JOHNS HOPKINS
APPLIED PHYSICS LABORATORY

LSIC Surface Power Telecon

June 22nd, 2023

Begins at 11:03

Lunar Surface Innovation
CONSORTIUM

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

LSIC | 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!

LSIC | Lunar Proving Grounds Definition Workshop
July 12-13, 2023

APL

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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.

This is a discussion-based workshop, no abstracts will be solicited!

Registration is now open!

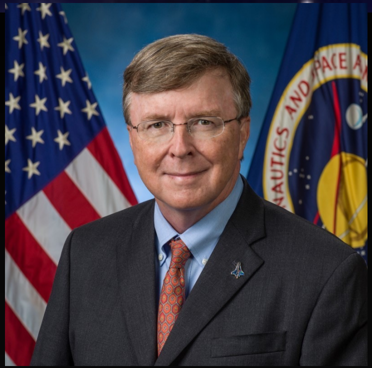
Objectives:

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 <u>OPEN</u>***
- 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

LSIC | August Telecon

We hope to see you all at our next telecon, which will take place on **Thursday August 24th, 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^2 scale and 2-3mm thick), to reject waste heat from the reactor system, and get the technology positioned for implementation.

LSIC | Joint E&C/EA Autonomy Workshop (Virtual 08/21- 08/22)

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)

LSIC | Confluence Tour

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Surface Power

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- Surface Power Year One Goal
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- Who's Who in LSIC-Surface Power
- SP Resources

Links to resources for starting conversations, subgroups, networking, and upcoming events

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Surface Power

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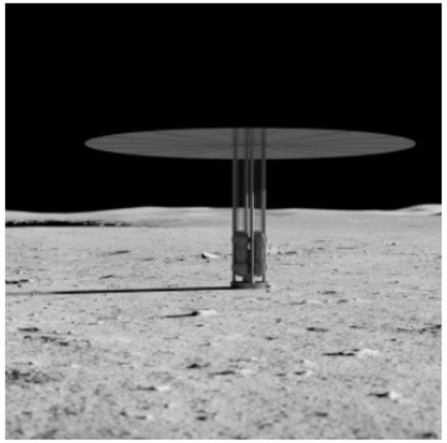
Vision Statement:

NASA needs power systems which can survive the lunar night and enable exploration. The over-arching 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

LSIC | Confluence Tour: Monthly Meetings Page

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SP Monthly Meeting

Created by Andrea Harman, last modified by Matt Clement on May 26, 2023

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

Links to zoom recordings and slides from old telecons

Meeting Information

https://jhuapl.zoomgov.com/j/1617206812?pwd=ZWhlaW5XRURsRmxJcWd4b1ZoeFFwUT09

Meeting ID: 161 720 6812

Password: 655310

One tap mobile

+16692545252,,1617206812# US (San Jose)

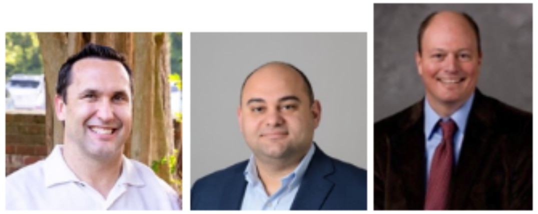
+16468287666,,1617206812# US (New York)

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)

Links to info on upcoming telecons

LSIC | Confluence Tour: Past Meeting Page (March 2023)

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    - 23 February 2023
    - **16 March 2023**
    - 13 April 2023
    - 25 May 2023
    - 22 June 2023
    - 24 August 2023
    - 28 September 2023
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Pages /... / 2023 SP Telecons

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16 March 2023

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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.

Speaker's abstract

Agenda:

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

Slides:

Speaker's slides

Zoom Recording:

Zoom Recording

LSIC | Slides and Recordings are also on lsic.jhuapl.edu!

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Surface Power

NASA needs power systems which can survive the lunar night and enable exploration. The over-arching 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. Succinctly, to enable the right power in the right place at the right time.

Go to Surface power page under "Our Work"

APL Staff

Contact all staff

- Sean Young — SP CO-LEAD
- Matt Clement — SP CO-LEAD AND FACILITATOR
- Samantha Andrade
- Julie Peck
- Joseph Kozak
- Claire Trop

Focus Group Subgroups Past Meetings

Click on "Past Meetings"

- August 2023 Telecon — Surface Power - Monthly FG
- July 2023 Telecon — Power System Reliability Workshop
- June 2023 Telecon — Surface Power - Monthly FG
- May 2023 Telecon — Surface Power - Monthly FG
- April 2023 Telecon — Surface Power - Monthly FG — Presentation — Recording

Slides and Zoom recordings

LSIC Wiki on Confluence

Open to LSIC members only.

To request access, please contact lsic-wiki-admins@listserv.jhuapl.edu.

LSIC Wiki

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Listserv Survey

Related News

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  - Power Beaming Summary Figure

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SP Resources

Created by Jodi Berdis, last modified by Matt Clement on May 05, 2023

Power Grids

Giachetti (2022): Resilience and Cost Trade Space for Microgrids on Islands

Photovoltaics

Lunar VSAT Solicitation (SpaceTech–REDDI–2020)

JPL (2017): Solar Power Technologies for Future Planetary Science Missions

Pappa et al. (2013): Solar Array Structures for 300 kW-Class Spacecraft

Fission Surface Power

Lee Mason (2023): A very brief summary of NASA's last attempt at FSP systems (2007-2015)

Fission Surface Power Phase I Statement of Work

Chrisopher Brath (August 2022): NASA Fission Surface Power Project Update

Nuclear Energy Institute (2018) Roadmap for the Deployment of Micro-Reactors for U.S. Department of Defense Domestic Installations

El-Genk (2009): Space Reactor Power Systems

Krasner et al. (1971): Conceptual Design of a Compact Fast Reactor for Space Power

Palac et al. (2016): STMD Nuclear Systems Kilopower Overview

Leyse et al. (1990): Space Nuclear Propulsion - The Low Pressure Nuclear Thermal Rocket

Power Management / Miscellaneous / Other

https://www.herox.com/WattsOnTheMoon - Watts on the Moon Challenge

Colozza (2020): Small Lunar Base Camp and In Situ Resource Utilization Oxygen Production Facility Power System Comparison

Oeftering et al. (2013): Advanced Modular Power Approach to Affordable, Supportable Space Systems

Bugby et al. (2022): Lunar Night Survivability of Cryocooled Instruments Using PALLETE Thermally-Switched Enclosures

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

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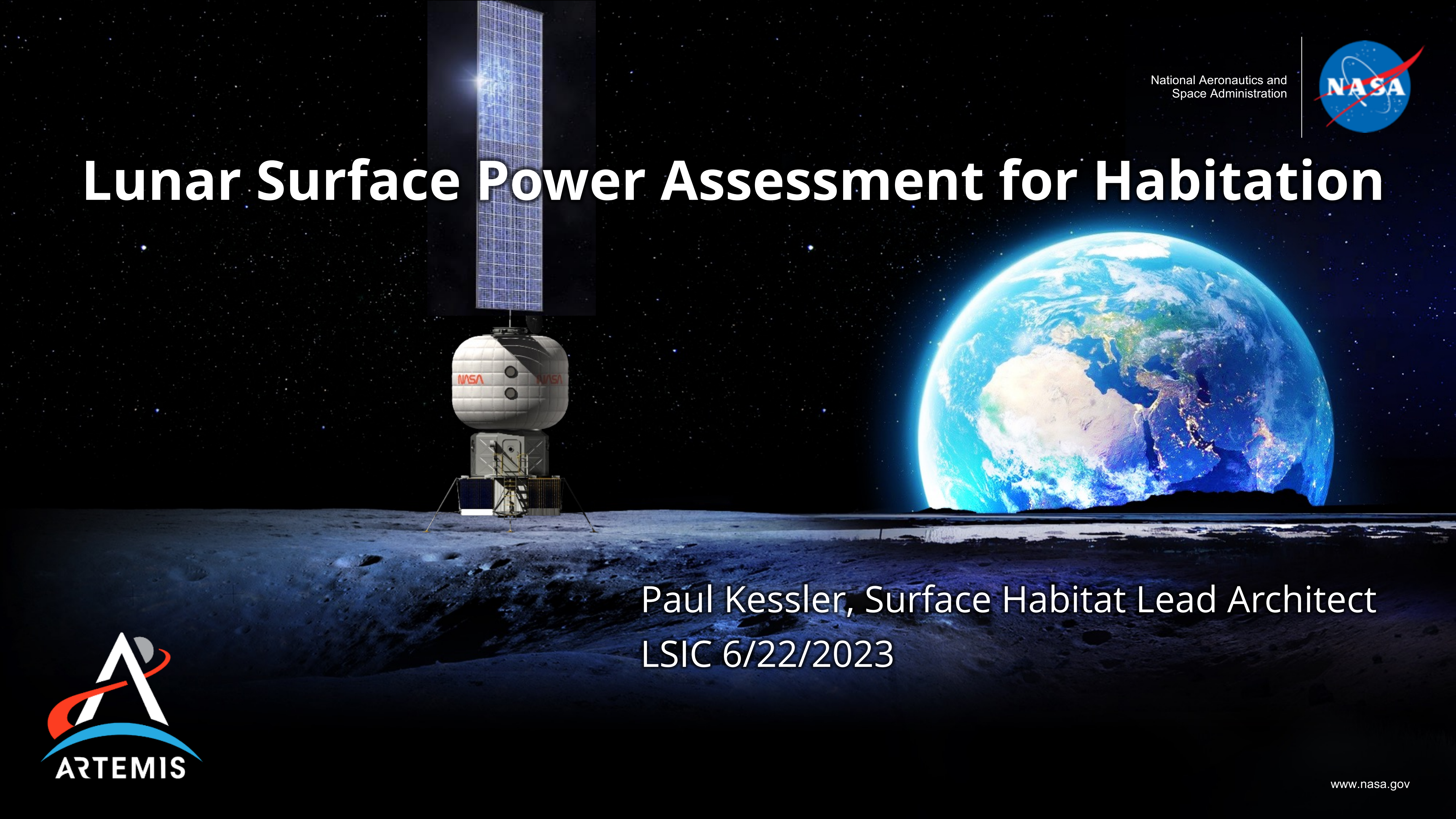


National Aeronautics and
Space Administration

Lunar Surface Power Assessment for Habitation

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

ARTEMIS

NASA's Habitation Systems Development Team

NASA Marshall Space Flight Center – Habitation Systems Development Office

Danny Harris
Habitation Concepts/Pre-Formulation Lead

Tiffany Nickens*
Habitation Concepts/Pre-Formulation Deputy Lead

Andrew Choate*
Transit Habitat Technical Lead

Paul Kessler*
Surface Habitat Technical Lead

James E. Johnson*
Habitation Systems Engineer

* Co-Authors

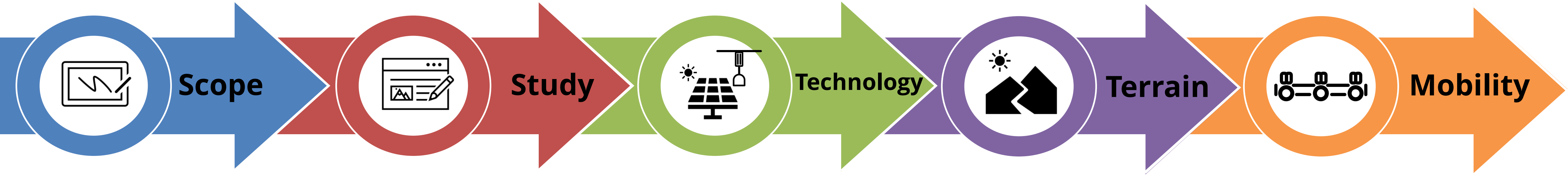
Background

- **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:

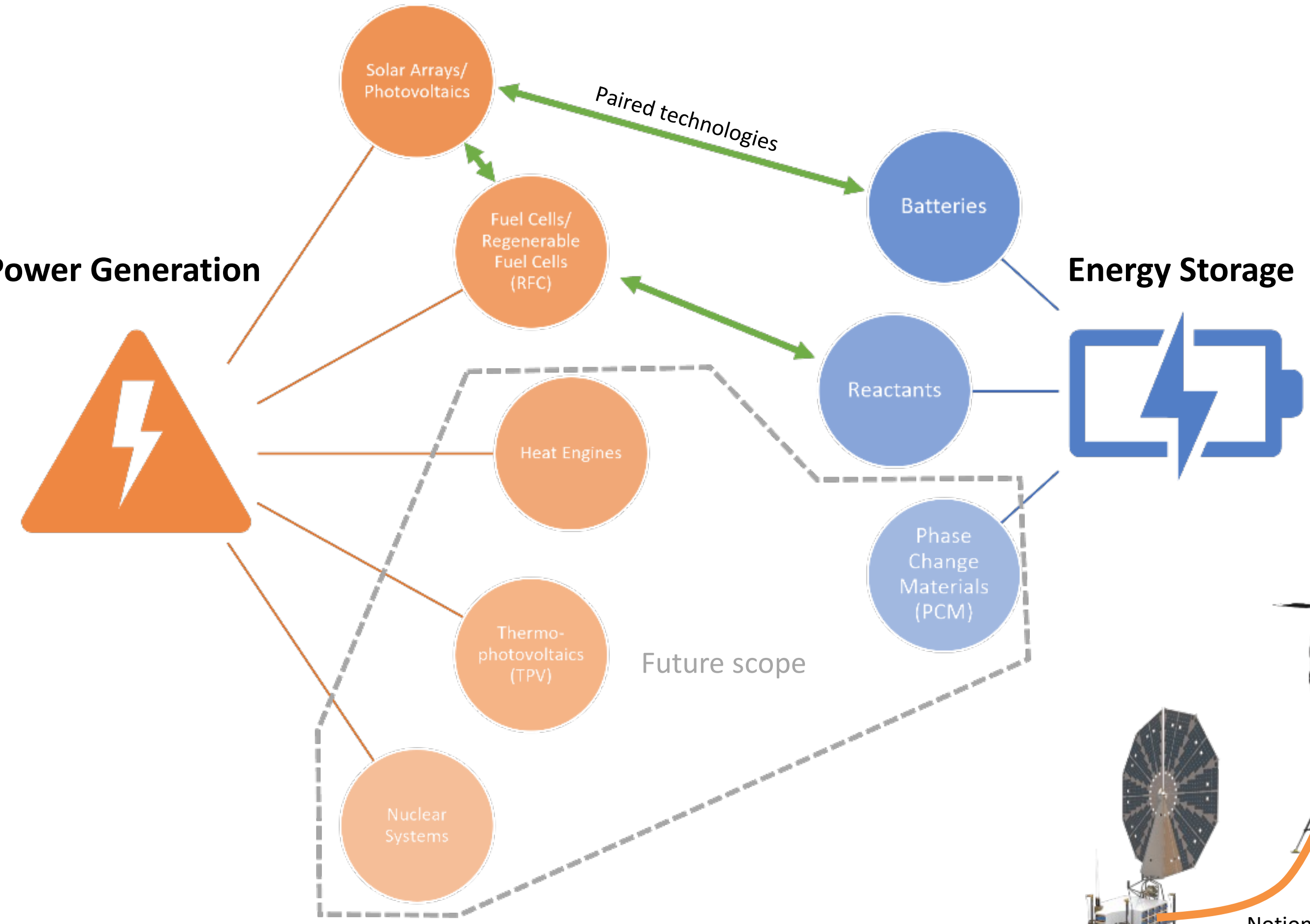
Arrive at a government reference, optimized power architecture for scalable lunar surface habitation, considering possible external power integration and mobile assets.



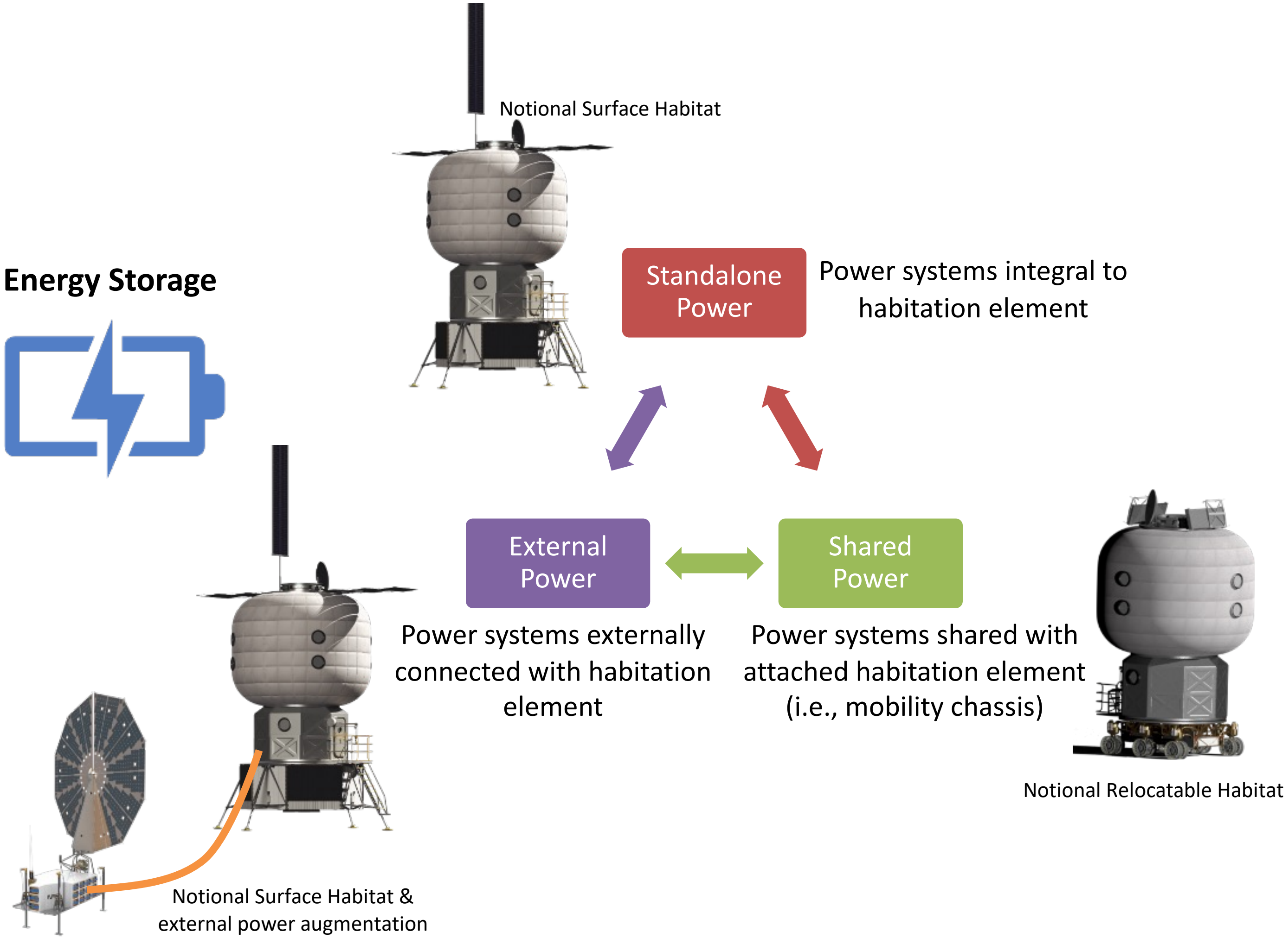
- **Define scope of lunar surface habitation power needs**
- **Summarize previous lunar power architecture studies & assumptions**
- **Assess current and near-future power generation & energy storage technologies**
- **Better quantify maximum expected terrain shadowing periods & variability for lunar 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



Power Integration Trade Space



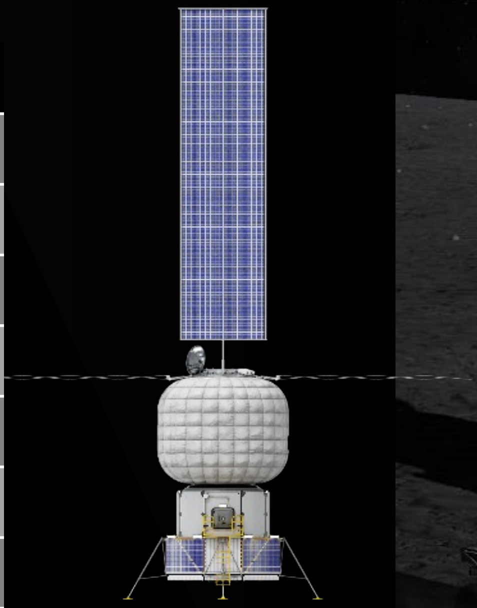
Surface Habitat Reference Concept

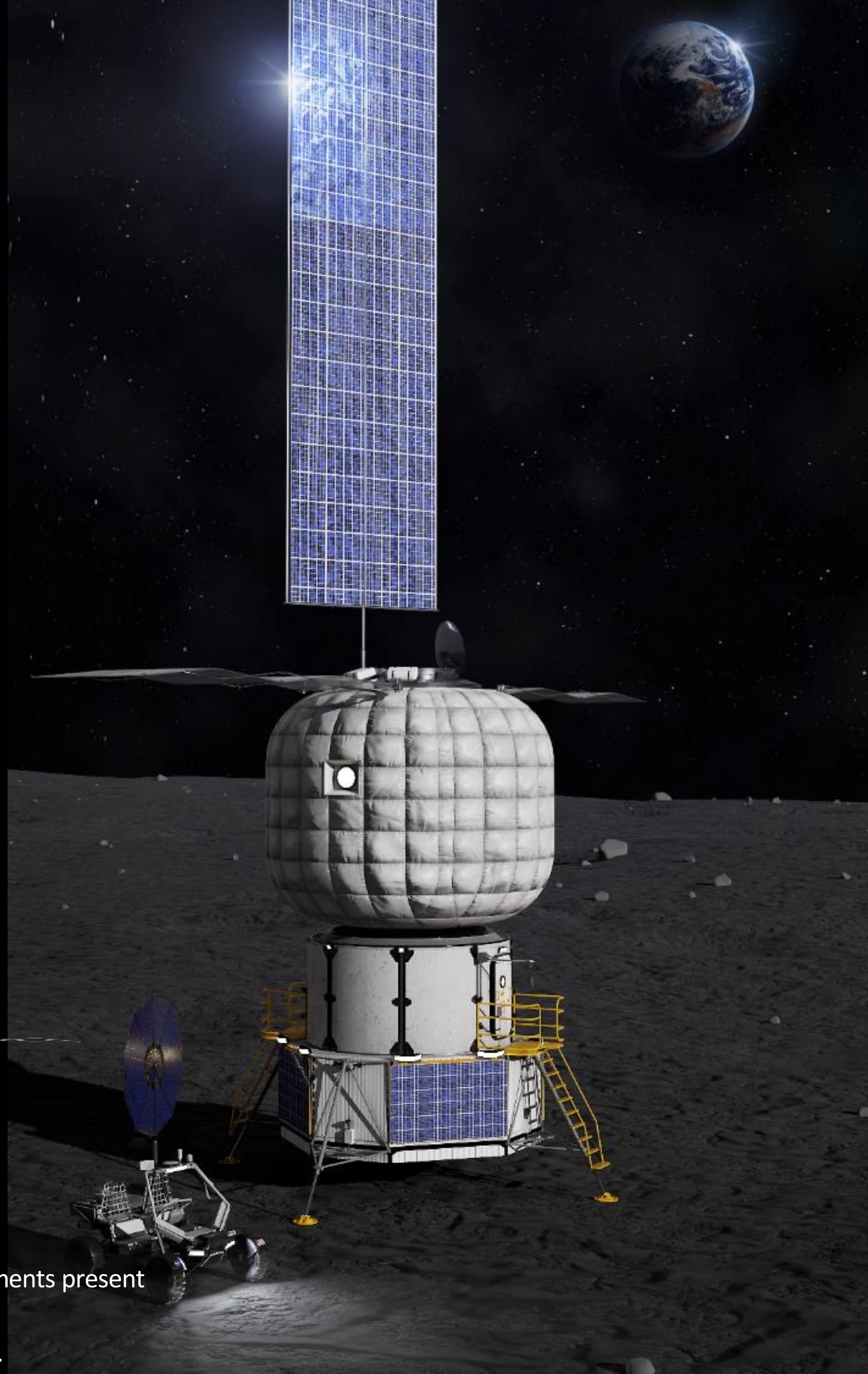
NASA's surface habitat concept serves as a central hub for building & initial sustainment of Artemis' **Foundational Exploration** activities

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[1]	
Crew Size	2 crew (nominal) – 4 crew (surge*)
Mission Duration	~30 days (initial) – 60 days (extended)
Lifetime	15 years
Mass Target	12 mt (goal)
Max Power	15 KWe
Pressurized Volume	~190 m^3
Operating Pressure	8.2 – 10.2 psia (70.3 – 56.5 kPa)
Oxygen Composition	34-26.5% (limits for 8.2-10.2 psia)



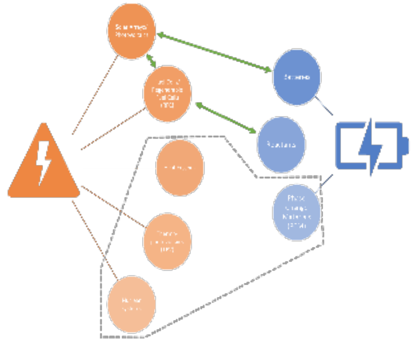


*Surge capacity when other elements present

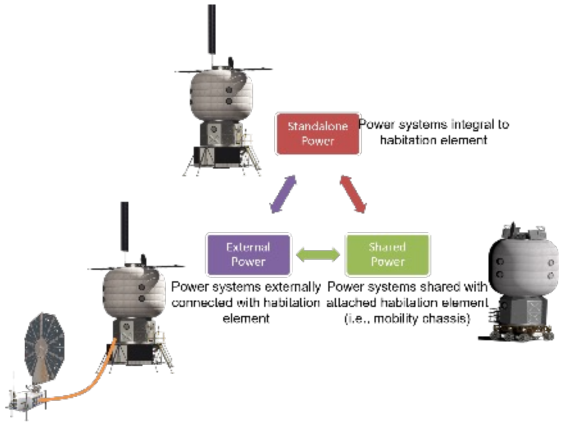
[1] Harris, Danny W., et al. *Moon to Mars (M2M) Habitation Considerations: A Snap Shot As of January 2022*. No. M-1538. 2022.

Assessment Processes

Power System Technology Trade Space



Power Integration Trade Space



Two assessments, in-parallel, one integrated story

Power System Technology Assessment

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 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

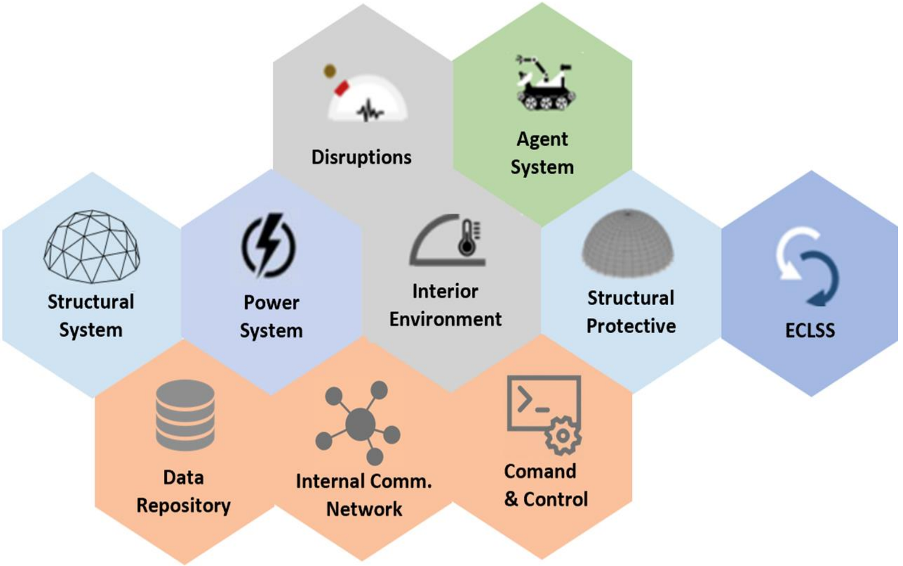
Resilient Extraterrestrial Habitats Institute

- 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)*

Funded by the National Aeronautics and Space Administration

Resilient Extraterrestrial Habitats Institute

- 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



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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**.

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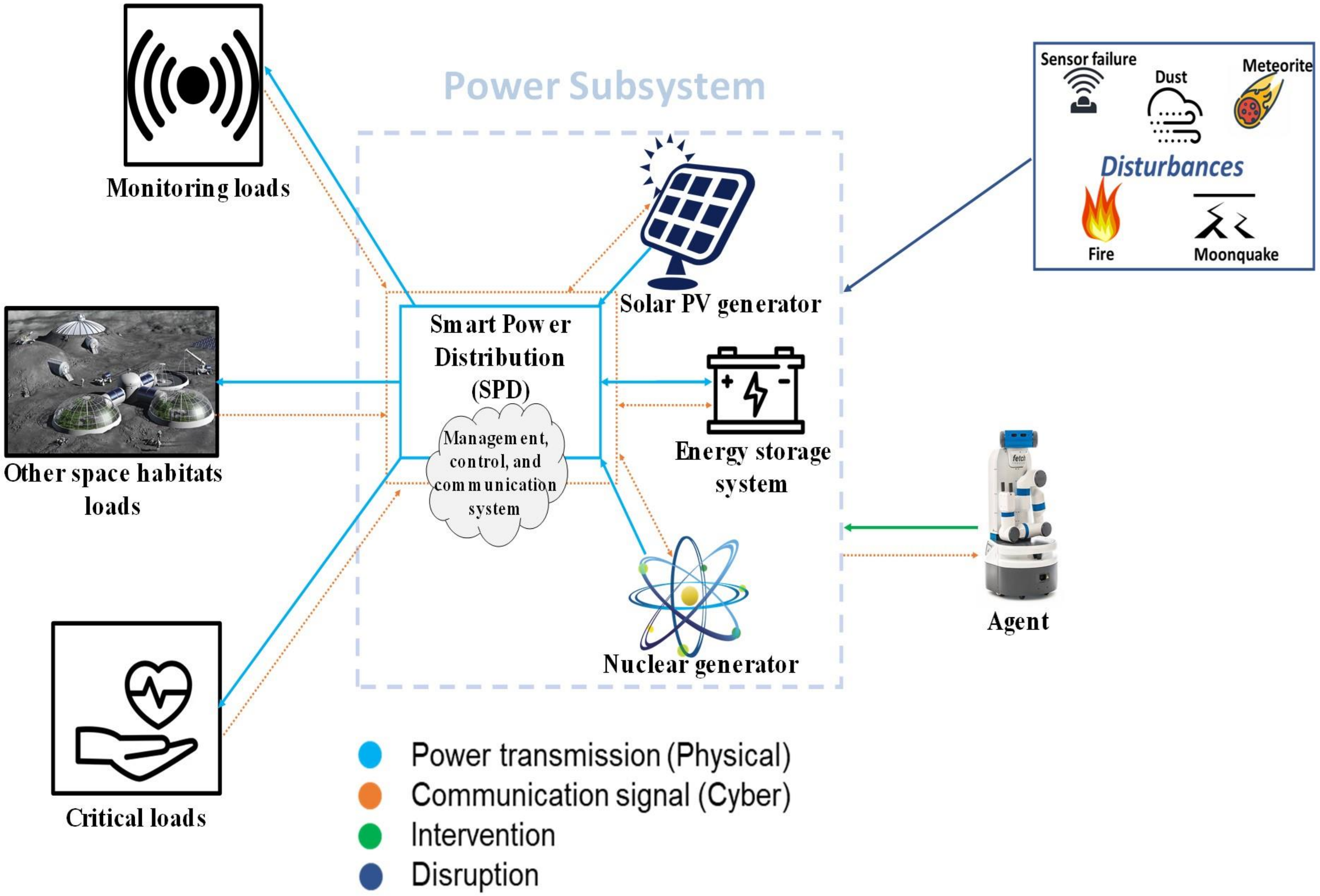
Proposed Extraterrestrial Microgrid



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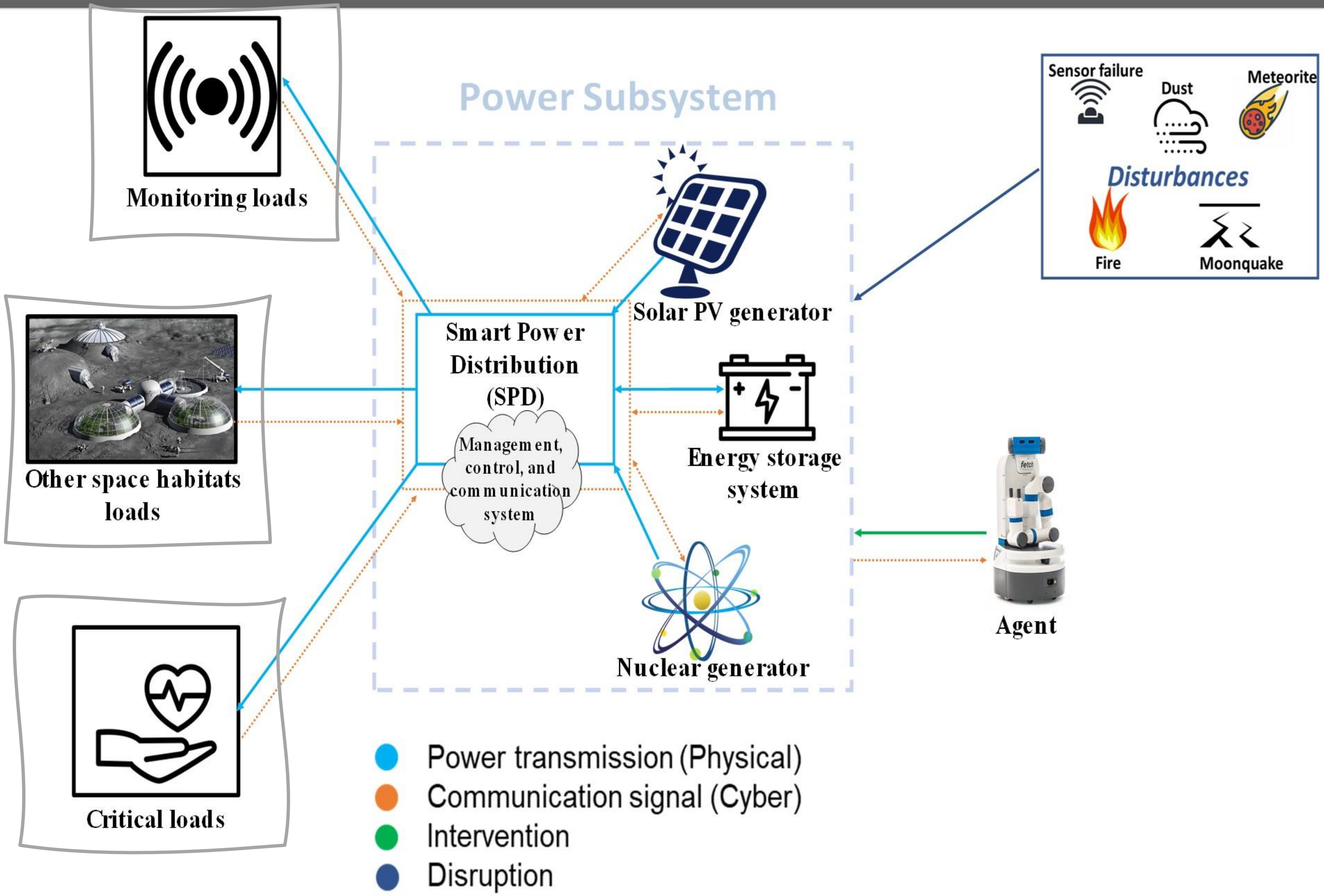
Proposed Extraterrestrial Microgrid
Electrical loads



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Proposed Extraterrestrial Microgrid

Electrical loads

- Electrical loads in extraterrestrial habitats vary in criticality and profile.

Life support

- Heating
- Cooling
- Pressure
- Air quality

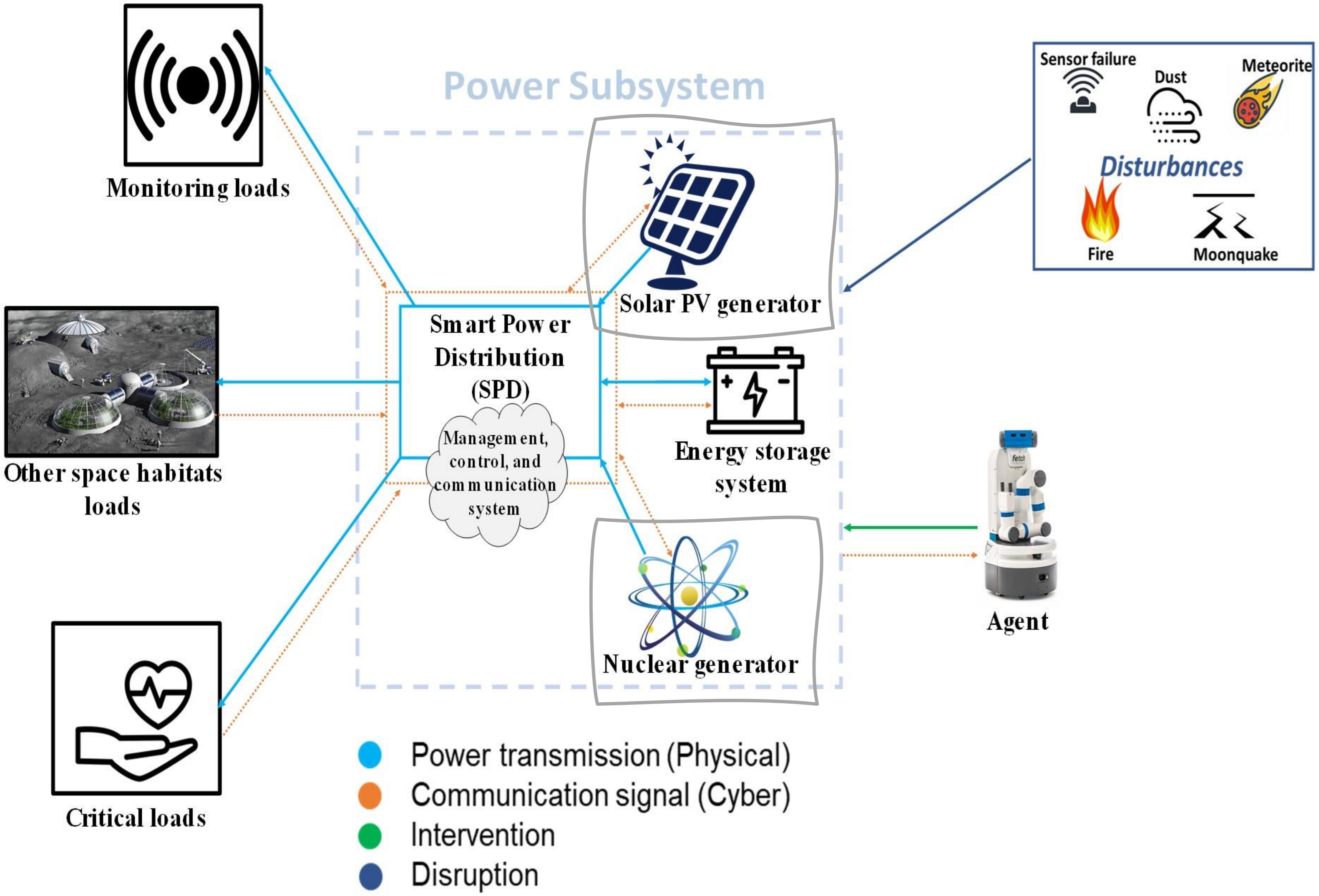
Monitoring loads

- Lighting
- Sensors
- FDD equipment

Other habitat loads

- Housekeeping
- Scientific instruments
- Rovers and EV chargers

Proposed Extraterrestrial Microgrid
Power generation



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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

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Proposed Extraterrestrial Microgrid

Power generation

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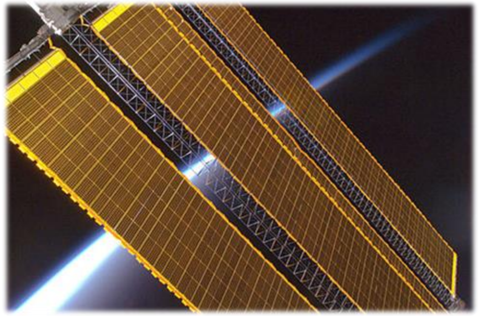
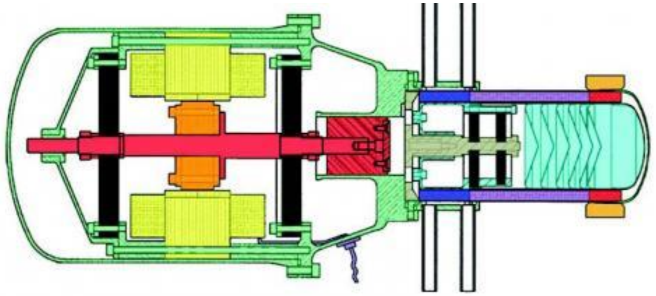


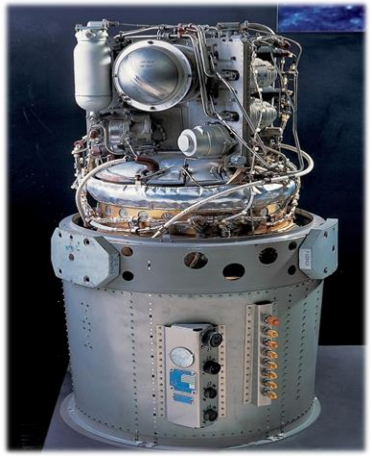
Multi-junction PV cells

- ✓ 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
- ✗ Low technology readiness level
- ✗ Reactor shielding requirement



Fuel cells

- ✓ High specific energy
- ✗ Low technology readiness level
- ✗ Limited resources in space

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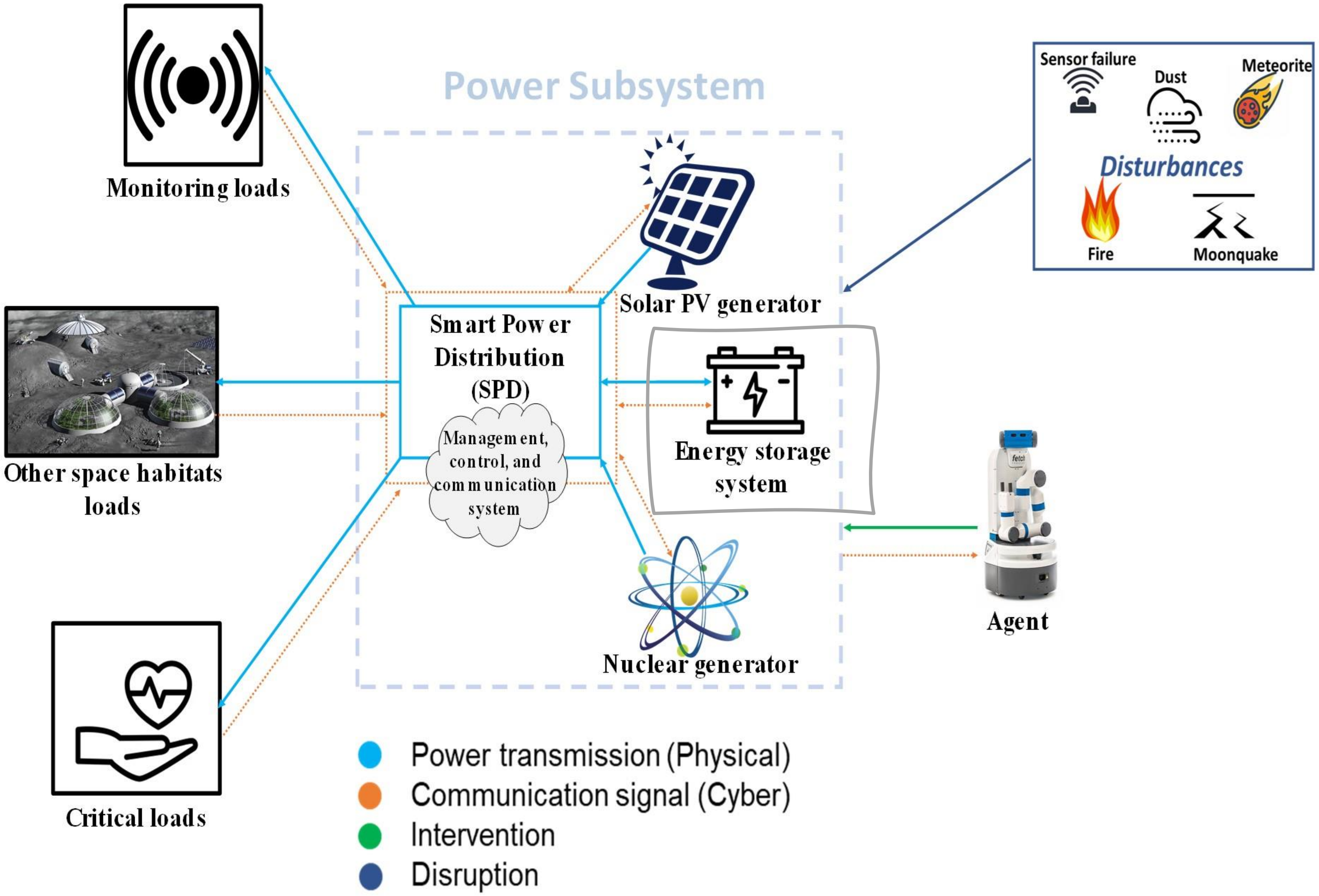
Proposed Extraterrestrial Microgrid
Energy storage



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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 $-40℃$
  - High specific energy (more than 250Wh/kg)
  - Long calendar life (more than five years)
  - Long cycle life
  - Radiation tolerance

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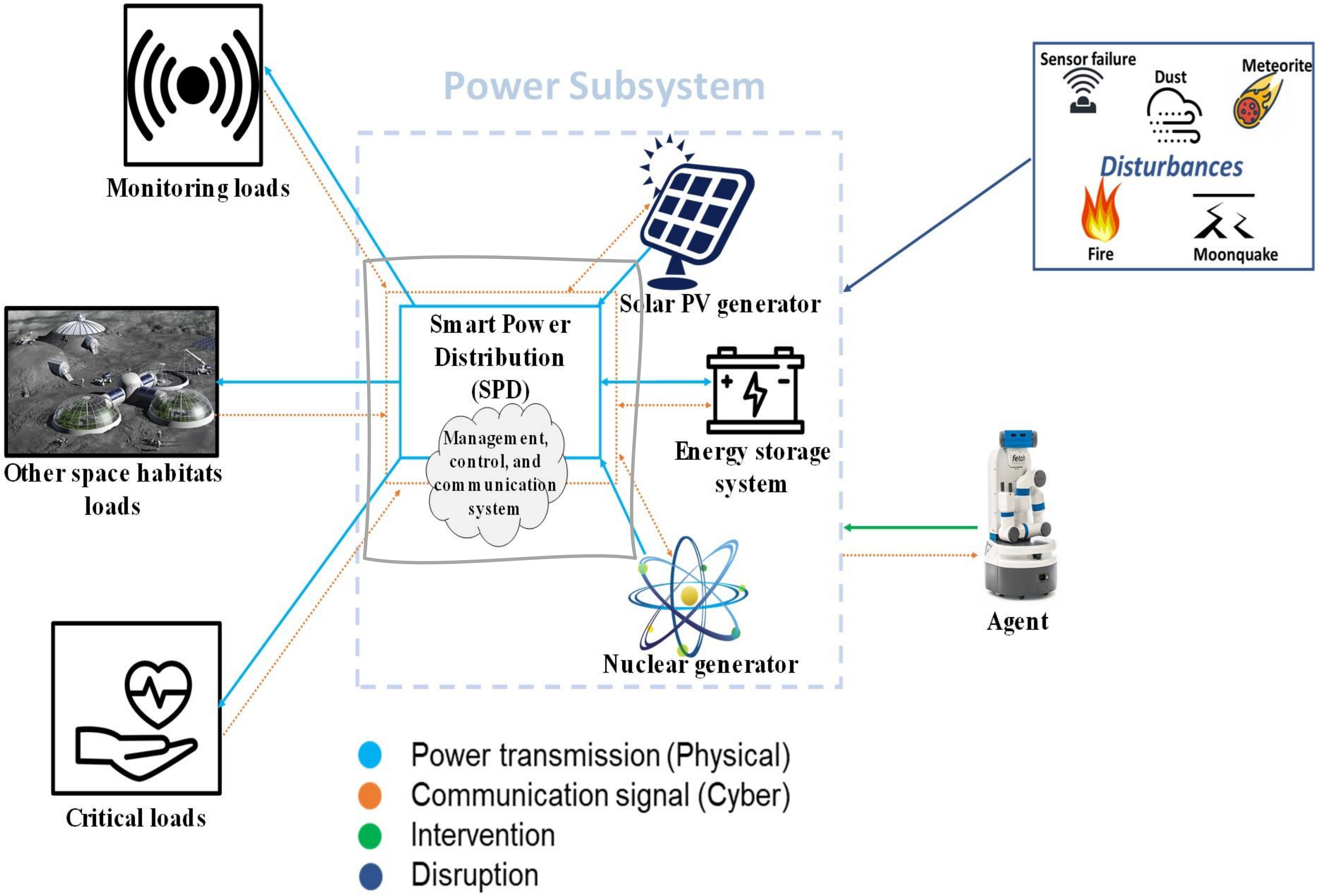
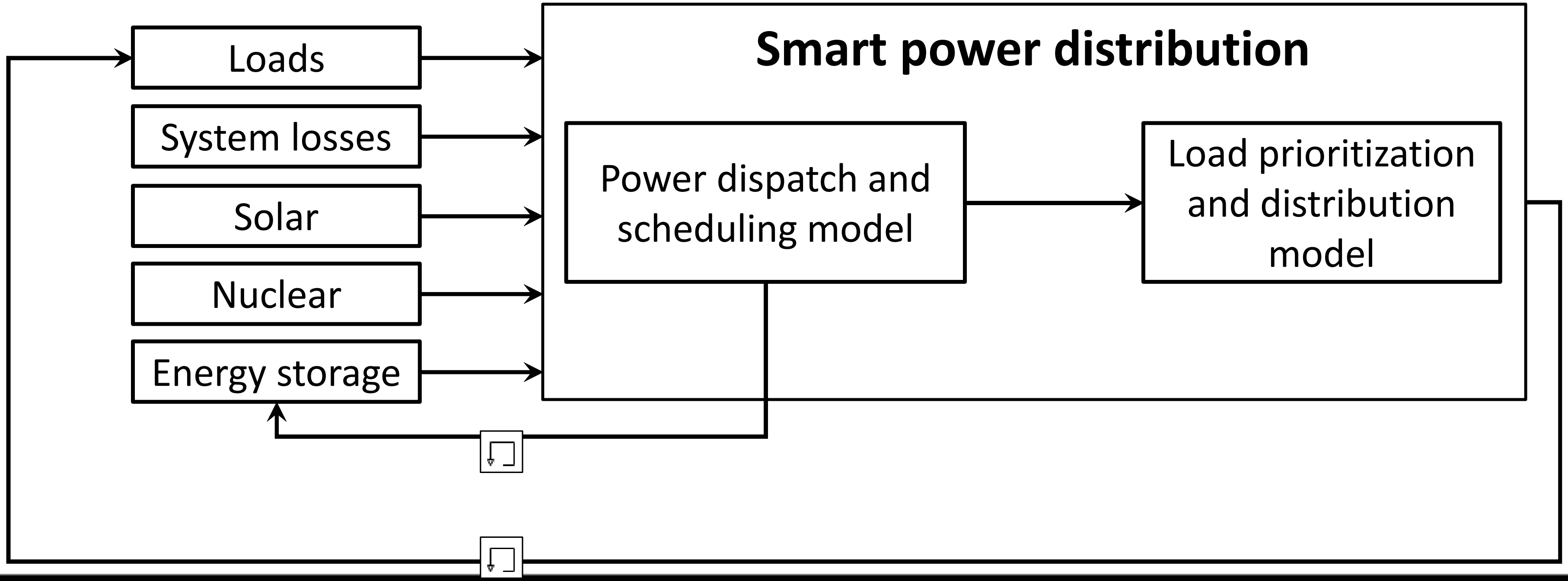
Proposed Extraterrestrial Microgrid
Smart power distribution



Proposed Extraterrestrial Microgrid
Smart power distribution

- The control and operation management system of space microgrids involves:
  - Scheduling resources
  - Planning the loads and their operating modes



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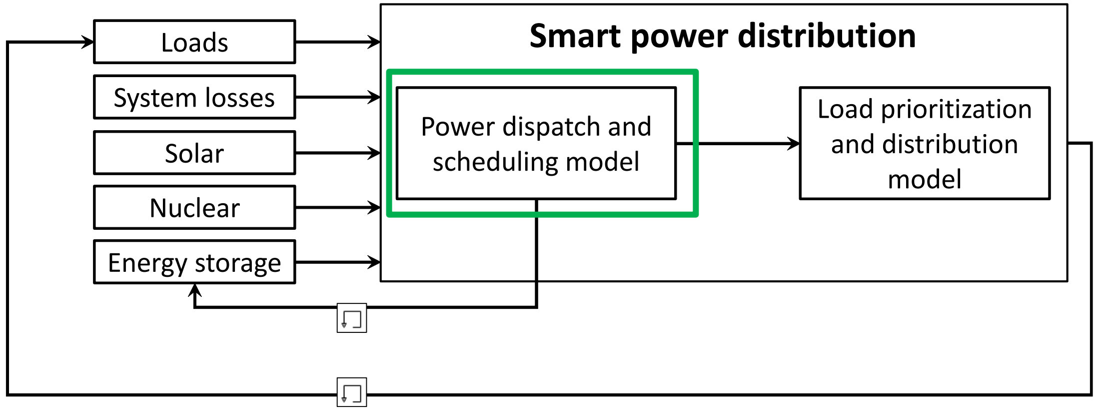
Proposed Extraterrestrial Microgrid
Smart power distribution – Scheduling model

- The proposed smart power distribution system has 3 modes of operations:

  - Mode 1:
    $\mathbf{Load} \leq \mathbf{Nuclear}$ → The power demand is supplied from the nuclear power only (ES is not needed, charged if needed)

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

  - Mode 3:
    $\boldsymbol{Nuclear} + \boldsymbol{Solar\ PV} < \boldsymbol{Load}$ → The power demand is supplied from the nuclear, solar and ES (ES is needed)



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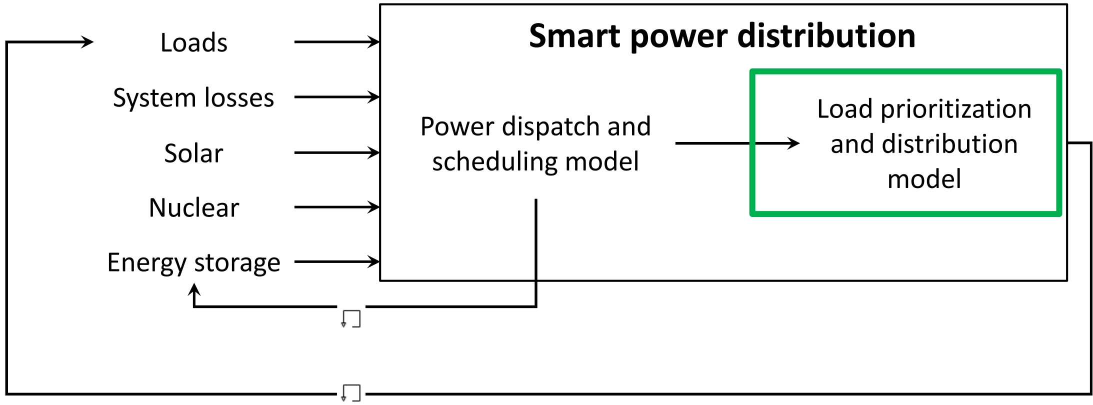
Proposed Extraterrestrial Microgrid
Smart power distribution – Distribution model

- 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

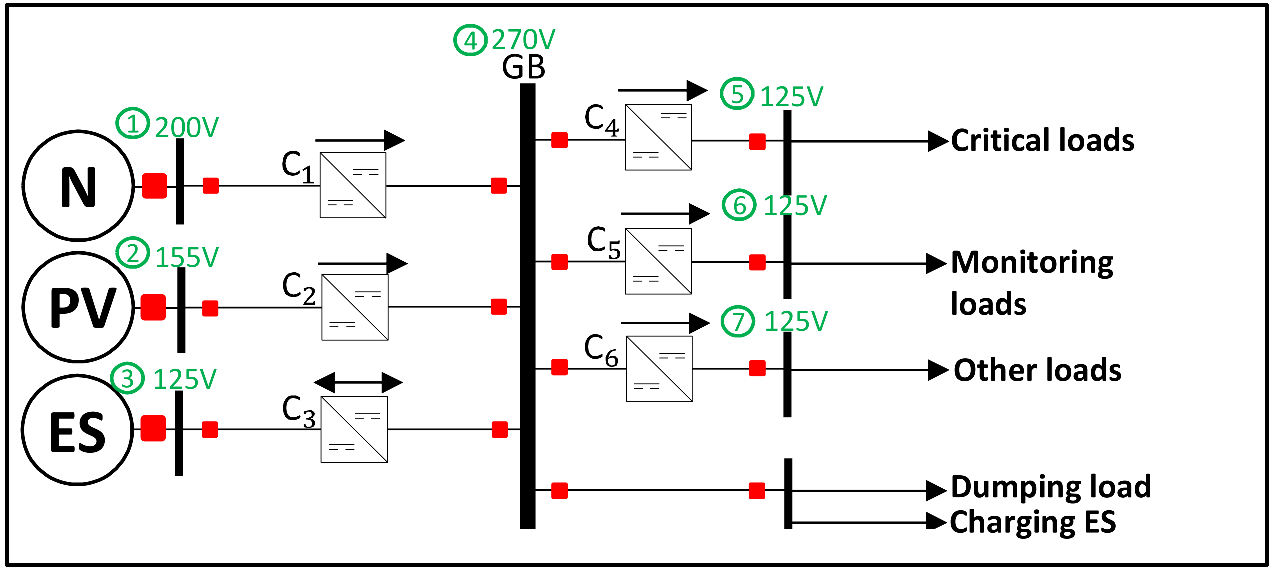
Ex: $P_{critical} < P_{GB} < P_{critical} + P_{FDD}$

→ $P_{charging} = P_{GB} - P_{critical}$

Proposed Extraterrestrial Microgrid

Smart power distribution

- **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

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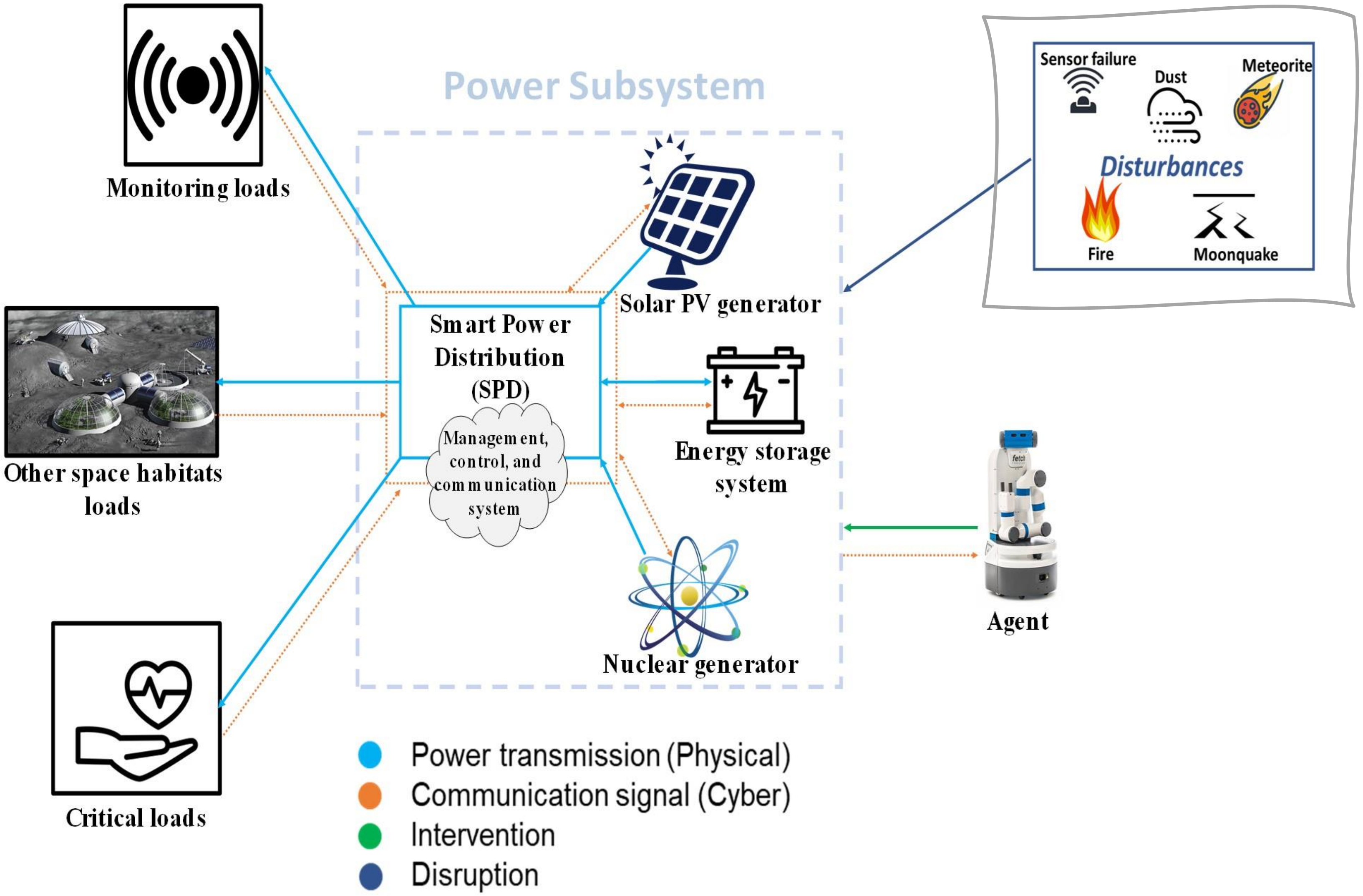
Environmental Challenges of Extraterrestrial Microgrid



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Environmental Challenges of Extraterrestrial Microgrids

- Extraterrestrial electrical power system environmental threats include:
  - Temperature extremes; e.g. −193.15℃ to 122.78℃ 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

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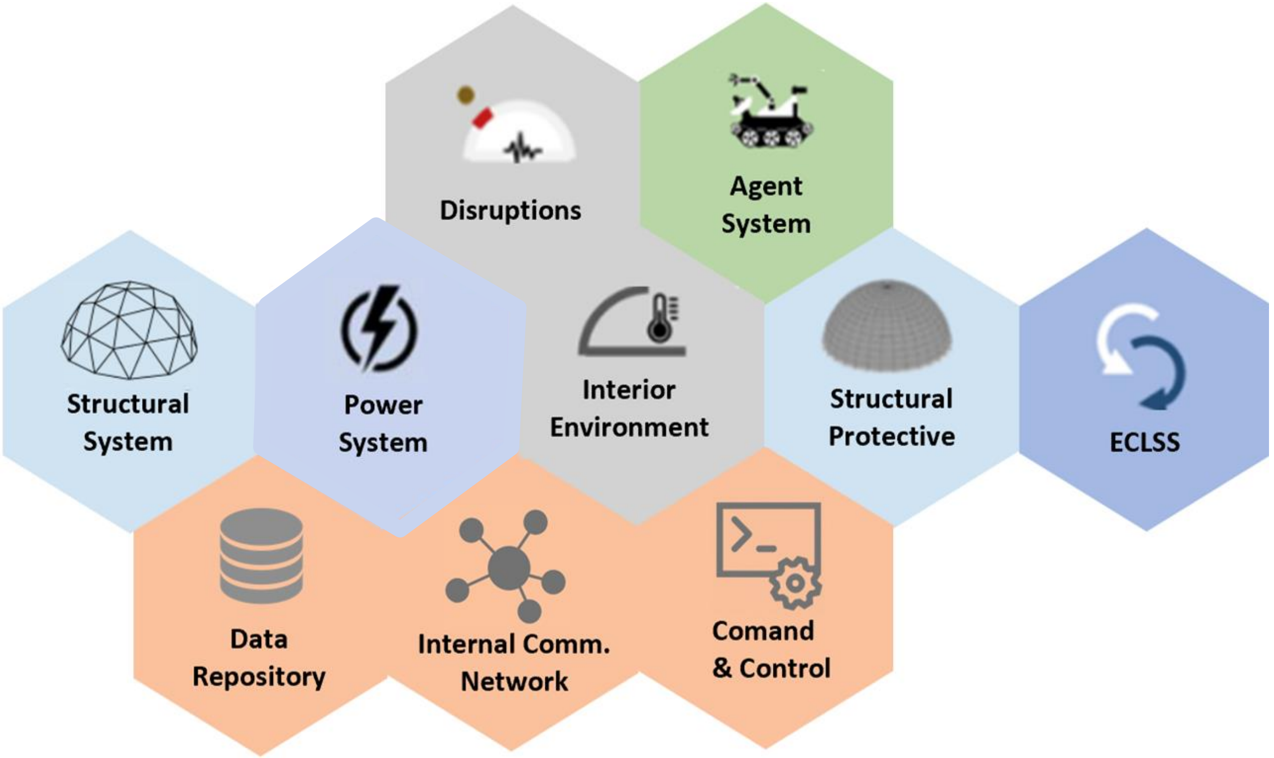
Effect of Power System damage in a space habitat

- 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

Parameter	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
Meteorite IL	-	High	High	High	High
Meteorite location	-	Nuclear reactor	Nuclear reactor	Habitat structure	Habitat structure
Period	Day	Night	Night	Night	Night
Dust level	Low	High	High	Moderate	Moderate
Robotic repair	-	Available	None	Available	None

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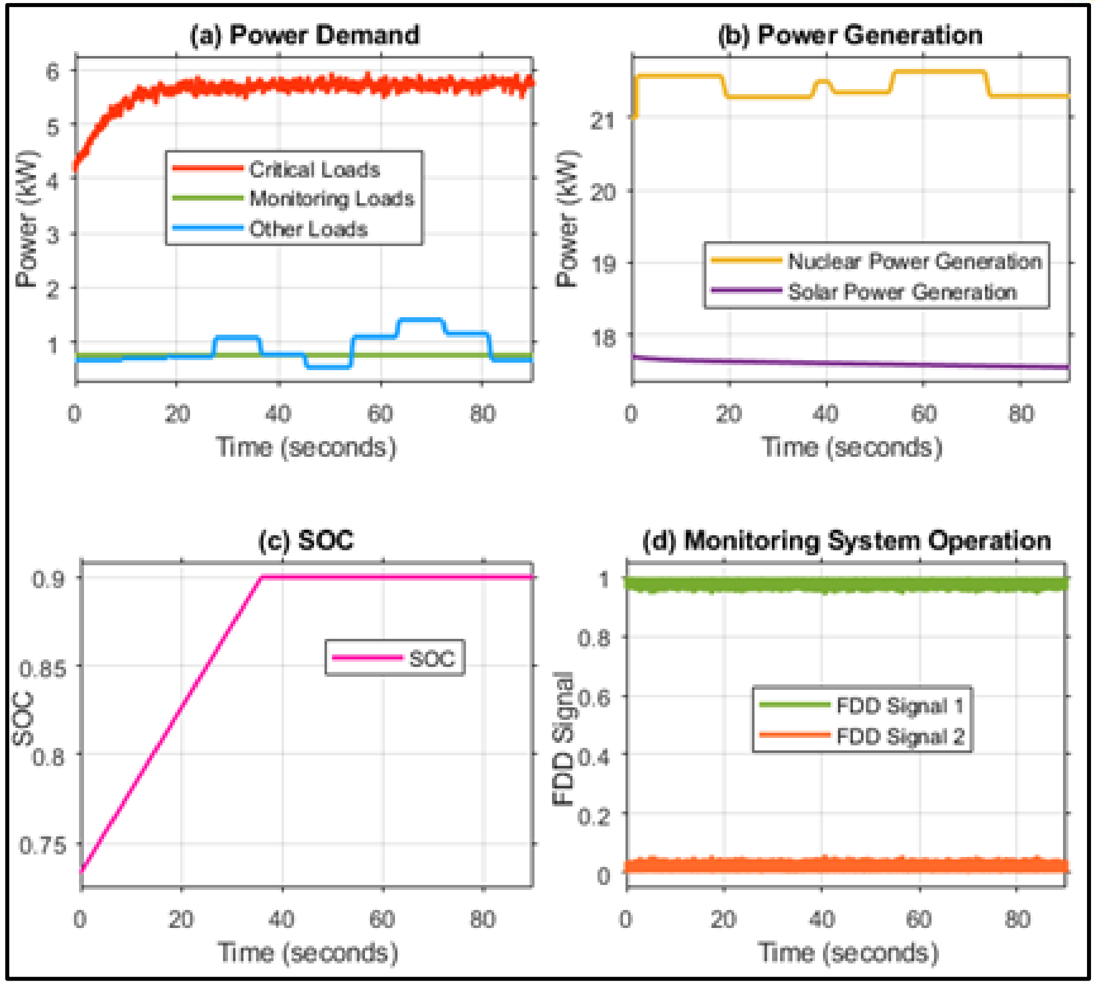
Effect of power system damage in a space habitat

Scenario 1 – Normal operation

- Simulation results show nominal operating conditions of the power system.



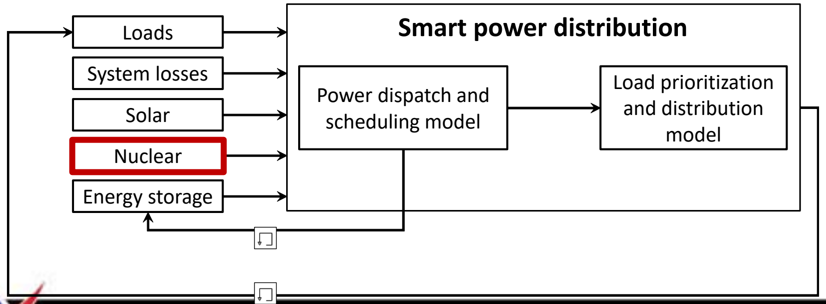
Note: The time scale is reduced to increase the simulation speed.

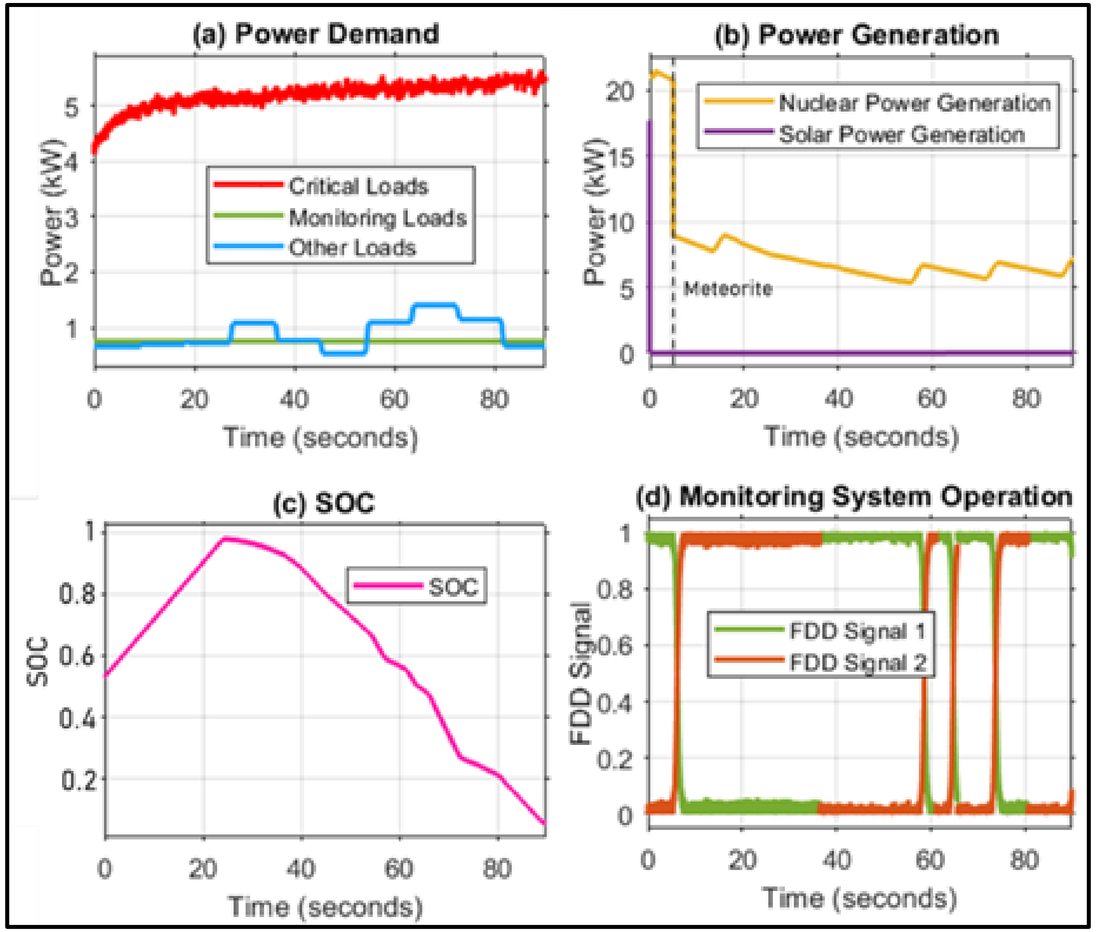
Effect of power system damage in a space habitat

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





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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

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