



Lunar Hydrogen Infrastructure

Presented by:

Ian Jakupca,
NASA Glenn Research Center

Presented to:

Hydrogen-Metal Systems
Gordon Research Conference
Castelldefels, Spain
30 June 2019





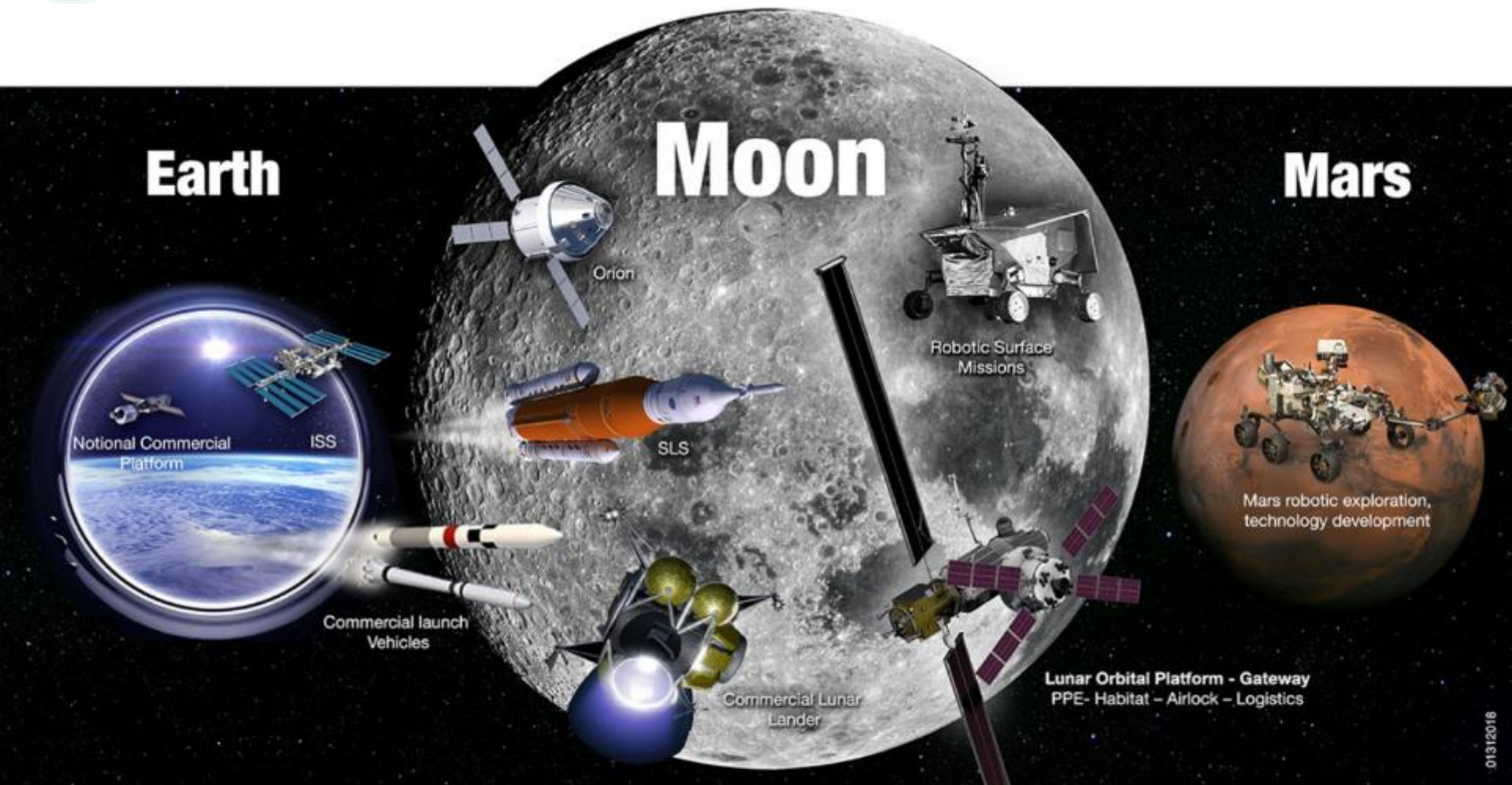
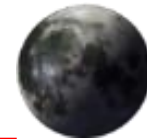
Presentation Overview



- NASA
- Logistics of Space Exploration
- Hydrogen Applications in Space
 - Propulsion
 - Power and Energy
 - Material Processing
- *In situ* Resource Utilization (ISRU)
 - Lunar Resources
 - Excavation Processes
- Economics of a Lunar Hydrogen Economy
- Discussion



NASA Overview and Objectives



Earth

Moon

Mars

Notional Commercial Platform

ISS

Orion

SLS

Robotic Surface Missions

Commercial launch Vehicles

Commercial Lunar Lander

Lunar Orbital Platform - Gateway
PPE - Habitat - Airlock - Logistics

Mars robotic exploration, technology development

In LEO

Commercial & International partnerships

In Cislunar Space

A return to the moon for long-term exploration

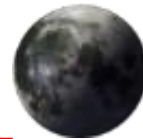
On Mars

Research to inform future crewed missions

01312016



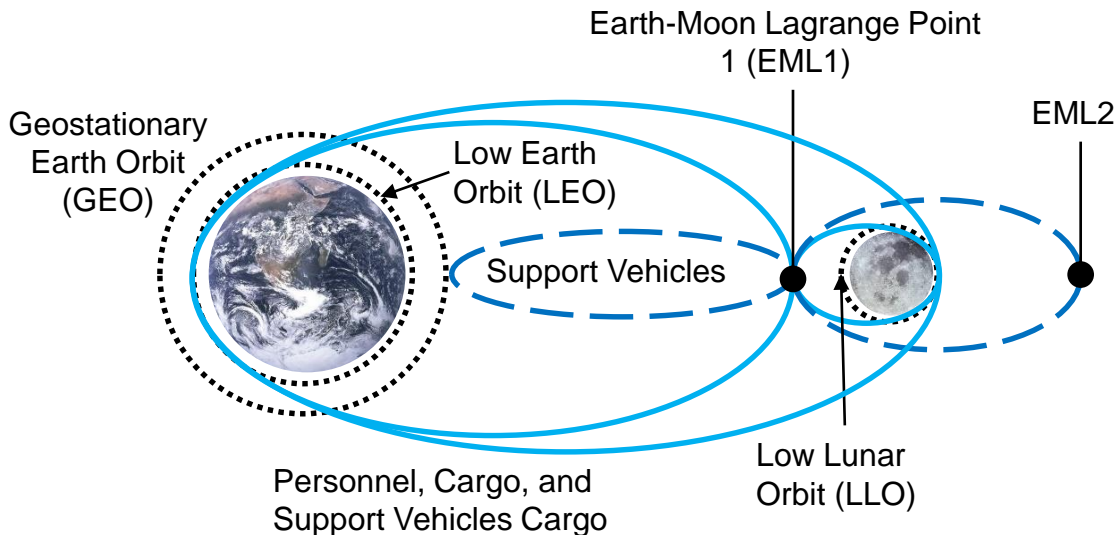
Space Exploration Logistics



- Enable exploration by staging required resources in forward locations
 - Earth Orbit (LEO, GEO)
 - LaGrange Points (EML1 and EML2)
 - Lunar Orbit
 - Lunar Surface
- Resources include propellant depots, propellant production facilities (initially H_2 and O_2), and consumable storage
- Gateway is the first element of the exploration infrastructure



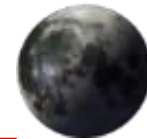
Gateway with Orion Service Module



Conceptual Crewed Lunar Outpost with production facilities⁴



Cis-Lunar Space



Lagrange Points of the Earth-Moon System as viewed from above the Earth-Moon Orbital Plane

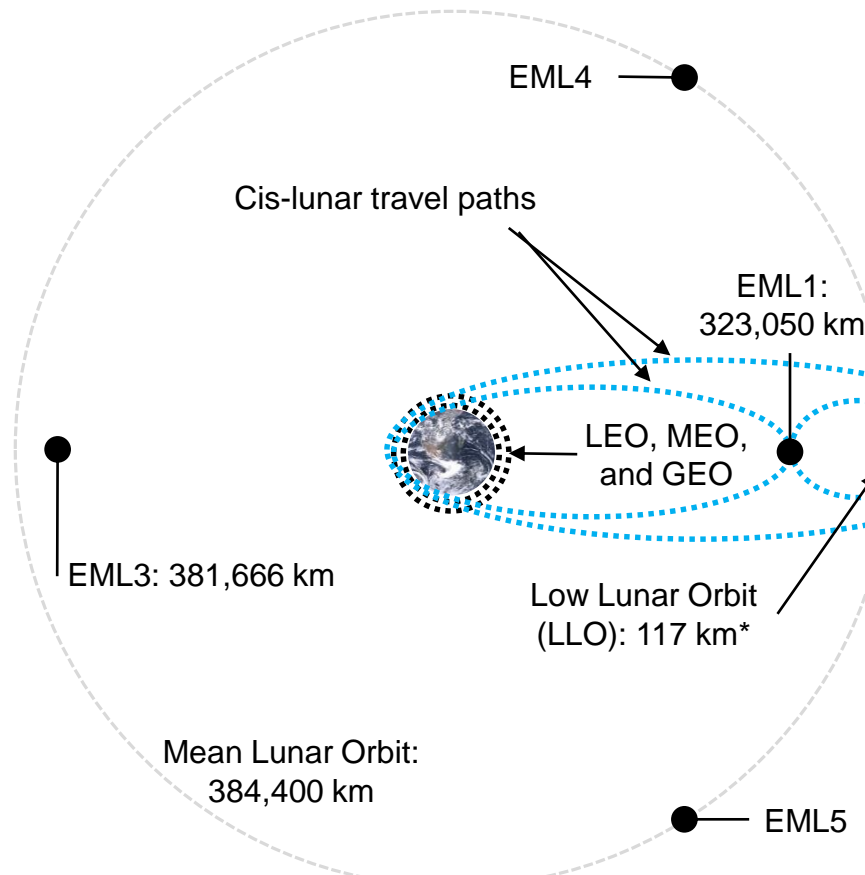
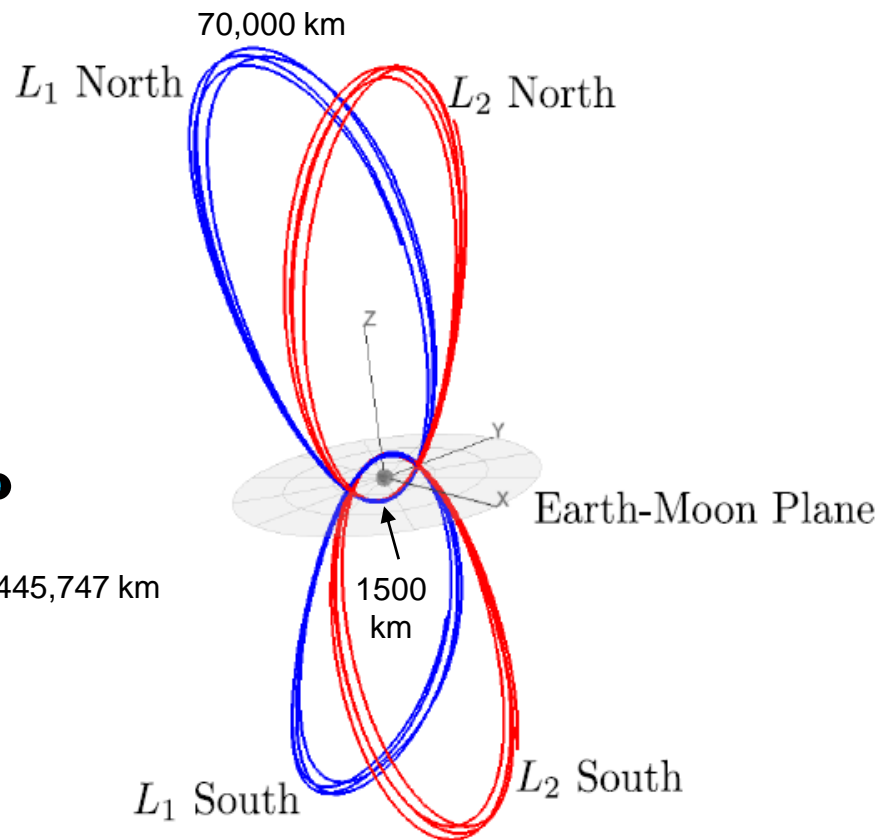


Image Not to Scale

- Diameter of Earth: 12,742 km
- Diameter of the Moon: 3,474 km
- Low Earth Orbit (LEO): <2,000 km
- Medium Earth Orbit (MEO): 2000 km to 35,786 km
- Geostationary Earth Orbit (GEO): 35,786 to 42,000 km



Lunar Near Rectilinear Halo Orbits (NHRO) as viewed from a Moon-Centric Inertial Frame of Reference

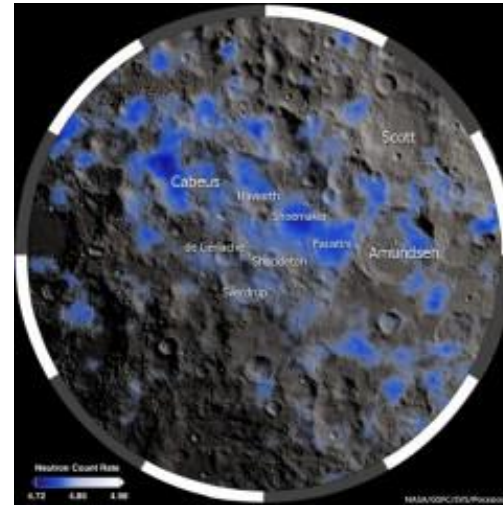
Image Source:
 UTILIZING THE DEEP SPACE GATEWAY AS A PLATFORM FOR
 DEPLOYING CUBESATS INTO LUNAR ORBIT. Fisher, Kenton R; NASA
 JSC. Deep Space Gateway Science Workshop 2018 (LPI Contrib. No. 2063)



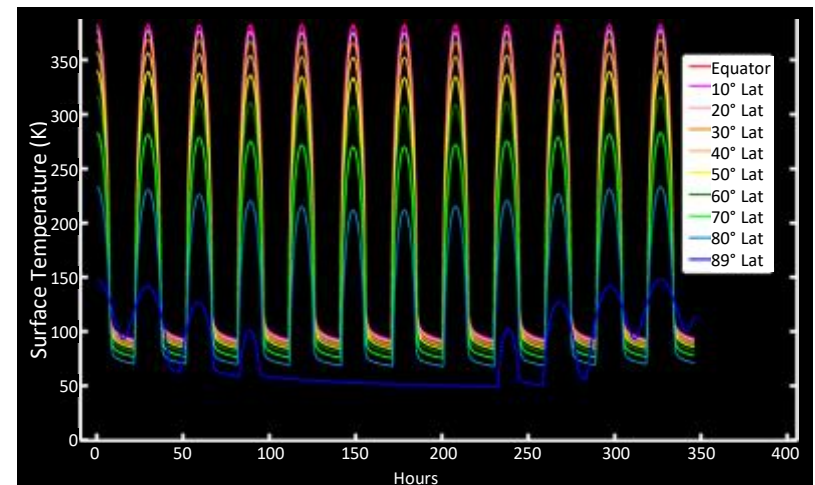
Lunar Hydrogen Infrastructure



- Lunar Hydrogen Infrastructure: Producing a needed commodity from local resources. This is a sub-set of *in situ* resource utilization (ISRU)
- ISRU enables persistent, large scale activities beyond Earth by reducing the **cost** of operating in space, on the moon, or Mars by providing a resource **“gear ratio”**
- Propellant generation concept currently is based on electrolyzing water recovered from lunar deposits of ice.



Regions likely to have water ice deposits on the Moon's south pole as identified by the NASA Lunar Reconnaissance Orbiter (LRO). Source: NASA / Goddard Space Flight Center



Average Temperature over a Lunar Day by latitude

Source: Lunar Reconnaissance Orbiter (LRO) Diviner Instrument



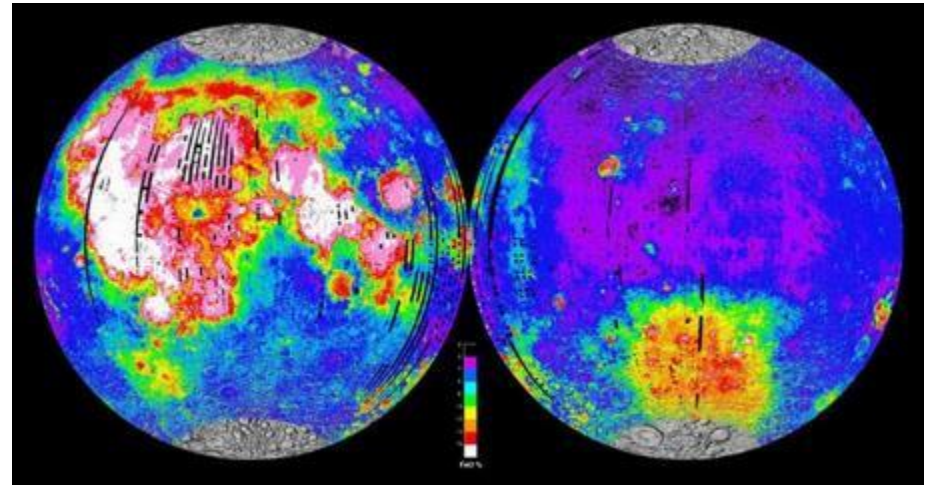
Space Hydrogen Applications



- Propulsion
 - Propellant
- Power and Energy Storage
 - Primary fuel cells
 - Regenerative fuel cells
- Material Processing
 - Reducing oxides
 - Refine metals
 - Release oxygen
 - Create water
 - Reacting with waste materials to generate plastic precursors



Carnegie-Mellon University / NASA
Scarab Rover powered by a H_2/O_2
Fuel Cell System

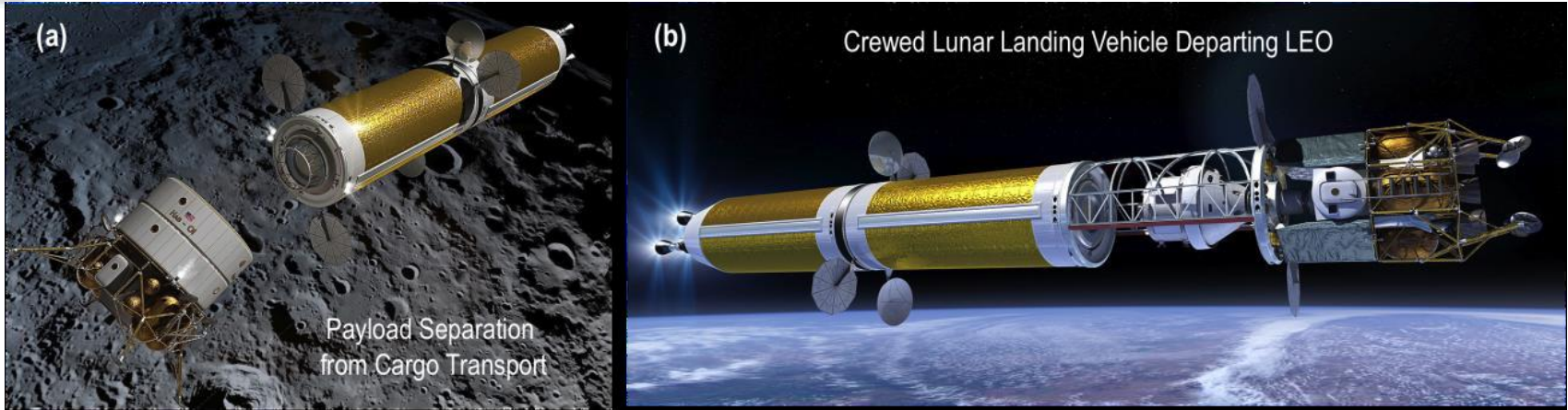


Global map of the iron concentration on the lunar surface created from data collected by the Clementine mission. Colors represent 2% increments of increasing FeO concentration from black (0%) to white (16%).

Source: NASA/Clementine



Hydrogen: Propellant



Conceptual Reusable Lunar Transfer Vehicles: a) Cargo and b) Crewed Lunar Landing

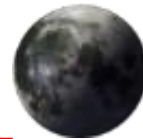


Gateway with Orion Service Module



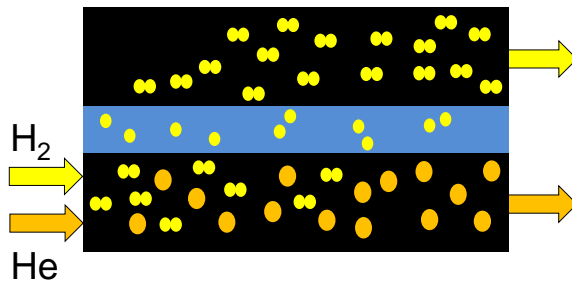
Developmental Engine Under Test

Space Launch System

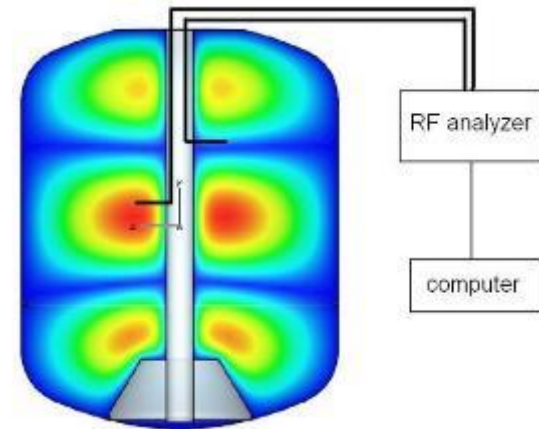


Control Issues

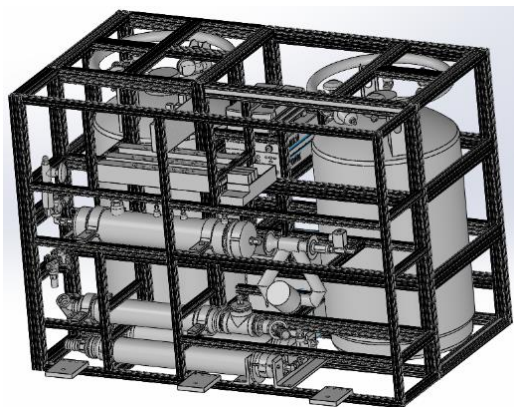
- Purity
- Level Sensing
- Cryogenic Transfer
- Cryogenic Stability



H₂ Purification and Recovery



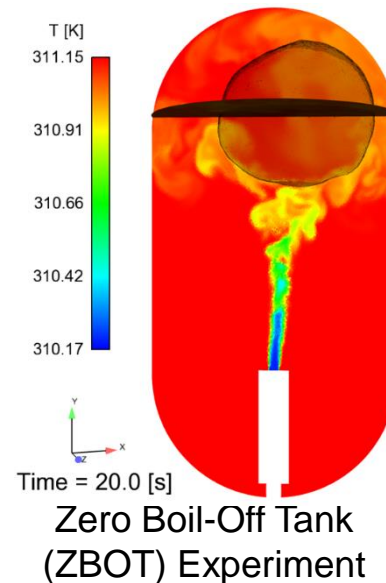
Radio Frequency Mass Gauge (RFMG)



Cryogenic Tank-to-Tank Transfer Experimental Set-up



CryoFILL Liquefaction and Storage



POWER to explore the

LUNAR SURFACE



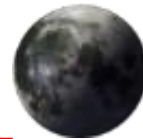
PS-02815-08

Multiple power technologies compose the Lunar Surface Power Architecture

- Solar photovoltaic systems generate power when illuminated
- Nuclear and radio isotope power systems provide constant power independent of sunlight
- Batteries meet energy storage needs for low energy applications
- Regenerative fuel cells provide high energy storage requirements especially where nuclear power may not be an option (e.g. in locations near humans)



Hydrogen: Power and Energy



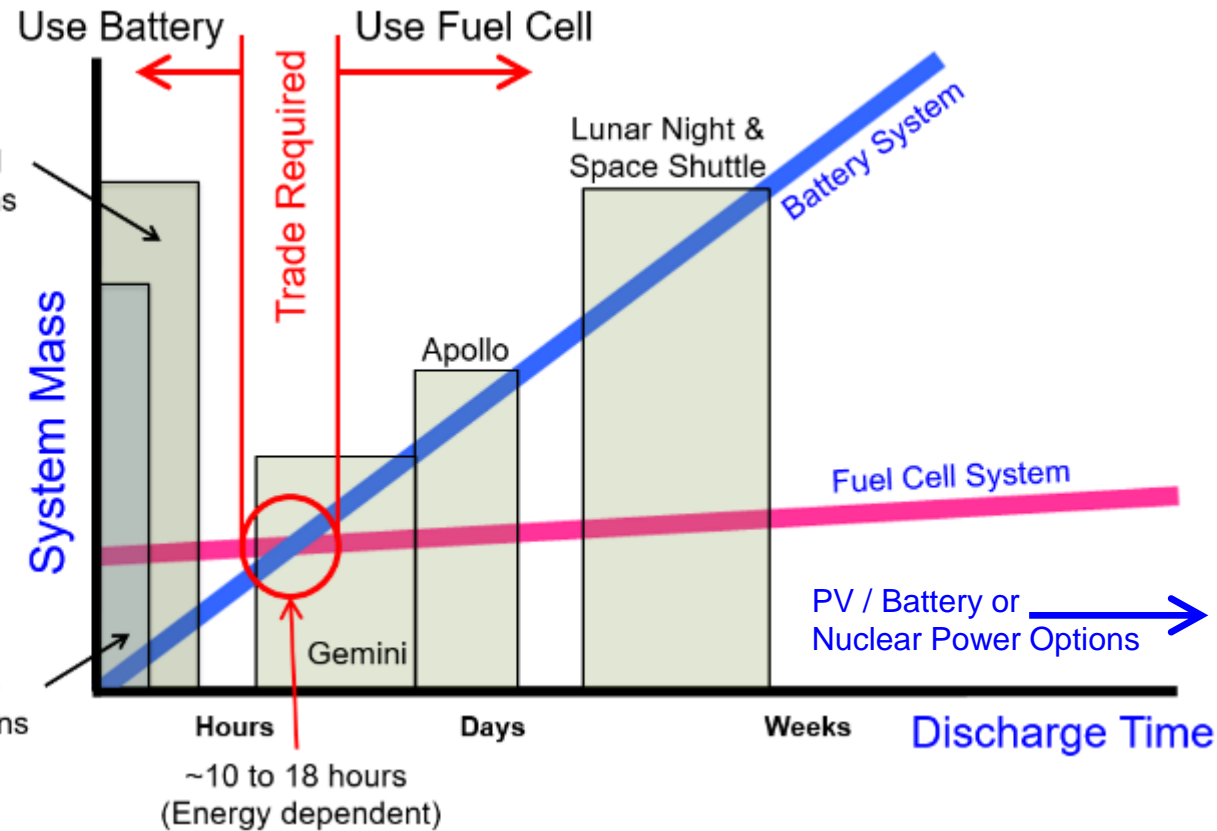
Venus Explorer



Rovers



Europa Lander



Landers



Crewed Lunar Habitats ¹¹

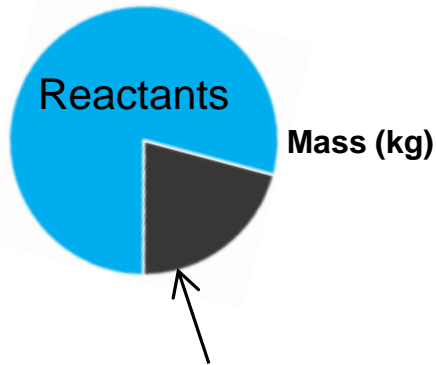


Energy Storage Comparison

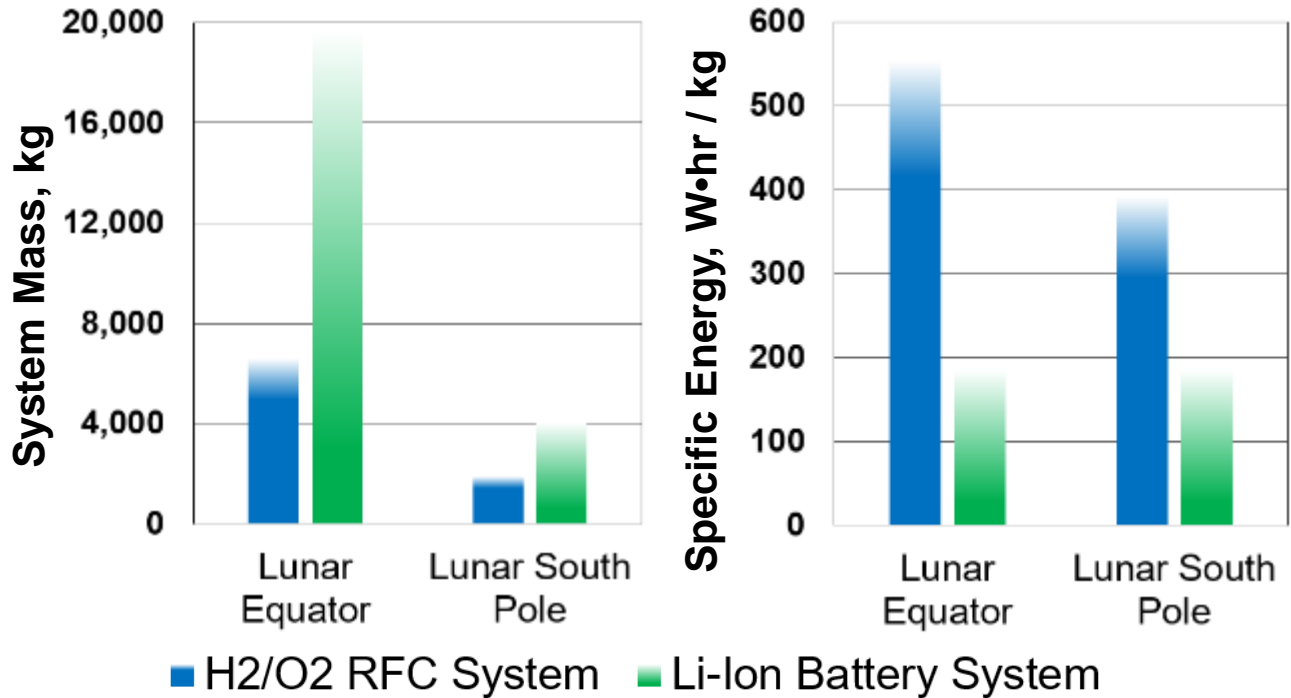
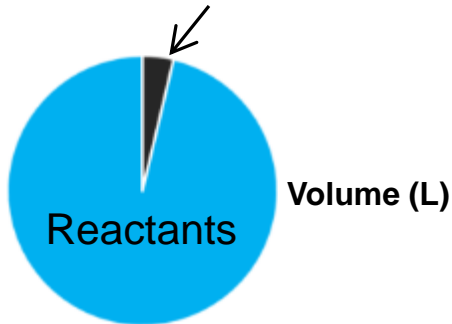


Comparing Energy Storage Options for a 10 kW Crewed Lunar Outpost Power System

H₂/O₂ Regenerative Fuel Cell System



All other elements: stacks, fluid/thermal systems, structure, etc.



Net Energy Storage by Site

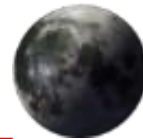
Lunar Equator = 3.64 MW•hr

Lunar South Pole = 0.75 MW•hr

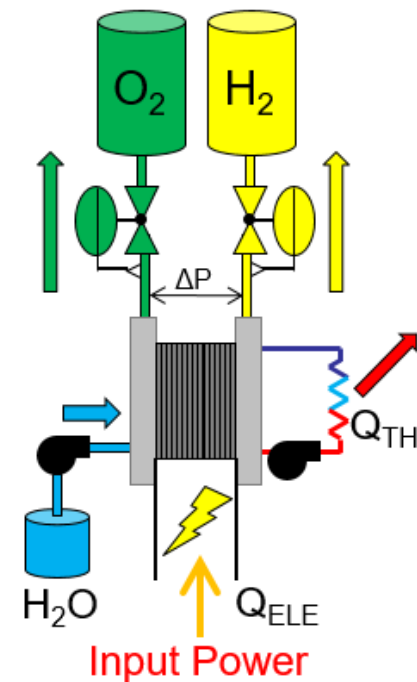
Battery specific energy independent of location.
RFC specific energy dependent on location-specific parameters.



Water Electrolysis



- Fundamental Process: $2\text{H}_2\text{O} + 4\text{e}^- \rightarrow 2\text{H}_2 + 2\text{O}_2$
 - Electrochemically dissociating water into hydrogen and oxygen
- Multiple pressure ranges
 - Low pressure (< 1.73 MPa (<250 psi)):
ISRU (Propellants) and Life Support (Outpost)
 - High pressure (12.4 to 20.7 MPa (1800 to 3000 psi)):
Energy storage and Life Support (EVA)
- Multiple Chemistry Options
 - Alkaline, Polymer Electrolyte Membrane (PEM), Solid Oxide
- Life Support:
 - Outpost: Process H_2O to generate breathing oxygen for crew
 - Extra Vehicular Activities (EVA): Stored oxygen for crew activities away from the Outpost or supporting vehicle(s)
- Energy Storage: Active chemistry in a regenerative fuel cell system
- ISRU: Process recovered H_2O to utilize H_2 and O_2



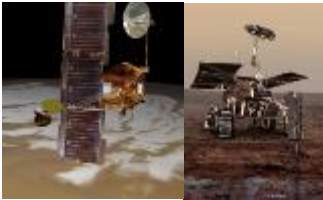


What is *In Situ* Resource Utilization (ISRU)?



ISRU involves any hardware or operation that harnesses and utilizes 'in-situ' resources to create products and services for robotic and human exploration

Resource Assessment (Prospecting)



Assessment and mapping of physical, mineral, chemical, and water resources, terrain, geology, and environment

Resource Acquisition



Excavation, drilling, atmosphere collection, and preparation/beneficiation before processing

Resource Processing/ Consumable Production



Extraction and processing of resources into products with immediate use or as feedstock for construction & manufacturing

- Propellants, life support gases, fuel cell reactants, etc.

In Situ Manufacturing



Production of replacement parts, complex products, machines, and integrated systems from feedstock derived from one or more processed resources

In Situ Construction



Civil engineering, infrastructure emplacement and structure construction using materials produced from *in situ* resources

- Radiation shields, landing pads, roads, berms, habitats, etc.

In Situ Energy



Generation and storage of electrical, thermal, and chemical energy with *in situ* derived materials

- Solar arrays, thermal storage and energy, chemical batteries, etc.

- **'ISRU' is a capability involving multiple elements to achieve final products** (mobility, product storage and delivery, power, crew and/or robotic maintenance, etc.)
- **'ISRU' does not exist on its own.** By definition it must connect and tie to users/customers of ISRU products and services



ISRU Integrated with Exploration Elements (Mission Consumables)



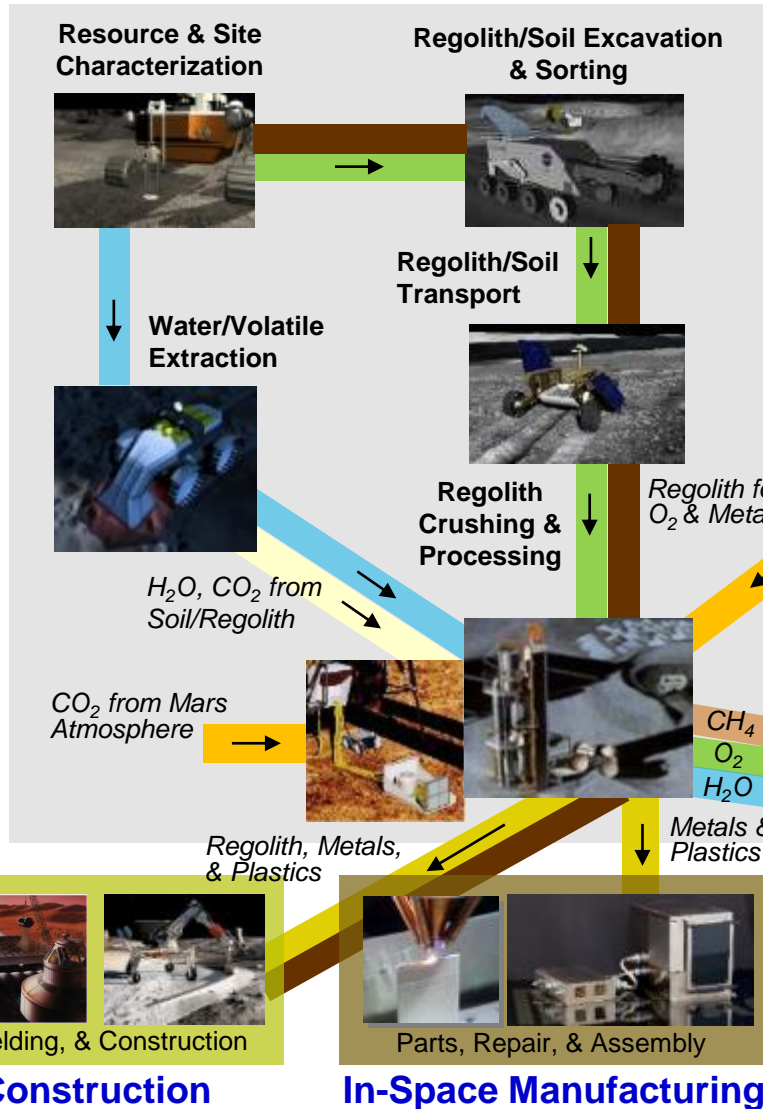
ISRU Functions & Elements

- Resource Prospecting/ Mapping
- Excavation
- Regolith Transport
- Regolith Processing for:
 - Water/Volatiles
 - Oxygen
 - Metals
- Atmosphere Collection
- Carbon Dioxide/Water Processing
- Manufacturing
- Civil Engineering & Construction

Support Functions & Elements

- Power Generation & Storage
- O₂, H₂, and CH₄ Storage and Transfer

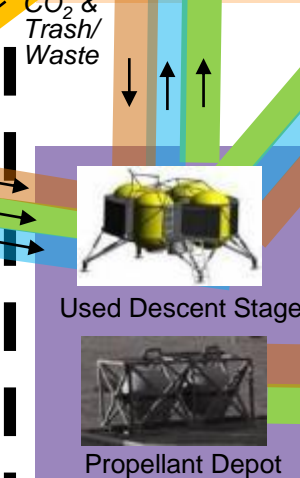
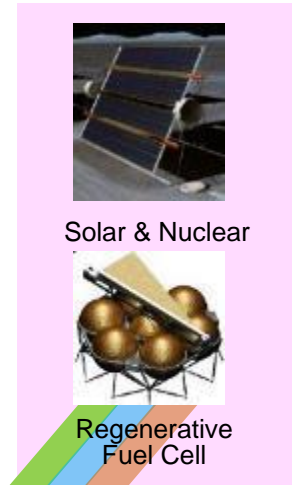
ISRU Resources & Processing



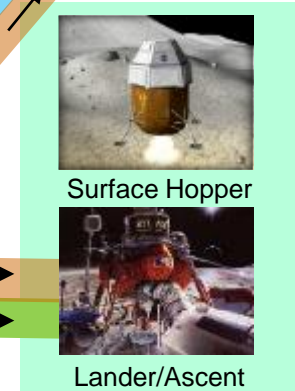
Life Support & EVA



Modular Power Systems



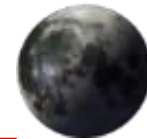
Storage



Lander/Ascent



Lunar Resources and Propellant Options



Propellant Options

Four major resources on the Moon:

Extracted

Processed

REGOLITH

Ilmenite - 15%

FeO•TiO₂ 98.5%

Olivine - 15%

2MgO•SiO₂ 56.6%

2FeO•SiO₂ 42.7%

Pyroxene - 50%

CaO•SiO₂ 36.7%

MgO•SiO₂ 29.2%

FeO•SiO₂ 17.6%

Al₂O₃•SiO₂ 9.6%

TiO₂•SiO₂ 6.9%

Anorthite - 20%

CaO•Al₂O₃•SiO₂ 97.7%



Oxidizer: **Oxygen (O₂)**

Fuel: Aluminum

Other: Silicon



SOLAR WIND VOLATILES (Apollo Data)

Hydrogen (H₂)

50 - 150 ppm

Helium (He)

3 - 50 ppm

Helium-3 (³He)

10⁻² ppm

Carbon (C)

100 - 150 ppm



Oxidizer:

Fuel: Hydrogen (H₂)

Other: Carbon



POLAR/NEA VOLATILES

Carbon Monoxide (CO)

5.7%

Hydrogen (H₂)

1.4%

Water/Ice (H₂O)

5.5%

M³ OH/H₂O

0.1 to 0.8% on surface

LAMP H₂O Frost

1 to 2% on surface

Mini SAR

Potential ice sheets



Oxidizer:

Fuel: **Hydrogen (H₂)**

Water

Carbon Monoxide



TRASH/WASTE

Plastic/packaging

Food/Plant/Bio Waste

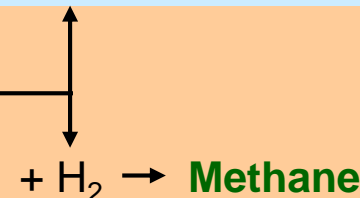
Carbon Structures



Fuel:

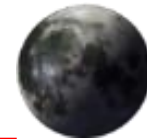
Hydrogen

Carbon/Carbon Dioxide





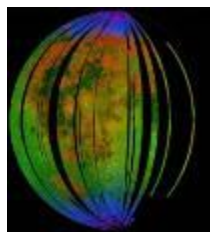
Global Assessment of Lunar Volatiles



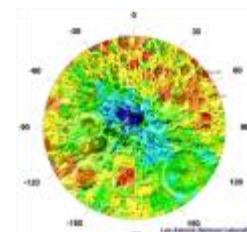
Apollo Samples



Moon Mineralogical Mapper (M³)



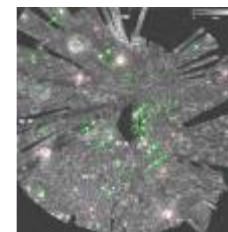
Lunar Prospector Lunar Recon Orbiter (LRO)



Lunar Crater Observation & Sensing Sat. (LCROSS)



Clementine Chandrayaan LRO Mini SAR/RF



	Solar Wind	Core Derived Water	Water/Hydroxyl	Polar Volatiles	Polar Ice
Instrument	Apollo samples Neutron Spectrometer	Apollo samples	M3/DIVINER	LCROSS	Mini SAR/RF
Concentration	Hydrogen (50 to 150 ppm) Carbon (100 to 150 ppm) Helium (3 to 50 ppm)	0.1 to 0.3 wt % water in Apatite 0 to 50 ppm water in volcanic glass	0.1 to 1% water; 1-2% frost in shadowed craters	3 to 10% Water equivalent Solar wind & cometary volatiles (CO, CO₂, H₂, NH₃, organics)	Ice layers
Location	Regolith everywhere	Regolith; Apatite	Upper latitudes	Poles	Poles; Permanent shadowed craters
Environment	Sunlit	Sunlit	Low sun angle Permanent shadow <100 K	Low or no sunlight; Temperatures sustained at <100 K	<100 K, no sunlight
Depth	Top several meters; Gardened	Top 10's of meters	Top mm's of regolith	Below 10 to 20 cm of desiccated layer	Top 2 meters



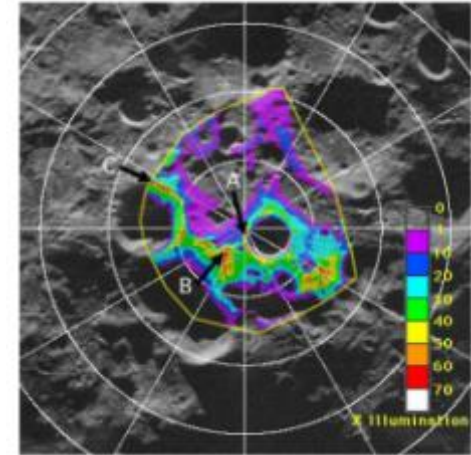
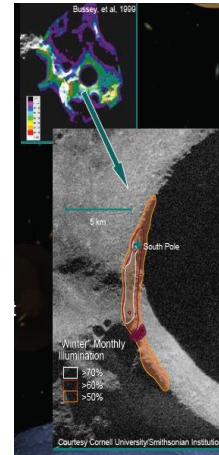
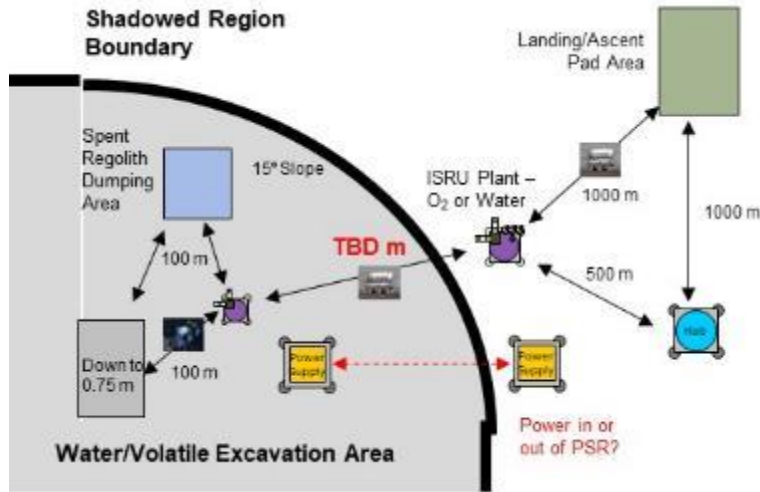


Lunar Locations and ISRU



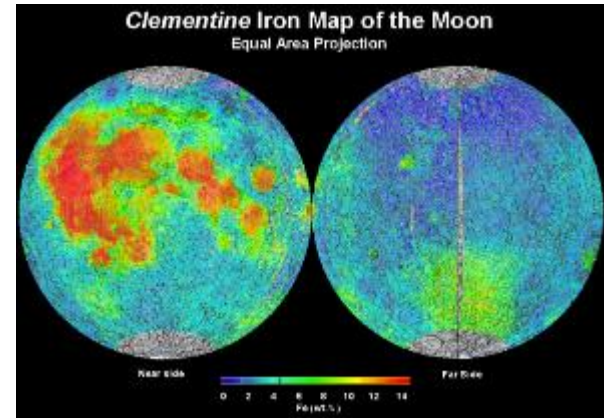
Polar Locations – *Optimal location for sustained surface operations*

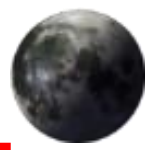
- Areas of near permanent sunlight (>70% sunlight per year)
 - Lower thermal extremes and greater use of solar power
 - Regolith based resources for oxygen and metals; Highland regolith (iron poor)
- Areas of permanent shadow
 - Cold locations for cryogenic storage, instruments, and thermal energy generation
 - Polar volatiles may include hydrogen, water, ammonia, carbon monoxide, and organics



Equatorial Locations

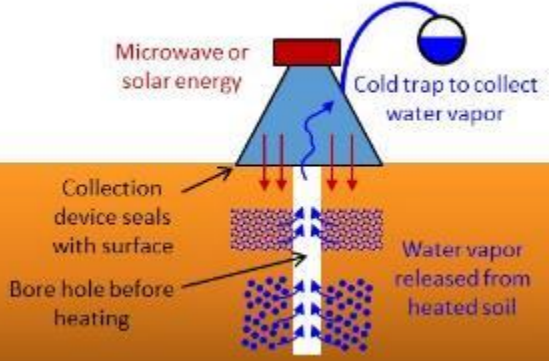
- Equal day/night durations (~14 days)
- Significant temperature swings from day to night
- Mare and highland material; more diverse mineral opportunities as a function of location
 - High and low Titanium mares (ilmenite and iron oxides)
 - Pyroclastic glasses (iron and water/hydrogen source)
 - KREEP (Potassium, Rare Earth Elements, Phosphorus)



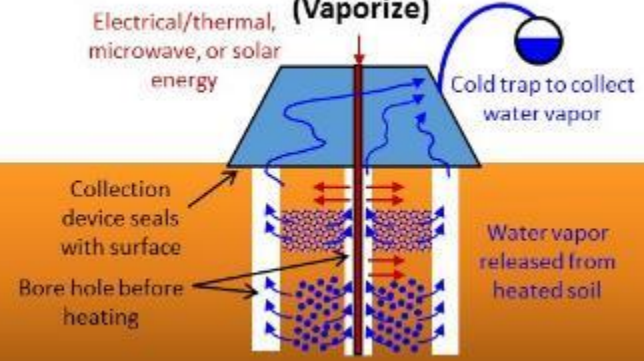


In Situ Water Extraction vs Excavation and Processing Trade Space

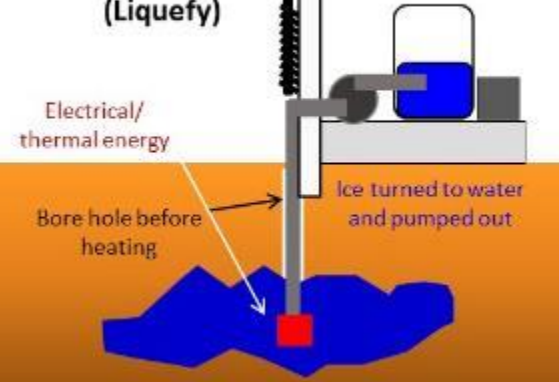
Beamed Energy



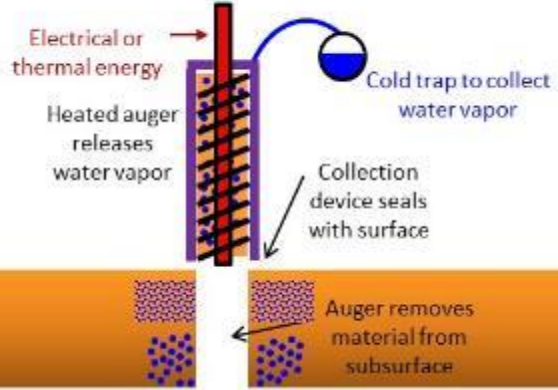
Down Hole Energy (Vaporize)



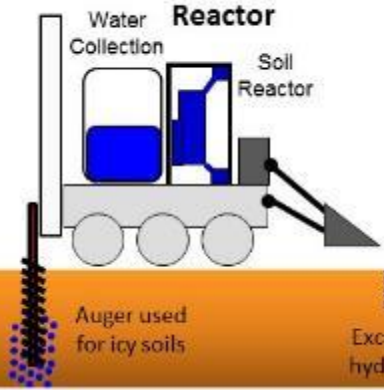
Down Hole Energy (Liquefy)



Combined Excavator/Reactor

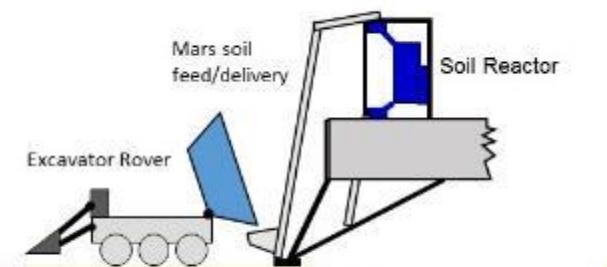


On Rover



Separate Excavator/Soil

Excavation & Delivery to Stationary Reactor



- = Water-coated or hydrated soils
- = Ice/soil mixtures; permafrost
- = Subsurface ice sheets

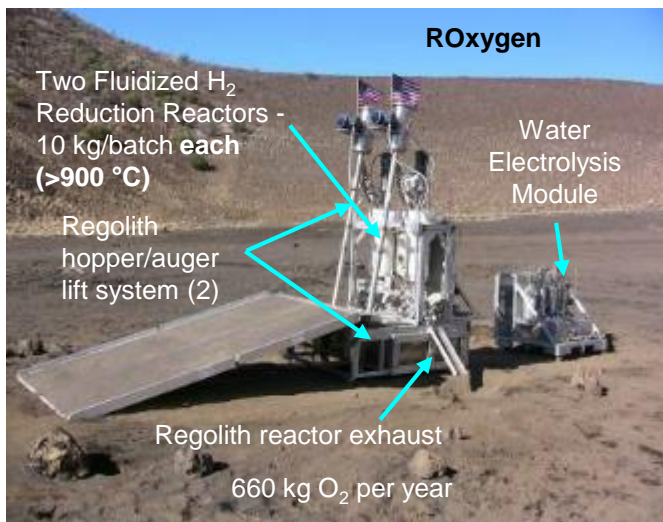


Lunar Processing – Oxygen & Metal Extraction

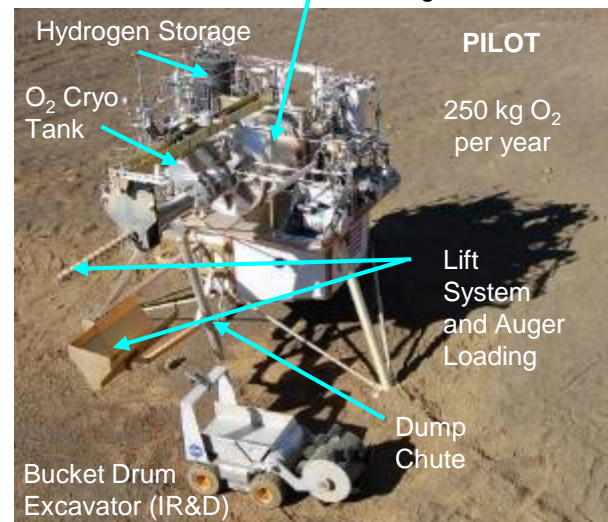


Hydrogen Reduction of Regolith

Rotating H₂ Reduction Reactor - 17 kg/batch



1. Heat Regolith to >900 C
2. React with Hydrogen to Make Water
3. Crack Water to Make O₂



Carbothermal Reduction of Regolith

125 to 250 kg O₂ per year

1. Melt Regolith to >1600 C
2. React with Methane to produce CO and H₂
3. Convert CO and H₂ to Methane & Water
4. Crack Water to Make O₂

Solar Concentrator & Fiber-optic Cables

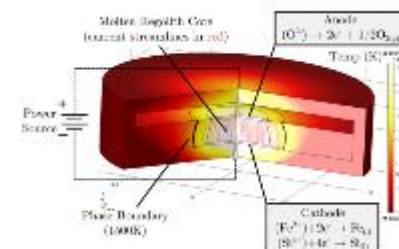
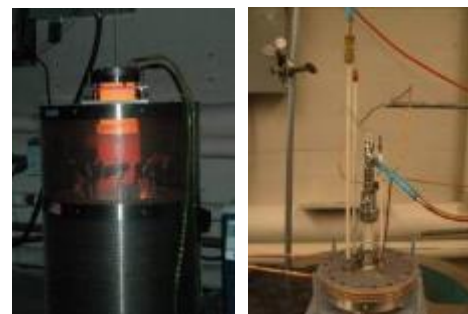
Regolith Reduction Chamber

Pneumatic Lift System and Auger Loading



Molten Electrolysis of Regolith

1. Melt Regolith to >1600 C
2. Apply Voltage to Electrodes To Release Oxygen



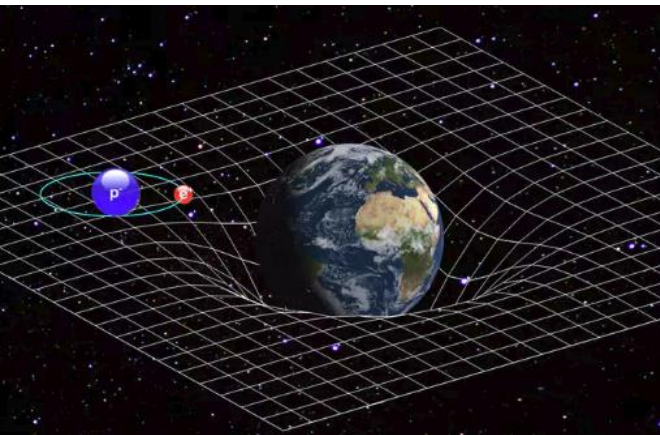


Leverage (Gear) Ratios using ISRU



Every 1 kg of propellant made on the Moon or Mars saves from 7.4 to 11.3 kg in LEO

Potential 334.5 mT launch mass saved in LEO
= 3 to 5 SLS launches avoided per Mars Ascent



- ① LEO
- ② Lunar Destination Orbit
- ③ Lunar Surface
- ④ Lunar Rendezvous Orbit
- ⑤ Earth Surface

A Kilogram of Mass
Delivered Here...

...Adds This Much
Initial Architecture
Mass in LEO

...Adds This
Much To the
Launch Pad
Mass

A Kilogram of Mass Delivered Here...	...Adds This Much Initial Architecture Mass in LEO	...Adds This Much To the Launch Pad Mass
Ground to LEO	-	20.4 kg
LEO to Lunar Orbit (#1→#2)	4.3 kg	87.7 kg
LEO to Lunar Surface (#1→#3, e.g., Descent Stage)	7.5 kg	153 kg
LEO to Lunar Orbit to Earth Surface (#1→#4→#5, e.g., Orion Crew Module)	9.0 kg	183.6 kg
Lunar Surface to Earth Surface (#3→#5, e.g., Lunar Sample)	12.0 kg	244.8 kg
LEO to Lunar Surface to Lunar Orbit (#1→#3→#4, e.g., Ascent Stage)	14.7 kg	300 kg
LEO to Lunar Surface to Earth Surface (#1→#3→#5, e.g., Crew)	19.4 kg	395.8 kg



Economics of ISRU for Space Applications (1)




A 'Useful' Resource Depends on the Location, What is needed, How much is needed, How often it is needed, and How difficult is it to extract the resource

▪ Location

- Resource must be assessable: slopes, rock distributions, surface characteristics, etc.
- Resource must be within reasonable distance of mining infrastructure: power, logistics, maintenance, processing, storage, etc.

▪ Resource extraction must be 'Economical'

- **Concentration and distribution of resource and infrastructure needed to extract and process the resource must allow for Return on Investment (ROI) for:**

- 
- **Mass ROI** - mass of equipment and unique infrastructure compared to bringing product and support equipment from Earth. Impacts number and size of launch vehicles from Earth
 - 1 kg delivered to the Moon or Mars surface = 7.5 to 11 kg launched into Low Earth Orbit
 - **Cost ROI** - cost of development and certification of equipment and unique infrastructure compared to elimination of launch costs or reuse of assets (ex. reusable vs single use landers)
 - **Time ROI** - time required to notice impact of using resource: extra exploration or science hardware, extended operations, newly enabled capabilities, etc.
 - **Mission/Crew Safety ROI** - increased safety of product compared to limitations of delivering product from Earth: launch mass limits, time gap between need and delivery, etc.

- **Amount of product needed must justify investment in extraction and processing**

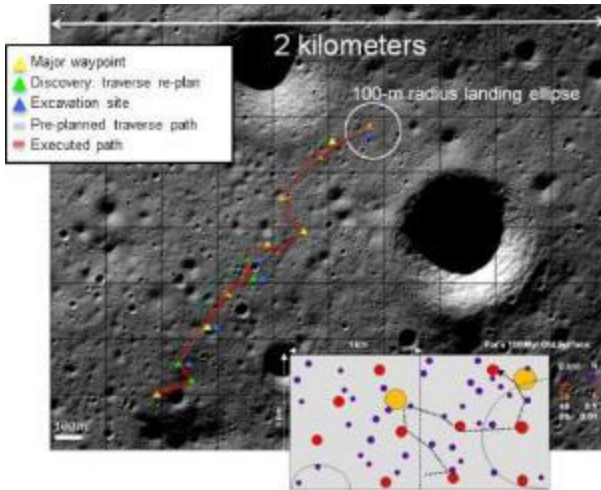
- Requires long-term view of exploration and commercialization strategy to maximize benefits
- Metric: mass/year product vs mass of Infrastructure

- **Transportation of product to 'Market' (location of use) must be considered**

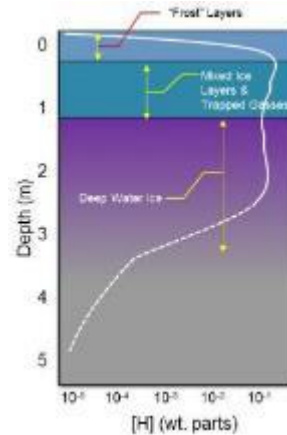
- Use of product at extraction location most economical

Need to assess the extent of the resource 'ore body'

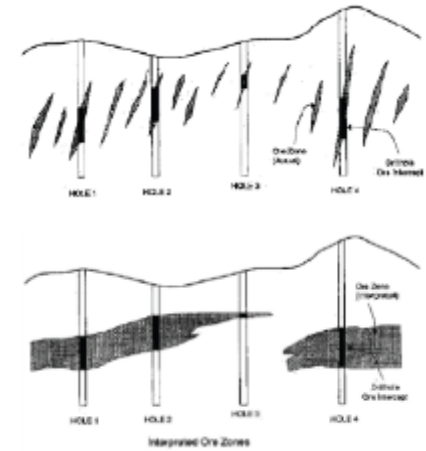
Need to Evaluate Local Region (1 to 5 km)



Need to Determine Vertical Profile



Need to Determine Distribution



Need to assess What is needed, How much is needed, How often it is needed

Resource Product Needs

Location	Product	Amount (kg)	Need/Time	Use
Moon	O ₂	1000	Per Year	Crew Breathing - Life Support Consumable
	O ₂	3000 - 3500	2x Per Year	Non-Reusable Crew Ascent Vehicle Propulsion - Surface to Low Lunar Orbit: Earth fuel
	O ₂	~16000	2x Per Year	Reusable Ascent/Descent Propulsion - Surface to L ₁ /L ₂ : Earth Fuel (4000 kg payload)
	O ₂ /H ₂	~30,000	2x Per Year	Reusable Ascent/Descent Propulsion - Surface to L ₁ /L ₂ (4000 kg payload)
	H ₂ O	150,000	2x Per Year	Lunar Human Outpost & Reusable Transportation
	O ₂ /H ₂	150,000	Per Year	Amount needed for Propellant Delivery to LDRO for Human Mars Mission
Mars	O ₂ /CH ₄	22,728/6978	Per Use/1x 480 Days	Non-Reusable Crew Ascent Vehicle Propulsion - Surface to High Mars Orbit
	O ₂ /CH ₄	59,000/17,100	Per Use/1 or 2x Per Yr	Reusable Ascent/Descent Propulsion - Surface to Mars Orbit
	H ₂ O	3,075	Surface/500 Days	Life Support System Closure
	H ₂ O	15,700	Per Use/1x 480 Days	Extracted H ₂ O to Make Non-Reusable Ascent Vehicle Propellant
	H ₂ O	38,300	Per Use/1 or 2x Per Yr	Extracted H ₂ O to Make Reusable Ascent/Descent Vehicle Propellant

□ = Initial Requirement □ = Horizon Goal



Space Commercialization & Mining

Promote Terrestrial Involvement in Space & ISRU: Spin In-Spin Out



Private Industry

Resource Prospecting



Deep Space Industries

Planetary Resources

US Government Interest & Legislation

US Space Law & Directives

H. R. 2262—18

"CHAPTER 513—SPACE RESOURCE COMMERCIAL EXPLORATION AND UTILIZATION

"§ 51303. Asteroid resource and space resource rights

"A United States citizen engaged in commercial recovery of an asteroid resource or a space resource under this chapter shall be entitled to any asteroid resource or space resource obtained, including to possess, own, transport, use, and sell the asteroid

US Commercial Space Launch Competitiveness Act

Public Law 114-90
114th Congress

An Act

Nov. 25, 2015
(H. R. 2262)

To facilitate a pro-growth environment for the developing commercial space industry by encouraging private sector investment and creating more stable and predictable regulatory conditions, and for other purposes.

Space Directive 1

58501

Presidential Documents

Space Policy Directive-1 of December 11, 2017

Reinvigorating America's Human Space Exploration Program

Commercial Cargo & Crew



ATK
Cygnus

SpaceX

SpaceX
Dragon2

Boeing
CST-100

SNC Dream Chaser

NASA NextSTEP Broad Agency Announcements

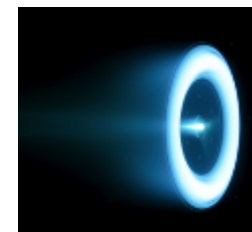
Crew habitats



FabLab



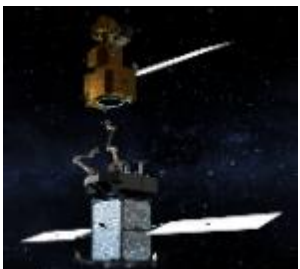
Power & Propulsion Studies



ISRU

ULA Cislunar 1000 Vision

Satellite Servicing



Use lunar derived propellants

Commercial Lunar Payload Services (CLPS) & NASA Payloads





Presentation Overview



- NASA
- Logistics of Space Exploration
- Hydrogen Applications in Space
 - Propulsion
 - Power and Energy
 - Material Processing
- *In situ* Resource Utilization (ISRU)
 - Lunar Resources
 - Excavation Processes
- Economics of a Lunar Hydrogen Economy
- Discussion



Acknowledgements



NASA has many development activities supported by a number of high quality people across the country. This list is not exhaustive and only includes the most significant contributors to the development of this presentation.

Headquarters

- *Gerald (Jerry) Sanders, Lead for In-Situ Resource Utilization (ISRU) System Capability Leadership Team*
- *Lee Mason, Space Technology Mission Directorate, Deputy Chief Engineer*

Jet Propulsion Laboratory

- *Erik Brandon, Ph.D, Electrochemical Technologies*
- *Ratnakumar Bugga, Ph.D, Electrochemical Technologies*

Marshall Space Flight Center

- *Kevin Takada, Environmental Control Systems*

Kennedy Space Center

- *Erik Dirschka, PE, Propellant Management*

Glenn Research Center

- *Dianne Linne, ISRU Project Manager*
- *William R. Bennett, Photovoltaic and Electrochemical Systems*
- *Ryan Gilligan, Cryogenic and Fluid Systems*
- *Wesley L. Johnson, Cryogenic and Fluid Systems*
- *Phillip J. Smith, Photovoltaic and Electrochemical Systems*
- *Shay Ellafrits, Photovoltaic and Electrochemical Systems*



Thank you for your attention

