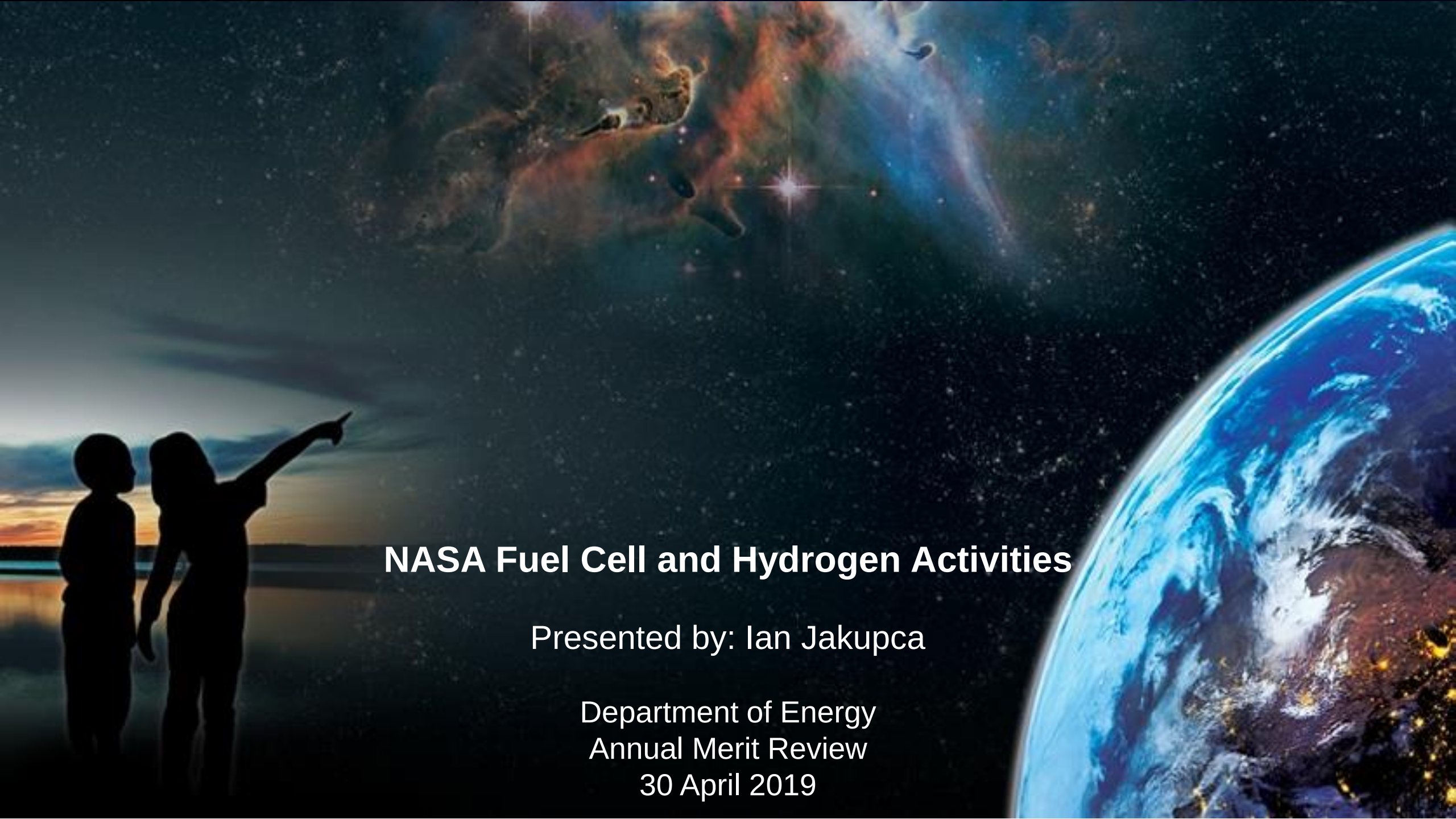


# NASA Fuel Cell and Hydrogen Activities

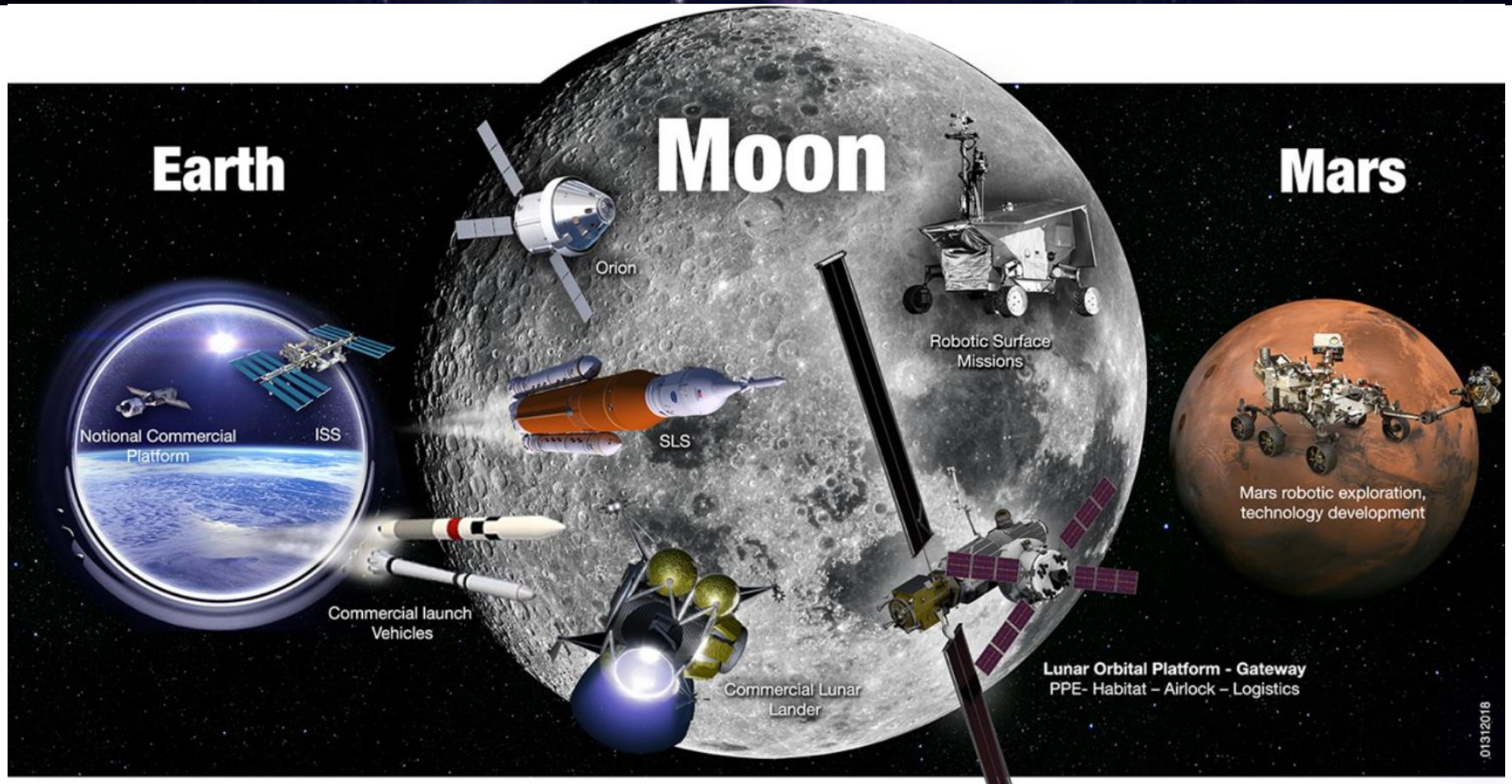
Presented by: Ian Jakupca

Department of Energy
Annual Merit Review
30 April 2019

# Overview

- **National Aeronautic and Space Administration**
- **Definitions**
- **NASA Near Term Activities**
- **Energy Storage and Power**
  - Batteries
  - Fuel Cells
  - Regenerative Fuel Cells
  - Electrolysis
- **ISRU**
- **Cryogenics**
- **Review**

# National Aeronautics and Space Administration




**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

# Acknowledgements

***NASA has many development activities supported by a number of high quality people across the country. This list only includes the most significant contributors to the development of this presentation.***

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- *Wesley L. Johnson, Cryogenic and Fluid Systems*
- *Lisa Kohout, Photovoltaic and Electrochemical Systems*
- *Dianne Linne, ISRU Project Manager*
- *Phillip J. Smith, Photovoltaic and Electrochemical Systems*
- *Tim Smith, Chief, Space Technology Project Office*

# Electrochemical System Definitions

## Primary Power

Discharge Power Only

**Description**

- Energy conversion system that supplies electricity to customer system
- Operation limited by initial stored energy

**Examples**

- Nuclear (e.g. RTG, KiloPower)
- Primary Batteries
- Primary Fuel Cells

**NASA Applications:**

Missions without access to continuous power (e.g. PV)

- All NASA applications require electrical power
- Each primary power solution fits a particular suite of NASA missions

## Energy Storage

Charge + Store + Discharge

**Description**

- Stores excess energy for later use
- Supplies power when baseline power supply (e.g. PV) is no longer available
- Tied to external energy source

**Examples**

- Rechargeable Batteries
- Regenerative Fuel Cells

**NASA Applications:**

Ensuring Continuous Power

- Satellites (PV + Battery)
- ISS (PV + Battery)
- Surface Systems (exploration platforms, ISRU, crewed)
- Platforms to survive Lunar Night

## Commodity Generation

Chemical Conversion

**Description**

- Converts supplied chemical feedstock into useful commodities
- Requires external energy source (e.g. thermal, chemical, electrical, etc.)

**Examples**

- ISS Oxygen Generators (OGA, Elektron)
- ISRU Propellant Generation

**NASA Applications:**

Life-support, ISRU

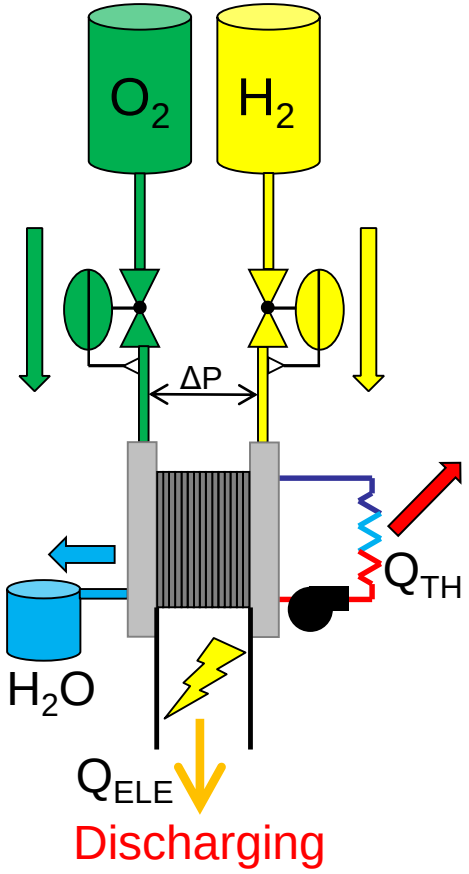
- Oxygen Generation
- Propellant Generation
- Material Processing
- Recharging Regenerative Fuel Cells

# Electrochemical System Definitions

## Primary Fuel Cell

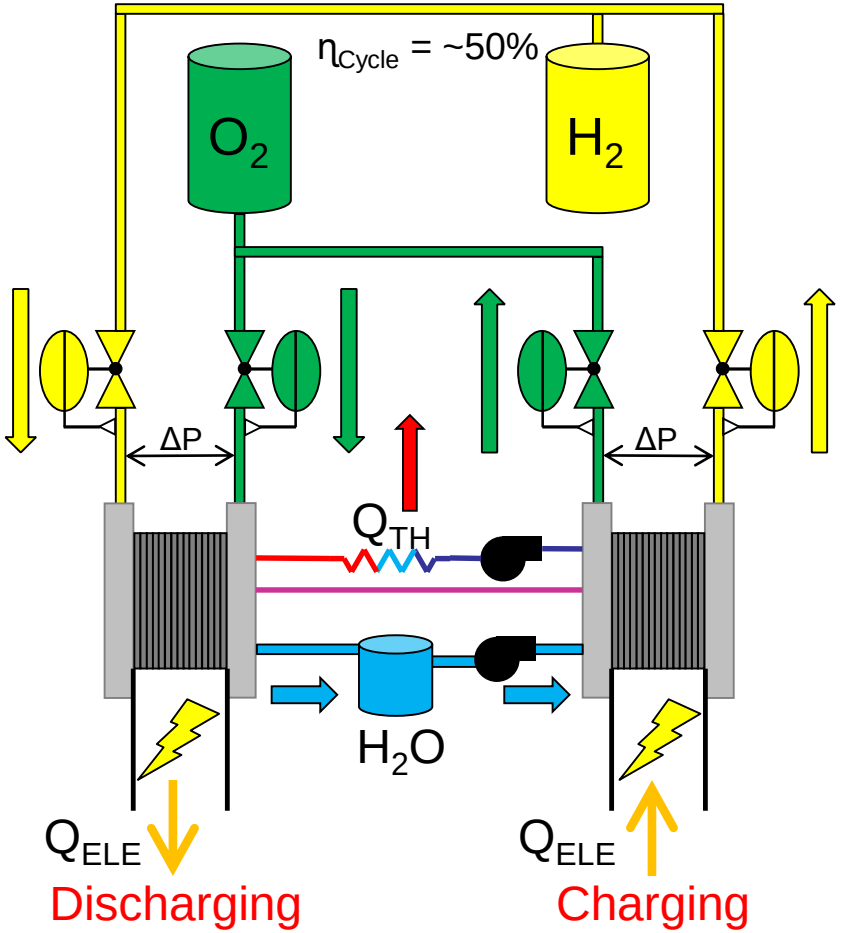
Discharge Power Only

$2H_2 + O_2 \rightarrow 2H_2O + 4e^- + \text{Heat}$




## Regenerative Fuel Cell

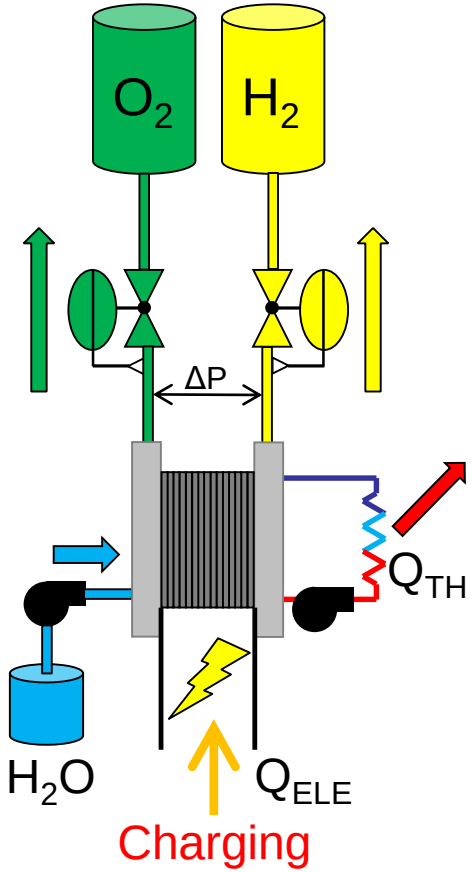
Charge + Store + Discharge




## Electrolysis

Chemical Conversion

$2H_2O + 4e^- \rightarrow 2H_2 + O_2 + \text{Heat}$



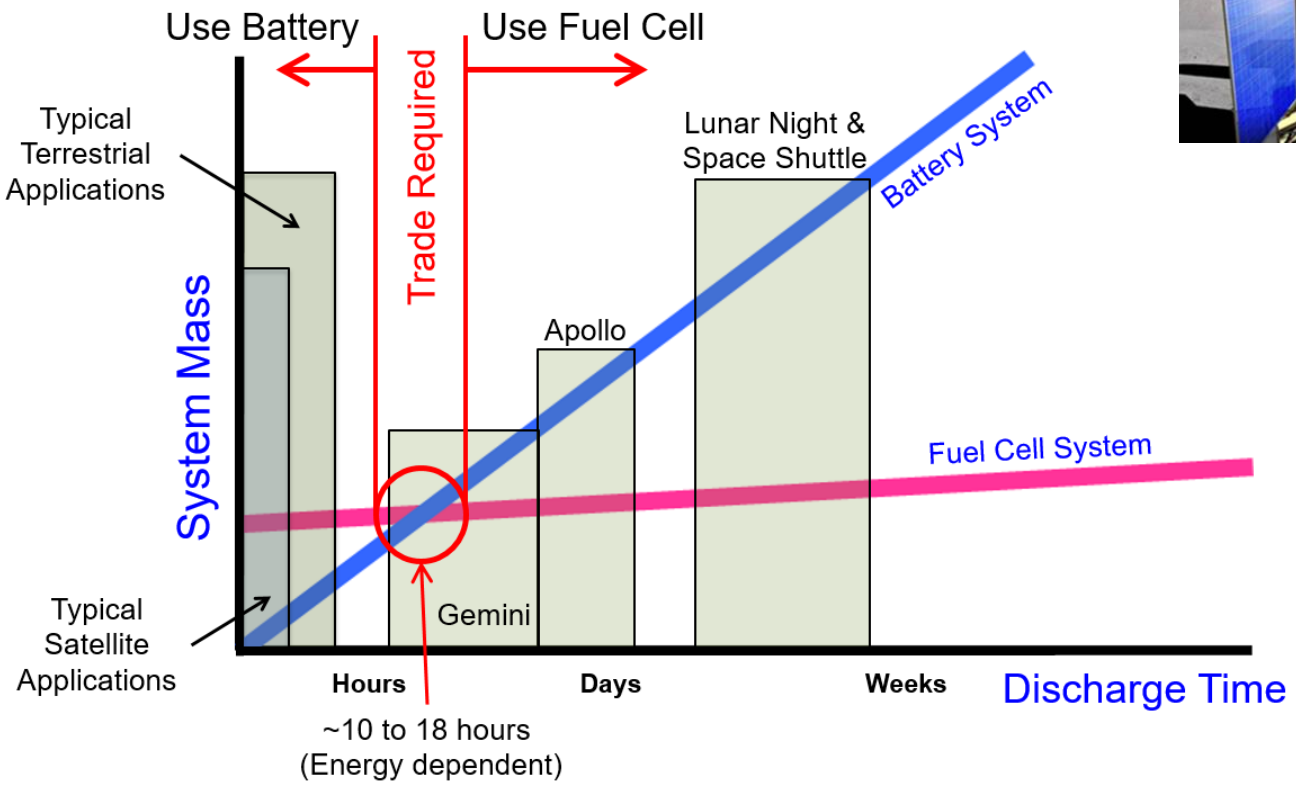

Regenerative Fuel Cell = Fuel Cell + Interconnecting Fluidic System + Electrolysis

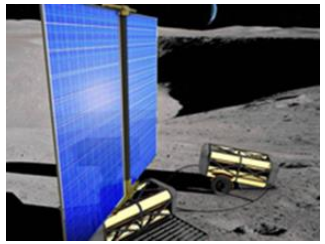
**Each power technology contributes to an integrated Regenerative Fuel Cells (RFCs) for Lunar Exploration**

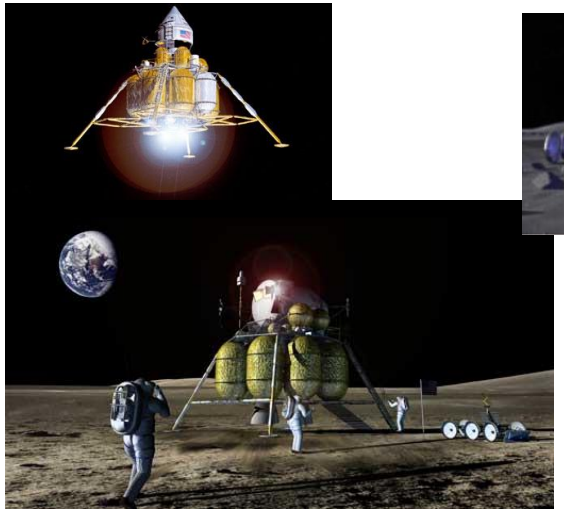
- Batteries meet energy storage needs for low energy applications
- RFCs address high energy storage requirements where nuclear power may not be an option (in locations near humans)
- Nuclear and radio isotope power systems provide constant power independent of sunlight

# Energy Storage Options for Space Applications

| **Energy Options for Space Applications** | Battery = TRL 9<br>Primary Fuel Cell = TRL 5<br>Regenerative Fuel Cell = TRL 3 |
|---|---|



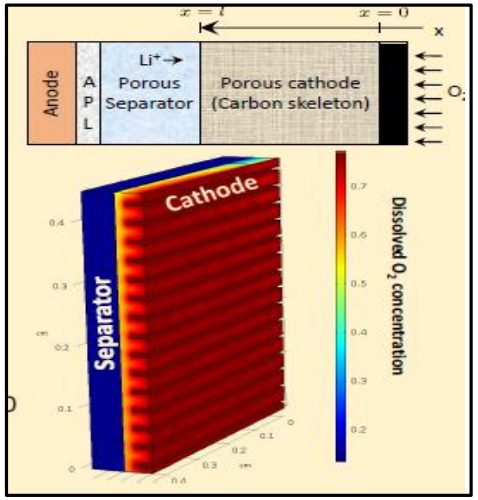


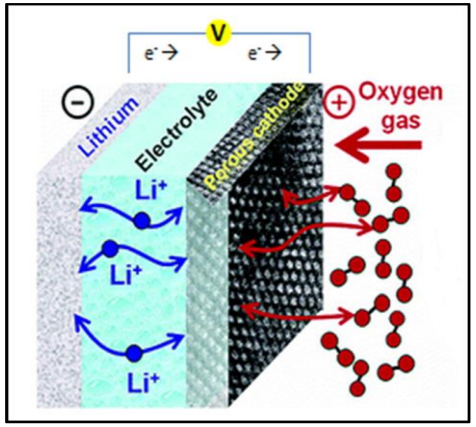
- Current energy storage technologies are insufficient for NASA exploration missions
- Availability of flight-qualified fuel cells ended with the Space Shuttle Program
- Terrestrial fuel cells not directly portable to space applications
  - Different wetted material requirements (air vs. pure $O_2$)
  - Different internal flow characteristics
- No space-qualified high-pressure electrolyzer exists
  - ISS $O_2$ Generators are low pressure electrolyzers
  - Terrestrial electrolyzers have demonstrated >200 ATM operation

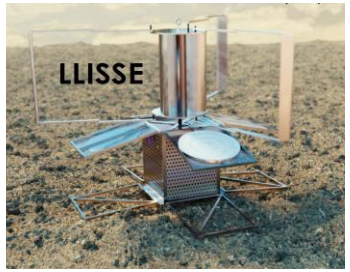
# Battery Activities in Support of NASA Missions

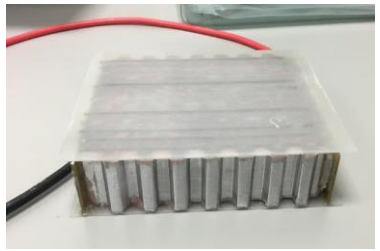
- Low temperature electrolytes to extend operating temperatures for outer planetary missions
- High temperature batteries for Venus missions
- Non-flammable separator/electrolyte systems
- Solid-state high specific energy, high power batteries
- Li-air batteries for aircraft applications

  Improved cathode and electrolyte stability in Lithium-Oxygen batteries
- Multi-functional load-bearing energy storage
- X-57 Maxwell distributed electric propulsion flight demonstration
- Safe battery designs and assessments for aerospace applications



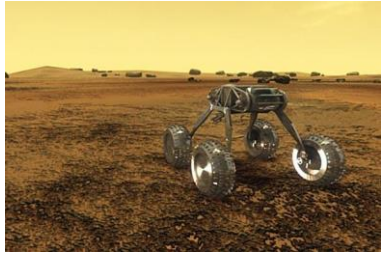



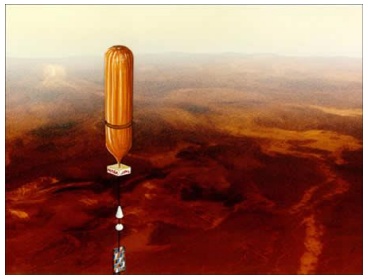



# Energy Storage System Needs for Future Planetary Missions

- **Primary Batteries/Fuel Cells for Surface Probes:**
  - High Temperature Operation (> 465C)
  - High Specific Energy (>400 Wh/kg)
  - Operation in Corrosive Environments
- **Rechargeable Batteries for Aerial Platforms:**
  - High Temperature Operation (300-465C)
  - Operation in Corrosive Environments
  - Low-Medium Cycle Life
  - High Specific Energy (>200 Wh/kg)
  - Operation in High Pressures

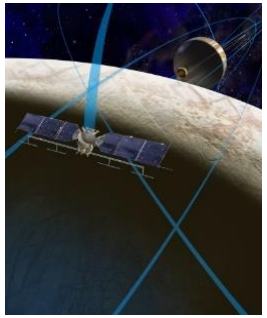




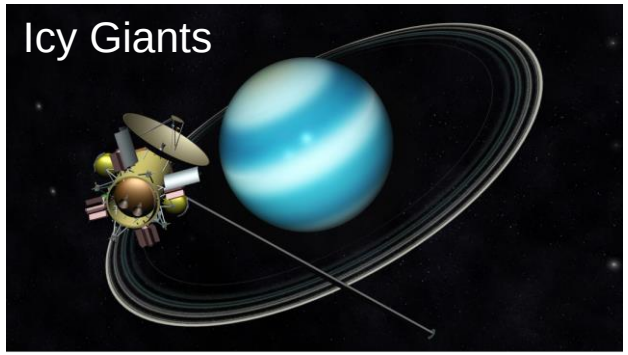
Inner Planets

Outer Planets

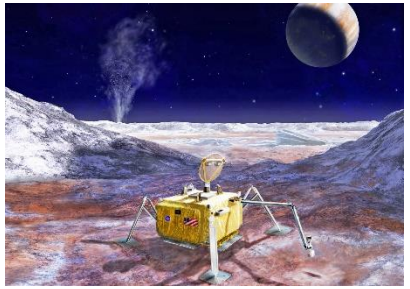
- **Primary Batteries/Fuel cells for planetary landers/probes:**
  - High Specific Energy (> 500 Wh/kg),
  - Long Life (> 15 years),
  - Radiation Tolerance  & Sterilizable by heat or radiation
- **Rechargeable Batteries for flyby/orbital missions:**
  - High Specific Energy (> 250 Wh/kg)
  - Long Life (> 15 years)
  - Radiation Tolerance & Sterilizable by heat or radiation.
- **Low temperature Batteries for Probes and Landers:**
  - Low Temperature Primary batteries (< -80C)
  - Low Temperature Rechargeable Batteries (< -60 C)



Europa Orbiter




Uranus/Neptune missions

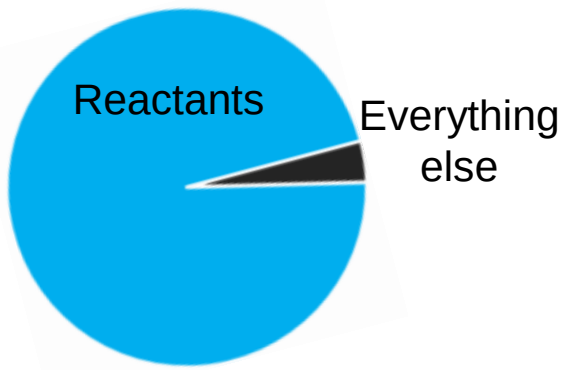


Europa Lander

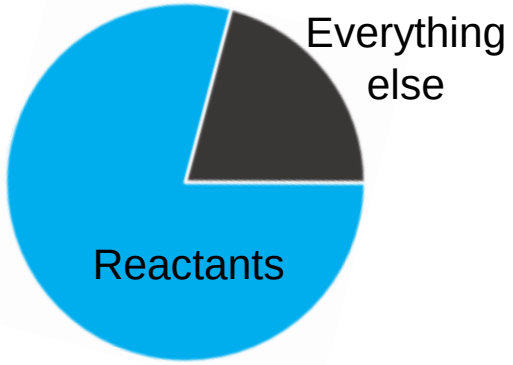
All images are Artist's Concepts

# Lunar RFC Trade Study Results

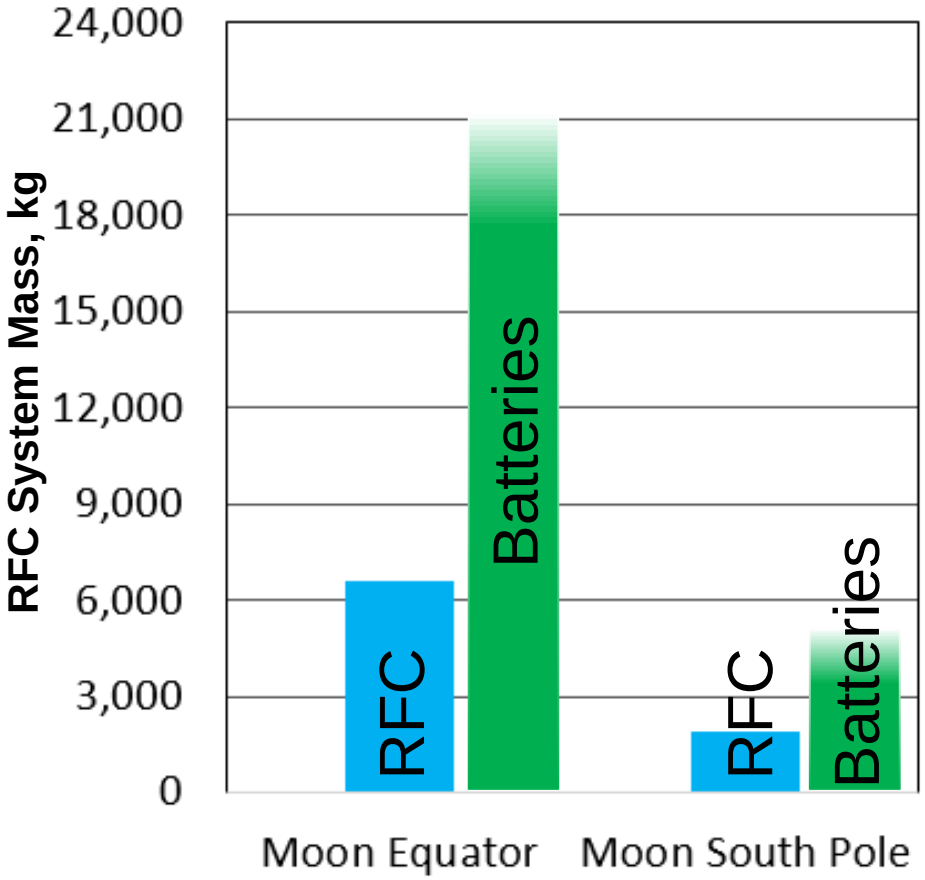
## 10 kW $H_2/O_2$ RFC Energy Storage System for Lunar Outpost



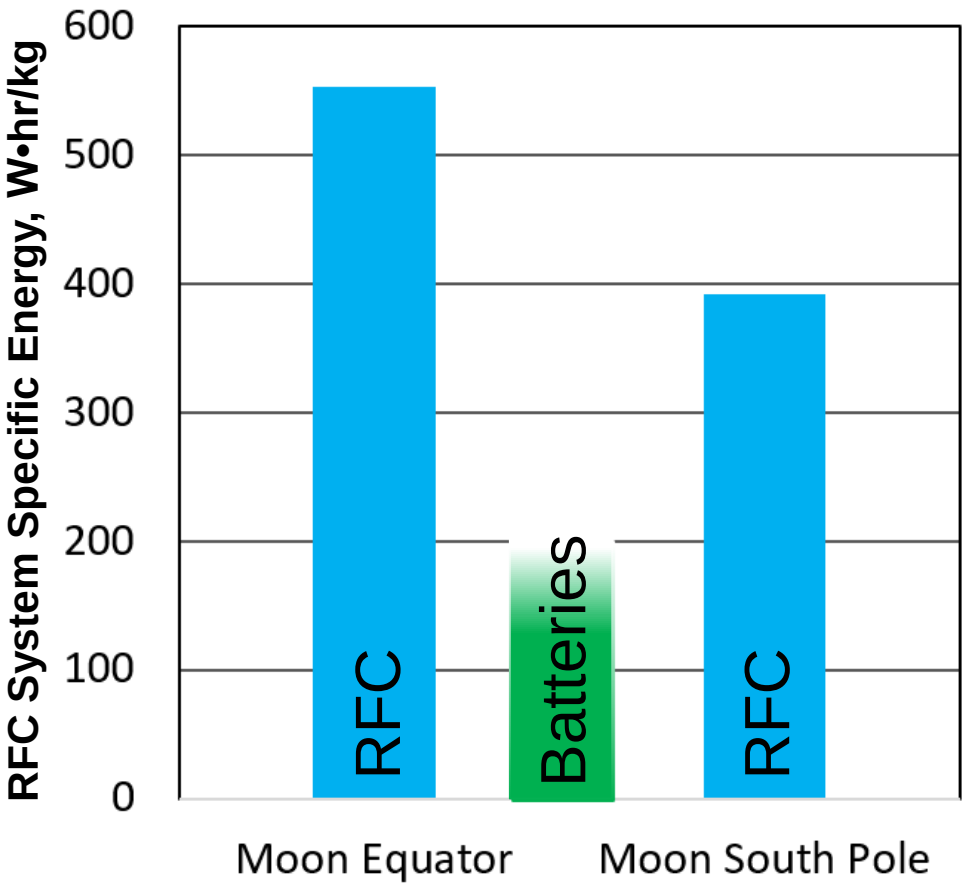

**Volume ($m^3$)**




**Mass (kg)**

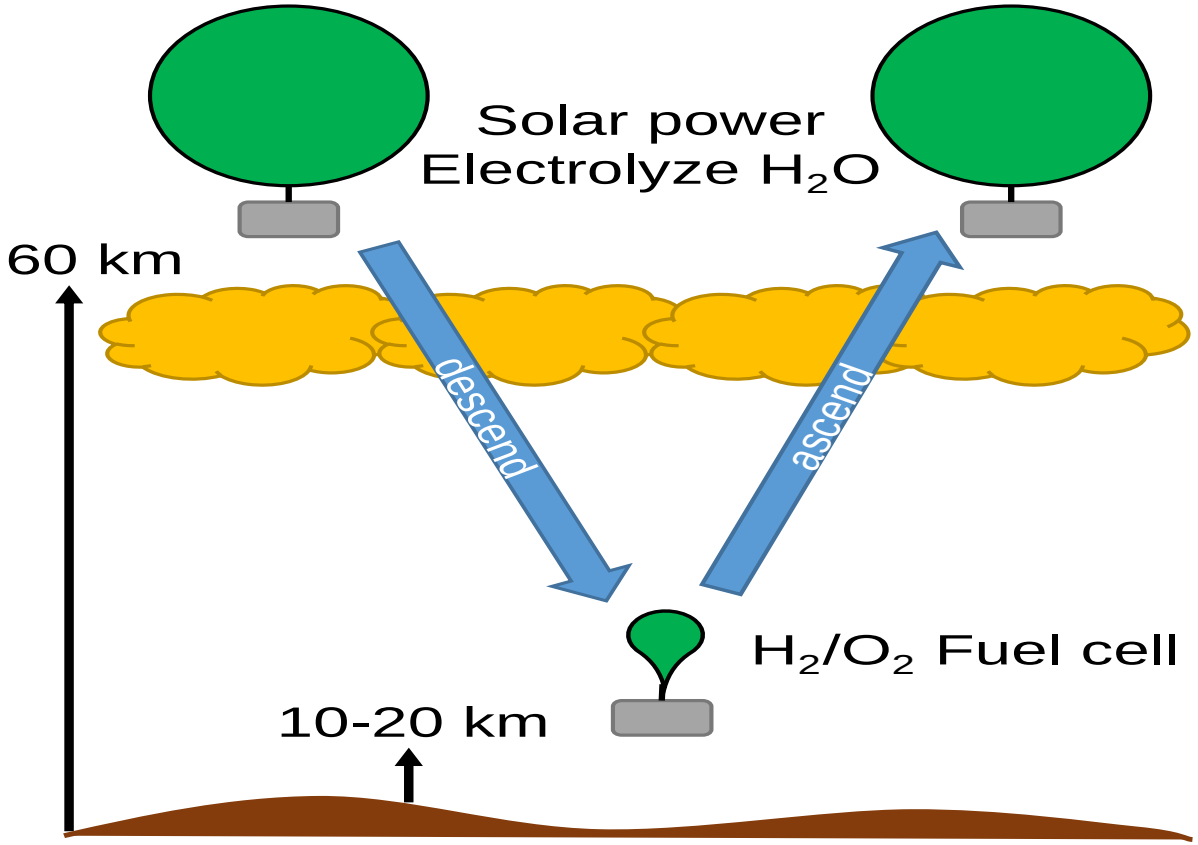



RFCs enable missions to survive the lunar night




RFC specific energy dependent on location.
Battery specific energy independent of location.

# Venus Power Concept for Variable Altitude Balloon




**Above the clouds**
- SOEC recharges $H_2$ & $O_2$ from $H_2O$
- Consumes stored $H_2O$
- Solar array powers probe

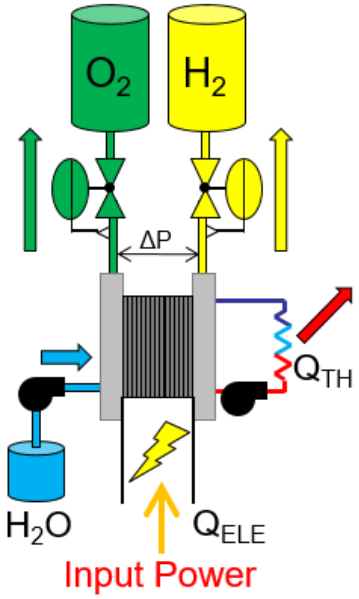
$H_2$ from balloon into hydride to descend below the clouds

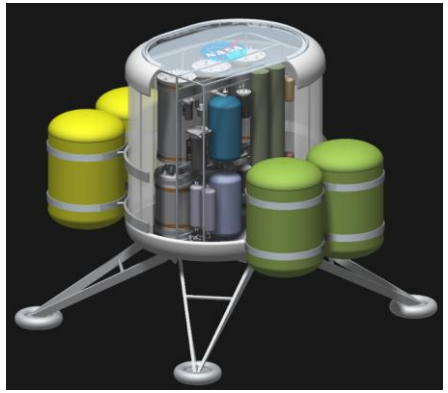
$H_2$ from hydride into balloon to ascend above the clouds

**Below the clouds**
- SOFC generates power from $H_2$ & $O_2$ to power probe
- Store $H_2O$ byproduct

- A solar array powers the probe at high altitude and generates $H_2$ and $O_2$ with Solid Oxide Electrolysis Cell (SOEC) using water carried from ground as a closed-system.
- Metal hydride $H_2$ storage and compressed gas $O_2$ storage
- Solid Oxide Fuel Cell (SOFC) will powers the probe at low altitudes from the stored $H_2$ and $O_2$.
- $H_2$-filled balloon will be used for buoyancy and altitude control (60-15 km).

# Electrolysis within NASA



## Fundamental Process

- Electrochemically dissociating water into gaseous hydrogen and oxygen
- Multiple chemistries – Polymer Electrolyte Membrane (PEM), Alkaline, Solid Oxide
- Multiple pressure ranges
  - ISRU & Life support = low pressure
  - Energy storage = high pressure

**Life Support:** Process recovered $H_2O$ to release oxygen to source breathing oxygen

- Redesign ISS Oxygen Generator assembly for increased safety, pressure, reliability, and life
- Evaluate Hydrogen safety sensors

**Energy Storage:** Recharge RFC system by processing fuel cell product $H_2O$ into $H_2$ fuel and $O_2$ oxidizer for fuel cell operation

**ISRU:** Process recovered $H_2O$ to utilizing the resulting $H_2$ and $O_2$

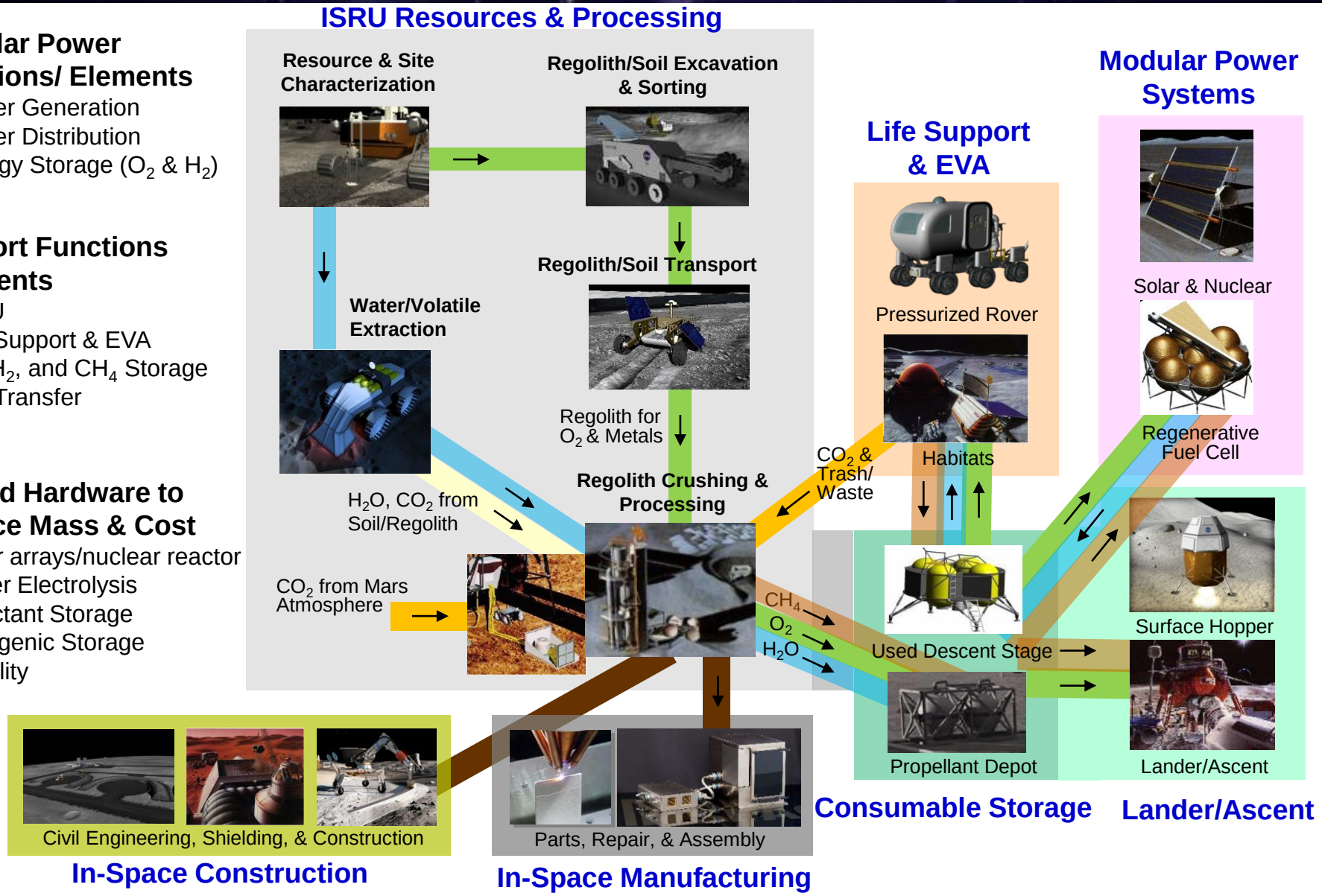
- Hydrogen Reduction – Hydrogen for material processing
- Life Support – Oxygen to source breathing oxygen
- Propellant Generation – Oxygen for liquefaction and storage

# In-situ Resource Utilization (ISRU)

**Modular Power Functions/ Elements**
- Power Generation
- Power Distribution
- Energy Storage ($O_2$ & $H_2$)

**Support Functions /Elements**
- ISRU
- Life Support & EVA
- $O_2$, $H_2$, and $CH_4$ Storage and Transfer

**Shared Hardware to Reduce Mass & Cost**
- Solar arrays/nuclear reactor
- Water Electrolysis
- Reactant Storage
- Cryogenic Storage
- Mobility



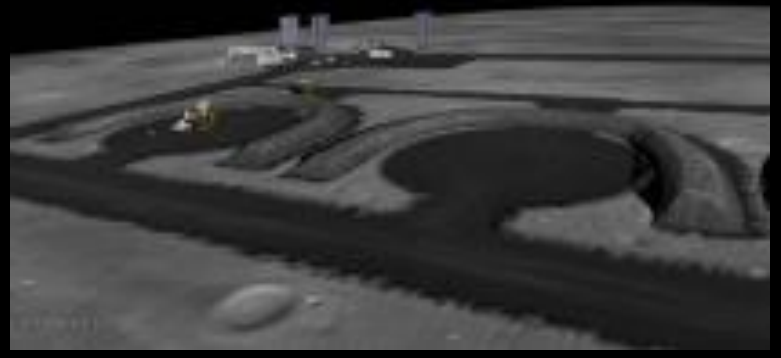
# Lunar ISRU Mission Capability Concepts

Resource Prospecting – Looking for Polar Ice

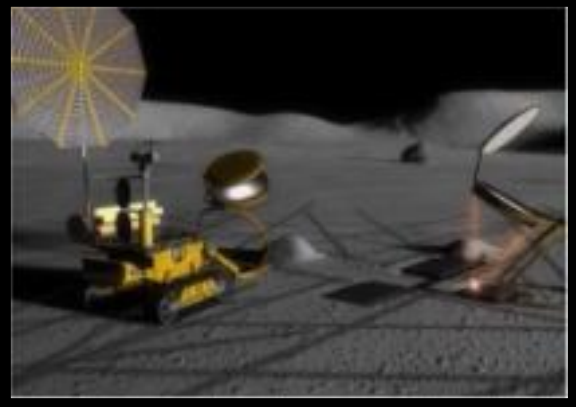
Excavation & Regolith Processing for $O_2$ Production

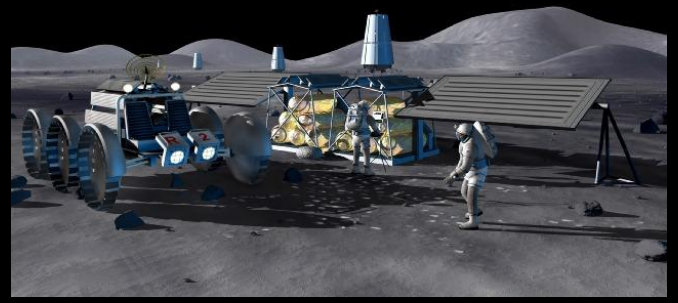
Carbothermal Processing with Altair Lander Assets

Thermal Energy Storage Construction



Landing Pads, Berm, and Road Construction





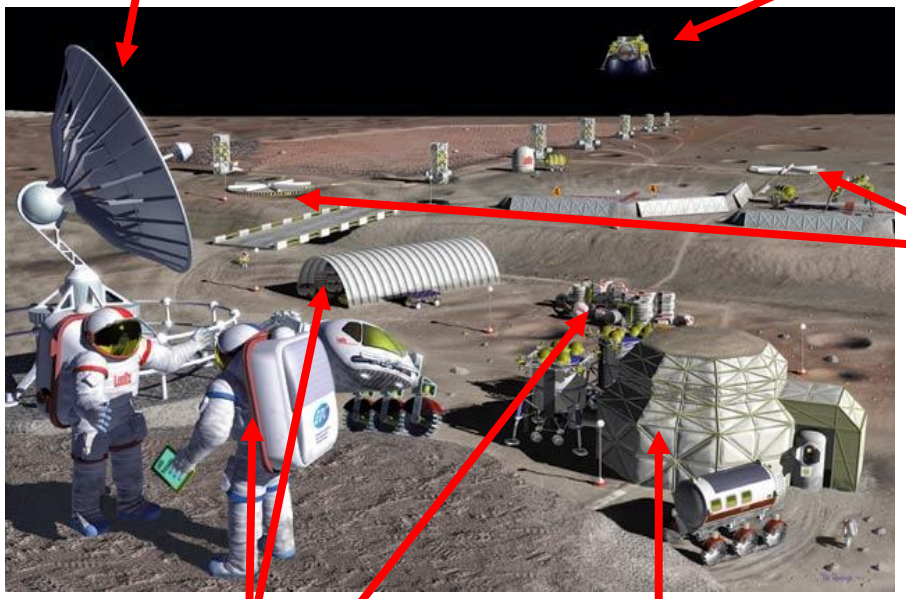
Consumable Depots for Crew & Power

# ISRU is Similar to Establishing Remote Mining Infrastructure and Operations on Earth

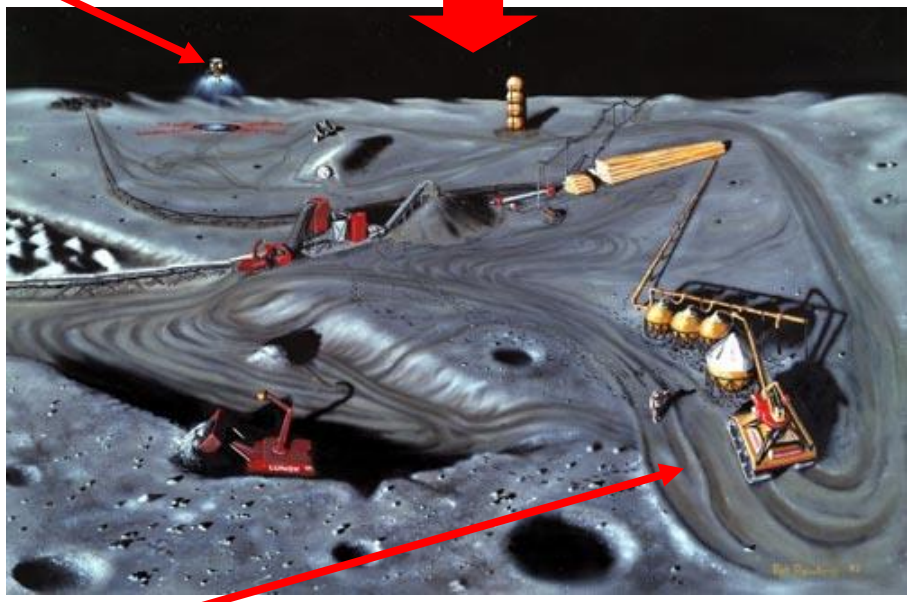
Communications
- To/From Site
- Local

Transportation to/from Site:
- Navigation Aids
- Loading & Off-loading Aids
- Fuel & Support Services

Planned, Mapped, and Coordinated Mining Ops:
Areas for: i) Excavation, ii) Processing, and iii) Tailings



Power:
- Generation
- Storage
- Distribution

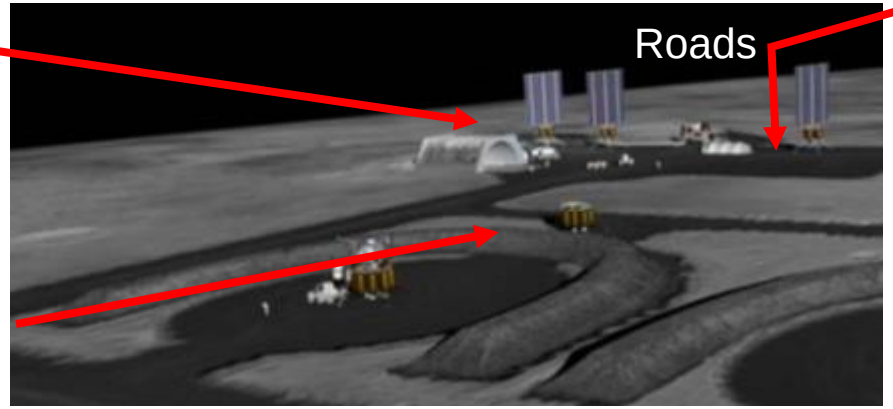


Maintenance & Repair

Living Quarters & Crew Support Services

Logistics Management

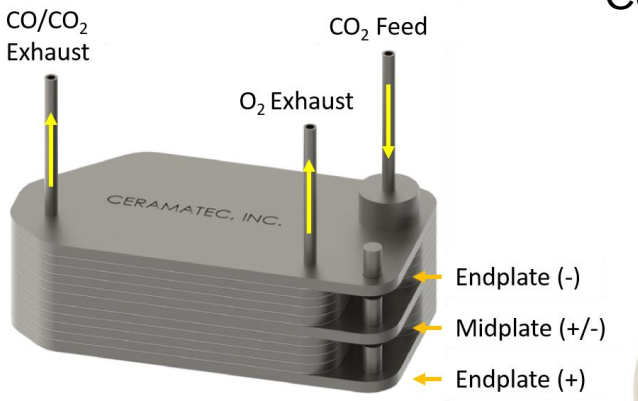
Construction and Emplacement



# Reactant Processing and Storage

## Oxygen

### MOXIE $O_2$ Generator

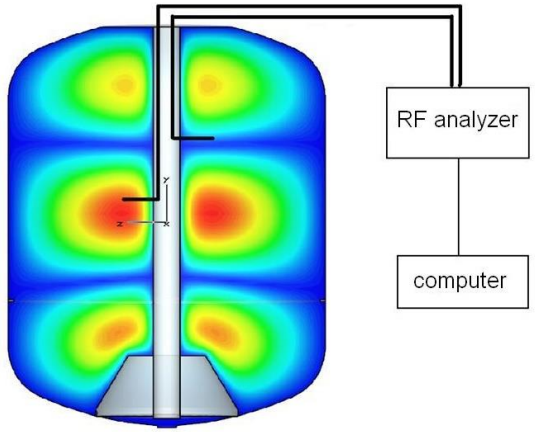



### Oxygen Concentrators

### Tank-to-Tank Transfer

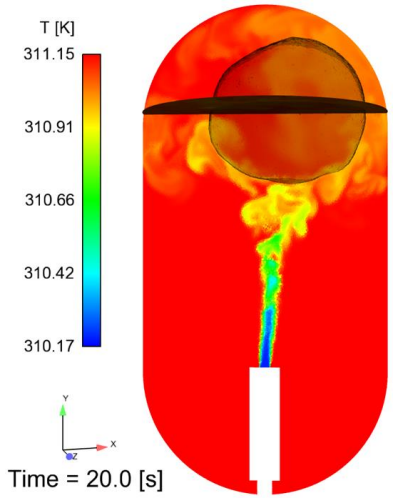
### CryoFILL Liquefaction and Storage

### Radio Frequency Mass Gauge (RFMG)

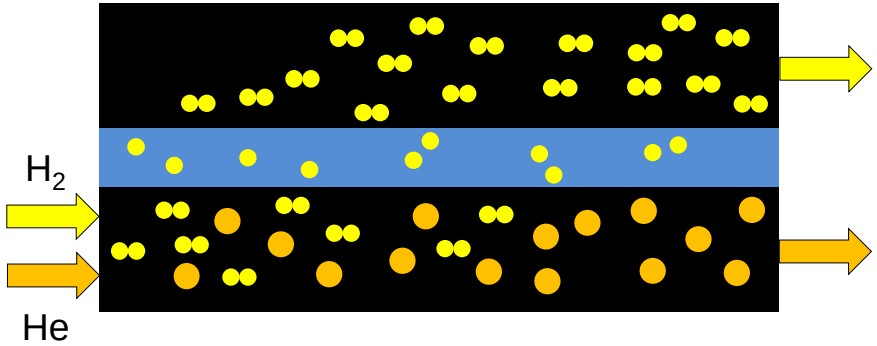



## Hydrogen

### Zero Boil-Off Tank (ZBOT) Experiment

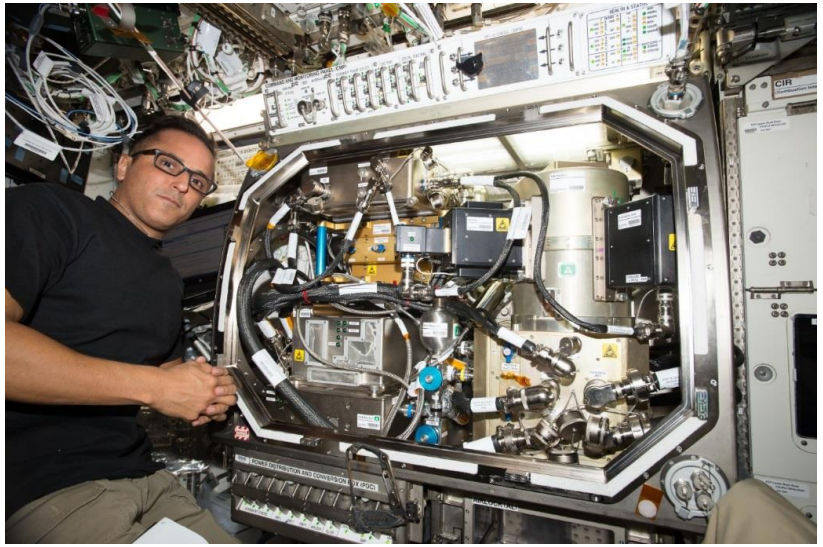


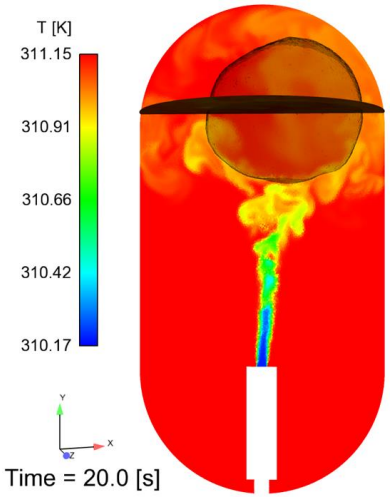

### Purification and Recovery



# Zero Boil-off Cryogenics

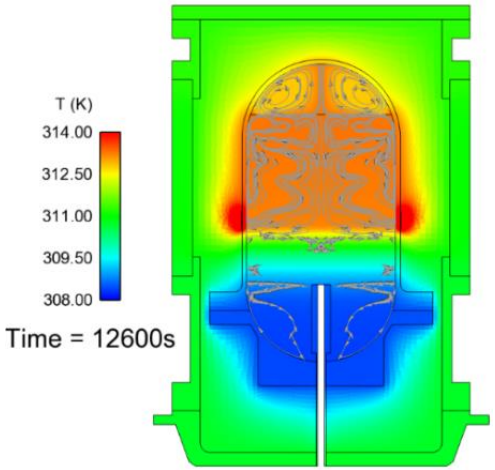
Zero Boil-Off Tank (ZBOT) Experiment:
Hardware in MSG Aboard ISS

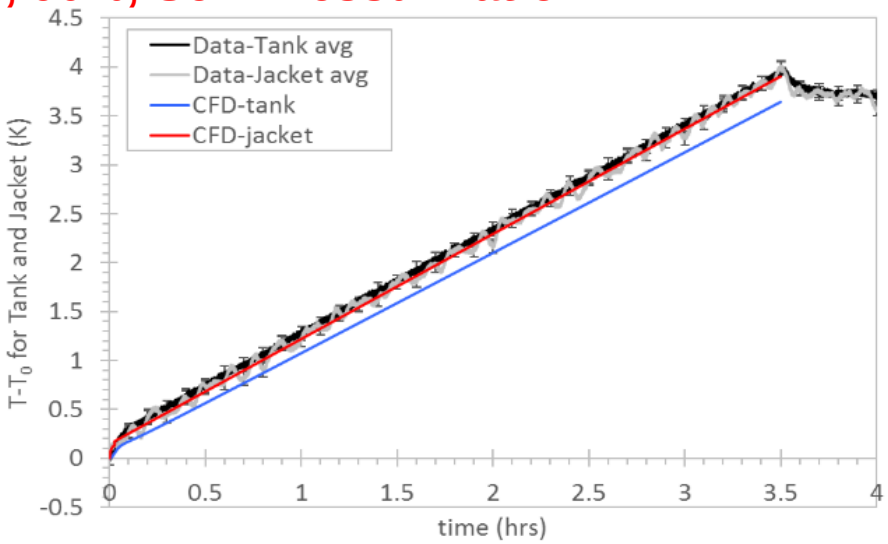




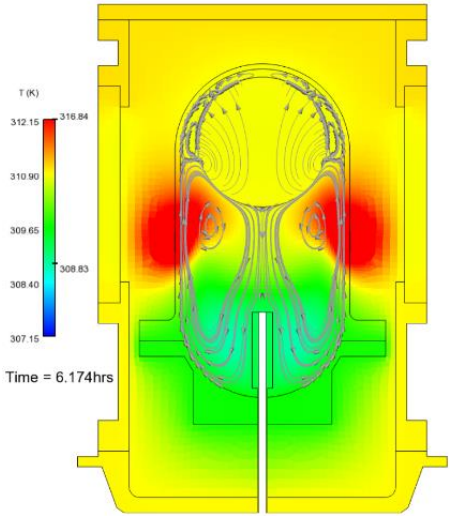

ZBOT Experiment
During Jet Mixing

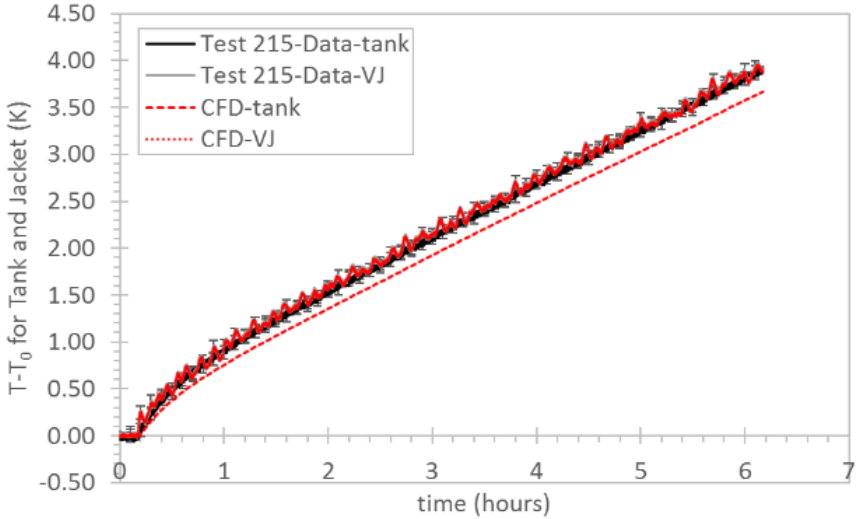
## 1g (1W), 90%, Self-Pressurization




## Micro-g (0.5W), 70%, Self-Pressurization



**Thank you for your attention.**

**Questions?**

# Major Challenges of Solar System Missions

## Extreme Environments in Planetary Missions

- Some missions require high radiation resistant power systems
- Outer planetary surface missions require low temperature power systems
- Some outer planetary missions require power systems that can operate in deep space and in dense or tenuous atmospheres



Io

Europa



Io-Volcano

Inner planetary missions require power systems that can operate in very high temperature environments



Triton Pluto Titan



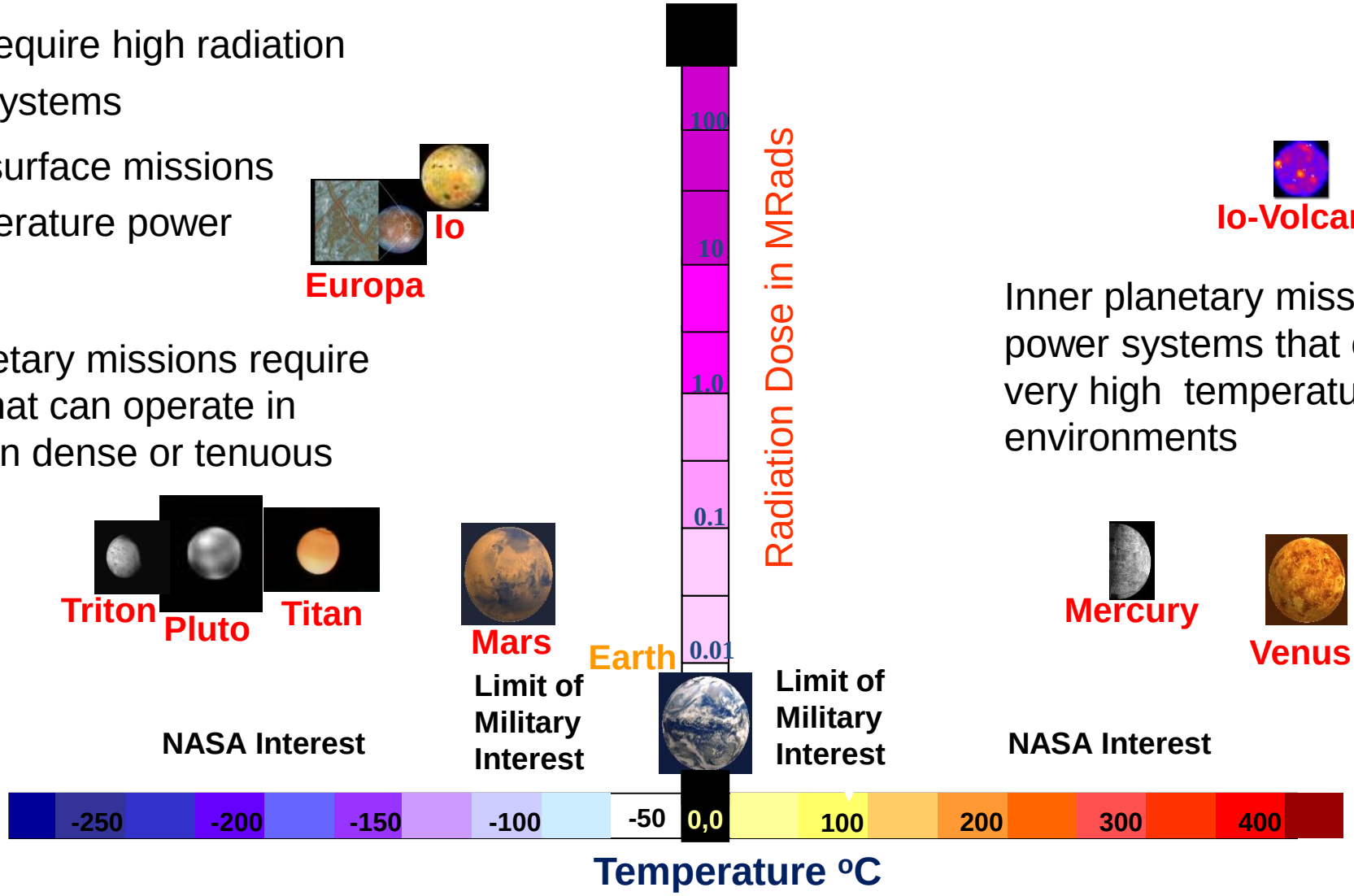
Mars



Mercury



Venus



# Representative Examples of Aeronautics Mission Requirements

| Mission | Number of Passengers | Typical Range | Power Level | Specific Energy | EAP Configurations |
|---|---|---|---|---|---|
| Urban Mobility | ≤ 4 | < 50 miles | 200-500 kW | 250 – 400 Whr/kg | • All electric<br>• Hybrid Electric |
| Thin Haul | ≤ 9 | < 600 miles | 200-500 kW | 300 – 600 Whr/kg | • Hybrid Electric |
| Short Haul Aircraft | 40-80 | < 600 miles | 500-1500 kW | 300 – 600 Whr/kg | • Hybrid Electric |
| Single Aisle | 150-190 | 900 mile typical mission, 3500 mile maximum range | 1000-5000 kW | 750 – 1000 Whr/kg minimum | • Hybrid Electric<br>• Turbo Electric |

# In-situ Venus Missions

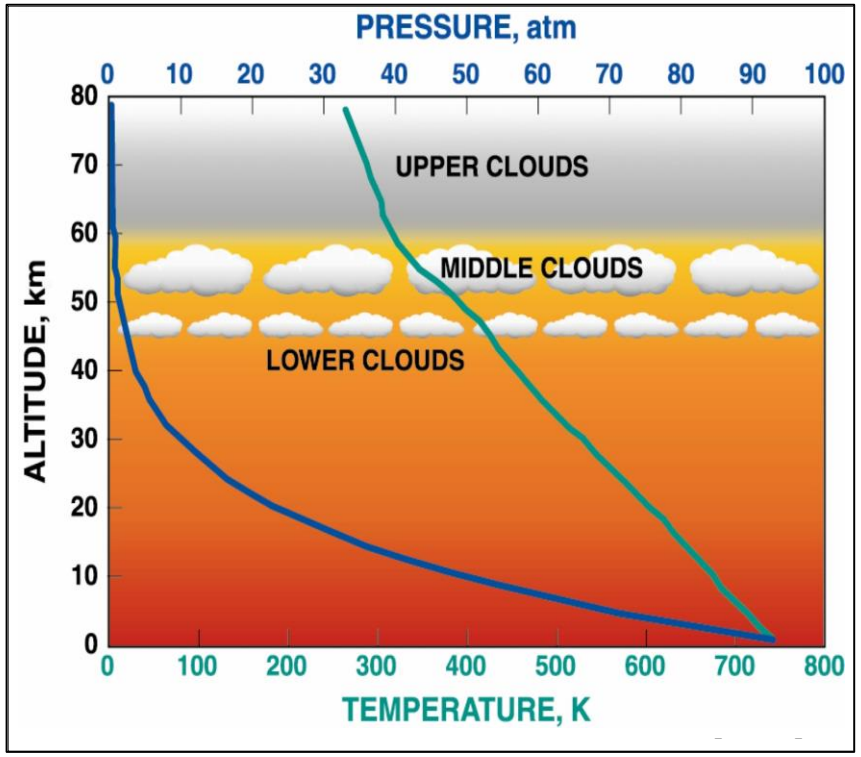
## The Need for In-Situ missions:

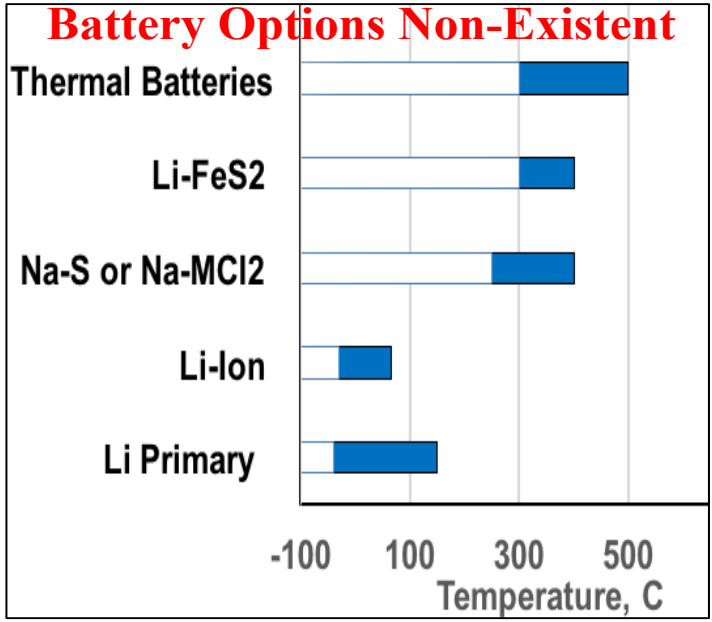
Despite years of exploration, major questions remain:

- What is the precise chemical composition of the atmosphere and how does it vary with location and altitude?
- When and How did the Greenhouse effect occur on Venus
- How did the atmosphere of Venus form and evolve?
- What are the morphology, chemical make-up, and variability of the Venusian clouds and their impact on the climate?
- What are the processes controlling the atmospheric super-rotation?
- What are the processes governing Venus seismicity and its interior structure?
- How have the interior, surface, and atmosphere interacted as a coupled system over time?

## The Problem

- Hostile environment of high temperature and pressure (465°C and 92 atm of $CO_2$) makes surface and low-altitude missions challenging.
- Cloud opacity limits orbital/balloon observations
- Conventional power sources, PV or RTG may not be applicable. New power technologies desired to enable missions

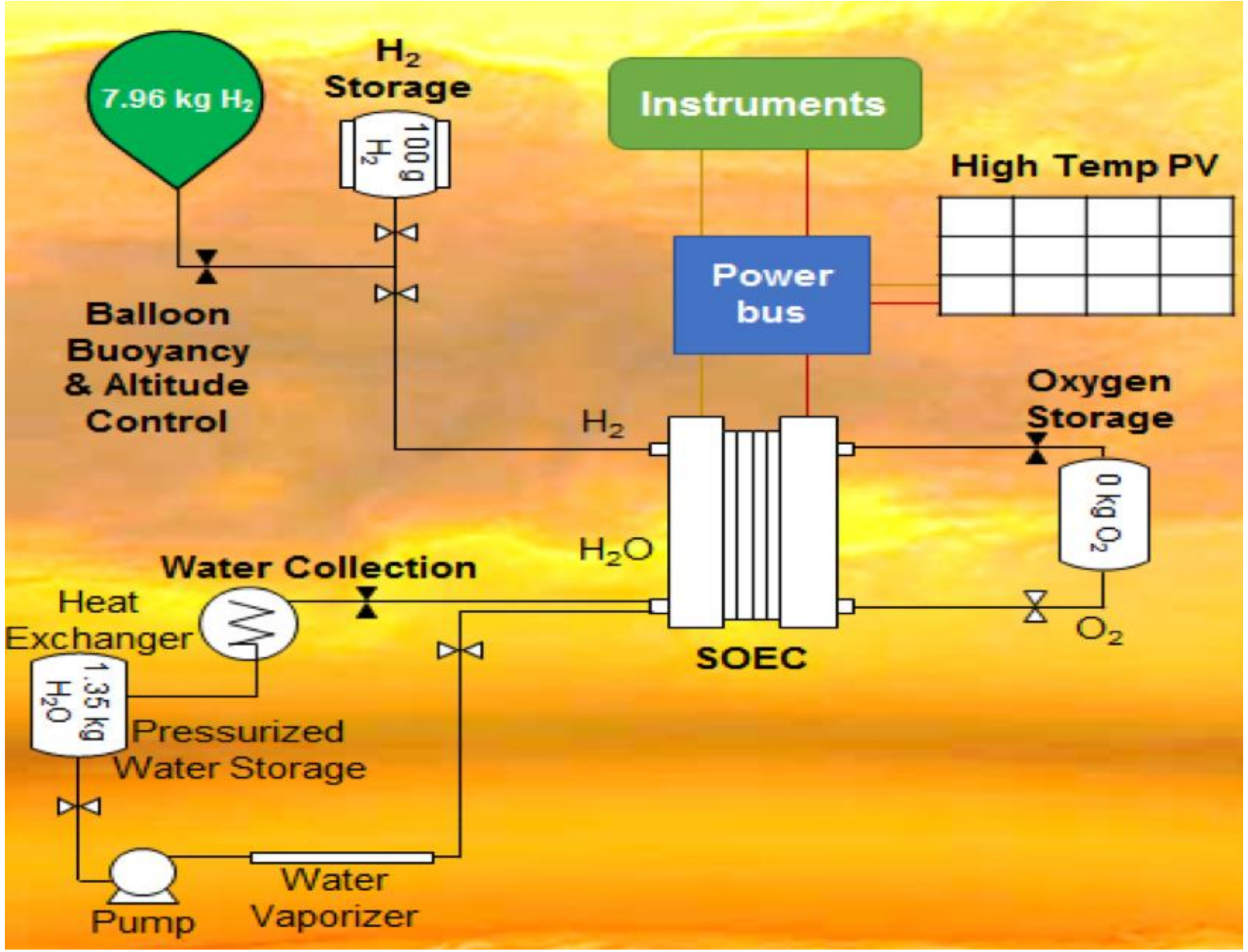


# New Power Concept for Variable Altitude Venus Balloon Operation

Altitude Control

- $H_2$-filled balloon for buoyancy and altitude control (60-15 km)
- To Ascend: move $H_2$ from hydride into balloon
- To Descend: move $H_2$ from balloon into hydride




Solar array powers the probe at high altitude and generates $H_2$ and $O_2$ with Solid Oxide Electrolysis Cell (SOEC) from stored $H_2O$

At low altitudes, the SOEC operates reversibly as a Fuel Cell to power the probe from the stored $H_2$ and $O_2$ and stores the byproduct $H_2O$

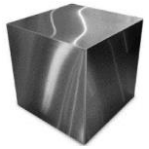
# Portability of Terrestrial Technology to Aerospace Applications

| | Component | Aerospace TRL Level | Portability of Terrestrial Technology to Aerospace Applications | Remaining Technical Challenge |
|---|---|---|---|---|
| Electrolyzer Technology | Electrochemistry | 9 | High | |
| | Materials | 5+ | High | High Pressure, Mass |
| | Seals | 5+ | High | High Pressure, Mass |
| | Gas Management | 5+ | Moderate | High Pressure, Mass |
| Fuel Cell Technology | Flow Fields | 5+ | High | |
| | Bipolar Plates | 5+ | Moderate | $O_2$ vs air |
| | Materials | 5+ | Moderate | $O_2$ vs air |
| | Electrochemistry | 5+ | Low | $O_2$ vs air, Performance |
| | Water Management | 5+ | Low | Flow Rate, $\mu g$ |
| Reactant Storage and Management | Fluidic Components | 8+ | Moderate | $O_2$ vs air |
| | Procedures | 5 | Moderate | $O_2$ vs air, Performance |
| | Thermal | 8+ | Moderate | $\mu g$, Vacuum |
| | Materials | 8+ | Low | $O_2$ vs air |
| | Water Management | 5+ | Low | $O_2$ vs air, $\mu g$ |
| FC / EZ / RFC System Avionics | Hardware/PCB | 8+ | High | |
| | Power Management | 8+ | High | |
| | Structure | 8+ | High | |
| | Thermal | 8+ | High | |
| | Instrumentation | 8+ | Moderate | |

**NOTE:** Not all relevant technologies exist within the same application nor are at the same TRL.

Elements of multiple terrestrial applications are required to meet specific NASA mission requirements.

# In-situ Resource Utilization (ISRU)

| | Moon | Mars | Asteroids | Uses |
|---|---|---|---|---|
| **Water (Hydrogen)** | Icy Regolith in Permanently Shadowed Regions (PSR) | Hydrated Soils/Minerals: Zypsum, Jarosite, Phylosilicates, Polyhdrated Sulfates | Subsurface Regolith on C-type Carbonaceous Chondrites | ▪ Drinking, radiation shielding, plant growth, cleaning & washing<br>▪ Making Oxygen and Hydrogen |
| **Oxygen** | Solar wind hydrogen with Oxygen | Subsurface Icy Soils in Mid-latitudes to Poles | | |
| | Minerals in Lunar Regolith: Ilmenite, Pyroxene, Olivine, Anorthite | Carbon Dioxide in the atmosphere (~96%) | Minerals in Regolith on S-type Ordinary and Enstatite Chondrites | ▪ Breathing<br>▪ Oxidizer for Propulsion and Power |
| | ▪ $CO$, $CO_2$, and HC's in PSR<br>▪ Solar Wind from Sun (~50 ppm) | Carbon Dioxide in the atmosphere (~96%) | Hydrocarbons and Tars (PAHs) in Regolith on C-type Carbonaceous Chondrites | ▪ Fuel Production for Propulsion and Power<br>▪ Plastic and Petrochemical Production |
| **Metals**  | Minerals in Lunar Regolith<br>▪ Iron/Ti: Ilmenite<br>▪ Silicon: Pyroxene, Olivine, Anorthite<br>▪ Magnesium: Mg-rich Silicates<br>▪ Al: Anorthitic Plagioclase | Minerals in Mars Soils/Rocks<br>▪ Iron: Ilmenite, Hematite, Magnetite, Jarosite, Smectite<br>▪ Silicon: Silica, Phyllosilicates<br>▪ Aluminum: Laterites, Aluminosilicates, Plagioclase<br>▪ Magnesium: Mg-sulfates, Carbonates, & Smectites, Mg-rich Olivine | Minerals in Regolith/Rocks on S-type Stony Iron and M-type Metal Asteroids | ▪ *In situ* fabrication of parts<br>▪ Electical power generation and transmission |

**Note: Rare Earth Elements (REE) and Platinum Group Metals (PGM) are not driving Resources of interest for Human Exploration**