National Aeronautics and Space Administration

Fission Surface Power Project

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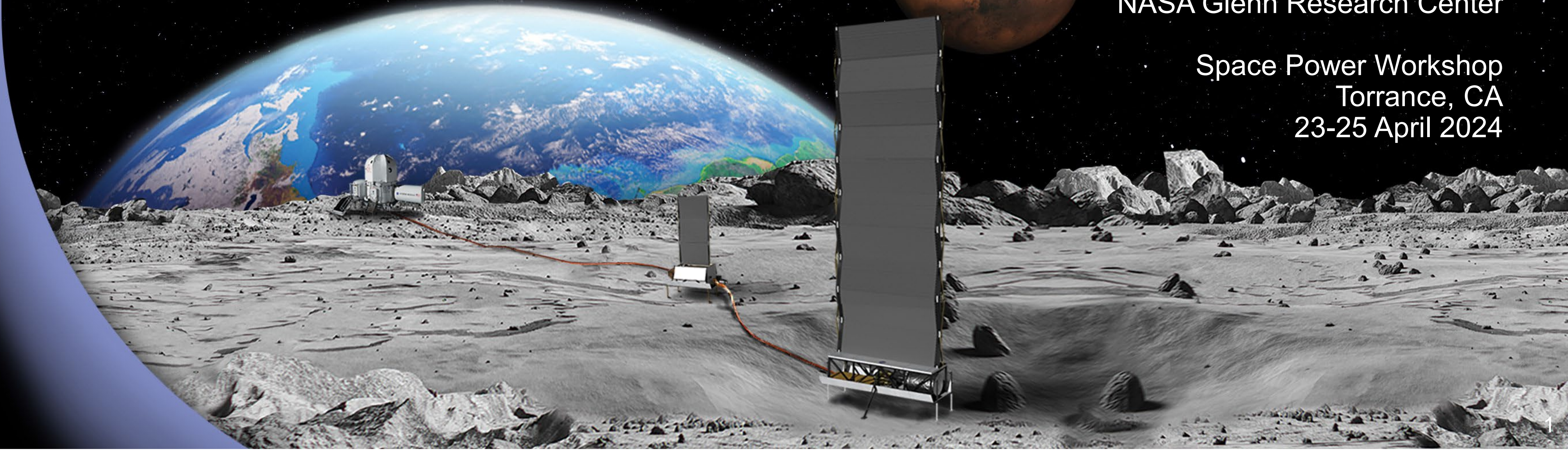
Space Power Workshop
Torrance, CA
23-25 April 2024

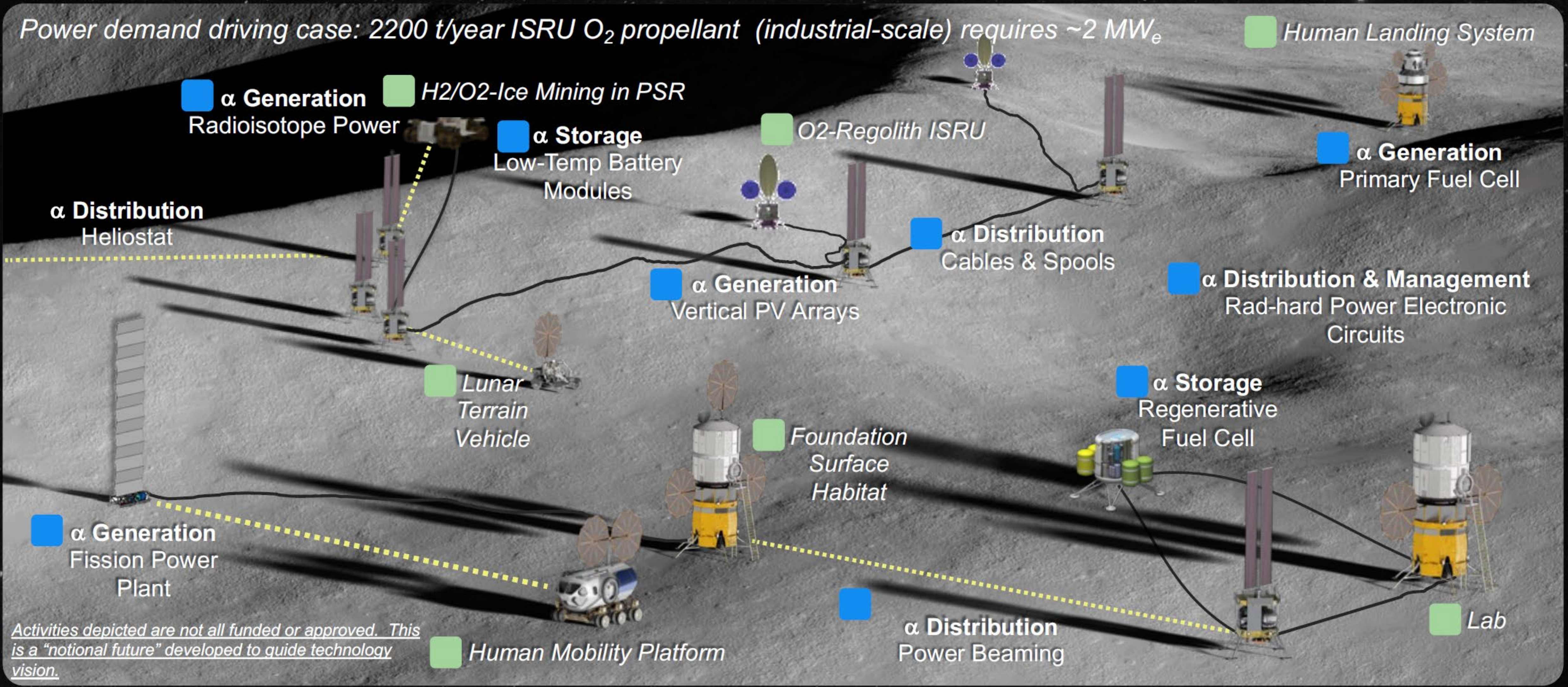


Power Architecture Building Blocks

Phase α South Pole Facilities: Handoff from Artemis Base Camp to Industry (~2030+)

Power system

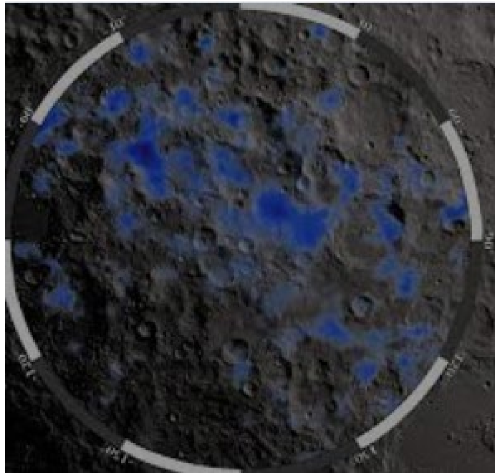
Load



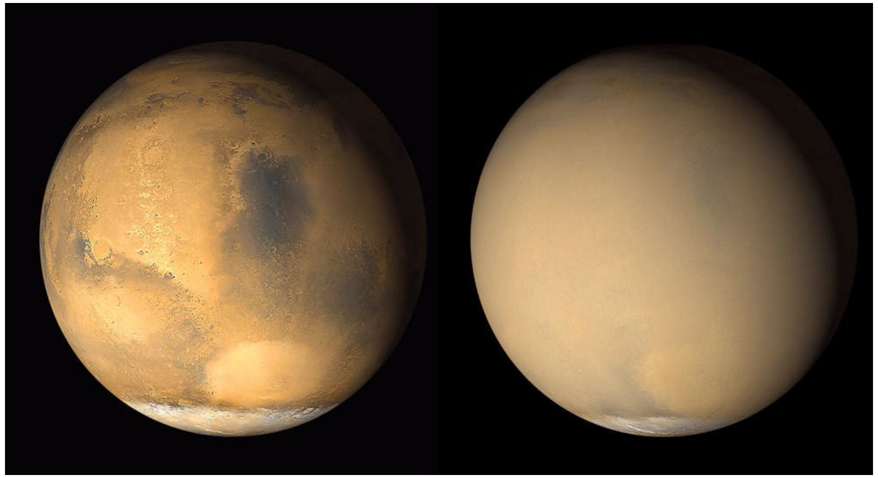
Surface Power Challenges: Moon & Mars

- Moon:
  - Lunar night can be up to 14.5 Earth days long
  - Lunar night temperatures ~ 50K to 100K, depending on location
  - Lunar permanently shadowed regions (PSR) may contain water ice and are of great interest to explorers
- Mars:
  - Mars insolation on average 43% of that at Earth orbit
  - Mars has recurring planet-wide dust storms that can last for weeks or months and drastically reduce solar energy-to-ground

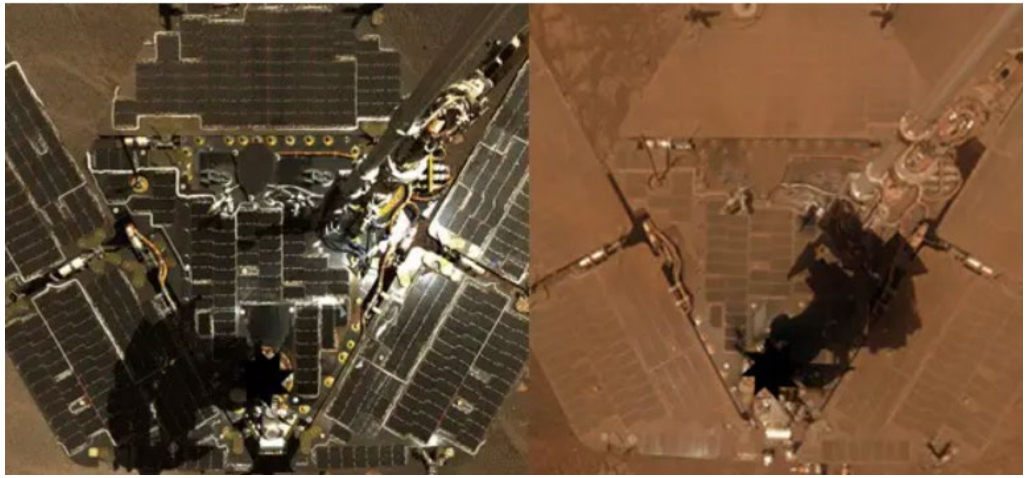
PSR



Martian dust storm global coverage

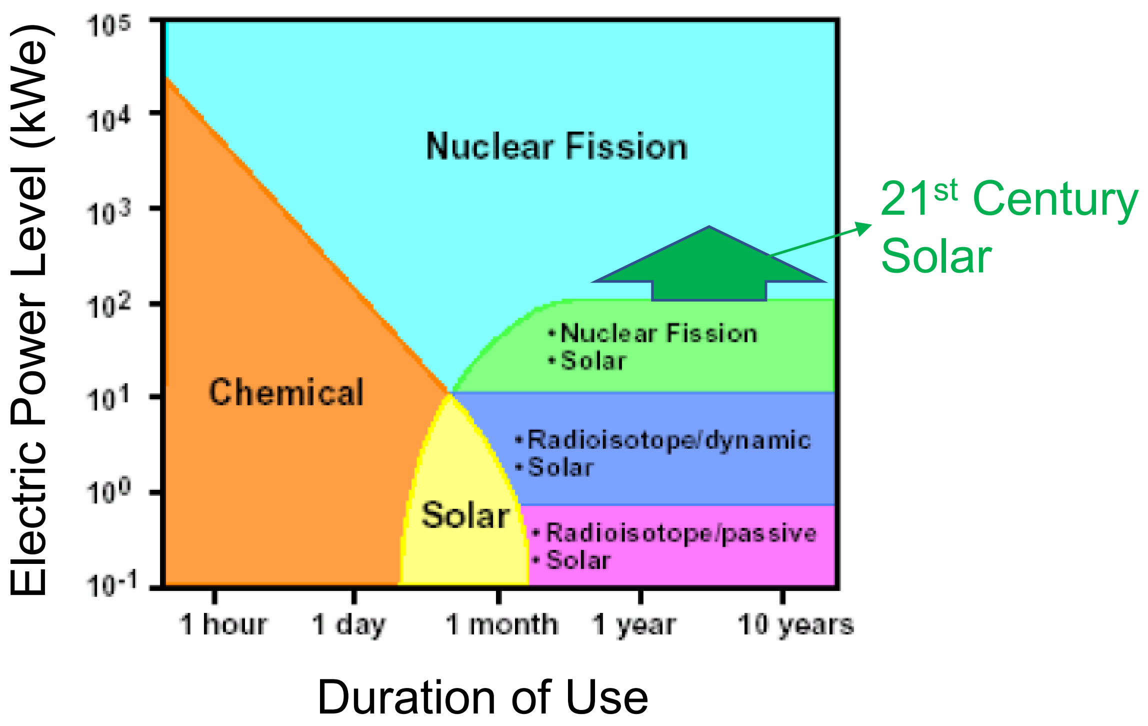


Opportunity – before and after Mars dust

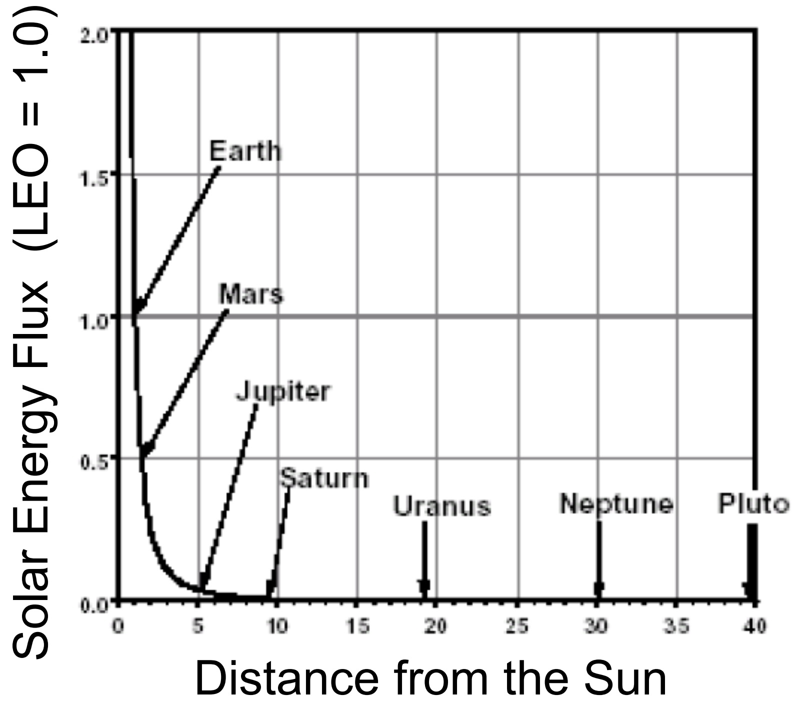


Surface Power Generation Options

- **Space power options:**
  - Solar + Batteries (chemical)
  - Fuel Cells (chemical)
  - Nuclear
    - RTG
    - Fission



- **Solar is typically chosen and for good reasons:**
  - Technical Maturity
  - Experience Base
  - Cost



Graphs after Angelo and Buden, Space Nuclear Power, Krieger, Melbourne, Fl., USA, 1985.

Solar + Batteries

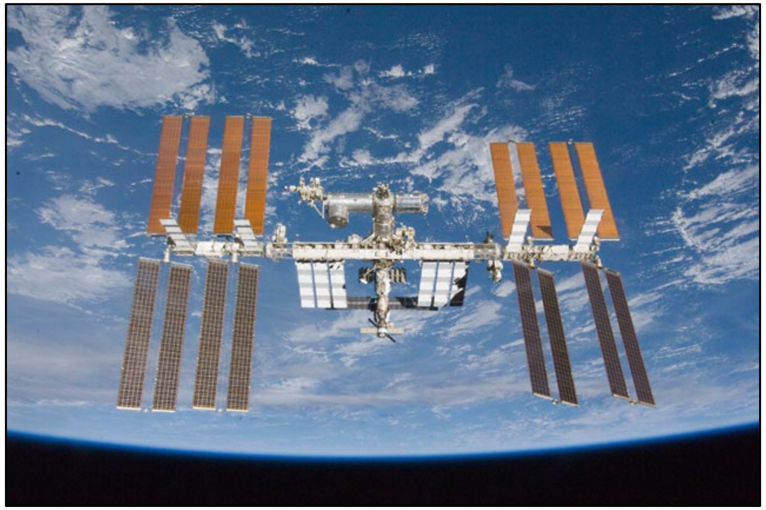
- **Battery mass can be a challenge during lengthy periods in shadow**

- **International Space Station (ISS) example**:
  - ISS eclipses are ~ 35 min long
  - Requiring 24 li-ion batteries at 10,440 lbs (4,735kg) total

- **Now scale that to a Lunar night ~2 weeks long:**
  - Battery system masses ~7,000,000 lbs (3,200,000 kg)

- (see “Passive Survival of the Lunar Night with Cryogenically-Operable Electronics” presentation – Thursday afternoon)

ISS solar array configuration



That’s 197 kg of battery … for just

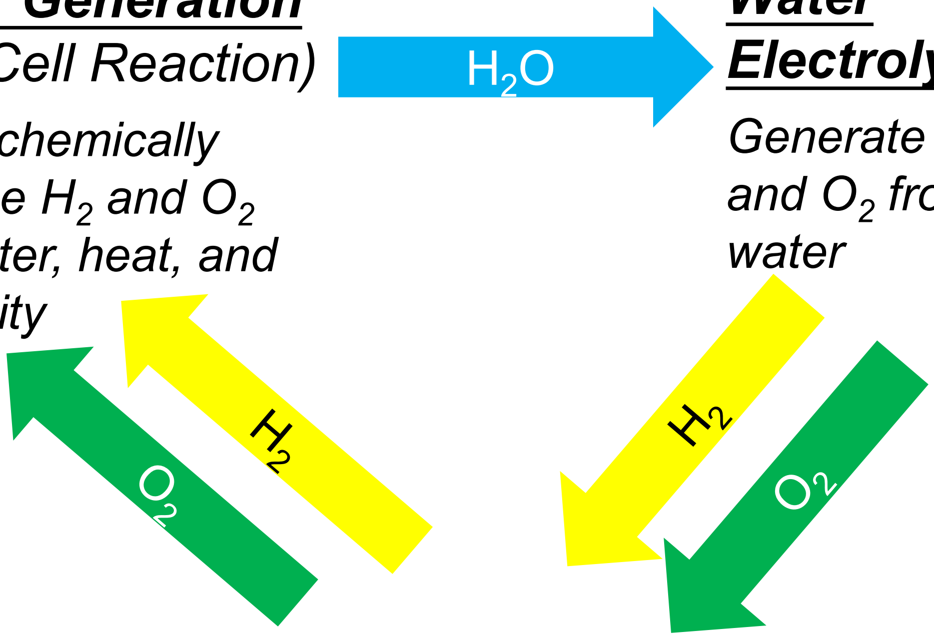
Fuel Cells

Power Generation
(Fuel Cell Reaction)

Electrochemically combine H_2 and O_2 into water, heat, and electricity

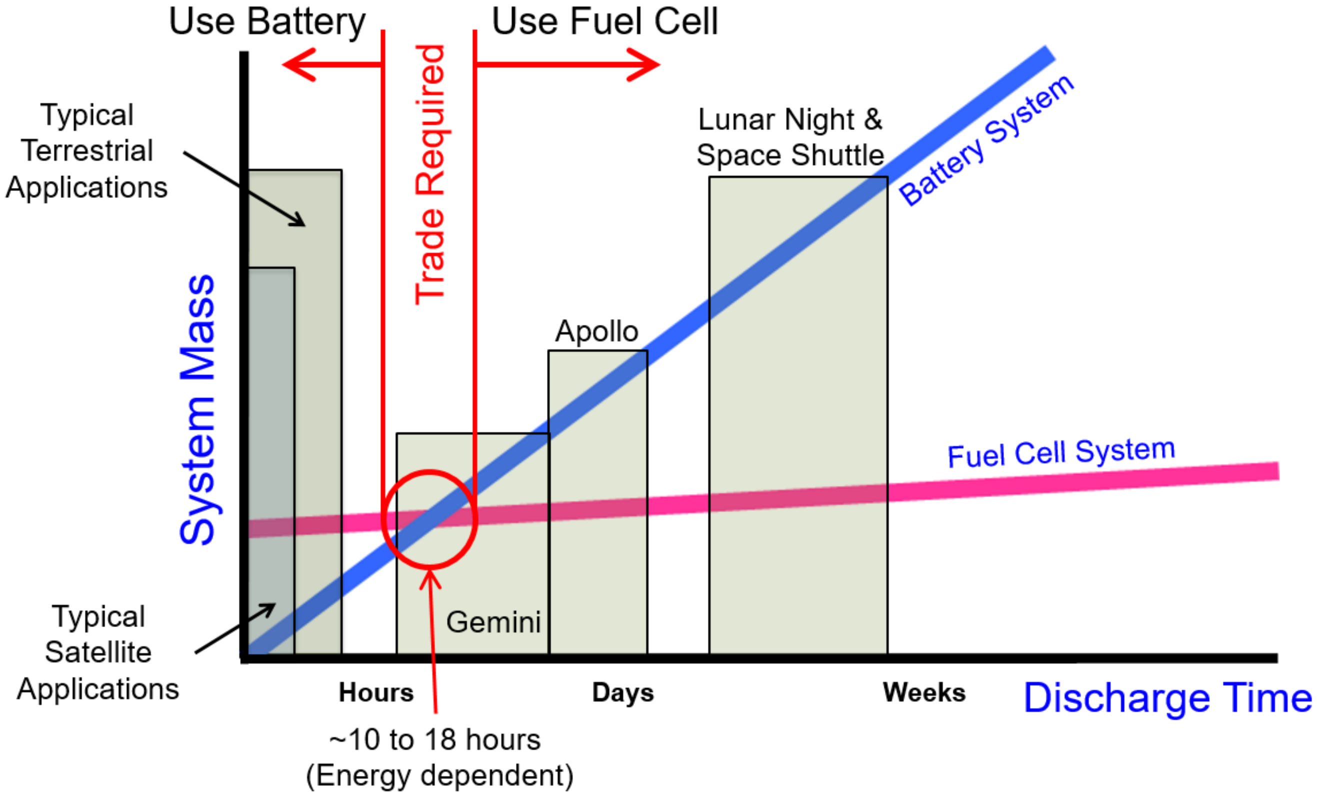
Water Electrolysis

Generate H_2 and O_2 from water



Energy Storage

Long-term storage and management of H_2, O_2 & H_2O



Fuel Cells SOA

Application Power Requirements

- Lunar / Mars Landers: ~ 2 kW to ≤ 10 kW (TRL 3 for Solid Oxide, TRL 5/6 for PEM)
- Lunar / Mars surface systems: ~ 2 kW to ≤ 10 kW modules (TRL 3 for Solid Oxide, TRL 5/6 for PEM)

Electrolysis SOA

- Low Pressure (< 0.3 MPa, < 45 psia) (TRL 9, ISS Oxygen Generator Assembly flying ~ 20 years)
- Medium Pressure (<1.7 MPa, < 250 psia) (TRL 5 for PEM, no Solid oxide development)
- High Pressure (> 10 MPa, > 1,500 psia) (TRL 3 / 4 for PEM, no Solid oxide development)
- Contaminated Water Sources for ISRU (TRL 3 for PEM, TRL 3 / 4 for Solid oxide)

Why Nuclear?

<u>Energy Density:</u>

Liquid oxygen/hydrogen = 1.35×10^{7} J/kg

Why Nuclear?

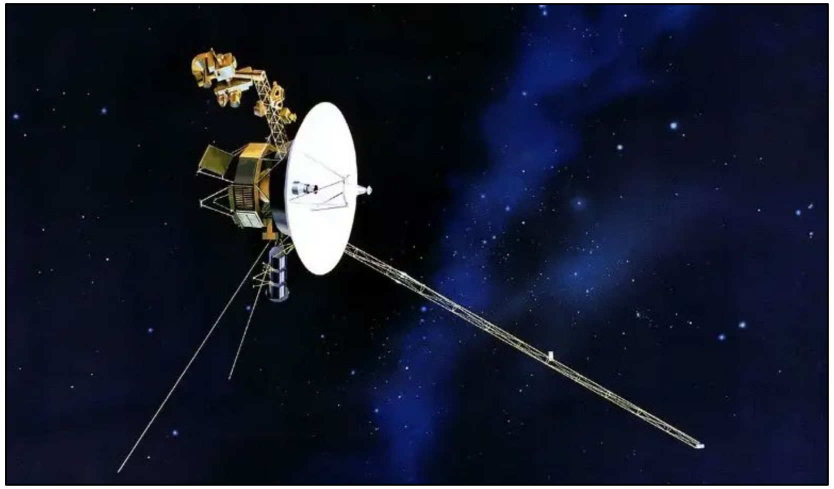
Energy Density:
Liquid oxygen/hydrogen = 1.35×10^{7} J/kg

Uranium-235 fission = 8.2×10^{13} J/kg

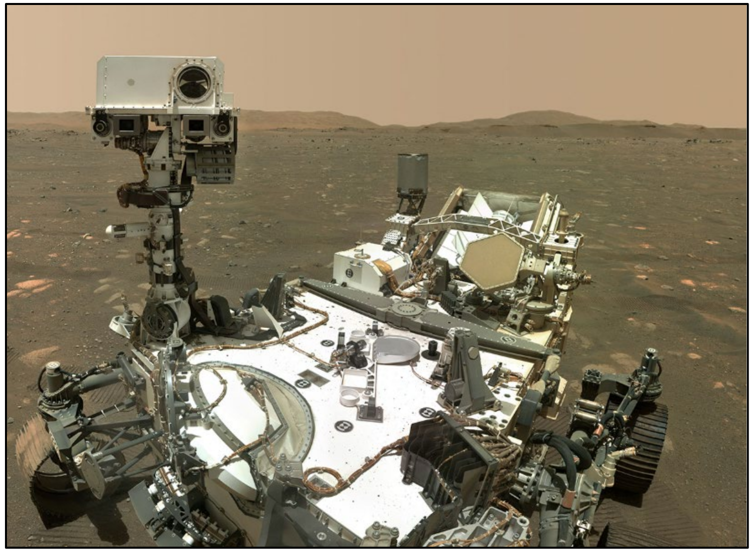
Radioisotope Thermoelectric Generator (RTG)

- Plutonium-238 decay produces heat
- One side of thermocouple sees the heat production, other side is space or planetary environment
- Excess heat used to maintain spacecraft operating temps
- Some famous RTGs and multi-mission RTGs: Pioneer, Voyager, Galileo, Cassini, New Horizons, Viking, Curiosity, Perseverance
- Multi mission RTG – 110W freshly fueled
- Generally, scales well from watts to a kilowatt+
- Dynamic power conversion under development for RTGs

Voyagers

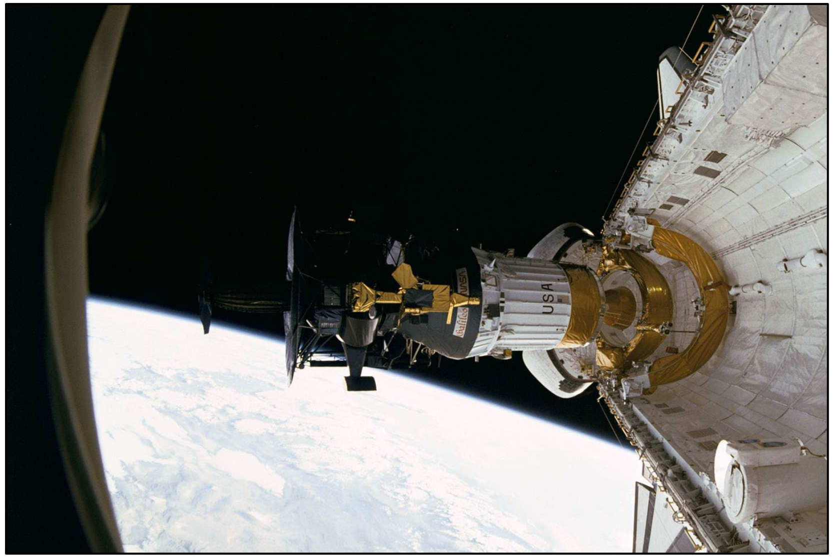


Perseverance



Cassini

Galileo



Fission

- Produces heat from the splitting of uranium atoms
- Heat transported to a converter
- Converted to electricity statically or dynamically
- Generally scales well from kilowatts to megawatts+
- First flight space reactor – Systems for Nuclear Auxiliary Power (SNAP) 10A 1965 (thermoelectric)
- Ground based demo – Kilopower Reactor Using Stirling Technology (KRUSTY) 2018 (Stirling)

KRUSTY

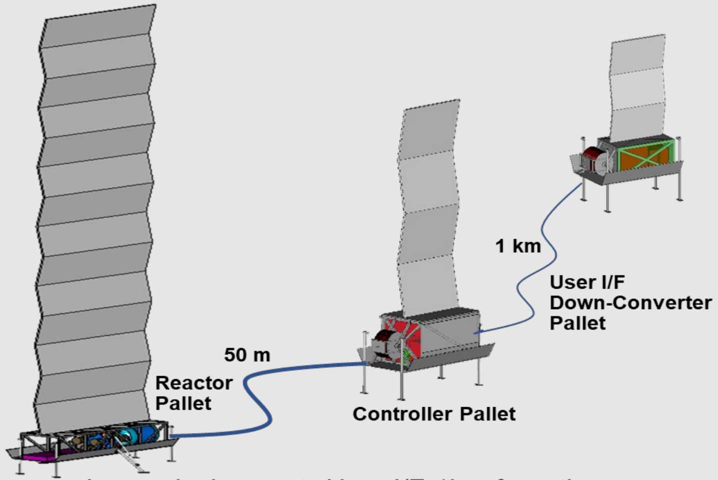
SNAP-10A

Fission Surface Power System Phase 1 Overview

- **NASA is working with the Department of Energy and their federally funded laboratories to establish a lunar Fission Surface Power (FSP) system that is directly applicable to Moon and Mars exploration**
- **This hardware development is part of NASA Space Technology Mission Directorate's (STMD) Technology Demonstration Missions (TDM) Program**
- **Requirements for design studies only…may change for flight**
- **Autonomous nuclear power system:**
  - Launched, placed on the Moon's surface by a lander,
  - Transported to its operational location,
  - Connected to a user power interface up to a kilometer away
- **10 year life**
  - Consisting of a 1-year demonstration followed by
  - Operational support to Moon surface exploration missions
- **Designed to be extensible to Mars surface missions**

Key Design Characteristics

- 40 kWe output at 120 Vdc
- Fits on a lander
- Operate on the lander, or be transported
- 10-year life



- Lunar deployment. User I/F 1km from the reactor

Deployed configuration

Government Reference Design Example

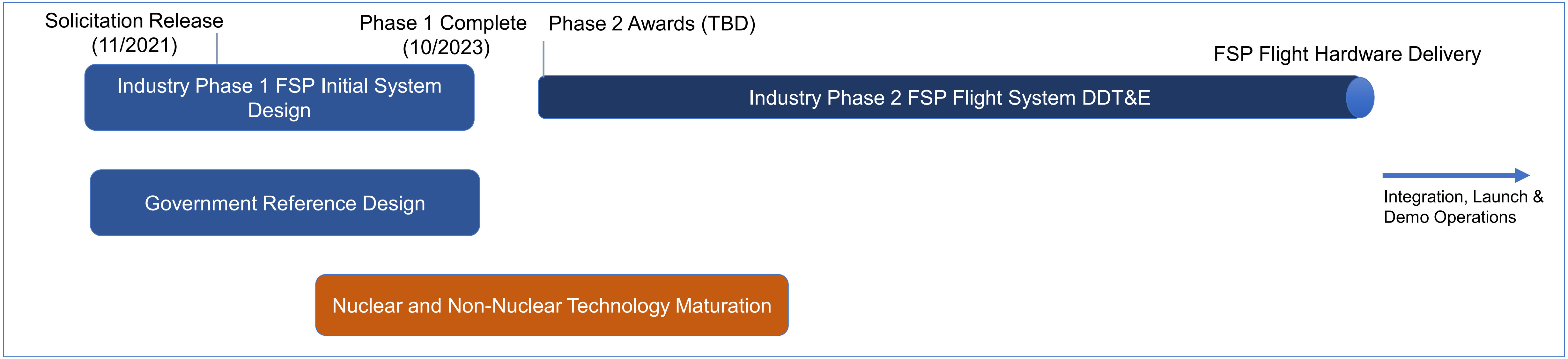
Fission Surface Power System Development Strategy

- **Awarded three Phase 1 - FSP System Design Contracts**
- **Completed government reference design work**
- **Government Technology Maturation underway**
  - Department of Energy (DOE) working on metal hydride moderators, shielding and instrumentation and controls
  - NASA/DOE FSP Team holding periodic webinars for industry and other government agencies
  - NASA non-nuclear power management and distribution development, thermal, and power conversion work underway
- **Phase 2**
  - Will be a separate, open and competitive procurement for qualification and flight unit

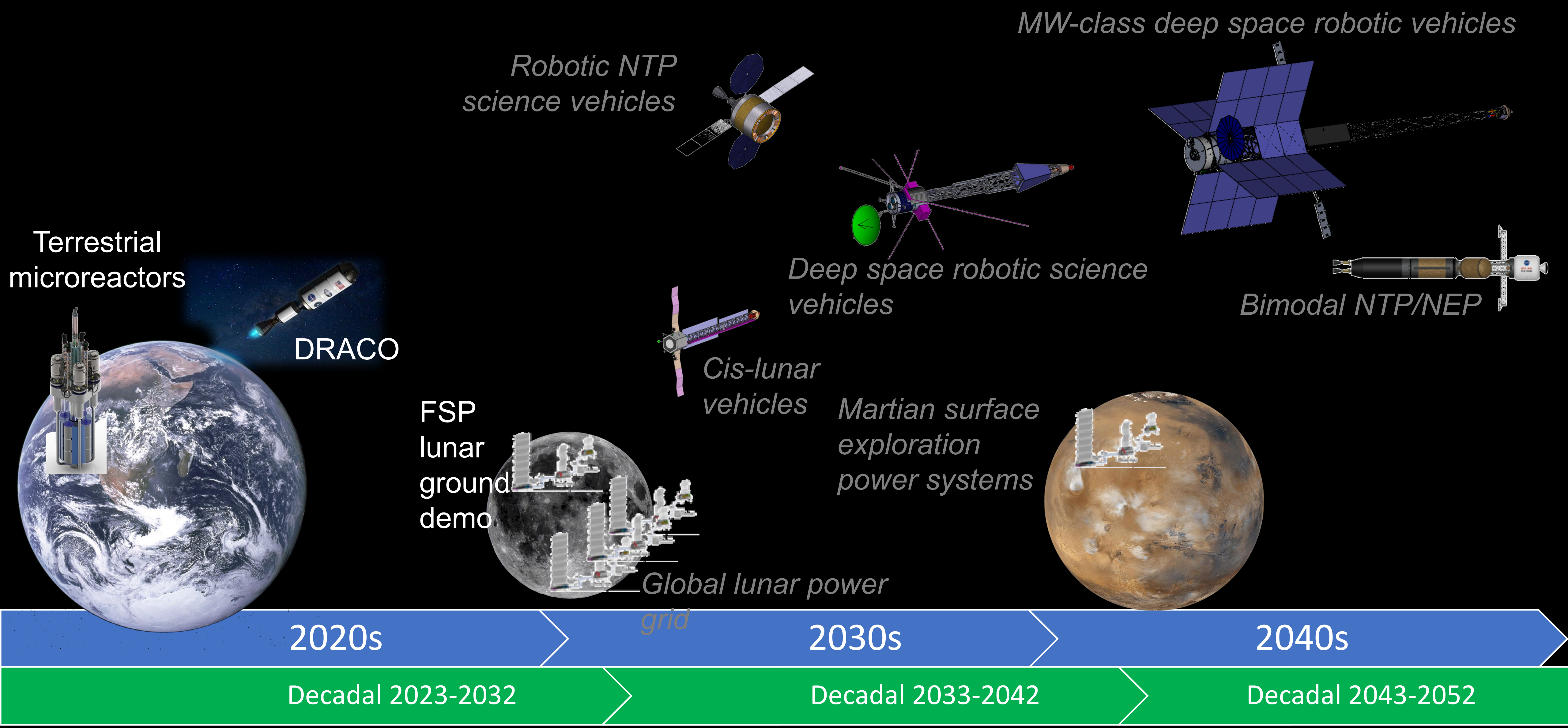
Westinghouse / Aerojet Rocketdyne

Intuitive Machines / X-energy

Lockheed Martin / BWXT (BWX Technologies, Inc.)



Notional Future Fission Power and Propulsion Systems



Key: white = planned effort or mission *grey = notional future effort or mission*

Summary

- NASA intends to develop and fly a family of complementary surface power technologies
- NASA is working with the Department of Energy and their federally funded laboratories to establish a lunar fission surface power system that is directly applicable for Moon and Mars
- NASA-GRC technology investments are targeting key non-nuclear systems needs, including power conversion solutions, radiation hardening of electronics, and power distribution capabilities critical to nuclear systems
- NASA will continue to be closely engaged with industry, academia, and other external stakeholders to seek innovative, unique designs for fission surface power systems

Questions?

Thank You!