MOXIE: A Martian Year of ISRU on Mars.

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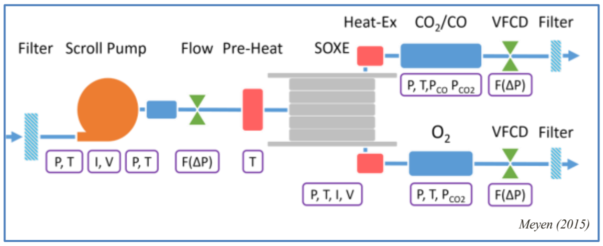
Introduction: Currently on Mars aboard the Perseverance rover, the Mars Oxygen ISRU Experiment (MOXIE) is a prototype of a system that will someday produce many tons of oxygen from martian air in support of a human mission. Most of that oxygen will be used as the major component of the propellant needed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

Assuming pre-deployment one 26-month cycle ahead of the crewed mission, an oxygen ISRU system will need to produce 2-3 kg per hour, utilizing upwards of 20 kW power, without substantial interruption for an Earth year. This level of sustained reliability in an operating mode while subject to the diurnally and seasonally changing martian temperature and pressure is unprecedented, and the justification for including a technology demonstrator in the Perseverance mission was not just to determine whether the technology was appropriate for Mars, but also to explore whether such a demanding concept of operations is viable



Meyen (2015)

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

How it works [1]: MOXIE (Fig. 1) first 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 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. A major advantage of the SOE approach is that it intrinsically separates the oxygen product from the waste stream, requiring no subsequent purification step.

Development Challenges: MOXIE development was challenged by a lack of flight heritage, the need to demonstrate extreme reliability, the severe downsizing needed to fit within rover resource allocation, and the prospect of repeated thermal cycling in order to conform to the available power profile.

Heritage. While similar technologies (scroll pumps, solid oxide fuel cells) are routinely used on Earth, the challenges of adaptation to the martian environment benefited from no prior TRL advancement.

Reliability. The long-term vision of sustained, unattended operation over many months is perhaps more typical of rover design than of a science instrument. The development process strongly (and successfully) emphasized risk reduction over performance, and it was only after many months of experimentation on Mars and in the laboratory that production in excess of 10 g/hr was realized and advanced control capabilities were tested.

Scaling. 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. One consequence is that power efficiency of the flight unit is of order 10% relative to "wall plug" power, while analysis shows that this will improve to ~90% in a full-scale system with active pressure regulation and a more traditionally insulated oven [2].

Thermal cycling. While SOE technology is highly efficient and reliable, it requires operation at elevated temperature (800˚C for MOXIE), and can suffer degradation if cycled to ambient temperature and back. While a full-scale system would operate continually, with only the rare shutdown for maintenance, Perseverance power constraints demand that MOXIE be operated only occasionally (approximately every 6-8 weeks to date), with a full shutdown between runs. This requirement drove an intensive development effort to minimize cycle-to-cycle degradation.

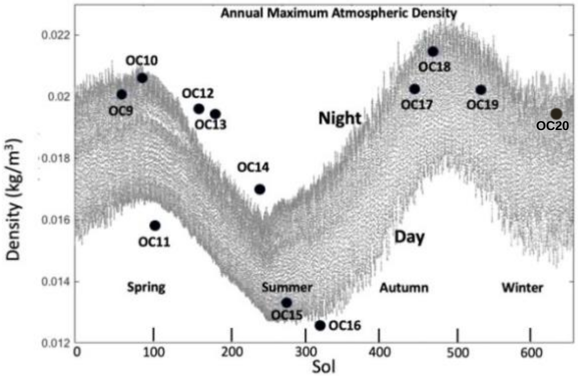


Figure 2: Models of the martian atmosphere at Jezero define a range of atmospheric density with large diurnal and seasonal variation. MOXIE Operational Cycles (OC) #9-20 have sampled most of the annual cycle, primarily at night but with 3 daytime runs[4].

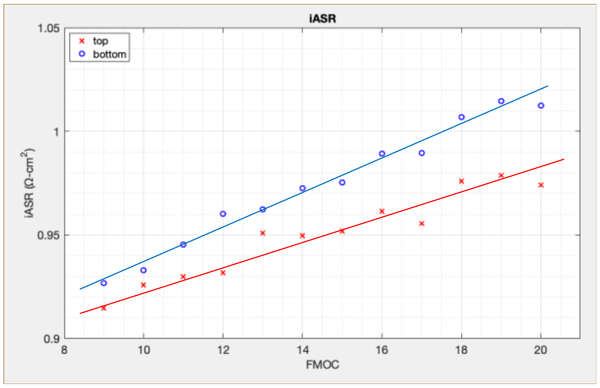


Figure 3: Changes in intrinsic Area Specific Resistance (iASR) from run to run are sufficiently small to allow MOXIE to run for dozens of cycles while still meeting development requirements. Prior to the first oxygen-producing Flight Model Operating Cycle on Mars (FMOC-09) the instrument had been operated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

MOXIE on Mars: MOXIE was integrated into the belly of the Perseverance rover, launched with the mission on July 30, 2020 and landed on Mars on February 18, 2021. As of this writing, MOXIE has completed 12 oxygen-producing runs, generating a total of 92 grams of O_2 in 15.5 hrs and demonstrating the ability to produce more than 10.5 grams of O_2 per hour with unmeasurably small levels of impurity as long as a small anode overpressure is maintained [3]. The initial design requirement was 6 g/hr at 98% purity (99.6% is typical for propulsion or breathing).

It has been found that MOXIE's production rate is constrained primarily by cell area, the current-voltage relationship, and the need to stay below the threshold potential for carbon formation. It nonetheless retains some sensitivity to CO_2 density, which changes by nearly a factor of two over the course of a martian year (Fig. 2), and the highest production rates have been achieved near peak density.

The best single 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 definition of area specific resistance by addition of a term that adjusts for variations of gas composition across the cell. Run-to-run increases on Mars (Fig. 3) have been effectively linear, although a parabolic dependence is expected over the long term. 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. For comparison, MOXIE runs allow a safety margin of 100 mV per cell.

Next steps: The MOXIE demonstrator has achieved high reliability and provided valuable guidance to a full-scale next-generation design. In order to achieve robust autonomy for that system, better characterization and calibration capabilities will be needed both on the ground and on Mars, with corresponding control enhancements. As an example, it was found that poorly-characterized electrical lead resistances totaled up ~700mΩ, compared to an equivalent 10-cell stack resistance of ~440 mΩ, introducing an uncertainty that if not recognized and mitigated could have potentially compromised the ability to select safe and effective operational settings.

As discussed above, the constraints of Perseverance drove a design with poor power efficiency. While the path to high efficiency is clear, it remains to be demonstrated. Similarly, 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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References: [1] Hecht, M. *et al.* (2021), *Space Sci Rev* **217**:9. [2] Hoffman, J.A. *et al.*, proc. 73rd International Astronautical Congress Paris, France, 18-22 September 2022. [3] Hoffman, J., *et al.* (2022), *Science Advances* **8**, Issue 35. [4] Newman, C.E. *et al.* (2021) *Space Sci. Rev.* **217**:20.