National Aeronautics and Space Administration

Fuel Cell Research and Development for Earth and Space Applications

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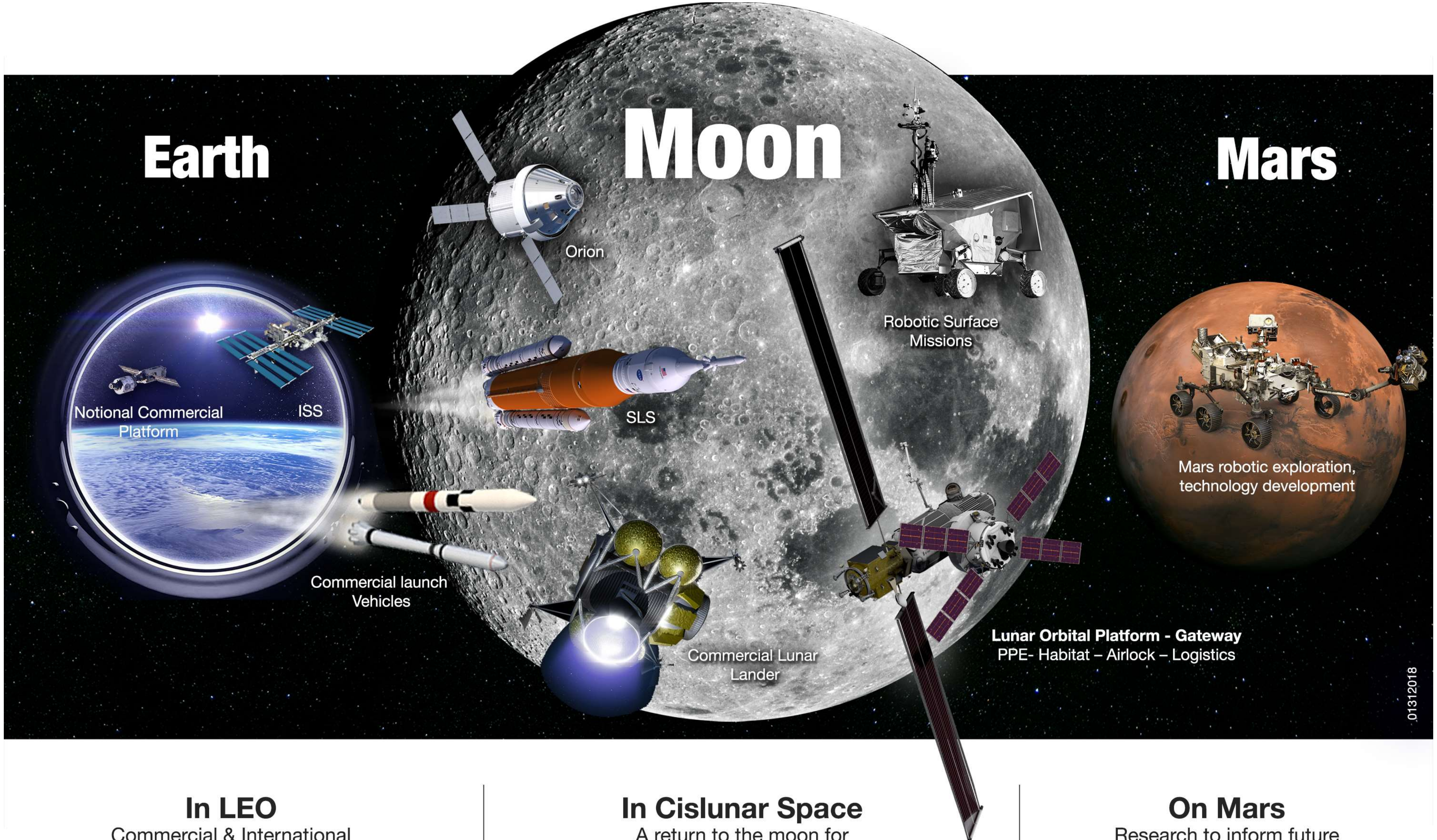
Presentation Outline

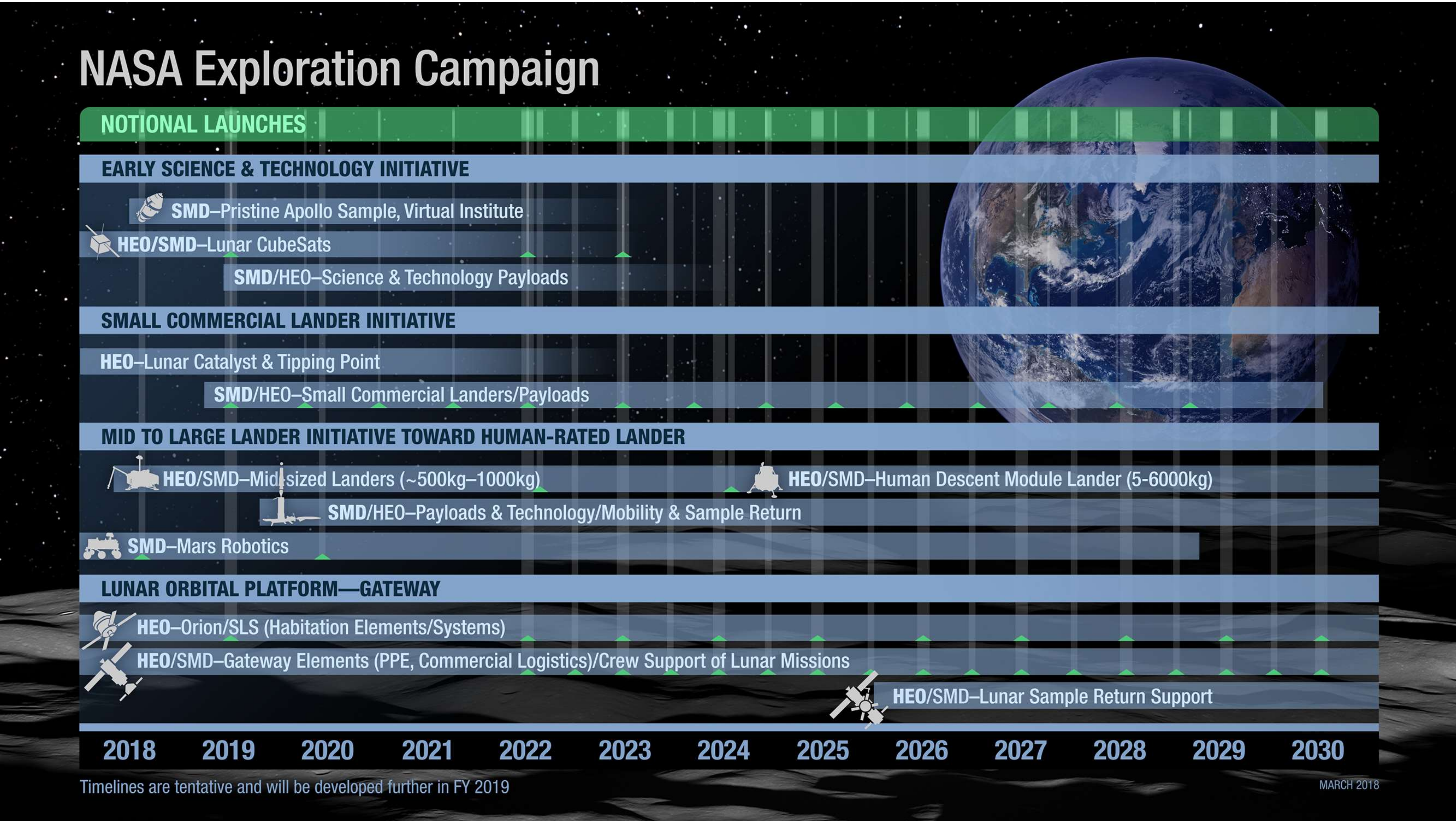
- **NASA – Overview and Scope**
- **Background**
  - Power and Energy Systems
  - Applicable Types of Electrochemical Systems
  - Energy Storage: Batteries vs. Regenerative Fuel Cells (RFC)
  - Comparison of Fuel Cell Technologies: Aerospace vs. Terrestrial
- **Active NASA Fuel Cell research**
  - Power Generation
  - Energy Storage
  - Commodity Generation
- **Review**

NASA Centers and Facilities

LUNAR EXPLORATION CAMPAIGN

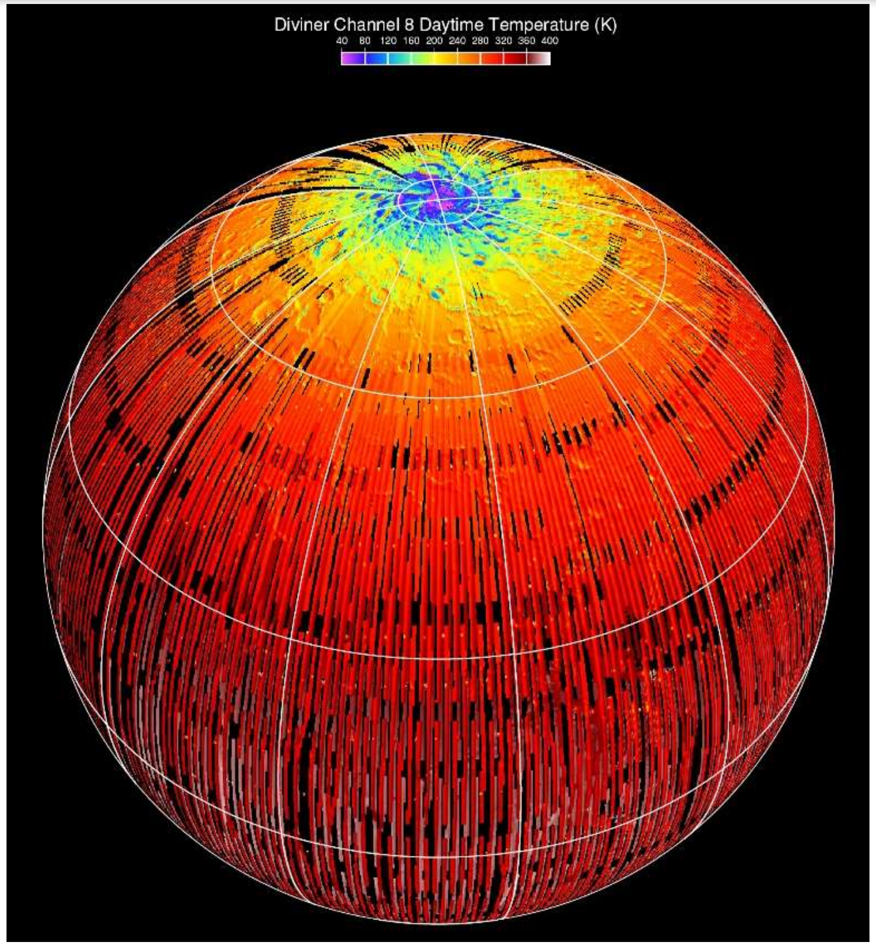


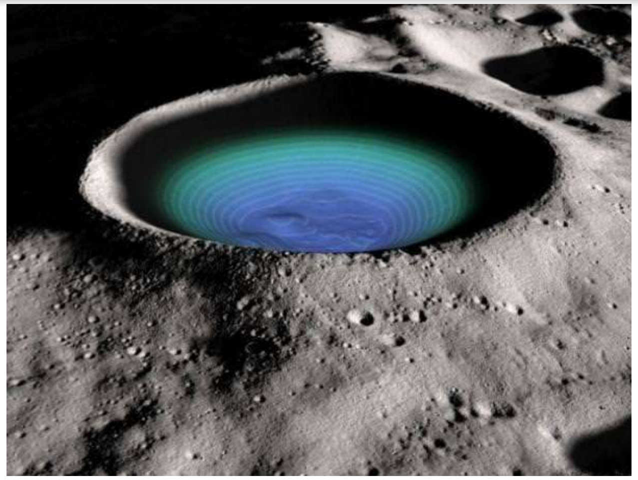
In LEO	In Cislunar Space	On Mars
Commercial & International partnerships	A return to the moon for long-term exploration	Research to inform future crewed missions

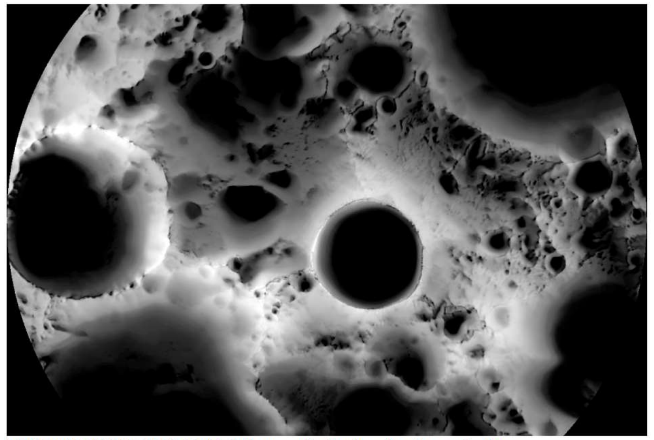


NASA Exploration Campaign
NOTIONAL LAUNCHES
EARLY SCIENCE & TECHNOLOGY INITIATIVE
SMD–Pristine Apollo Sample, Virtual Institute
HEO/SMD–Lunar CubeSats
SMD/HEO–Science & Technology Payloads
SMALL COMMERCIAL LANDER INITIATIVE
HEO–Lunar Catalyst & Tipping Point
SMD/HEO–Small Commercial Landers/Payloads
MID TO LARGE LANDER INITIATIVE TOWARD HUMAN-RATED LANDER
HEO/SMD–Mid-sized Landers (~500kg–1000kg)
HEO/SMD–Human Descent Module Lander (5-6000kg)
SMD/HEO–Payloads & Technology/Mobility & Sample Return
SMD–Mars Robotics
LUNAR ORBITAL PLATFORM—GATEWAY
HEO–Orion/SLS (Habitation Elements/Systems)
HEO/SMD–Gateway Elements (PPE, Commercial Logistics)/Crew Support of Lunar Missions
HEO/SMD–Lunar Sample Return Support
2018
2019
2020
2021
2022
2023
2024
2025
2026
2027
2028
2029
2030
Timelines are tentative and will be developed further in FY 2019
MARCH 2018

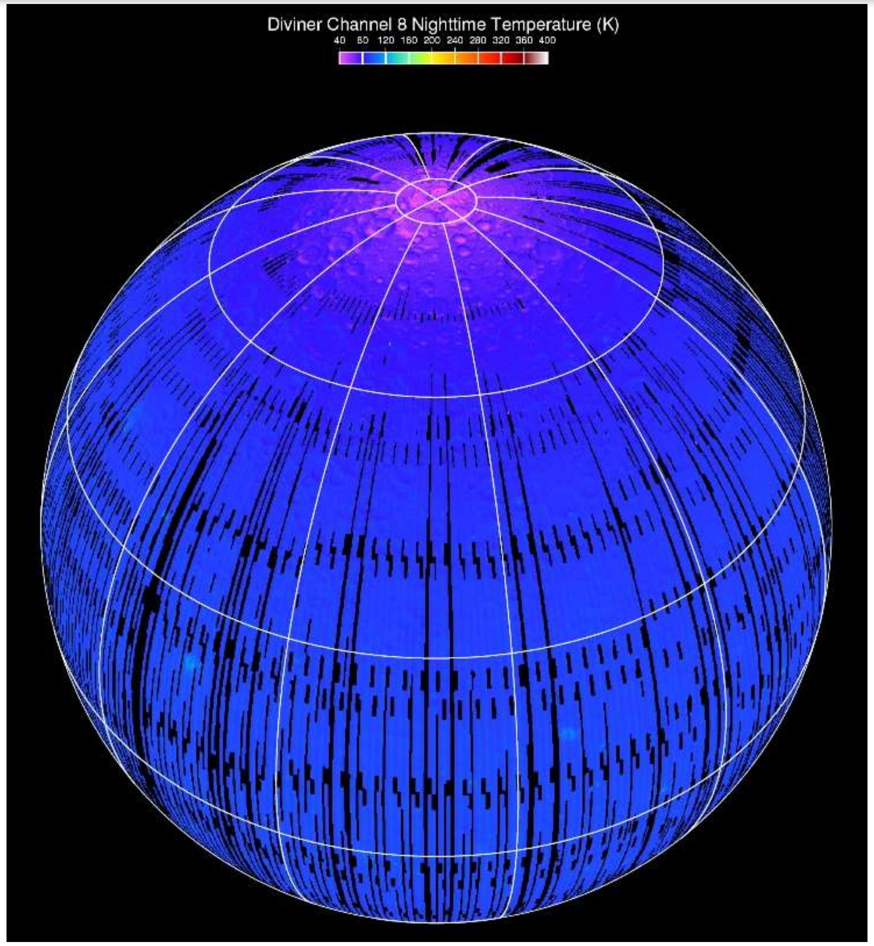
NASA's Lunar Reconnaissance Orbiter (LRO) Data







LUNAR RECONNAISSANCE ORBITER: Permanently Shadowed Regions on the Moon



- The average temperature on the Moon (at the equator and mid latitudes) varies from 90 Kelvin (-298 degrees Fahrenheit or -183 degrees Celsius), at night, to 379 Kelvin (224 degrees Fahrenheit or 106 degrees Celsius) during the day.
- Extremely cold temperatures within the permanently shadowed regions of large polar impact craters in the south polar region during the daytime is at 35 Kelvin (-397 degrees Fahrenheit or -238 degrees Celsius)
- Lunar day/night cycle lasts between 27.32 and 29.53 Earth days (655.7 to 708.7 hours)
- Regulating hardware in this environment requires both **power** and **energy**

Power and Energy Systems

Power Generation

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
- Photovoltaics

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

Summary of Applicable Electrochemical Chemistries

	Low Temperature		Moderate Temperature		High Temperature	
Cell Type	Proton Exchange Membrane (PEM)	Alkaline (AEM)	Alkaline (AFC)	Phosphoric Acid (PAFC)	Molten Carbonate (MCFC)	Solid Oxide (SOFC)
Electrolyte	Ionic Polymer Membrane	Anionic Polymer Membrane	KOH in asbestos matrix	Phosphoric Acid in SiC structure	Liquid carbonate in $LiAlO_2$ structure	Anionic Conducting Ceramic
Operating Temperature	10 – 80 ˚ C	20 – 70 ˚ C	70 – 225 ˚ C	200 – 250 ˚ C	~650 ˚ C	600 – 1,000 ˚ C
Charge Carrier	H^+	OH^-	OH^-	H^+	CO_3^{2-}	O^{2-}
Load Slew Rate Capability	Very High (> 1k's mA/cm^2/s)	High (~ 1k's mA/cm^2/s)	High (~ 1k's mA/cm^2/s)	High (~ 1k's mA/cm^2/s)	Low to Medium (~100's mA/cm^2/s)	Low (~10's mA/cm^2/s)
Fuel	Pure H_2				H_2, CO, Short Hydrocarbons	
Product Water Cavity	Oxygen	Hydrog			Hydrogen	
Product Water	Liquid Product				Vapor, externally separated	
CO Tolerance	< 2 ppm	< 2 ppm	< 5 ppm	< 50 ppm	Fuel	
Reformer Complexity	Very High	High	High		Minimal	
Aerospace Viability	Promising	TBR (Low TRL)	No longer in production	Not Viable	Not Viable	Promising
Terrestrial Availability	High (Increasing)	Developmental (Increasing)	N/A	Moderate (Stable)	Moderate (Increasing)	High (Increasing)
Terrestrial Markets C = Commercial I = Industrial R = Residential	Transportation, Logistics, Stationary Power (C, I, & R)	Transportation, Logistics (C)	N/A	Stationary Power (C)	Co-generation and Stationary Power (C & I)	Co-generation and Stationary Power (C, I, & R)

Feasible for Aerospace Applications

Summary of Applicable Electrochemical Chemistries

	PEM	AEM	Alkaline	Solid Oxide
Key Notes	• Commonly used in mobile terrestrial applications • Terrestrial systems vent Oxygen to remove product water from stack • Mature for terrestrial applications, needs development for Aerospace	• Solid polymer electrolyte • Developing technology not yet deployed	• Liquid electrolyte suspended in asbestos structure • Hydrogen recirculates to remove product water from stack • Used in Space Shuttle	• Commonly used in stationary terrestrial applications • Terrestrial systems vent hydrogen to remove product water from stack • Mature for terrestrial applications, needs development for Aerospace
Advantages	• Rapid reaction kinetics support transient load response capability • Support wide range of current densities • Minimal start times (typ. < 1 min) • Demonstrated high pressure operation • Solid polymer electrolyte eliminates migration of acidic electrolyte	• Reaction kinetics support transient load response capability • Relatively high tolerance to contaminant gases • Solid polymer eliminates migration of corrosive electrolyte • Higher pH enables larger selection for wetted materials	• Reaction kinetics support transient load response capability • Relatively high tolerance to contaminant gases • Higher pH enables larger selection for wetted materials	• Wide range of fuels (Anode) • Can be configured to internally reform hydrocarbons • Relatively high tolerance to contaminant gases in Hydrogen • Resistant to freezing when stored
Disadvantages	• Very sensitive to CO or Sulfur contaminants in Hydrogen stream • Water-based system limits temperature regimes	• Limited operational life • Limited pressure capability	• No longer available as company divested both IP and fabrication capability • EPA restricted use of asbestos • Liquid electrolyte migrates throughout fluid system requiring frequent and expensive servicing	• Ceramic electrolyte limits transient load response capability • Ceramic electrolyte limits start-up times to 10's of minutes to hours • Seals need development for Aerospace applications • Limited to low-pressure applications

Aerospace Electrochemical Systems

Fuel Cell

Power Generation

Discharging Only

Description

- Converts supplied reactant to DC electricity
- Operation limited by supplied reactants
- Not tied to external energy source

NASA Applications:

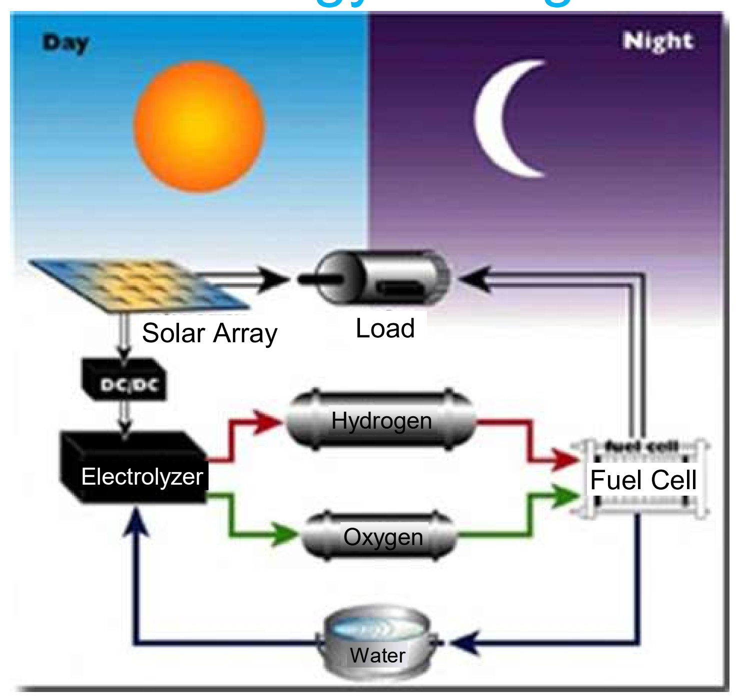
Sustained High-Power

- Crewed transit vehicles (Apollo, Gemini, STS, etc.)
- Power-intense rovers/landing platforms

Regenerative Fuel Cell

Energy Storage

Charging



Discharging

Description

- Stores supplied energy as gaseous reactants
- Discharges power as requested by external load
- Tied to external energy source

NASA Applications:

Ensuring Continuous Power

- Surface Systems (exploration platforms, ISRU, crewed)
- Platforms to survive Lunar Night

Electrolysis

Commodity Generation

$$2\ H_2O \rightarrow 2\ H_2 + O_2$$

or

$$2\ CO_2 \rightarrow 2\ CO + O_2$$

Description

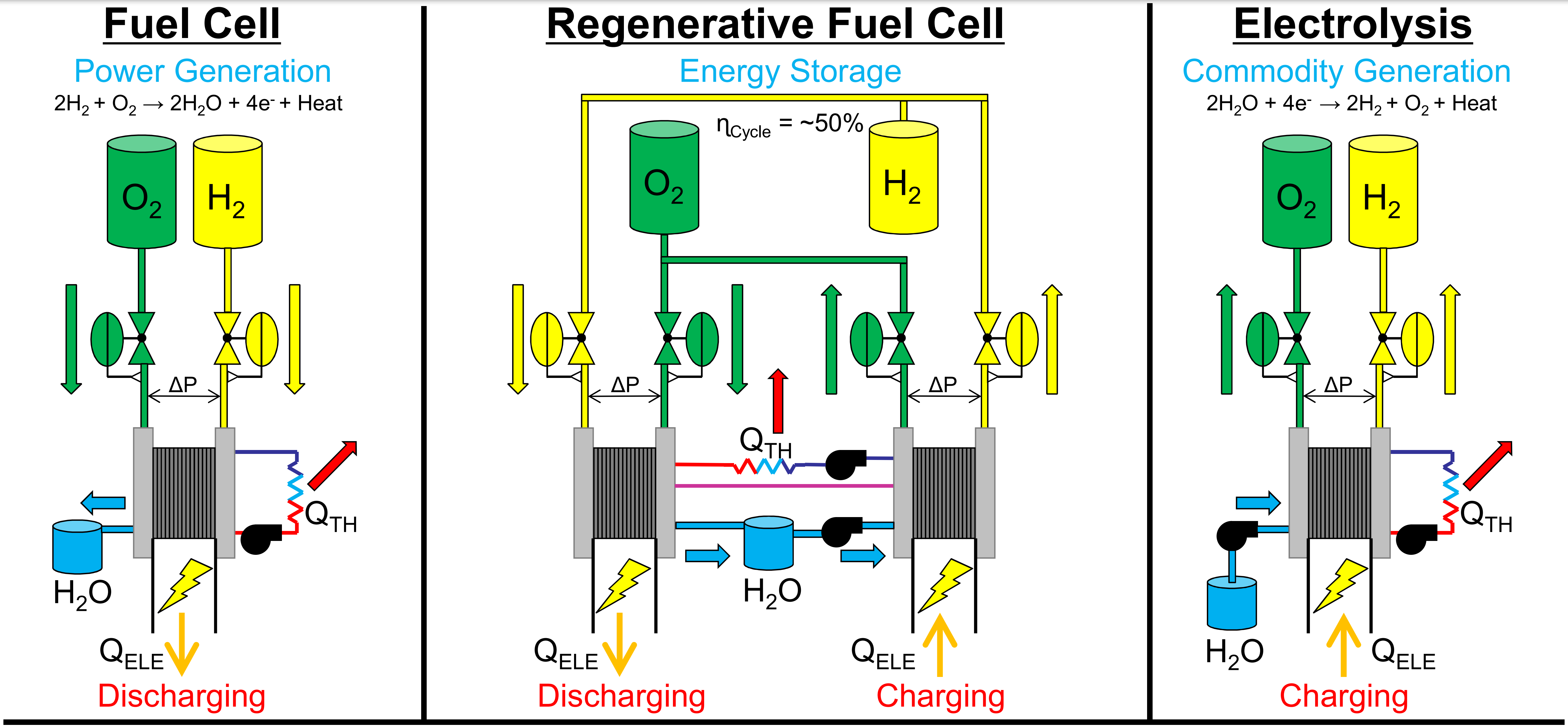
- Converts chemical feedstock into useful commodities
- Tied to external energy source

NASA Applications:

Life-support, ISRU

- Oxygen Generation
- Propellant Generation
- Material Processing

Example H_2/O_2 Aerospace Fuel Cell Systems



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

Definitions: Power and Energy System Metrics

Fuel Cell

Power Generation

Primary Metrics

- Specific Power (W/kg)
- Output Power (Watts)
- Mass (kg)
- Volume (L)
- Reliability (Hours/Days)

Technical Challenges

- Water Management
- Reactant Purity
- Thermal Control
- Con-Ops
- Shelf-life

Regenerative Fuel Cell

Energy Storage

Primary Metrics

- Specific Energy (W•hrs/kg)
- Reliability (Years)
- Stored Energy (kW•hrs)
- Mass (kg)
- Volume (L)

Technical Challenges

- Component Reliability
- Corrosion/Chemical Compatibility
- Reactant Purity
- Water Management
- Con-Ops
- Thermal
- EZ System Pressure
- Maintenance
- Shelf-life

Electrolysis

Commodity Generation

Primary Metrics

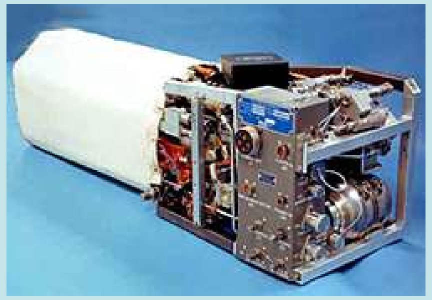
- Production Rate (kg/day)
- Reliability (Months/Years)
- System Pressure (Atm)
- Mass (kg)
- Volume (L)

Technical Challenges

- System Pressure
- Component Reliability
- Corrosion/Chemical Compatibility
- Fluid Purity
- Con-Ops
- Maintenance

Comparison of Fuel Cell Technologies

Aerospace



Space Shuttle Fuel Cell Stack

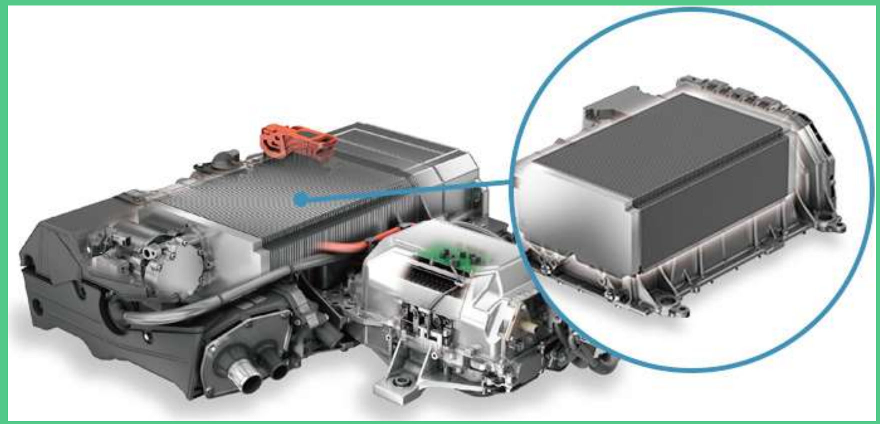
(1979 - 2014)

Differentiating Characteristics

- Pure Oxygen (stored, stoichiometric)
- Water Separation in *μg*

≠

Terrestrial



Toyota Mirai Fuel Cell[1]

Differentiating Characteristics

- Atmospheric Air (conditioned, excess flow)
- High air flow drives water removal

Fluid management issues and environmental conditions make aerospace and terrestrial fuel cells functionally dissimilar

Notes: [1] = http://www.toyota-global.com/innovation/environmental_technology/technology_file/fuel_cell_hybrid/fcstack.html

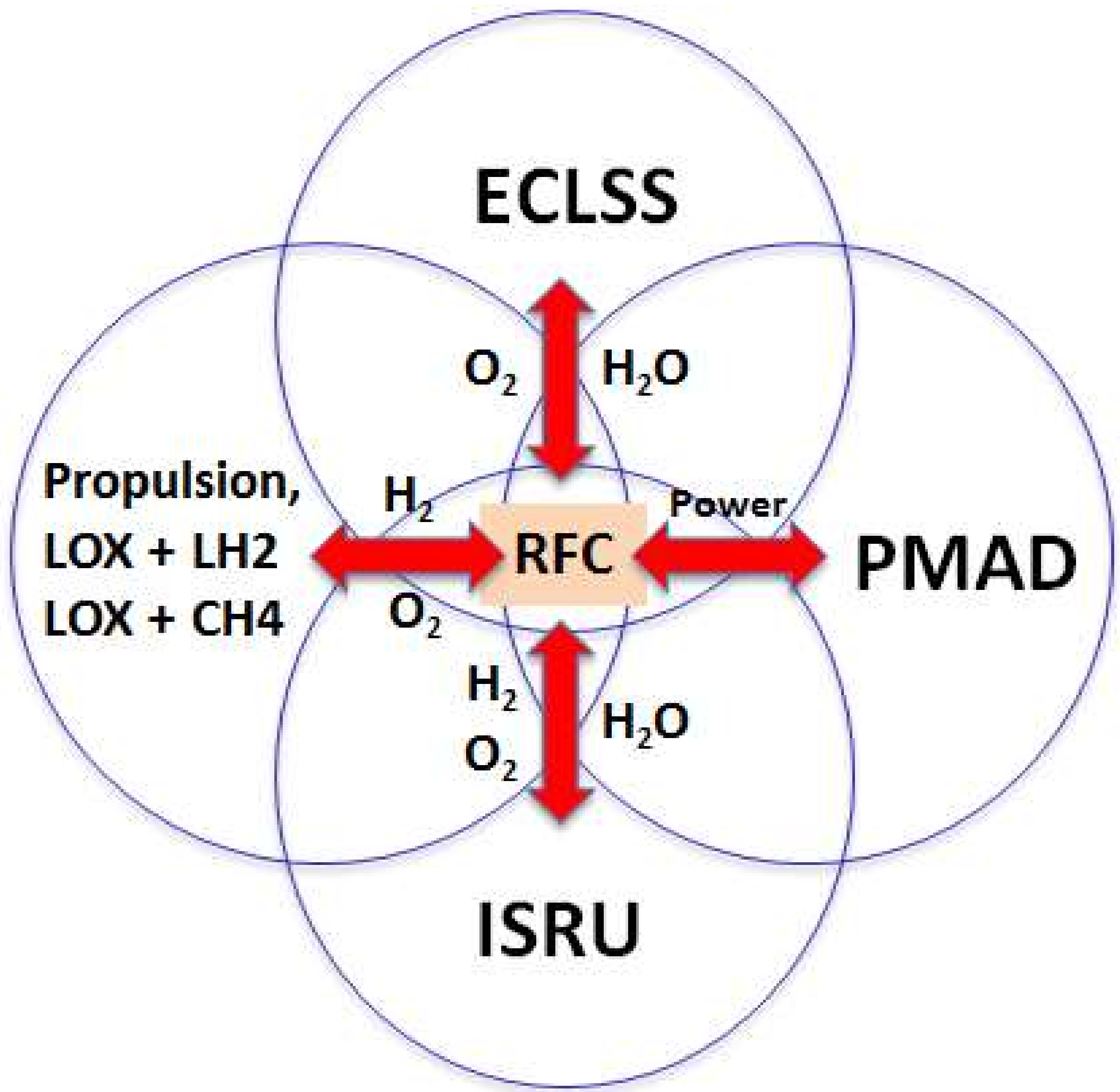
Cross-Cutting Technologies: Fuel Cells, Electrolyzers, and RFCs

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

Cross-Cutting Technologies: Fuel Cells, Electrolyzers, and RFCs

RFC systems, along with their core fuel cell and water electrolyzer technologies, share common reactants (hydrogen, oxygen, water) with multiple subsystems while supporting an electrical power interface.



NASA Fuel Cell Applications

Powering exploration activities

- <u>Power Generation: Fuel Cells</u>

➢ Electrification of Aircraft

❖ High-power rovers

❖ Entry/Descent/Landing (EDL)

- Upper Stage Platforms/Long loiter systems

<u>Commodity Generation: Electrolysis</u>

➢ ECLSS – Oxygen Generation

➢ ISRU – Propellant Generation

➢ ISRU – Reduction fluids for Material Processing and Fabrication

<u>Energy Storage: Regenerative Fuel Cell</u>

❖ Lunar Surface Systems

❖ Lunar Landers / Rovers

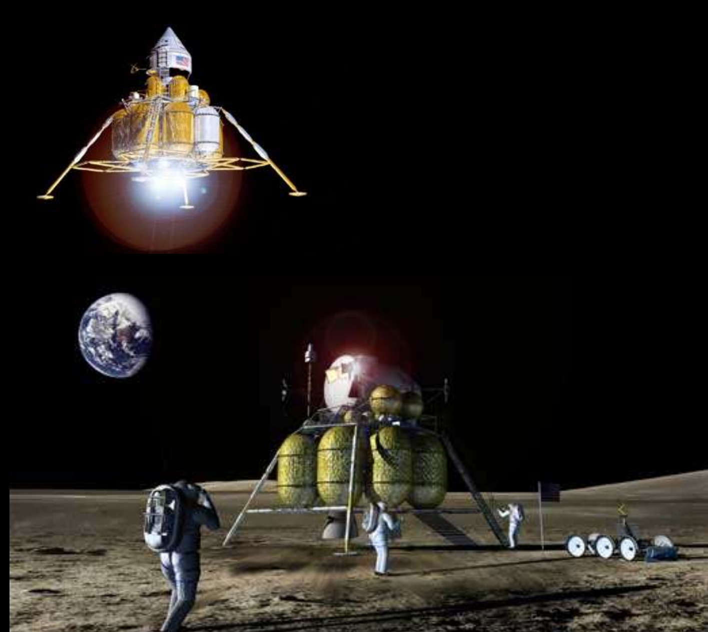
- HALE Un-crewed Aerial Systems (UAS)

<u>Legend</u>

➢ Hardware Development

❖ Analytical Development

- Recent work not funded this Fiscal Year



NASA Fuel Cell Applications

Powering exploration activities

- Power Generation: Fuel Cells
  - ➢ Electrification of Aircraft
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  - ❖ Entry/Descent/Landing (EDL)
- Upper Stage Platforms/Long loiter systems

Commodity Generation: Electrolysis

- ➢ ECLSS – Oxygen Generation
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Legend

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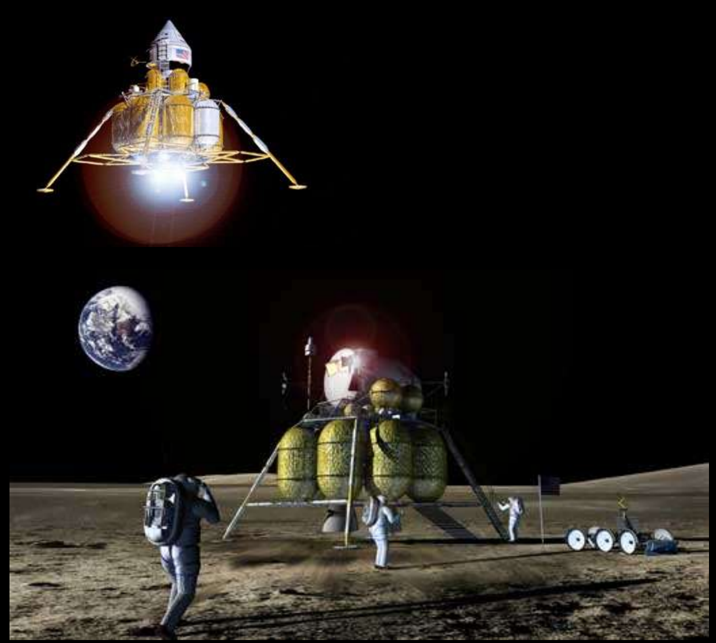


Energy Storage: Regenerative Fuel Cell

- ❖ Lunar Surface Systems
- ❖ Lunar Landers / Rovers
- • HALE Un-crewed Aerial Systems (UAS)

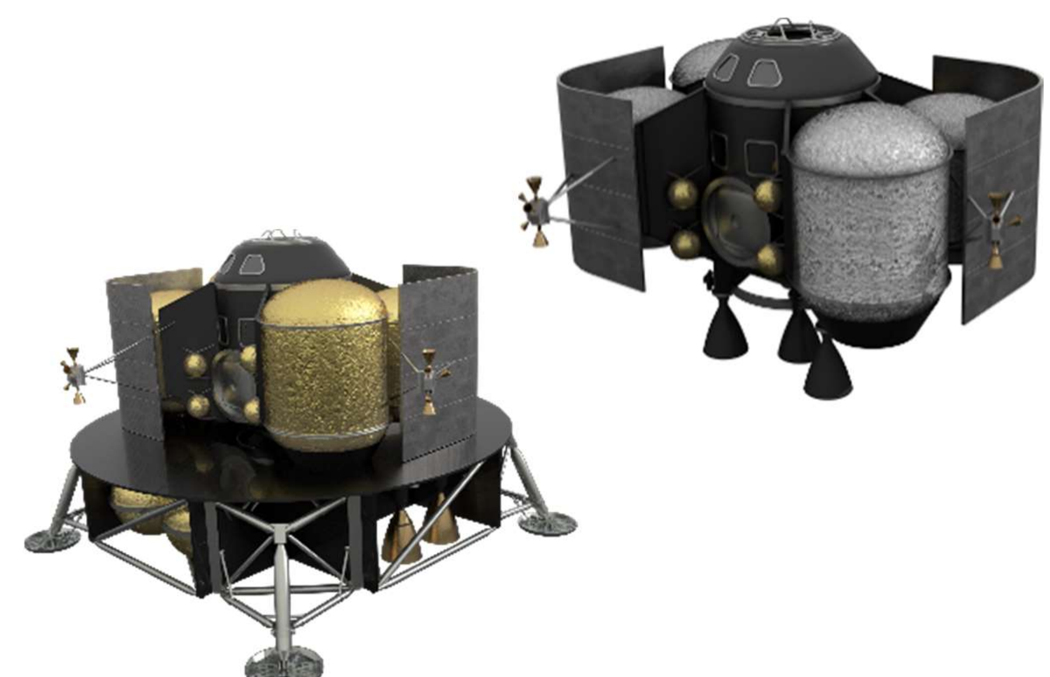
Power Generation: Fuel Cell Analytical Activities

High Power Fuel Cells

- Concept: Crewed transit vehicles, crewed rovers, or rovers with energy-intense experiments
- Application Power: 1 kW to >10 kW
- Future activities: Laboratory testing of next-generation air-independent stacks ranging from 250 W to 1.2 kW on pure and propellant-grade reactants
- Special Notes:
  Recent advances demonstrated autonomous operation and tolerance to vibration loads at launch levels

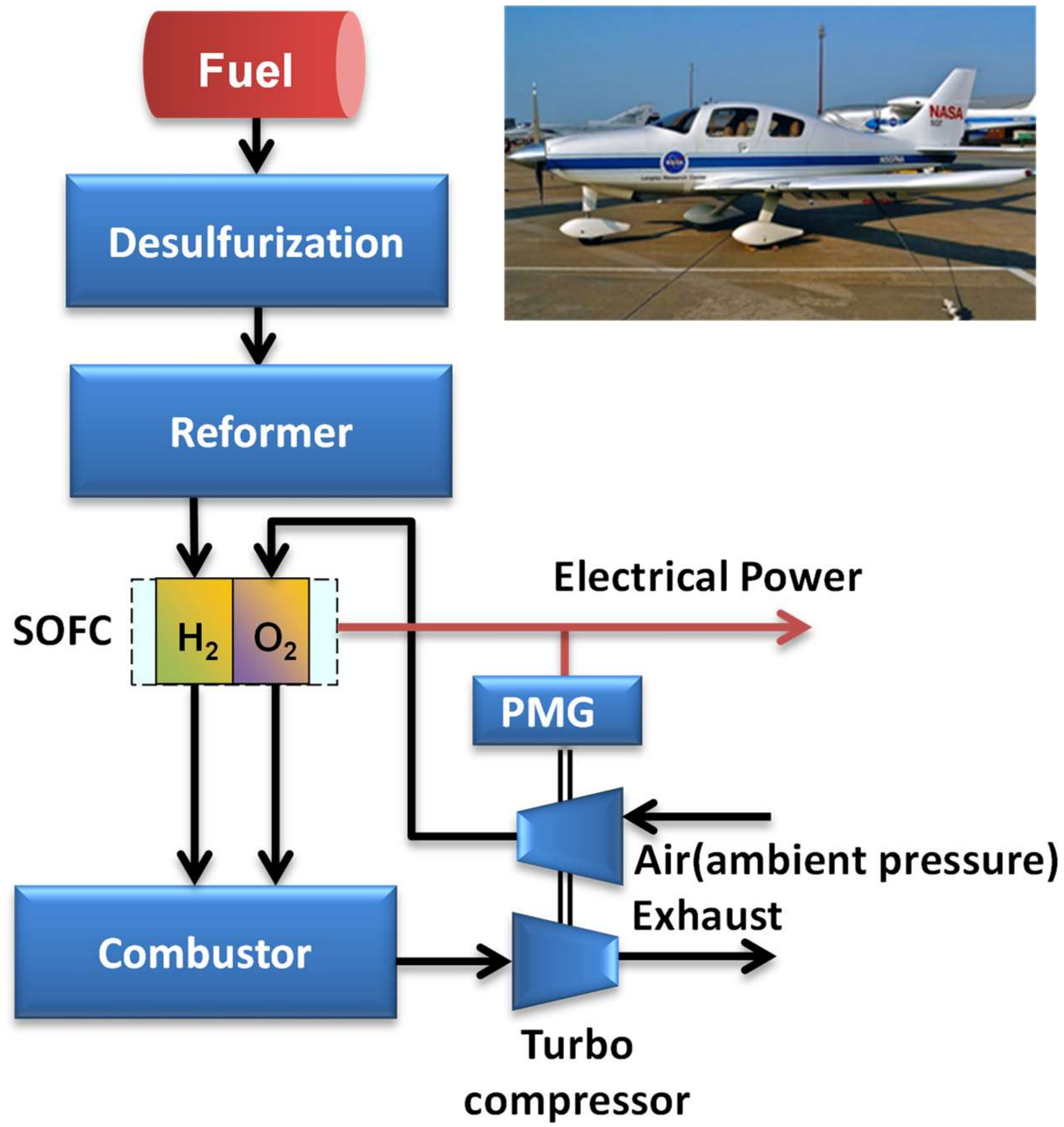
Entry Descent and Landing (EDL)

- Concept: Utilize excess propellant to provide electrical power from Mars orbit insertion through descent, landing, and start-up of primary surface power system
- Application Power Level: ~34 kW
- Future activities: Laboratory evaluation of pre-prototype
  sub-scale fuel cell stack operating on O_2/CH_4



Power Generation: Fuel Cells
Electrification of Aircraft

- Convert experimental X-57 to an electric aircraft
- Integration of key technologies to yield compelling performance to early adopters
  - Useful payload, speed, range for point-to-point transportation
  - Energy system that uses infrastructure-compatible reactants, allowing for immediate integration
  - High efficiency for compelling reduction in operating cost
- Early adopters serve as gateway to larger commercial market



High-Performance Baseline
- 160-190 knots cruise on 130-190kW
- 1100+ pounds for motor & energy system

Efficient Powertrain
- Turbine-like power-to-weight ratio at 90+% efficiency

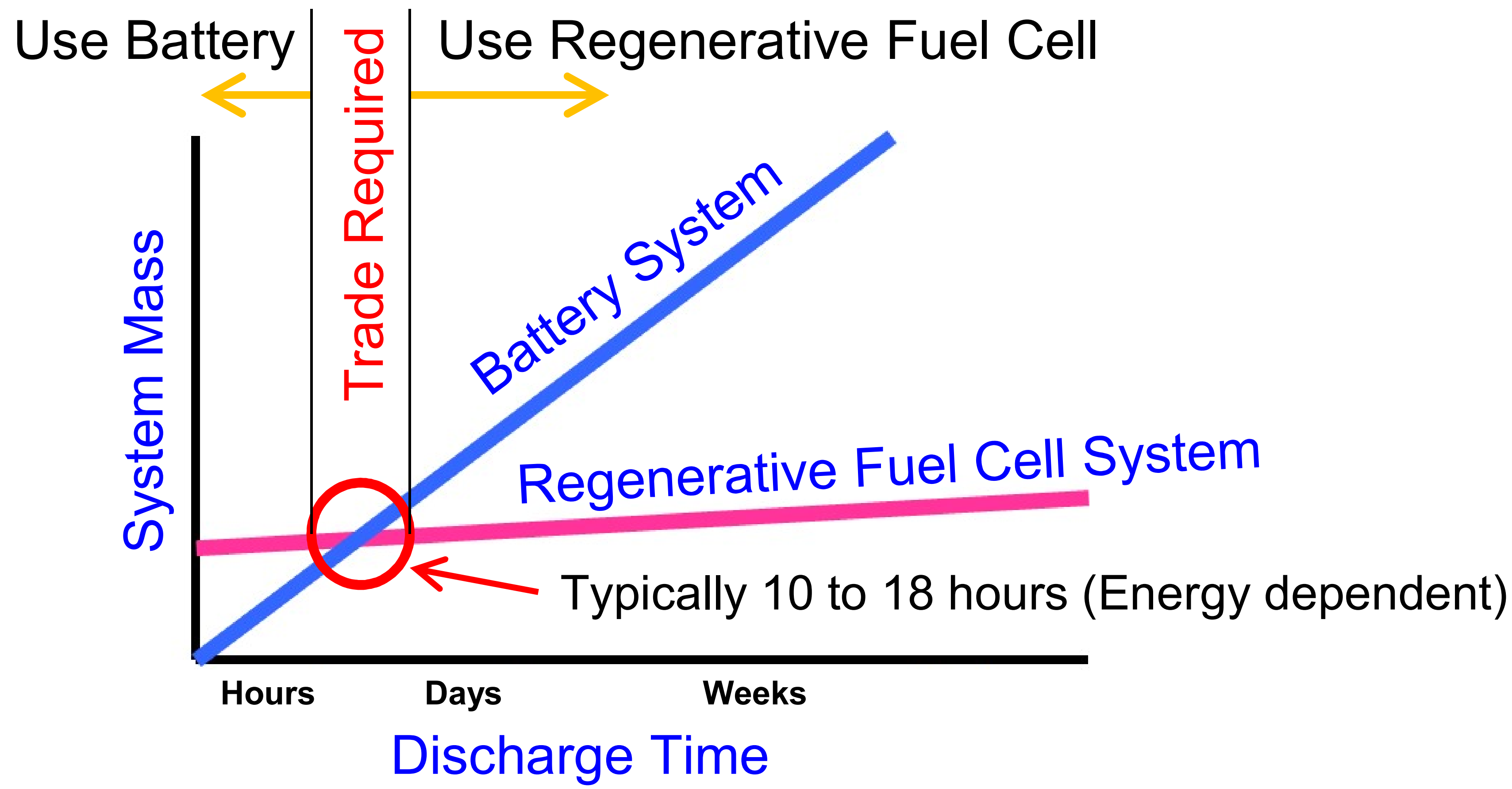
Hybrid Solid Oxide Fuel Cell Energy System
- >60% fuel-to-electricity efficiency
- Designed for cruise power; overdrive with moderate efficiency hit at takeoff and climb power

Primary Objective: **Demonstrate a 50% reduction in fuel cost** for an appropriate light aircraft cruise profile (payload, range, speed, and altitude).

POC: Nicholas Borer, nicholas.k.borer@nasa.gov

Energy Storage: Battery vs Regenerative Fuel Cell

Estimated cost to Lunar Surface: $1.5 M/kg to $1.8 M/kg



Energy Storage Options for 300 W_{ele} Lunar Surface System By Location

Lunar Site	Shaded Period	Energy Storage	Li-ion Mass	LRFC Mass	$ Savings @ $1.5 M/kg
	hours	kW•hrs	kg	kg	$M
South Pole	73	22	**137**	**40**	**$145.5**
Equator	356	107	**668**	**194**	**$711**
Lacus Mortis (45° N)	362	109	**679**	**197**	**$723**

Energy Storage: Regenerative Fuel Cell System

Reactant Storage		Low-pressure Storage (300 psig)		High-pressure Storage (3,000 psig)		Cryogenic Storage		Shared with Propellant		Dedicated Propellant	
Weight Factor	Evaluation Factors	Total	Rank	Total	Rank	Total	Rank	Total	Rank	Total	Rank
	Long Life/Performance	3.80		9.20		5.10		6.90		6.90	
0.9	Longevity (>50,000 hour run time)	0.9	1	3.6	4	1.8	2	2.7	3	2.7	3
0.9	Reliability	0.9	1	3.6	4	1.8	2	2.7	3	2.7	3
0.5	Shock/Vibration Tolerance	2	4	2	4	1.5	3	1.5	3	1.5	3
	Reactant Storage	4.50		0.00		-3.00		-1.00		-2.00	
0.5	Dewar/Speciaized Tank										
0.5	COPV Tank										
0.5	Soft Tank/Bladder										
	Water System Processing										
0.5	Reactant Storage Thermal Balance										
0.5	Passive Thermal Rejection										
0.5	Active Thermal Rejection										
0.5	Filtration/Purification Simplicity										
0.5	Ambient Thermal Storage										
0.5	RFC Reactant Thermal Efficiency										
	Integrated System										
0.5	Freeze Tolerance										
0.5	Total System Round-Trip Efficiency										
0.5	System Specific Energy (w/ storage)										
0.5	Balance of Plant Complexity										
0.5	System Mass optimization										
0.5	System Volume optimization										
	Fluid Transfer Complexity										
0.5	Cryogenic Hydrogen										
0.5	Cryogenic Methane										
0.5	Cryogenic Oxygen										
0.5	Gaseous Carbon Dioxide										
0.5	Gaseous Carbon Monoxide										
0.5	Gaseous Hydrogen										
0.5	Gaseous Methane										
0.5	Gaseous Oxygen										
0.5	Water Vapor										
	Total Score (57.2 possible)										

Electrolysis		PEM - Anode Feed		PEM - Cathode		PEM - Static		Solid Oxide H_2/O_2		Solid Oxide CO_2/O_2	
Weight Factor	Evaluation Factors	Total	Rank	Total	Rank	Total	Rank	Total	Rank	Total	Rank
	Long Life/Performance	12.90		12.90		10.20		11.60		10.70	
0.9	Stack Longevity (>50,000 hour run time)	2.7	3	2.7	3	1.8	2	2.7	3	1.8	2
0.9	Reliability	2.7	3	2.7	3	1.8	2	2.7	3	2.7	3
0.9	Shock/Vibration										
0.9	Load Cycle Durability (>1,0										
0.4	Thermal Cycle Durability (>6										
	Thermal Balance										
0.5	Active Thermal R										
0.5	High-Temp Operation (65										
0.5	Low-Temp Operation (										
0.5	Passive Thermal										
0.5	Thermal Control whe										
0.1	Rapid Startup (< 5										
	System										
0.9	Freeze										
0.9	High Pressure Operation (>1										
0.9	Longevity (>50,000 hour										
0.9	Sub-System Specific Energy (no										
0.7	Balance of Plant C										
0.7	Medium Pressure Operation (>										
0.5	System Mass opt										
0.5	System Volume opt										
	Reactant Purity Capabilit										
0.8	Clean Liqu										
0.8	Clean Wa										
0.8	Impure Liqu										
0.8	Impure Wa										
0.1	Carbo										
	Total Score (63.6 possi										

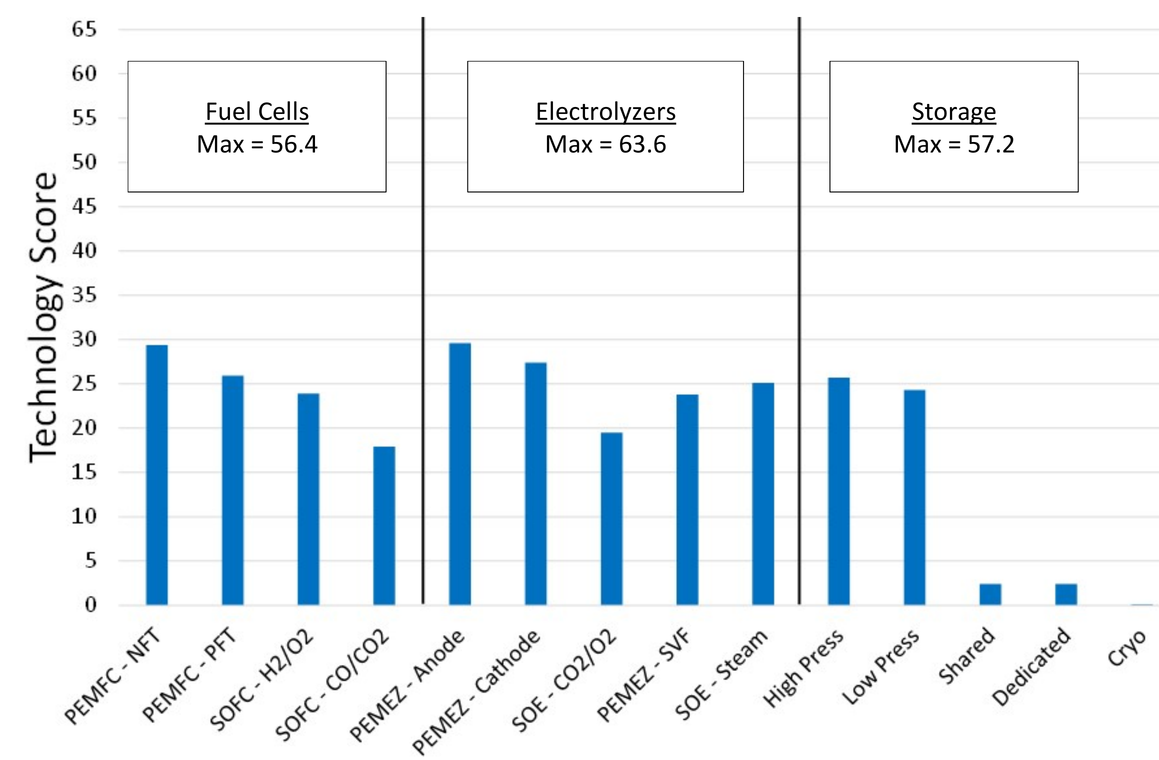
Fuel Cells		PEMFC - NFT		PEMFC - PFT		SOFC - H_2/O_2		SOFC - CO/O_2	
Weight Factor	Evaluation Factors	Total	Rank	Total	Rank	Total	Rank	Total	Rank
	Long Life/Performance	15.30		14.40		10.80		8.10	
0.9	Stop/Start Durability (>1,000)	3.6	4	3.6	4	2.7	3	2.7	3
0.9	Thermal Cycle Durability (>625)	3.6	4	3.6	4	1.8	2	1.8	2
0.9	Longevity (>50,000 hour run time)	2.7	3	2.7	3	1.8	2	0.9	1
0.9	Reliability	2.7	3	1.8	2	1.8	2	0.9	1
0.9	Shock/Vibration Tolerance	2.7	3	2.7	3	2.7	3	1.8	2
	Thermal Balance	0.20		0.20		3.00		3.00	
0.6	Low-Temp Operation (60-80 oC)	2.4	4	2.4	4	0	0	0	0
0.1	Rapid Startup (< 5 minutes)	0.3	3	0.3	3	-0.1	-1	-0.1	-1
0.4	High-Temp Operation (750-850 oC)	0	0	0	0	1.6	4	1.6	4
0.5	Active Thermal Rejection	-0.5	1	-0.5	1	0	0	0	0
0.5	Passive Thermal Rejection	-1	-2	-1	-2	1.5	3	1.5	3
0.5	Thermal Control when off-line	-1	-2	-1	-2	0	0	0	0
	System	12.70		10.10		8.90		6.10	
0.9	Sub-System Specific Energy (no storage)	3.6	4	2.7	3	0.9	1	0.9	1
0.7	Hermetic sealing	2.8	4	2.8	4	0.7	1	0.7	1
0.9	Round-trip efficiency	2.7	3	2.7	3	2.7	3	0.9	1
0.7	Minimum Balance of Plant Complexity	2.1	3	1.4	2	0.7	1	0.7	1
0.5	Operating Pressure (50 - 100 psia)	2	4	2	4	1	2	0.5	1
0.5	System Mass optimization	2	4	1.5	3	1	2	1	2
0.5	System Volume optimization	2	4	1.5	3	1	2	0.5	1
0.9	Freeze Tolerance	-1.8	-2	-1.8	-2	3.6	4	3.6	4
0.9	Longevity (>50,000 hour run time)	-2.7	-3	-2.7	-3	-2.7	-3	-2.7	-3
	RFC Reactant Capability	1.20		1.20		1.20		0.70	
0.2	Hydrogen (H2)	0.8	4	0.8	4	0.8	4	0	0
0.1	Oxygen (O2)	0.4	4	0.4	4	0.4	4	0.4	4
0.1	Carbon Monoxide (CO)	0	0	0	0	0	0	0.3	3
0.1	Hydrocarbon (CH4)	0	0	0	0	0	0	0	0
	Total Score (56.4 possible)	29.40		25.90		23.90		17.90	

Evaluation Factor Ranking

4 = Mature Technology with Heritage
3 = Successful Field Deployment
2 = Successful Field Demonstration
1 = Successful Laboratory Demonstrations
0 = Not Applicable
-1 = Unproven Solution Available
-2 = Significant Development Required
-3 = Major Advancement Required
-4 = Prohibitive / Not Possible

* Reversable process (Fuel Cell/Electrolysis)

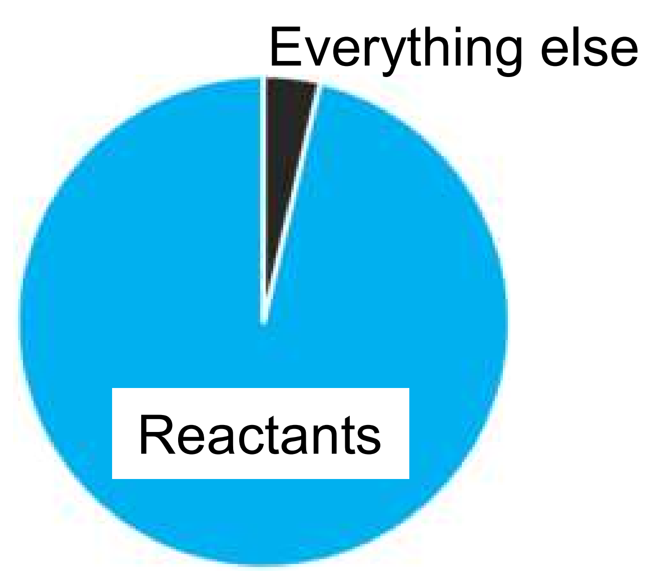
Each RFC sub-system traded across multiple parameters



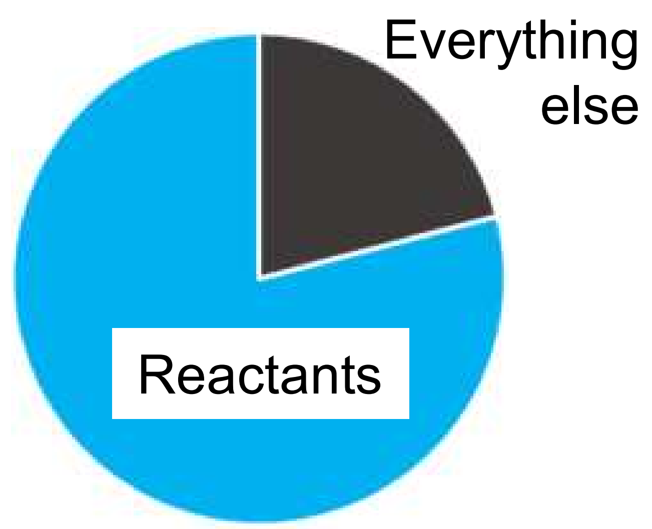
Energy Storage: Regenerative Fuel Cell Trade Studies

- **Regenerative Fuel Cell (RFC) Model**
  - Developed detailed RFC integrated system model to conduct sensitivity studies and mission trades
  - Conducted parameter sensitivity study
    - Location primary parameter
    - Round-trip efficiency dominant metric
  - Compared Solid Oxide and PEM chemistries
    - SOE not feasible for high pressure gas storage
    - SOFC limits electrical slew if sole power source
  - Rotating components fail at a higher rate than electrochemical hardware
- **Crewed Surface Outpost Trade Study Results**
  - System development at low TRL
  - Location determines required energy storage which sizes RFC
  - PEM-based RFC near-term solution for Lunar base
  - Burdened[2] RFC could achieve up a specific energy to 510 W•hr/kg

10 kW PEM RFC Energy Storage System for Equatorial Lunar Outpost



Volume (m^3)



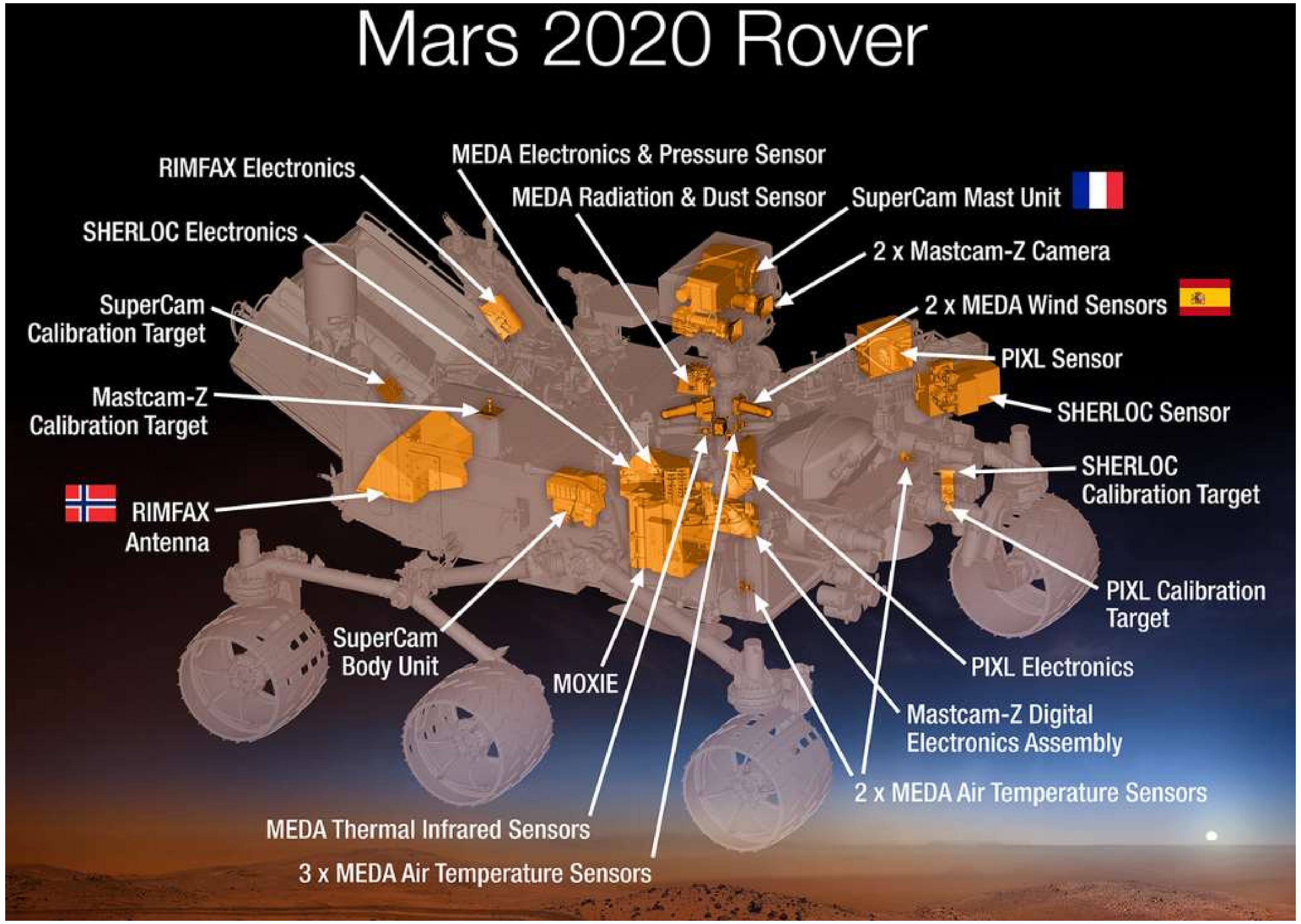
Mass (kg)

Energy Storage: Regenerative Fuel Cell System

Category	Element	Relative Maturity	Notes
Electrochemical	PEM: Electrolysis	Advanced	ISS has flown but with major servicing requirements (every 201 days) and low pressure
	PEM: Fuel Cell	Medium	Terrestrial hardware available but no Flight qualified hardware exists
	Solid Oxide: Electrolysis	Low	MOXIE promising but existing leak rates challenging for $H_2/H_2O/O_2$ RFC application
		Very Low	Seal and pressure impose severe limitations for RFC application. Increasing scale a major concern. Limited CO/CO_2 life data available
	Solid Oxide: Fuel Cell	Low	Terrestrial hardware available but has unacceptable seal and pressure issues for an Aerospace application
		Very Low	Increasing scale a major concern. Limited CO/O_2 life data available
Reactant Management	Storage	Mature	Many examples of fluid storage flight hardware
	Fluid Management	Medium	Life, durability, and reliability issues for components and system
	Reactants	Medium	Material Compatibility and contamination issues over projected mission duration
	Water Management	Low	Purity and freezing issues over projected mission duration. Most ECLSS solutions not applicable to RFC application
PMAD	Control	Medium	New bus voltage and new operating environment require new designs and test programs
	System	Medium	Thermal and electrical insulation/grounding at new power levels
Thermal	Deployment	Medium	Surface deployment options not yet demonstrated at scale required by RFC
	Surfaces	Medium	Maintaining radiative surface not demonstrated in relevant environment at scale without servicing
System	ConOps	Low	Demonstrated RFCs require prohibitive maintenance schedules subject to a range of operational methodologies
	Reliability / Life	Very Low	Limited life data available in relevant environment except for computer (CPU)
	Instrumentation	Low	Calibration drift and durability are mission-limiting issues
	Maintenance	Very Low	Maintenance and servicing a mission-limiting issue. Robotic servicing reduces maintenance complexity and required spares. Robotic capabilities not demonstrated.

Commodity Generation: Oxygen

- **Mars Oxygen In-Situ Resource Utilization Experiment (MOXIE)**
  - **Flight demonstration experiment as a part of the Mars 2020 rover mission**
  - **Generates gO_2 from CO_2 in Mars atmosphere (~1% scale) using Solid Oxide Electrolysis (SOE)**
  - **Proof-of-concept for generating propellant oxygen for Mars Ascent Vehicle (MAV) or breathing oxygen for astronauts**



- **Oxygen Generator Assembly (OGA)**
  - **ECLSS recovers ~ 90% of all water**
  - **Existing technology on-board the ISS since 2008**
  - **Advancing towards a smaller and lighter-weight version for scheduled upgrade in FY21**
  - **Hazard evaluation testing at WSTF**

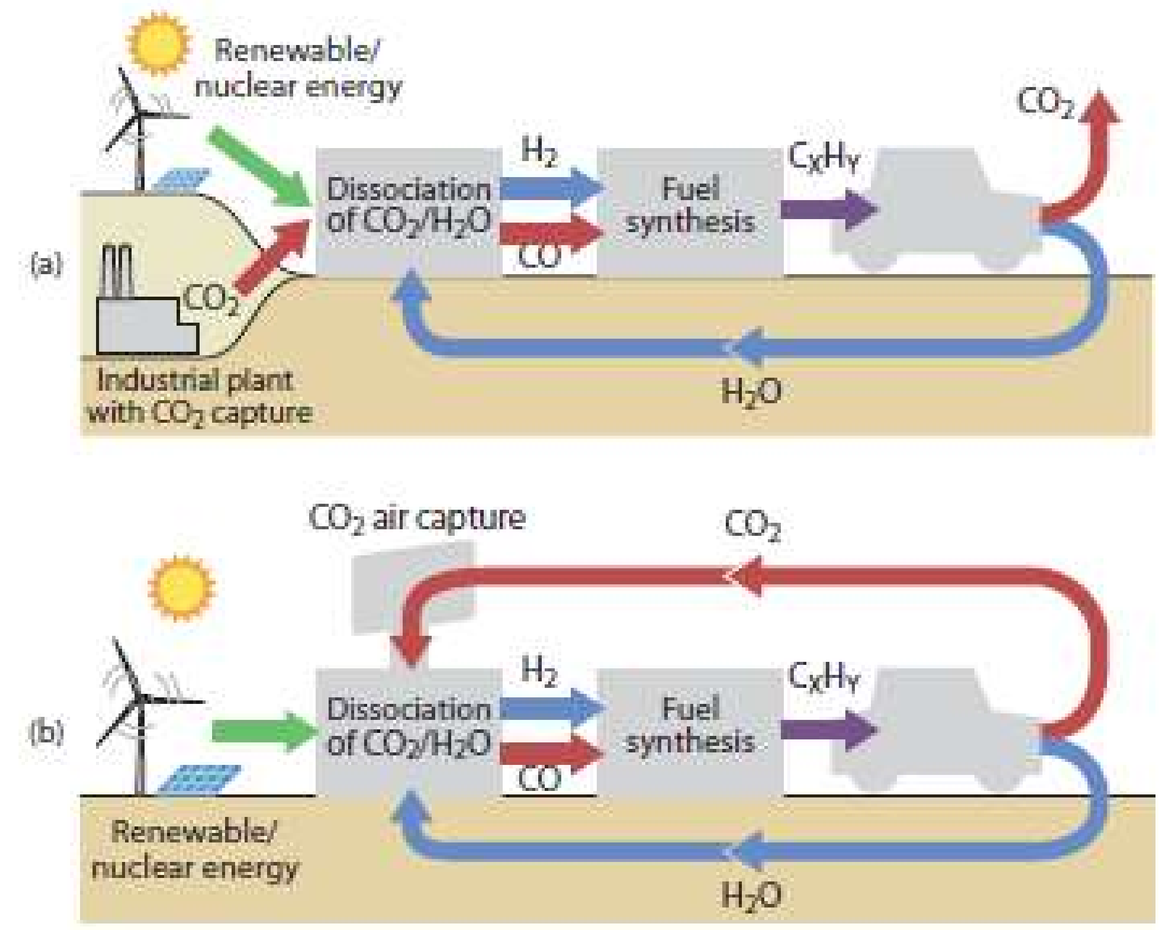
- **Flight-qualified High Pressure electrolysis**
  - **ECLSS systems to generate 3,000 psi gO_2 by FY24**
  - **Evaluating existing system modifications to maintain mass while increasing generation pressure**
  - **Investigations into conserving gH_2 by-product**

Commodity Generation: Hydrocarbon Fuel Synthesis

A *Green* Energy Application for SOE Co-Electrolysis:

Manufacture of synthetic fuels from captured CO_2 and renewable energy

- Combined CO_2 and H_2O electrolysis produces CO and H_2, a basic feedstock in the chemical industry (referred to as synthesis gas, or “syngas”)
- Syngas can be utilized to produce a wide variety of liquid hydrocarbons via the Fischer-Tropsch (F-T) process.
  - F-T process is a mature technology presently used to manufacture synthetic lubricants, etc.
  - Sasol (South Africa) produces gasoline and diesel fuel on a large scale via F-T.
- Recent review paper trade study concluded that synthetic gasoline could be produced for costs as low as $2/gal.*
- Allows the “recycling” of atmospheric CO_2 while maintaining our present hydrocarbon fuel infrastructure.

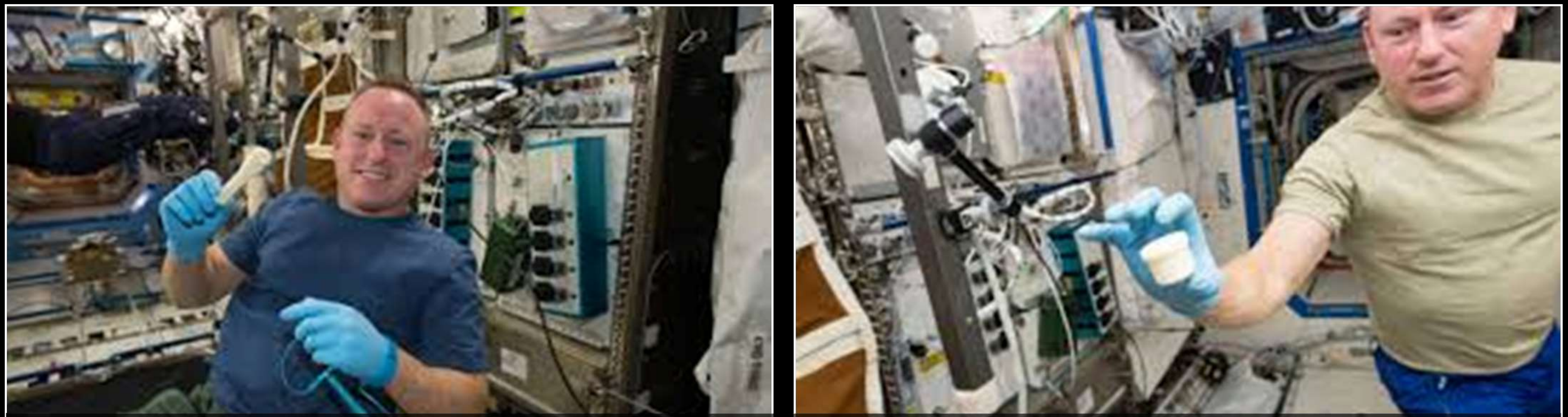


Two possible CO_2-recycling scenarios:
(a)CO2 recycled from industrial plant emissions (potential to reduce CO_2 net emissions by 50%).
(b) Closed loop carbon recycling via CO_2 capture from Earth’s atmosphere (near-zero net emissions).

* Study and above graphic from Graves et al., *Renewable and Sustainable Energy Reviews*, 15, (2011) 1-23.

IN-SPACE MANUFACTURING

ON-DEMAND MANUFACTURING TECHNOLOGIES FOR DEEP SPACE MISSIONS



3-D printer installed on International Space Station in 2014. Crews aboard station have successfully used the printer to manufacture parts and tools on-demand.

Issued new appendix to NextSTEP Broad Agency Announcement soliciting proposals for development of first-generation, in-space, multi-material fabrication laboratory, or FabLab, for space missions.

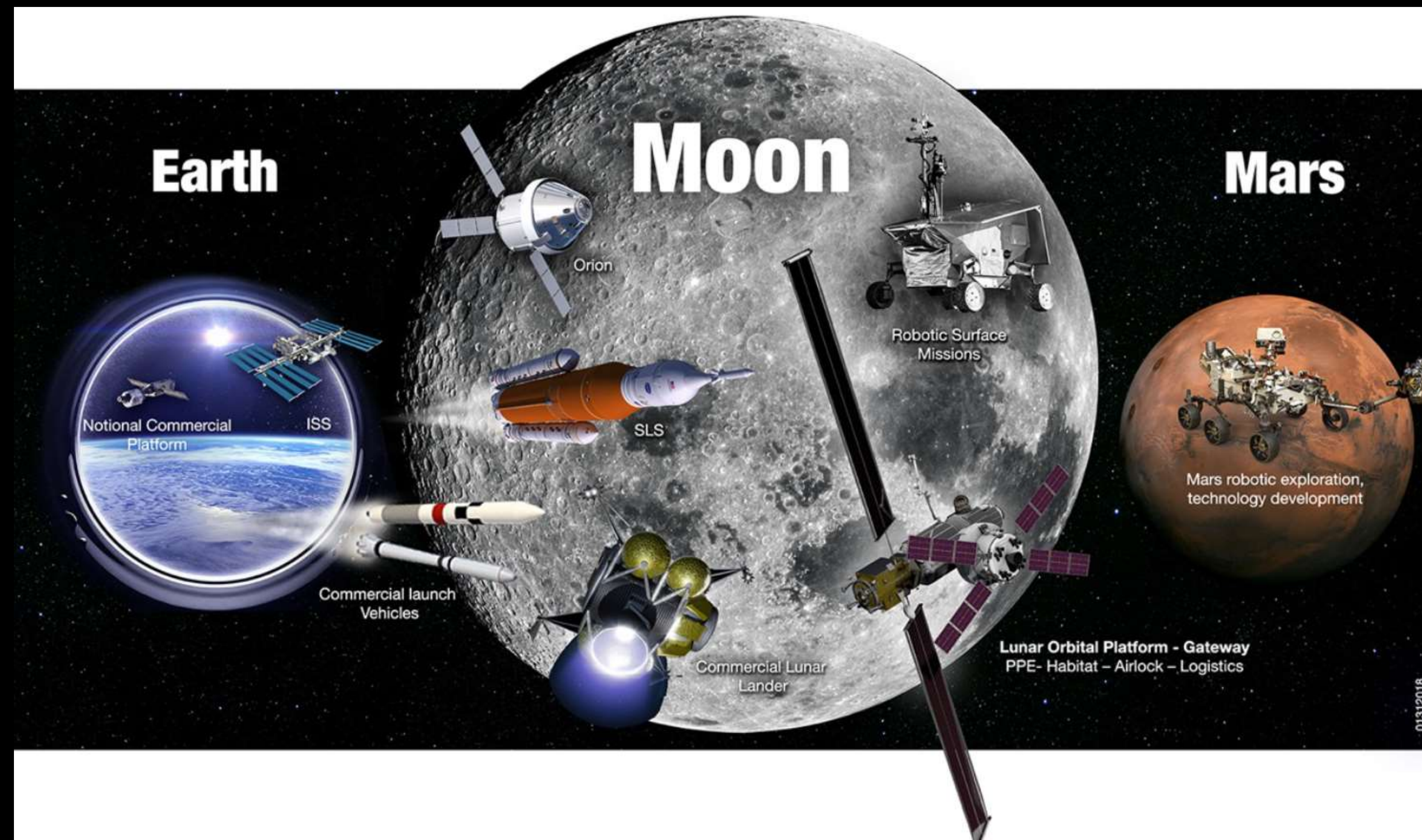
First student-designed 3-D tool printed aboard station in 2016

In-Space Manufacturing logo created through Freelancer crowd-sourced challenge.

NASA Fuel Cell Applications

Powering exploration activities

Electrified Aircraft
Primary Power



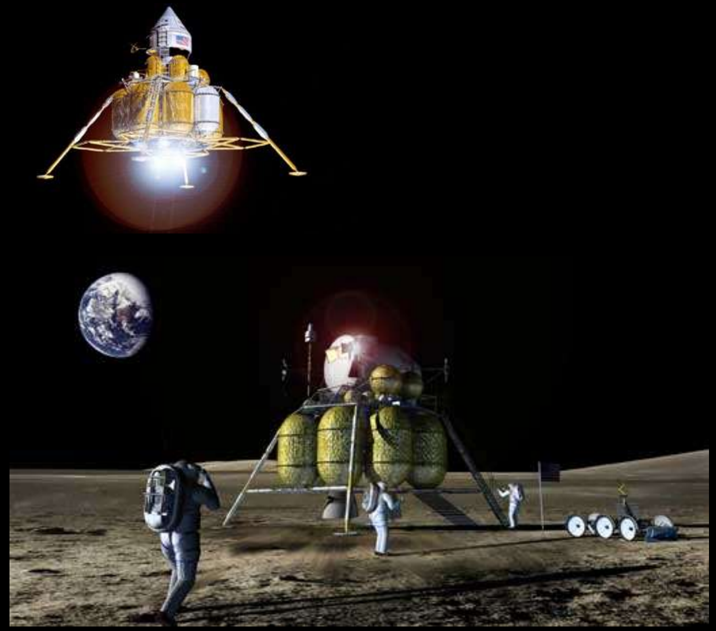
Landers
Primary Power

Lunar Outposts
Energy Storage

Martian Outposts and Rovers

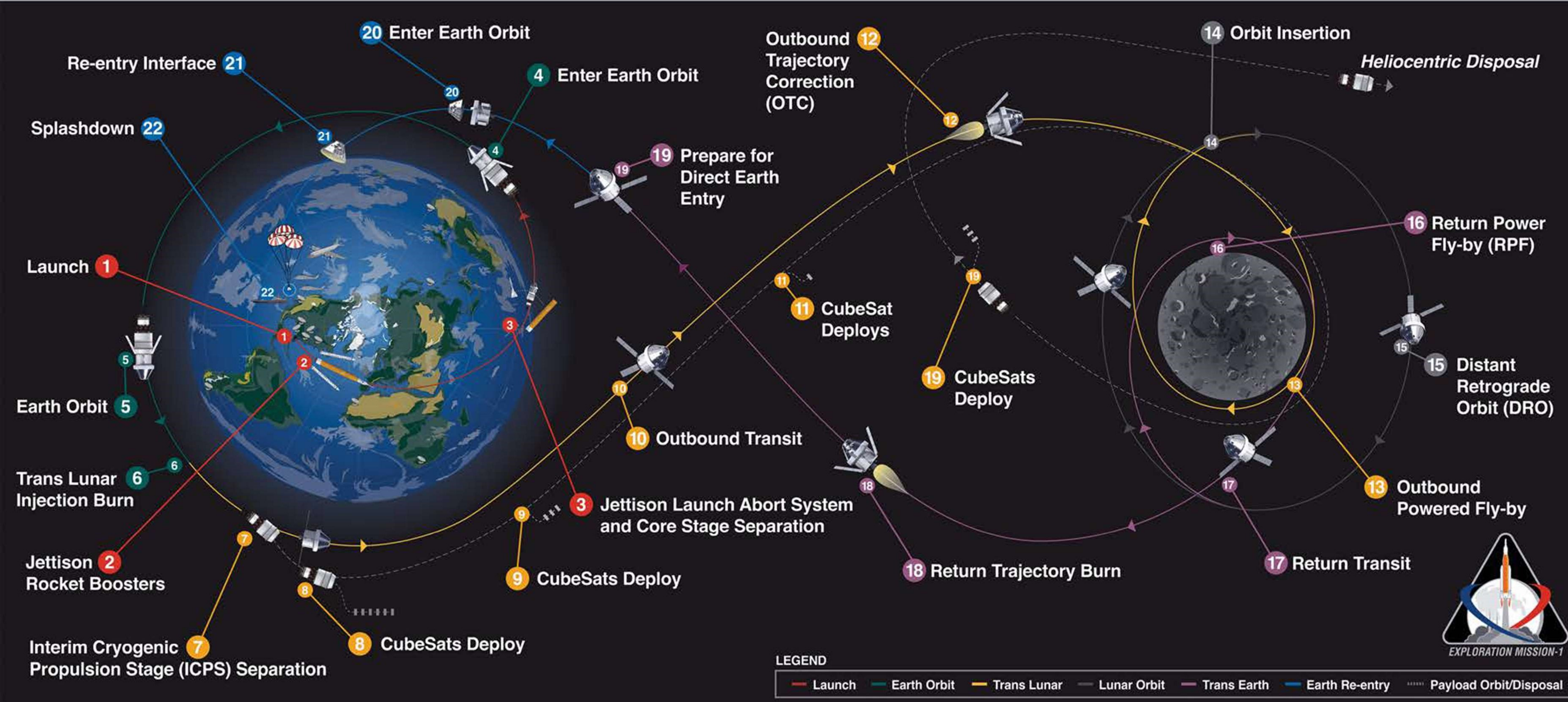
Primary Power
Energy Storage
Commodity Generation

Back-up Slides



EXPLORATION MISSION-1

The first uncrewed, integrated flight test of NASA's Deep Space Exploration Systems. The Orion spacecraft and Space Launch System rocket will launch from a modernized Kennedy spaceport.

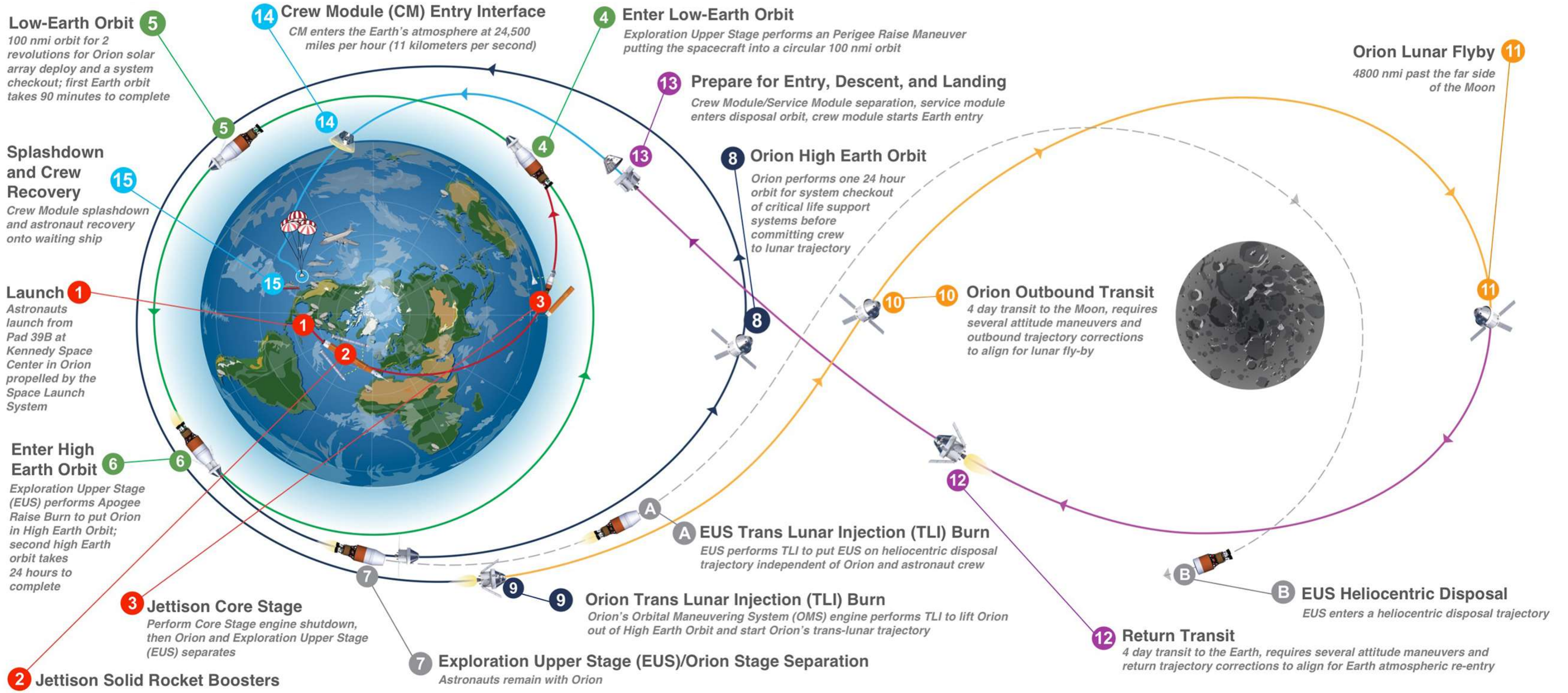


Total distance traveled: 1.3 million miles – Mission duration: 25.5 days – Re-entry speed: 24,500 mph (Mach 32) – 13 CubeSats deployed

EXPLORATION MISSION-2

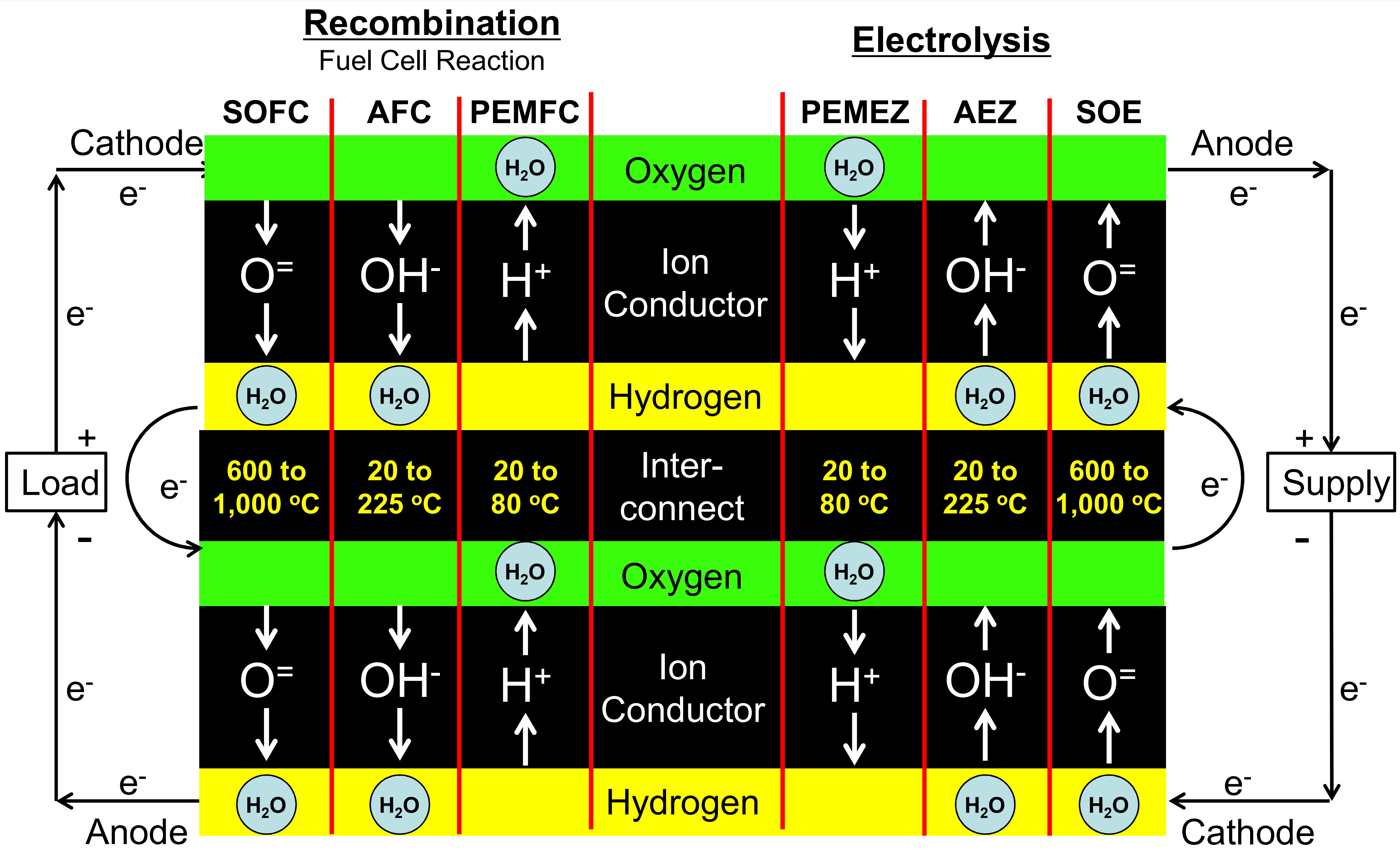
National Aeronautics and Space Administration

The first crewed, integrated flight test of NASA's Deep Space Exploration System, the Orion spacecraft and Space Launch System launching from a modernized Kennedy Spaceport.



4 astronauts - Total distance traveled: 1,090,320 km - Mission duration: 9 days – Re-entry speed 24,500 mph (Mach 32) – 9 metric ton Co-Manifested Payload deploy

Summary of Applicable Electrochemical Reactions



Habitation Systems

Habitation Systems Elements

	Habitation Systems Elements	TODAY Space Station	FUTURE Deep Space
LIFE SUPPORT	Excursions from Earth are possible with artificially produced breathing air, drinking water and other conditions for survival. Atmosphere Management, Water Management, Waste Management	~50% O_2 Recovery from CO_2 90% H_2O Recovery < 6 mo mean time before failure (for some components)	75%+ O_2 Recovery from CO_2 98%+ H_2O Recovery >30 mo mean time before failure
ENVIRONMENTAL MONITORING	NASA living spaces are designed with controls and integrity that ensure the comfort and safety of inhabitants. Pressure O_2 & N_2, Moisture, Particles, Microbes, Chemicals, Sound	Limited, crew-intensive on-board capability Reliance on sample return to Earth for analysis	On-board analysis capability with no sample return Identify and quantify species and organisms in air & water
CREW HEALTH	Astronauts are provided tools to perform successfully while preserving their well-being and long-term health. Monitoring, Exercise, Diagnostics, Treatment, Food Storage & Management	Bulky fitness equipment Limited medical capability Frequent food system resupply	Smaller, efficient equipment Onboard medical capability Long-duration food system
EVA: EXTRA-VEHICULAR ACTIVITY	Long-term exploration depends on the ability to physically investigate the unknown for resources and knowledge. Mobility, Life Support, Science and Exploration	Upper body high mobility for limited sizing range Low interval between maintenance, contamination sensitive, and consumables limit EVA time Construction and repair focused tools; excessive inventory of unique tools	Full body mobility for expanded sizing range Increased time between maintenance cycles, contamination resistant system, 25% increase in EVA time Geological sampling and surveying equipment; common generic tool kit

Habitation Systems

Habitation Systems Elements

TODAY – Space Station | **FUTURE** – Deep Space

RADIATION PROTECTION

During each journey, radiation from the sun and other sources poses a significant threat to humans and spacecraft.

Monitoring – Tracking – Modeling – Mitigation

TODAY Space Station	FUTURE Deep Space
Node 2 crew quarters (CQ) with polyethylene reduce impacts of proton irradiation.	Solar particle event storm shelter, optimized position of on-board materials and CQ
Large multi-layer detectors & small pixel detectors – real-time dosimetry, environment monitoring, tracking, model validation & verification	Small distributed pixel detector systems – real-time dosimetry, environment monitoring, and tracking
Bulky gas-based detectors – real-time dosimetry	Small actively read-out detectors for crew – real-time dosimetry
Small solid-state crystal detectors – passive dosimetry (analyzed post-mission)	

FIRE SAFETY

Throughout every mission, NASA is committed to minimizing critical risks to human safety.

Detection – Protection – Suppression – Cleanup

TODAY Space Station	FUTURE Deep Space
Large CO_2 Suppressant Tanks	Water Mist portable fire extinguisher
2-cartridge mask	Single Cartridge Mask
Obsolete combustion prod. sensor	Exploration combustion product monitor
Only depress/repress clean-up	Smoke eater

LOGISTICS

Sustainable living outside of Earth requires explorers to reduce, recycle, reuse, and repurpose materials.

Tracking – Clothing – Packaging – Trash

TODAY Space Station	FUTURE Deep Space
Manual scans, displaced items	Automatic, autonomous RFID
Disposable cotton clothing	Long-wear clothing/laundry
Packaging disposed	Bags/foam repurposed w/3D printer
Bag and discard	Resource recovery, then disposal

CROSS-CUTTING

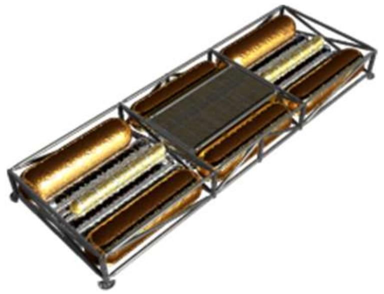
Powerful, efficient, and safe launch systems will protect and deliver crews and materials across new horizons.

Robotics – Power – Communication – Docking – Avionics, Autonomy & Software – Thermal – Materials

TODAY Space Station	FUTURE Deep Space
Minimal on-board autonomy	Ops independent of Earth & crew
Near-continuous ground-crew communications	Up to 40-minute comm delay
Some common interfaces, modules controlled separately	Widespread common interfaces, modules/systems integrated
	Manufacture replacement parts in space

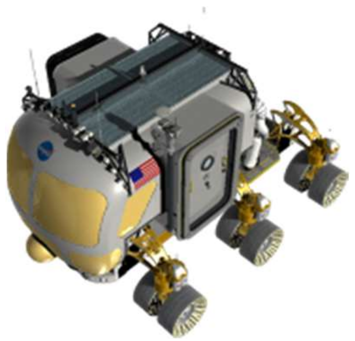
NASA Fuel Cell Applications

Lunar Architecture Studies identified regenerative fuel cells and rechargeable batteries as enabling technologies, where enabling technologies are defined as having:
"overwhelming agreement that the program cannot proceed without them."

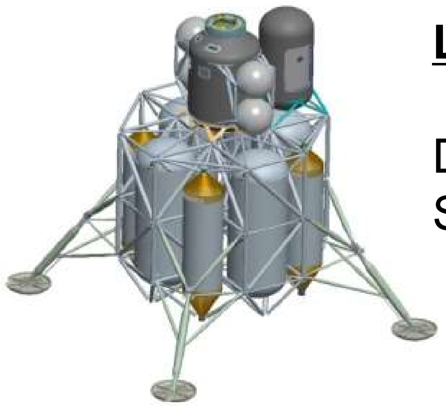


Surface Systems

Surface Power: Maintenance-free operation of **regenerative fuel cells** for >10,000 hours using ~2000 psi electrolyzers. Power level TBD (2-3 kW modules for current architecture).
Reliable, long-duration maintenance-free operation; human-safe operation; architecture compatibility; high specific-energy, high system efficiency.



Mobility Systems: Reliable, safe, primary power from batteries and fuel cells, and energy storage from secondary batteries and **regenerative fuel cells** in small mass and volume. Human-safe operation; reliable, maintenance-free operation; architecture compatibility; high specific-power and high specific-energy.



Lander

Descent Stage: Functional **primary fuel cell** with 3-kW nominal power, 6-kW peak power.
Human-safe reliable operation; high energy-density; architecture compatibility (operate on residual propellants).