The Mars Oxygen ISRU Experiment (MOXIE) Michael H. Hecht,[1] Donald R. Rapp,[2] and Jeffrey A. Hoffman[3] for the MOXIE Team. [1]MIT Haystack Observatory, Westford, MA. Email: mhecht@haystack.mit.edu. [2]JPL (retired). Email: drdrapp@earthlink.net. [3]M.I.T. Dept. of Aeronautics and Astronautics, Cambridge, MA. Email: jhoffma1@mit.edu.

Introduction: As the only planet in the solar system other than Earth whose surface is likely to be hospitable to human explorers, Mars has been widely viewed as the next significant post-Apollo human destination. One of the many factors that distinguish such a round trip from lunar exploration is the tremendous mass of propellant that must be transported for ascent from the much deeper gravity well of the martian surface. Preliminary mission models suggest that more than 30 metric tons of oxygen will be needed as the oxidant for this ascent, representing about 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].

If the oxygen required for ascent is instead produced on Mars by In Situ Resource Utilization (ISRU) using indigenous CO_2 as a feedstock, it will eliminate the need for these expensive launches. In this scheme, the ascent vehicle, power source, and chemical processing plant is sent toward Mars ~26 months before human departure from Earth, and the oxygen tanks of the ascent vehicle are filled prior to the final decision to send the crew. Analogous systems might also support future robotic return missions.

The substantial risks of such an architecture demand an *in situ* test to evaluate the effects of actual Mars mission conditions of launch and landing, dust, wind, radiation, electrostatic charging and discharge, thermal cycles, reduced gravity, and enforced autonomy, as well as unknowns intrinsic to the first operation of a production facility of any kind on another planet.

Recently selected to fly on NASA's Mars 2020 mission, MOXIE is a 1% scale model of an oxygen processing plant that might support a human expedition sometime in the 2030s. MOXIE will produce 22g/hr of O_2 on Mars with >99.6% purity during 50 sols. More than a technology demonstration, MOXIE exercises a range of control parameters, probes performance margins, provides diagnostics of health and degradation, and exploits redundancy and modularity to explore technology options. The goal is to understand the parameters and protocols, the risks, development challenges, margins and threats, the constraints and requirements of a full-scale Mars In Situ Resource Utilization (ISRU) facility.

Technical Approach: The two major steps in O_2 production are (1) CO_2 accumulation and compression, and (2) Conversion of CO_2 to O_2. MOXIE also carries a high resolution microscopic imager for dust characterization.

Conversion of CO_2 to O_2. MOXIE uses a solid oxide electrolysis (SOXE) stack developed by Ceramatec, Inc. for converting CO_2 to O_2. 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, as illustrated in Fig. 1. The stacks operate in the 800–850°C range.

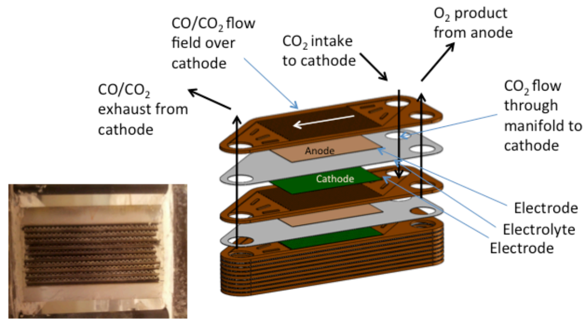

Fig 1. SOXE design and sample stack. The side view of an actual stack is shown at left.

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.

The reaction chemistry uniquely determines both the minimum electrical current and the minimum CO_2 flow required to produce O_2 at a given rate. For MOXIE, the reaction requires 108 W to produce 22 g/hr O_2. To this must be added ~40 W to compensate for heat loss due to convection and radiation and ~20 W to pre-heat incoming CO_2, for a total of ~168 W.

CO_2 acquisition and compression (CAC). The atmosphere of Mars varies from ~7-9 mbar in the northern hemisphere, low elevation landing sites that are likely to be selected for both Mars 2020 and an even-

tual human landing. This atmosphere contains about 95.5% CO_2; the remainder is largely Ar and N_2.

In soliciting an oxygen production investigation, NASA encouraged the proposal of an Advanced Technology Option that would significantly reduce the resources required to meet the requirements. Accordingly, MOXIE proposed a straightforward but technically less mature direct-compression system that continuously feeds CO_2 to the electrolytic conversion system at a pressure of ~0.1 bar.

As a backup, MOXIE is prepared to fly a batch-mode system that cryogenically compresses CO_2 to ~1 bar prior to initiation of the conversion process. Residual Ar and N_2 is occasionally flushed out to maintain an overall positive pressure differential between the outside atmosphere and the accumulation chamber. When sufficient CO_2 is accumulated, the chamber is sealed off from the atmosphere and warmed, producing high-pressure CO_2 that is stored for later use. However, the need to process the CO_2 over a large temperature range and two phase changes while managing the corresponding latent heat makes this approach energetically unfavorable.

Dust Imager: As part of its assessment of potential sources of performance degradation, MOXIE will characterize the size distribution and physical properties of dust in the inlet stream with optical microscopy, using a methodology and instrumentation derived from the Phoenix mission [2]. The Phoenix microscope returned the only images of Mars with resolved individual martian soil grains (Fig. 2), and it determined the particle size distribution (PSD) of martian soil [3]. MOXIE will fly a simplified version of the Phoenix microscope station, using residual Phoenix hardware, to compare the PSD of *airborne* particulates with the soil PSD measured by Phoenix. The 2μ pixel size will suffice to count nearly all the airborne particles, with some detail resolvable for a large fraction.

Extensibility to Full Scale: In a human scale Mars mission, the ISRU system would be operated continuously in a steady state without interruption for many months, adapting autonomously to atmospheric variability (temperature, pressure, dust). Such a full-scale system would produce roughly 25-30 metric tons of O_2 during the ~17-month period between arrival of the ISRU system and ascent vehicle on Mars, and the decision to launch the human crew at the next launch opportunity. This requires a production rate of approximately 2.2 kg/hr.

The SOXE architecture is a stack of cells, arranged vertically like a multi-story building. The two MOXIE stacks each utilize 11 cells. An assembly of 100 stacks, each containing 20 MOXIE-sized cells, would produce >2 kg/hr of O_2 with an energy investment of ~12 kW.

A full-size CO_2 acquisition system requires 8 kg/hr of martian atmosphere, ~0.14 m^3/s at 7 mbar. This can be accomplished with a three-stage centrifugal compressor followed by a single-stage scroll compressor, for a total compressor mass of 38 kg that requires < 1.1 kW power.

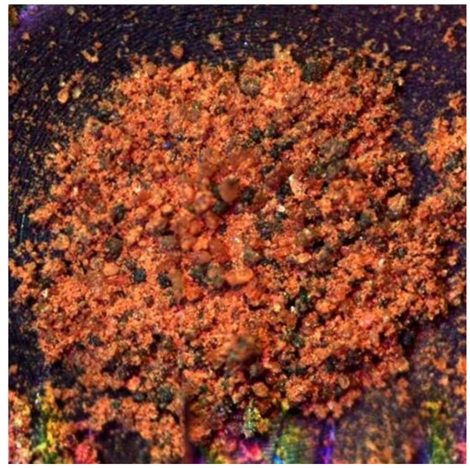

Fig. 3. This 2x2 mm microscope image from the Phoenix mission shows the mix of finer reddish particles, likely to dominate an airborne sample, and coarser gem-like polished grains that are transported by saltation and unlikely to be found in the air. The MOXIE images will be monochromatic.

Acknowledgments: MOXIE development is supported by the NASA HEOMD and STMD offices. We are particularly grateful to support from JPL and MIT, as well as our partners Ceramatec and Creare, in the preparation of the MOXIE proposal.

References: [1] Drake B. ed. (2007) Mars Design Reference Architecture 5.0, NASA/SP–2009–566-ADD. [2] Hecht, M.H. *et al.* (2008) *J. Geophys. Res.* **113**, E00A22. [3] Pike, W.T et al. (2011) *Geophys. Res. Lett* 38, L4201.