The Mars Oxygen ISRU Experiment (MOXIE) on the Mars 2020 Rover Michael H. Hecht,[1] and Jeffrey A. Hoffman[2] for the MOXIE Team. [1]MIT Haystack Observatory, Westford, MA. Email: mhecht@haystack.mit.edu. [2]M.I.T. Dept. of Aeronautics and Astronautics, Cambridge, MA. Email: jhoffma1@mit.edu.

Introduction: A substantial reduction in the cost and complexity of a human mission to Mars can be realized by *in situ resource utilization (ISRU),* using resources at our destination to supplement the payload brought from Earth. Low-hanging fruit for such a mission is *in situ* production of oxygen, which is consumed in prodigious quantity by the lift-off of an ascent vehicle from Mars. The most readily accessible source of oxygen is the martian atmosphere itself.

The Mars Oxygen ISRU Experiment (MOXIE), a technology demonstration on NASA's 2020 Mars rover, is a progenitor of the "oxygenator" used by the fictional Mark Watney as portrayed in Andy Weir's *The Martian*. MOXIE ingests the thin CO_2 that comprises 96% of the Martian air, and exhales O_2 – somewhat like a tree, but without benefit of water as a reactant.

Mission models suggest that in excess of 30 metric tons of oxygen will be needed as the oxidant for the ascent of a human crew from Mars, representing ~78% of the propellant mass in a CH_4/O_2 propulsion system. This would translate into 400 metric tons in Earth orbit – requiring 4 to 5 heavy lift launches [1].

Approach: In development at the Jet Propulsion Laboratory, MOXIE is a ~1% scale model of an oxygen processing plant that might support a human expedition sometime in the 2030s. MOXIE is expected to produce ~10g/hr of O_2 on Mars with >99.6% purity. Fig. 1 illustrates the two major steps in O_2 production – CO_2 accumulation and compression, and conversion of CO_2 to O_2. Also of importance is the process monitoring and control system, our primary source of knowledge from experiments on Mars and in the laboratory. MOXIE fills a 24x24x31 cm volume within the rover body, as shown in Fig. 2.

MOXIE's solid oxide electrolysis (SOXE) stack for converting CO_2 to O_2 [2] is designed and built by Ceramatec, Inc.. Its working elements are stacked scandia-stabilized zirconia (ScSZ) electrolyte-supported cells with thin screen-printed electrodes, coated with a catalytic cathode on one side and an anode on the other. These are separated by expansion-matched interconnects that direct the source, exhaust, and product gases to and from their respective manifolds. The stacks nominally operate at 800°C.

When CO_2 flows over the catalyzed cathode surface under an applied electric potential, it is electrolyzed according to the reaction $CO_2 + 2e^- \Rightarrow CO + O^{=}$. The CO is exhausted, while the oxygen ion is electrochemically driven through the solid oxide electrolyte to the anode, where it is oxidized ($O^{=} \Rightarrow O + 2e^-$). The O atoms combine to produce the gaseous O_2 that is released from the anode cavity at a rate proportional to current, $\dot{n}_{O_2} = \frac{I}{4F}$, where F is Faraday's constant.

Having designated atmospheric CO_2 as the source of oxygen, the choice of solid oxide electrolysis is largely uncontested, though lower-temperature solutions such as polymer electrolytic membranes may become important in the future. For MOXIE and future systems, the more contentious trade is over the method of collecting and compressing CO_2. In the context of the Mars 2020 mission direct mechanical pumping was chosen as the most practical and resource-efficient solution, as it allows real time operation without intermediate storage despite the limited mass, volume, and power resources of Mars 2020. A scroll pump is under development from Air Squared, Inc. for this purpose. Future implementations, possibly less limited by either space or power, may choose an integrated approach that uses cryogenics for CO_2 collection, gaseous product separation, and liquefied gas storage.

Dust filtering is also a critical technology, not so much because Mars is so dusty, but because small pressure drops that would be of no significance in the Earth environment can severely impact the throughput of a collection system at Mars ambient pressure. For MOXIE, conventional pleated HEPA filters appear to offer sufficient collecting area to treat the air drawn through the filter with tolerable degradation during the limited allocated operating time (nominally 15 two-hour runs during the primary mission). Recent experiments in a Mars wind tunnel addressed this issue, as well as exploring the impact of dust passively accumulated when MOXIE is not in operation. In future implementations, a dust-tolerant first-stage pump, electrostatic dust removal, or cyclonic particle separation may be preferred.

Performance: MOXIE oxygen production rate is limited by several factors:

- SOXE capability
- Pump capability
- Power supply capability
- Safe operating conditions
- Atmospheric pressure
- Impedance from filters and dust accumulation

The production capability of the SOXE itself is uniquely determined from knowledge of the areaspecific resistance (ASR), typically ~2.0 for this system; the open-circuit voltage (OCV), typically 0.8V; the overall cell area (A), 10 cells at 22.7 cm^2 each; and the choice of operating voltage, typically 1.2 V. This voltage is adjusted such that the SOXE doesn't use more than a selected fraction of the available CO_2, the utilization fraction, which is expected to be ~50% to allow for spatial variation that might result in carbon deposition in CO_2-starved areas.

Since MOXIE's scroll pump is volumetric, oxygen production is limited both by its capacity and by the external conditions that determine the density and quantity of air that can be drawn in. The atmospheric pressure of Mars varies by as much as a factor of 2 with elevation, by up to 30% with season, and by up to ~10% with time of day. Weather variations, by comparison, are a few percent or less, except during severe dust storms, which can increase the pressure by up to ~12%. The available CO_2 is largely predictable as a function of time-of-day and season once the landing site is known; but that decision is unlikely to be made until after MOXIE is delivered. MOXIE has therefore been designed to accommodate the full range of sites under consideration, all at relatively high elevation compared to previous landings.

Other production constraints include the SOXE power supply limit of 4A current, corresponding to 12 g/hr O_2 production for the 10-cell stack. Also, since MOXIE is inside a warm rover box, production may be limited at times by its own heat generation. Safe operating conditions are currently being determined for SOXE voltage, temperature, and pump speed.

Fig. 3 factors all these limits together for anticipated operating conditions. It is notable that SOXE performance is not anticipated to be the limiting factor under any conditions.

Acknowledgments: MOXIE development is supported by the NASA HEOMD, STMD, and SMD Directorates. The technical progess reported here is largely due to the tremendous effort of the implementation team at JPL, as well as our partners at Ceramatec and Air Squared.

References: [1] Drake B. ed. (2007) Mars Design Reference Architecture 5.0, NASA/SP–2009–566-ADD. [2] Hartvigsen, J.J. et al. (2015), proc. ECS Conf. on Electrochemical Energy Conversion & Storage with SOFC-XIV, Glasgow, Scotland.

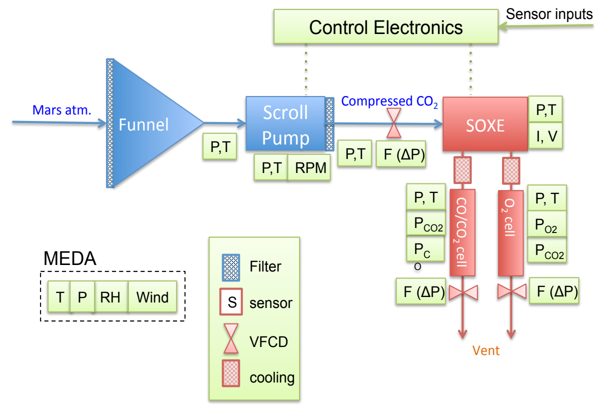

Fig 1. SOXE design components showing collection and compression system, electrolysis, monitor and control. MEDA is a separate meteorological instrument that characterizes environmental conditions of inlet gas.

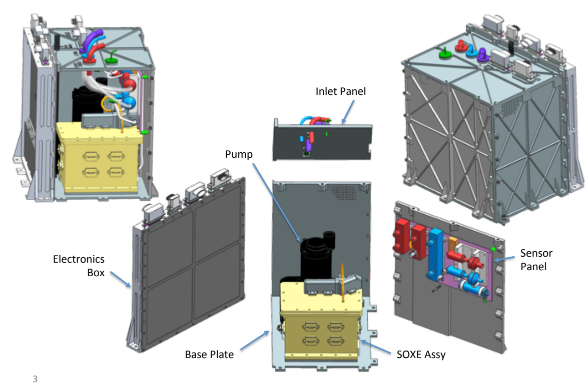

Fig 2. The MOXIE assembly consists of the SOXE and pump, electronics, analytical equipment, plumbing, and structure. All fits in a 24x24x31 cm volume.

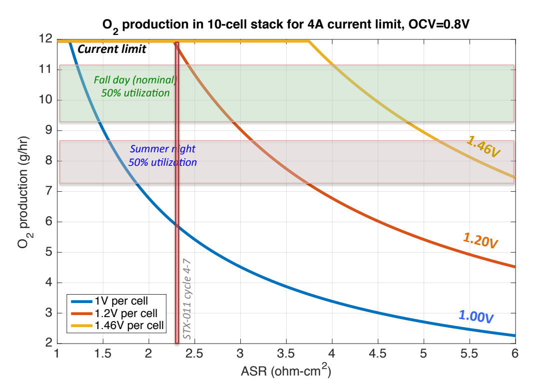

Fig 3. Anticipated O_2 production falls on the intersection of the red vertical line, showing a characteristic SOXE ASR, and a horizontal line representing the external pressure. The voltage is then adjusted accordingly. Once a site is chosen, the pink and green bands will collapse into horizontal lines representing high and low pressure conditions at the site. A 50% CO_2 utilization fraction is assumed for the y-axis.