Solid Oxide Electrolysis Technology Development for the First Ever Successful ISRU Demonstration.

N. Davis, J. Elwell, J. Hartvigsen, and S. Elangovan, OxEon Energy, 257 River Bend Way, Suite 300, North Salt Lake, UT 84054, nathan@OxEonEnergy.com

Introduction: In 2014, NASA announced seven new science instruments that would be included in the Mars2020 rover mission.[1] Of these instruments, MOXIE, the Mars Oxygen ISRU (In Situ Resource Utilization) Experiment, resulted in the first successful ISRU demonstration in history. The announcement started a 23-month timeline that propelled the Solid Oxide Electrolyzer (SOXE) at the heart of MOXIE from technology readiness level (TRL) 3 to TRL 6 flight qualified SOXE hardware. OxEon was at the core of the design, development, and production of the flight hardware in accordance with all structural, mechanical, thermal, and electrical requirements to qualify for integration into the full MOXIE system and subsequently into the Perseverance Rover.

Background and Design: The conceptual design for the MOXIE program focused on using the heritage SOEC design with improvements based on the requirements not only for dry CO_2 electrolysis to produce pure O_2, but also for survival of launch, entry, descent, and landing (EDL), and the system constraints imposed by operation on the Rover. Tables 1 and 2 provide the overall operational and materials requirement drivers between the OxEon Heritage and the final SOXE design. These considerations led the team through the preliminary design and overall refinement process with the use of CAD and Multiphysics modeling software packages. These requirements also drove the stack operating regime characteristics.

Table 1: Operational Parameter Requirements

Operational Parameter	Heritage	SOXE
Gas Flow	Cross flow	Internally manifolded for O_2 Purity & dP
Feed Type	Steam + feed gas	DRY CO_2 from the Maritan Atmosphere
Feed Rate	Variable	30-80 g/hr
Product	System Dependent	99.6% Pure O_2, internal manifolding
Structural	Stationary Applications	Robust to survive Launch, EDL Shock and Vibe, Compression Load Requirements
Power	As Needed	Highly constrained
Mass	As Needed	1 kg max
Volume	As Needed	Rigidly constrained
Operation	Continuous runs (10,000+ hours)	20+ 120-minute cycles
Operating Pressure	Earth Ambient	Inlet Pressures of 0.3-1.2 bar Exhaust Pressures of 0-1.2 bar
Heating Ramps	100°C/hour from ambient to 800C	90 minutes (~515°C/hour) from ambient (potentially -40°C) to 800°C
Heat Application	Stack housed inside furnace enclosure	Heaters on endplates only

Table 2: Materials Requirement Drivers

Material Drivers	Heritage	SOXE	Reason for Change
Interconnects (IC)	Stamped Ferritic Stainless	Powder metallurgy (CFY, **Plansee**)	CTE Match between IC and electrolyte for durable sealing
Seals	Edge Rail/ Compression	Glass Seals	Internal Manifold for O2 purity requirements, dP
Current Busbars	Welded Tabs	Brazed rod / welded wire	Mass and heat leak path reduction, change in interconnect material
Feed Manifolds	Cross flow	Inlet tube / internal manifold	O2 purity
Anode Electrode	Perovskite	Perovskite	Same class
Cathode Electrode	Modified Cermet	Modified Cermet	Limit degradation during operational cycling
Electrolyte	ScSZ	ScSz	No change

Flight Qualification: With the completion of the preliminary design phase, the approach to flight qualification required functional testing of multiple stacks built to the final stack design package standards. Structural qualification included stack performance tests including post compressive load testing and shock and vibrational testing. These successful test results are shown in Figure 1 and Table 3.

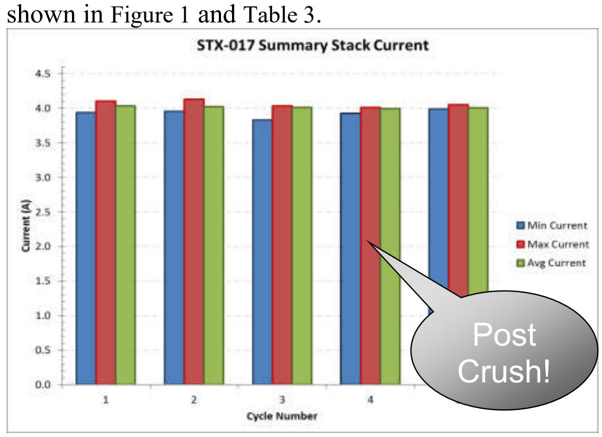

Figure 1: Post Compressive Load Operational Test Results (PF+3dB)

Table 3: Post Shock and Vibe Operational Test Results

Stack ID	Test(s) Performed	Outcome
CSA-001R2	Z axis vibration to PF level Low temperature thermal cycling •3 cycles RT to -55°C •59 cycles RT to -40°C •1 cycle to -65°C	•No leakage •Minor change in performance •Negligible change in O2 purity
JSA-002	3 axis vibration to PF level Shock testing on X and Z axes	•No leakage •Minor change in performance •Negligible change in O2 purity
JSA-004	3 axis vibration to PF + 3 dB •Stack tube stubs fitted with masses to simulate flight nertial loads on braze joints	•No leakage •Minor change in performance •Negligible change in O2 purity •Post-vibe CT scans show no evidence of crack growth in braze joints

Extended operational testing was conducted to provide a margin of safety on the mission target of 10 total operational cycles. Testing was conducted on multiple stacks through 20 operational cycles with an oxygen purity and production meeting or exceeding the program targets. The successful results from the testing can be seen in Figure 2, Figure 3, and Figure 4.

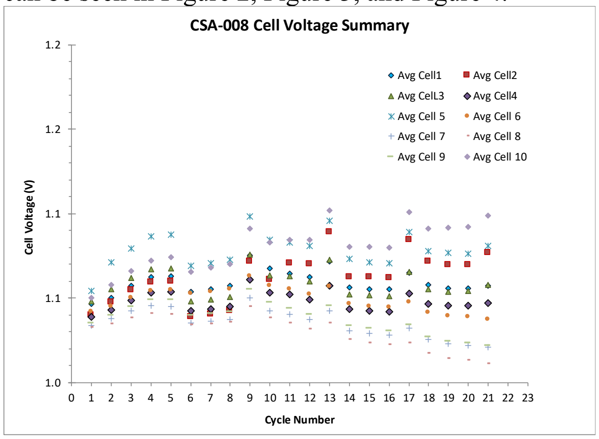

Figure 2: Cell Voltages at each Operational Cycle

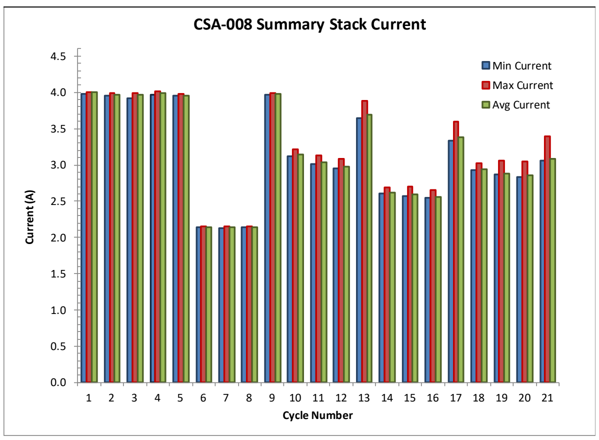

Figure 3. Stack Current by Operational Cycle

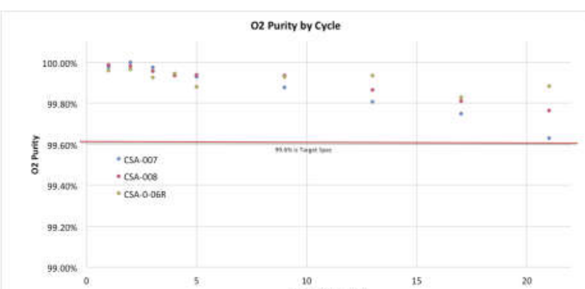

Figure 4. Oxygen Purity by Operational Cycle for all Stacks Tested

An additional stack was taken to 60 total operational cycles, meeting the oxygen production and purity requirements for the overall program, proving a 3x margin of safety.

Through the full flight qualification testing, manufacturing repeatability was measured by comparing the baseline run sweep data for 20 consecutive stack builds, as can be seen in Figure 5. The process capability showed tight grouping for each of the 20 stacks and confirmed the manufacturing process control achieved.

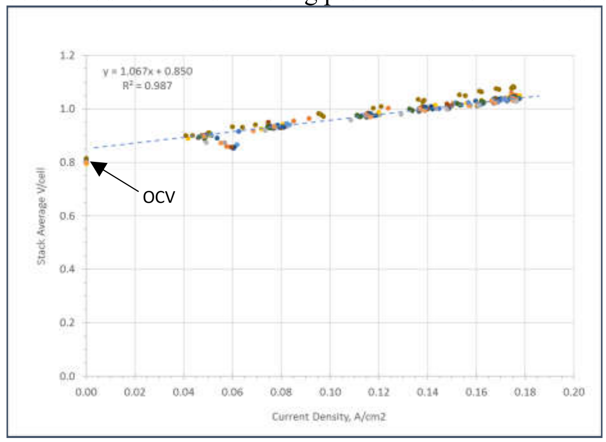

Figure 5. Baseline Operational Comparison for 20 Consecutively Built Stacks

Flight Test Success – TRL9: On April 20 of 2021, 3.5 years post hardware delivery by the OxEon Team to NASA, the downlink containing operational data from MOXIE was confirmed. NASA reported that "after the 2-hour warm up period, MOXIE began producing oxygen at a rate of 6 g/hr. The rate was reduced two times during the run (labeled as "current sweeps") in order to assess the status of the instr ument. After an hour of operation, the total oxygen produced was about 5.4 g, enough to keep an astronaut healthy for about 10 minutes of normal activity."[2]

With the first operational cycle success, the SOXE became the world's first TRL 9 SOEC and the first ISRU demonstration in history. Prior to this momentous achievement and due to the success of the SOXE reaching TRL 6, NASA has continued to fund the OxEon team in the scale up and coupling of this technology for both the target of a manned-Martian mission, as well as an application for lunar ISRU fuel production. The MOXIE system has since gone on to complete multiple operational cycles, each a complete success, meeting expected performance.

References: [1] NASA Press Release 14-208 (2014). [2] NASA Press Release 21-044 (2021).

Acknowledgments: This material is based on work supported by NASA through JPL's prime contract under JPL subcontract number 1515459. The authors would like to acknowledge the contributions of Michael Hecht (MIT, MOXIE Principal Investigator, PI), Jeff Hoffman (MIT, MOXIE Deputy PI), Jeff Mellstrom (JPL, MOXIE Project Manager), Carl Guernsey (JPL, SOXE Contract Technical Manager), Gerald Voecks (JPL, SOXE lead) in support of the SOXE Development Role on MOXIE.