Benefits of Mars ISRU Regolith Water Processing: a case study for the NASA Evolvable Mars Campaign

J. E. Kleinhenz[1], A. Paz[2], and R.P. Mueller[3] [1]NASA Glenn Research Center (21000 Brookpark Rd, Cleveland, OH 44135, Julie.E.Kleinhenz@nasa.gov), [2]NASA Johnson Space Center (Houston, TX, 77058, aaron.paz-1@nasa.gov), NASA Kennedy Space Center (Kennedy Space Center, FL 32899, Rob.Mueller@nasa.gov)

Introduction: Since the publication of the Mars Design Reference Architecture (DRA) 5.0 [1] in 2009, ISRU has been baselined as an enabling technology for Mars human exploration. However, DRA 5.0 only addressed ISRU for oxygen production using Mars atmospheric CO_2. Using water from the Martian regolith in addition to the atmospheric CO_2 would enable the production of both liquid Methane (LCH_4) and liquid Oxygen (LOX), thus fully fueling a Mars return vehicle, and could supply water for various other applications such as life support, radiation shielding, plant growth, etc. This approach was not previously baselined due to the perceived complexities and mass penalties involved in mining the regolith. A study was therefore commissioned by the NASA Evolvable Mars Campaign (EMC) to estimate the quantitative benefits and trades involved in an end to end Mars water ISRU system. This four month study was completed in March 2016.

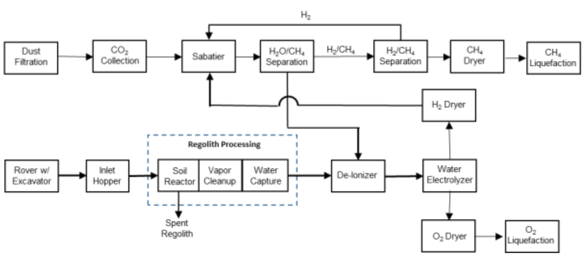

Figure 1: Schematic of a full ISRU LOX/LCH_4 system, with all the subsystems.

Approach & Assumptions: The end-to-end ISRU system schematic is shown in Fig. 1. The subsystems technologies selected in the study were those with highest flight readiness that have the most available data in terms of performance, mass, power, and volume estimates so that a system model could be built. Many technologies are either in-house technology development efforts, NASA solicited technologies, and relevant off-the-shelf technologies The system model was built in Microsoft Excel, which was chosen for its wide accessibility. Top level global variables were based on the needs of the Mars Ascent Vehicle (MAV) [2] with the requirements shown in Fig. 2. Each subsystem also includes variables for individual parametric studies at the subsystem level.

Production: The MAV engines operate at mixture ratios between 3:1 and 3.5:1 (oxygen:methane) Since the Sabatier reactor in the ISRU system produces at a 4:1 ratio, excess oxygen will be produced. Therefore, methane is the driver for the production rate.

Time: The mission timeline was based on the assumption that the ISRU system will be emplaced one mission opportunity ahead of human arrival, and that the MAV must be fully fueled prior to human departure from earth. Mars launch windows are every 26 months. Assuming a 9 month transit and one month of margin, ISRU production must take place in 480 days.

		Total mass needed	Rate at 480days continuous operation
Requirement:	CH_4	6978 kg	0.61 kg/hr
Reactants needed to meet requirement:	H_2O	15701 kg (785,050 kg 2% soil)	1.36 kg/hr (68.2 kg/hr soil@2%)
	CO_2	19190 kg	1.67 kg/hr
Results in:	O_2	27912 kg total (22728 kg propellant, 1906 kg Life support, 3278 kg leftover)	2.43 kg/hr

Figure 2: Production requirements for a Regolith water ISRU system. The methane requirement for the MAV is the driving requirement.

Water Resource: The water resource was assumed to come from granular surface material, namely hydrated minerals. Unlike potential ice resources, subsurface access is not required, simplifying excavation. A bucket drum excavator [3] is currently in development for this purpose. The Mars Water ISRU Planning (M-WIP) study, which occurred in concert with this EMC study, identified reference cases for these resources. Two bounding cases were used in this study: Typical regolith (as represented in Gale Crater [4]) which is low yield (1.6wt% water) but relatively ubiquitous across Mars; and Sulfate rich deposits (8wt% water) which are higher yield but are landing site dependent.

System Boundaries: The ISRU plant is assumed be immobile, located at the fixed outpost site. Human mission will continue to return to this landing site so that assets can be reused. The total ISRU production requirement is met by 3 fully independent ISRU plants each operating at 40% of the needed production rate. This allows for redundancy and flexibility to alterative mission scenarios. (All the results shown below are for the combined 3-module system). Mobile excavators will deliver fresh regolith to the plant and remove the spent regolith. The products are assumed to feed directly into pre-exiting storage tanks (e.g. MAV propellant tanks). However, the ISRU system does bookkeep the mass/power of the cyro-coolers needed to liquefy these products. The power source is assumed to be the same fission reactor(s) that will be will be needed for human presence; ISRU will use the reactor(s) when humans are not present. Radiators are also not currently included in this ISRU case study because they will be integral to the lander. However, heat rejection requirements are currently being coordinated with the MAV team.

Results: The following results compare three different ISRU cases. The first two cases are the water processing options where both propellants, LOX and LCH_4, for the MAV are produced via ISRU. The first is the 'best case' granular resource (sulfate-rich regolith 8wt% water) and the second is the typical regolith (1.6 wt% water). The third case is a LOX-only production case as baselined in DRA5.0. The LOX-only system model used here uses solid oxide electrolysis to produce 25mt of oxygen (MAV propellant + Life support, see Fig. 2). The same top level mission requirements and 3-module approach were used in this case.

The first set of results in Fig. 3, shows the comparison of the ISRU system hardware. Individual subsystem masses are called out in order to identify power and mass drivers to target future technology trades. The type of granular regolith water resource used does not have a large impact on total mass, with the sulfate case only showing a slight mass reduction. The benefit of a water-rich regolith is in the power consumption. The power for Sulfate-rich case is comparable to the power needed for a LOX-only ISRU system. It should be noted that the power needed to extract the water is thermal, and could be harnessed from non-electrical sources (eg waste heat from the fission reactor), thus reducing power requirements further.

Figure 3: ISRU system hardware comparison in terms of mass (left) and power (right) for each subsystem.

To truly consider the benefits of ISRU, it is important to consider the total mass savings. Therefore, Figure 4 shows the "total mass" which includes the mass of the ISRU hardware systems from Fig. 3 as well as the mass of any propellants supplied from earth. Therefore, case 1 and 2 (LOX/LCH_4 ISRU systems) consist only of hardware mass, case 3 (LOX-only ISRU) includes both hardware and methane mass, and case 4 is just the total mass of propellant (LOX and LCH_4) needed to fuel the MAV.

Since the majority of the MAV propellant is Oxygen, the LOX-only ISRU shows a 75% mass reduction over the No-ISRU option. However the hardware mass of the LOX/LCH_4 case is less than one metric ton higher than the hardware for a LOX-only system Yet, that one additional ton saves 7mt of methane from earth. Note that these earth-based propellant masses (including the No-ISRU case) do not account for the additional propellant or system mass which would be required to deliver that MAV propellant to Mars from LEO. Thus the advantage of a combined ISRU LOX/LCH_4 production system would be even greater than indicated.

ISRU system Mass Comparison (ISRU Hardware + Propellant from Earth)		
The ISRU system leverages the power and radiator systems that are pre-positioned by the lander for human systems. So these are not explicitly part of the ISRU system.		
	Total Mass, mt	Ratio: Propellant produced per kg of landed mass
Case 1 ISRU for LOX & LCH_4: Sulfates	1.6	22.1
Case 2 ISRU for LOX & LCH_4: Regolith	1.7	20.5
Case 3 ISRU for LOX only (no water)	8.0 (1mt hardware + 7mt Methane)	3.1
Case 4 Propellant only (no ISRU)	31.6 (24mt Oxygen + 7mt Methane)	na

Figure 4: Comparison considering landed mass needed to fuel the MAV (ISRU hardware and earth-based propellants).

The evaluation metric, shown in last column, is the ratio of propellant produced per total mass. So, for every kg of system total mass, a LOX/LCH_4 ISRU system produces over 20 kg of propellant, while a LOX-only ISRU system produces 3 kg of propellant. Therefore, harnessing even the lowest yield Mars regolith water resource for ISRU offers a 6x improvement over an LOX-only ISRU in the terms of the mass of propellant generated for each kg of total ISRU system mass.

References: [1] Drake, B.G. (2009) NASA-SP-2009-566 [2] Polsgrove, T. et al. (2015), AIAA2015-4416 [3] Mueller, R.P et al. (2016) ASCE Earth & Space [4] Leshin, L.A et al (2013) Science 341, 1238937