Assessing the Feasibility of a Martian ISRU Propellant Plant

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In-situ resource utilization (ISRU) is the process of extracting local resources to provide consumables for propulsion and regenerate resources for life support systems rather than transporting consumables from Earth. Numerous multidisciplinary technologies are required to interact and synergize to develop efficient ISRU systems. Cost-effective techniques to extract consumables from the environment is a critical element of the supply chain that enables a sustained presence on the Martian surface. To assess the feasibility of a full-scale Martian ISRU architecture, the Systems Engineering and Integration (SE&I) ISRU Modeling and Analysis (SIMA) project developed the Mission Analysis and Integration Tool (MAIT), a modeling tool capable of calculating the mass, power, and volume requirements of an ISRU plant based on location, production requirements, Concept of Operations (ConOps), and environmental conditions [1]. This modeling tool works by combining subsystem models created by government, industry, or academia into a standardized framework to integrate all subsystem models into a single model. This allows for the interactions between all subsystems in an ISRU process to be parametrically assessed and optimized rather that individually analyzing each subsystem.

The Martian ISRU system model investigated in this paper produces liquid methane (CH_4) and oxygen (O_2) propellant by extracting carbon dioxide (CO_2) from the atmosphere and water from mining ice embedded in the Martian surface. The ISRU plant is broken into four sub-processes, denoted by background color in Fig. 1: (1) water supply (blue), (2) electrolysis (orange), (3) methane production (green), and (4) storage (pink). The water supply sub-process consists of a Rodwell mine, two transport vehicles, and a feed steam generator. The Rodwell mine pumps heat into a frozen ice sheet to melt water and remove for processing [2]. This water is transported to the main ISRU plant where it is combined with recycled water from other subsystems (electrolysis and methane production) and heated to produce steam. The electrolysis sub-process consists of a series of heat exchanges (HX) and a Solid Oxide

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Electrolysis (SOE) assembly [3]. The heat exchangers preheat the steam entering the SOE, and the SOE uses a stack of cells to electrolyze the incoming water. A condenser downstream of the SOE anode separates the unreacted water from hydrogen (H_2) gas. The methane production sub-process consists of a series of CO_2 pumps, reverse water gas shift (RWGS) reactors, condensers, and methanation reactors [4]. Atmospheric CO_2 is pulled into the system using a scroll pump. The RWGS reactors shift the incoming carbon from CO_2 to carbon monoxide (CO) to improve the efficiency of the downstream methanation reactors. The storage sub-process involves liquefying and storing the O_2 (from SOE) and CH_4 (from methanation). Both gases are liquefied using a 90 K cryocooler and stored in insulated aluminum tanks with a maximum length constraint of 3 meters.

To assess the feasibility of a Martian ISRU plant, a trade study was created to determine the mass, power, and volume of two plants capable of producing 30 and 300 metric tons (mt) of propellant, based on an O_2 to CH_4 fuel mixture (by mass) of 3.5:1, in one Martian year. For each propellant production goal, the model was run with a parametric sweep of five variables to assess the sensitivity of the model to various design parameters. The results of these parametric sweeps were used to identify the critical design parameters. The power system was adjusted to determine the trade-off of using fission surface power (FSP) compared to solar arrays and batteries. The ratio of CO_2 to H_2 in the methanation subsystem was adjusted to determine the optimal ratio from a system perspective. The layers of insulation, numbers of stacks in the SOE, and efficiency of the condensing radiators were also assessed.

The ISRU system assessed in this paper was found to be a feasible and advantageous method of producing liquid methane and oxygen on the Martian surface. The ISRU system provides a significant return on landed mass for both plant sizes investigated in this study over the course of a Martian year (~687 Earth days). The system met a return on landed mass even when adjusted to create a fully redundant system with mass growth allowances as specified in the American Institute of Aeronautics and Astronautics (AIAA) standard "Mass Properties Control for Space Systems" (AIAA S-120A-2015) [5]. The return on landed mass was found to grow at larger production targets indicating that the system becomes more efficient (in terms of landed mass) at higher production rates.

In additional to proving feasibility of the system in terms of return on landed mass, this study identified six primary takeaways from the data generated using the Martian ISRU system model.

(1) The model calculated that power generation systems account for a significant portion of the landed mass (34% of the total mass for 30 mt plant and 59% of the total mass for the 300 mt plant). This was for fission surface power, which traded better than solar arrays with batteries. Research and development into reducing the mass of the power generation systems could drastically reduce the overall system mass.
(2) Identifying the optimal ratio of H_2 to CO_2 in the methanation process is critical. Changing the ratio by just 10% can impact the overall system mass by up to 2.5%. Higher H_2 concentrations result in lower masses for the RWGS and methanation reactors but higher mass and power for the SOE and water collection system.
(3) The water transport system between the Rodwell mine and the ISRU plant must be appropriately sized. The model assessed in this study used an oversized tanker which resulted in a large mass for the 30 mt plant. The ConOps of transportation of water from the Rodwell mine can likely be further optimized to minimize landed mass and power usage.
(4) The efficiency of the condensing radiators has a significant impact on the overall system mass. Reducing the efficiency by 10% will increase the overall system mass

by nearly 2%. For this reason, it is important to develop efficient condensing radiators capable of removing nearly all water out of a humid gas stream.

(5) **The SOE is the largest power draw of the system. The SOE consumes 53% and 62% of the total plant power for the 30 mt and 300 mt plants, respectively. By contrast, the mass of the SOE is a small contributor to the system mass. For this reason, the SOE should be developed to be as power efficient as possible, even at the cost of higher mass.**

(6) **Using metal storage vessels results in a large contribution to the overall system mass. The liquefaction and storage processes make up nearly 25% of the total system mass for a 300 mt plant. For this reason, alternative storage technologies (from metal) should be investigated in the future as a way of reducing the overall system mass.**

These six takeaways demonstrate the importance of assessing an ISRU plant from a system level and highlight the key technologies that must be addressed to increase the feasibility of a Martian ISRU plant.

I. Optional Supporting Materials

A. Images, Figures, and Tables

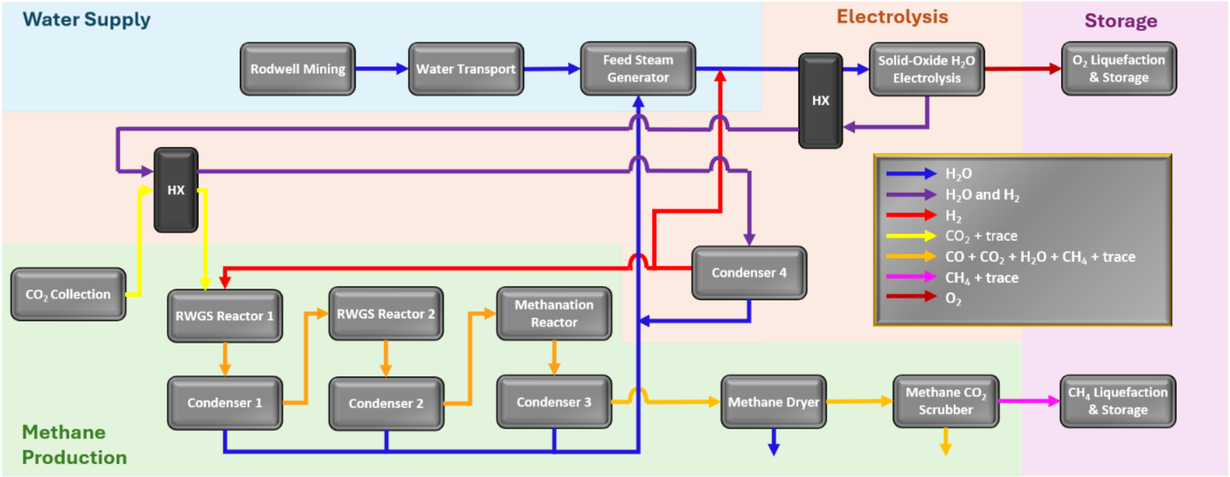

Fig. 1 Mars ISRU Propellant Plant. Background color indicates sub-process of ISRU plant. Arrow color indicates constituents in a given stream.

B. References

[1] Carlson, A., Andersen, N., and Collins, J. "In-Situ Resource Utilization Modeling of a Lunar Water Processing System", *International Conference on Environmental Systems*, ICES-2024-53, Louisville, KY, 2024.
[2] Lunardini, V. J, & Rand, J. "Thermal Design of an Antarctic Water Well". Special Report 95-10, U.S. Army Corps of Engineers Cold Regions Research & Engineering Laboratory. 1995.
[3] Hollist, .M, et. Al., "Solid Oxide Electrolysis Based Lunar PSR Ice Processing System for Propellant Hydrogen and Oxygen Production", ICES-2022-275, St Paul, MN, 2022.

[4] “NextSTEP-2 ISRU System Analysis”, OxEon Energy, Internal Document.
[5] “Mass Properties Control for Space Systems”, AIAA S-120A-2015.