MOXIE Comissioning and Laboratory Operations at the MIT Haystack Observatory. P. Steen[1], M. H. Hecht[2], J. G. SooHoo[2], J. Swoboda[2], R.P Schaefer[2], C. E. Eckert[2], C. Alcalde[2], A. M. Liu[3], S. Hariharan[3], K. J. Horn[3], J. A. Hoffman[3], J. J. Hartvigsen[4], A. M. Aboobaker[5], and the MOXIE Team. [1]MIT Haystack Observatory, 99 Millstone Rd., Westford, MA 01886, psteen@mit.edu, [2]MIT Haystack Observatory, 99 Millstone Rd., Westford, MA 01886, [3]MIT Department of Aeronautics and Astronautics, Cambridge, MA, 02139, [4]OxEon Energy, Salt Lake City, UT, [5]NASA Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA.

Introduction: The Mars Oxygen In-Situ Resource Utilization Experiment (MOXIE) is a payload aboard the Mars Perservereance rover that demonstrates dissociation of atmospheric CO_2 to produce O_2 using solid oxide electrolysis (SOE) [1]. The Flight Model (FM) operating on Mars, has a twin Engineering Model (EM) with the same subsystem components and configuration. A third model, the so-called laboratory FlatSat (FS), utilizes similar subsystem components to the EM and FM but is maintained in an accessible configuration so that modifications to the system can be made, including the addition of instrumentation or variations to flow paths. Both the EM and FS are currently operated in a laboratory at the MIT Haystack Observatory.

The FM, EM, and FS were all built around an electrolysis system developed by Ceramatec, Inc. (now OxEon Energy) and a compressor developed by Air Squared Inc. All three were designed, integrated, tested, and operated at Caltech's Jet Propulsion Laboratory (JPL) prior to delivery to MIT. A suite of commissioning procedures derived from initial tests at JPL was applied to the FS and EM at MIT to verify that the MOXIE system functions as expected, to more fully characterize the system in a manner only possible in the laboratory, and to pioneer new methods and techniques prior to their use on Mars.

Laboratory Configuration: The EM and FS are configured in separate vacuum chamber test beds at the MIT Haystack Observatory. Each MOXIE model is mounted to a temperature controlled baseplate to reject heat produced by the compressor, emulating a thermal plate in the rover that ultimately dumps heat to the martian environment.

On Mars, the FM uses the compressor to draw in atmosphere from outside the rover and feeds the gas, which contains >95% CO_2, through the SOE stack. The stack operates at ~800˚C and converts up to ~50% of the source gas to CO, producing a separate stream of O_2 at a purity of >99.9% when operated with a slight anode overpressure [2]. This method of gas delivery is available in the laboratory as well as a direct feed gas configuration that bypasses the compressor.

In the *compressor feed configuration* (EM and FS) pure CO_2 is drawn from the vacuum chamber and fed through the ten-cell electrolysis stack, as on Mars. A cathode exhaust recirculation line to the compressor inlet ensures that the inlet gas stack contains sufficient CO to provide a reducing environment that will prevent oxidation of the cathode. A challenge in the laboratory is to maintain sufficiently stable pressure in the vacuum chamber to emulate the ambient environment on Mars despite changes in rate of compressor feed. This is acccomplished at the MIT lab with an inlet mass flow controller and a precision feedback system that uses an active conductance valve to meter the chamber exhaust gas flow to a vacuum pump.

For certain experiments it has been advantageous to operate the FS in a *direct feed configuration*, which involves bypassing the MOXIE compressor and directly metering flow into the electrolysis stack from a gas bottle and mass flow controller. A mixture of 98% CO_2 and 2% CO is used in this configuration to replace cathode exhaust recirculation.

Finally, full thermal cycles to the operating temperature of 800˚C and back to room temperature are not only time consuming, but are a known source of degradation of SOE stacks. To minimize the need for cycling during development of protocols, circuitry has been developed to simulate the current-voltage relationship of the stack in room temperature testing.

Experiments and results: At the time of writing, two EM runs have been completed at MIT, following 15 previous cycles at JPL and one by the manufacturer. The first included a technique referred to as a "thermal sweep" to estimate internal resistances, primarily from leads, that are not attributable to the SOE stack itself. The internal resistance is a critical quantity needed to assess stack health and cycle-related changes. Additional runs are planned to validate future FM runs, the primary purpose of the EM.

The FS has been more extensively used to test new techniques prior to their use on Mars, and as a vehicle for characterization that requires laboratory capabilities not available on Mars. These include validation of a constant-voltage operating mode that offers improved safety as well as more responsive control than the previously used constant-current mode, which uses a relatively slow digital feedback technique.

In other experiments, the thermal sweep technique mentioned above has been validated using the FS by comparison with independent resistance measurements. A related "unbalanced stack" technique has also been validated that allows estimation of the middle lead resistance, which normally has cancelling currents running in opposite directions from power supplies that drive the two 5-cell half-stacks.

Other experiments include testing of an *active compressor flow rate control* capability built into the software but not previously validated. Rather than simply commanding the compressor to a specific speed intended to yield a projected flow rate for an assumed martian atmospheric density, in this mode a control loop uses the measured gas pressure at the cathode exhaust to actively control the compressor speed. In the laboratory it was possible to purposefully and accurately vary the gas density in the chamber in preparation for operation in the weather-driven martian environment.

The viability of a full-scale MOXIE system to support human missions to Mars demands substantial improvement in wall-plug efficiency relative to the current design, which is severely constrained by rover resources. This will be largely accomplished by reducion in *compressor power*, which will be realized in part by operation at lower outlet pressure. A suite of characterization tests recently completed with the FS have determined volumetric efficiency and power consumption as a function of flow rate and outlet gas pressure.

In related experiments, the impact of low cathode pressure on electrolysis was characterized. In addition to power efficiency, this mode is expected to raise the Nernst threshold for carbon production, allowing higher oxygen production rates.

Conclusion: Beyond merely facilitating and validating planned operation of MOXIE on Mars, operation of the FS and EM in the laboratory has provided new insights by enabling experimentation free of rover constraints and bringing the full capability of laboratory instrumentation to bear. These laboratory activities have helped inform design approaches for full-scale ISRU systems and may be used to evaluate related technologies in the future. Ongoing technical developments include the introduction of unattended but failsafe operation, and future experiments will include extended lifetime tests using that capability.

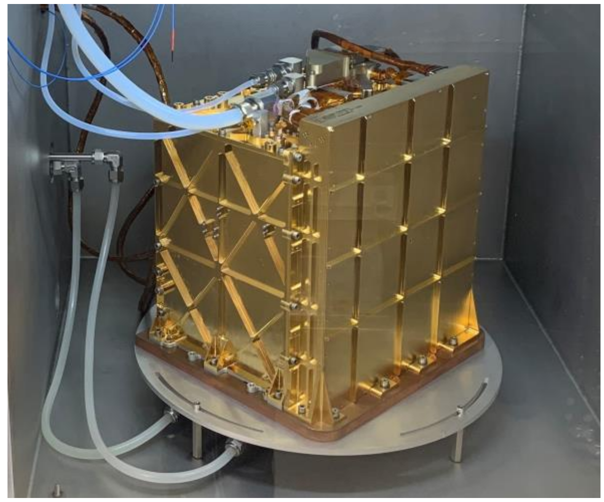

Figure 1: The MOXIE engineering model (EM) is packaged like the FM, with minor differences in fabrication.

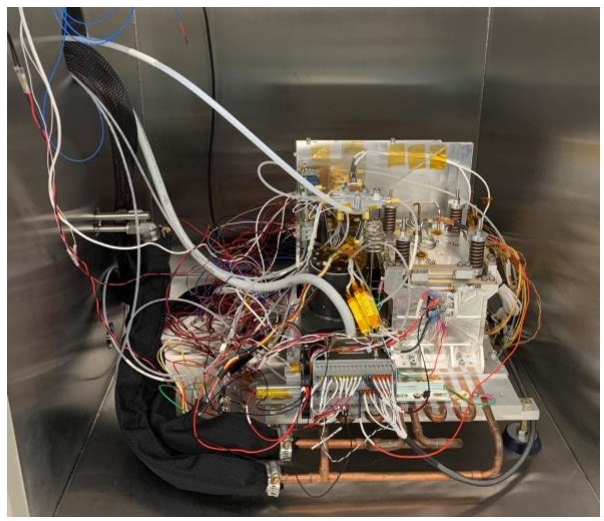

Figure 2: The MOXIE FlatSat (FS) is an open assembly using the same subsystem components as the EM.

References: [1] Hecht, M. *et al.* (2021), *Space Sci Rev* **217:**9. [2] Hoffman, J., *et al.* (2022), *Science Advances* **8**, Issue 35.