MOXIE: A Martian Year of ISRU on Mars. M. H. Hecht[1], J. A. Hoffman[2], J. J. Hartvigsen[3], A. M. Aboobaker[4] D. Rapp[5], J. G. SooHoo[6] , M.B. Madsen[7], 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, [3]OxEon Energy, Salt Lake City, UT, [4]NASA Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA [5]South Pasadena, CA (ret.), [6]MIT Haystack Observatory, Westford, MA, [7]Niels Bohr Institute, University of Copenhagen, Copenhagen, Denmark

Introduction: Currently on Mars aboard the Perseverance rover, the Mars Oxygen ISRU Experiment (MOXIE) is a small-scale technical demonstratration of a system that will someday produce tons of oxygen from martian air in support of a human mission. Most of that oxygen will be used for the methane-LOx propellant needed to return the astronauts to orbit at the conclusion of their mission, with a fraction providing make-up oxygen for the human habitat.

Assuming pre-deployment one 26-month cycle ahead of the crewed mission, an oxygen ISRU system will need to produce 2-3 kg/hr of pure oxygen product, utilizing upwards of 20 kW power, without substantial interruption for an Earth year. While power constraints on the Perseverance rover preclude continuous testing for more than an hour at a time, MOXIE has been operated intermittently for more than a martian year (~2 Earth years), demonstrating sustained reliability while subject to the diurnally and seasonally changing martian temperature and pressure environment.

How it works [1]: MOXIE collects, filters, and compresses the thin martian air, which consists of 95% CO_2 and small amounts of nitrogen and argon, 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 (SOE) developed by Ceramatec, Inc. (now OxEon Energy). CO_2 is thermally and catalytically decomposed to gaseous CO and divalent oxygen ions, and the oxygen ions are selectively drawn through the scandia-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. A major advantage of the SOE approach is that it intrinsically separates the oxygen product from the waste stream, requiring no subsequent purification step.

Performance on Mars: MOXIE was launched with the Perseverance mission on July 30, 2020 and landed on Mars on February 18, 2021. As of this writing, MOXIE has completed 13 oxygen-producing runs (Fig. 1), generating a total of 100 grams of O_2 in 1000 minutes while demonstrating the ability to produce more than 10.5 grams/hr of O_2 with unmeasurably small levels of impurity as long as a small anode overpressure is maintained (Fig. 2) [2]. The initial design requirement was 6 g/hr at a minimum of 98% purity.

MOXIE's production rate is determined by cell area, the current-voltage relationship, and the need to stay below the threshold potential for carbon formation. It is also constrained by ambient CO_2 density, which changes by nearly a factor of two over the course of a martian year (Fig. 1), and the highest production rates have been achieved near peak density.

The best figure of merit for SOE performance has been found to be intrinsic Area Specific Resistance (iASR), which is the per-cell slope of the current-voltage relationship sufficiently above the Nernst potential threshold for oxygen production. This quantity differs from the traditional area specific resistance by addition of a term that adjusts for variations of gas composition across the cell. SOE technology is known to suffer degradation if cycled repeatedly between ambient temperature and operating temperature (800˚C for MOXIE). Due to power constraints MOXIE is operated approximately every 6-8 months, requiring a full thermal cycle each time. Nonetheless, cycle-to-cycle increases in iASR (Fig. 3) have been small and effectively linear. Since each MOXIE cell has 22.7 cm^2 surface area, the change over 12 runs, $< 0.1\ \Omega\text{-cm}^2$, is equivalent to a change in voltage of < 10 mV per cell at 2A current. By comparison, MOXIE runs allow a safety margin of up to 100 mV per cell.

Scaling up: With careful operation, MOXIE has been found to be surprisingly robust against thermal cycling, dust, and changes in atmospheric density and temperature. It will scale favorably; a system capable of producing oxygen at the needed rate of 2-3 kg/hr will weigh substantially less than 1 ton, will fit within a cubic meter envelope, and will operate comfortably within a 25 kW power allocation, including liquefaction. In practice, the challenge of scaling MOXIE *down* to the resource constraints of the Perseverance rover was probably greater than the future challenge of scaling it up to the 2-3 kg/hr production required for a human mission.

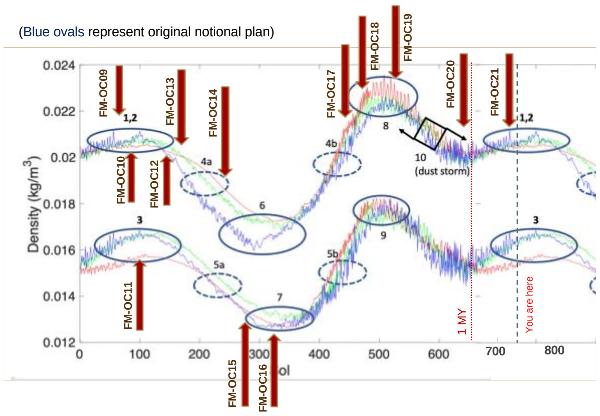

Figure 1: Models of the martian atmosphere at Jezero define a range of atmospheric density with large diurnal and seasonal variation [3]. MOXIE Operational Cycles (OC) #9-21 have sampled most of the annual cycle, primarily at night but with 3 daytime runs.

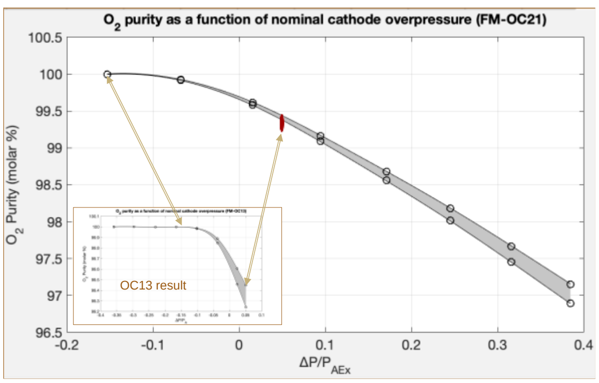

Figure 2: 100% purity of the oxygen stream can be achieved to the resolution of the measurement as long as an anode overpressure is maintained. A small amount of CO2 contamination can be seen in the case of cathode overpressure, but this has not changed measurably over 18 months and 8 run cycles.

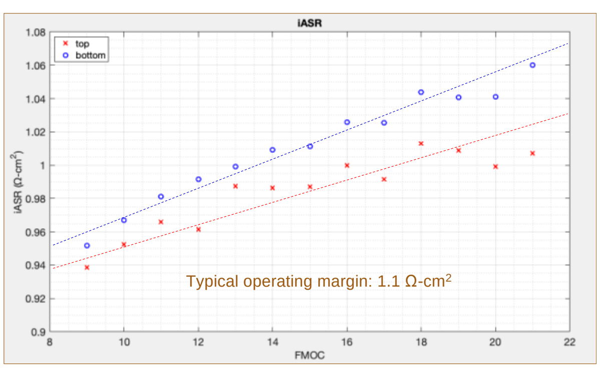

Figure 3: Changes in intrinsic Area Specific Resistance (iASR) from run to run are sufficiently small to allow MOXIE to run for dozens of cycles while still meeting development requirements. Prior to the first oxygen-producing Flight Model Operating Cycle on Mars (FMOC-09) the instrument had been operated 7 times on Earth and had been cycled once on Mars to perform a heater checkout (FMOC-08).

One consequence of the severe downsizing is that power efficiency of the flight unit is of order 10% relative to "wall plug" power. Analysis shows that this will improve to ~90% in a full-scale system with a few simple changes, including operation at much lower cathode pressure (which has now been demonstrated in the laboratory), a well-insulated surrounding oven, and efficient heat exchange from gas inlet to outlet. [4].

Additional straightforward changes will greatly improve autonomy and safety, including separate voltage sense wires (instead of sensing through power leads), accurate flow metering, improved composition sensing, and a capable processor with dynamically tunable algorithms.

Dust filtering is not expected to be a challenge, as the great majority of dust will not pass through even the simplest baffle geometry.

Materials improvements currently in development also promise to improve yield and greatly enhance resistance to carbon deposition.

Finally, the requirement that a future system be capable of unattended operation for thousands of hours could not be demonstrated on Mars and remains to be done in the laboratory.

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