TESTING OF SOLID OXIDE ELECTROLYSIS SYSTEM AND BALANCE OF PLANT FOR H2/O2 PRODUCTION FROM LUNAR WATER.
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Introduction: OxEon LLC and the Colorado School of Mines have been performing technology readiness level (TRL)-enhancing research on water electrolysis technology for the Moon, focusing on solid oxide electrolysis (SOXE) stack systems. This research project has been funded through the NASA Tipping Points program and has been performed over the past two years, focusing on modeling and simulation in the first year [1] and hands-on laboratory testing in the second. This presentation highlights the latter part of the research, specifically integration testing of the SOXE stack at Colorado School of Mines and its supporting balance-of-plant (BoP).

Purpose of the Research: NASA's second Strategic Goal is to achieve sustainable long term exploration and utilization [2]. One of the most important resources on the closest extraterrestrial body, the Moon, is water, recently visually confirmed to exist in large quantities on the lunar surface, largely in the polar regions [3]. Potentially, one of the most economically valuable uses of water is splitting it into hydrogen and oxygen, the most powerful commonly-used propellants in launch vehicles. To do so economically, and with transferrable ISRU applications, it is necessary that the electrolysis process be operable in a lunar environment, and as such mass- and energy-efficient.

SOXE technology fulfills these criteria, in part by electrolyzing water in its pressurized steam phase at high temperatures above 700°C. This reduces the necessary Gibbs free energy of electrolysis, and also assists in necessary liquefication of the resulting hydrogen and oxygen by pressurizing the products in advance. The challenges of SOXE are the same as its advantages—due to the high temperatures of operation, significant and carefully-designed integrated BoP subsystems are required to support electrolysis stack operation. This paper describes the fabrication, procurement, and testing of BoP subsystems, as well as integrated testing of these subsystems with the electrolysis stack over the past year.

System Design: The overall SOXE system consists of a.) The solid oxide electrolysis stack, b.) Two heat exchangers, designed to transfer heat from the oxygen and hydrogen products to the incoming steam, c.) A compressor, d.) A steam generator, designed to cool oxygen and produce steam, and e.) A hydrogen dryer, designed to preheat liquid water, cool hydrogen, and condense any unelectrolyzed steam out of the hydrogen, along with connecting valves, steam, water, and gas lines, electrical components, heaters, sensors, pressure regulators, and control software. The first two were fabricated and tested by OxEon LLC [4], the latter three fabricated (and in the case of the compressor, procured) by Colorado School of Mines (see Fig. 1). The compressor was procured from Air Squared Inc.

Fig. 1. BoP (left) and shipped SOXE stack (right)

Testing: Over the past year, testing and integration was performed on the BoP and the electrolysis stack, with the target Key Production Parameter (KPP) of 1.8 kg of hydrogen produced per day during 24 hour operation at steady state.

Electrolysis Stack. OxEon LLC performed warmup, steady-state, and cool-down testing of their stack and recuperators, using steam at superheated inlet temperatures as their input. Obstacles encountered during testing included leaks discovered at the sides of the cells, which were meticulously tracked down and mitigated. It was determined that long-term steady state testing should have pressure limits not exceeding 2.5 bar. After successful completion of stack and recuperator testing, the stack was shipped to Mines (see Fig. 1) for integration with the BoP and testing in the Mines CSR lab vacuum chamber.

BoP. The Mines BoP components were fabricated, integrated, and tested one subsystem at a time, starting with the compressor, then moving onto the steam generator and hydrogen dryer in succession, as follows:

- The compressor was extensively tested and its flow mapped over multiple pressure ratios and speeds for air and steam. Coolant flow and preventing condensation of the steam in the lines were a challenge. It was necessary to procure and use more than one compressor for this testing.

- The steam generator's production and steady state performance was tested in conjunction with compressor operation. Control systems were programmed, tested, and modified throughout the project for liquid level, internal pressure, and steam temperature.
- The hydrogen dryer was tested using simulated humid "hydrogen" flow using nitrogen filtered through a humidity bottle as a stand-in. Because liquid water flows larger than the required production steam flow rate were necessary to achieve sufficient heat transfer, a water recycle line was built with associated control valves to regulate liquid water flow after the hydrogen dryer into the steam generator and back into the water input reservoir.
- Additionally, a recycle line for humid "hydrogen" back into the steam flowing through the compressor and into the stack was created such that hydrogen could be recycled back to the stack electrodes. This is necessary for long-term stack operation, as pure undiluted steam at high temperatures can oxidize the electrodes. An orifice was designed for choked flow of recycled hydrogen, after initial attempts at using a proportional valve were unsatisfactory.
- Insulation was designed to cover the entirety of the BoP not sharing a boundary with the stack, and fabricated from graphite panels and multi-layer insulation (MLI).

Vacuum chamber testing. After successful BoP testing and integration, the stack and BoP were integrated together and tested in the vacuum chamber at relevant lunar conditions. The chamber and its internal cryoshroud was extensively prepped and refurbished for cryovac conditions, with expected temperatures down to 90 K. Initial vacuum chamber testing showed pressures in the 10^{-4} torr range, with cryoshroud temperatures (produced by liquid nitrogen) at 120 K. The chamber's extensive preparation is shown in part in Fig. 2.

To prepare for hydrogen production and safe hydrogen disposal, a combustor was fabricated and placed in a high position in the lab high bay, which required some re-assembly of lab utilities. Prior to use,

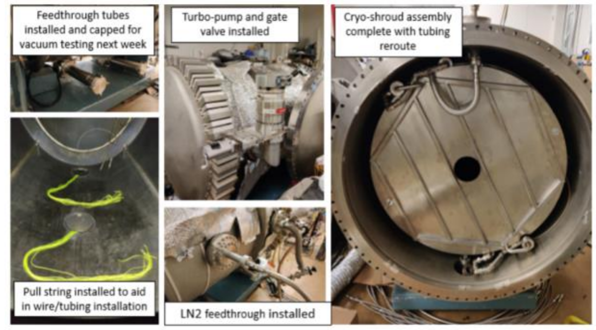

Fig. 2. Vacuum chamber preparation.

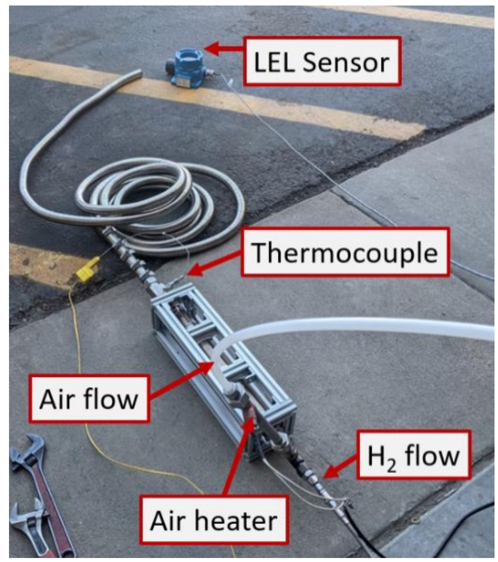

Fig. 3. Combustor testing.

the combustor was tested using gas with 5% hydrogen molar content outside the lab. (See Fig. 3).

Integrated tests of the SOXE electrolysis stack and BoP in the vacuum chamber in concert with the combustor are ongoing. The OxEon and Mines teams will be working toward the goal of achieving our KPPs and reaching TRL 6 as the project wraps up at the end of June.

Conclusion: The OxEon and Mines teams are proud of the work they have done to further this technology over the past year and a half, and look forward to contributing to NASA's quest to make use of space resources as we return to the Moon—this time to stay.

References:

[1] Dickson D. et al. (2021) *IEEE Aero Conf.* [2] *NASA Strategic Plan 2018* (2018). [3] Li, S. et al, *PNAS, 115(36)*, 8907-8912. [4] Hartvigsen J. (2021) *ECS MS, 1,* 194.