MOXIE Delivered!

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Introduction: NASA's upcoming Mars 2020 mission (M2020) [1] carries the Mars OXygen ISRU Experiment (MOXIE), which converts atmospheric CO_2 into O_2 as an ISRU technology demonstration [2]. On a future human mission, such a process will be used to provide up to 30 metric tons of liquid oxygen (LOx) for ascent vehicle propellant in the 16 months preceding launch of a human crew to Mars [3].

Ref. [2] describes the major MOXIE subsystems and shows how they are arranged in the body of the M2020 rover. The CO_2 Acquisition and Compression (CAC) system collects Martian atmosphere, filters it, and pressurizes it to ~0.5 bar using a mechanical scroll compressor developed by Air Squared, Inc.; the Solid OXide Electrolyzer (SOXE), developed by Ceramatec, Inc. (now OxEon Energy), electrochemically converts the compressed CO_2 into the product O_2 and waste CO at ~800°C [4]. The process monitor and control (PMC) subsystem provides the means to optimize and evaluate the efficacy of operation.

MOXIE Delivery: The flight model (FM) MOXIE was installed into the Mars 2020 Rover in March, 2019 (Figure 1). Work in progress at JPL includes lifetime testing of a SOXE assembly in the laboratory (the compressor has already been tested for hundreds of hours). The "FlatSat" and other engineering hardware will be sent to a new laboratory at MIT for characterization and further calibration studies.

Operating strategy: The Mars 2020 mission will launch in August of 2020 and land in February of 2021. Once on Mars, MOXIE expects to operate for a ~2 hour session every 2 months. Each operation will consume up to 1000 W-hr of spacecraft energy, corresponding to the full payload allocation for a typical day. Three mission phases are planned: *Characterizaation*, when MOXIE subsystems will be checked out, the system will be commissioned, and performance will be increased incrementally from run to run until reaching maximum output; *Operation*, where MOXIE robustness will be assessed in a range of environmental conditions over much of the mission; and *Exploration*, where improved operational modes will be tested, limits of performance will be probed, and degradation under stress will be characterized.

Approach to data analysis: MOXIE's ground data system is currently under development. Data curation is managed in a MATLAB environment that bundles all versions of data and command information as distinct fields in common STRUCT variables. A common dashboard enables the user to access command development tools, static and dynamic numerical simulations, laboratory testbed control, toos to generate archival data for the Planetary Data System, and all prior data.

Command Development manages three types of tables: The Run Control Table (RCT) that dictates the stepwise operation of MOXIE, a Parameter Table that specifies safety limits and other fixed quantities, and a Metadata table that describes contextual parameters for simulation and data analysis purposes. The data itself may be stored in CSV or flight-like binary formats as well as the native MATLAB (.mat) format. Reduced Data Records (RDR) will be produced in pipeline fashion from the Digital Numbers (DN) returned by the spacecraft, progressing to: Nominal Engineering Units (EU), maintained constant throughout the mission; Calibrated EU, specific to a particular run or simulation; and Calculated Quantities such as ASR or CO_2 utilization factors. More advanced products will be developed and archived using custom analysis procedures.

Expected performance: MOXIE is expected to produce between 6-12 g/hr O_2 in normal operation, with 6 g/hr representing the end-of-life design requirement and 12 g/hr representing a power supply limit. Here end-of-life is defined as 10 cycles on Mars but, from a testing perspective, represents performance after 60 cycles. The design requirement for oxygen purity is 98% but, in practice, >99.6% (nominal for laboratory oxygen) is always achieved.

The factors that limit performance are (a) the power supply capability, (b) the SOXE capability, and (c) the compressor capability, determined in large part by the local air density which is not only landing site dependent, but can vary by up to a factor of 2 seasonally. In practice, these factors are well-balanced in MOXIE, and it is unclear which will actually limit performance on Mars.

The monitor and control system turned out to be more challenging than expected, and ultimately has some deficiencies. Measurement error is expected to be several percent on all sensors, notably including SOXE stack voltage and temperature. This will constrain operation to safe values well away from the Nernst threshold for coking (carbon formation). In addition to measurement uncertainty, temperature gradients across the stack are expected to be 10º or more, similarly constraining the operating temperature range. Moreover, while the voltage across each cell in the initial test stacks could be monitored, such connections are not provided in the flight model because they are not robust and leak heat out of the 800ºC hot zone. Fortunately, the key measured quantities can be accessed through redundant measurement approaches. For example, oxygen production can be determined from SOXE current, an oxygen sensor, a CO sensor, or an anode pressure sensor.

In order to provide uniform contact between interconnects and electrodes, it is required to compress the stack to several hundred pounds. Together with the severe thermal insulation requirements, this drives the SOXE packaging architecture to a design that provides external compression through rigid insulating materials. The spring design compensates for the inevitable compression and creep of the insulation.

The primary mechanism driving ASR increase is expected to be materials degradation (e.g. microcracks) due to thermal cycling. Two other potential degradation mehanisms are carbon deposition, which is avoided by careful selection of operating voltages and temperatures, and cathode oxidation, which has been mitigated by recirculating product CO to the inlet in order to provide a reducing environment.

Experiments and models have shown that the MOXIE filter is robust, even with respect to a hypothetical 10,000 hrs of operations such as would be typical for a full-scale mission. Dust mitigation is far less of a problem than expected, and may turn out to be negligible [5]. This is because (a) dust particles on Mars are ~10x larger than material typically used for testing of HEPA filters, reducing pressure drops by a comparable factor, and (b) MOXIE operates in the transition flow regime [5], reducing pressure drops by an additional factor of 3-5.

Next generation improvements: Oxeon Energy is currently working on a scaled-up stack design with ~30x the capacity of a MOXIE stack. An array of 5-10 such units in a common, compact package would serve the needs of a full-scale mission producing oxygen at a rate of >2 kg/hr. Other improvements are being introduced to reduce the tendency to coke or oxidize. New designs to reduce or eliminate the need for compression would be advantageous, but are not currently being pursued to our knowledge.

A lesson-learned from MOXIE is that it is not as important as once thought to operate the SOXE at the highest possible voltage and the lowest possible ASR. More modest values simply require an increase in cell area, with negligible impact on overall power utilization. Since the stack itself is a relatively small part of the overall system mass, there is little incentive to improve these performance parameters.

Air Squared is similarly working on a scaled up version of a compressor that could be assembled into a small array to support a full scale mission. For MOXIE, the compressor is a large fraction of the mass and power budget, but this could be substantially reduced by operating at lower pressure. Optimizing both the pump and the SOXE for operation at ~100 mbar is highly desirable.

With MOXIE technology, filters are expected to consume a disproportionate amount of mass and volume in a full-scale system. This has less to do with dust tolerance than with the intrinsic resistance of the filter material to air flow. Identifying lower resistance material should therefore be a high priority. Also, additional research is needed on dust entrainment and capture through a baffle; initial indications are that placing the filter orthogonal to the airflow is sufficient to reject as much as 96% of the dust.

Fig 1. The completed MOXIE box is shown here being lowered into the rover. Still to be installed are the filtering and inlet assembly, a conducted emissions mitigation module, and the exhaust and inlet tubing.

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References: [1] Williford, K. H., et al. (2018) in *From Habitability to Life on Mars*, Cabrol, N.A., and E.A. Grin, eds., Elsevier. [2] Hoffman, J.A., Rapp D., & Hecht, M.H, (2015) *AIAA SPACE 2015 Conference and Exposition,* AIAA SPACE Forum, (AIAA 2015-4561). [3] Drake B. ed., 2007. *Mars Design Reference Architecture 5.0*, NASA/SP–2009–566-ADD. [4] Hartvigsen, J.J. et al. (2015). Proc. ECS Conf. on Electrochemical Energy Conversion & Storage with SOFC-XIV, Glasgow, Scotland. [5] Hecht, M. H. et al. (2018), in *Dust in the Atmosphere of Mars and its Impact on Human Exploration,* ed. J.S. Levine et al., Cambridge Scholars. [6] Pich, J. (1971). *J. Colloid*

Interface Sci. 37, 912–917. [7] Lemmon, M.T. et al. (2004), *Science* 306, 1753.