Kiloton Class ISRU Systems for LO_2/LCH_4 Propellant Production on the Mars Surface

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As part of the 2023 strategic analysis cycle to explore the trade space, the NASA Mars Architecture Team wanted to explore what it takes to produce in situ on Mars many hundreds of tons of propellants for a large all-chemical transportation system. The conceptual operations and design of the LO_2/LCH_4 in situ resource utilization (ISRU) water acquisition, propellant production and liquification system was assigned to the NASA Compass concurrent engineering team with support from various NASA ISRU, cryogenic fluid management, and surface power experts. The conceptual point design examined one case producing 300 t of LO_2/LCH_4 from the Mars atmosphere and delivered water in 20 months and storing the liquified propellants in a to-be-reused lander. Several of these large single-stage, all-chemical class large vertical landers would deliver the required ISRU equipment. The required 150 t of water stock for the ISRU system was traded between three options: delivered, pumped from subsurface ice deposits or extracted from surface soils. The large propellant production systems consist of atmospheric CO_2 collection scroll pumps, a combined solid oxide electrolysis and methanation system to convert the CO_2 and water into gaseous O_2 and CH_4, and various dryers, scrubbers, and separators to remove the excess water, CO_2 and H_2. The liquefaction system consisted of 90 K cryocoolers to provide cold Ne to the launch vehicle tanks to liquify these CH_4 and O_2 gases and store them as rocket propellants. The systems are deployed using a 6 t (payload) capable chassis derived from conceptual pressurized rover designs. In total, the propellant production and liquefaction systems required three propellant production pallets, two liquefaction pallets, two water tankers, and six 40 kW-fission surface power systems (FSPS) with cabling. All this equipment was found to notionally fit inside two- 75 metric ton payload capacity Mars ascent and landing vehicles (MALV). For the case where 150 t of water delivered from Earth, four cargo MALVs are required for the full system. The same is true when the 150 t of water is extracted through surface mining. For the borehole system, only 3 cargo MALVs are necessary. A comparison of approaches in terms of number of landers, number and type of elements, power and time is made.

I. Introduction

As part of the 2023 strategic analysis cycle, the NASA Mars Architecture Team wanted to explore what it takes to produce in situ on Mars many hundreds of tons of propellants for a Mars ascent vehicle. This was one of many Mars architectures under study including nuclear electric propulsion combined with chemical, solar electric propulsion combined with chemical, and nuclear thermal propulsion. This ISRU architecture assumed a 75 t payload class, single stage, MALV that could enter Mars hyperbolically, perform aero-deceleration, and land on the Mars surface. This vehicle, if refueled using in-situ propellants could then return the crew to at least a 5-sol Mars orbit. The conceptual MALV was designed by NASA Marshall Space Flight Center (MSFC)/Advanced Concepts Office (ACO) and is shown in Fig. 1 [1]

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Fig. 1 Conceptual Mars Lander

The conceptual operations and element designs of the water collection, propellant production, and liquefaction systems for this LO_2/LCH_4 rocket were assigned to the NASA Compass concurrent engineering team with support from various NASA ISRU, cryogenic fluid management, and surface power experts. The conceptual point designs examined one scenario producing 300 t of LO_2/LCH_4 from Mars atmosphere and water delivered from Earth in 20 months and storing the liquified propellants in the MALV to later be used by the crew for launch to orbit. Two additional design options evaluated use two potential in-situ water sources in lieu of bringing the water from Earth: subsurface ice and surface soil mining.

These efforts focused on the water collection, processing, conversion to O_2 and CH_4 gases and liquefaction systems sizing, deployment, operations, technologies, and risks. Figures of merit included: performance (production rate), mass, robustness, cost, and life. The designs were made to be single fault tolerant. Due to known Mars dust storm events of many months, a nuclear power source was assumed instead of solar. The recent government conceptual design Lunar 40 kW FSPS was modified for use on Mars to power the ISRU systems [2]. For this study the required 150 t of water for the ISRU system was assumed delivered from Earth or mined on Mars. NASA Kennedy Space Center (KSC) designed the surface water transportation pallet (water tanker) and water storage [3] in parallel to the Compass water extraction options, propellant production pallet, and liquefaction pallet designs.

For each element of the architecture, a discussion of the concept of operations of the elements follows along with descriptions of the support systems. This paper presents layouts, element components/processes, and notional MALV manifesting of the ISRU ‘pallets.’ A mass breakout is included. Also discussed are the advantages and limitations of each element, along with technology readiness levels (TRL) and potential risks.

The concept of operations for the core of the Mars ISRU system (propellant production, liquefaction, and storage) was found to be quite involved and is shown in Fig. 2. The user of the ISRU systems is the large single stage, all chemical MALV, that, after delivering some of the ISRU equipment, is loaded with ISRU propellants and used by the crew to reach a 5-sol Mars parking orbit. Several of these MALVs would deliver the rest of the required ISRU equipment, including power and surface transportation. The initial option looked at having the 150 t of water (to process with Mars CO_2 atmosphere to make the O_2 and CH_4 ascent propellants) delivered by two MALVs at -104 and -78 months (before crew ascent). Another study assumption was that only one MALV could be delivered every Mars opportunity. The assumed power systems (multiple 40 kW lunar FSPs) would be delivered at the next Mars opportunity (-49 months), then would be deployed from the MALV at least 1 km from lander, to reduce risk from potentially damaging debris caused by subsequent MALV landings. These FSPs could share most of the design attributes of the lunar version but would need to be positioned side by side for proper shielding operation and throttled down once the propellants were produced and the crew arrive to minimize radiation impacts on the crew during their Mars stay.

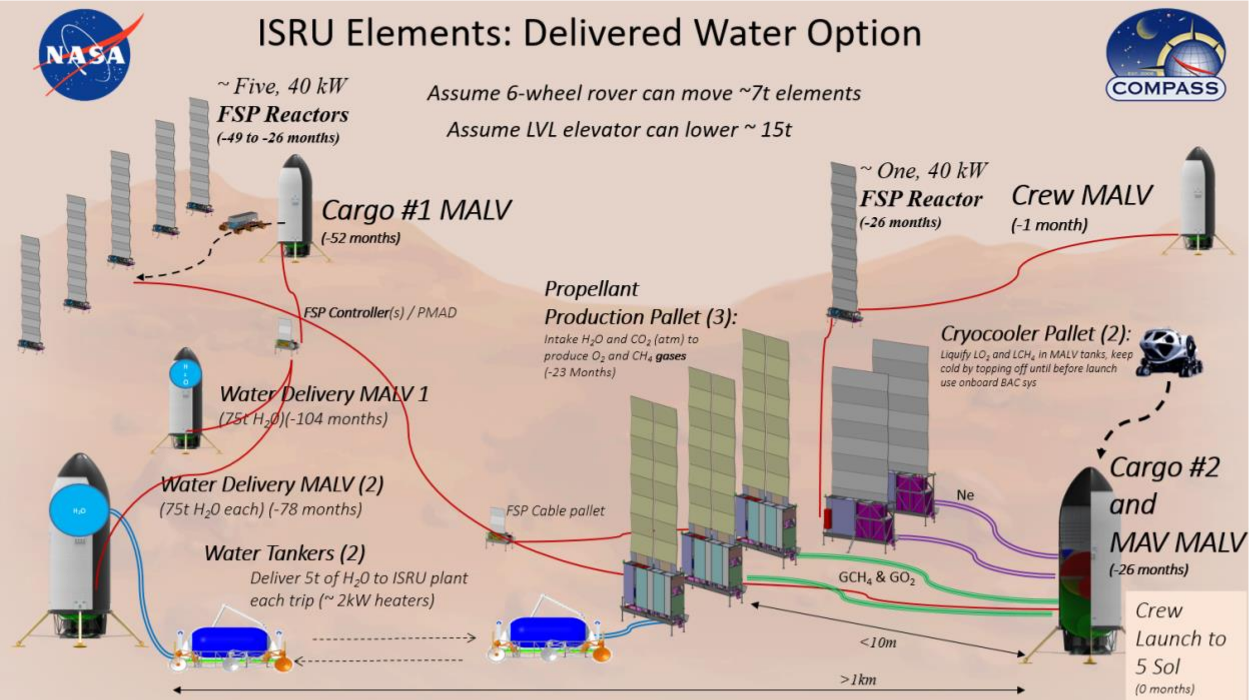


Fig. 2 ISRU Propellant Production Plant and Liquefaction Pallet Elements Concept of Operations

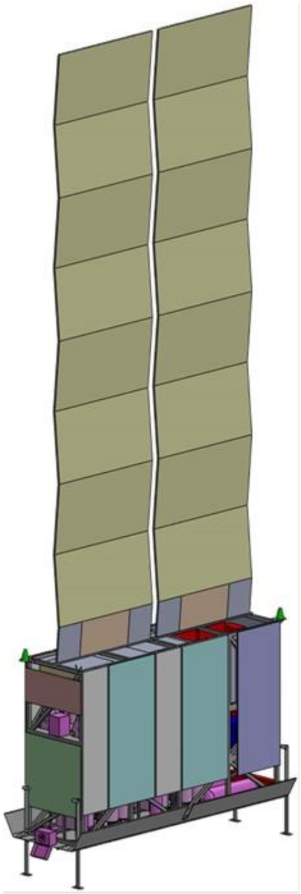


Fig. 3 Propellant Production Pallet

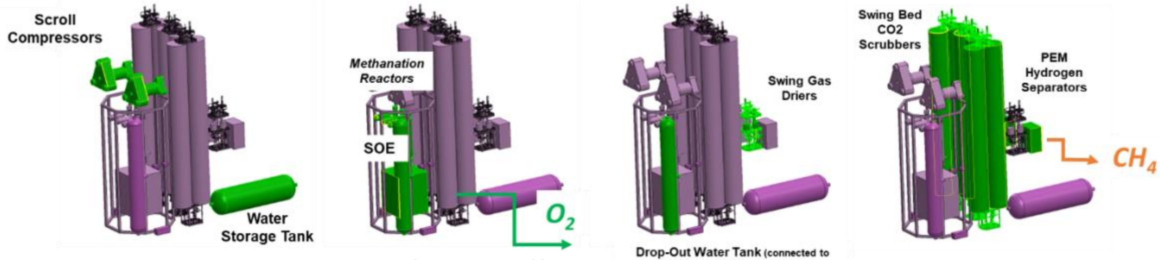
At the next Mars opportunity (-26 months) the propellant production and liquefaction systems would be delivered, deployed and begin operation. Two surface water transportation pallets carried by the autonomous chassis (capable of ~ 5 t water each) will shuttle the water from the delivery MALVs in 22, ~ 1 km trips to the ISRU propellant production plant. The 300 t of gaseous O_2 and CH_4 is produced and then transferred to the crew ascent MALV for liquefaction and storage before the crew descends on the next opposition opportunity, 26 months later. With the crew ascent MALV refueled, the crew board and ascend to 5-sol orbit for rendezvous with an Earth return vehicle that could use various propulsion technologies. The large propellant production system consists of atmospheric CO_2 collection scroll pumps, electrolysis, Sabatier, and dryers. The chassis to move the large power, ISRU and liquefaction pallets was scaled from conceptual pressurized rover chassis designs. These pallets were used to carry all the elements and could be picked up and slid off multiple times by a common chassis. The pallets are about 4.5 m long and about 1.5 m wide.

In an effort to simplify the transportation of propellants, it was decided to transport the water from the source location (i.e., water delivered from Earth and stored in MALV payload tanks or Martian water feedstock) to the propellant production and liquefaction pallets which themselves could be placed within 10 meters of the MALV to be refueled. This eliminated the need for transport and pumping of cryogenic propellants. Instead, only water is needed to be pumped into the propellant production pallet, the produced O_2 and CH_4 gases are sent to the MALV tanks where cold (90 K gaseous Ne) would be pumped from the liquefaction pallet, also located near the MALV, to liquify the O_2 and CH_4 gases in the MALV tanks. Thus, only liquid water and gaseous O_2, CH_4, and Ne need to be pumped between elements.

Producing and storing 300 t of LO_2/LCH_4 in 20 months requires multiple elements. Three ~ 5.4 t, ISRU pallets using a total of ~190 kW continuous (5+1 ISRU strings) performs the production of the O_2 and CH_4. Two liquefaction pallets are needed to liquify the ISRU produced GO_2 and GCH_4 using the broad area cooling built into the MALV main propulsion tanks, using a total of ~45 kW. In total roughly 230 kW of continuous power (~ 11.5 MWhr/t propellant) is required for the propellant production and liquification.

A. ISRU Propellant Production Pallet

The propellant production pallet is shown in Fig. 3. Due to volume requirements, three pallets are needed to produce the 300 t of GO_2 and GCH_4. The full system can process water and atmospheric CO_2 into gaseous O_2 (~18.5 kg/hr) and CH_4 (~4.6 kg/hr).



1. *Atmosphere (CO_2) pumped with scroll compressors and H_2O gathered from storage tank (delivered by water tanker pallet).*

2. *CO_2 and H_20 processed by SOE module into a product **O_2** stream (which is cooled and sent to the user to be liquefied), H_20 (which is condensed and resent to SOE) and a CO_2/CO/H_2 stream (which is processed by methanation reactors into **CH_4**/H_20/H_2/CO_2).*

3. *H_2O is again separated out with condenser radiator and swing gas dryers and sent to the drop-out water tank to be reprocessed.*

4. *Remaining CO_2 and H_2 gases removed by CO_2 scrubbers and then PEM separators, respectively. Remaining product **CH_4** gas cooled and sent to user to be liquified.*

Fig. 4 ISRU Pallet Components and Processes

Each 5.4 t pallet uses a total of ~62 kW continuous. Fig. 4 shows the CO_2 collection (atm pumps), electrolysis, Sabatier reactor, condensers, and dryer subcomponents. These systems were based on past work, albeit at a smaller scale (ref Kleinhenz). The core of the conversion process from CO_2 and water is the electrolysis unit which, by using alternating plates, can produce both O_2 and CH_4 using H_2O and CO_2 [3]. Each ISRU pallet can process ~ 75 kW of power each from FSPSs and each requires a switchgear for high power loads. The thermal system requires multiple radiators for the electrolyzer, methanators, condensers, and support equipment for a total of ~38 square meters effective area. The mechanical system uses a cage for the ISRU components and integrates it into a common pallet to be moved by the 6-wheel common chassis. Control strings for the plant operations communicate by either an orbiter ultra high frequency (UHF) or a surface Wi-Fi system.

B. Liquefaction Pallets

The system to liquify the 300 t of GO_2/GCH_4 in 20 months on Mars is broken into two pallets due to the limits of the 6-wheel autonomous chassis. The liquefaction pallets' only job is to produce cold Ne to liquify and maintain the O_2 and CH_4 propellants on the crew ascent MALV. The core of the system is the 90K cryocoolers producing 90K Ne gas. The cryocooler systems in this design are based on current development and testing [4] [5]. The liquification pallet is shown in Fig. 5. Each pallet has twelve, 90 K cryocoolers to process a combined system total of gaseous O_2 (~15 kg/hr) and CH_4 (~4 kg/hr) into liquid. Each 3.5 t liquefaction pallet uses a total of ~21 kW providing 90K Ne to broad area cooling systems on the main propulsion tanks on the MALV. The thermal system design specified multiple radiators, each offering an effective area of about 40 square meters, to serve the needs of the cryocoolers and switchgear. Similar mechanical, power and command/communication systems are used as in the propellant production pallet.

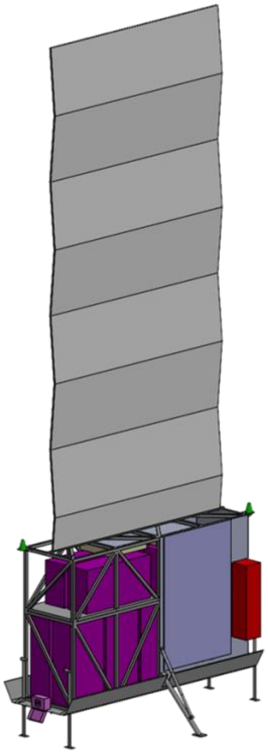


Fig. 5 Liquification Pallet

Table 1 shows the mass breakdowns for both the propellant production and liquefaction pallets. The propellant production equipment dominates the mass of that pallet as does the cryogenic system on the liquefaction pallet. Note that the support systems to the core propellant production or cryogenic system is about the same mass again. The power system and thermal systems were mainly the switchgear and radiators, respectively.

Table 1.   ISRU Propellant Production Plant and Liquefaction Pallets Mass Breakdown

MEL Summary: Case 1_Large_Scale_Mars_ISRU CD-2023-199	ISRU Propellant Production Plant	Liquefaction Pallet	TOTAL
Main Subsystems	**Basic Mass (kg)**	**Basic Mass (kg)**	**Total Basic Mass(kg)**
Command & Data Handling	133	12	145
Communications and Tracking	9	9	18
Electrical Power Subsystem	546	449	995
Thermal Control (Non-Propellant)	560	377	937
ISRU Equipment	1900	0	1900
Cryogenic Fluid Management	84	1258	1342
Structures and Mechanisms	837	485	1322
Element Total	***4068***	***2590***	***6658***
Element Dry Mass (no prop,consum)	4068	2590	6658
Element Mass Growth Allowance (Aggregate)	740	521	1261
MGA Percentage	18%	20%	19%
Predicted Mass (Basic + MGA)	4807	3111	7919
System Level Mass Margin	610	389	999
System Level Growth Percentage	15%	15%	15%
Element Dry Mass (Basic+MGA+Margin)	5417	3500	8917
3 Propellant Production Pallets and 2 Liquefaction Pallets	***16252***	***7000***	***23252***

C. Water Cargo Delivery Option

Roughly 150 t of water is needed for the ISRU processing. Three options were evaluated by the team. The simplest option was to bring the water from Earth in two cargo landers, keep it warm until ready for production, and then transport it using a water tanker to the propellant production plant. The more complex options were to mine water on Mars, either below the surface or on it.

Regardless of the water source, a method of transferring the water to the ISRU plant was needed. The water transfer concept of operation called for a minimum of two surface water transportation pallets, each capable of carrying approximately 5 t of water. These pallets were to shuttle water from the water delivery MALVs or from mining operations to where it was needed. Both the water storage and surface water transportation pallet designs were performed by the KSC team and published elsewhere [3].

D. Launcher Packaging Assessment

The team assessed top-level packaging of the various required pallets to determine how many MALVs would be needed to deliver the necessary components. A first order, sample packaging for one of the landers is shown in Fig. 6. Only notional masses for structures for launch support and unloading cranes has been made, but all of the pallets are arranged vertically to make better use of the space. A notional ‘attic’ is assumed to carry some of the smaller elements such as power cable and surface water transportation pallets. Each pallet is assumed to be sequentially removed by the six-wheel chassis and in turn deployed on the surface using the MALV’s built-in elevator. Even with a 10 percent assessment for structure to hold the various pallets in place, it is evident that a volume limitation, not a delivered mass limitation, is driving the number of MALVs required.

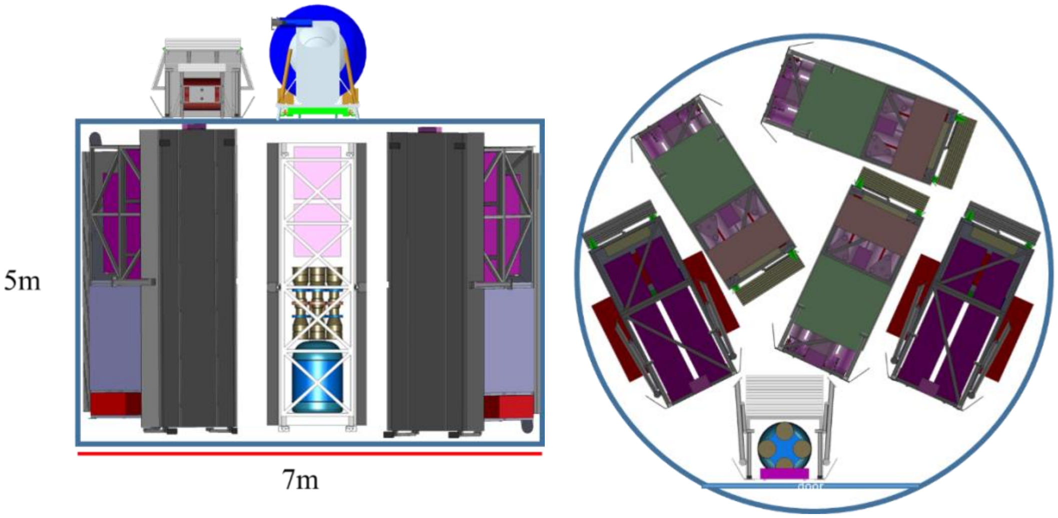


Fig. 6 Notional Layout of ISRU Pallets in LVL

E. ISRU Launch Manifest and Power Requirements

Table 2 shows the total manifest for the ISRU elements (except for the additional two MALVs needed to deliver the 150 t of water). Both launches for the power and ISRU systems (respectively) are less than the available 75 t of payload capacity.

Table 2. ISRU Launch Manifest (Earth Water option)

Mars Mission Description *Assumptions:* *• 2 crew, 30 sols on the surface*							FSP, Water Pallet		ISRU, FSP, Water Pallet	
							MALV 1		MALV 2	
Category		Mars Element/System	Basic Mass (kg)	Mass Growth Allowance (MGA)	Mass Margin	Control Limit (kg)	Count	Mass w/ Margins	Count	Mass w/ Margins
MARS SURFACE SYSTEM PAYLOADS	Power - 40 kW FSP	1km Cable and Spool	597	30%	15%	**866**	5	4,331	1	866
		Power Distribution System (included	1,258	20%	15%	-		-		-
		Controller/Voltage Convertor pallet (50m from the reactor pallet)		32%	15%	**1,849**	5	9,246	1	1,849
		40 kW Reactor	5,590	16%	15%	**7,323**	5	36,615	1	7,323
	ISRU	ISRU Pallet	5,417	18%	15%	**7,215**		-	3	21,645
		Liquifaction & Cryocooling Pallet	3,500	20%	15%	**4,729**		-	2	9,459
		Water Tanker Pallet	3,000	20%	15%	**4,050**	1	4,050	1	4,050
	Robotics	Lightweight Manipulator - Payload=5 t	748	0%	15%	**860**	1	860	1	860
		Lightweight Manipulator - Payload=8 t	1,188	0%	15%	**1,366**	1	1,366	1	1,366
		6-wheel payload mobility chassis	2,000	0%	15%	**2,300**	2	4,600	1	2,300
		Robotic Helicopter	5	5%	15%	**6.0**		-		-
	Logistics Rollup		1,327			**1,373.1**				
	Crew Mobility	Pressurized Rover (PR)	6,540	15%	15%	**8,502**		-		-
		Mars Terrain Vehicle (Unpressurized)	961	23%	15%	**1,324**		-		-
	Science Rollup		2,536			**2,541.2**				
INTEGRATION	Payload Integration	10% of Lander Capacity	5,251	0%	0%	**5,251**		6,107		5,309
MARS CREW SUPPORT SYSTEM PAYLOADS	Crew	2 Crewmembers	175	0%	0%	**175**		-		-
		Crew Cabin	2,072	14%	15%	**3,368**		-	1	3,368
	EVA Rollup		305			**370.2**				
OPTIONAL	Optional Items	Medical Kit Placeholder	10	0%	15%	**11.5**		-		-
	Total Mass including Optional Items (kg)							**67,175**		**58,395**

A summary of the power required by all the ISRU elements is shown in Table 3, demonstrating that six 40 kW FSPs are needed. The propellant production pallets required ~187 kW of power, while the liquefaction pallets needed only ~42 kW. A small amount of additional power for the MALV, mobility chassis recharging, and Earth water heating is also required (~ 8 kW).

Table 3. ISRU Element Power Requirements

Element	Power per Unit (kW) (30% growth)	QTY	Total Power (kW)
ISRU Propellant Production Plant	62.4	3	187.3
Liquefaction Pallet	20.7	2	41.5
MALV (with crew cabin)	2.8	1	2.8
Mobility Chassis	1.3	2	2.6
Water conditioning	1.3	2	2.6
Total (kW)			237
FSP Unit Power (kW)			40
# of FSPs			6

F. Propellant Production and Liquefaction Pallets Lessons Learned, TRLs, and Risks

The use of a six-wheel chassis and pallet system initially employed for FSP units appears to be an effective strategy for the mobilization and deployment of equipment within the constraints of the MALV cargo volume and its door/elevator dimensions [2]. The potential for scaling up the ISRU, liquefaction, and water units is limited by both the MALV available volume and the deployer; hence, without a larger lander design, the current dimensions of these units are maximized.

The limitation of volume over mass is particularly evident when considering the density of the ISRU equipment in relation to the storage capacity of the MALVs. The MALV payload mass capabilities are not fully utilized due to these volumetric constraints. Similar to the FSP units, the radiators required for these systems are substantial in size and necessitate deployment once on the Martian surface. The effective radiator area needed is substantial, with the ISRU systems requiring approximately 38 square meters, cryocoolers around 40 square meters, and FSPS necessitating roughly 130 square meters.

Many of the subsystems of these pallets have technologies less than TRL 6. The communication strategy relies on a Wi-Fi system, which has yet to be demonstrated on Mars and is at TRL 5 for that location. For power management and distribution on the pallets, the autonomous modular power system (AMPS) was also at TRL 5. Thermal control is managed by a pump loop system on Mars, which has reached TRL 5, demonstrating that the technology has been tested and proven in a simulated environment. The propellant production components, including solid oxide electrolysis (SOE) and methanation processes, are at TRL 5, while swing beds, scrubbers, and proton exchange membrane (PEM) systems are less mature at TRL 4.

Cryogenic fluid management technology includes a 150 W/90 K cryocooler at TRL 4, indicating that it is still in the prototype development stage. The O_2 compressor, liquefaction operations, supply lines, broad area cooling system, and fluid management technologies such as water pumps and the inlet plenum, are all at TRL 5. The dust tolerant automated umbilical (DTAU) [6] is evaluated at TRL 4.

The main risks are the uncertainty of longevity for both the 150 W/90 K cryocoolers and the electrolysis/Sabatier propellant production systems. Whether these systems could process more than 300 t of propellants needs to be evaluated. Other risks include the impacts of dust on the radiators, non-condensable contaminates on liquefaction operations, and gas propellant lines connecting the ISRU and MALV.

G. In-situ Water from Subsurface Ice Deposits

In lieu of bringing the water from Earth, sources of in-situ water have been found a few meters just beneath Mars's surface. While early radar attempts to find large liquid water reservoirs deep under the surface failed, significant amounts of water ice were found just below the surface at higher latitudes. Indeed, the higher the latitude the closer to the surface the ice was found (Fig. 7). In fact, large 'cliffs' of water ice, over 100 meters high, have been observed from orbit facing away from the summer sun [7].

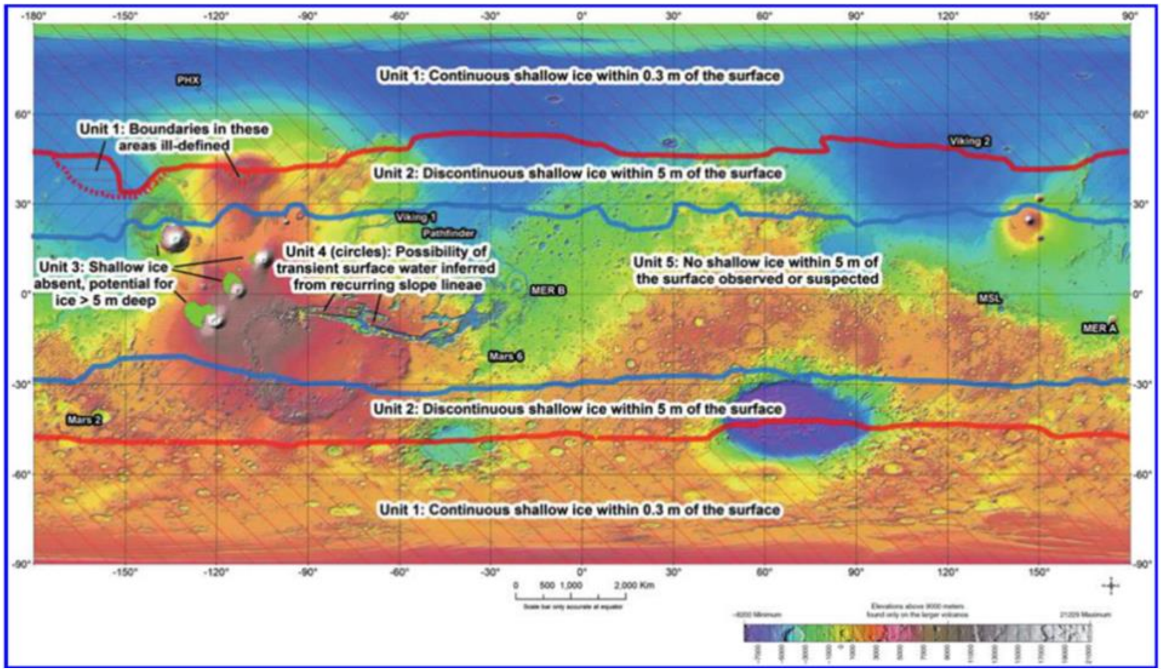


Fig. 7 Predicted Mars Water Subsurface Ice Availability

Several authors have suggested drilling into these, melting the ice and pumping up the water—similar to how arctic and Antarctic research bases mine water for base operations [8] [9]. Use of this approach on Mars would have additional challenges of landing near the ice deposits and drilling through the several meters of mineral overburden before reaching them, and it should be noted that significant research and operational assessments would be needed to ensure compliance with applicable planetary protection constraints.

The Compass Team performed a conceptual design to evaluate what such a mining system might look like and how it would perform. These borehole or water drill rigs would replace the tanks of water brought from Earth. Their operation is shown in Fig. 8.

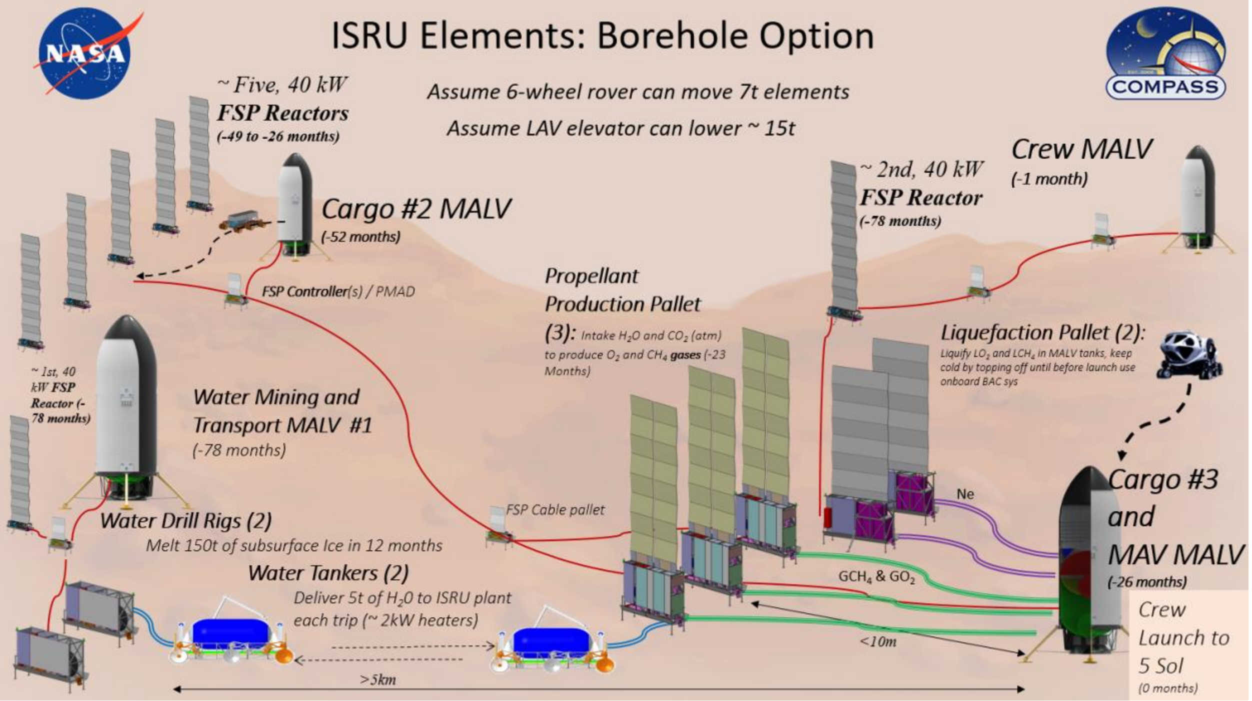


Fig. 8 ISRU Concept of Operations using Borehole Water Rigs

The Borehole pallet design is based heavily on the Small Business Innovation Research design and testing performed by Honeybee [10] [11] and, in turn, terrestrial tube mining processes [12]. The design is shown in Fig. 9 and Fig. 10. It combines the tube process with a cutting head to penetrate the expected ~ 2m of mineral overburden. It then transitions to the use of ~10 kW of heaters all along the tube to melt the water into a 15 m reservoir to generate the required 150 t of water. This design stores the water in this cavity until the water tanker can deliver the water in 5 t portions to the propellant production pallets. This also keeps the water mine as shallow as possible.

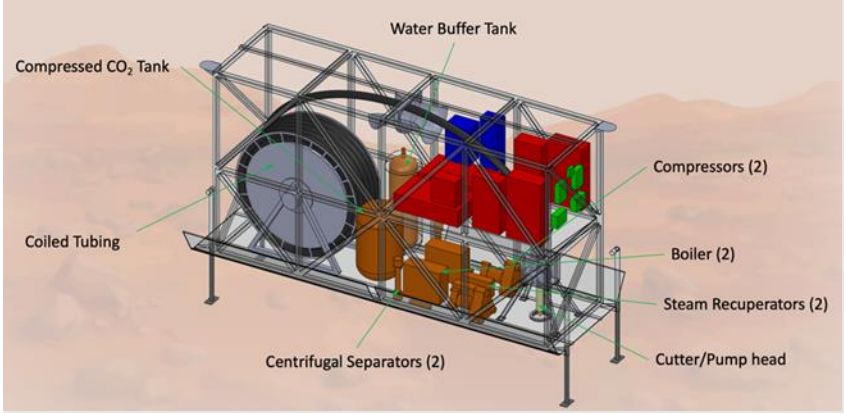


Fig. 9 Borehole Well Rig

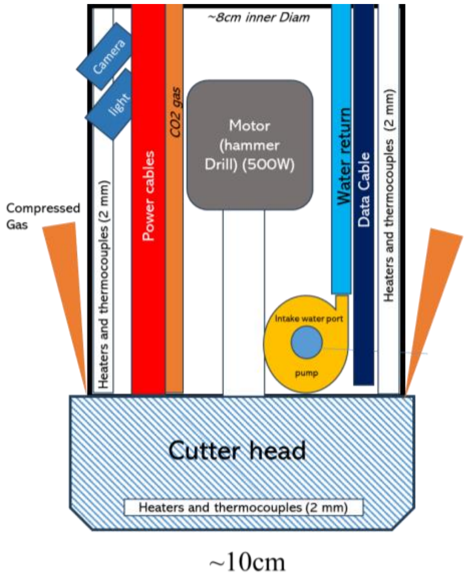
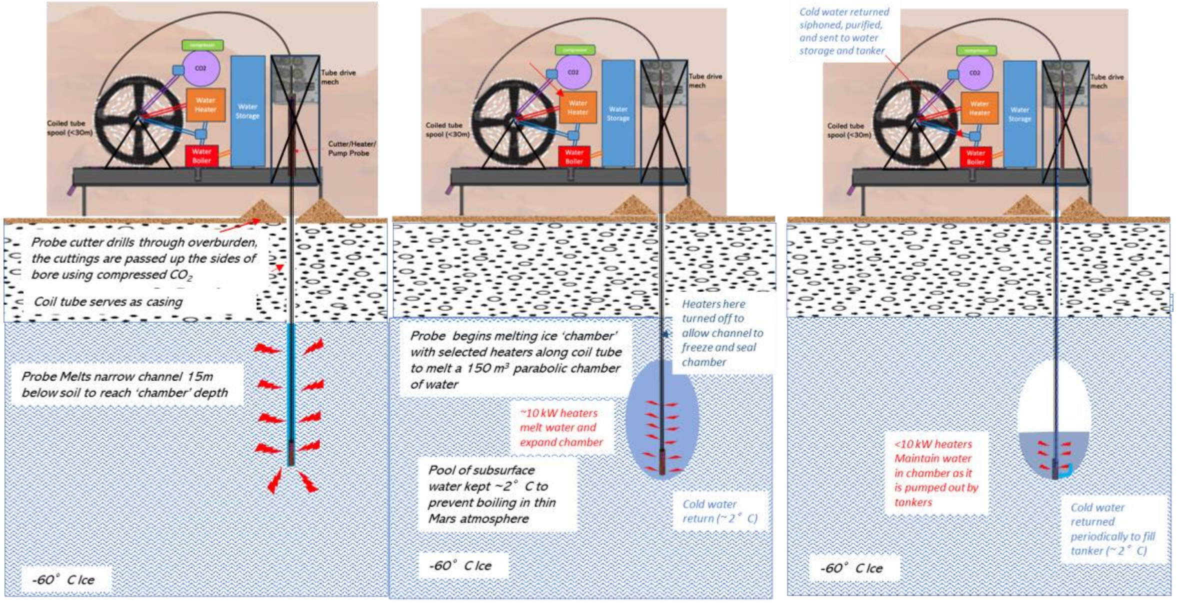


Fig. 10. Notional Tube Drill Cutter/Pump Head

While this design requires a continuous 10 kW of power to keep the melted water from refreezing, it is deemed simpler than either constructing large water storage tanks on the surface or using the MALV's former LO_2 tanks for storage, requiring that the water be moved by the tanker twice. The operational steps of the borehole rig are shown in Fig. 11.



Phase 1: *Drill through overburden (<10m) and then melt into chamber depth (0.63 m/hr best case) ~15m below overburden) (~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).*

Fig. 11 Borehole Rig Operations

A 500 W hammer drill would cut through the overburden soil. The design adds a motor to push a coil of tube down into the borehole. Once the ice is reached, the 10 kW of heaters are used to continue boring by melting and, once at depth, to melt the storage reservoir. An additional 10 kW is allocated for water processing, mainly boiling the water for planetary protection concerns. Factoring in a 30 percent growth in power needs, the total peak power is projected to be around 27.5 kW. For the thermal design, heaters and thermocouples are distributed along roughly 20 meters of coiled stainless-steel tubing and the probe, enabling temperature control throughout the system. This allows for turning off the heating at the top of the water storage chamber so that the top of the water cavity can freeze and seal the chamber. This in turn allows the build-up of a few pounds per square inch (PSI) to prevent sublimation of the subsurface water.

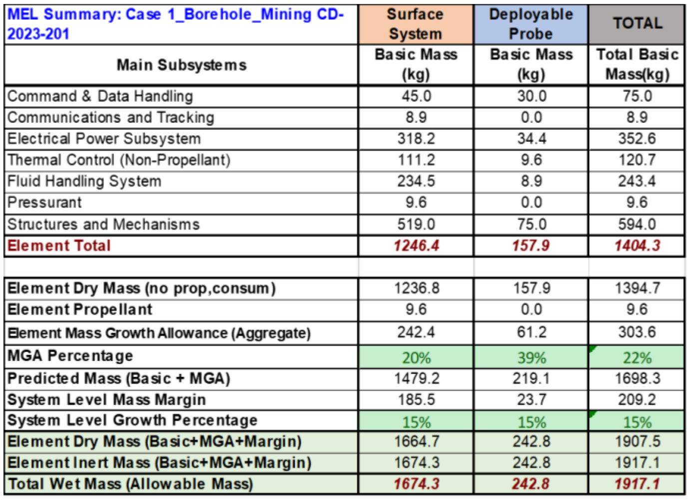
At the surface a cooling mechanism is facilitated by multiple radiators with a collective effective area of about 17 square meters, designed to cool the equipment and condense the extracted water vapor.

The fluid systems utilize CO_2 compressed gas (gathered from the Martian atmosphere) to clear the cuttings from the drilling process. Additionally, a water pump is employed to elevate the ullage gas of the water to the necessary pressure for condensation and subsequent transportation. From a mechanical standpoint, the drilling system incorporates coiled tubing attached to a cutter probe, all of which is mounted on a common pallet. This pallet is transported by a six-wheel common chassis, ensuring mobility and stability across the Martian terrain. Command and data handling (C&DH) operations are centralized in a control rig, which is in turn managed via UHF and Wi-Fi communications, allowing for remote controlling of the entire system.

The borehole system assumes 27.5 kW of electrical power from an FSPS delivered on the same MALV with the borehole system. While it would be possible to utilize waste heat from the reactor to assist in melting the ice, the interface challenges of joining a reactor with the borehole unit were left as an alternative for later evaluation.

The resulting borehole rig masses are shown in Table 4. Based on terrestrial experience an entire second borehole rig is added to the design in case the drill failed or got stuck in the ice. A baseline assumption is to send a subscale pilot plant to both find the water ice and demonstrate the tube drilling/melting approach. The borehole rig approach was found to be beneficial compared to delivering the water from Earth from a landed mass and timeline perspective as it saved both a MALV cargo lander as well as 26 months. It did add complexity in the form of planetary protection concerns and a new element (borehole system), as well as an additional FSPS.

Table 4. Borehole Drill Rig Mass Breakdown



MEL Summary: Case 1_Borehole_Mining CD-2023-201	Surface System	Deployable Probe	TOTAL
Main Subsystems	Basic Mass (kg)	Basic Mass (kg)	Total Basic Mass(kg)
Command & Data Handling	45.0	30.0	75.0
Communications and Tracking	8.9	0.0	8.9
Electrical Power Subsystem	318.2	34.4	352.6
Thermal Control (Non-Propellant)	111.2	9.6	120.7
Fluid Handling System	234.5	8.9	243.4
Pressurant	9.6	0.0	9.6
Structures and Mechanisms	519.0	75.0	594.0
Element Total	*1246.4*	*157.9*	*1404.3*
Element Dry Mass (no prop,consum)	1236.8	157.9	1394.7
Element Propellant	9.6	0.0	9.6
Element Mass Growth Allowance (Aggregate)	242.4	61.2	303.6
MGA Percentage	20%	39%	22%
Predicted Mass (Basic + MGA)	1479.2	219.1	1698.3
System Level Mass Margin	185.5	23.7	209.2
System Level Growth Percentage	15%	15%	15%
Element Dry Mass (Basic+MGA+Margin)	1664.7	242.8	1907.5
Element Inert Mass (Basic+MGA+Margin)	1674.3	242.8	1917.1
Total Wet Mass (Allowable Mass)	*1674.3*	*242.8*	*1917.1*

H. ISRU Launch Manifest with the Borehole Water Acquisition

By tallying up the required elements and performing a first order loading it was found that in most cases, the conceptual MALV design was again volume limited. Table 5 shows the total manifest for the Borehole ISRU elements. The first launch carries the borehole rigs, water tankers and required power. The second brings the balance of the FSPs, while the final launch carries the ISRU propellant production and liquefaction pallets. This last MALV will both store the cryogens and provide the crew with launch to a 5 sol Martian orbit.

Table 5. Borehole Option ISRU Manifest

Mars Mission Description *Assumptions:* • *2 crew, 30 sols on the surface*							Water mining, FSP, Water Pallets		FSPs		ISRU Production Systems	
							MALV 1		MALV 2		MALV 3	
Category		Mars Element/System	Basic Mass (kg)	Mass Growth Allowance (MGA)	Mass Margin	Control Limit (kg)	Count	Mass w/ Margins	Count	Mass w/ Margins	Count	Mass w/ Margins
MARS SURFACE SYSTEM PAYLOADS	Power - 40 kW FSP	1km Cable and Spool	597	30%	15%	866	2	1,732	5	4,331		-
		Power Distribution System (included		20%	15%	-		-		-		-
		Controller/Voltage Convertor pallet (50m from the reactor pallet)	1,258	32%	15%	1,849	2	3,699	5	9,246	1	1,849
		40 kW Reactor	5,590	16%	15%	7,323	2	14,646	5	36,615	1	7,323
	ISRU	ISRU Pallet	4,068	18%	15%	5,418		-		-	2	10,836
		Liquifaction & Cryocooling Pallet	2,590	20%	15%	3,500		-		-	2	7,000
		Water Tanker Pallet	3,000	20%	15%	4,050	2	8,100		-		-
	Robotics	Lightweight Manipulator - Payload=5 t	748	0%	15%	860	1	860	1	860	1	860
		Lightweight Manipulator - Payload=8 t	1,188	0%	15%	1,366	1	1,366	1	1,366	1	1,366
		6-wheel payload mobility chassis	2,000	0%	15%	2,300	1	2,300	2	4,600	1	2,300
		Robotic Helicopter	5	5%	15%	6.0	2	12		-		-
	Logistics Rollup		1,327			1,373.1		-				
	Crew Mobility	Pressurized Rover (PR)	6,540	15%	15%	8,502		-		-		-
		Mars Terrain Vehicle (Unpressurized)	961	23%	15%	1,324		-		-		-
	Science Rollup		2,536			2,541.2		-				
INTEGRATION	Payload Integration	10% of Lander Capacity	5,251	0%	0%	5,251		3,655		5,702		3,490
MARS CREW SUPPORT SYSTEM PAYLOADS	Crew	2 Crewmembers	175	0%	0%	175		-		-		-
		Crew Cabin	2,072	14%	15%	3,368		-		-	1	3,368
	EVA Rollup		305			370.2						
OPTIONAL	Optional Items	Medical Kit Placeholder	10	0%	15%	11.5		-		-		-
Water Mining	Water mining	Borehole pallets	1,395	22%	15%	1,917.1	2	3,834		-		
	Total Mass including Optional Items (kg)							40,204		62,720		38,392

I. Borehole Mining Lessons Learned and TRLs

Extracting water from Martian sub-surface ice appears to be a practical option when employing a combined soil/ice drilling apparatus, with the stipulation that landings occur at latitudes greater than 30 degrees to ensure accessibility to the ice. The borehole rig integrates a drill head capable of penetrating the soil and electric heaters to thaw the ice, thereby avoiding the potential freezing of the coiled tubing to the wall of the borehole. This configuration also facilitates the creation of a seal within the well, providing additional assurance that the subsurface water pool remains in a liquid state across a wider range of water temperatures.

Several of the subsystems need more technology development. In addition to some of the support systems (Wi-Fi, AMPS, and DTAU from the propellant production and liquefaction pallets), several technologies unique to the borehole need development. The Centrifugal Separator, essential for separating particulates from fluids without the need for filtration media, is assessed between TRL 5 and 6, denoting advanced developmental stages with significant demonstration in relevant environments. The boiler system, which is crucial for heating and vaporizing substances, shares a comparable readiness at TRL 5/6.

A deployable probe harness, which is part of the instrumentation suite, is currently at TRL 4. The coiled tube system, which includes a cutter head and an electric melter for penetrating Martian dirt and ice, respectively, is evaluated at TRL 4/5 following subscale tests by Honeybee Robotics. The entire thermal system, involving heat distribution and management technology, as well as the purification system is at TRL 4.

The main risks for the borehole mining system include the coiled pipe/cutter head getting stuck in the overburden or the subsurface water chamber cannot be sealed, gets too warm, and the water begins to sublimate. Both valve seat and ice contaminates are a concern as well as the impacts of dust on the above ground systems. Planetary protection in both directions is of a major concern and has only been addressed in the borehole system with UV lights to sterilize the probe head and tubing before it penetrates the soil and boiling the ice water to purify it. Although the borehole approach may offer an efficient engineering solution, more thorough analysis is warranted to understand how planetary protection constraints will add to the operational complexity and landed mass needs for this approach.

J. In-situ Water from Surface Soils

An alternative to the borehole for gathering in-situ water on Mars is to extract it from the surface soils. Previous studies on the availability and potential extraction of water from soils showed that certain areas contained water rich (~ 10 percent) minerals on the surface (e.g. gypsum) but these were only in special locations [13]. In order to provide a Mars-wide in-situ water availability that would eliminate the need to land the crew at certain sites (like the borehole approach), normal or ‘garden’ variety soil was assumed as the ore for the water extraction process. Because ‘garden’ soils on Mars have been found to only have ~1 percent water it would be the most challenging in-situ approach requiring the most soil excavated (e.g., a about 29,000 t of soil ‘ore’ to extract the required 150 t of water) and the most equipment.

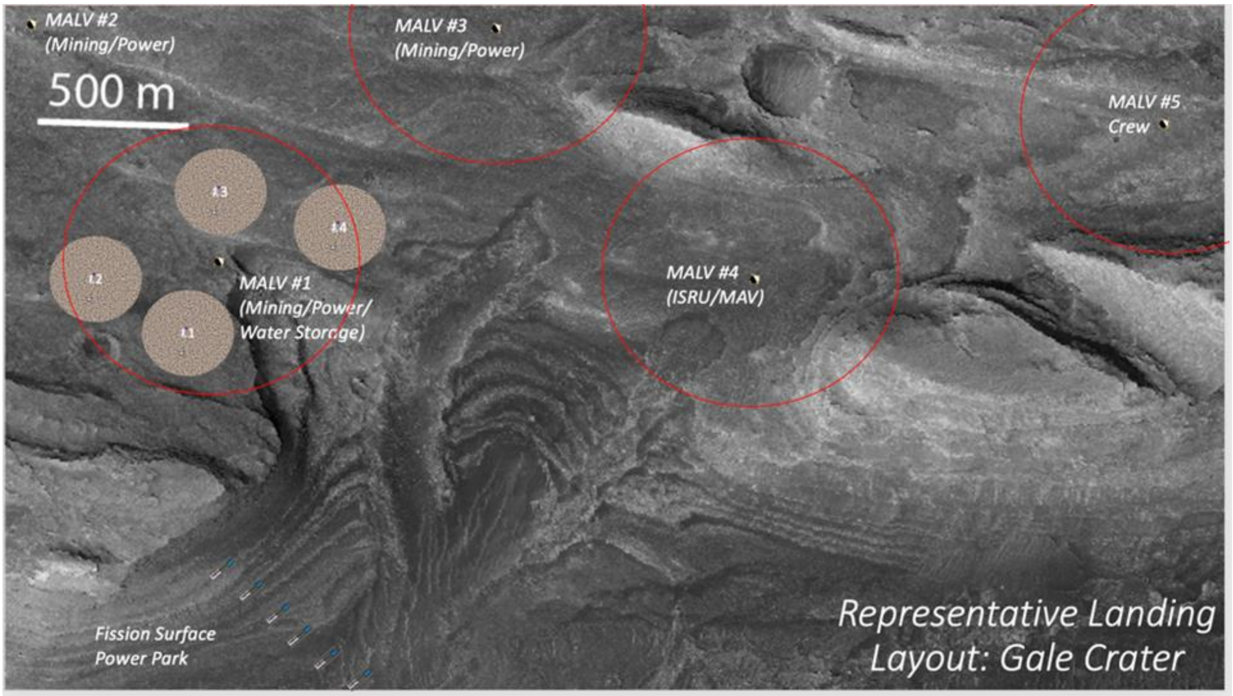


Fig. 12 Potential Surface Mining ISRU Layout

Fig. 12 shows a notional surface mining approach, along with the other elements and landers (each separated by the 1km landing keep out zone). Four, 220 m diameter surface mines would be required, each with a processing plant at the middle and each having a dedicated excavator. The excavator was based on the current Regolith Advanced Surface Systems Operations Robot (RASSOR) design [14] under consideration for the moon but scaled up by 2.5 times in each physical dimension to allow for carrying larger loads and reduce the estimated large number of smaller RASSORs required otherwise. This excavator was termed the RASSORX and is shown in Fig. 13 with Table 6 giving its performance parameters.

Table 6 Estimated RASSORX Performance Parameters

Metric	Value
Dry Mass	1333 kg (assumed PR 1:1)
Regolith Payload Mass	1333 kg
Cycle Time (100m case)	20 minutes
Power/Cycle	206 Whr
Battery Size	3.5 kWhr
Cycles/Battery Charge	13
Operational time/Battery Charge	4.3 hrs
Battery Charging Time @ 2kW	1.8 hrs

It was found that a loader, like a conveyor belt, will also be needed to lift the ore from the RASSORXs to the Water Extraction Rigs (WERs). This design could not be completed in the allotted time, but a representative mass and volume was assumed. Not only would the RASSORX supply the loader with ore, but it would also be responsible for carrying the tailings (waste soil) for disposal on the way back to the mine.

Fig. 13 RASSOR and RASSORX

The conceptual design study for water extraction on Mars involved a comprehensive mining operation, estimated to span 78 months with staged power levels of 25 percent, 50 percent, and 100 percent. The system was sized to accumulate 150 t of water within 44 months under full power operations. Approximately 29,000 t of regolith would need to be excavated from an area covering around 220,000 square meters, equating to over 50 acres. This operation would be distributed across four surface mines, each with a diameter of 220 meters and a depth of 12.5 centimeters in a single pass.

In this scenario, a single RASSORX at each mine was conceptualized to collect about 1333 kilograms of regolith per trip, with a round trip time of 20 minutes. To meet the target, four trips per day would be necessary, with each RASSORX operating for four hours on a single battery charge capable of 12 trips, utilizing a battery with a 3.5 kWhr capacity (assuming an 80 percent Depth of Discharge, equating to 2.8 kWhr).

The RASSORX units were envisioned to deposit the gathered ore into a loader, which remained to be designed. This loader would include a grizzly rock screen to filter out large stones and facilitate loading the ore into the WER at a minimum rate of 4 kilograms per minute. The hopper's dimensions were projected to be around 1.1 by 1 meter, with its top situated 3.15 meters above the surface for ease of access from a notional loader.

Recharging of the RASSORX units was anticipated to occur over a 2-hour period at the WER station. Concurrently, over the 78-month operation, tailings from the mining process would be collected by the RASSORX after ore deposition and transported back to the mining area. Options for the disposal of these tailings included spreading them across the already mined surface or forming piles. The same RASSORX units used for ore collection were also considered for tailings transport, maintaining the system's efficiency.

The WER water extraction conceptual design is shown in Fig. 14. The water extraction process begins with water vapor generated by auger dryers, which is then pressurized to 7 PSI and heated to 575K using a multi-stage compressor. This compressor is in turn cooled by an electronics radiator. The water vapor is subsequently condensed within a roughly 2 square meter radiator, bringing the temperature down to 353K under the same pressure.

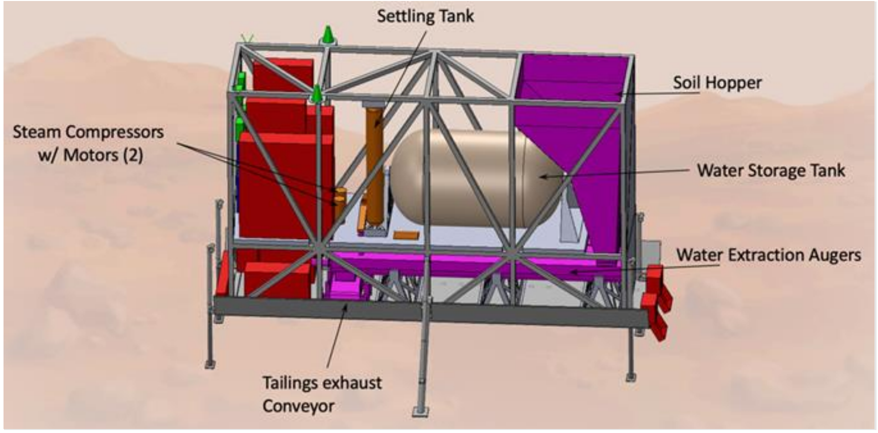


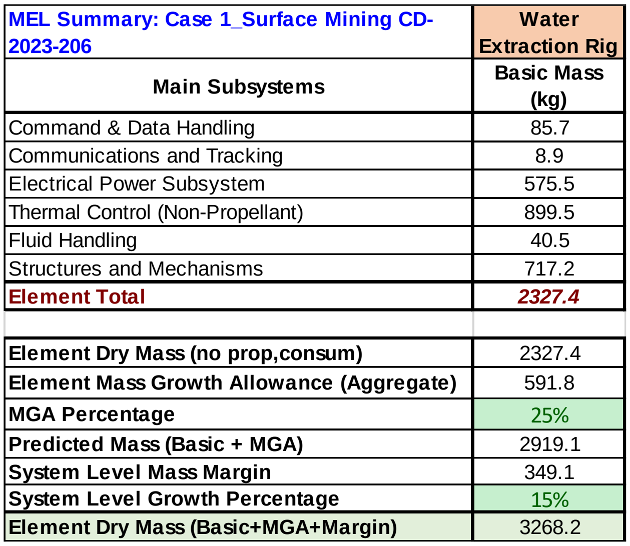
Fig. 14 Water Extraction Rig

Following condensation, undissolved dust particles are removed in a drop-out tank. The filtered water is then transferred to a storage tank with a capacity of approximately 600 kilograms. This tank is designed to accumulate three weeks' worth of water production, estimated at 29 kilograms per day, whose ullage gas is then pumped up to 14 PSI to be compatible with the water tanker. This tanker is scheduled to off-load the water every three weeks, filling sequentially eight times at the mining sites (two times per site) before delivering the water to the first MALV whose LO_2 tanks are capable of storing water. Once the water is all produced and stored in the MALV and the ISRU production plant arrives, the surface water transportation pallet will remove the water and transport it to the propellant production pallets.

For power requirements, the WER operates with peak power demands of around 35 kW for heaters and approximately 7 kW for water processing; with an added 30 percent for power growth, the total power requirement is estimated at about 55 kW. Thermally, the system employs heaters with a capacity of around 35 kW, integral to the auger mechanism. These heaters heat the solid regolith to approximately 575K to facilitate the removal of water as vapor. Cooling and condensation within the system are managed by multiple radiators with a collective effective area of about 11 square meters. Fluid dynamics within the WER include water pumps that raise the water pressure to 1 atmosphere, necessary for condensation and transport. Mechanical components include auger tubes and leg stabilizers. The rig's operations are managed via a C&DH unit, incorporating UHF and Wi-Fi systems for control and communication.

The master equipment list for a WER is shown in Table 7. Being an electrically heated process, the power switching and thermal systems along with the structures (augers) dominate the WER masses.

Table 7 Water Extraction Rig Mass Breakdown



MEL Summary: Case 1_Surface Mining CD-2023-206	**Water Extraction Rig**
Main Subsystems	**Basic Mass (kg)**
Command & Data Handling	85.7
Communications and Tracking	8.9
Electrical Power Subsystem	575.5
Thermal Control (Non-Propellant)	899.5
Fluid Handling	40.5
Structures and Mechanisms	717.2
Element Total	***2327.4***
Element Dry Mass (no prop,consum)	2327.4
Element Mass Growth Allowance (Aggregate)	591.8
MGA Percentage	25%
Predicted Mass (Basic + MGA)	2919.1
System Level Mass Margin	349.1
System Level Growth Percentage	15%
Element Dry Mass (Basic+MGA+Margin)	3268.2

K. ISRU Launch Manifest with the Surface Mining for Water Acquisition

As mentioned previously, a staggered approach to placing power and mining elements was used to make the most of the time between Mars opportunities as shown in Fig. 15. The first, second and third landers bring power, WERs, RASSORXs, Loaders and water tankers. The fourth lander carries the ISRU propellant production and liquefaction pallets. As with the other architectures this last MALV will both store the cryogens and provide the crew with launch to a 5 Sol Martian orbit. The top-level view of the ISRU with surface mining is shown in Fig. 16.

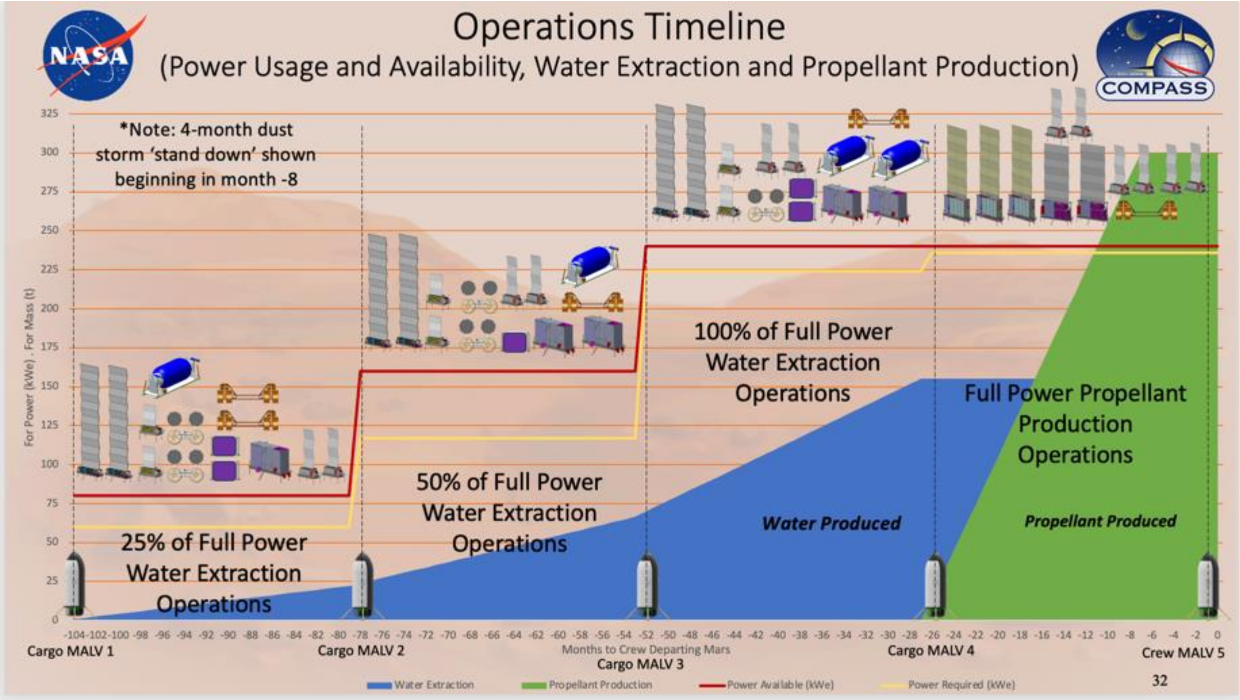


Fig. 15 Staggered Mars Surface Mining Approach

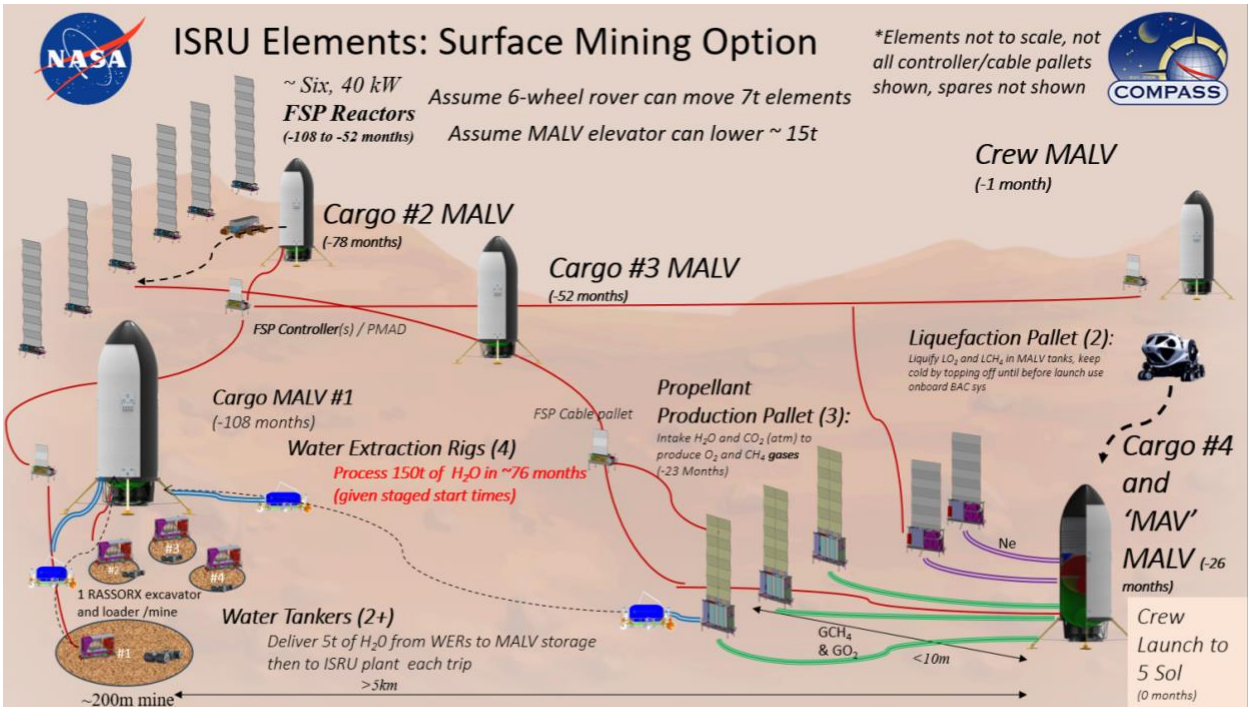


Fig. 16 ISRU Concept of Operations, Surface Mining Option

By tallying up the required elements and performing a first order loading it was found that in all cases, the conceptual MALV design was volume limited. Table 8 shows the total manifest for the ISRU elements.

Table 8 ISRU Manifest, Surface Mining Option

Mars Mission Description *Assumptions:* - *2 crew, 30 sols on the surface*							Quarter Power Water Extraction		Half Power Water Extraction		Full Power Water Extraction		Propellant ISRU Production	
							MALV 1		MALV 2		MALV 3		MALV 4	
Category		Mars Element/System	Basic Mass (kg)	Mass Growth Allowance (MGA)	Mass Margin	Control Limit (kg)	Count	Mass w/ Margins	Count	Mass w/ Margins	Count	Mass w/ Margins	Count	Mass w/ Margins
MARS SURFACE SYSTEM PAYLOADS	Power - 40 kW FSP	1km Cable and Spool	597	30%	15%	**866**	2	1,732	2	1,732	2	1,732	6	5,197
		Power Distribution System (included		20%	15%	**-**		-		-		-		-
		Controller/Voltage Convertor pallet (~160m from the reactor pallet)	1,445	32%	15%	**2,124**	2	4,248	2	4,248	2	4,248		-
		40 kW Reactor	5,590	16%	15%	**7,323**	2	14,646	2	14,646	2	14,646		-
	ISRU	ISRU Pallet	4,068	18%	15%	**5,410**		-		-		-	3	16,231
		Liquifaction & Cryocooling Pallet	2,590	20%	15%	**3,501**		-		-		-	2	7,001
		Water Tanker Pallet (Tank only)	794	30%	15%	**1,153**	1	1,153	1	1,153	2	2,306		-
		RASSORX	1,333	25%	15%	**1,866**	2	3,732	2	3,732	1	1,866		-
		Water Extraction Plant	3,268	25%	15%	**4,589**	1	4,589	2	9,179	2	9,179		-
		Loaders (mass is ROM)	2,000	25%	15%	**2,800**	2	5,600	1	2,800	2	5,600		-
		TBD		20%	15%	**-**		-		-		-		-
	Robotics	Lightweight Manipulator - Payload=5 t	748	0%	15%	**860**	1	860	1	860		-	1	860
		Lightweight Manipulator - Payload=8 t	1,188	0%	15%	**1,366**	1	1,366	1	1,366		-	1	1,366
		6-wheel payload mobility chassis	2,448	27%	15%	**3,467**	2	6,934	1	3,467	1	3,467	1	3,467
		Robotic Helicopter	5	5%	15%	**6.0**		-		-		-		-
	Logistics Rollup													
	Crew Mobility	Pressurized Rover (PR)	6,540	15%	15%	**8,502**		-		-		-		-
		Mars Terrain Vehicle (Unpressurized)	961	23%	15%	**1,324**		-		-		-		-
	Science Rollup													
INTEGRATION	Payload Integration	10% of Lander Capacity	5,300	0%	0%	**5,300**		4,486		4,318		4,304		3,749
MARS CREW SUPPORT SYSTEM PAYLOADS	Crew	2 Crewmembers	175	0%	0%	**175**		-		-		-		-
		Crew Cabin	2,072	14%	15%	**3,368**		-		-		-	1	3,368
	EVA	Launch-Entry Assembly (LEA) Suits - 2 crew	30	0%	15%	**34.3**		-		-		-		-
		mEMU - 2 crew	178	0%	15%	**204**		-		-		-		-
		EVA Suit Tools - 2 crew	42	20%	15%	**56.3**		-		-		-		-
		EVA Spares - 2 crew	56	20%	15%	**75.4**		-		-		-		-
OPTIONAL	Optional Items	Medical Kit Placeholder	10	0%	15%	**11.5**		-		-		-		-
		Total Mass including Optional Items (kg)						**49,347**		**47,502**		**47,349**		**41,240**

L. Surface Mining Lessons Learned and TRLs

Mining soil with a 1 percent water content on Mars, termed 'garden soil,' necessitates considerable infrastructure and duration to yield the requisite 150 t of water. The garden soil approach, in terms of time and MALVs required, is on par with simply transporting the water directly. It demands the introduction of at least three new surface elements: RASSORXs, Loaders, and WERs.

The viability of these mining elements for reuse in subsequent missions at the same Martian site could potentially render them a more favorable option over sending additional water. However, the type and extent of maintenance needed to enable these systems to gather and process an estimated 29,000 t of soil for a second mission warrant careful assessment.

The mining operation would occupy an area of approximately 50 acres, equivalent to the size of 50 football fields, and is expected to produce a volume of ore that would fill around 300 train coal cars. The scale of this operation highlights the substantial logistical considerations involved in utilizing indigenous Martian resources for water extraction.

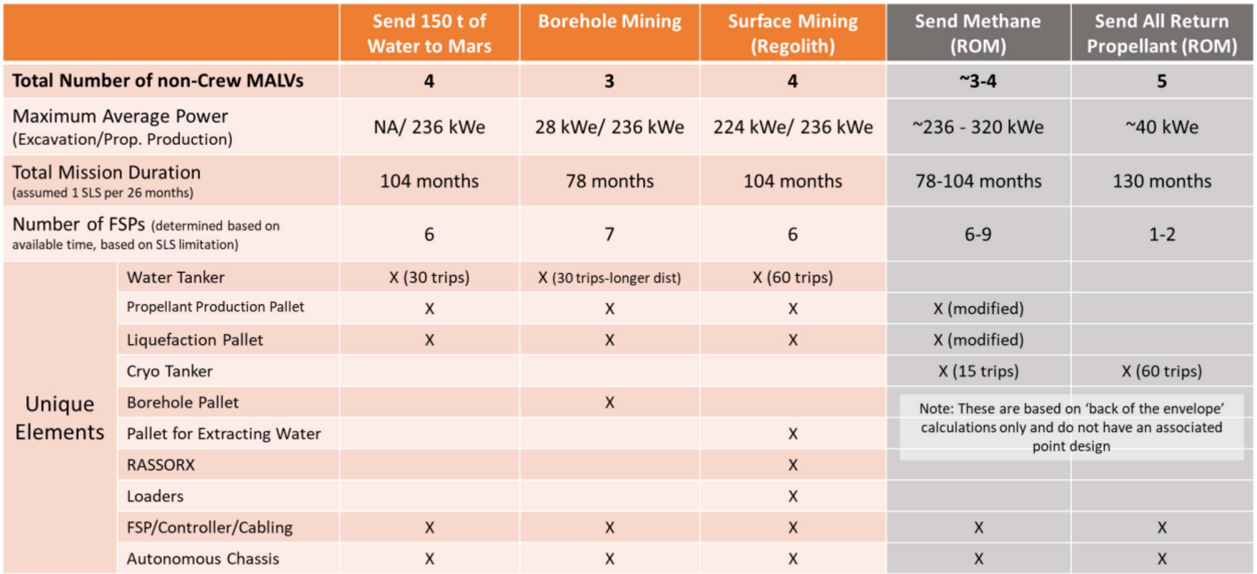
The TRLs for various components of a Martian resource processing system were assessed, highlighting their stages of development. The Auger Dryer system, which is used to remove moisture from Martian soil, is at TRL 3-4, indicating that it is in the experimental proof-of-concept stage. The Power Management and Distribution Harness (PMAD/Harness) capable of handling 3000 VDC also reaches TRL 5. A Multi-stage compressor essential for pressurizing gases has been developed to a similar stage, achieving TRL 5. RASSORX, the loader, and the high-temperature motors to run the water extraction augers, have been developed to TRL 4-5.

The main risks of the surface mining approach are clogging, jamming, and just plain wearing out of the equipment to process ~ 29,000 t of soil. Other risks include reuse of the LO_2 tank for water storage and the ever-present dust of the Martian environment. As with the borehole approach, additional planetary protection constraints may further increase operational complexity and landed mass.

M. **Comparison of Approaches**

The various conceptual designs of the ISRU equipment allows for a comparison of the required mass, power, time and indeed, number and type of elements needed to produce LO_2/LCH_4 on Mars. Several options are summarized comparing these needs for the 300 t of LO_2/LCH_4 not only including the ISRU approaches (with the sub-trade of water source) but the simpler approaches of delivering just the CH_4 and producing just the LO_2 from the atmosphere as well as just delivering the 300 t LO_2/LCH_4 propellant. Table 9 shows the options side by side.

Table 9 Mars 300 t ISRU Options Compared



		Send 150 t of Water to Mars	Borehole Mining	Surface Mining (Regolith)	Send Methane (ROM)	Send All Return Propellant (ROM)
Total Number of non-Crew MALVs		**4**	**3**	**4**	**~3-4**	**5**
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 (assumed 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)		
	Propellant Production Pallet	X	X	X	X (modified)	
	Liquefaction Pallet	X	X	X	X (modified)	
	Cryo Tanker				X (15 trips)	X (60 trips)
	Borehole Pallet		X			
	Pallet for Extracting Water			X		
	RASSORX			X		
	Loaders			X		
	FSP/Controller/Cabling	X	X	X	X	X
	Autonomous Chassis	X	X	X	X	X

Note: These are based on 'back of the envelope' calculations only and do not have an associated point design

If the figure of merit is number of launches the borehole mining approach shows that it can save a MALV as well as propellant production time at the expense of an additional FSP. The borehole approach is limited to where on the surface of Mars the crew can go which might not match all exploration needs, including planetary protection risks. The surface mining approach, assuming global application with only 1 percent water in the soil takes as much time and launches as taking the water to Mars from Earth and requires new elements and technologies and more water tanker trips. Applying the approach to certain 10 percent water rich soil areas could make it more attractive but would be as location limiting as the borehole approach, albeit with different location limitations.

Two options not evaluated in these concept studies would be to send either all the cryogenic propellant or just the liquid CH_4 and make the LO_2 using ISRU methods. The latter has been suggested before for smaller (10's of tons) cryogenic propellant loads. Taking all the propellant would take the most LVLs and time (due to the single LVL launch per opportunity). Taking just the liquid CH_4 might be as good at the borehole approach in terms of time and launchers but needs further assessment at this propellant level. An added complexity would be the need to replace the relatively simple water tankers with cryogenic tankers to fuel up the MALV.

Indeed, just taking the water seems to be the easiest approach in the near term. The great promise of ISRU is reusing the systems to produce water for the next mission, saving resending the ISRU equipment. This has at least two challenges. First it would require revisiting the same landing site and would not be appropriate for crew visiting different locations on Mars since the ISRU equipment most probably could not be transported to the new site. Second and just as important is the lifetime of the ISRU components. The mining of 150 t of water and the subsequent production of 300 t of cryogenic propellants requires many subsystems which might not have the lifetime needed to do a repeat performance. Developers just don't know lifetimes of their systems yet. Perhaps robotic or crew replacement units of worn-out parts (pumps, electrolysis units, augers, motors) could be implemented.

This study only produced enough propellant to get the crew in an MALV back to a Mars 5 sol parking orbit, to be picked up by an interplanetary vehicle to return the crew to Earth. In order to send the MALV all the way back to Earth might require four to five times more propellant. To the first order the 300 t ISRU system could be scaled up to the 1200 t or 1500 t case. A linear scaling seems appropriate for the overall architecture parameters. Sending just the water would require eight or more MALVs. Sending all the cryogenic propellant would require 16-20 MALVs (each of which needs multiple refuelings in Earth orbit before journeying to Mars). Only sending all the cryogens would keep the landing power needs low, perhaps only 40 kW. The borehole option might only require 12 – 15 landers for the first landing. Reuse of the ISRU for subsequent landings (assumed in the same location) is key. Any approaches involving ISRU would easily require over 1 MWe of power and a new nuclear power plant since sending and operating 25 FSPs might become unwieldy.

In summary, Compass has assessed several options for implementing ISRU on Mars to make propellant – an often-mentioned feature of sustained human Mars missions. The concepts begin to show the magnitude of the surface infrastructure needed to implement any of these approaches. It also indicates a significantly complex robotic operation to both set up and operate this infrastructure before the crew arrives, introducing a significant challenge to ensure that all of these robotic operations operate successfully over a period of time measured in years for this human mission to succeed. Finally, these approaches likely add additional site selection criteria that may be in conflict with desirable scientific/exploration mission objectives. Finally, it was shown that the Compass process can reveal changes that should be considered in certain element design features (e.g., MALV payload volume) and operations.

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