CO_2 Electrolysis with High Conversion Fraction for CO Utilization and Energy Efficiency

M. H. Hecht[1], Parker Steen[2], Jeffrey Hoffman[3], Kyle Horn[3]. [1]Planetary Science Institute, Tucson, AZ, 85719 mhecht@mit.edu [2]MIT Haystack Observatory, Westford, MA 01886, [3]MIT Dept. of Aeronautics and Astronautics, Cambridge, MA, 02139

Introduction: The Mars Oxygen ISRU Experiment (MOXIE) on the Perseverance rover [1, 2] used solid oxide electrolysis (SOE) to generate oxygen from the 95% CO_2 thin atmosphere of Mars according to the reaction $2CO_2 \rightleftarrows 2CO + O_2$. The primary goal of MOXIE was to make oxygen at a rate of at least 6 g/hr (12 g/hr was achieved, the maximum allowed by the power supply), with secondary goals addressing purity of the product and robustness of the system.There were no goals associated with energy efficiency and it was not tracked as a figure of merit. Not surprisingly, the resulting efficiency was poor, with typically 15-20% of the power provided going directly to the electrochemical reaction (Fig. 1). The largest portion went to gas compression, with heat loss second. The mitigation of heat loss is a straightforward engineering effort given additional mass and volume, while reducing compression power can be accomplished operationally.

Compressor efficiency: Compressor power is a strong function of flow and compression ratio, which in this case is determined by cathode pressure. As will be shown, an order of magnitude reduction relative to typical MOXIE operation can be realized simply by increasing the fraction of CO_2 converted to O_2 and CO, which reduces the feed gas demand, and operating the SOE at low cathode pressure, which reduces the compressor load. Additional benefits accrue from such operation. Low cathode pressure increases the SOE safety factor by raising the threshold voltage for carbon production, or coking (Fig 2), and increasing the CO concentration in the exhaust stream will be critically important for its downstream utilization.

Conversion Fraction: While O_2 was the primary MOXIE product because of the enormous quantities needed for propulsion, the CO produced by the reaction will eventually be needed for purposes including co-electrolysis with water for synthesis of methane fuel and other organic compounds, or as a first-stage fuel for power and energy storage. Conversion fraction (F_c) was not tracked for the MOXIE program but was retrieved for this study from the telemetry of cathode pressure (proportional to flow in the MOXIE design) and electron current (proportional to CO production rate).

On Mars, the average MOXIE F_c varied between 0.28 and 0.38 (Fig. 3). The maximum value exceeded 0.4 in only two cases. The first was run FMOC-13, which reached ~0.47. The second, and the focus of this presentation, occurred in an interval of a few minutes in one of the later runs, FM-OC22, when F_c reached as high as 0.9 (Fig. 4).

The circumstance of the high Fc operation was an interval when flow was reduced in order to lower the cathode pressure to 0.2 bar in order to validate the safety and efficacy of such operation for future implementations. Current, a function of voltage, was then gradually stepped up while maintaining an adequate safety margin with respect to the coking threshold $V_N(C)$ as shown in Fig. 5. As an experiment, a smaller margin was tolerated for a period of 5 minutes within the box outlined in red, corresponding to the highest current step. The combination of low flow and high O_2 production resulted in the observed high F_c.

An immediate result of the high Fc, low pressure operation was the reduction of compressor power relative to the electrochemical power intrinsic to the reaction, as shown in Fig. 6. The compressor power dropped to ~10W compared to ~30W for electrochemistry. This is an acceptable ratio for a full scale system, in contrast to the result in Fig. 1.

On to Venus: CO purity is of particular importance for replenishment of buoyant gases to extend the life of scientific balloons on Venus [3]. Both the O_2 and CO products of electrolysis can be used for this purpose but, the CO is of greater value since the reaction produces two CO molecules for each O_2 molecule. For the mixed CO/CO_2 stream to be useable it should have at least the buoyancy of the O_2, which corresponds to $F_c = 0.75$. This must be achieved near the ambient pressure, ~0.5 bar, substantially higher than the FMOC-22 result, and the capability must be maintained for of order 10 years, necessitating higher voltages than a pristine stack and more risk of exceeding the coking threshold. It also must be maintained for hours at a time, not the few minutes demonstrated in FMOC-22.

Fig 7 shows the result of a recent laboratory test in a representative configuration for this application. Cathode pressure was maintained at 0.5 bar and the target $F_c = 0.75$ was successfully maintained for 25 minutes. High F_c operation reduced the O_2 production rate by ~15%, which is readily compensated for by adding stack area. The SOE stack was in a later stage of its life with an iASR of 2.5-3.0 compared to 1.0 for the FM.

Acknowledgements: The described work is funded by an award from the NASA Innovative Advanced Concepts Program (NIAC). One of us (K.H.) is supported by the MIT MathWorks Fellowship program.

Exploring Venus with Electrolysis. M. H. Hecht et al.

References: [1] Hecht, M.H *et al.* (2021), *Space Sci Rev* **217**:9. [2] Hoffman, J., *et al.* (2022), *Science Advances* **8**:35. [3] Hecht, M.H *et al.* (2025), *Proc. Space Resources Roundtable*, abstract 16-2.

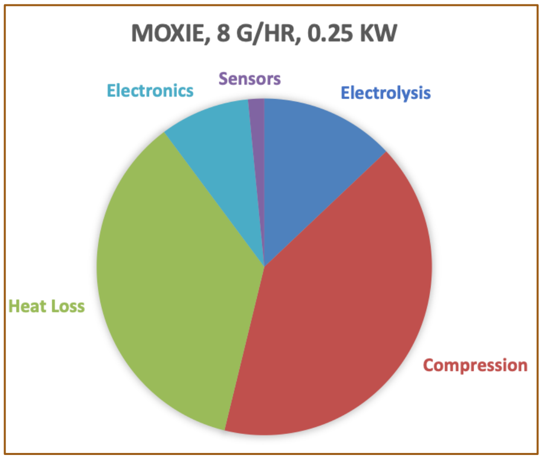

Figure 1. Typical power allocation for a MOXIE run.

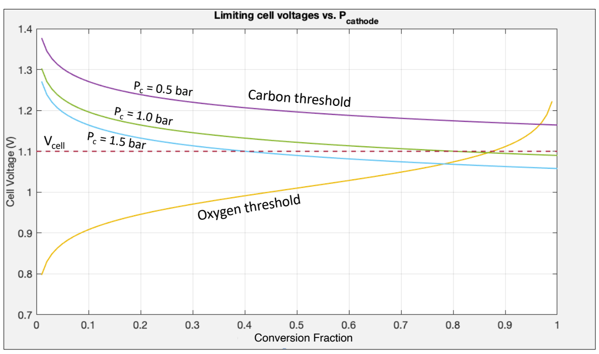

Figure 2. Nernst potenials $V_N(O_2)$ and $V_N(C)$ vs cathode pressure as a function of conversion fraction F_c, demonstrating an increased safety factor at low pressure.

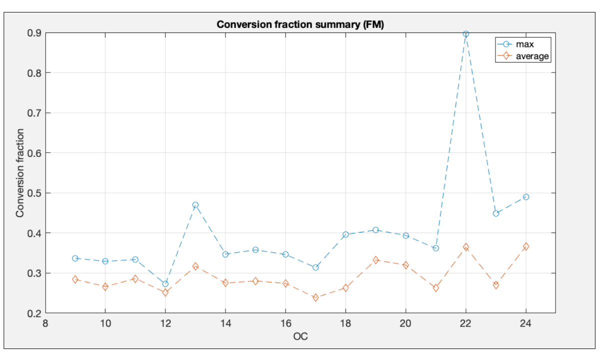

Figure 3. The average and maximum F_c for each operational cycle (OC) of the flight unit (FM) on Mars

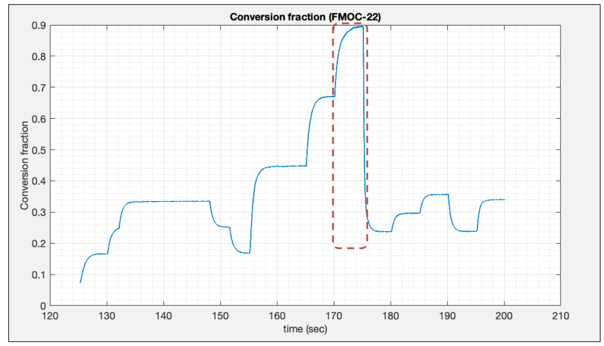

Figure 4. F_c for run FMOC-22. The interval discussed in the text is highlighted by the red box.

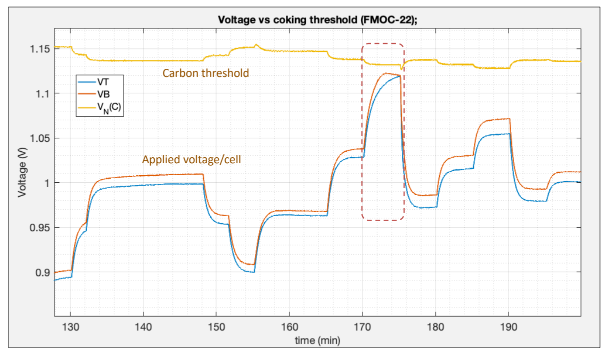

Figure 5. Average cell voltage for top and bottom half-stacks (VT, VB) vs $V_N(C)$ for same run

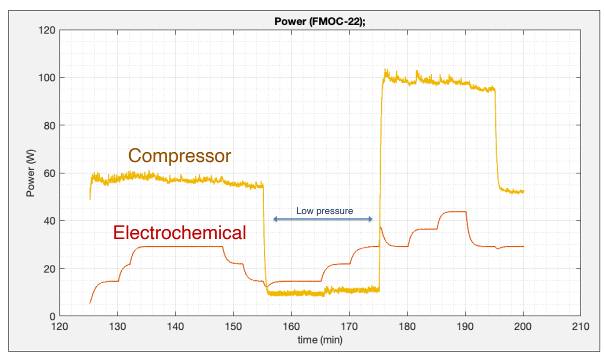

Figure 6. Comparison of electrochemical to compressor power for same run

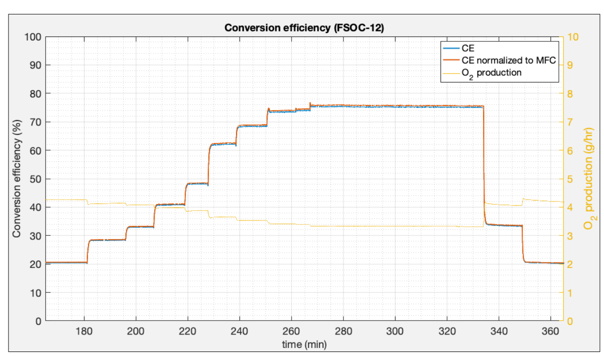

Figure 7. F_c and O_2 yield vs time for Venus balloon test