MOXIE: Epilogue. M. H. Hecht[1], J. A. Hoffman[2], P. Steen[1], 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

Introduction: The Mars Oxygen ISRU Experiment (MOXIE) on the Perseverance Rover ended its successful mission on Sept. 30, 2024, having satisfied all its success criteria and doubled the required oxygen production rate [1-3]. MOXIE suffered no failures over the course of its 16 runs on Mars.

MOXIE high level development requirements specified the capability to: Produce oxygen at a rate of 6 g/hr, with a goal of 8 g/hr; produce oxygen with a purity of 95%, with a goal of 98%; and to satisfy the above two requirements after 10 cycles of operation.

From a tactical perspective, the science team had several practical objectives on Mars, including determining the minimum acceptable warmup and thermal equilibration time prior to initiating oxygen production; calibrating poorly defined quantities such as electrical lead resistance, warming in the inlet tube, or sensor transfer functions; monitoring key figures of merit, such as oxygen purity and indicators of stack aging; minimizing transients when changing configurations; and refining the limits of operation without risking carbon production (coking). All of these were accomplished.

The primary lesson learned from the MOXIE project is that with careful operation, the technology is surprisingly robust against thermal cycling, dust, changes in atmospheric density and temperature. Performance of MOXIE on Mars was in every way consistent with performance on Earth.

In the MOXIE development phase, focus was on efficacy and risk reduction, not on performance optimization. In the Operations phase, potential improvements were identified that would substantially reduce power consumption and improve safety and autonomy. A few of these are described below.

Operation at low cathode pressure. It is now understood that substantial advantages will accrue from operation at the lowest possible cathode pressure consistent with the intrinsic flow restriction of the SOXE stack. The primary benefit is a major reduction in compressor power demand, which currently dominates the MOXIE power budget. Lower cathode pressure also increases the gap between the oxygen and carbon Nernst potentials, a safety benefit, and decreases the mechanical stress on the delicate SOXE components, which adds robustness and reduces structural overhead.

With the current SOXE design, internal flow resistance limits the minimum inlet pressure to ~100 mbar. Redesign is needed to reduce that flow resistance another order of magnitude.

In addition, compressor redesign is needed to take advantage of the reduced outlet pressure. Fig. 1 shows laboratory measurements of compressor power demand as a function of outlet pressure at a fixed rotation speed of 2000 rpm, sufficient to support operation at ~2A, corresponding to ~30W directly into electrochemical conversion. Notable in the figure is that while the actual compression power at low outlet pressure is acceptably small, the power required for the compressor just to spin in a vacuum, without doing compression work, is comparable to the electrochemical energy demand. This needs to be reduced, possibly by scaling up to a larger compressor volume and slowing rotation speed.

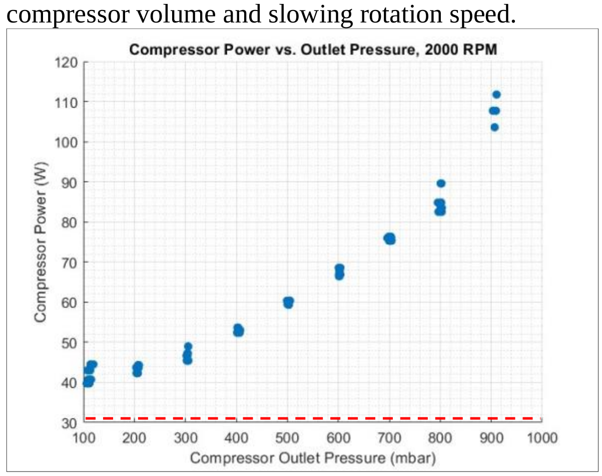

Figure 1: Compressor power consumption as a function of outlet pressure at 2000 rpm. The dashed line indicates the power required to spin in a vacuum.

Improvements in voltage monitoring and control. From a system perspective, there are two schools of thought on how to operate a human-scale MOXIE system. One strategy is to specify the oxygen output rate and scale MOXIE to be able to produce at that rate under all environmental conditions. That approach allows the balance of plant to always run at optimal efficiency.

The other strategy is to produce the maximum oxygen possible under any given environmental condition while maintaining safety with respect to the coking threshold. This is illustrated in Figure 2. MOXIE could not readily operate in such a mode because it does not directly measure the voltage across the stack. Instead, it senses stack voltage across the power leads, which suffer from voltage drops due to lead resistance that are comparable to the voltage across the stack itself. Separate voltage sense wires (or, at a minimum, accurate knowledge of the lead resistance) would resolve that issue. If feasible, cell-level voltage modeling would offer even greater improvements in robustness.

Thermal management of flow stream. The low ambient martian temperature increases the atmospheric density, offering a potential power advantage to the MOXIE compressor. In practice, most of this advantage is lost as a result of warming of the gas in the inlet system. Significant improvement could be achieved by shortening and insulating the inlet tubing and by thermally coupling the compressor inlet to the martian environment rather than to the Rover Avionics Mounting Panel (RAMP), as is currently done.

In addition, while not justifiable for a system that produces oxygen only for an hour, a continuously running system would realize significant power advantages from a heat exchanger that transfers thermal energy from the exhaust gases into the feed gas stream.

Reduced dust filter flow resistance: In the thin martian atmospheric, delivery of feedstock to MOXIE is highly sensitive to even very small flow resistance of upstream filters. A significant laboratory finding was that nearly all martian dust is effectively removed from the flowstream by a simple baffle that abruptly changes the direction of gas flow. As a result, it was found that the flow resistance of the clean filter itself establishes the minimum filter area required. To further reduce the considerable mass and volume of the filter will require selection or development of a filter material with significantly lower flow resistance, possibly at the cost of lowered performance.

In summary, the MOXIE Project can boast a number of accomplishments that substantially advance the prospects for ISRU on Mars.

- The MOXIE design was shown to translate from the laboratory to Mars without degradation in performance.
- MOXIE exceeded development requirements for production by a factor of 2 and achieved unmeasurably small oxygen impurity levels.
- MOXIE demonstrated figures of merit, notably iASR and simple purity measures, that will serve as benchmarks for future systems.
- MOXIE retired risk by characterizing poorly known properties including lead and series resistance, stack ASR, and crossover leakage.
- MOXIE validated safer modes of operation, including fixed voltage, cathode-pressure feedback, and voltage feed-forward.
- The MOXIE Team developed accurate predictive models of performance.
- MOXIE students modeled a full-scale, highly power efficient system design.
- The MOXIE Team demonstrated that dust is of little concern in a full-scale system
- Through professional and public outreach, MOXIE has demonstrated to the engineering community and to the general public that ISRU is a safe, reliable, and effective way to decrease the cost and complexity of human exploration.

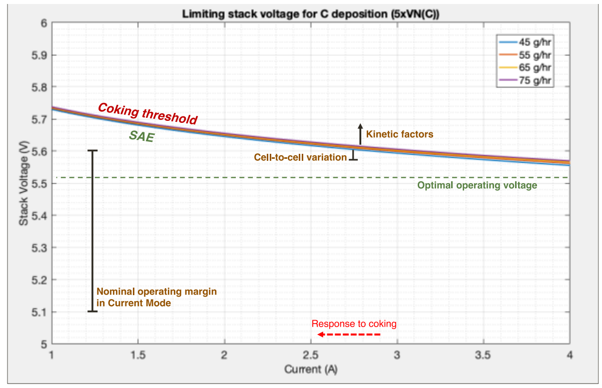

Figure 2: The Nernst potential for carbon formation is a weak function of current and an even weaker function of flow rate. For comparison, the error bar indicates the safety margin maintained in early MOXIE runs. Small deviations downward from this level are expected due to cell-to-cell variations as noted, but kinetic factors and new materials can raise the threshold. The "optimal operating voltage" refers to the voltage across the stack itself. As shown, degradation of the cell by coking would reduce the current in such a constant-voltage mode, increasing the safety margin and presumably arresting the coking. Note that this illustration is for a 5-cell half-stack.

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References: [1] Hecht, M. *et al.* (2021), *Space Sci Rev* **217:**9. [2] Hoffman, J., *et al.* (2022), *Science Advances* **8**, Issue 35. [3] Hoffman, J.A. *et al.*, proc. 73rd International Astronautical Congress Paris, France, 18-22 September 2022.