MOXIE: A year of ISRU on Mars. M. H. Hecht,[1] E. Hinterman[2], J. A. Hoffman[3] and the MOXIE Team, [1]MIT Haystack Observatory, 99 Millstone Rd., Westford, MA 01886, mhecht@mit.edu, [2] MIT Department of Aeronautics and Astronautics; Cambridge, MA 02139, mccleanj@mit.edu, [3]MIT Department of Aeronautics and Astronautics; Cambridge, MA, 02139 jhoffma1@mit.edu

Currently on Mars aboard the Perseverance rover, the Mars Oxygen ISRU Experiment (MOXIE) is a prototype of a system that will someday produce many tons of oxygen from martian air, in support of a human mission. The bulk of the oxygen would be used as the major component of the propellant needed to return astronauts to orbit at the conclusion of their mission.

MOXIE (Figure 1) first collects, filters, and compresses the thin martian air, which consists of 95% CO_2 and small amounts of nitrogen and argon at a pressure of <10 mbar, using a custom scroll pump developed by Air Squared, Inc. It then pre-heats the gas to ~800˚C and injects it into a stack of 10 solid oxide electrolysis cells (SOXE) developed by Ceramatec, Inc. (now OxEon Energy). CO_2 is thermally and catalytically decomposed according to the reaction $CO_2 \rightarrow CO + O^{2-}$ at the cathode of the electrolysis cells, then the oxygen ions are selectively drawn through the yttrium-stabilized zirconia electrolyte where they recombine at the anode into O_2 molecules. The transfer of 4 electrons from anode to cathode completes the circuit and provides the motive force for the reaction. The pure oxygen product is characterized, then released through a precision aperture, while CO fuel and unused CO_2 are similarly characterized and discharged through an exhaust port.

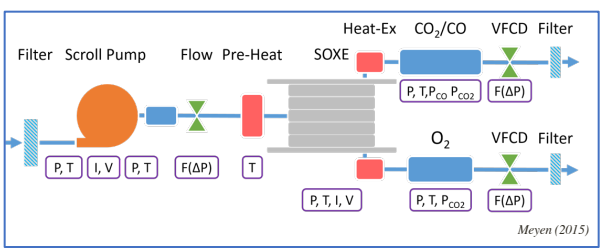

Figure 1: MOXIE first collects and compresses martian air, then preheats it before introducing it into the solid oxide electrolysis (SOXE) element. Output product and the waste stream are chacterized and vented through a viscous flow control device (SOXE)

MOXIE was integrated into the belly of the Perseverance rover (Figure 2), launched with the mission on July 30, 2020 and landed on Mars on February 18, 2021. During the first year of the mission MOXIE made 8 oxygen-producing runs (Table 1), demonstrating the ability to consistently produce 6-8 grams of O_2 per hour, with unmeasurably small levels of impurity. The production rate is dependent on the atmospheric density at any given time at the Perseverance location, which is operating at substantially higher altitude (hence lower density) than previous Mars landers. The lowest densities define the minimum rate, but even though the density changes by nearly a factor of two over the course of a martian year, the maximum oxygen production rate is constrained by the current-voltage relationship and the need to stay below the threshold potential for carbon formation.

MOXIE runs have been scheduled 1-2 months apart such that they are distributed across seasons. Time of

Figure 2: MOXIE being lowered into the Perseverance Rover

day for operation has also been varied from run to run, while avoiding sharp transitions in local conditions. All runs begin with a standard current-voltage (I-V) profile in order to determine the area-specific resistance (ASR) and track any degradation over time. MOXIE's first oxygen production on April 20, 2021 was conservatively scheduled in the early morning hours, when the atmospheric density was as much as 20% higher than at the early afternoon minimum.

Planning of MOXIE operations is dominated by the need to maintain safe conditions while at the same time exploring the limits of performance and characterizing the state of the system. MOXIE is typically operated in a constant-current mode, introducing uncertainties into the operating voltage. To compound these uncertainties, there are significant voltage drops elsewhere in the system across series resistances that are dominated by the Inconel electrical leads. Determining the variation of performance with SOXE temperature is a one method used to distinguish the resistance across the membrane, which is a strong function of temperature, from those series resistances.

Subsequent runs evaluated operation at different inlet flows and SOXE temperature; upcoming runs will test alternative control configurations such as voltage-

feedback control instead of current-feedback control or cathode pressure feedback control of compressor speed. Development of a "smart" control system is a high priority for future work and will be explored in a laboratory setting during the MOXIE campaign.

Using a detailed optimization model, a systems architecture has recently been defined for an extensible MOXIE system of sufficient capacity to support a human mission. Designated the Big Atmospheric MOXIE (BAM), the primary subsystems of interest are the solid oxide electrolysis (SOE) stack, the compressor, the liquefaction system, and the heat exchanger. The model has been validated with data from scaled-up SOE cell testing, past MOXIE experiments, and components used in industry. Model results validate earlier estimates of approximately 1 metric ton for the ISRU portion of the system (exluding power, liquefaction, and ascent vehicle), including 15% overall margin.

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References: [1] Hecht, M., Hoffman, J., Rapp, D. *et al.* (2021), Mars Oxygen ISRU Experiment (MOXIE), *Space Sci Rev* **217,** article 9. https://doi.org/10.1007/s11214-020-00782-8.

OC #	FM-OC9	FM-OC10	FM-OC11	FM-OC12	FM-OC13	FM-OC14	FM-OC15	FM-OC16	TOTALS
Comment	1st oxygen!	1st microphone	1st daytime run	1st Temperature sweep (to determine series resistance)	1st flow sweep (to determine oxygen purity)	Generic nighttime run (intermediate density)	Generic nighttime run (low density)	Generic daytime run (lowest density, just after dust eveny)	**8 runs**
Sol	60	81	100	155	176	241	276	317	
Total O2 (g)	5.4	6.9	6.9	8.9	8.1	6.9	6.8	6.7	**56.64 grams O2**
Peak rate (g/hr)	6.0	8.0	8.0	6.0	6.9	7.6	7.2	7.0	
Duration (min)	59	74	71	96	82	74	74	74	**604 total minutes**
Time of day	Night	Night	Day	Night	Night	Night	Day	Day	
Microphone	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	
Predecessors	Aliveness test (Sol 4) RCT check (sol 13) Full health check (sol 14) Compressor sweep (sol 55)	Compressor sweep w/ microphone (sol 79)	Daytime compressor sweep w/ microphone (sol 96)	None	None	None	None	None	

Figure 4: MOXIE oxygen production runs on Mars