Scale Up and Coupling of the MOXIE Solid Oxide Electrolyzer for Mission-Scale Lunar and Martian Applications.

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Introduction: On April 20, 2021 the Mars Oxygen ISRU experiment (MOXIE) achieved the first demonstration of fuel production by electrolysis on another world[1][2]. Since that time, MOXIE has successfully produced O_2 from Martian atmospheric CO_2 13 times as of this publication. Since developing the Solid Oxide Electrolysis (SOXE) stacks for the Mars 2020 MOXIE program in 2017, the OxEon team has made significant advancements in both the scale and capabilities of the technology with the support of a NASA Next Space Technologies for Exploration Partnerships-2 (NextSTEP-2), a Space Technology Mission Directorate (SMTD) Tipping Point, and Small Business Innovation Research (SBIR) award. Newer variants of the SOXE stack have a five-fold increase in cell area and a 6.5-fold increase in cells per stack, for a stack scaled 33-times the 0.5% scale of the device in the MOXIE system. A set of six of these OxEon mission-scale SOXE stacks will produce 30 tons of propellant O_2 to fuel a Mars Ascent Vehicle (MAV) in the 19-month window between landing an unfueled MAV pre-supply mission and the next launch opportunity for the first crewed Mars Mission, meeting target requirements for a return mission. Demonstration systems have been built and successfully tested with the mission-scale stacks, under relevant test conditions for both Lunar and Martian applications.

Mission-Scale SOXE stack development: The MOXIE system requirements of operating in a near vacuum environment, through multiple, rapid thermocycles, resulting in significant changes to OxEon's heritage SOXE stack design. An interconnect material having a near perfect thermal expansion to the scandia stabilized zirconia (ScSZ) electrolyte supported cells enabled the use of a hermetic glass seal on a fully sealed anode perimeter capable of internally manifolded O_2 collection. Mid-FY2019, OxEon started a project under a NASA, NextSTEP award[3]. One key objective of the program was to scale up the MOXIE ISRU stack design to SOXE stacks of a size suitable for system modules capable of 2.3 kg/hr oxygen production rates. The final stack scale was limited by the interconnect size that could be manufactured with the vendor's available production pressures used to press the power metal, which matched the size of OxEon's heritage cell footprints. This allowed for the cathode inlet-exit port configurations to be retained while changes were made to the anode facing side of the interconnect to incorporate a fully sealed anode perimeter with internal O_2 collection ports. The addition of O_2 collection ports required some minor modifications to the cathode side flow field and a small decrease in the total cell active area. A comparison of the SOXE stacks from MOXIE and a 33-times larger mission-scale stack are shown in Figure 1 below.

Figure 1. Size comparison between MOXIE SOXE and mission-scale SOXE stacks.

Lunar mission-scale demonstration system: A Lunar demonstration system was designed and tested under a NASA SMTD Tipping Point award with the goal of developing a SOXE stack and packaging to support operation at temperature and pressure of a Permanently Shadowed Region (PSR) Lunar environment for the production of propellant H_2 and O_2 from Lunar ice [4]. This was a joint effort between OxEon Energy and the Colorado School of Mines (Mines). The breadboard demonstration system shown in Figure 2 was designed to integrate a mission-scale SOXE stack with a thermally integrated BOP, including intake of cold liquid H_2O from ice processing, vaporization, steam, compression, heat recover, and H_2 drying. The demonstration system was tested in the cryo-vacuum chamber at Mines to demonstrate operation at relevant conditions and the data collected was used to provide a technoeconomic analysis (TEA) of the technology with respect to scale-up for actual Lunar PSR application.

The final system was able to exceed a program threshold H_2 production of 1.5 kg/day by nearly 50%, demonstrating up to 2.2 kg/day H_2. It was also able to demonstrate H_2O utilization as high as 99% and electrochemical compression of the O_2 product pressure up to 360 kPa. A specific power threshold goal of 50 kWh/kg-H_2 was also exceeded with the system demonstrating an average of 48.8 kWh/kg-H_2 during relevant condition testing.

The Lunar demonstration system represents a 1/258 scale of a full 162 mT/yr. H_2 Lunar system that was the focus of the TEA. Scale-up recommendations from the study identified the stack as the majority of the system mass and energy consumption and pointed to taller stacks and grouping of stacks onto shared baseplates as a source of mass reduction. The TEA found that the SOXE breadboard technology can be scaled to support commercial propellant production on the moon.

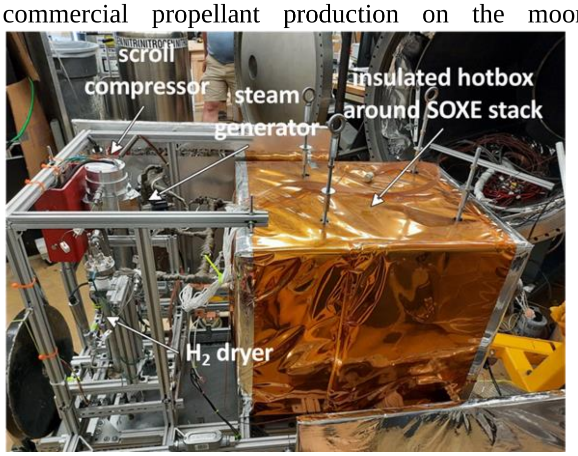
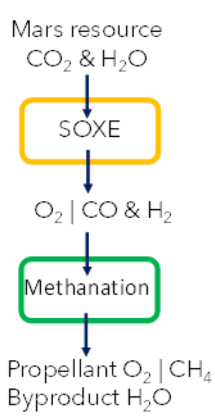


Figure 2. Lunar breadboard SOXE with BOP system for producing propellant H_2 and O_2 from H_2O.

Martian mission-scale demonstration system: A Martian SOXE demonstration system was designed and tested under a NASA NextSTEP award with the goal of designing and integrating a SOXE stack and methanation reactor breadboard system capable of producing high purity O_2 and methane from Martian atmospheric CO_2 and Mars near-surface water, as shown in the process diagram at left. Both the CO_2 and H_2O are electrolyzed in the SOXE stack to produce high purity O_2 and synthesis gas. The synthesis gas is then fed to a methanation reactor where >99% of the CO feed is converted into CH_4.



A demonstration system illustrated in Figure 3 was built and underwent both subsystem testing and integrated system testing prior to a relevant condition test demonstration in the Mars chamber at Jet Propulsion Laboratory (JPL). At a nominal co-electrolysis operating condition of 20 A, the stack generated 310 g/hr > 99.9% pure O_2. The stack generated synthesis gas at this operating condition produced 78 g/hr CH_4 in the reactor. Additional work is ongoing to determine the upper SOXE operation limits for co-electrolysis mode that will avoid carbon deposition by CO, but the system was briefly pushed to 35 A, which is a typical operation condition for steam electrolysis. At 35 A, the stack O_2 production reached 543 g/hr and the methanation production in the reactor reached 136 g/hr.

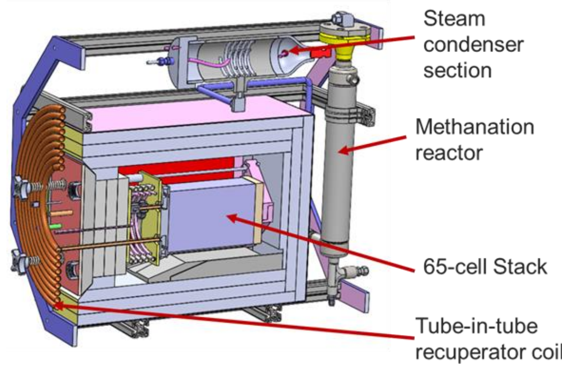


Figure 3. Martian demonstration system for producing O_2 and methane from CO_2 and water.

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