National Aeronautics and Space Administration

In Situ Resource Utilization (ISRU) Overview 2023

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In-Situ Resource Utilization

The Moon

- Oxygen – Lunar regolith is ~45% oxygen
- Water Ice- Located at the poles
- Metals – Iron, Aluminum, Titanium, Magnesium
- Metalloids – Silicon
- Regolith – Can be used as a construction material
- Solar Wind Volatiles – Helium 3 can be used for nuclear fusion
- Abundant solar energy

Mars

- Oxygen – Can be extracted from CO_2 atmosphere
- Water in Regolith – Anywhere on the surface
- Water Ice – Under the surface in some locations
- Metals – Iron, Aluminum, Titanium, Magnesium
- Metalloids - Silicon
- Regolith – Can be used as a construction material

Image Credit: NASA

Water on the Moon

- 1994 : Clementine indicated the presence of water ice at the poles based on the response of radar interactions with the surface
- 1998: Lunar Prospector detected hydrogen using a neutron spectrometer and estimated the content of water ice to be 300 million metric tons
- 2008: Chandrayaan-1 puts the estimate at 600 million metric tons (240,000 Olympic swimming pools)
- 2009: LRO/LCROSS provided definitive proof of water ice in Cabeus crater

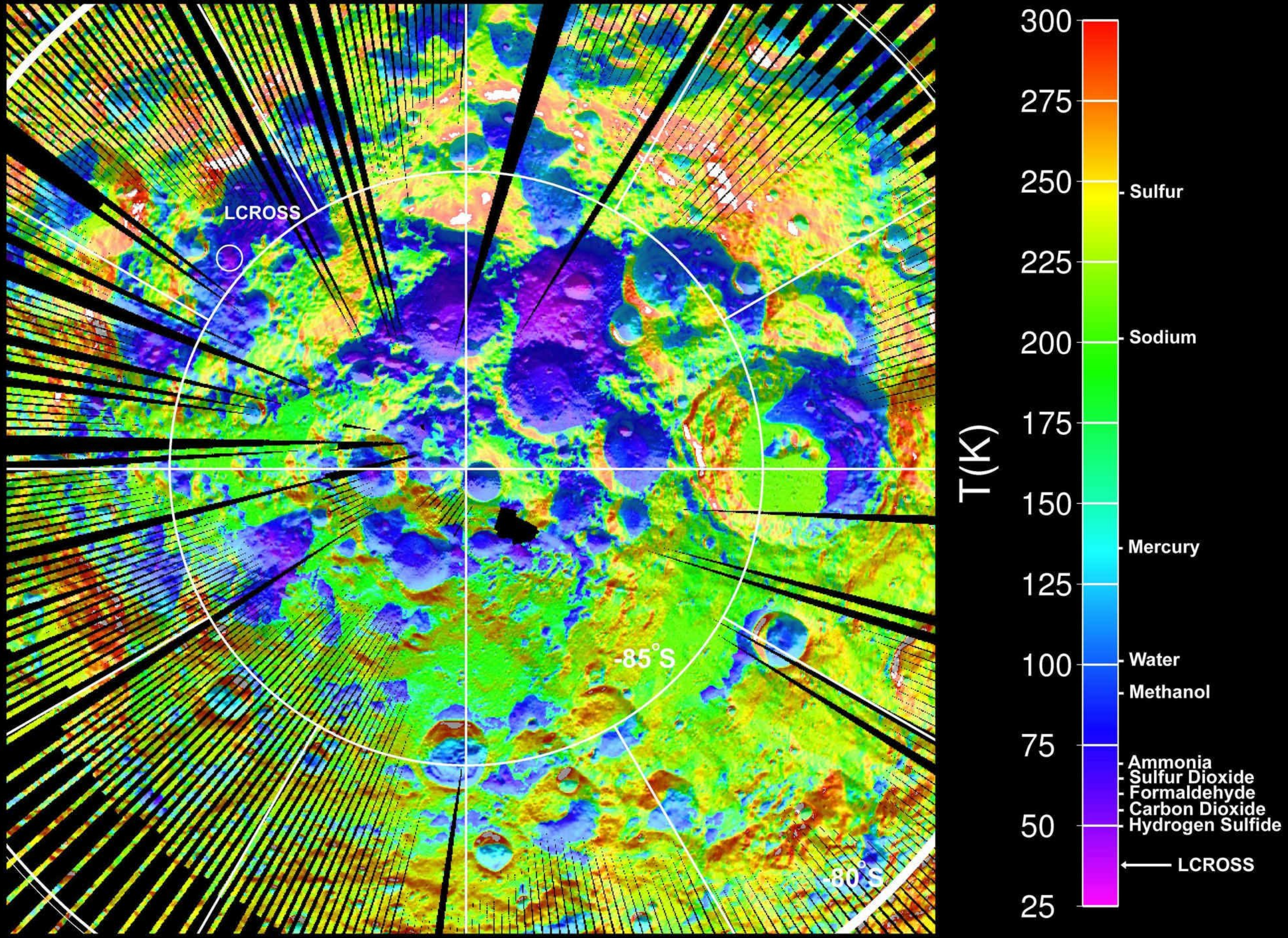


Image Credit: UCLA/NASA/JPL/GSFC

LRO/LCROSS

- **Lunar Reconnaissance Orbiter (LRO)**
  - Launched June 18, 2009
  - Still active
- **Lunar Crater Observation and Sensing Satellite (LCROSS)**
  - Launched June 18, 2009
  - Centaur crashed into the surface of Cabeus crater at 11:31 UT October 9th, 2009
  - LCROSS crashed into the surface 4 minutes later after analyzing the impact plume
  - LRO analyzed plume from orbit

Table 1. Summary of the total water vapor and ice and ejecta dust in the NIR instrument FOV. Values shown are the average value across the averaging period, and errors are 1 SD.

	Water mass (kg)			
Time (s)	Gas	Ice	Dust mass (kg)	Total water %
0–23	82.4 ± 25	58.5 ± 8.2	3148 ± 787	4.5 ± 1.4
23–30	24.5 ± 8.1	131 ± 8.3	2434 ± 609	6.4 ± 1.7
123–180	52.5 ± 2.6	15.8 ± 2.2	942.5 ± 236	7.2 ± 1.9
Average	53 ± 15	68 ± 10	2175 ± 544	5.6 ± 2.9

Colaprete, A., Schultz, P., Heldmann, J., Wooden, D., Shirley, M., Ennico, K., ... & Sollitt, L. (2010). Detection of water in the LCROSS ejecta plume. *science*, *330*(6003), 463-468.

Actual presentation will play the video from the link below

https://www.youtube.com/watch?v=l2CfQV0UCAk

Video Credit: NASA/GSFC

Water on the Moon

- Water electrolysis can be used to convert water into hydrogen and oxygen using an electric current from a solar panel or other source of power

$$2H_20 \longrightarrow 2H_2 + O_2$$

- Oxygen gas can be used for breathing
- Oxygen and hydrogen gas can be used to run a fuel cell
- Liquid hydrogen and liquid oxygen can be used as rocket propellant
- Saturn V , Space Shuttle , and SLS all use LOX/LH2 propellant

Image Credit: NASA

Actual Presentation will play Bill Nelson Video (uploaded separately to STRIVES)

Video Credit: NBC Nightly News

Water on the Moon – PRIME 1

- **As of now, the LCROSS impact data is the single data point we have on the relative concentration of water ice anywhere on the moon**
- **The Polar Resources Ice Mining Experiment – 1 (PRIME-1) is scheduled to launch in November 2023**

Image Credit: Intuative Machines

Actual presentation will play the video from the link below

https://www.youtube.com/watch?v=w7f5Jm7uxaY

Video Credit: NASA/KSC

Water on the Moon – VIPER

The Volatiles Investigating Polar Exploration Rover (VIPER) is scheduled for a launch in late 2024

Image Credit: NASA/Daniel Rutter

Actual presentation will play the video from the link below

https://www.youtube.com/watch?v=pvf1Csn1wRU

Video Credit: NASA/ARC

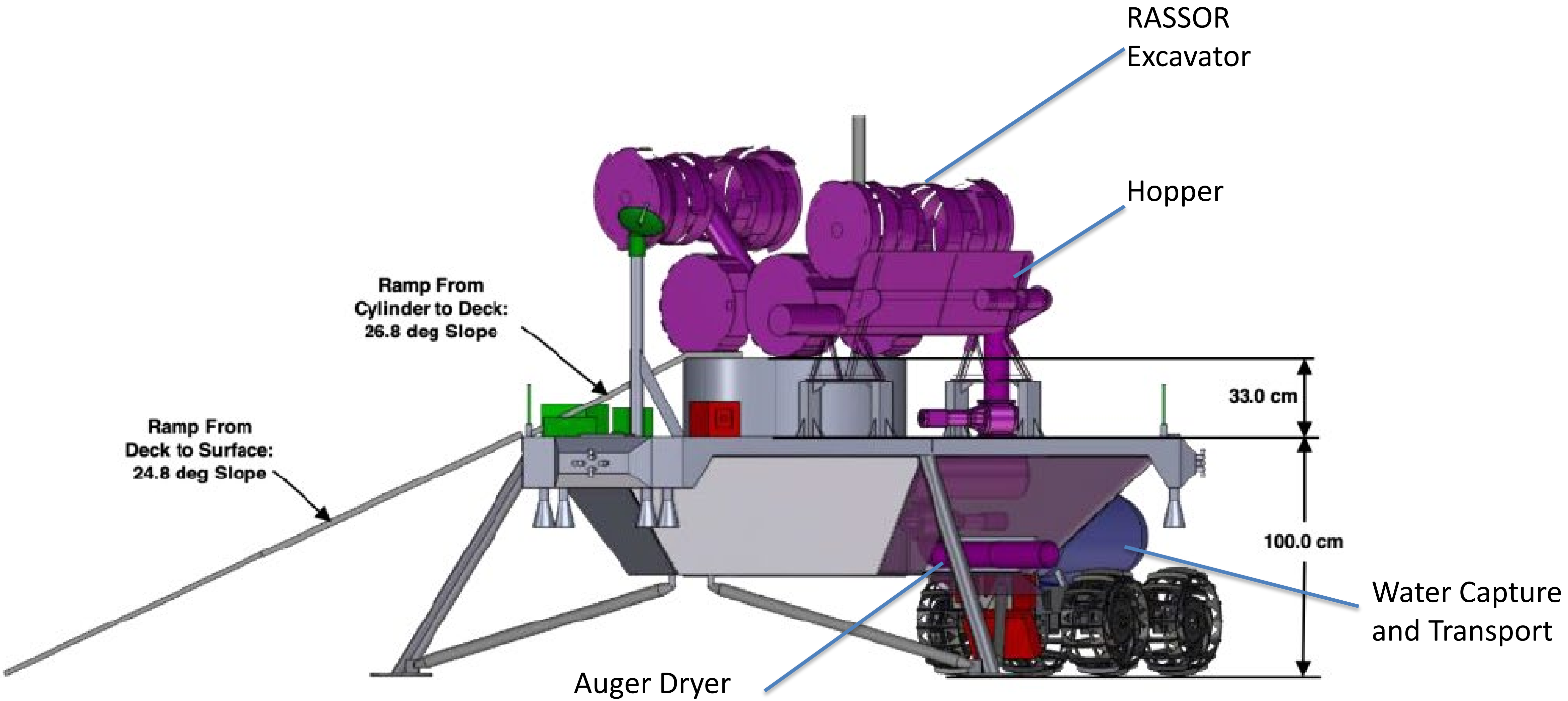
Water on the Moon – Light WAVE

- **Both PRIME-1 and VIPER will not capture water. Instruments will observe water vapor and other volatiles as they sublime and are released to the vacuum of space.**
- **The Light Water Analysis and Volatiles Extraction (Light WAVE) subsystem is designed to quantify and capture water ice extracted from the lunar surface.**

Image Credit: NASA/Daniel Rutter

Actual Presentation will play OVEN video (uploaded separately to STRIVES)

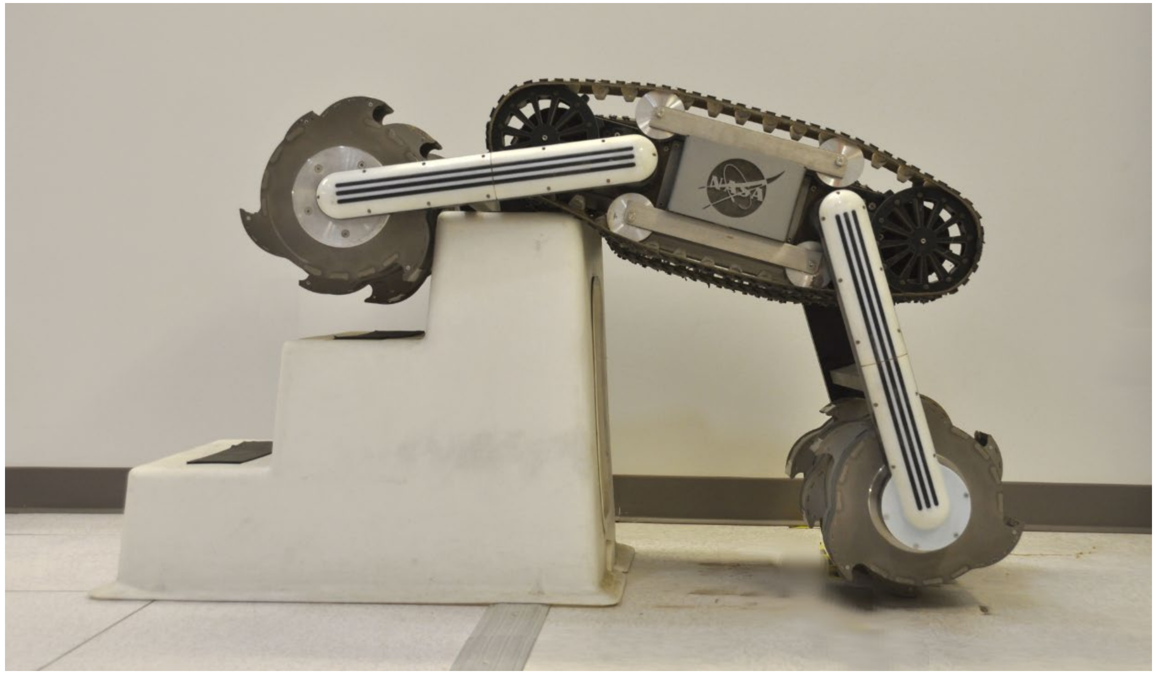
Lunar Ice Mining



[Linne, D. L., Kleinhenz, J. E., & Paz, A. (2020). Lunar water pilot plant conceptual design. In *ASCEND 2020* (p. 4236).]

Lunar Ice Mining - Excavation

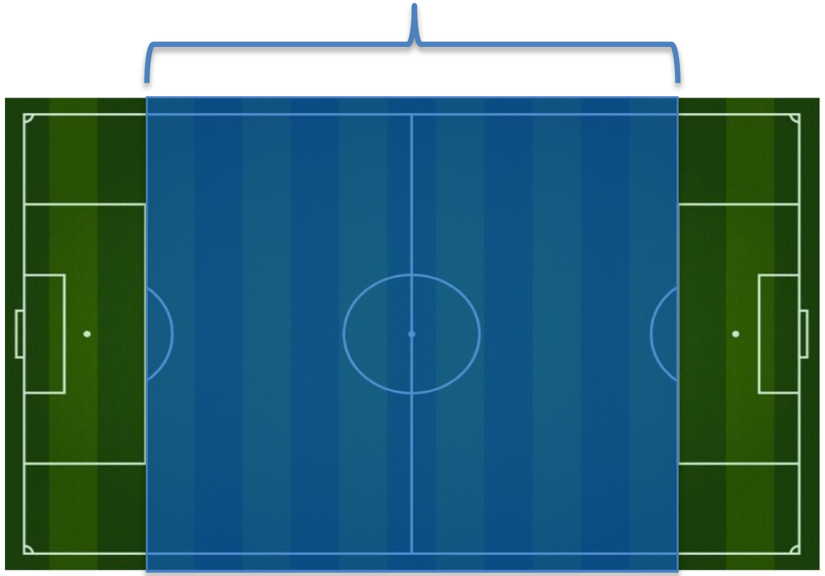
- 10 Tonnes (1000kg) of oxygen per year is considered a full-scale production rate until more information becomes available on lunar landers
- 10 Tonnes of oxygen per year requires 15 Tonnes of water
- Assuming 5% water ice, with a density of 1.25 g/cc and an excavation depth of 5 cm, it would take ~67% of the area of a football pitch to produce 15 Tonnes of water



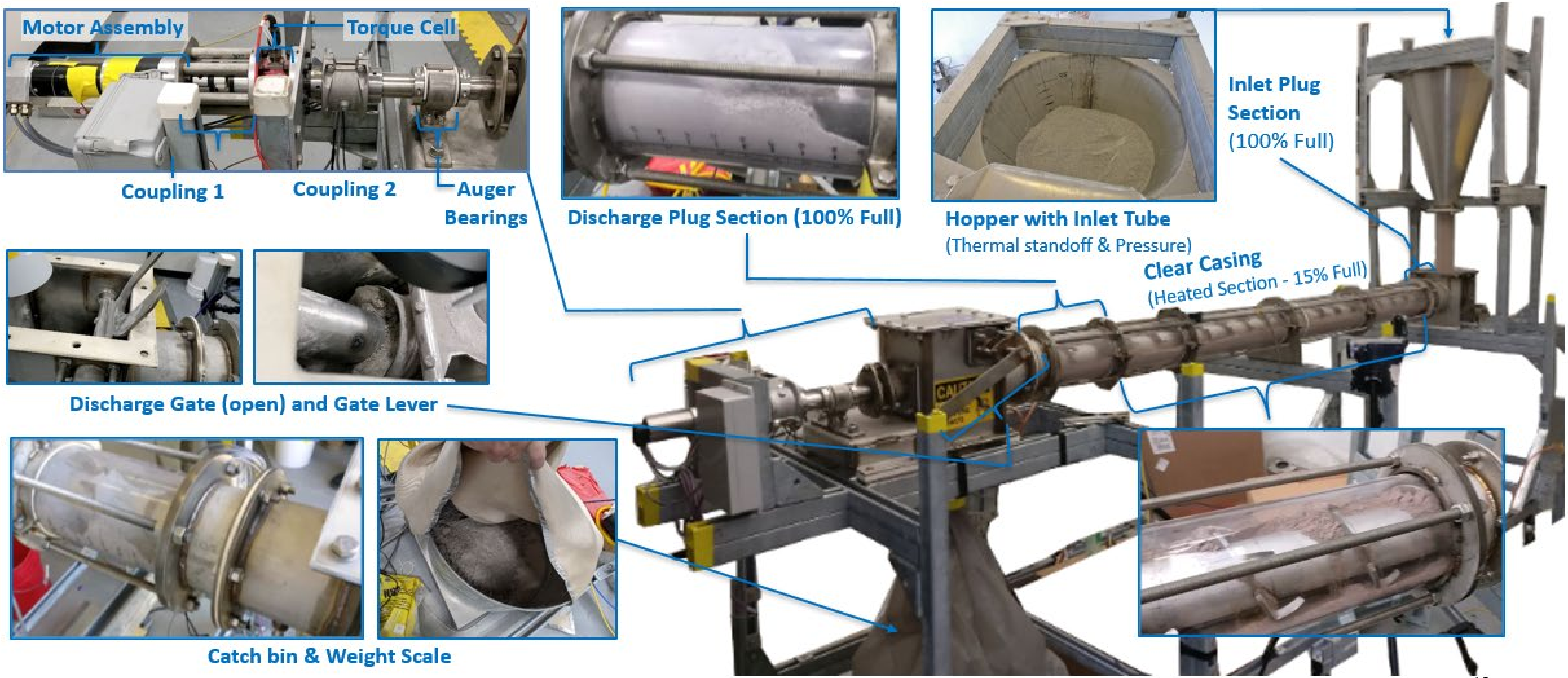
Regolith Advanced Surface Systems Operations Robot (RASSOR)

Image Credit: NASA/KSC

5% and 5cm deep



Lunar Ice Mining – Water Extraction



Water Purification and Deionization

Conductivity (microsiemens/cm^2)	Resistivity (Mega Ohm/cm^2)
0.056	18
0.063	16
0.071	14
0.083	12
0.100	10
0.133	7.5
0.200	5
0.500	2
1.000	1
1.333	0.75
2.000	0.5
4.000	0.25
10.000	0.1
20.000	0.05
40.000	0.25
100.000	0.01
200.000	0.005
500.000	0.002
1000.000	0.001
2000.000	0.0005
5000.000	0.0002
10000.000	0.0001

Typical PEM electrolyzer feedwater requirements (deionized water)

EDI performance (0.84 at inlet, 13.25 at outlet)

Distilled water

Water mixed with LHT simulant, distilled and filtered to <0.5 microns

Tap water

Water from IHOP (WIPE 1.0) [2]

Mixed volatile stream (CO, H_2, H_2S, NH_3, SO_2, CH_3OH, CH_4, CO_2) after freeze distillation (ICICLE) [1]

Acronyms:
EDI: Electrodeionization
IHOP: ISRU water purification and Hydrogen/Oxygen Production
ICICLE: ISRU Collector of Ice in a Cold Environment
LHS: Lunar Highlands Simulant
PEM: Proton Exchange Membrane
WIPE: Water, ISRU-derived, Purification Equipment

References:
[1] Holquist, J., Gellenbeck, S., Bower, C., & Tewes, P. (2021, July). Experimental Proof of Concept of a Cold Trap as a Purification Step for Lunar Water Processing. 50th International Conference on Environmental Systems.
[2] Holquist, J., Gellenbeck, S., Connor, J., Rivera, R., Bower, C., & Tewes, P. (2022, July). Demonstration of Paragon's Water Purification Assembly for Lunar Water Processing. 51st International Conference on Environmental Systems.

Water Electrolysis

Proton Exchange Membrane

Pros

- Flight heritage (ISS)
- Efficient gas compression
- High operating pressures
- Relatively low operating temperature

Cons

- Liquid water must be kept above 0º C during lunar night
- Feedwater must be deionized
- Radiator is required to reject waste heat
- Oxygen dryer is required

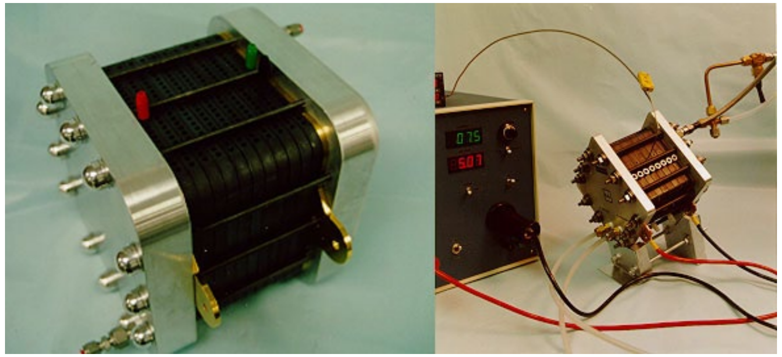


Image Credit: NASA/SBIR

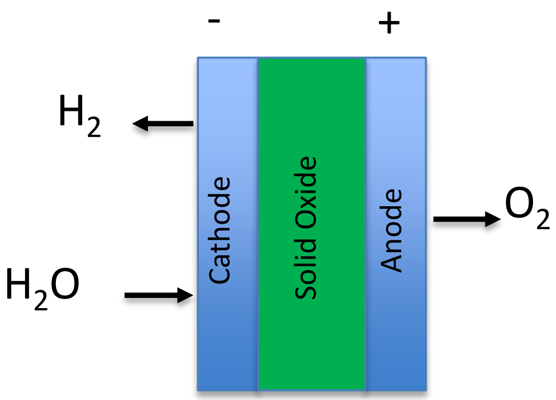
Solid Oxide

Pros

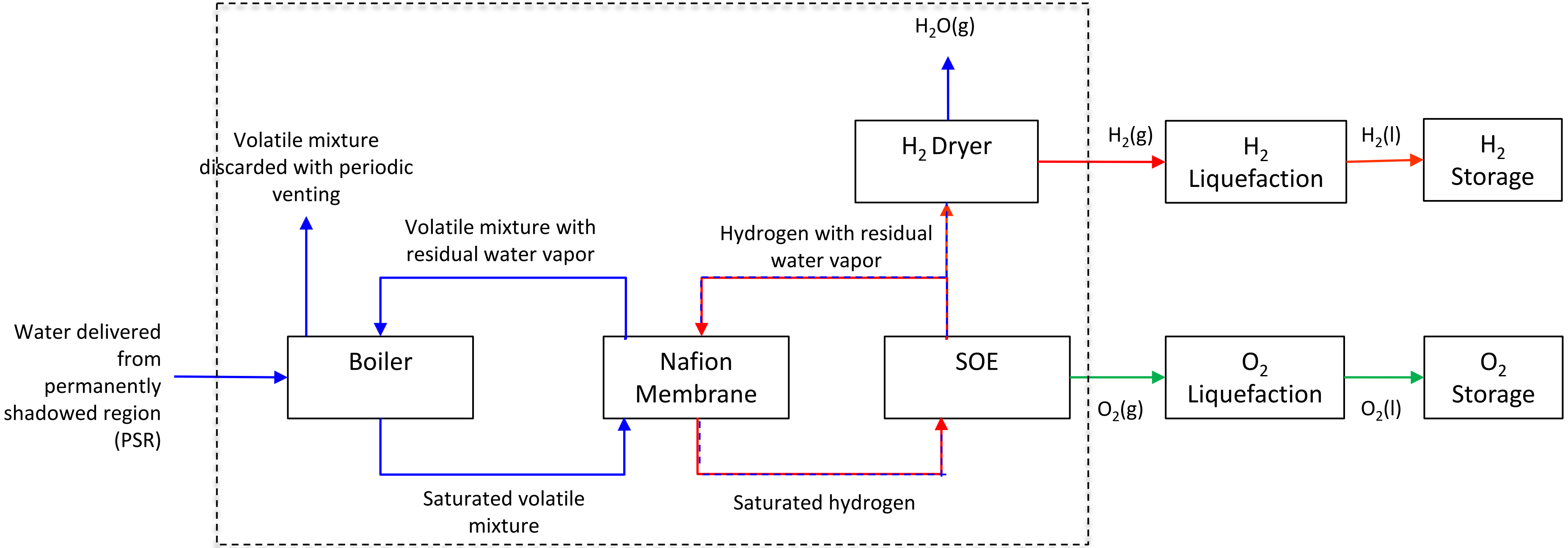
- Does not require deionized feedwater
- Oxygen is dry and pure
- Flight heritage (MOXIE)
- Should be able to survive lunar night with minimal power
- Waste heat can be used to keep stack at operating temperature

Cons

- Low operating pressure (< 30 psia)
- High operating temperature (~800 º C)
- Output gases are hot and may require more liquefaction power
- Water will need to be vaporized twice, once for extraction and again for electrolysis



Propellant from Lunar Water Concept



Subsystems identified for laboratory demonstration in 2024

Simplified flow diagram for a lunar propellant production plant that uses no consumables

Hydrogen Liquefaction

HYDROGEN LIQUEFACTION		
Oxygen Mass	10	tonnes
LOX/Fuel Ratio	6	
H2 Mass Required	**1.67**	tonnes
Mass of 20W/20K crycooler	106.3	kg
Fuel Liquefaction Thermal Lift Required	**429**	W
Number of Cryocoolers Required	**22**	
Mass of Cryocoolers & Radiators	**2.34**	tonnes
Return on Landed Mass in 1 year	**0.71**	

One of the biggest challenges with using water to make propellant is hydrogen liquefaction. Using the current state-of-the-art liquefaction technology, it would take 2.34 Tonnes worth of liquefaction hardware to produce 1.67 Tonnes worth of liquid hydrogen per year.

Nugent, B. T., Grotenrath, R. J., & Johnson, W. L. (2022). 20 Watt 20 Kelvin Reverse Turbo-Brayton Cycle Cryocooler Testing and Applications.

Oxygen from Regolith – Chemical Composition

Image Credit: NASA

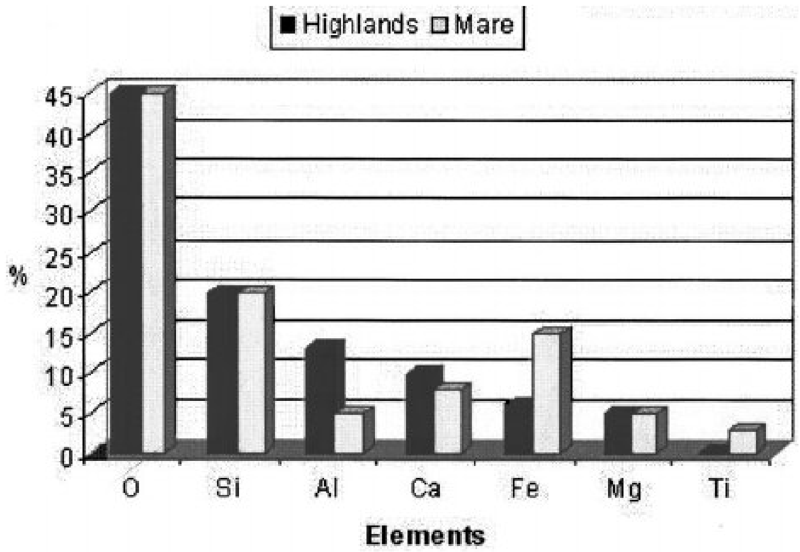
The darker areas of the Moon are called Mare

The lighter areas of the Moon are called Highlands

Sample	SiO_2	Al_2O_3	TiO_2	FeO	MgO	CaO	Na_2O	K_2O	MnO
Lunar: 10019	41.1	13.7	8.25	15.7	7.86	11.9	0.93	0.14	0.22
Lunar: 10022	43	13	7	16	8	12	0.54	0.12	0.23
Lunar: 70161	40.34	11.6	8.99	17.01	9.79	10.98	0.32	0.08	0.23
Lunar: 64501	53.63	12.77	3.47	13.37	3.57	9.2	0.73	1	0.2
Lunar: 14053	48	12	1.5	16	8.4	12	0.38	0.14	0.29

Examples of Lunar Regolith Chemical Composition

Loftus, D. J., Tranfield, E. M., Rask, J. C., & McCrosssin, C. (2008). The chemical reactivity of lunar dust relevant to human exploration of the Moon.



Ruess, F., Schaenzlin, J., & Benaroya, H. (2006). Structural design of a lunar habitat. *Journal of Aerospace Engineering*, *19*(3), 133-157.

Oxygen from Regolith – Hydrogen Reduction

$$FeO + H_2 \longrightarrow Fe + H_2O$$

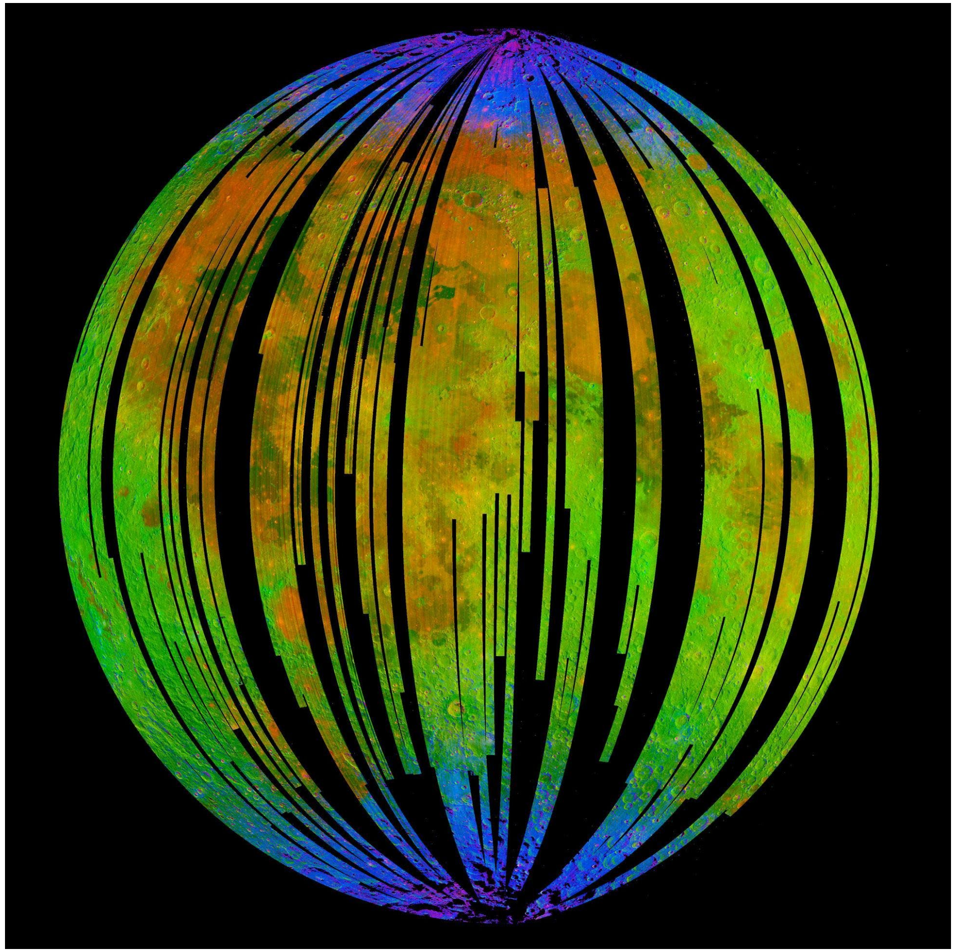


Image Credit: ISRO/NASA/JPL-Caltech/Brown Univ./USGS

Oxygen from Regolith : Solar-Carbothermal Reduction

Excavator
Canadian Space Agency

Tephra

Carbothermal Reactor
Orbitec (Now Sierra Space)

Heat

Solar Concentrator
Physical Sciences Inc.

$$Si0 + C\,H_4 \longrightarrow Si + CO + 2H_2$$

$$CO + 4H_2 \longrightarrow CH_4 + H_2O$$

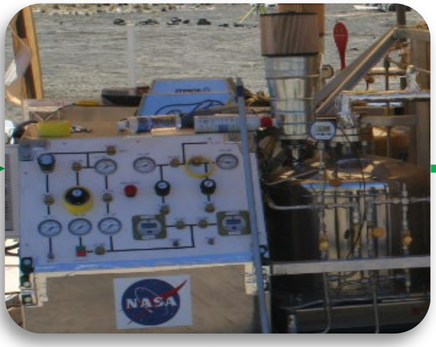
$$2H_2O \longrightarrow 2H_2 + O_2$$

H_2O

Heat

Water Electrolysis
Johnson Space Center

O_2



Liquefaction
Johnson Space Center

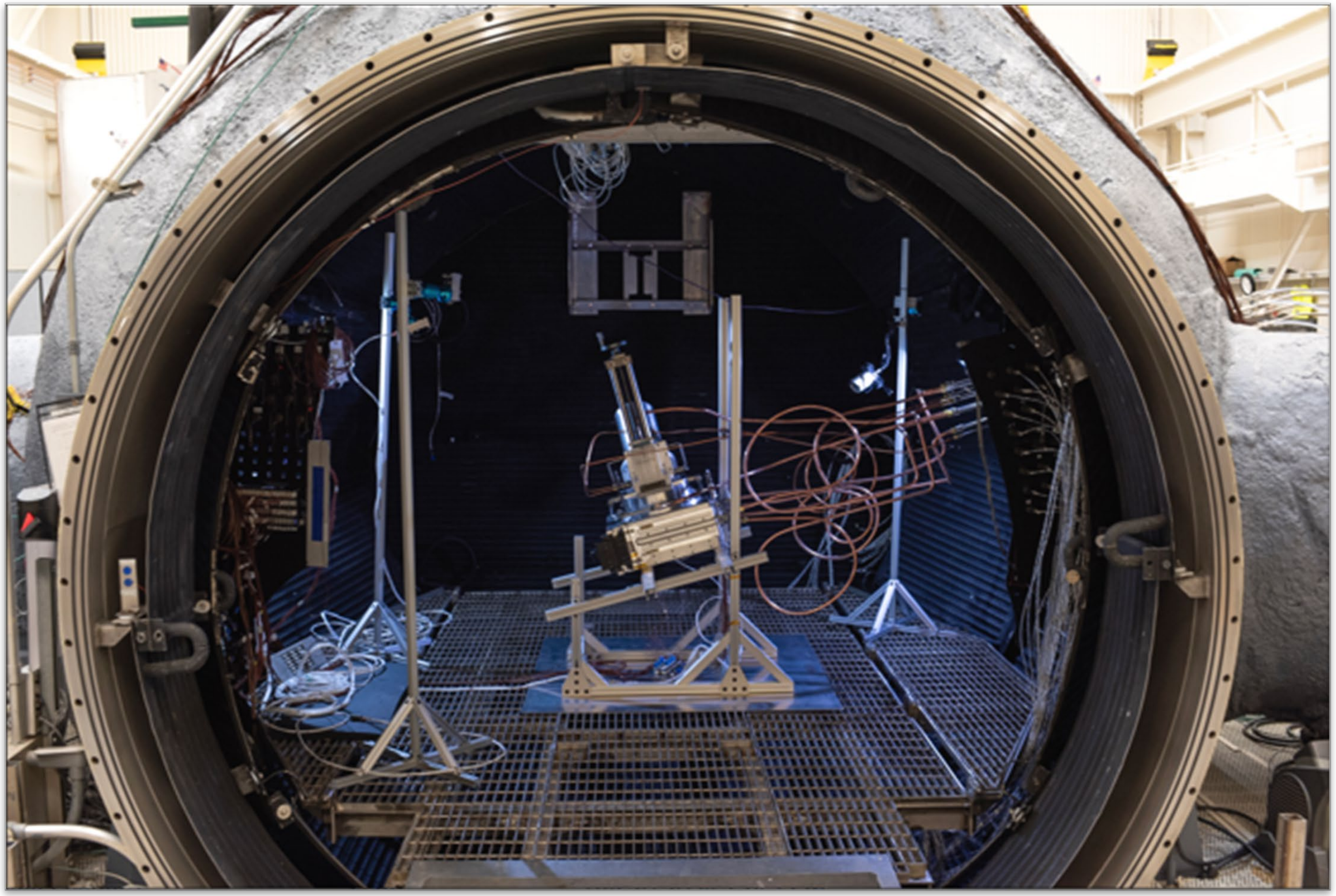
LOX

Propulsion
Johnson Space Center

Plume

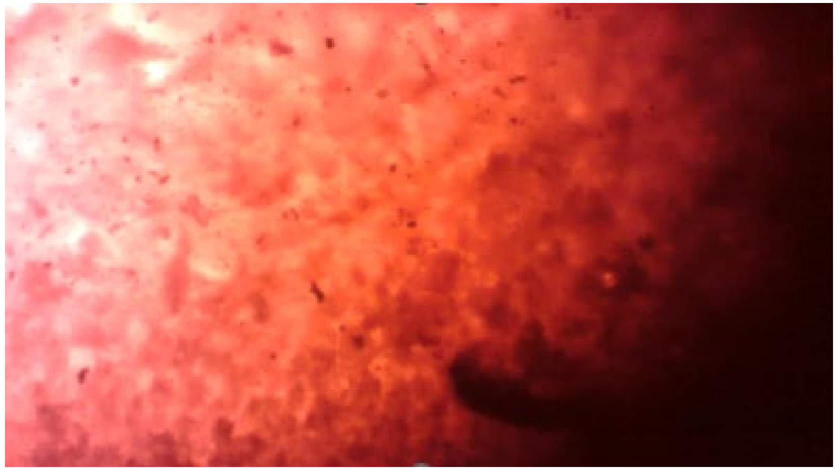
Sintered Pad
Physical Sciences Inc.
NORCAT

Oxygen From Regolith : Solar-Carbothermal Reduction



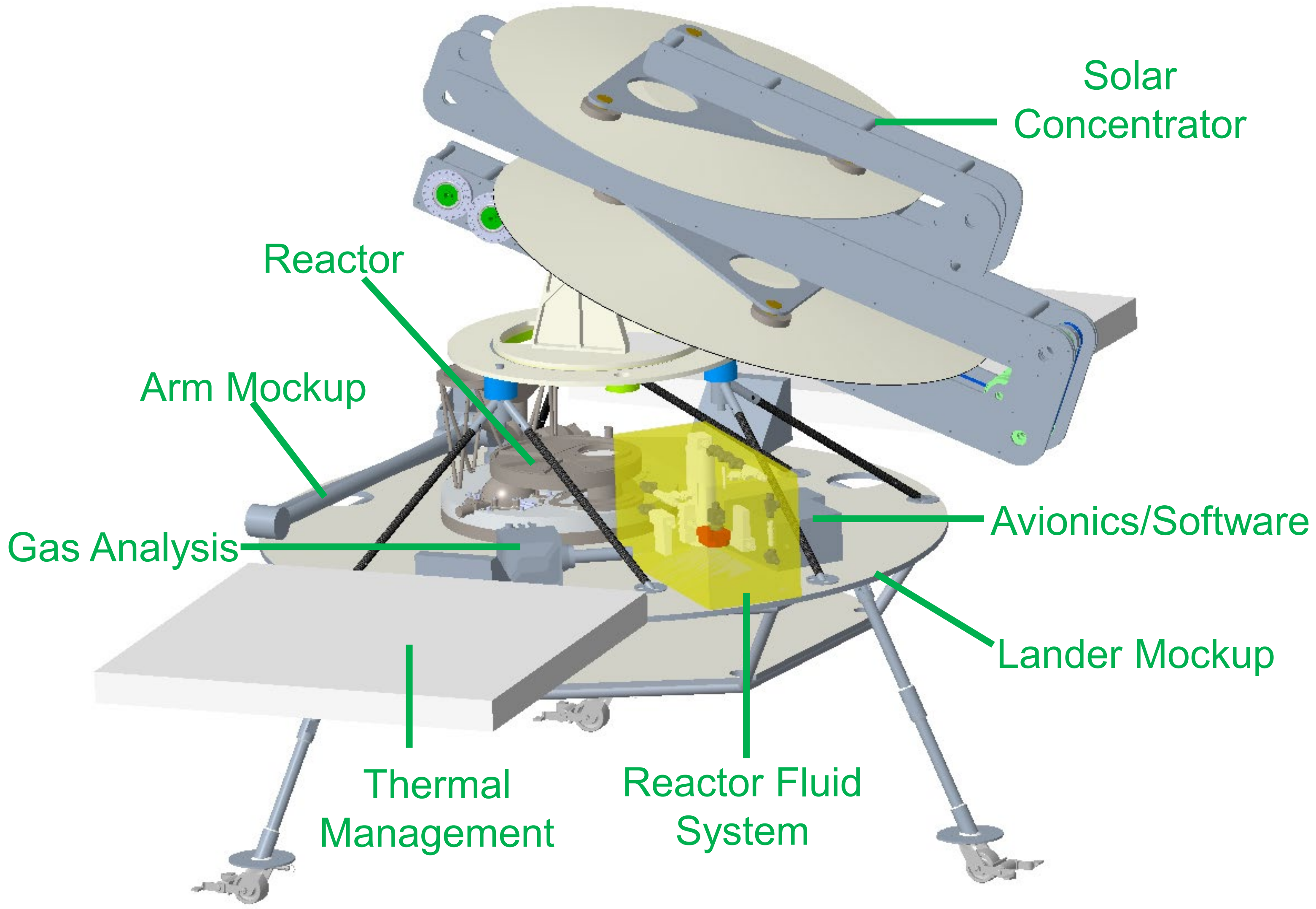
This test will be repeated in 2024 with an automated reactor being developed by Sierra Space through the Carbothermal Oxygen Production Reactor (COPR) Tipping Point project

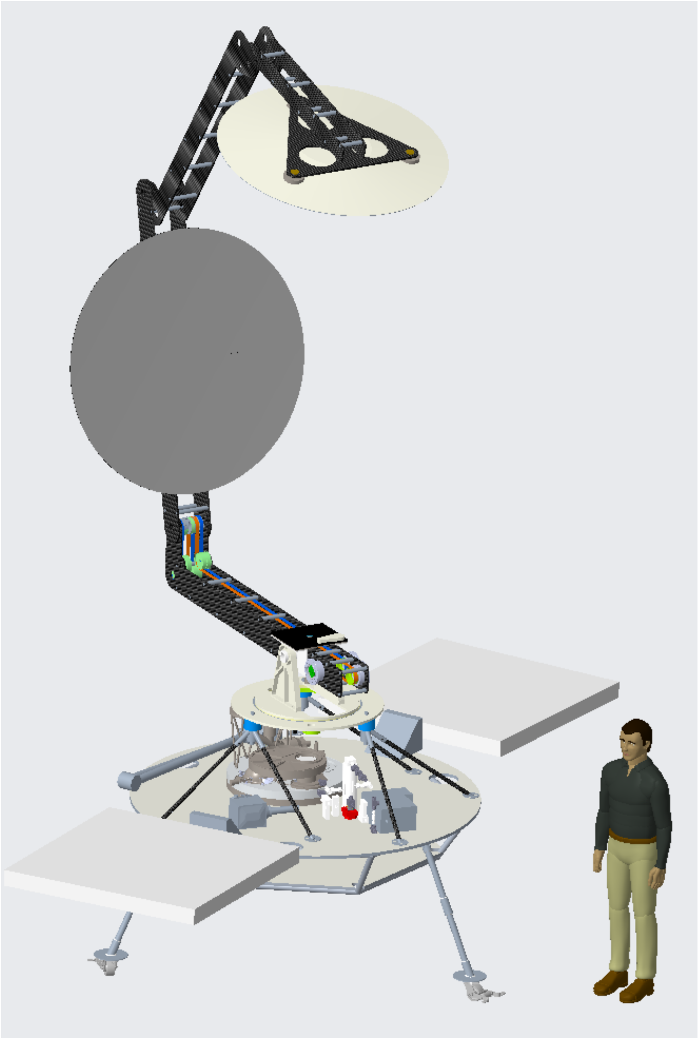
Image Credit: NASA/JPL-Caltech



Test Number	g/KWh*
CaRD Ambient	13.42
CaRD Vacuum 1	11.53
CaRD Vacuum 2	15.79
CaRD Vacuum 3	10.77

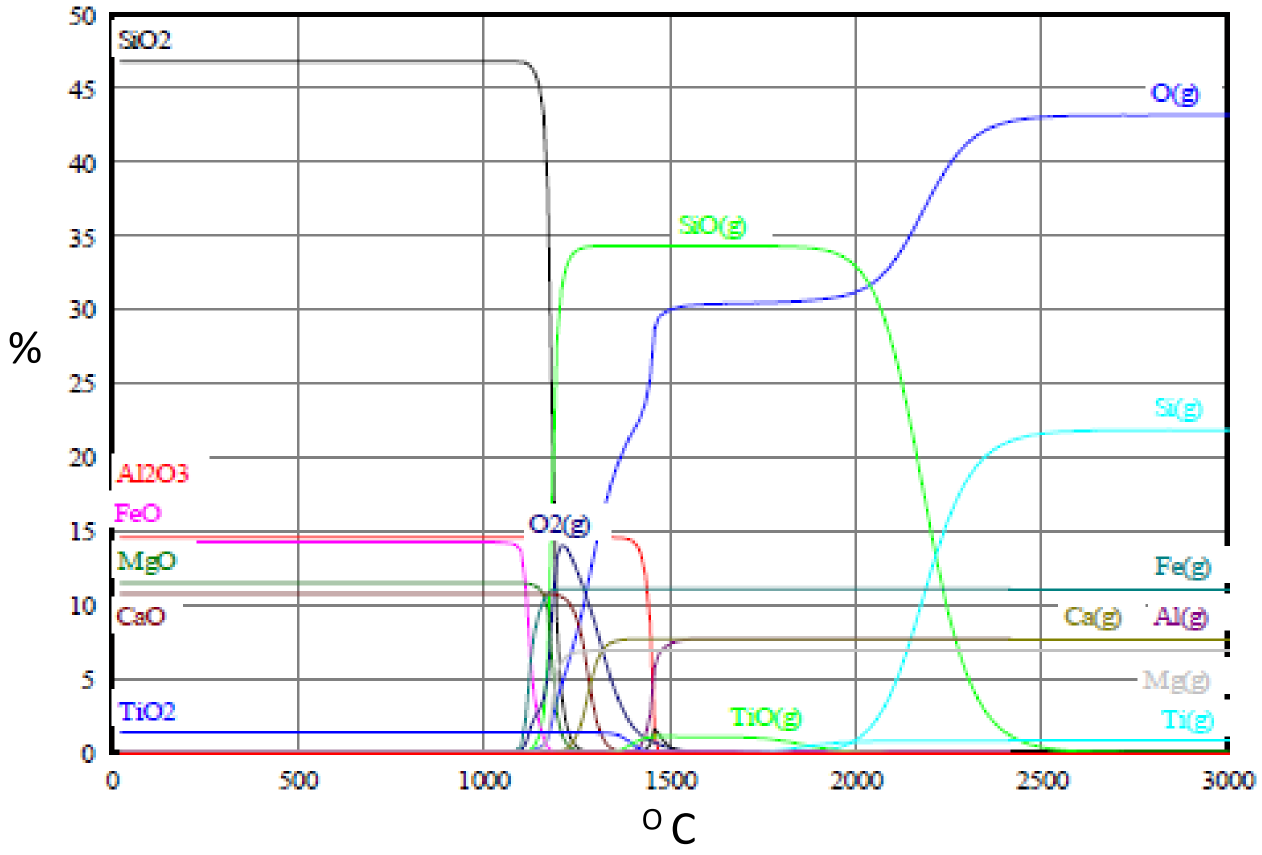
Oxygen From Regolith : Solar-Carbothermal Reduction





Oxygen From Regolith : MRE and Vacuum Pyrolysis

- Molten Regolith Electrolysis is being developed by multiple teams
- Blue Origin's Blue Alchemist technology is using Molten Regolith Electrolysis to produce solar panels.
  - See press release: https://www.blueorigin.com/news/blue-alchemist-powers-our-lunar-future
- Vacuum Pyrolysis has been demonstrated to separate oxygen from various metals found in lunar regolith



Matchett, J. O. H. N. (2006). Production of lunar oxygen through vacuum pyrolysis. *George Washington University: Washington, DC, USA*.

Martian Atmosphere

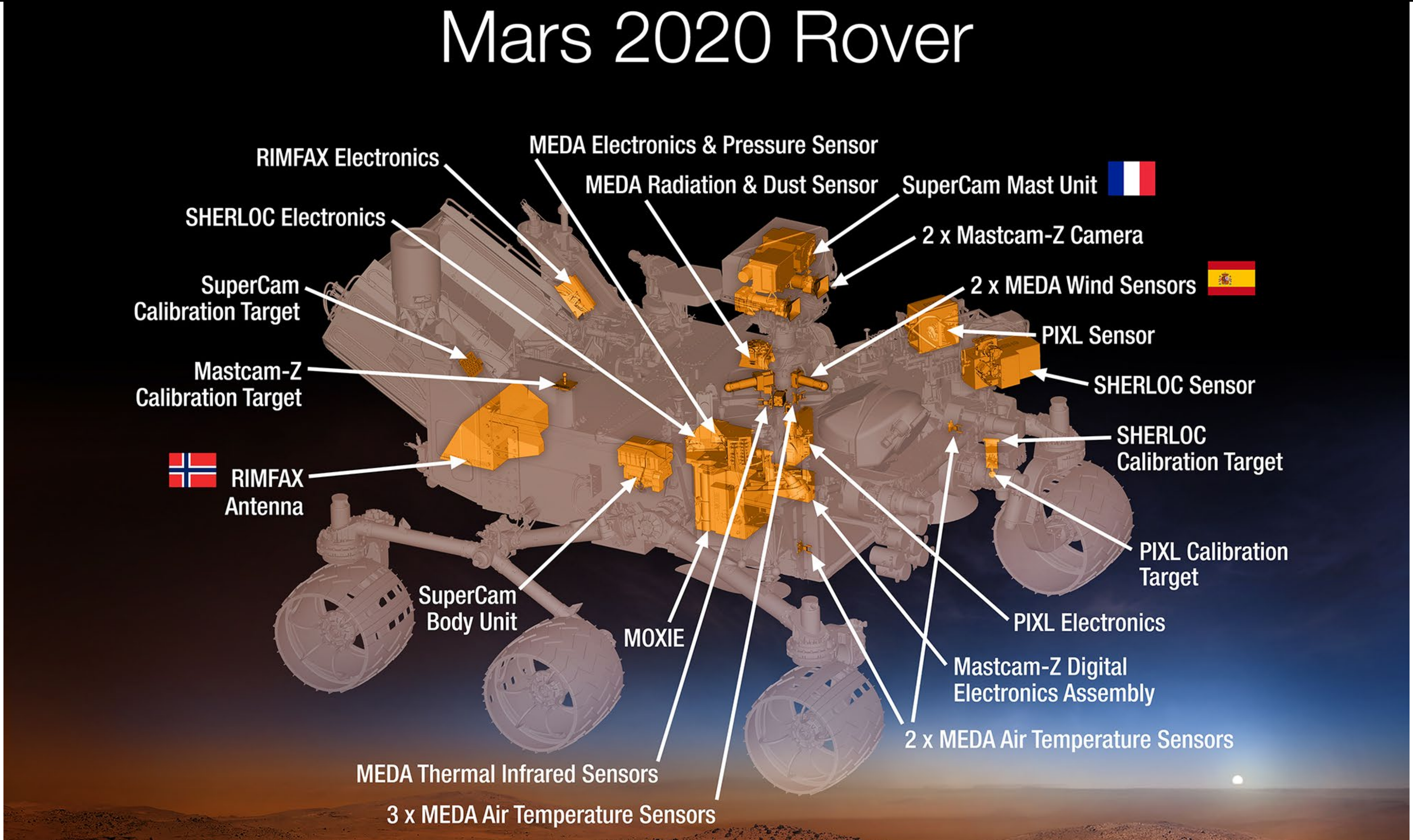


Image Credit: NASA/JPL

Actual presentation will play the video from the link below

https://www.youtube.com/watch?v=n1viNk1eNnM

Video Credit: NASA

Water on Mars

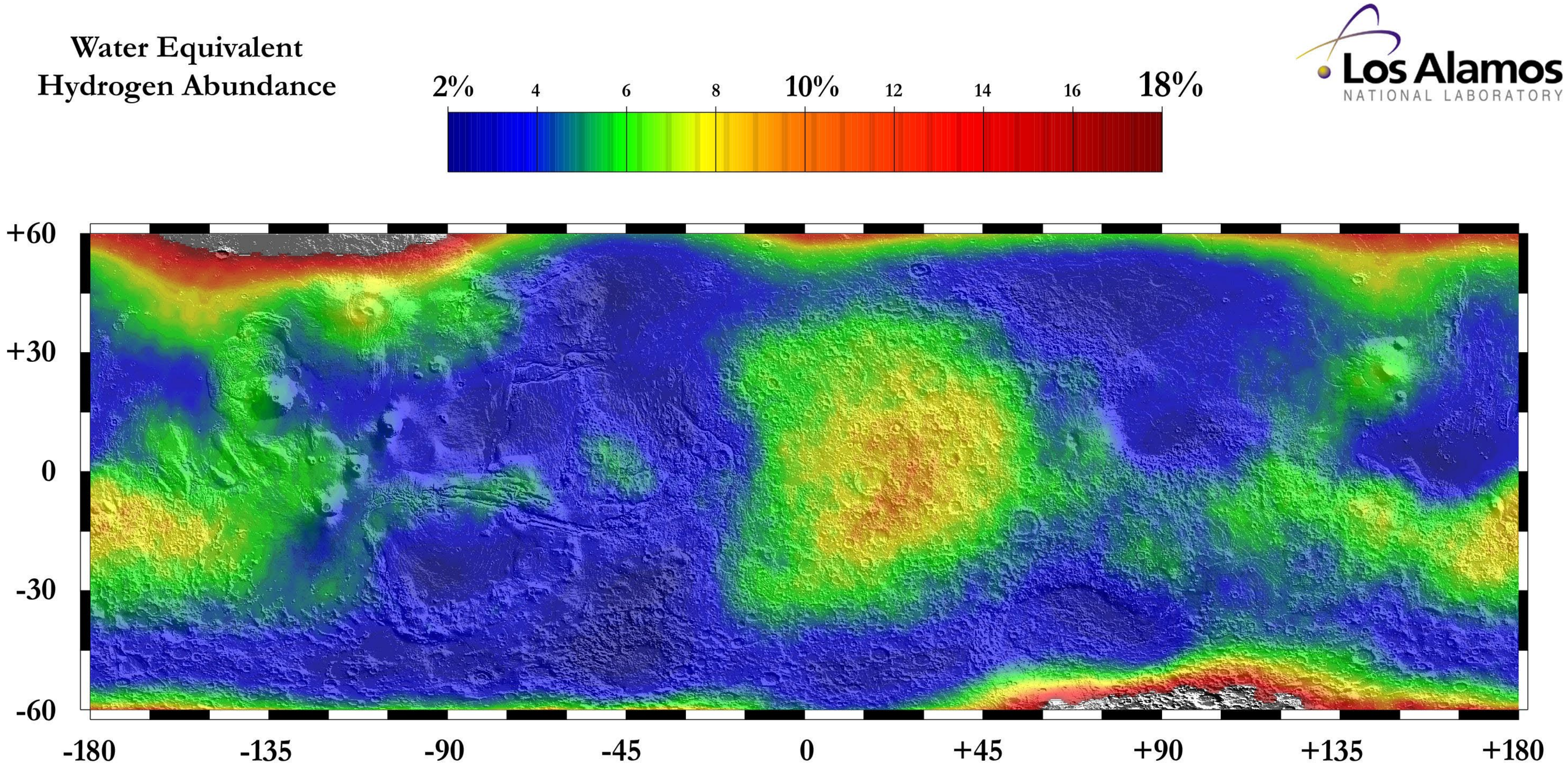


Image Credit: NASA/JPL-Caltech

Water on Mars

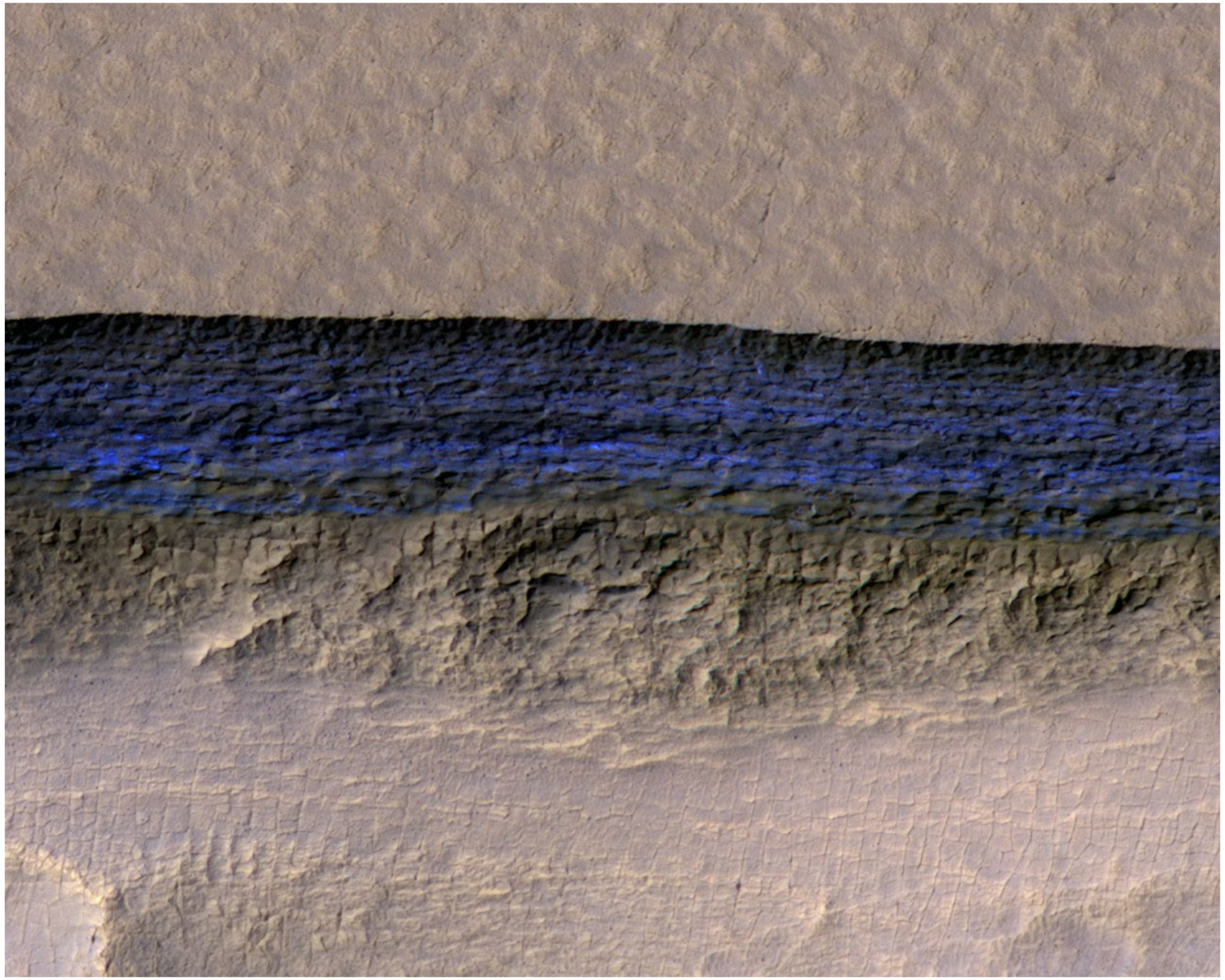
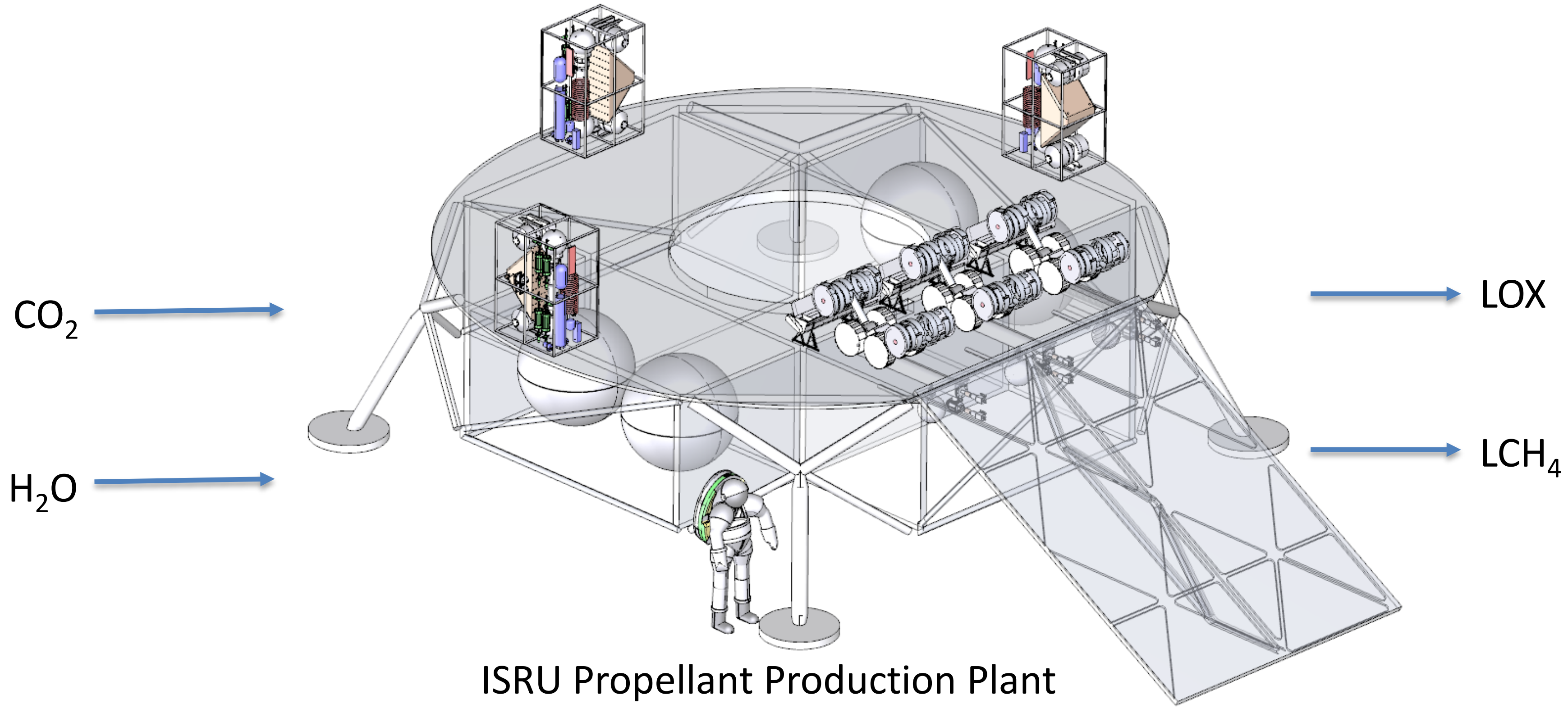


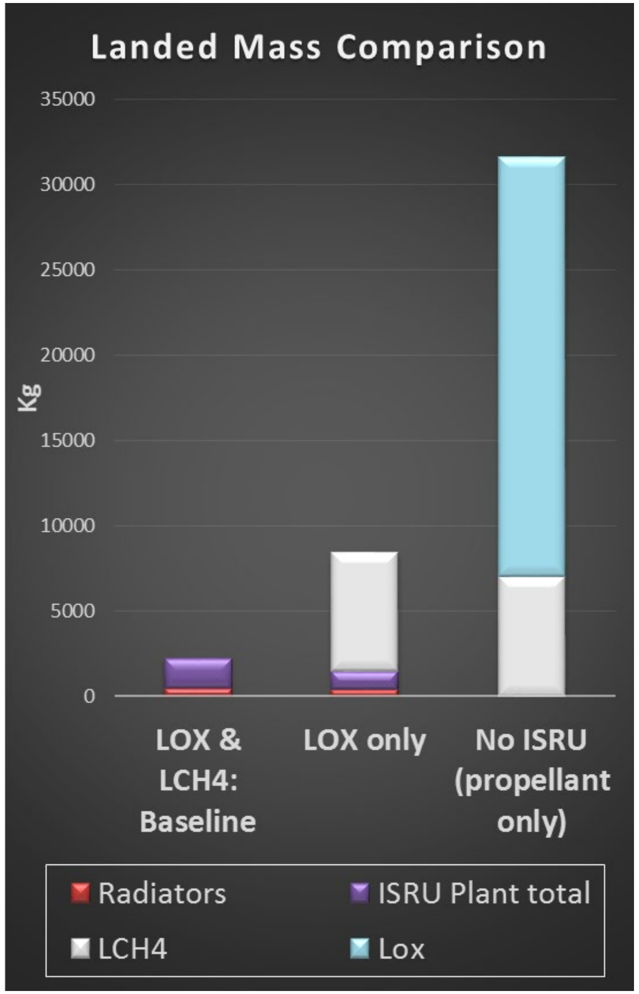
Image Credit: NASA/JPL-Caltech/UA/USGS

A cross-section of underground ice is exposed at the steep slope that appears bright blue in this enhanced-color view from the HiRISE camera on NASA's Mars Reconnaissance Orbiter. The scene is about 550 yards wide. The scarp drops about 140 yards from the level ground in the upper third of the image.

Propellant Production on Mars



ISRU Propellant Production Plant

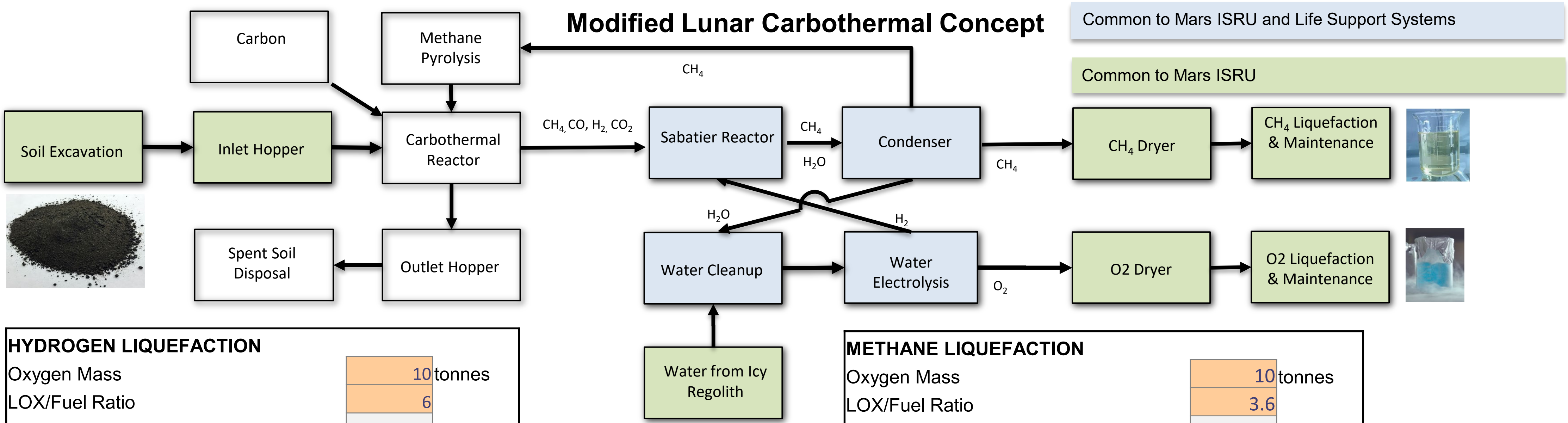


- An Oxygen-only propellant production plant on Mars could make ~3 times its own mass in oxygen in 480 days
- An LOX/LCH4 propellant production plant on Mars could make ~ 18 times its own mass in propellant in 480 days

Kleinhenz, J. E., & Paz, A. (2017). An ISRU propellant production system for a fully fueled Mars Ascent Vehicle. In *10th Symposium on Space Resource Utilization* (p. 0423).

Moon to Mars

Modified Lunar Carbothermal Concept



HYDROGEN LIQUEFACTION		
Oxygen Mass	10	tonnes
LOX/Fuel Ratio	6	
H2 Mass Required	1.67	tonnes
Carbon Mass Required (tonnes)	0	tonnes
Mass of 20W/20K crycooler	106.3	kg
Fuel Liquefaction Thermal Lift Required	429	W
Number of Cryocoolers Required	22	
Mass of Cryocoolers & Radiators	2.34	tonnes
Return on Landed Mass in 1 year	0.71	

METHANE LIQUEFACTION		
Oxygen Mass	10	tonnes
LOX/Fuel Ratio	3.6	
CH4 Mass Required	2.78	tonnes
Carbon Mass Required (tonnes)	2.08	tonnes
Mass of Cryotel GT	3.1	kg
Fuel Liquefaction Thermal Lift Required	169	W
Number of Cryocoolers Required	8	
Mass of Cryocoolers & Radiators	0.065	tonnes
Return on Landed Mass in 1 year	1.30	

If we bring carbon to the Moon

1) We can test all of the technologies required to produce propellant on Mars

2) We can utilize hydrogen from water by feeding water into a system that is already in place to extract oxygen from regolith

3) It will much easier to liquefy and store methane than hydrogen.

ISRU Technology Impact on Earth

- Water electrolysis can be used to produce hydrogen at a large scale
- Hydrogen reduction of iron oxides is being used to make steel with no carbon emissions
- Solar-carbothermal reduction and molten regolith electrolysis can be used to produce silicon with no carbon emissions
- Sabatier process can convert carbon dioxide and hydrogen into methane
- Carbon dioxide and water can be used to make plastics

Image Credit: NASA

Thank You!

"Exploration is in our nature. We began as wanderers, and we are wanderers still. We have lingered long enough on the shores of the cosmic ocean. We are ready at last to set sail for the stars."

-Carl Sagan

Image Credit: NASA

Backup

Lunar Ice Mining

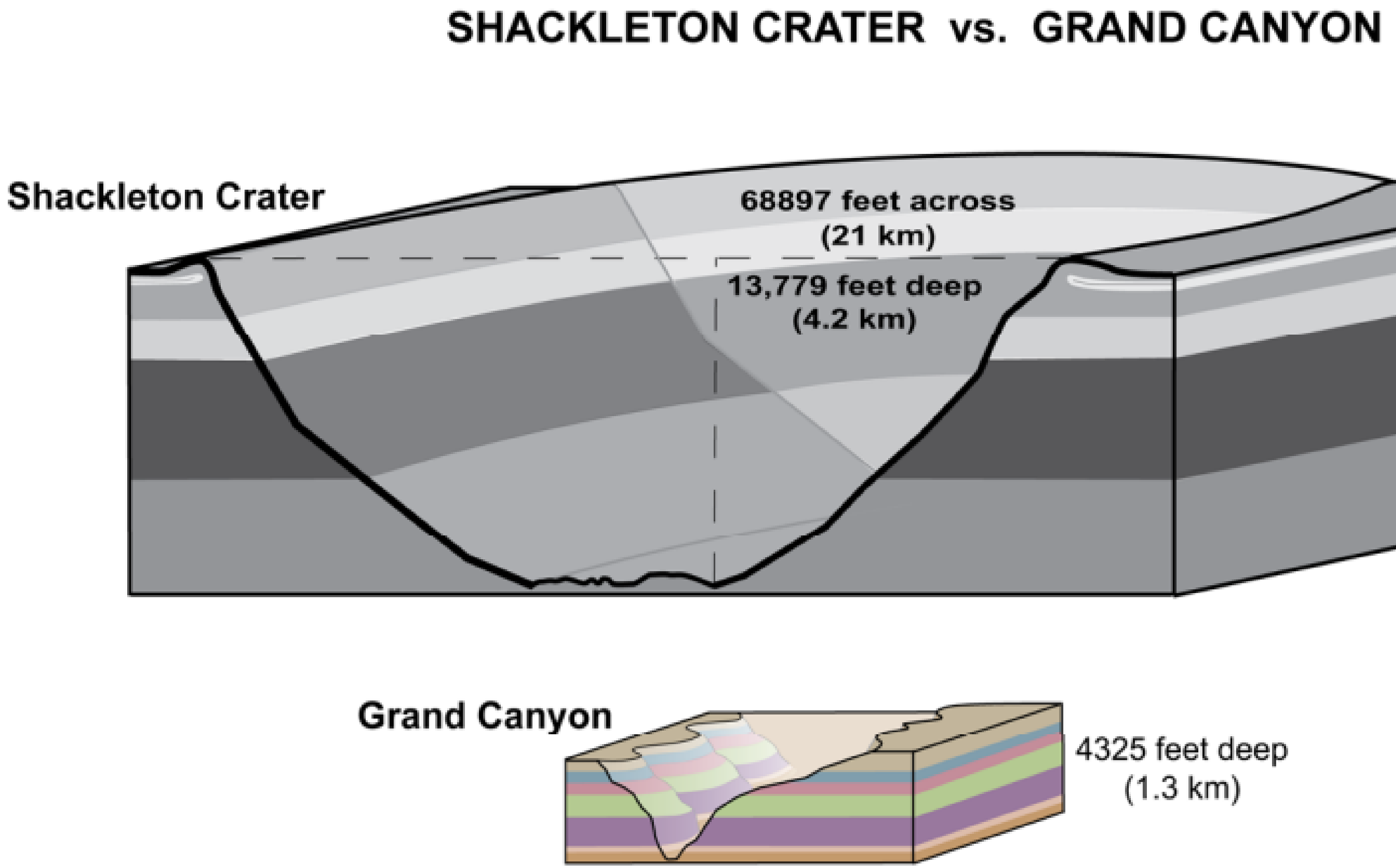
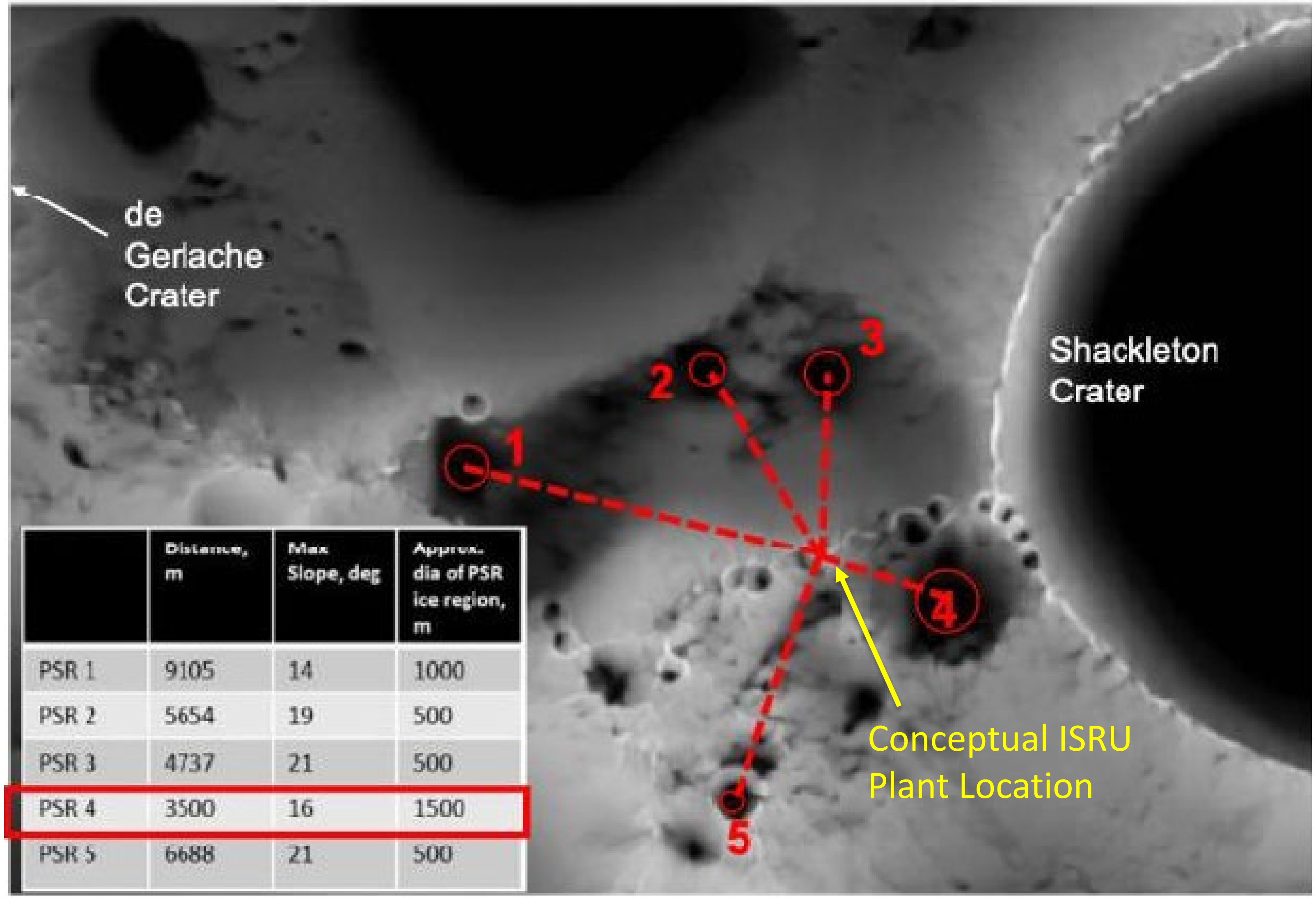


Image Credit: Lunar Planetary Institute

https://www.lpi.usra.edu/exploration/multimedia/LunarLandscapesShackleton%20Crater.pdf

Lunar Ice Mining



	Distance, m	Max Slope, deg	Approx. dia of PSR ice region, m
PSR 1	9105	14	1000
PSR 2	5654	19	500
PSR 3	4737	21	500
PSR 4	3500	16	1500
PSR 5	6688	21	500

Linne, D. L., Kleinhenz, J. E., & Paz, A. (2020). Lunar water pilot plant conceptual design. In *ASCEND 2020* (p. 4236).

Lunar Ice Mining

Production plant:

- Water tank
- PEM water electolyzer
- Gas dryers
- Hydrogen Liquefaction & Storage
- Oxygen Liquefaction and Storage

Ridge Water Tank:

Water is pumped from mobile tanker to the ridge water tank.

Water Tankers x2:

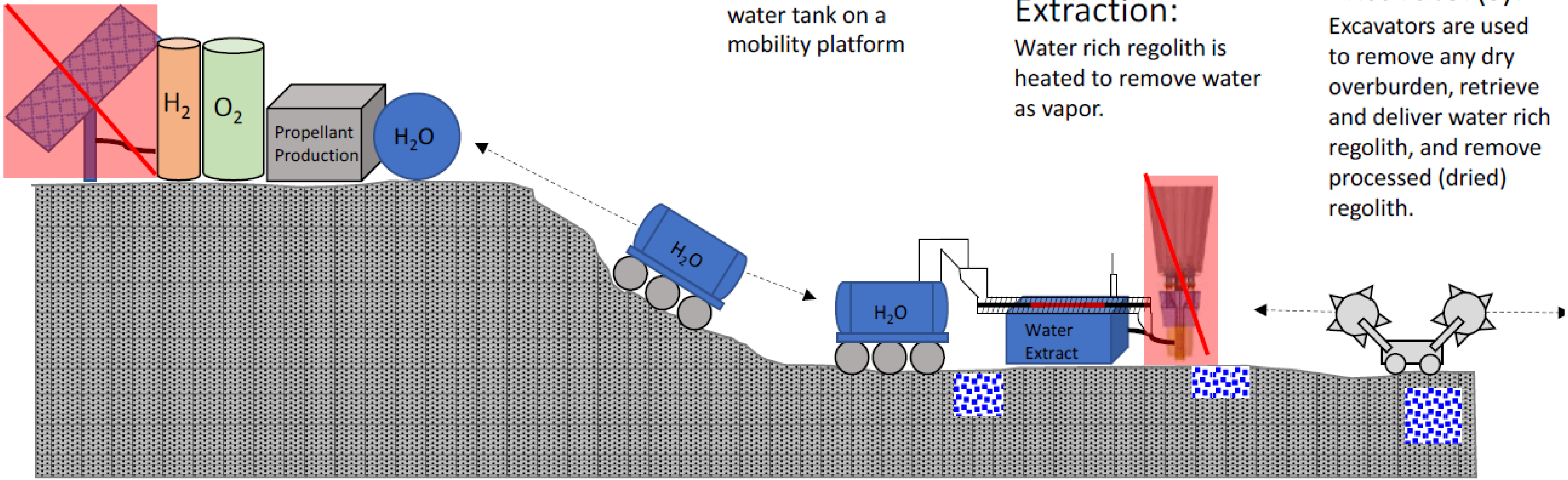
Extracted water is condensed (frozen) into a water tank on a mobility platform

Water Extraction:

Water rich regolith is heated to remove water as vapor.

Excavator(s):

Excavators are used to remove any dry overburden, retrieve and deliver water rich regolith, and remove processed (dried) regolith.



Kleinhenz, J. E., & Paz, A. (2020). Case studies for lunar isru systems utilizing polar water. In *ASCEND 2020* (p. 4042).