeorites, and electrically charged dust particles
- Vacuum
- Solar ultraviolet radiation
- Plasma
- Surface charging and arcing
- Other possible hazards such as a fire in the interior environment of a space habitat
Effect of Power System damage in a space habitat

- Power system components are developed and integrated into a **modular space habitat model** in MATLAB Simulink
Effect of Power System damage in a space habitat

- Different disturbance types and robotic repair capabilities, are simulated to examine the:
  - Response of the space microgrid during environmental disruptions
  - Effect of power system damage on the space habitat functions

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Scenario 1</th>
<th>Scenario 2</th>
<th>Scenario 3</th>
<th>Scenario 4</th>
<th>Scenario 5</th>
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<tbody>
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<td>-</td>
<td>High</td>
<td>High</td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td>Meteorite location</td>
<td>-</td>
<td>Nuclear reactor</td>
<td>Nuclear reactor</td>
<td>Habitat structure</td>
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<tr>
<td>Period</td>
<td>Day</td>
<td>Night</td>
<td>Night</td>
<td>Night</td>
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<tr>
<td>Dust level</td>
<td>Low</td>
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<td>High</td>
<td>Moderate</td>
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<tr>
<td>Robotic repair</td>
<td>-</td>
<td>Available</td>
<td>None</td>
<td>Available</td>
<td>None</td>
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</table>
Simulation results show nominal operating conditions of the power system.

Note: The time scale is reduced to increase the simulation speed.
Effect of power system damage in a space habitat
Scenario 2 – Meteorite on habitat structure with robotic intervention

Simulation results show:

- Decrease in nuclear-generated power due to meteorite
- Gradual decrease in nuclear generation due to dust accumulation
- Gradual recover of the system
- Decrease in the SOC
- Normal and continuous operating conditions of the habitat’s monitoring system

Simulation results show:

- Decrease in nuclear-generated power due to meteorite
- Gradual decrease in nuclear generation due to dust accumulation
- Gradual recover of the system
- Decrease in the SOC
- Normal and continuous operating conditions of the habitat’s monitoring system
Conclusion and Future Work

- This work:
  - Proposed a microgrid architecture for space habitats
  - Addressed the nontechnical and environmental challenges of space microgrids
  - Showed the effect of external disturbances on the microgrid's functionality and the power system's criticality in maintaining the space habitat operation

- Simulation results showed the criticality of the load management and control in maintaining the space habitat functionality

- Future work will propose possible approaches to improve the system's resilience and availability