NASA Fuel Cell and Hydrogen Activities

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Department of Energy
Annual Merit Review
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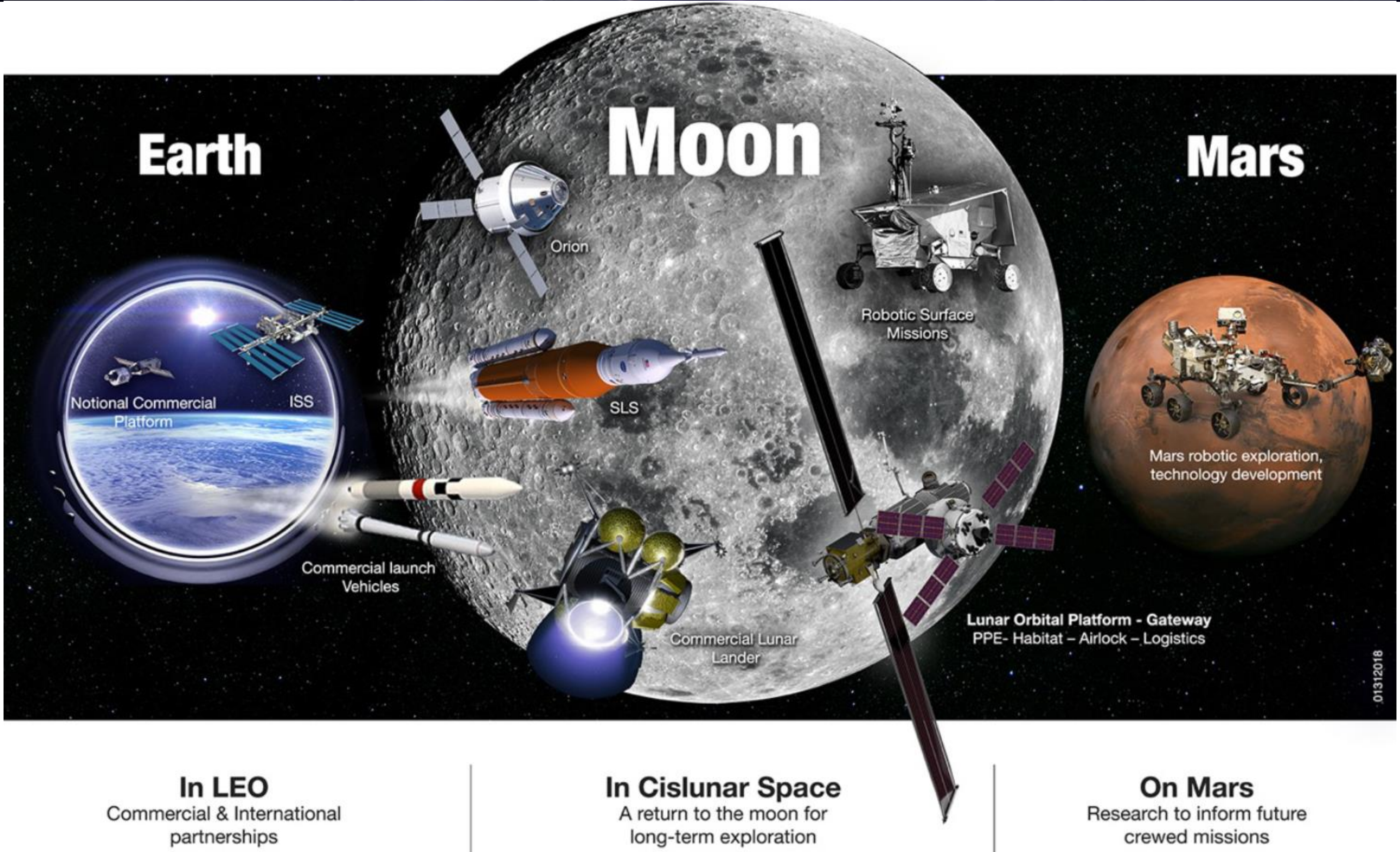
Overview

- **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



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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

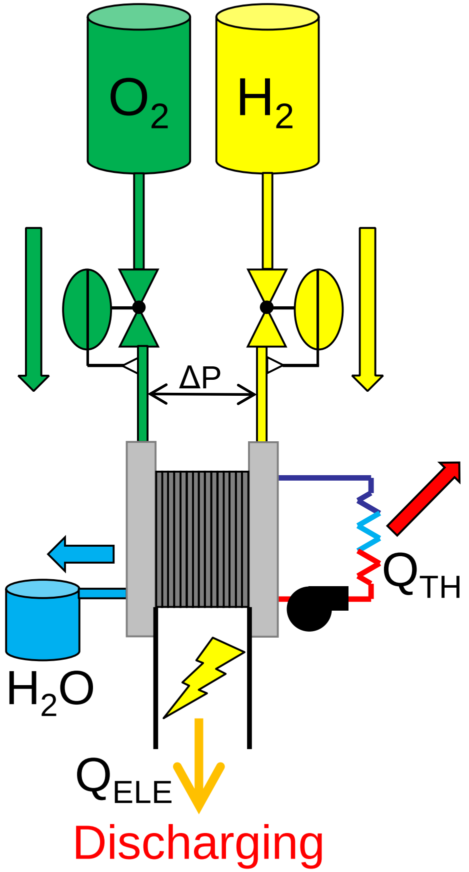
NASA Applications:
Life-support, ISRU
- Oxygen Generation
- Propellant Generation
- Material Processing
- Recharging Regenerative Fuel Cells

Electrochemical System Definitions

Primary Fuel Cell

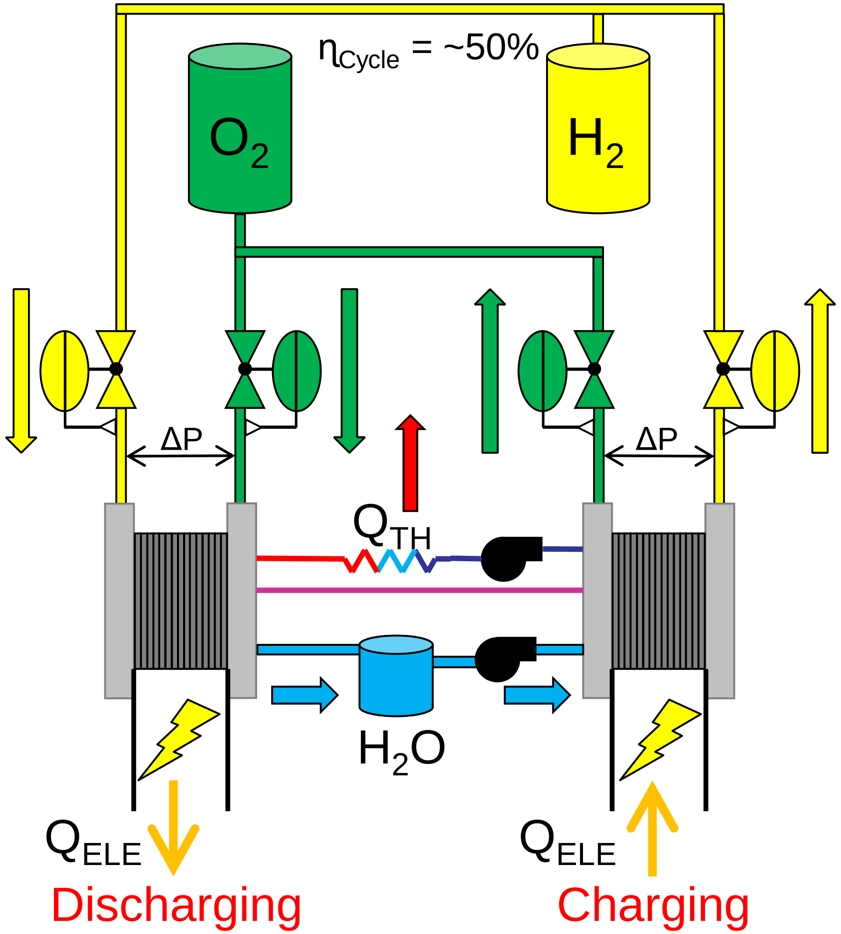
Discharge Power Only

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



Regenerative Fuel Cell

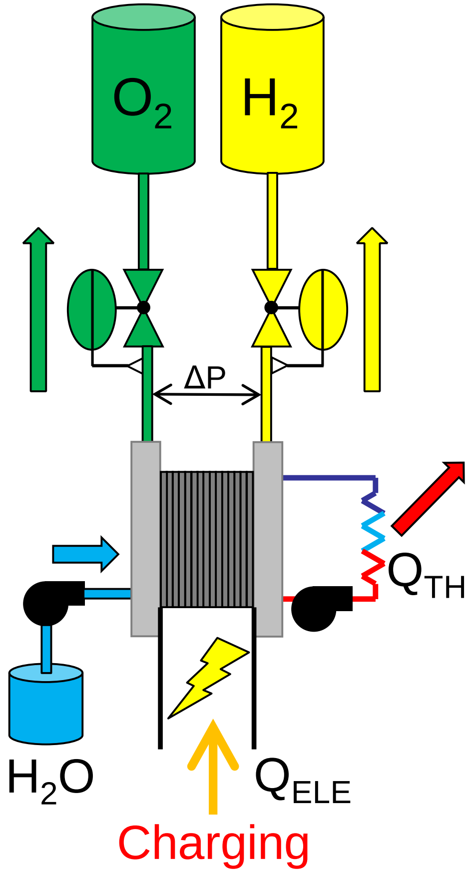
Charge + Store + Discharge



Electrolysis

Chemical Conversion

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



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

POWER to explore the

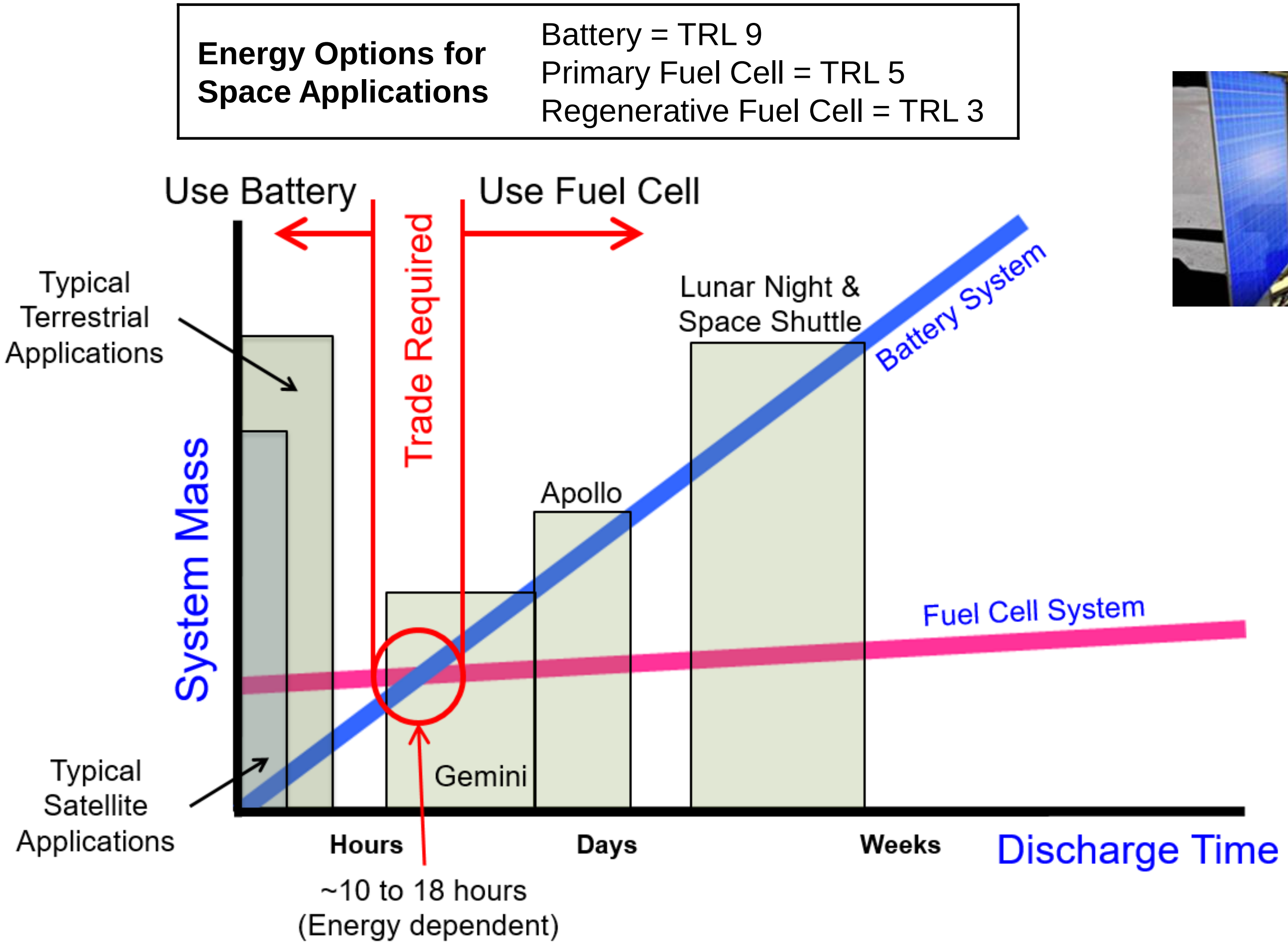
LUNAR SURFACE

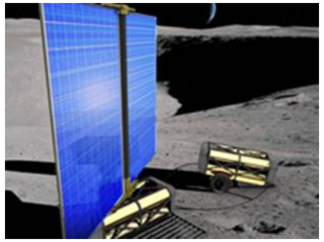
Multiple power technologies comprise the Lunar Surface Power Architecture

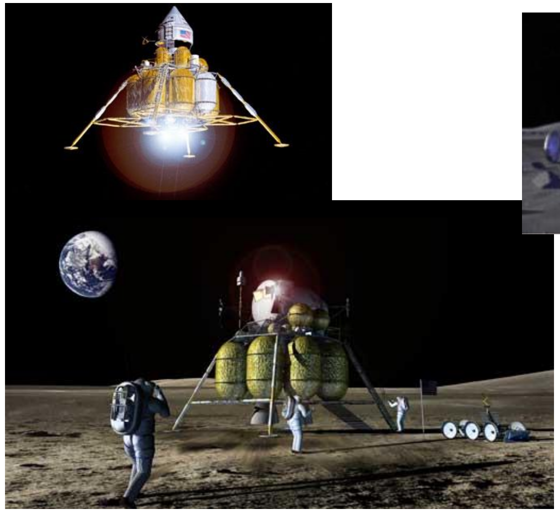
Each power technology contributes to an integrated Regenerative Fuel Cells (RFCs) for Lunar Exploration

- 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





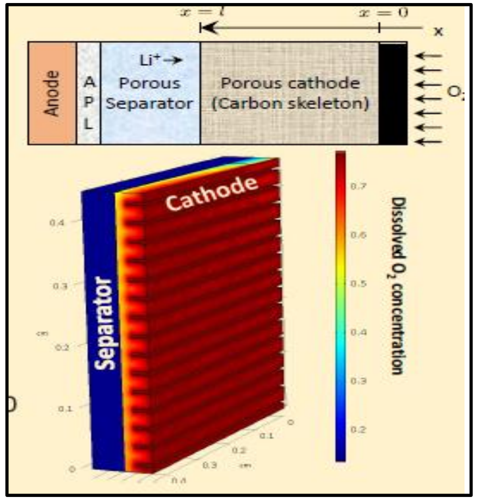


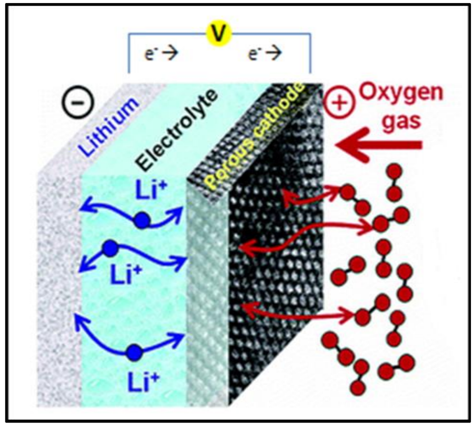
- Current energy storage technologies are insufficient for NASA exploration missions
- Availability of flight-qualified fuel cells ended with the Space Shuttle Program
- Terrestrial fuel cells not directly portable to space applications
  - Different wetted material requirements (air vs. pure O_2)
  - 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

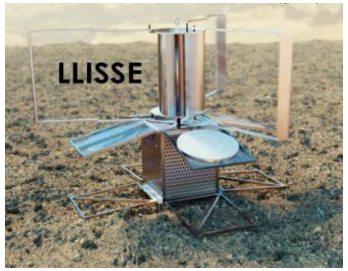
Battery Activities in Support of NASA Missions

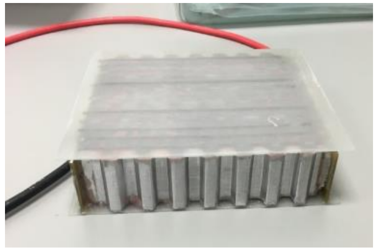
- Low temperature electrolytes to extend operating temperatures for outer planetary missions
- High temperature batteries for Venus missions
- Non-flammable separator/electrolyte systems
- Solid-state high specific energy, high power batteries
- Li-air batteries for aircraft applications

  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



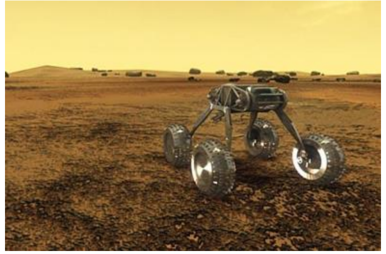


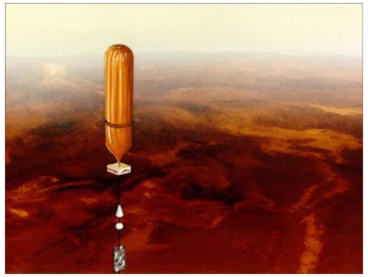




Energy Storage System Needs for Future Planetary Missions

- **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

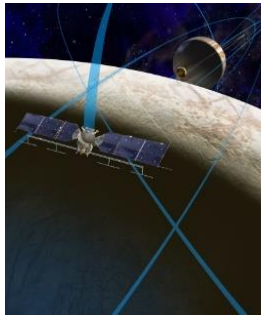




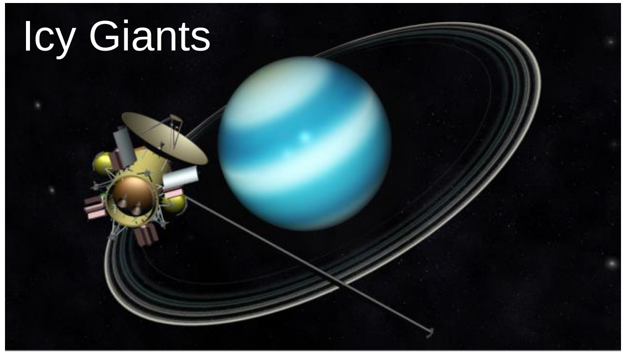
Inner Planets

Outer Planets

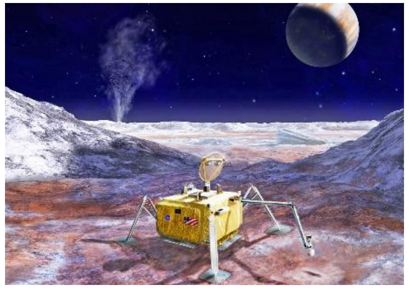
- **Primary Batteries/Fuel cells for planetary landers/probes:**
  - High Specific Energy (> 500 Wh/kg),
  - Long Life (> 15 years),
  - Radiation Tolerance & Sterilizable by heat or radiation
- **Rechargeable Batteries for flyby/orbital missions:**
  - High Specific Energy (> 250 Wh/kg)
  - Long Life (> 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

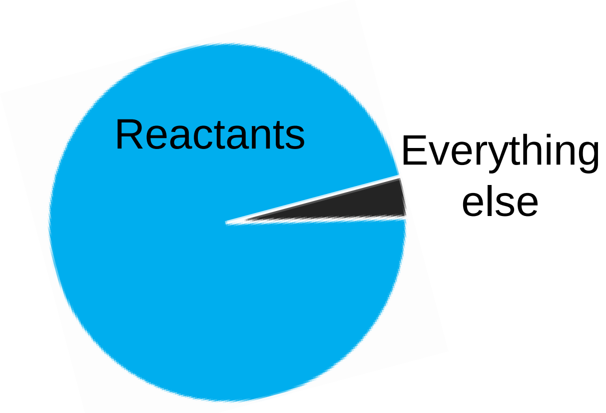


Europa Lander

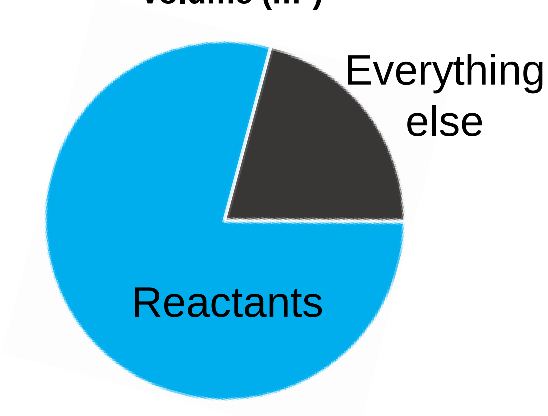
All images are Artist's Concepts

Lunar RFC Trade Study Results

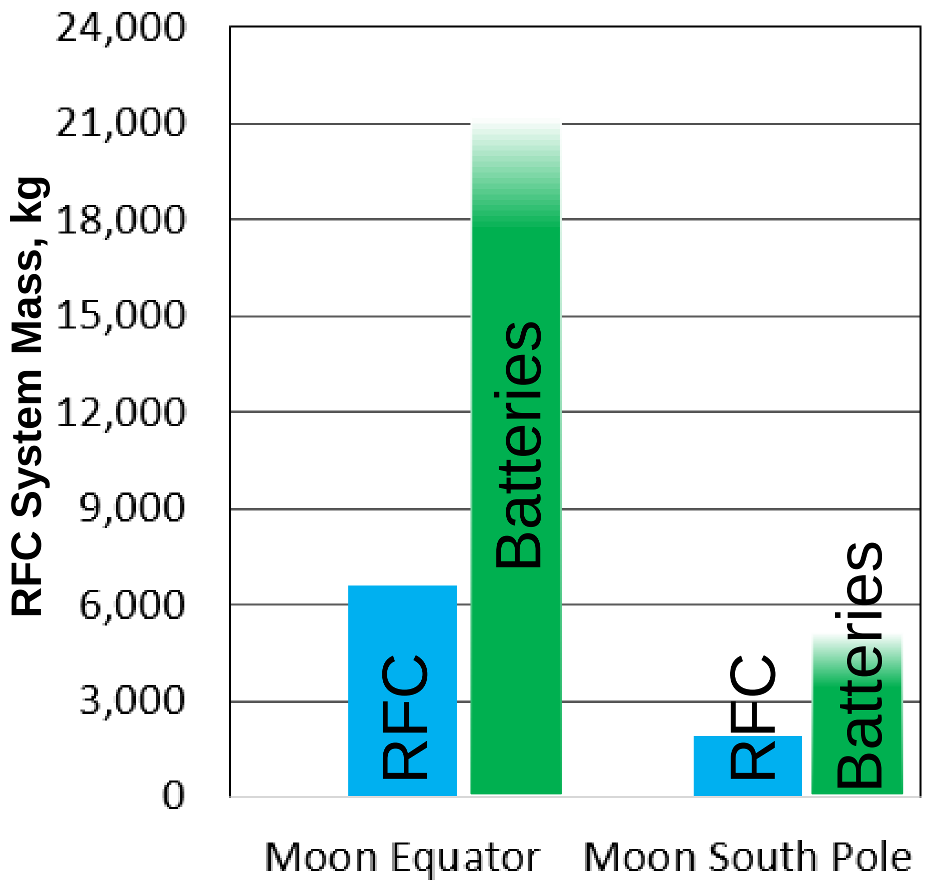
10 kW H_2/O_2 RFC Energy Storage System for Lunar Outpost



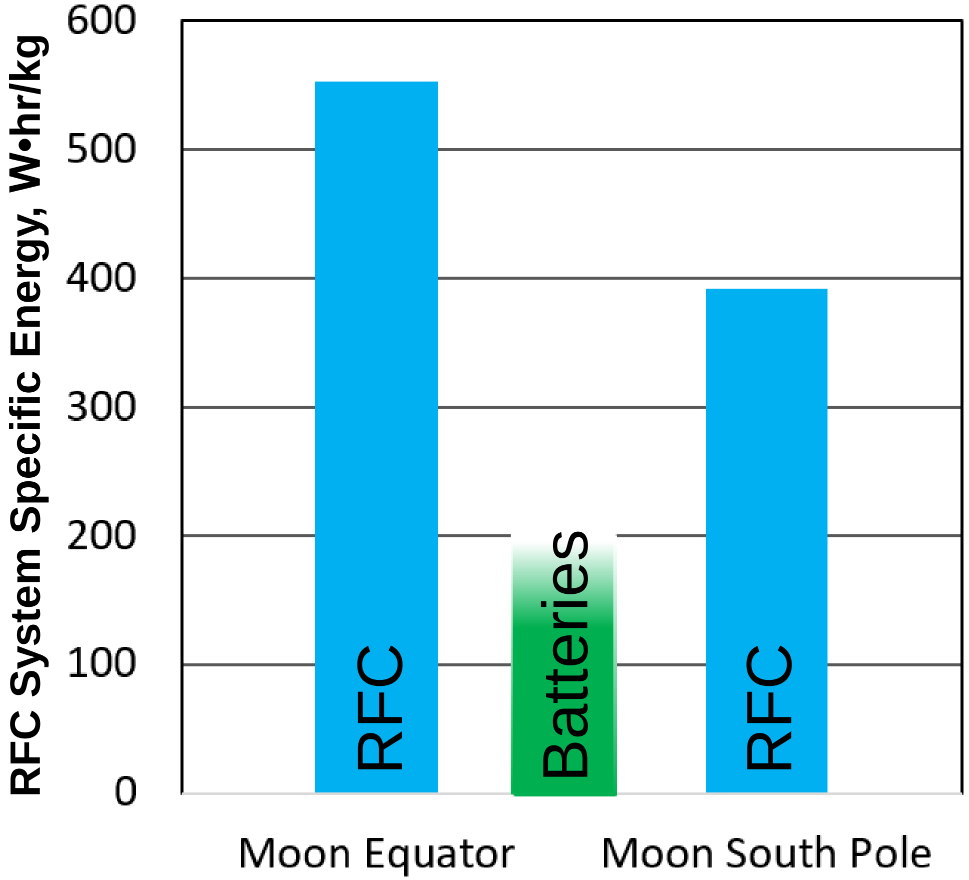
Volume (m^3)



Mass (kg)

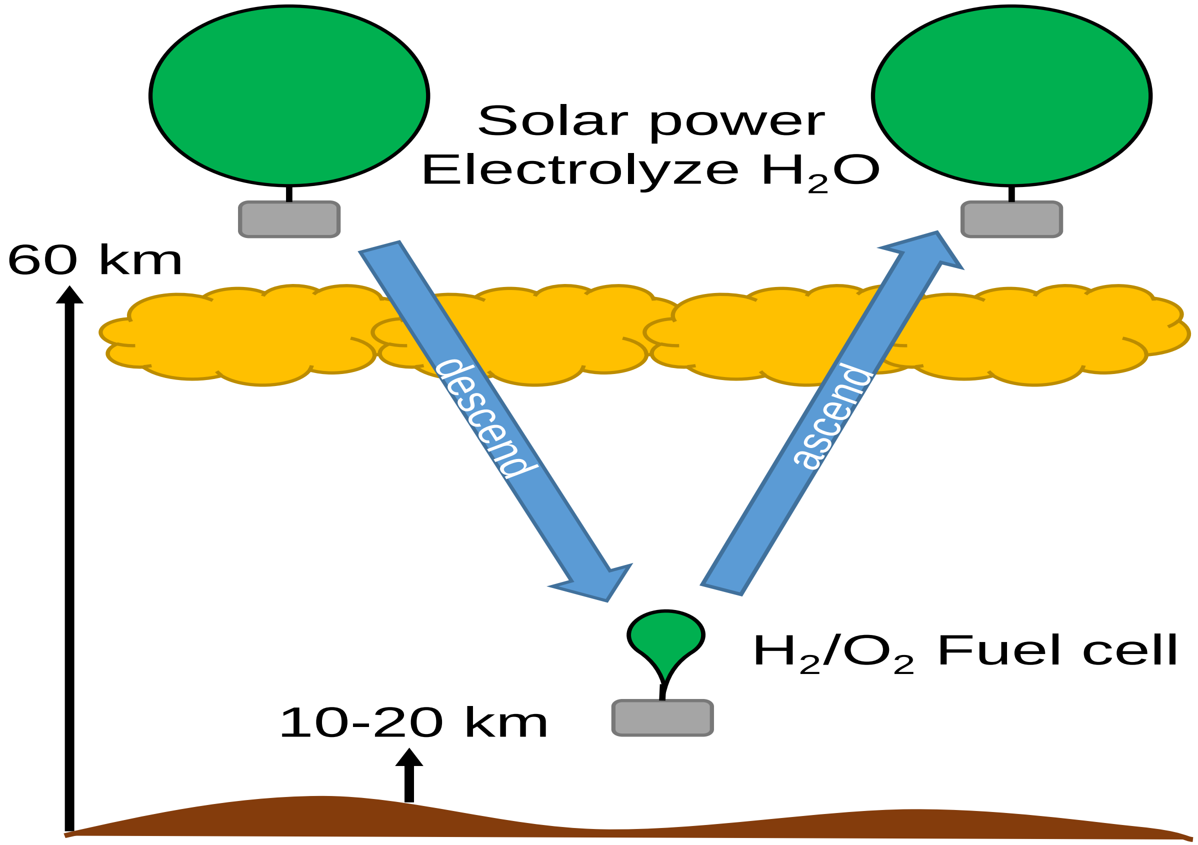


RFCs enable missions to survive the lunar night



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

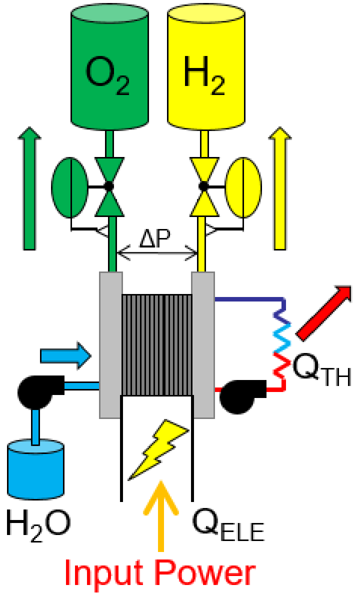
H_2 from hydride into balloon to ascend above the clouds

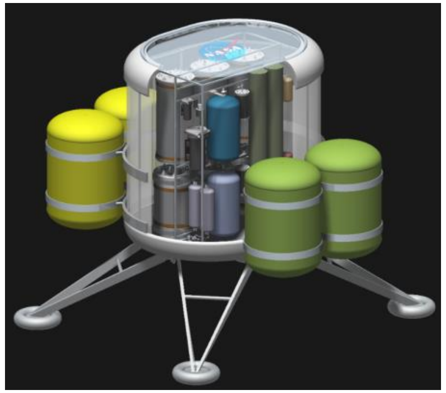
Below the clouds

- 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

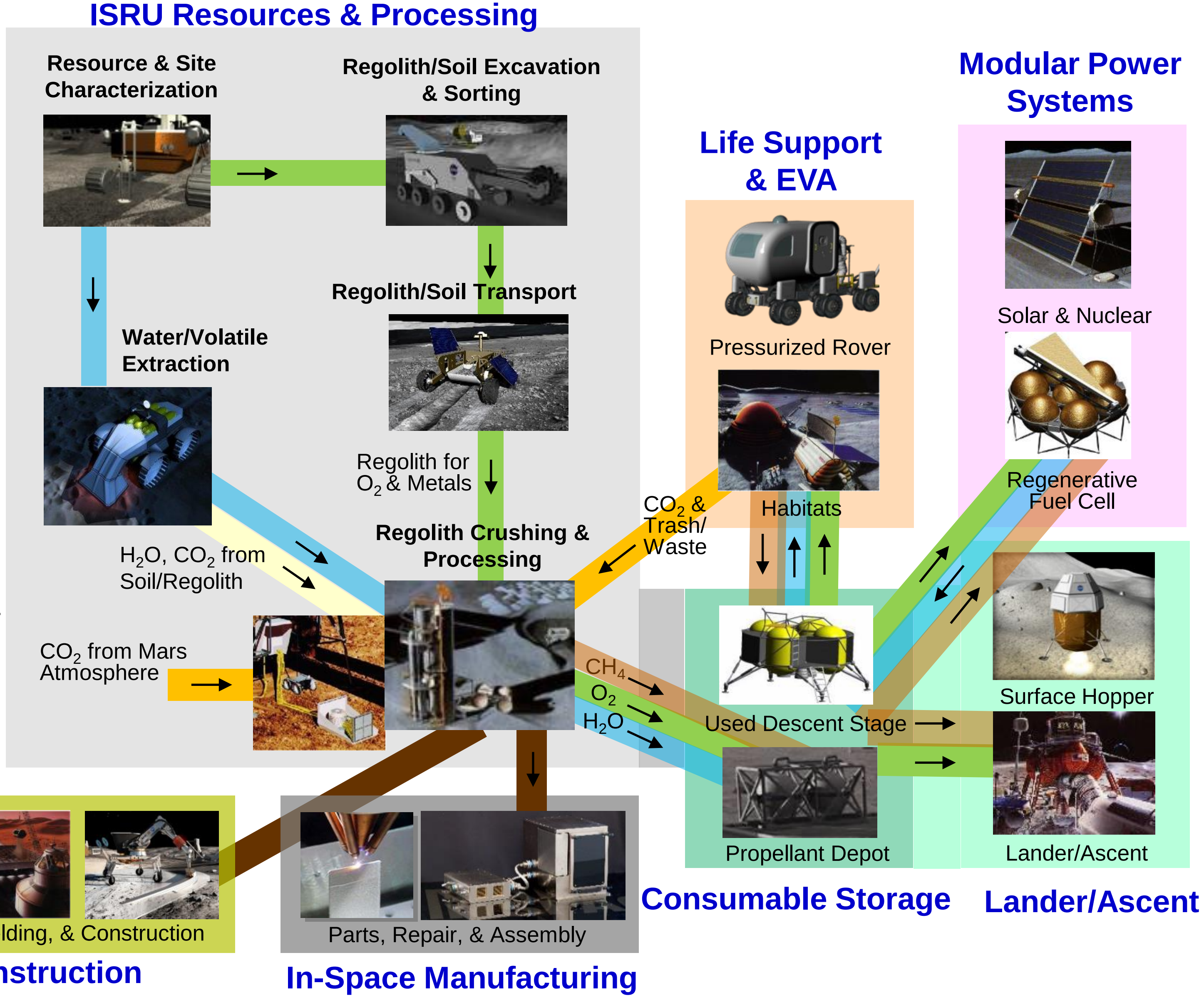
- Power Generation
- Power Distribution
- Energy Storage (O_2 & H_2)

Support Functions /Elements

- ISRU
- Life Support & EVA
- O_2, H_2, and CH_4 Storage and Transfer

Shared Hardware to Reduce Mass & Cost

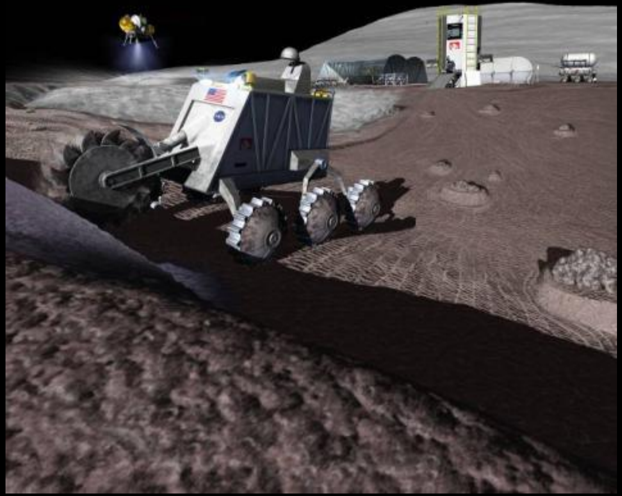
- Solar arrays/nuclear reactor
- Water Electrolysis
- Reactant Storage
- Cryogenic Storage
- Mobility

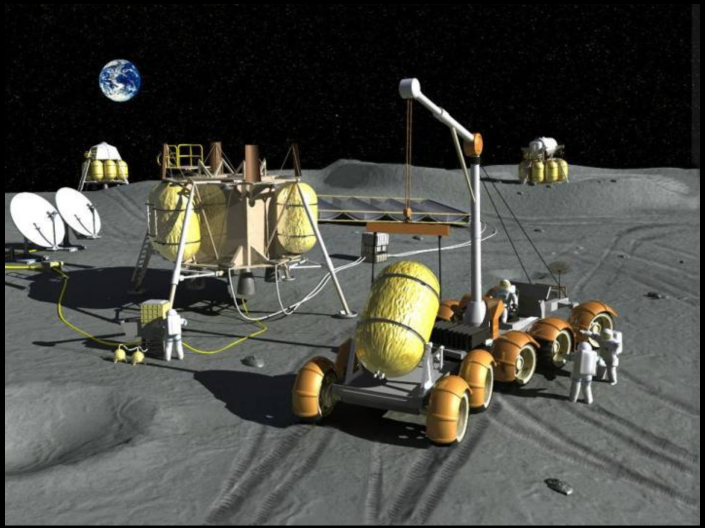


Lunar ISRU Mission Capability Concepts

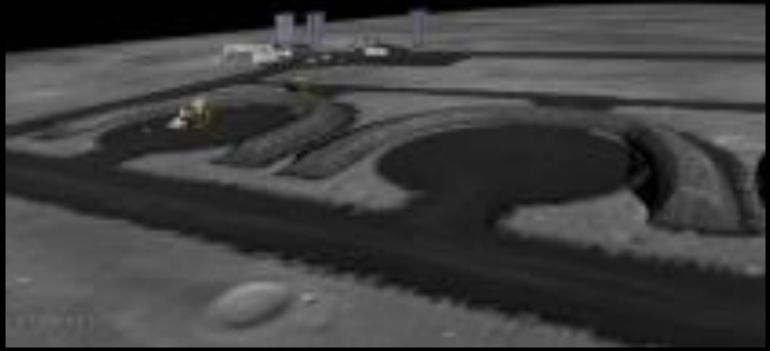
Resource Prospecting – Looking for Polar Ice

Excavation & Regolith Processing for O_2 Production



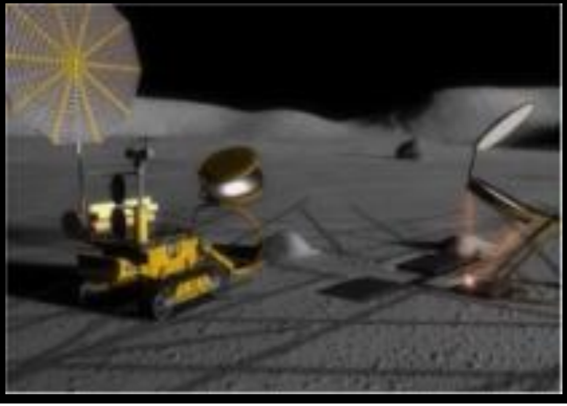


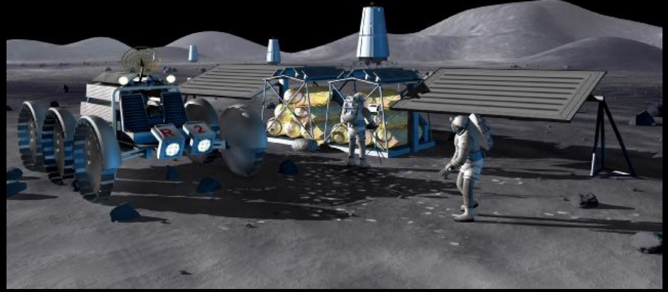
Carbothermal Processing with Altair Lander Assets



Landing Pads, Berm, and Road Construction

Thermal Energy Storage Construction





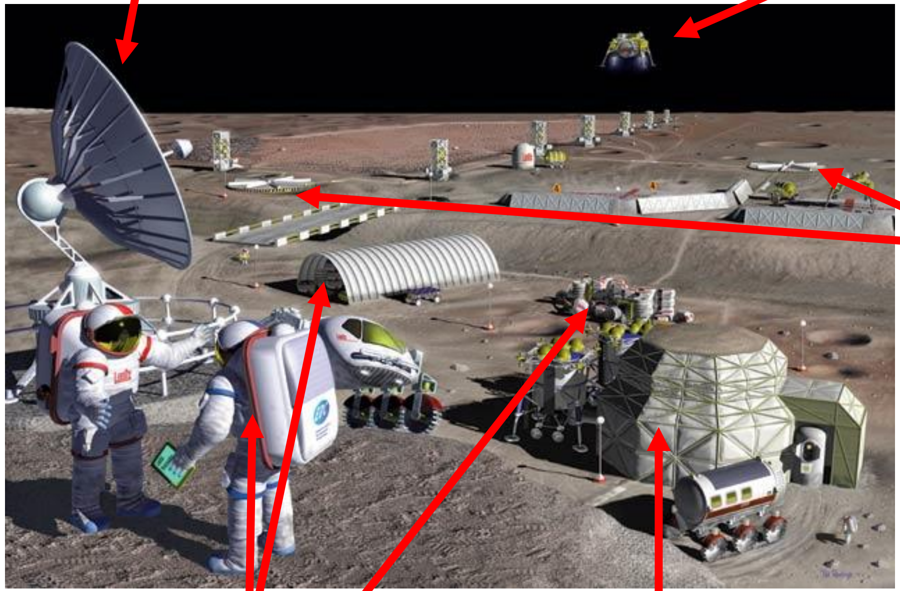
Consumable Depots for Crew & Power

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

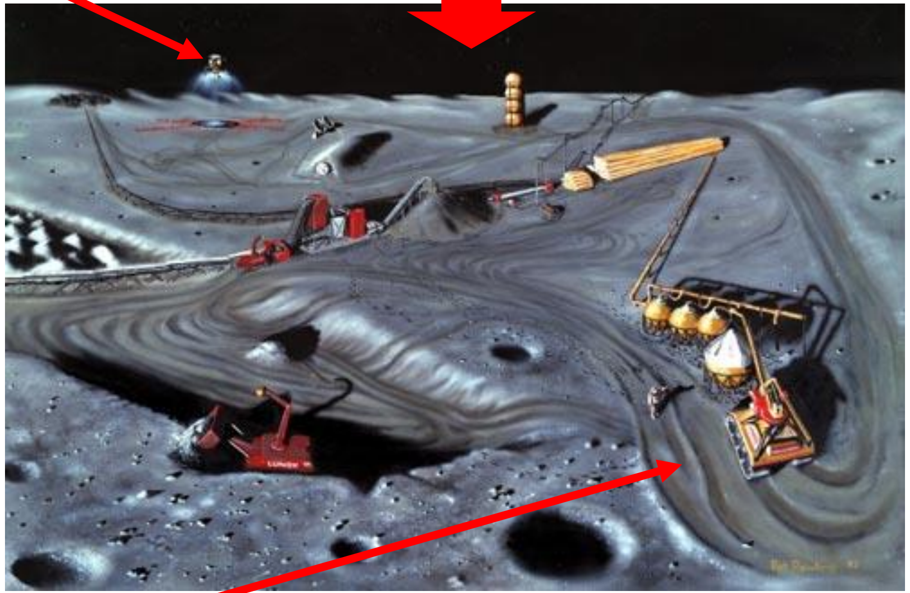
Communications
- To/From Site
- Local

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

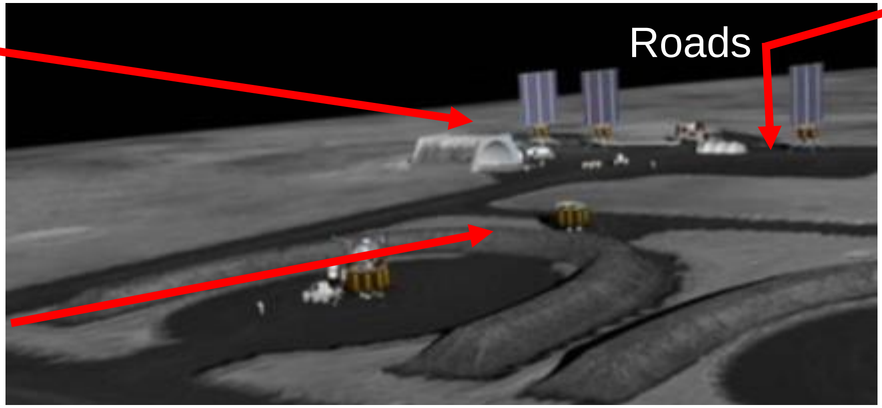


Maintenance & Repair

Living Quarters & Crew Support Services

Logistics Management

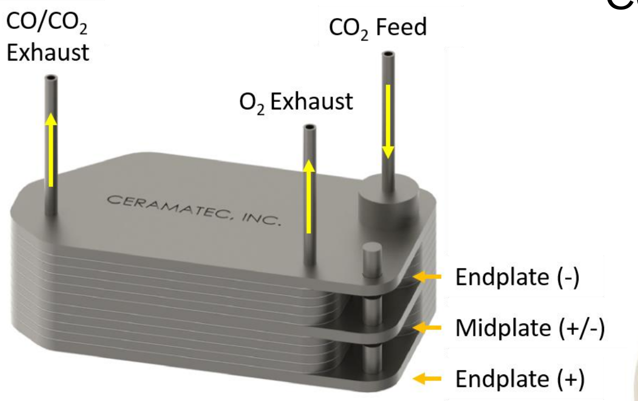
Construction and Emplacement



Reactant Processing and Storage

Oxygen

MOXIE O_2 Generator

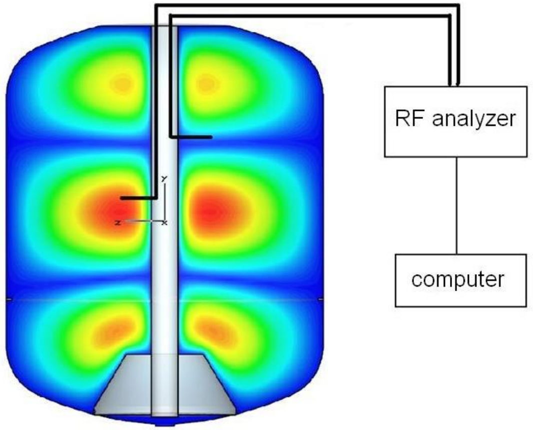


Oxygen Concentrators

CryoFILL Liquefaction and Storage

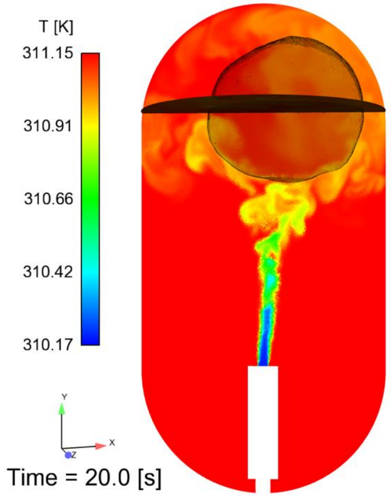
Tank-to-Tank Transfer

Radio Frequency Mass Gauge (RFMG)

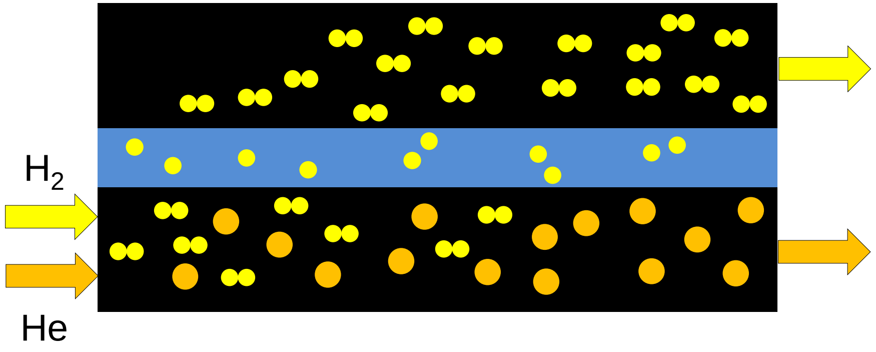


Hydrogen

Zero Boil-Off Tank (ZBOT) Experiment

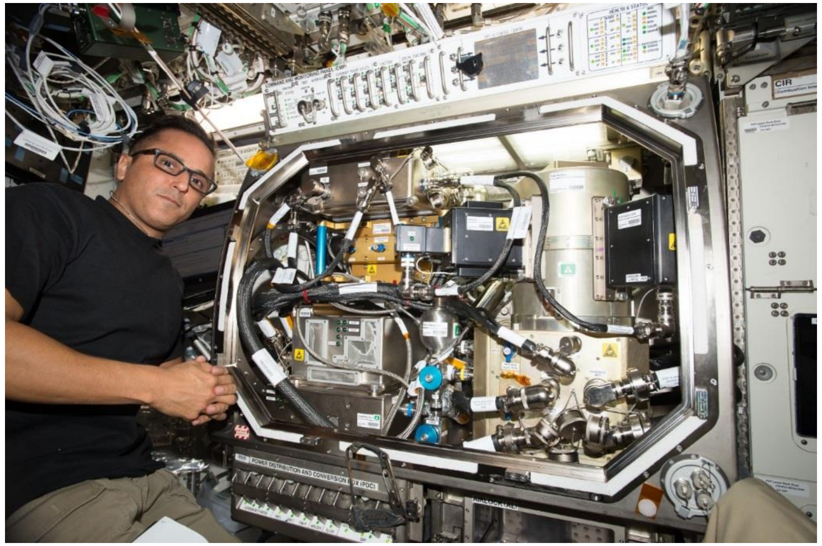


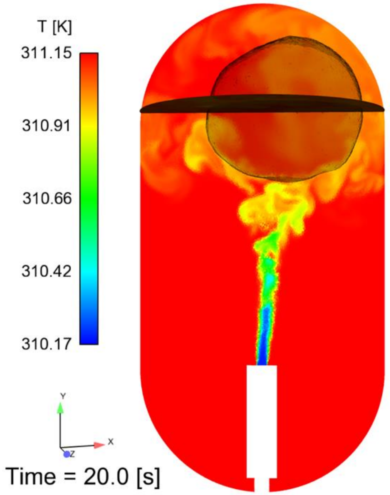
Purification and Recovery



Zero Boil-off Cryogenics

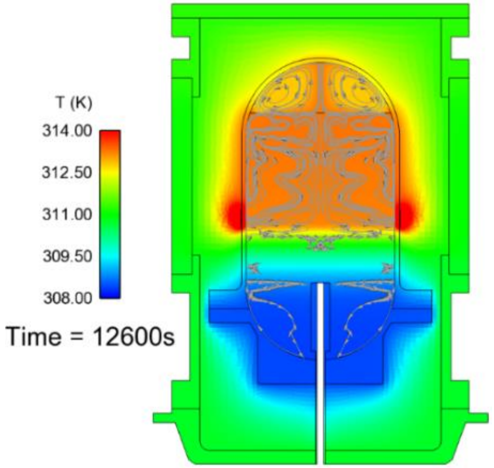
Zero Boil-Off Tank (ZBOT) Experiment:
Hardware in MSG Aboard ISS

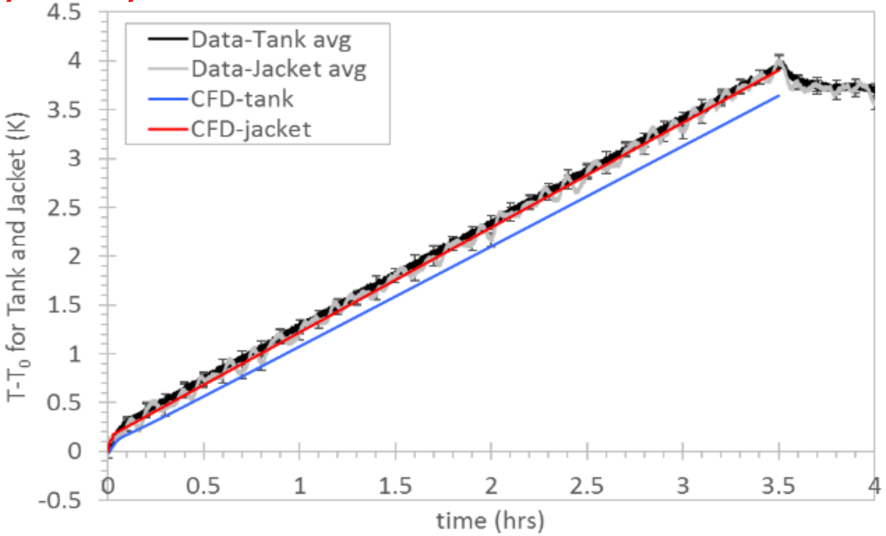




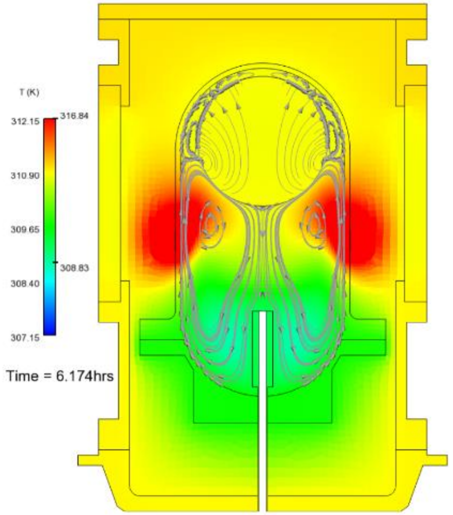
ZBOT Experiment During Jet Mixing

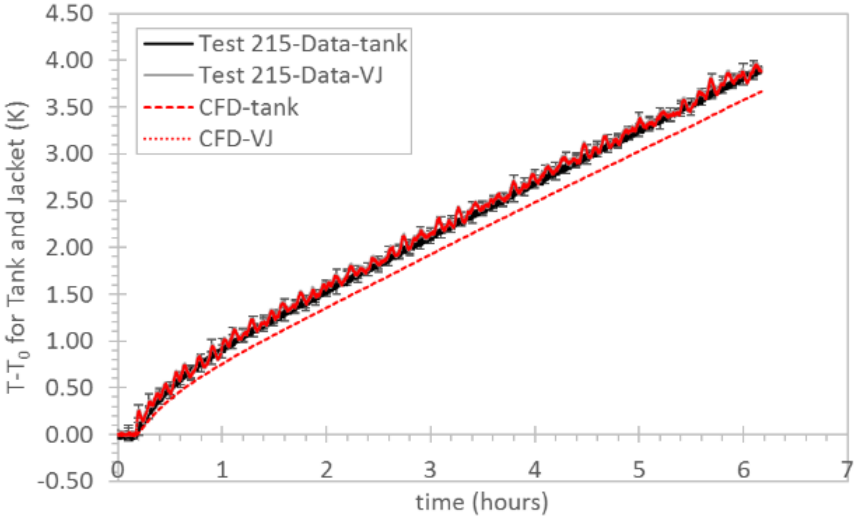
1g (1W), 90%, Self-Pressurization





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





Thank you for your attention.

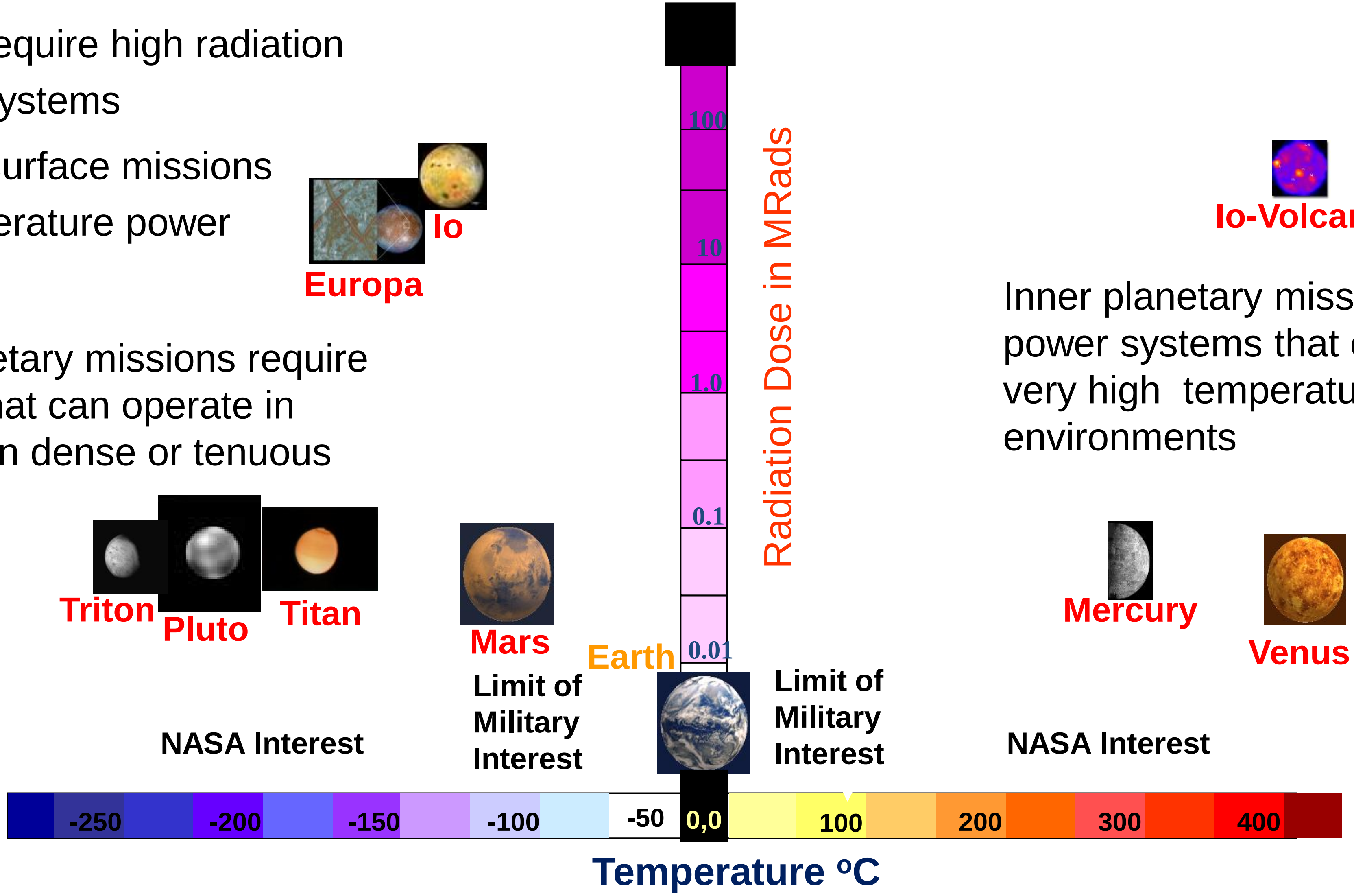
Questions?

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

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



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 • 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 • Turbo Electric

In-situ Venus Missions

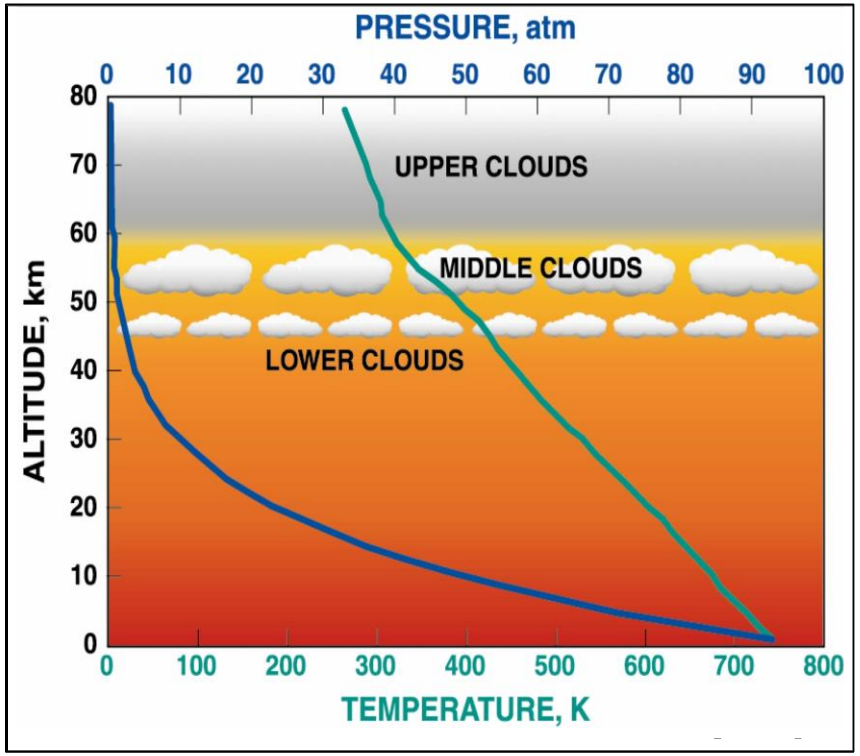
The Need for In-Situ missions:

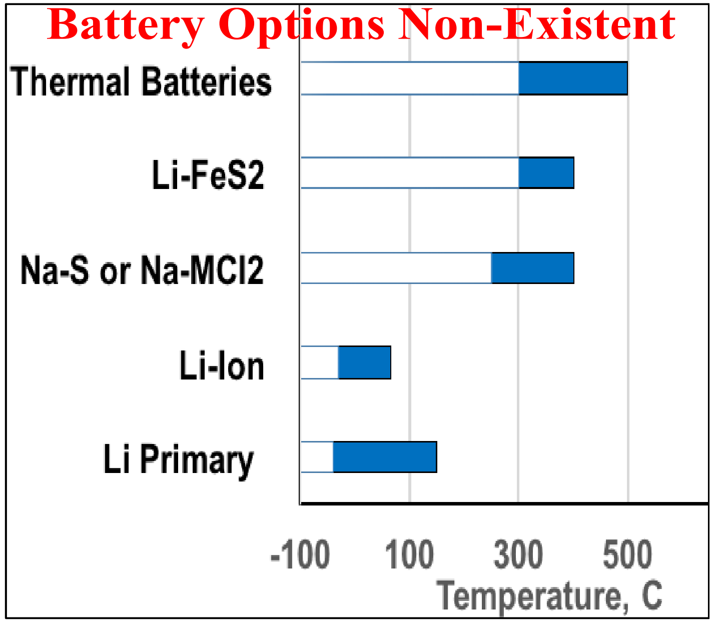
Despite years of exploration, major questions remain:

- 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

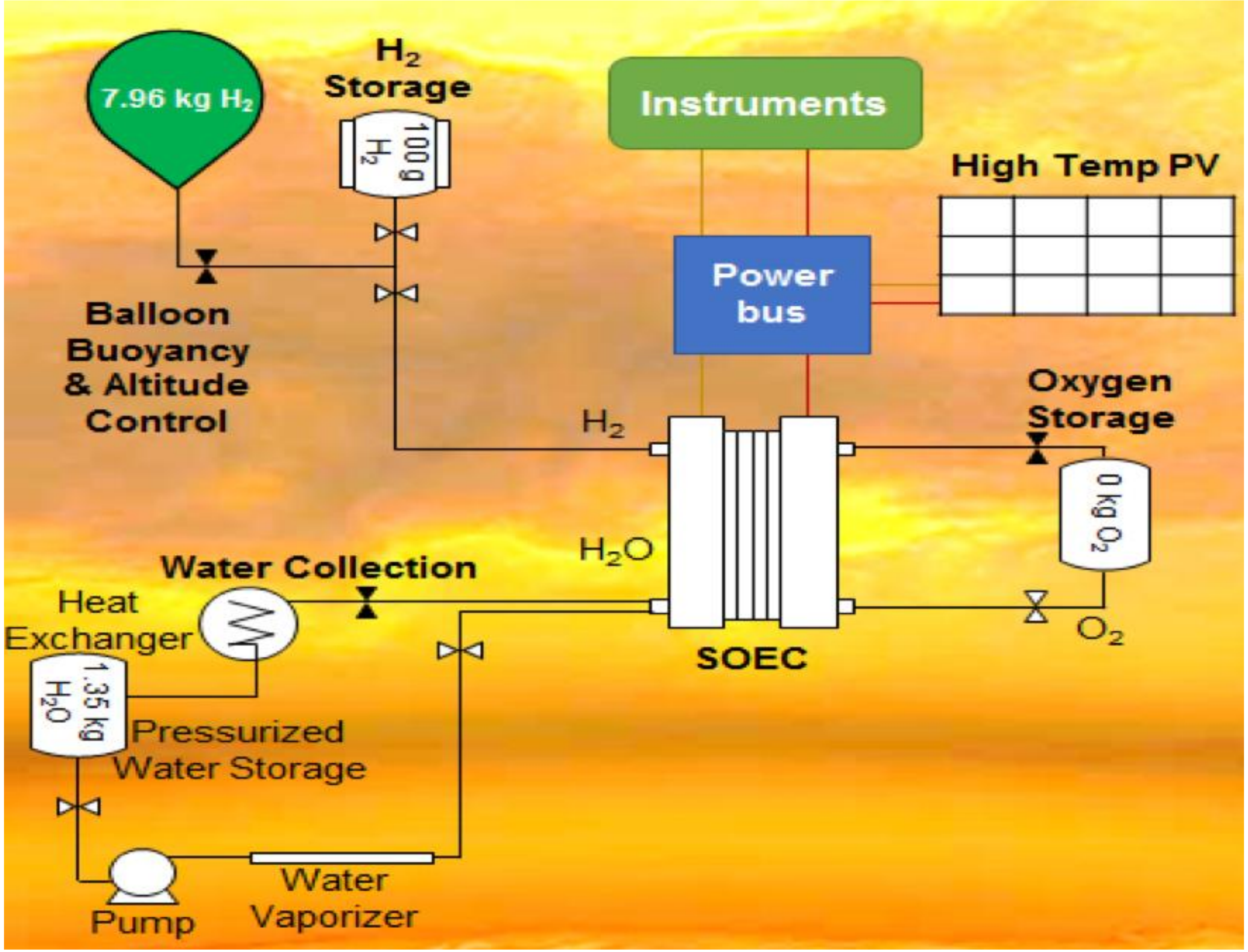
- Hostile environment of high temperature and pressure (465°C and 92 atm of CO_2) makes surface and low-altitude missions challenging.
- Cloud opacity limits orbital/balloon observations
- Conventional power sources, PV or RTG may not be applicable. New power technologies desired to enable missions





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

Group	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, μg
Reactant Storage and Management	Fluidic Components	8+	Moderate	O_2 vs air
	Procedures	5	Moderate	O_2 vs air, Performance
	Thermal	8+	Moderate	μg, Vacuum
	Materials	8+	Low	O_2 vs air
	Water Management	5+	Low	O_2 vs air, μg
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 ▪ Making Oxygen and Hydrogen
	Solar wind hydrogen with Oxygen	Subsurface Icy Soils in Mid-latitudes to Poles		
Oxygen	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 ▪ Oxidizer for Propulsion and Power
[redacted]	▪ CO, CO_2, and HC's in PSR ▪ 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 ▪ Plastic and Petrochemical Production
Metals	Minerals in Lunar Regolith ▪ Iron/Ti: Ilmenite ▪ Silicon: Pyroxene, Olivine, Anorthite ▪ Magnesium: Mg-rich Silicates ▪ Al: Anorthitic Plagioclase	Minerals in Mars Soils/Rocks ▪ Iron: Ilmenite, Hematite, Magnetite, Jarosite, Smectite ▪ Silicon: Silica, Phyllosilicates ▪ Aluminum: Laterites, Aluminosilicates, Plagioclase ▪ 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 ▪ Electical power generation and transmission

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