



# Kiloton Class ISRU Systems for LO<sub>2</sub>/LCH<sub>4</sub> Propellant Production on the Mars Surface



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AIAA SciTech Forum 2024 – Orlando, FL



# Team Photo





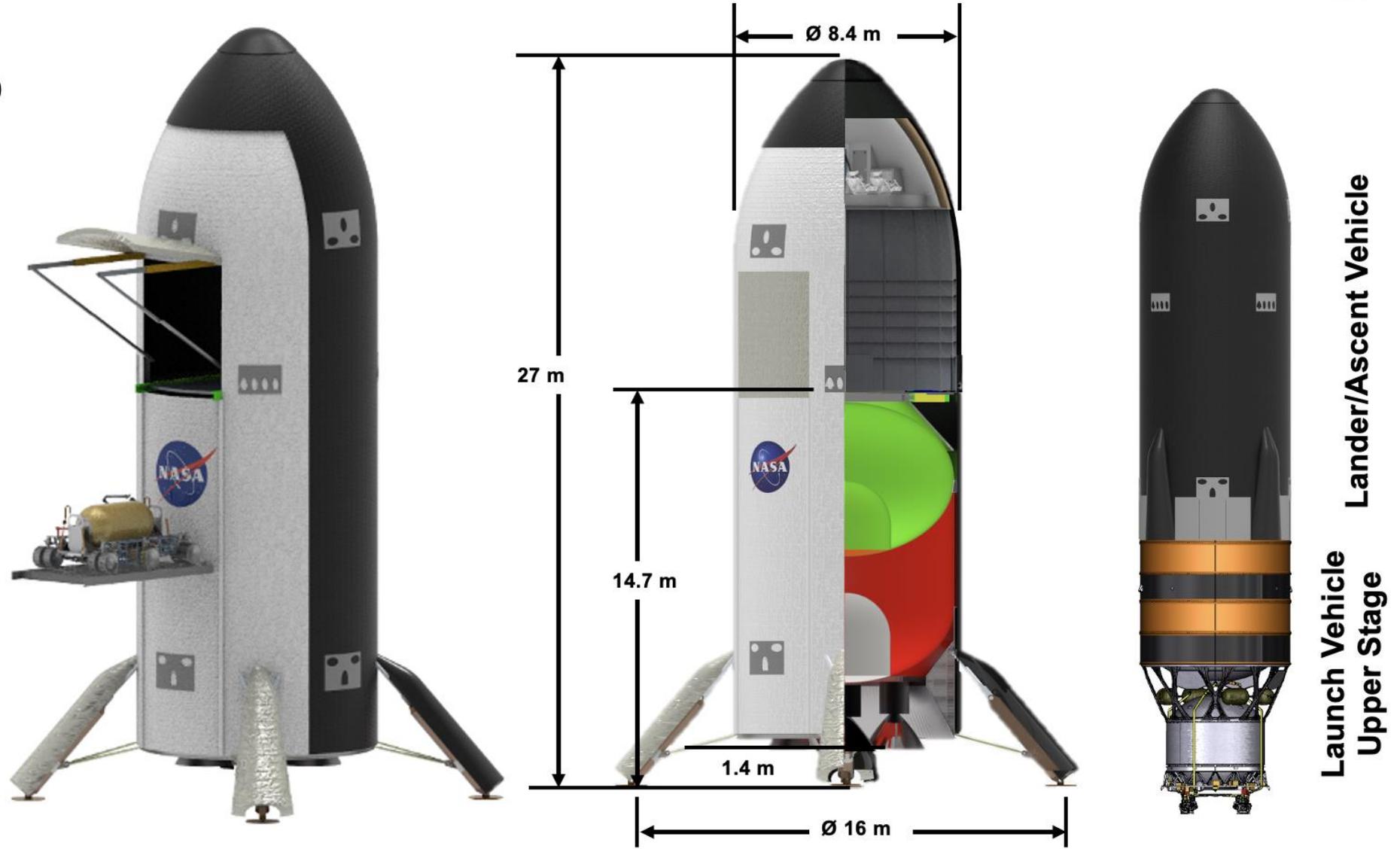
# Kiloton Class Mars Propellant ISRU



- Four Compass ‘runs’ in addition to MSFC and KSC components to fill out the required elements of the system to explore what it would take to manufacture ascent propellant on Mars for a representative heavy-class lander/ascent vehicle
  - (see D. Trent et al, “Design of a Family of Mars Chemical Transportation Elements”, 2024)
- Compass concurrent engineering runs included technologists and their equipment (cryocoolers, Sabatier, electrolysis, water drills, surface mining and processing....)
- Compass provided the integration function to track what is needed to produce and store 300t of  $LO_2/LCH_4$
- This presentation will introduce you to
  - The concept of operations and where they need to find their ‘ores’
  - The unique ISRU elements and their main attributes
  - Roll-up of number, mass, power, time for each option
  - How these elements might stow in a lander
  - Architectural comparison of some of the different options to fuel a chemical lander on Mars

# Mars Ascent Launch Vehicle

- Launched on top of SLS
- Multiple MALVs send crew and cargos to Mars
- Needs ~ 300t of LOX/LCH4 refueled to take crew back to 5 SOL Mars Orbit for rendezvous with return vehicle





# Assumptions



- 26 months on surface- between cargo landing and crew landing decision
- ISRU modules to make 300t  $\text{LO}_2/\text{LCH}_4$  propellants in 20 months
  - 6 month overhead: 3 month commissioning, 1 month margin, 2 months for dust-storm (still run storage)
- Constraint if using SLS for delivery: Only One Cargo flight per opportunity
  - Requires > 26 months to get all equipment there (especially for water gathering systems) but this extra time reduces power requirements in some cases
- Fault Tolerance
  - Single fault tolerant (except for tanks and reactors)



# *Three Architectures Explored to Produce 300t of $LO_2/LCH_4$*



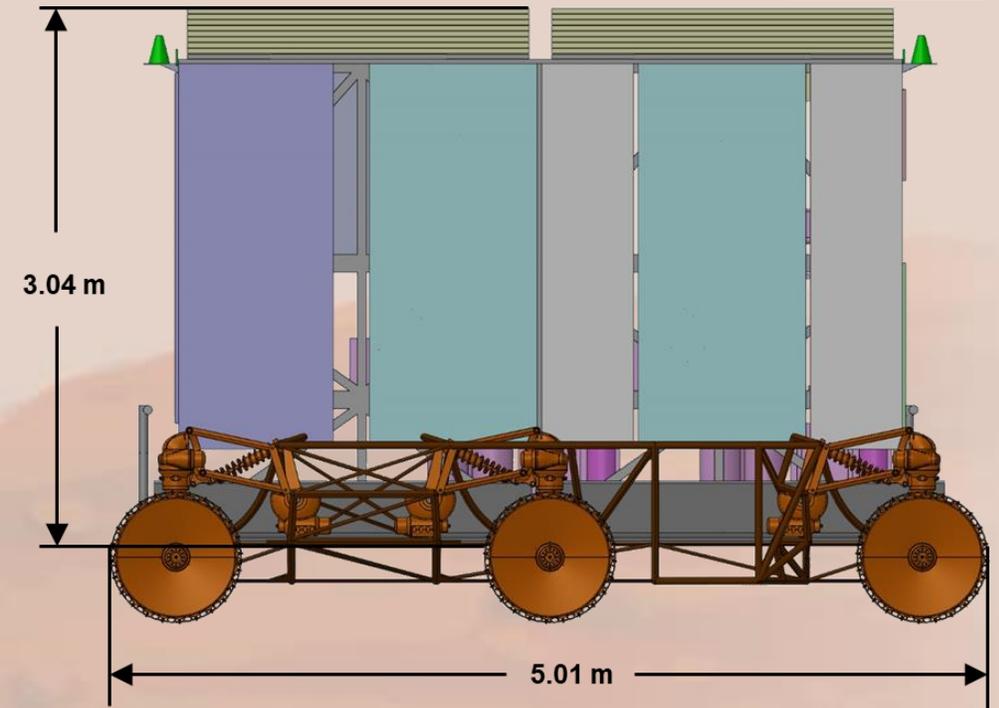
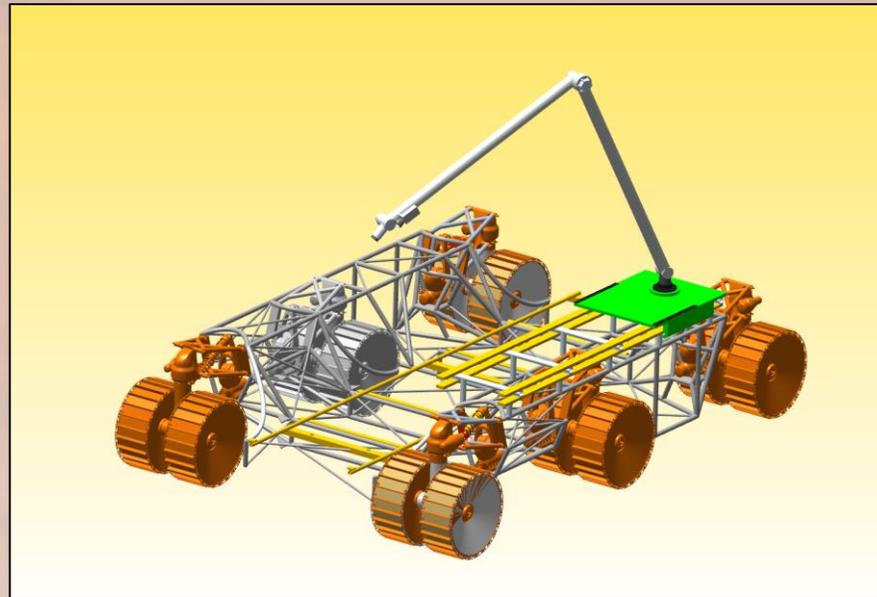
1. ISRU using pumped  $CO_2$  atmosphere and Earth water (~150t)
2. Subsurface drilling/melting of ice deposits for the 150t of water
3. Surface mining of garden variety soils to extract the 150t of water



# Deployment



- All ISRU, Power, and transport elements designed to fit a pallet design which is carried and deployed by a common 6-wheeled chassis (assumed similar to the pressurized habitat rover chassis)
- 6-wheel chassis are reusable for multiple deployments



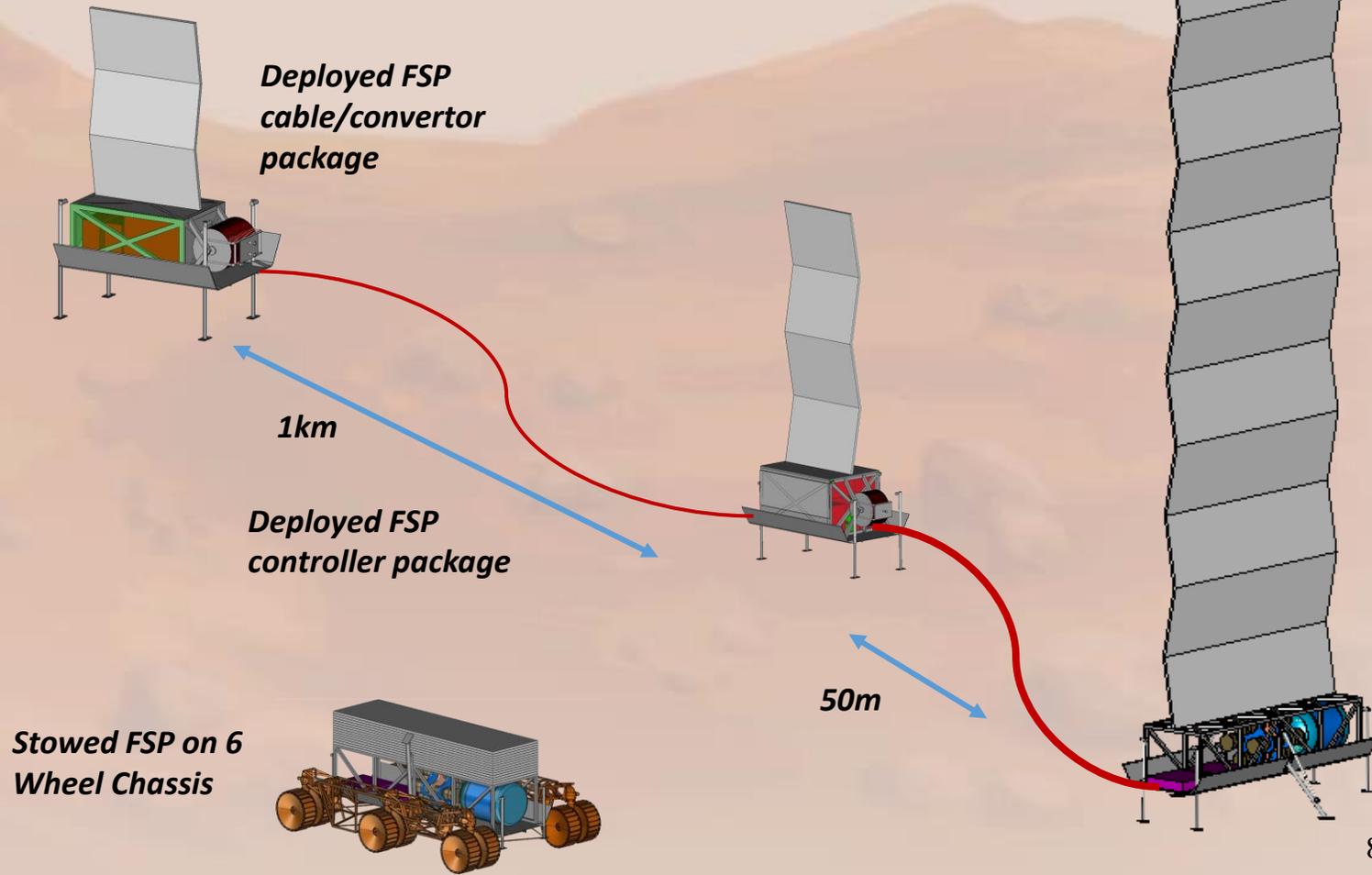
*ISRU plant on Chassis*



# Derived Lunar 40 kWe Fission Power System for Mars ISRU

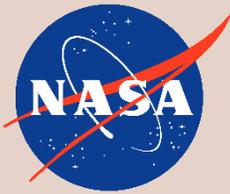


- **Users:** Human lander, ISRU and cryogenic storage
- **Power (each):** 40 kWe reactor 1km cable to users
  - Eight, 6 kWe Stirlings
  - Radiation tolerance set to 100 krad in controller
  - Radiation at Stirlings set to 25 Mrad
  - <5 mrem/hr at >1 km from habitat
  - Utilize same rover to deploy 1km, +/- 2800VDC cable
- **Thermal:**
  - Deployable Reactor Package: 133 m<sup>2</sup> radiator for Stirlings, sized for polar operations
- **Total FSP Mass** ~ 10,000 kg (~2t rover not included)
- FSPs added to manifest as needed by ISRU





# ISRU with Earth Water Option



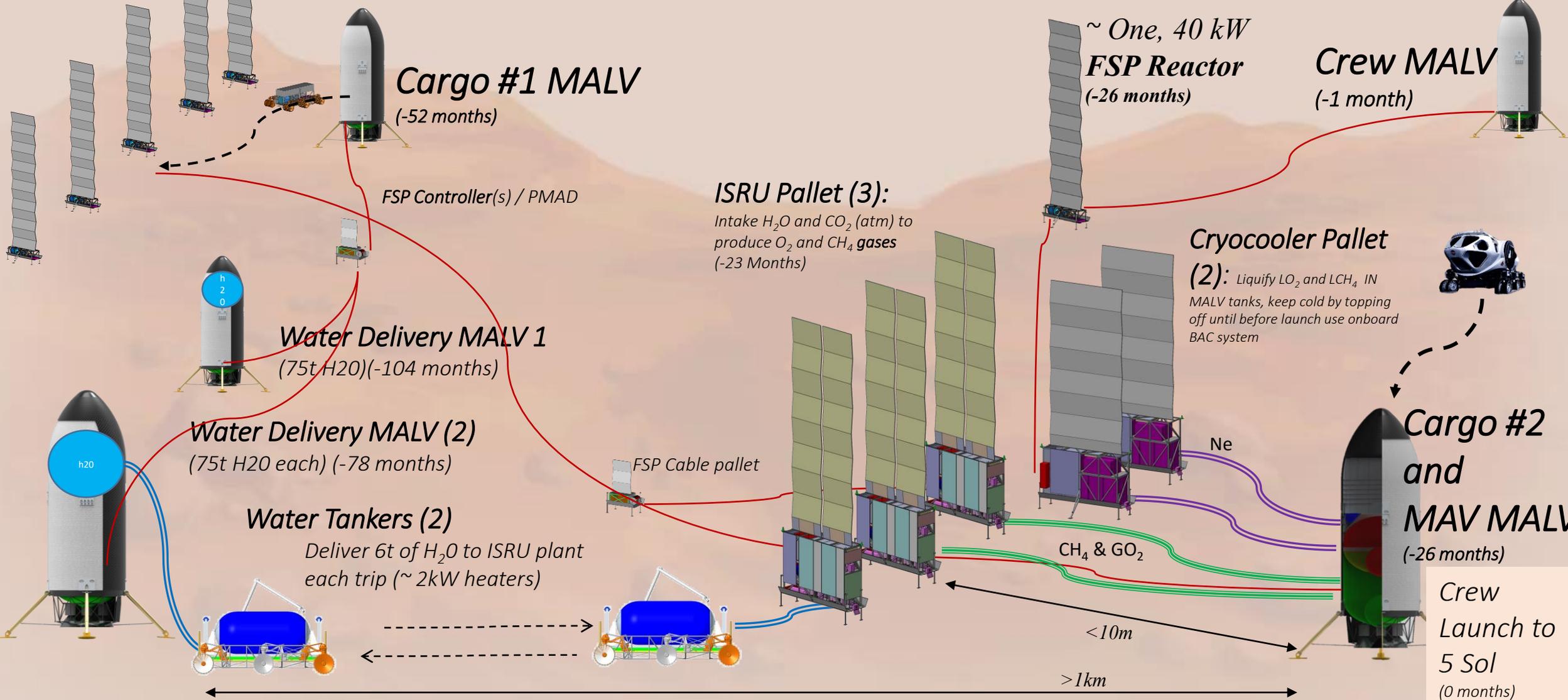
# Animated ISRU Elements: Transported Water Option



~ Five, 40 kW  
**FSP Reactors**  
(-49 to -26 months)

Assume 6-wheel rover can move ~7t elements

Assume MALV elevator can lower ~ 15t



**Cargo #1 MALV**  
(-52 months)

~ One, 40 kW  
**FSP Reactor**  
(-26 months)

**Crew MALV**  
(-1 month)

FSP Controller(s) / PMAD

**ISRU Pallet (3):**  
Intake H<sub>2</sub>O and CO<sub>2</sub> (atm) to  
produce O<sub>2</sub> and CH<sub>4</sub> gases  
(-23 Months)

**Cryocooler Pallet  
(2):** Liquefy LO<sub>2</sub> and LCH<sub>4</sub> IN  
MALV tanks, keep cold by topping  
off until before launch use onboard  
BAC system

**Water Delivery MALV 1**  
(75t H<sub>2</sub>O)(-104 months)

**Water Delivery MALV (2)**  
(75t H<sub>2</sub>O each) (-78 months)

**Water Tankers (2)**  
Deliver 6t of H<sub>2</sub>O to ISRU plant  
each trip (~ 2kW heaters)

FSP Cable pallet

Ne

**Cargo #2  
and  
MAV MALV**  
(-26 months)

CH<sub>4</sub> & GO<sub>2</sub>

Crew  
Launch to  
5 Sol  
(0 months)

<10m

>1km

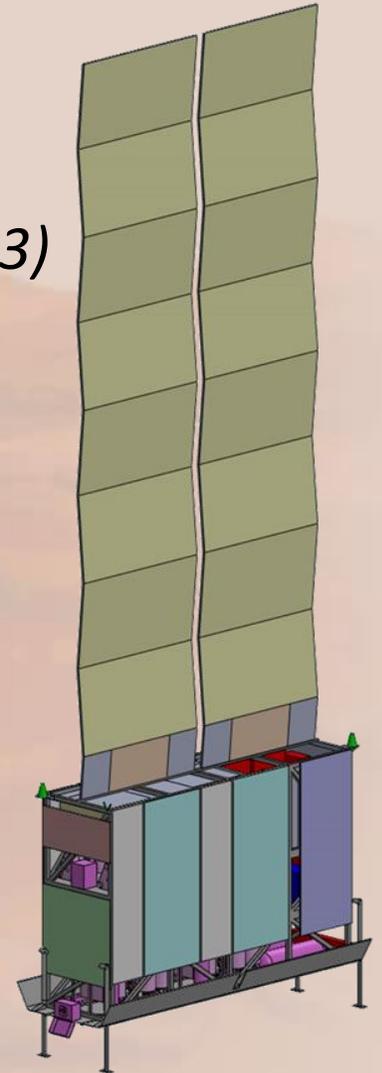
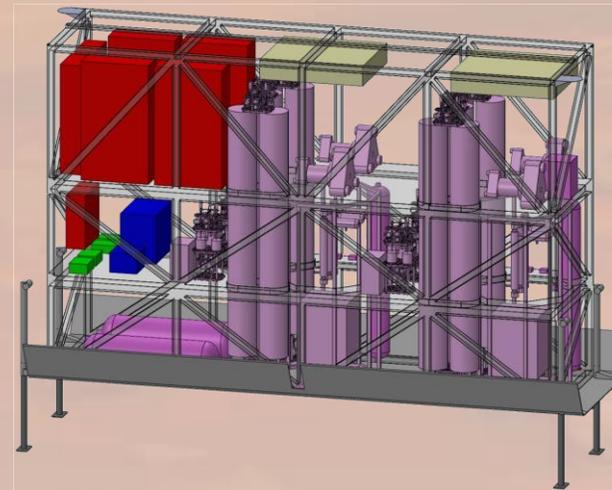


# Mars 300t LO<sub>2</sub>/LCH<sub>4</sub> ISRU Pallet

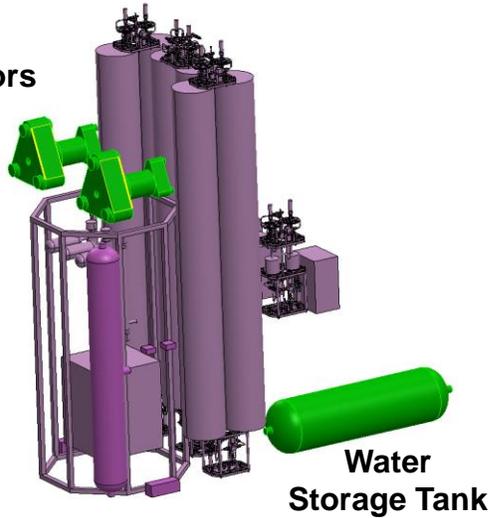


- **Plants to produce 300t of GO<sub>2</sub>/GCH<sub>4</sub> in 20 months on Mars**
- **ISRU equipment:** to process water and atmospheric CO<sub>2</sub> into gaseous O<sub>2</sub> (~18.5 kg/hr) and CH<sub>4</sub> (~4.6 kg/hr)
  - Three, 5.4 t pallets using a total of ~190 kW continuous (5+1 ISRU strings)
    - CO<sub>2</sub> collection (atm pumps), Electrolysis, Sabatier, condensers, Driers,
- **Power:** 62 kW each from fission surface power units, switchgear for high power loads
- **Thermal:** Multiple radiators for electrolyzer, methanators, condensers, etc : ~38 m<sup>2</sup> effective area
- **Mass:** 5417 kg

*ISRU plant  
deployed (1 of 3)*

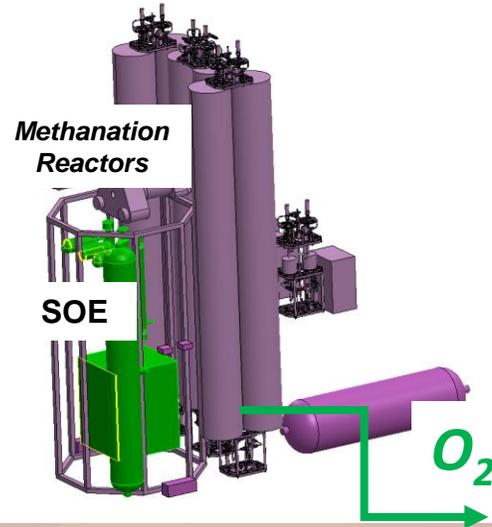


## Scroll Compressors



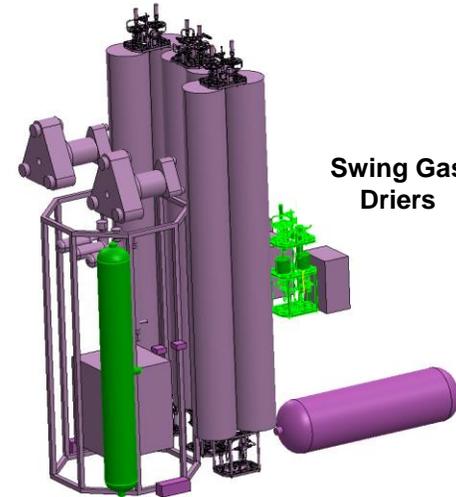
1. Atmosphere ( $\text{CO}_2$ ) pumped with scroll compressors and  $\text{H}_2\text{O}$  gathered from storage tank (delivered by water tanker pallet).

## Methanation Reactors



2.  $\text{CO}_2$  and  $\text{H}_2\text{O}$  processed by SOE module into a product  $\text{O}_2$  stream (which is cooled and sent to the user to be liquefied),  $\text{H}_2\text{O}$  (which is condensed and resent to SOE) and a  $\text{CO}_2/\text{CO}/\text{H}_2$  stream (which is processed by methanation reactors into  $\text{CH}_4/\text{H}_2\text{O}/\text{H}_2/\text{CO}_2$ ).

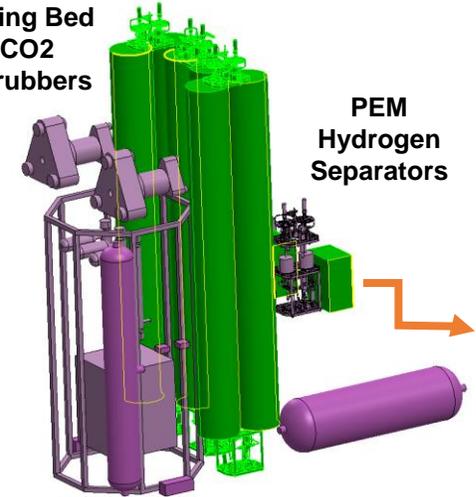
## Swing Gas Driers



Drop-Out Water Tank (connected to condenser radiator –not shown)

3.  $\text{H}_2\text{O}$  is again separated out with condenser radiator and swing gas driers and sent to the drop-out water tank to be reprocessed.

## Swing Bed $\text{CO}_2$ Scrubbers



$\text{CH}_4$

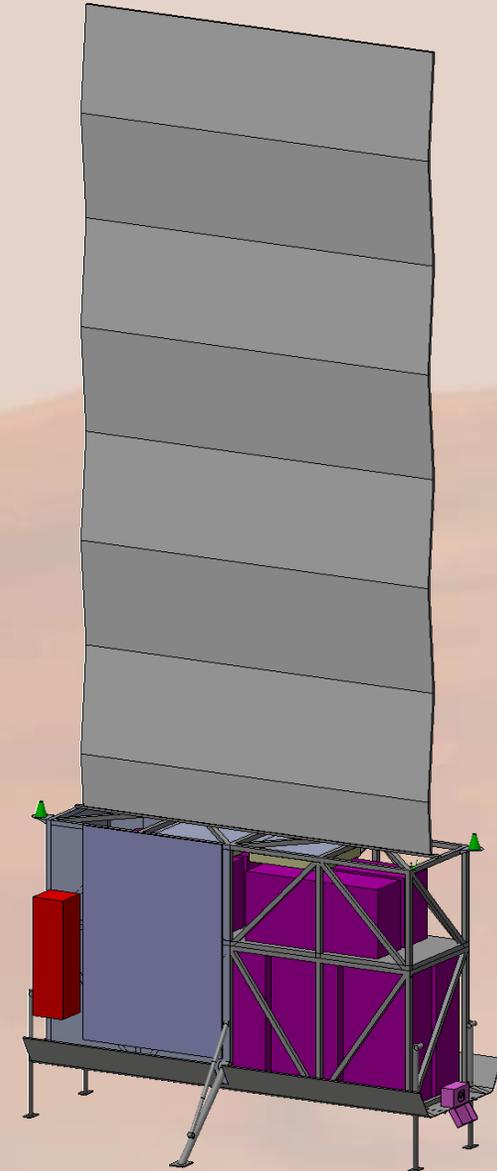
4. Remaining  $\text{CO}_2$  and  $\text{H}_2$  gases removed by  $\text{CO}_2$  scrubbers and then PEM separators, respectively. Remaining product  $\text{CH}_4$  gas cooled and sent to user to be liquefied.



# Mars 300t LO<sub>2</sub>/LCH<sub>4</sub> Cryocooler Pallet



- **Plants to liquify 300t of GO<sub>2</sub>/GCH<sub>4</sub> in 20 months on Mars**
- **90 K Cryocoolers:** to process gaseous O<sub>2</sub> (~15 kg/hr) and CH<sub>4</sub> (~4 kg/hr) into liquid
  - Two 3.5 t pallets using a total of ~45 kW providing 90K Neon to broad area cooling tanks on the Large Vertical Launcher
- **Power:** ~ 20 kW each from fission surface power units, switchgear for high power loads
- **Thermal:** Multiple radiators for cryocoolers and switchgear: ~40 m<sup>2</sup> effective area each
- **Mass:** 3500 kg each



*Cryocooler plant (1 of 2)*



# ISRU Propellant Production (300 t) Elements (water from Earth)



## ISRU System

Total Mass: 5.5 t ea Peak

Power Need: ~62 kWe ea

Qty for 300t system: 3

## Cryocooler System

Total Mass: 3.5 t ea

Peak Power Need: ~20 kWe ea

Qty for 300t system: 2

Note: This image only shows elements designed by the Compass team. Additional items including the Surface Water Transport, Autonomous Chassis and Water Storage on the MALV are also needed.

## Fission Surface Power

Total Mass: 10 t

(including auxiliary pallets)

Power Provided: 40 kWe

Qty for 300t system: 7

Two Water Delivery MALVs  
and Two Surface Water  
Transports

FSP Control System

FSP User System

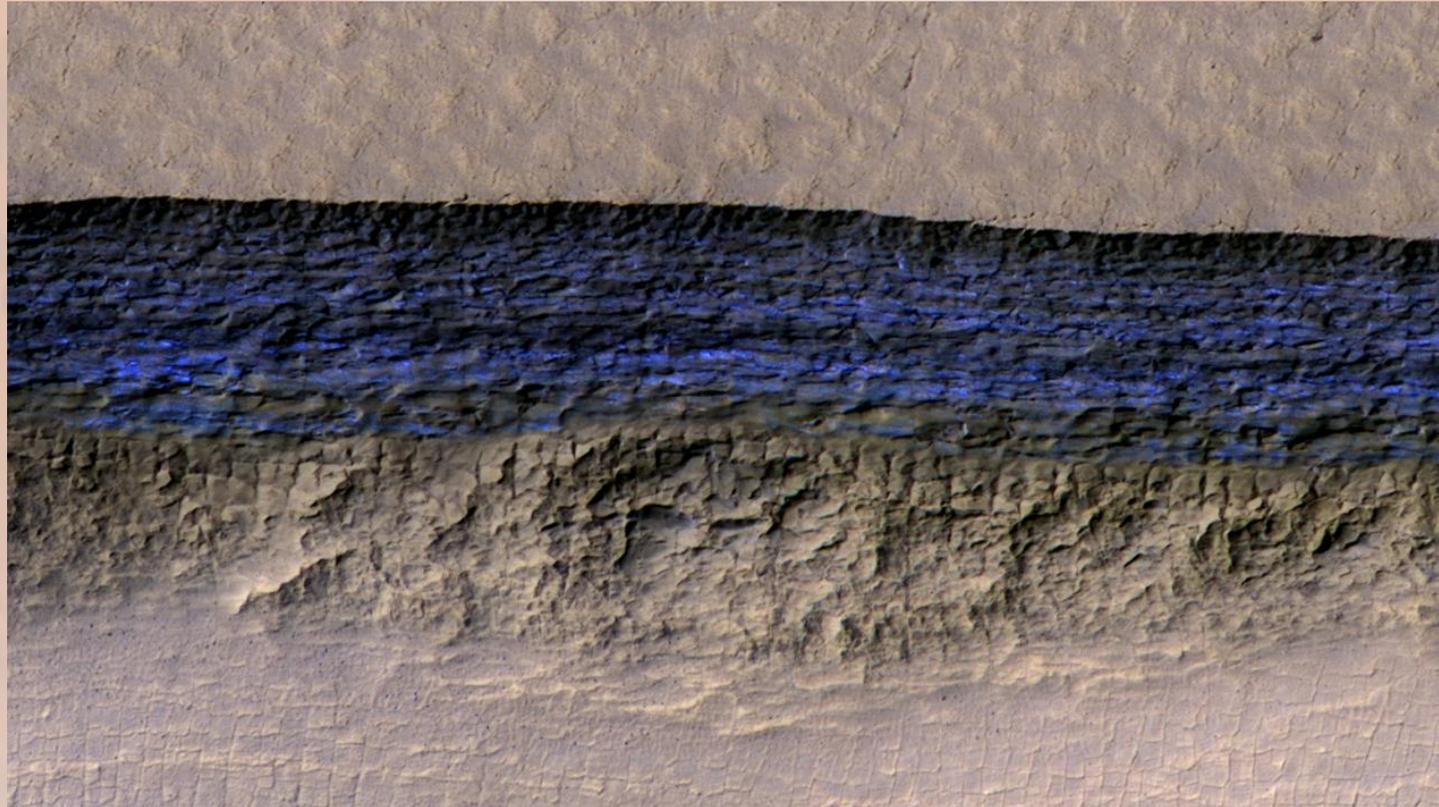
Approx. 6 ft (1.8 m)

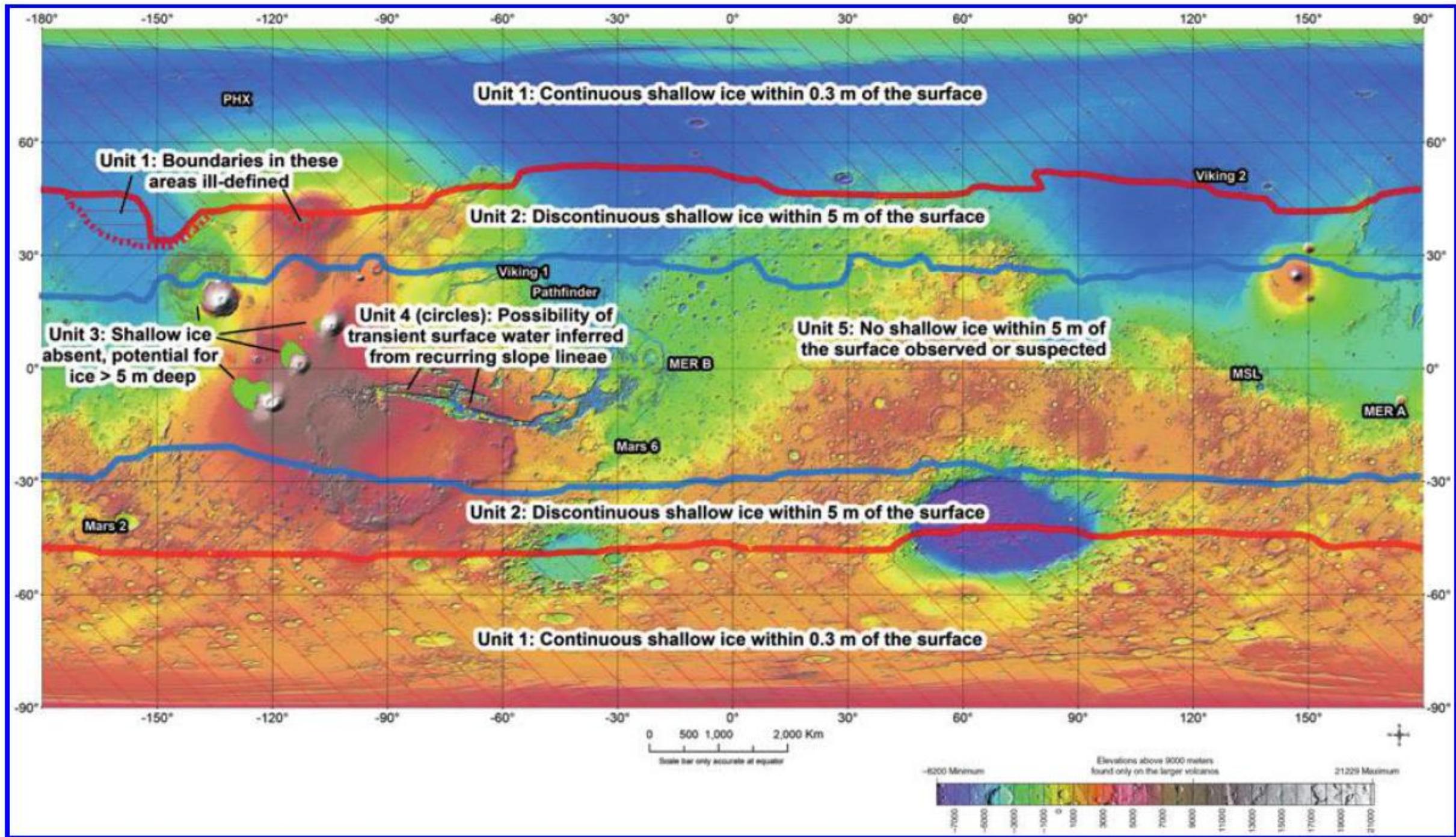
Approx. 6 ft (1.8 m)



# ISRU with Subsurface Well Option

*~ 100m cliff of  
water ice pointing  
to wards Mars  
Pole*





# Other Subsurface Sources: Lobates



- This example site is located in the southern hemisphere (40.5 deg. S, 102.4 deg. E)
- The lobate debris apron, assumed to be covering a large ice deposit.
- ***Geologic Map of MTM–40252 and –40257 Quadrangles, Reull Vallis Region, Mars*** By Scott C. Mest and David A. Crown, 2002



# Animated ISRU Elements: Water Well Option



~ Five, 40 kW  
**FSP Reactors**  
(-49 to -26 months)

Assume 6 wheel rover can move 7t elements  
Assume MALV elevator can lower ~ 15t

**Crew MALV**  
(-1 month)

**Cargo #2 MALV**  
(-52 months)

~ 2nd, 40 kW  
**FSP Reactor**  
(-78 months)

~ 1st, 40 kW  
**FSP Reactor**  
(-78 months)

**Water Mining and Transport MALV #1**  
(-78 months)

**ISRU Pallet (3):**  
Intake  $H_2O$  and  $CO_2$  (atm) to produce  $O_2$  and  $CH_4$  gases  
(-23 Months)

**Cryocooler Pallet (2):** Liquefy  $LO_2$  and  $LCH_4$  IN MALV tanks, keep cold by topping off until before launch use onboard BAC sys



**Cargo #3 and MAV MALV**  
(-26 months)

Crew Launch to 5 Sol  
(0 months)

**Water Drill Rigs (2)**  
Melt 150t of subsurface Ice in 12 months

**Water Tankers (2)**  
Deliver 5t of  $H_2O$  to ISRU plant each trip

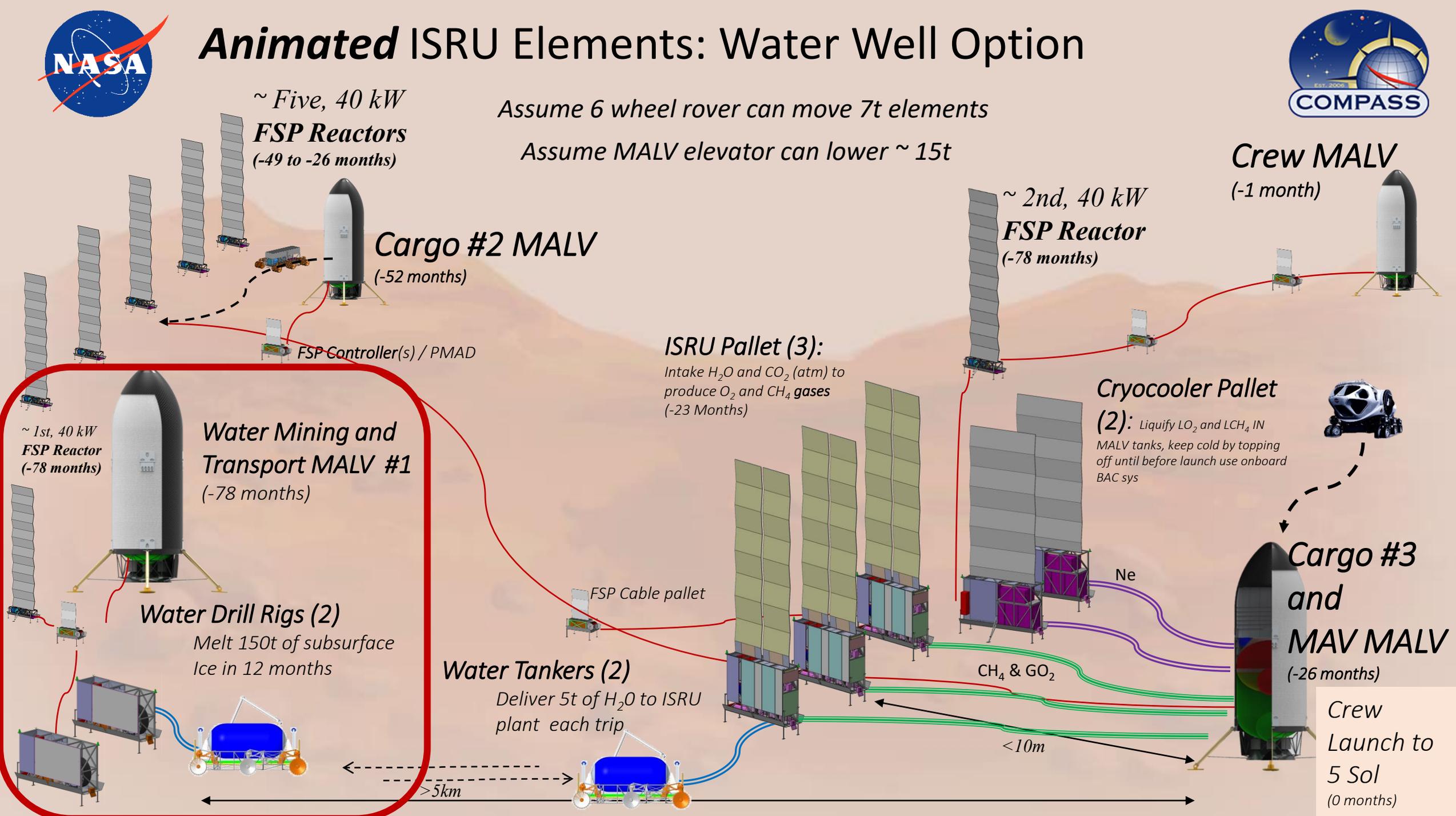
FSP Cable pallet

$CH_4$  &  $GO_2$

Ne

<10m

>5km

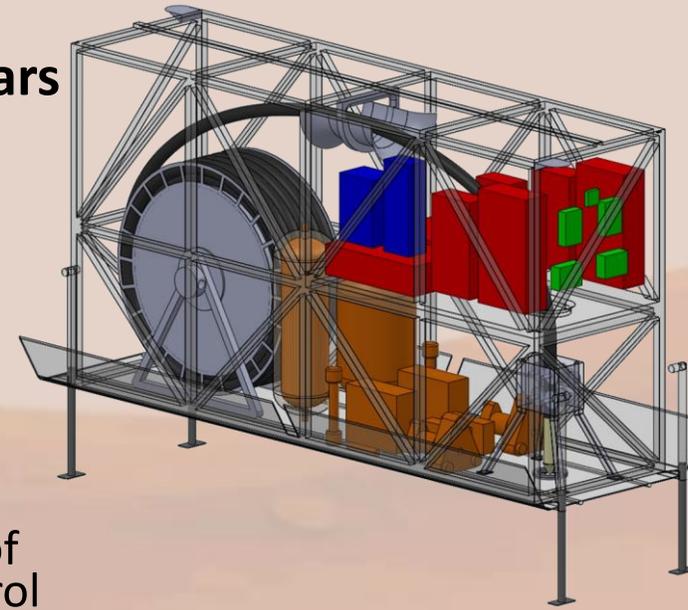




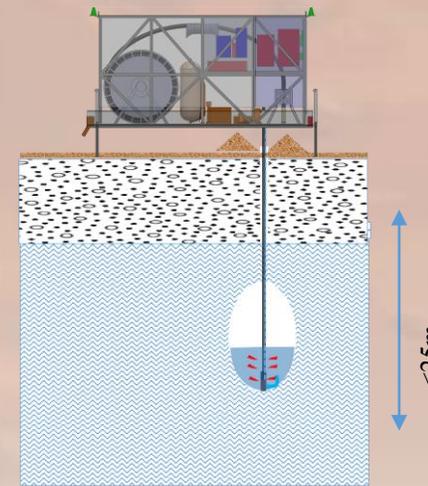
# Mars 150t Borehole Water Well Rig: Executive Summary



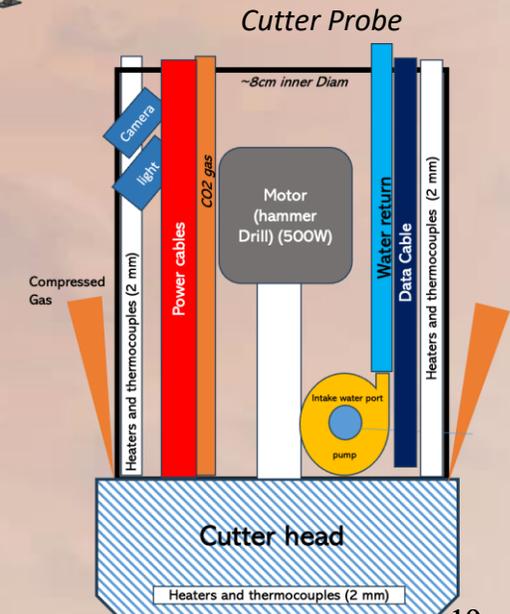
- **Drill/Pump Rigs to extract 150t of water from ice just below the surface in 20 months on Mars (>30° latitudes)**
- **Borehole equipment:**
  - Coiled Tubing
  - Probe with cutter head and heaters
- **Peak Power:** ~ 10 kWe for heaters, ~ 10 kWe for water processing → w 30% growth ~27.5 kWe
- **Thermal:**
  - ~ 10 kWe heaters and thermocouples on ~ 20m of coiled tube and Probe: Allows precise temp control of all parts of system
  - Multiple radiators for cooling equipment and condensing water : ~17 m<sup>2</sup> effective area
- **Fluids:**
  - CO<sub>2</sub> compressed gas for clearing cuttings, CO<sub>2</sub> atmospheric pump
  - Water pump to raise water
- **Mechanical:**
  - Coiled Tubing with cutter probe
- **Mass: 1917 kg**



Borehole Water Well Rig plant (1 of 2)



Water well Operation

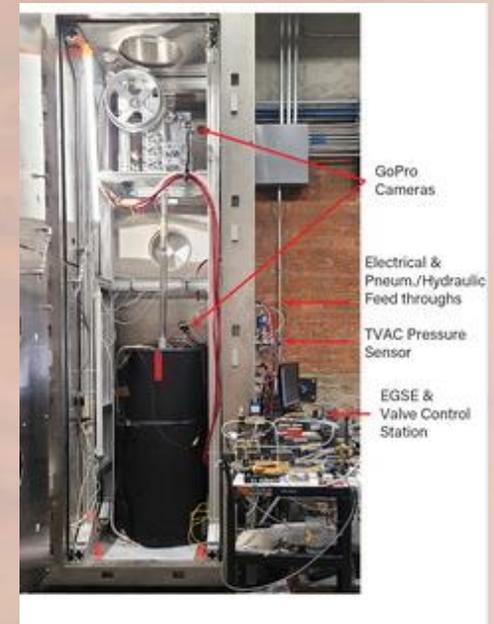




# Ice Drill Rig Layout



LANL Coiled-Tubing Deployed Micro-drilling System (2002)



Based on terrestrial coiled tubing and Honeybee Redwater SBIR demonstrator

Compressed CO<sub>2</sub> Tank

Water Buffer Tank

Compressors (2)

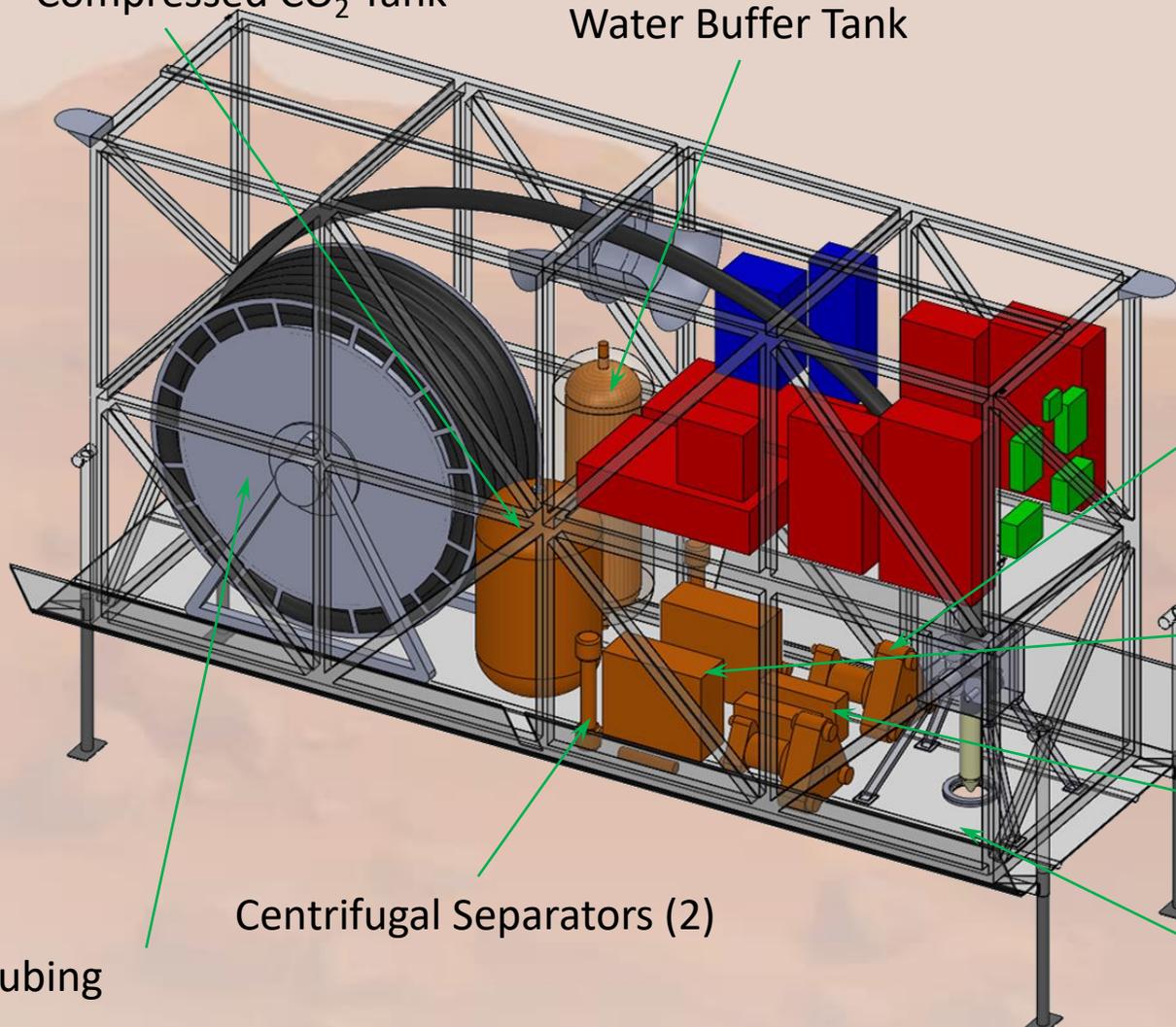
Boiler (2)

Steam Recuperators (2)

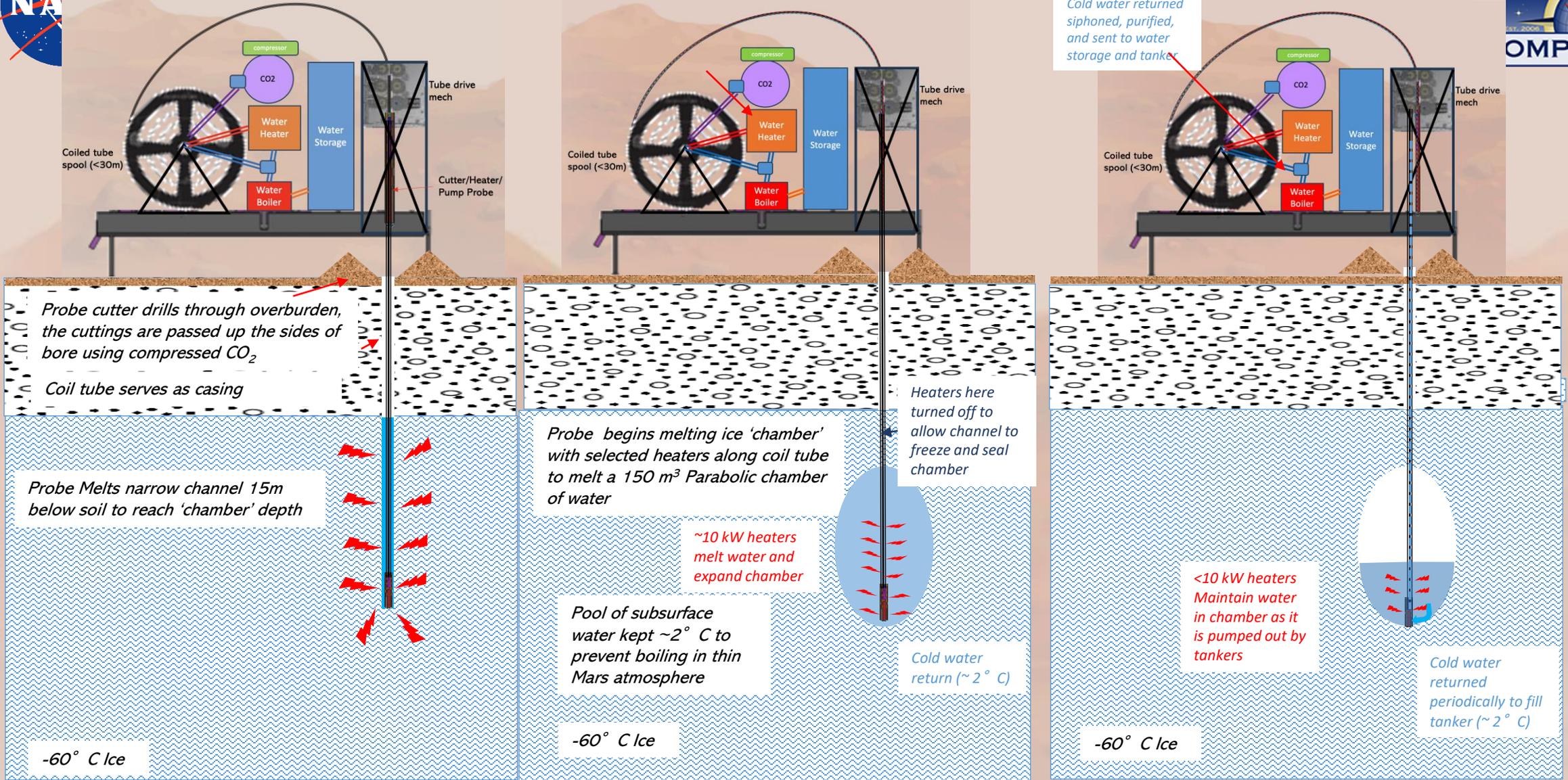
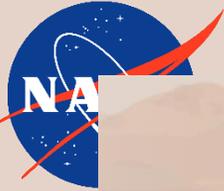
Cutter/Pump head

Centrifugal Separators (2)

Coiled Tubing



# Subsurface Water Well Development



**Phase 1:** Drill through overburden ( $<10\text{m}$ ) and then melt into chamber depth (0.63 m/hr best case)  $\sim 15\text{m}$  below overburden) ( $\sim 30$  days)

**Phase 2:** Use probe heaters to form the 150t water chamber (380 days)

**Phase 3:** Keep water warm, pump out water from chamber as needed to fill 5t water tankers (600 d, 30 trips).

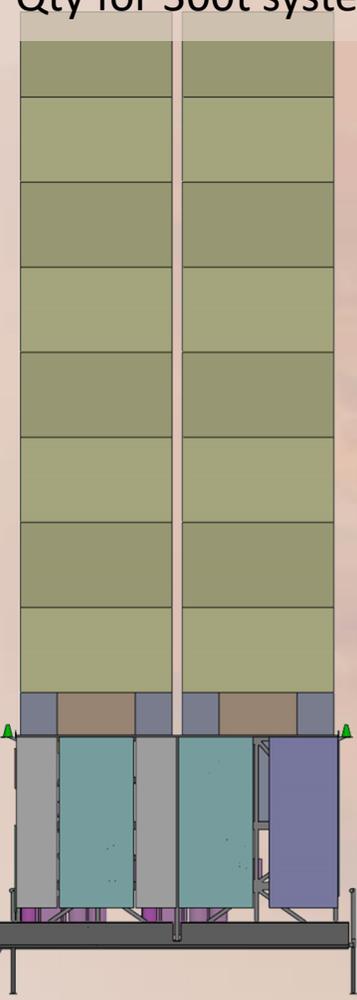


# Borehole Mining for ISRU Propellant Production (300 t) Elements



## ISRU System

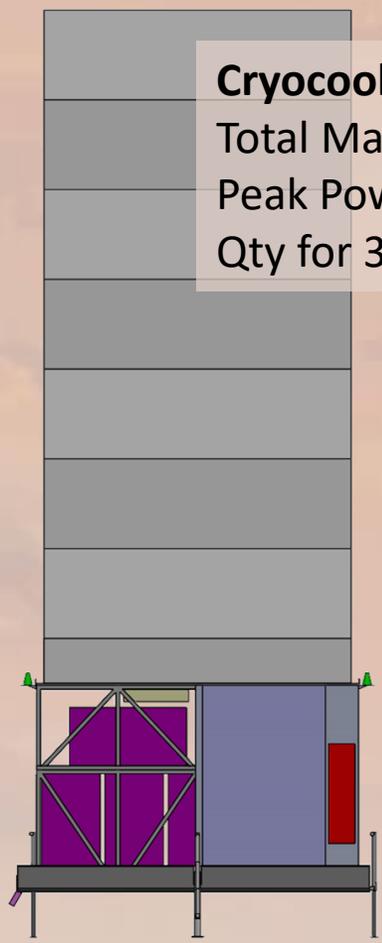
Total Mass: 5.5 t ea  
Peak Power Need: ~62 kWe ea  
Qty for 300t system: 3



Note: This image only shows elements designed by the Compass team. Additional items including the Surface Water Transport, Autonomous Chassis and Water Storage on the MALV are also needed.

## Cryocooler System

Total Mass: 3.5 t ea  
Peak Power Need: ~20 kWe ea  
Qty for 300t system: 2



Approx. 6 ft (1.8 m)

## Borehole Mining System

Total Mass: ~1.9 t ea  
Peak Power Need: ~27.5 kWe ea (only 1 pulls power)  
Qty for 300t system: 2 (for redundancy)



## FSP Control System



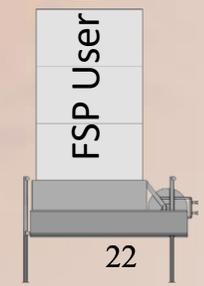
Approx. 6 ft (1.8 m)

## Fission Surface Power

Total Mass: 10 t  
(including auxiliary pallets)  
Power Provided: 40 kWe  
Qty for 300t system: 7



## FSP User System





# ISRU with Surface Mining Option



MALV #2  
(Mining/Power)

MALV #3  
(Mining/Power)

MALV #5  
Crew

500 m

MALV #1  
(Mining/Power/  
Water Storage)

#1  
#2  
#3  
#4

MALV #4  
(ISRU/MAV)

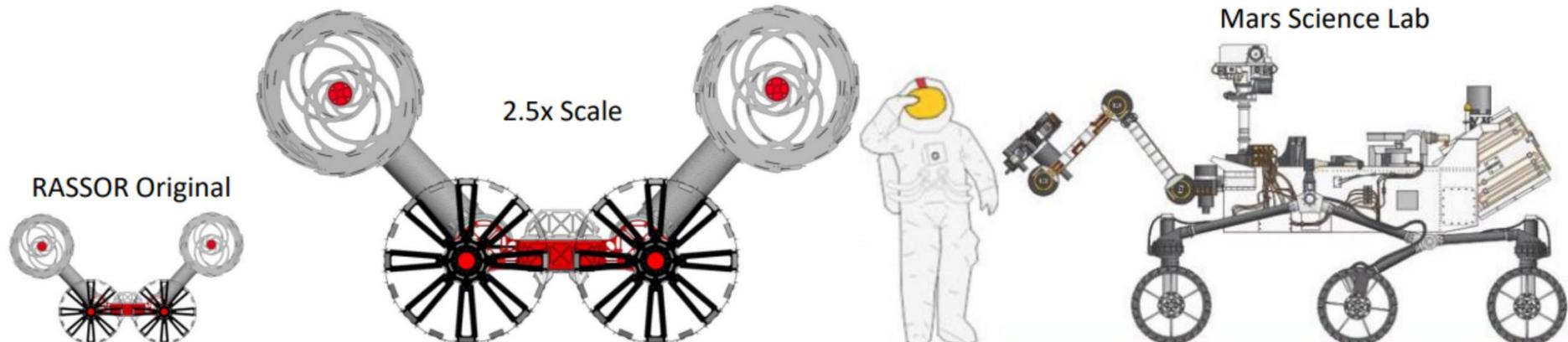
Fission Surface  
Power Park

Representative Landing  
Layout: Gale Crater

## Increasing RASSOR scale

- To meet the demand of 4 metric tons of excavated material per hour for LUNOX production RASSOR must be scaled up.
- A linear geometric scaling factor of 2.5x was assumed
  - Provides a point design to serve as a baseline
  - With additional inputs future work could focus on the optimal scale with consideration to power, mass, volume, and operational time.

Graphics Credit:  
HistoricSpacecraft.com

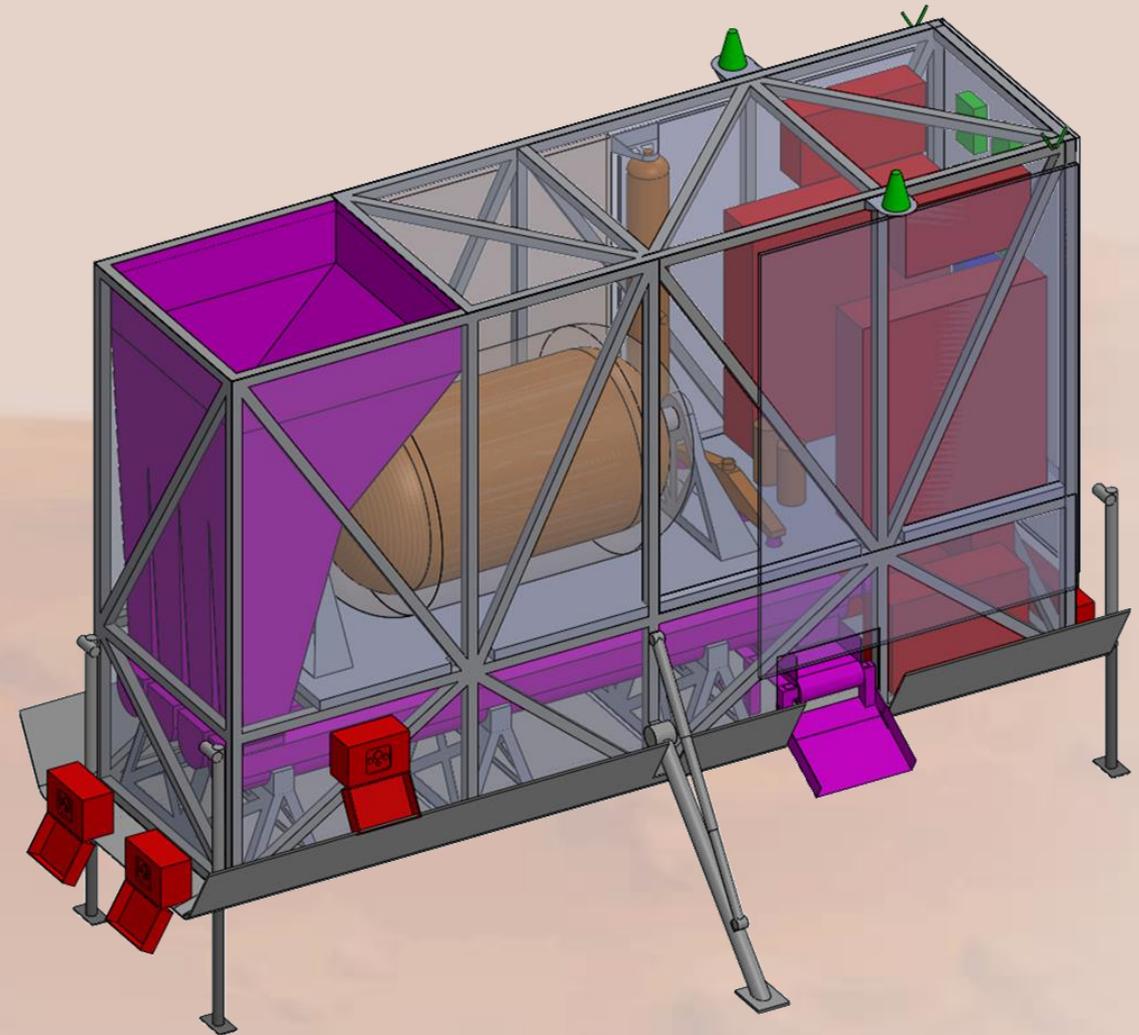




# Mars Water Extraction Rig: Executive Summary



- **WER processes 700 t of regolith producing 3.4 t of water per month**
- **WER Equipment:**
  - Collection Hopper, Auger Dryers, Water Compressors and Condensers, Water Storage
- **Peak Power: ~ 35 kWe for heaters, ~ 7 kWe for water processing → Including 30% power growth ~55 kWe**
- **Thermal:**
  - ~ 35 kWe heaters on an auger to heat solid to ~ 575K and remove water as vapor
  - Multiple radiators for cooling equipment and condensing water : ~11 m<sup>2</sup> effective area
- **Fluids:**
  - Water pumps up water pressure to 1 atm for condensing and transport
- **Mechanical:**
  - Auger tubes, leg stabilizers
- **Mass: 3300kg each**





# Test Dryer Auger

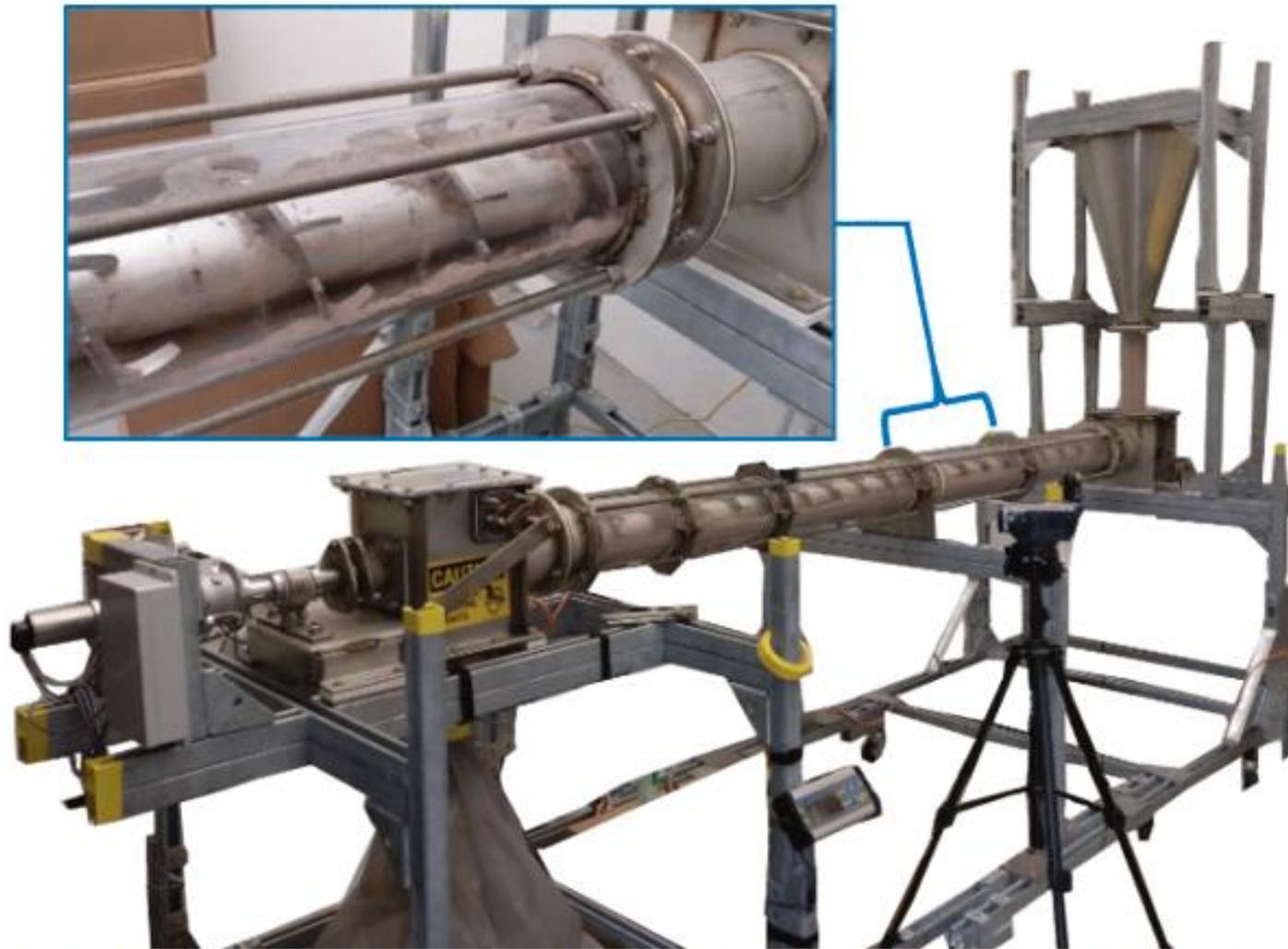
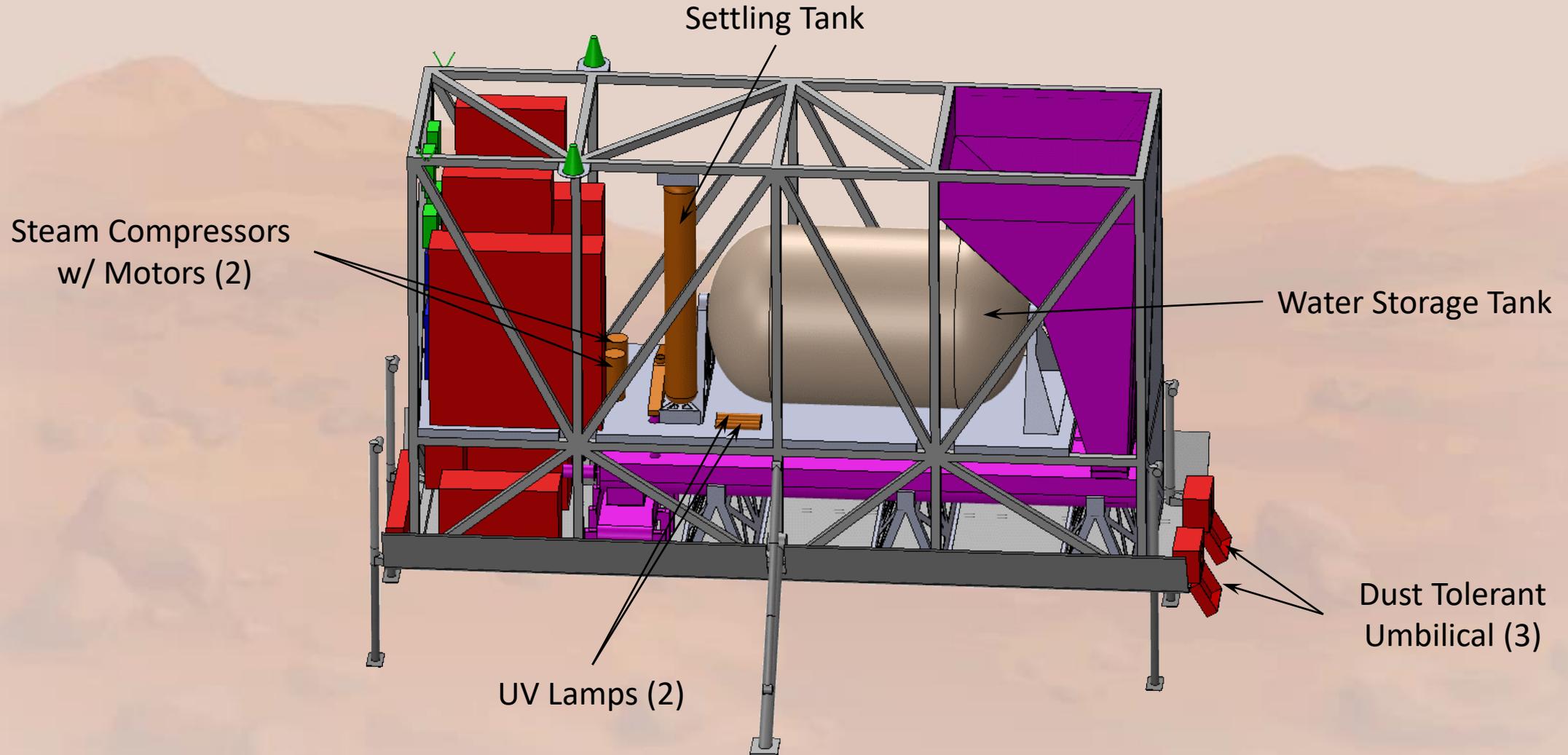


Figure 1 – LADI Breadboard (clear casing installed)

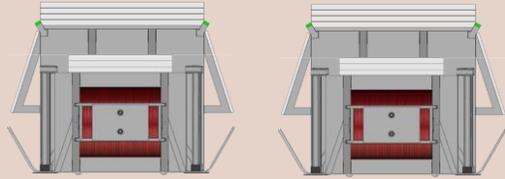


# Fluid System Layout

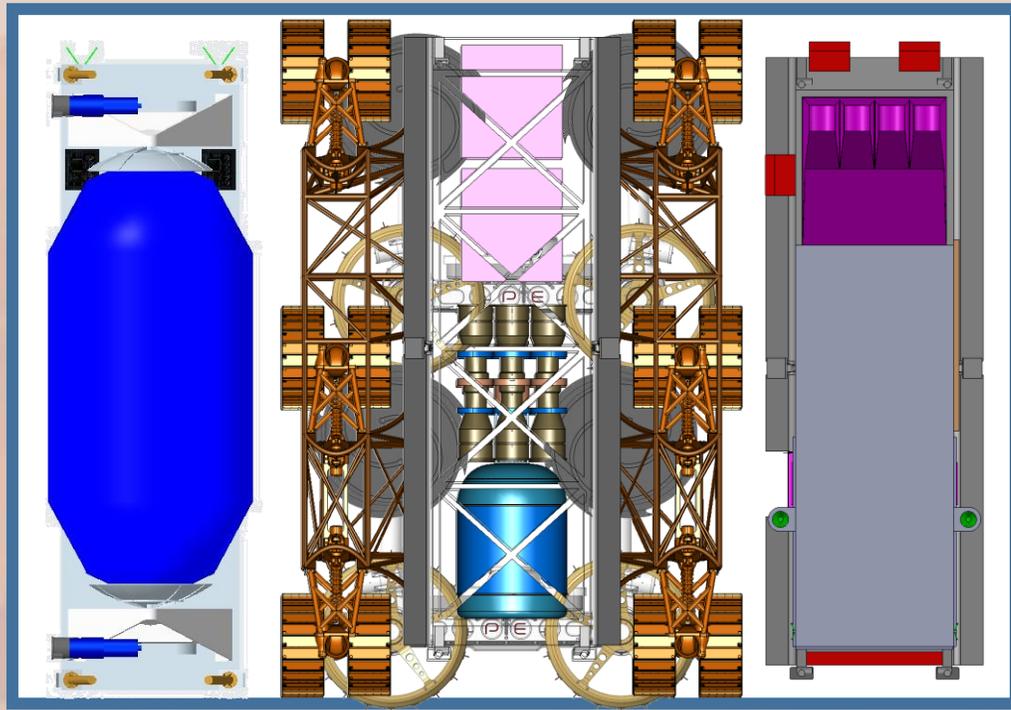




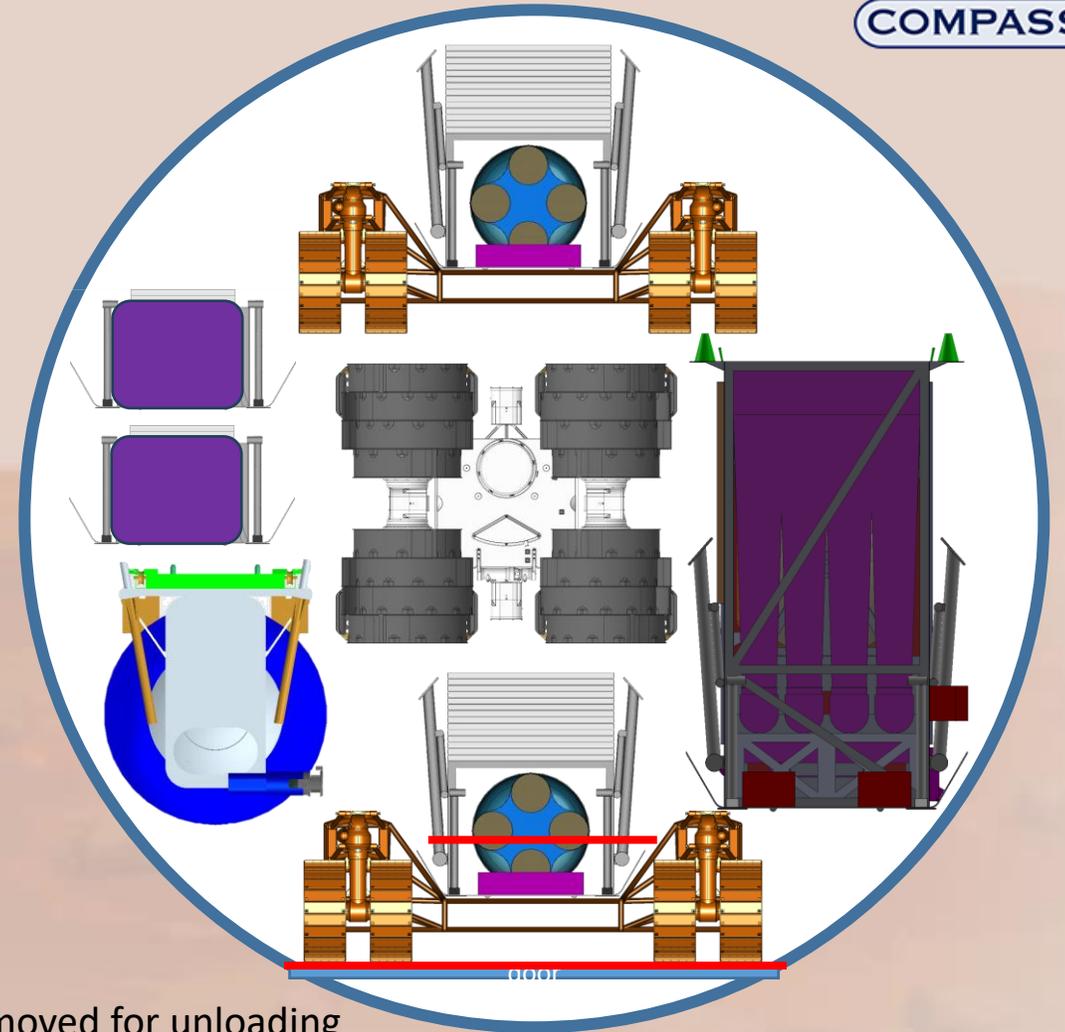
# Packaging Pallets on MALV Cargo Landers



5m



7m



- Payloads VERY tight; reality might require additional room to get payloads moved for unloading
- Payloads stacked vertically, interface brackets not shown, all loads might need to go through floor
- Two FSP reactor pallets with two reactor controllers/ 1 km cable carts stacked and one empty water tank pallet
- One WER pallet, two RASSORXs, and two loaders
- First FSP pallet and chassis lowered by craned onto deployed door



# Top Level Case Comparisons



		Send 150 t of Water to Mars	Borehole Mining	Surface Mining (Regolith)	Send Methane (ROM)	Send All Return Propellant (ROM)
<b>Total Number of non-Crew MALVs</b>		<b>4</b>	<b>3</b>	<b>4</b>	<b>~3-4</b>	<b>5</b>
Maximum Average Power (Excavation/Prop. Production)		NA/ 236 kWe	28 kWe/ 236 kWe	224 kWe/ 236 kWe	~236 - 320 kWe	~40 kWe
Total Mission Duration (Assuming 1 SLS per 26 months)		104 months	78 months	104 months	78-104 months	130 months
Number of FSPs (determined based on available time, based on SLS limitation)		6	7	6	6-9	1-2
Unique Elements	Water Tanker	X (30 trips)	X (30 trips-longer dist)	X (60 trips)		
	ISRU Pallet	X	X	X	X (modified)	
	Liquefaction Pallet	X	X	X	X (modified)	
	Cryo Tanker				<b>X (15 trips)</b>	<b>X (60 trips)</b>
	Borehole Pallet		X		Note: These are based on 'back of the envelope' calculations only and do not have an associated point design	
	Pallet for Extracting Water			X		
	RASSORX			X		
	Loaders			X		
	FSP/Controller/Cabling	X	X	X	X	X
	Autonomous Chassis	X	X	X	X	X



# Conclusions



- Several options for implementing ISRU on Mars to make 100's of tons of propellant were conceptualized— an often-mentioned feature of sustained human Mars missions
- The concepts begin to show the magnitude in time, power and complexity of the surface infrastructure needed to implement any of these approaches
  - Energy needs of  $> 11$  MWhr/t of propellant, even more when Mars water is acquired
- The most promising solution (subsurface water) is not globally available, limiting where the crew would land
  - This is also true of surface mining using gypsum (baseline design did NOT assume gypsum)
- Mining ice or soil has planetary protection implications to be evaluated
- Results demonstrate that *only by reuse of the ISRU equipment, and thereby revisiting a past landing site*, would the ISRU options begin to have an advantage, at least for 100's of tons of production
  - *This may be in conflict with desirable scientific/exploration mission objectives*

