Large-scale demonstration of molten regolith electrolysis for oxygen production in a relevant environment

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In late 2024, Kennedy Space Center (KSC), in collaboration with Lunar Resources Inc., conducted a large-scale demonstration of oxygen extraction from lunar regolith simulant using Molten Regolith Electrolysis (MRE). The experiment featured the LR-1 reactor, developed by Lunar Resources Inc., which processed 25 kg of regolith simulant and achieved an average oxygen production rate of 0.07 kg/hr under vacuum conditions. The electrochemical process was sustained for 9 hours, during which the regolith was maintained in a molten state, enabling continuous electrolysis. The reactor performed its functionalities inside the Atmospherically Sealed Simulator for In-situ System Testing (ASSIST) retrofitted to provide relevant environment conditions to the experiment while exposed to high temperatures. A custom-built Volatile Materials and Oxygen Measurement System (VMOMS) provided real-time monitoring and characterization of gas production throughout the experiment. Post-test analysis included sampling the reduced regolith to assess compositional changes. The experiment also validated that the process of Joule-heating of molten regolith could maintain the high-temperature regime necessary for sustained electrolysis. This demonstration marks a significant step toward maturing critical in-situ resource utilization (ISRU) technologies that support long-duration human presence on the Moon. The results and findings from this test will be detailed in this paper.

Acronyms and Nomenclature

ASSIST	=	Atmospherically Sealed Simulator for In-situ System Testing
MRE	=	Molten Regolith Electrolysis
GC	=	gas chromatograph/gas chromatography
KPP	=	key performance parameter
LR-1	=	Lunar Resources MRE reactor
O_2	=	diatomic molecular elemental oxygen
SiO_2	=	silicon dioxide, silica
VMOMS	=	Volatile Monitoring and Oxygen Measurement System
CAD	=	Computer Aid Design
CFD	=	Computational Fluids Dynamics
CT	=	Computer Tomography
XRD	=	X-Day Diffraction
SEM	=	Scanning Electron Microscopy
EDS	=	Elemental Dispersive Spectroscopy

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I. Introduction

IN-SITU production from lunar resources is the cornerstone for supporting a long-term sustainable presence on the moon. Oxygen production is one of the key elements identified to be utilized in human life support systems and oxidizers for propulsion systems. Oxygen is one of the most abundant resources present on the surface of the moon. The regolith compositions from different Apollo missions have been documented in the Lunar Regolith Simulant User's Guide [1]. In Apollo averaged regional lunar surface oxide bulk chemistry, SiO_2 is estimated at approximately 41.7 – 47.1 wt. % of the regolith bulk composition, while FeO is 6.6-16.47 wt. %. Several different techniques have been proposed over the years for extracting oxygen from lunar regolith [2]. Highlands and Mare are the two main categories for lunar regulation which point to SiO_2 as the main contributor of oxygen[3]. The thermophysical properties for these main categories have been characterized to inform the design and analysis for processing hardware such as ISRU reactors, excavators, and regolith transport devices [4]. One of the main technologies being developed to accomplish oxygen production on the moon is oxygen extraction from regolith by means of the molten regolith electrolysis (MRE) processes [5], [6]. This is an electrochemical process by which regolith is melted from its granular state and then electrolyzed in liquid form to produce molecular oxygen. MRE reactor modeling and analysis efforts provide guidance on the design of a large-scale reactor system capable of meeting NASA's need for several metric tons of oxygen produced in the lunar surface [7]. Advances in MRE for oxygen production provides grounds for technological development beyond the laboratory environment. Laboratory testing for regolith simulants of 500 g in combination with Joule heating modeling efforts have provided guidance to design an MRE experiment at a larger scale [8]. Continuous efforts have been made by the KSC MRE team to design an MRE reactor to melt and electrolyze regolith beyond a mass of 500 g [9]. Experimental data confirms current densities at around 0.5 A/cm^2 for voltage levels of 6 V and current from 5-10 A for small scale MRE experiments [10]. The theoretical O_2 production rate for an MRE process can be calculated according to the following:

$$O2_{Production} = M * \frac{I}{n*F} * Efficiency \quad [1]$$

Where I is the current, n is the number of electrons involved for a molar equivalent of reaction (n = 4 for the production of one molar equivalent of O_2), F is the Faraday constant, and M is the molar mass of oxygen. Several models for electrolysis of regolith suggested operating voltage levels of 0.96 V for FeO and 5.61 V for SiO_2 [7]. However, previous experiments conducted at KSC show that voltages higher than 40 V are needed to initiate the electrolysis reaction on lunar regolith at temperatures around 1573 K. Voltage values are expected to decrease as temperature increases due to the increase in electrical conductivity beyond 1573 K. Based on this phenomenon an experimental system can be engineered where high currents can be consumed to increase the oxygen production rate during an MRE experiment. Such a system needs to have the means for quantifying flow rate and oxygen concentration to derive the oxygen production rate. NASA's strategic goals call for systems capable of producing 1-10 metric tons of oxygen per year (this is also the mission duration). These systems need to be demonstrated on several scales to build confidence and increase production as the technology matures. To meet these goals, experimental data along with modeling has been investigated with a focus on higher oxygen production rate.

Kennedy Space Center, in collaboration with Lunar Resources, Inc., developed a system to conduct an MRE experiment in which 25 kg of regolith was processed through melting and electrolyzing phases to quantify the oxygen production rate. The result of this experiment is presented in this paper.

II. Experimental Setup

A. System Components

The extraction of oxygen from regolith utilizing the MRE electrochemical process was an endeavor that required several subsystems that supported the operation of the LR-1 reactor. For this experiment 3 main subsystems were considered: an MRE Reactor system, an oxygen quantification system, and a vacuum chamber system.

1. MRE Reactor LR-1

The LR-1 MRE Reactor is a proprietary design from Lunar Resources Inc. (Houston, TX). This reactor processed 25 kg of lunar regolith through melting and electrolysis to produce oxygen. This reactor is equipped with a heater system that increases the regolith temperature to the melting point at around 1573 K. The reactor is also equipped with an electrode system capable of performing electrolysis of the melted regolith. The reactor system was controlled by a data acquisition and control system that was designed in conjunction with KSC to energize and control the MRE reactor operations.

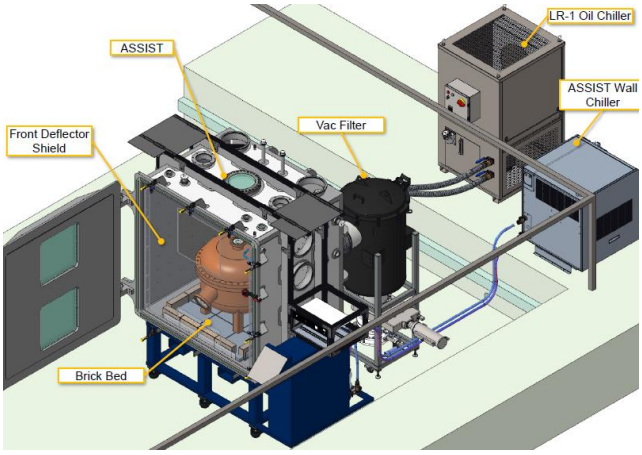

Figure 1. Computer aided design (CAD) model displaying the integrated MRE system with the LUNAR reactor (LR-1) and power/DAC, ASSIST chamber with chiller unit, and VMOMS.

2. Vacuum Chamber System

The high temperature operations of the LR-1 MRE Reactor require a specialized chamber that can sustain the radiated heat and still provide the required vacuum environmental conditions. The vacuum chamber system was composed of the main vacuum chamber (named the Atmospherically Sealed Simulator for In-situ System Testing (ASSIST) [11] chamber) in addition to several subsystems to support the MRE test (Figure 1). This vacuum chamber is equipped with a pump capable of producing a vacuum level of 1.33×10^{-4} Pa and supports a 1.4 m × 1.1 m × 1.4 m test volume. The chamber walls were equipped with a cooling system capable of providing 7 kW of cooling power. In addition, the chamber can support the cooling of exhaust gases with an oil chiller capable of delivering 10 kW of cooling power. The vacuum chamber has a monitoring system capable of providing real-time measurements of wall temperature and vacuum levels through the operations of the reactor. A ceramic firebrick pallet provided thermal protection for the bottom of the ASSIST chamber. As part of the development of the vacuum system, a transient thermal/CFD analysis of the reactor and thermal vacuum chamber was performed to ensure safe operations during a fully integrated test [12].

3. Oxygen Quantification System

The oxygen quantification system named Volatiles Monitoring Oxygen Measurement System (VMOMS) was the main gas quantification system for the MRE experiment (Figure 2). This technology assisted the MRE reactor in extracting gas volatiles produced during the MRE experiment and maintained an evacuated environment inside the reactor. VMOMS was designed and developed to characterize and quantify the gases produced during the experiment with a focus on oxygen concentration. Several instruments on VMOMS, including low (0.1 PPM) and high (95%) concentration oxygen sensors, an Inficon Transpector CPM200M Residual Gas Analyzer (RGA), and flow rate/temperature parameters, provided insight into the oxygen concentration, gas production, volatiles, and general gas composition.

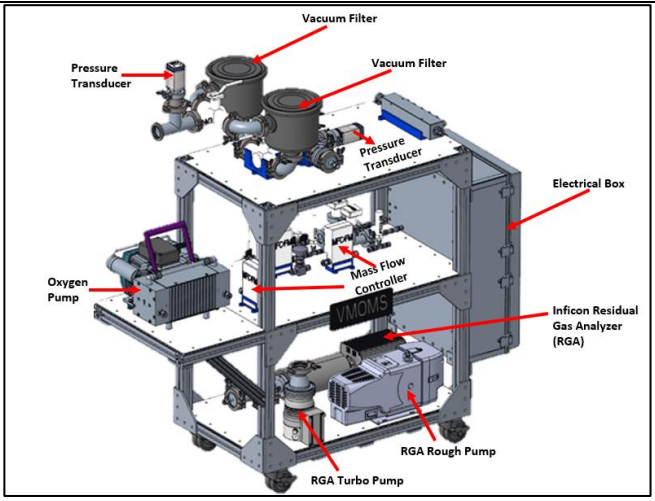

Figure 2. **Volatiles Monitoring Oxygen Measurement System (VMOMS) CAD model**

The Lunar Resources reactor (LR-1) system was operated under external vacuum conditions for 5 days at KSC. The reactor system was integrated with the ASSIST Chamber to provide a relevant environment, with the VMOMS system for oxygen quantifications, and several chillers for thermal control. During the main test, regolith

was heated from ambient temperature up to the molten state. The molten state allows the regolith to change its electrical properties from insulative to conductive; this allows Faradaic current to maintain the elevated melt temperature, thus providing the necessary conditions for electrolysis of the molten regolith. During the electrolysis phase, the melt produced several gases with oxygen having the highest concentration. The VMOMS system measured effluent flow and oxygen concentration during the MRE process. After completion of electrolysis, the reactor cooled to ambient conditions in the ASSIST chamber.

B. Integration

The MRE reactor underwent a series of integration efforts during the week of testing. The reactor is designed to deliver about 15 kW of heating power and 15 kW of electrolysis power to a target volume where molten regolith is located. Integration of electrical, controls, mechanical, and pneumatics was the main goal during the experiment. Being an oxygen rated system, the KSC team worked with Lunar Resources Inc. to ensure the containment of the gases being released by the MRE reactor during electrolysis.

C. Gas Production Management

Leak check procedures were performed to ensure that under test conditions all gases were evacuated as they were released. The teams worked together to ensure all heater system components, flanges, and fittings that represented a pressure boundary passed a leak check procedure and provided compliance with the operational parameter under test. The released gases by the electrochemical reaction were the main product to handle and analyze. The MRE reactor was able to produce the desired oxygen rich gases and route them to our gas instrumentation system for characterization and quantification.

D. Reactor Controls

One of the main subsystems of the MRE reactor is the control system. This system was developed in collaboration with KSC to ensure proper operation and execution of the experiment. This control system completed a series of verification and validation tests to ensure robustness of control and data collection throughout the experiment. Power distribution included a series of elements to safe the system in case of temperature limits being exceeded. In addition to dedicated internal reactor controls, the control system became an integrated part of the power supply system. This allowed integrated system control independent of the power supplies provided by the KSC team, and distributed the power to the reactor. All the signals and power were interfaced through a series of feedthrough and terminal busses inside the vacuum chamber. During the execution of the experiment, the control system was able to operate through initial checkouts, heating phase, electrolysis, and system cooldown.

III. Results

A. Operations

The KSC and Lunar Resources team followed a well-developed procedure to perform the integrated operation. The overall procedure can be divided into five main phases highlighted in Figure 3 (Pumpdown-Grey, Regolith Heating - red, Transition-white, Electrolysis – Blue, Cooldown – Green).

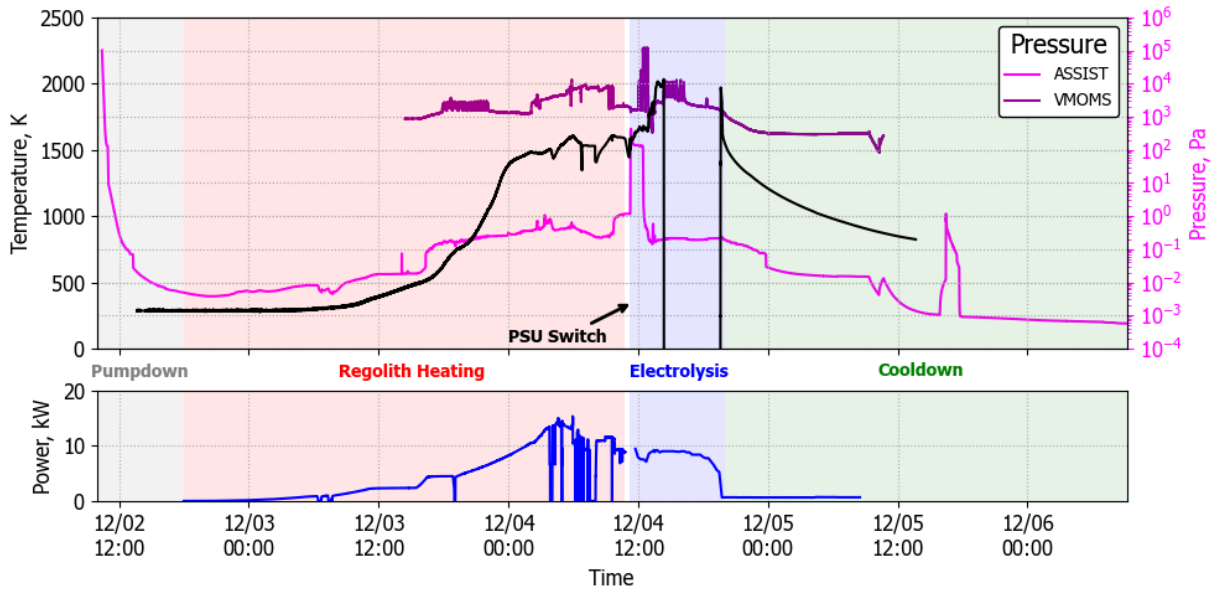

Figure 3. Regolith thermocouple (black), ASSIST and VMOMS pressure (purple, pink), and power (blue) used during the heating, electrolysis and cool down phase of the MRE test.

1. Pumpdown

During the pump down phase, the ASSIST Chamber along with the MRE reactor were evacuated to 10^{-4} Torr and 10 Torr respectively. The inherent behavior of releasing volatiles from regolith during the entire operation made the MRE reactor a continuous low-pressure source. The VMOMS system ensured that a continuous evacuation of gases took place to retrieve the volatiles needed for oxygen quantification.

2. Heating

During the heating phase, the temperature of the regolith was raised from ambient to a target of about 1573 K. A slow increase of temperature ensured homogenous heating throughout the 25 kg of regolith. This slow process allowed the system to release stored gases and water vapor. Simultaneously, the reactor was constantly evacuated by the VMOMS system and gases during the heating phase were vented. A current ramp rate of 0.2 to 0.3 Amp/min was applied to the heater system until it reached its maximum operating rating. Once the heater system reached its peak power, the power levels were maintained to allow the systems to reach a steady state temperature. Parallel efforts during the MRE main project focused on characterizing the gas composition [12].

3. Transition Phase

During the transition phase, regolith changes state from solid to liquid. This phase is non-linear and thermophysical properties of the regolith change. This transition shows discontinuities in the thermal conductivity data on the reference models and reduction in the model fidelity due to the rapid transition is reported. Empirical and model data was used to guide the experiment during this phase. The power system was configured to allow for a wide range of operational power parameters. Once the target temperature was achieved, several voltage values were applied to the electrodes to test for continuity across the melt. A voltage range from 12-200 V was available for the experiment. The initial current value was 12-15 A at 12V to initiate electrolysis. This phase accomplished the following objectives:

- Max power rating was reached on the heaters.
- Gas production was observed by increased pressure in the reactor.
- Electrolysis initiated at 45V.

Empirical testing with the available voltage range was implemented based on previous test experience from KSC team members that participated in the Gaseous Lunar Oxygen from Regolith Electrolysis (GaLORE) Project.

4. Electrolysis Phase

Once electrolysis was initiated, the melt allowed electrolysis to occur at 45 V consuming a current of 210 A across the anode system. The start of the electrolysis phase induced a rapid increase in the temperature of the melt, indicating the Joule heating phenomenon (see Figure 4). In the context of MRE, the Joule heating phenomenon can be observed when the melt transition from a non-conductive to a conductive media at elevated temperature. This transition turns the melt into an electrical resistor that produces its own heat when current is applied. At this point the melt becomes its own heater, and any external heater can operate at a lower state or turned off completely.

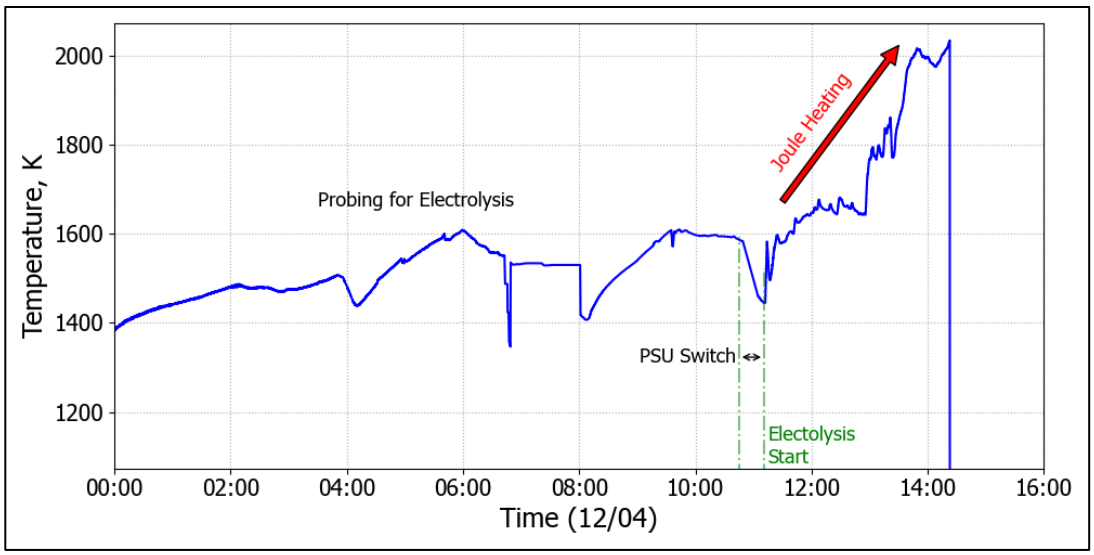

Figure 4. Electrolysis starts and Joule Heating phenomena observed. Proving for electrolysis: several voltages were applied (12-15V), PSU Switch: higher voltage power supply was enabled (up to 200V max).

During the electrolysis phase, the MRE reactor was able to sustain high temperature for a period exceeding 12 hours. Joule heating allowed temperatures beyond 1973 K in addition to a constant draw of power of about 9 kW. The maximum temperature reported is a limitation of the thermocouple maximum operating limit. During this phase, the VMOMS System was able to identify oxygen production concentration of above 80%.

5. Cooldown Phase

The end of the electrolysis phase was characterized by a decrease in temperature, gas production, and reduction in power consumption. Once these conditions were observed the team let the reactor passively cool down while monitoring the system. The end of the test concluded without any off-nominal conditions.

B. Key Performance Parameters

Several metrics that describe the performance of the reactor are calculated based on the test data. These parameters are called Key Performance Parameters (KPP).

- Produced Oxygen Mass (KPP1): During electrolysis, an oxygen sensor along with a flow meter will detect the oxygen concentration of the affluent gas and the flow rate of the gas generated by the reactor in real time. These parameters along with the electrolysis duration provides a measured value of the produced oxygen mass.
- Average Oxygen Production Rate (KPP2): Similar to KPP1, the oxygen sensor and flow meter provide the data necessary to calculate the oxygen production rate.
- Oxygen Production Energy Efficiency (KPP3): This metric represents the amount of energy spent per moles of oxygen produced. The power data from the power supplies is utilized along with the calculated values of KPP1 and KPP2.
- Energy Efficiency for Melt Phase (KPP4): This metric represents the amount of energy required to transition from granular to molten regolith.

VMOMS data provided information to calculate several Key Performance Parameters (KPPs) that characterized the performance of the reactor. The resulting KPPs based on testing and analysis are presented in Table 5.

Table 5. Recommended KPPs based on testing and analysis.

Performance Parameter	Units	Threshold Value	Project Goal	Measured
KPP 1: Produced Oxygen Mass (as percent of regolith melt mass). Test duration target **of** 9 hours at 210 Amps	Weight %	1.54	3.15	2.3
KPP 2: Average Oxygen Production Rate	kg/hr	0.04	0.08*	0.07
KPP 3: Oxygen Production Energy Efficiency (During electrolysis)	Mols O2/kW-hr	0.6	1.0	0.3
KPP 4: Energy Efficiency for Melt Phase (pre-electrolysis melt phase of regolith)**.	kJ/kg	N/A^	3,100	11,877 @ 1473.15 K 24,692 @ 1573.15 K
*Project value based on proprietary data and reactor design from LR **Theoretical energy required to raise temperature from 298.15 K to 1673.15 K and change phase of solid regolith phase to molten phase at ambient pressure. NA^: Reactor design data was not provided to calculate this value.				

Empirical data, analysis, and previous large scale MRE experiments results provided guidance for a wide range of parameters including the maximum current delivered for an expected voltage to drive the electrolysis process.

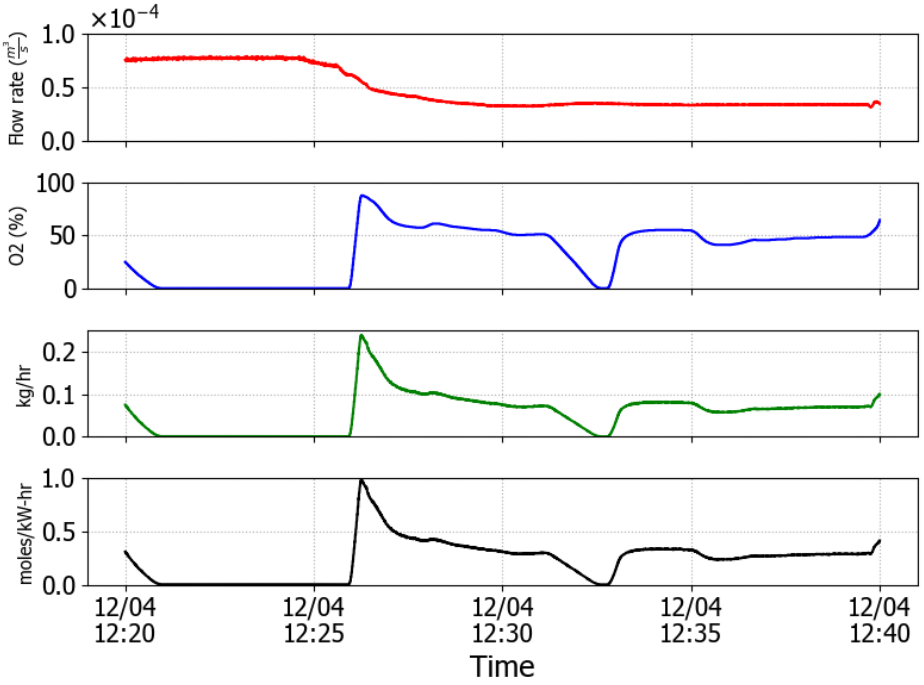

Figure 6. VMOMS data during electrolysis.

Figure 6 shows the oxygen concentration and gas production during the electrolysis phase. It is important to note that the percent oxygen presented here is lower than what was produced by the reactor because the VMOMS system included an argon dilution in order to safely handle the oxygen product. This data was utilized to calculate the oxygen production rate. Assuming the redox half-reaction to produce oxygen:

$$2O^{2-}(liquid) \longrightarrow O_2(gas) + 4e^- \quad [2]$$

4 electrons are required for each oxygen molecule generated. The electrolysis was performed at 210 Amperes (C/s). The number of *mol* of electrons per second can be calculated by the Faraday constant:

$$\frac{210C}{s} * 1\ mol \frac{e^-}{96500C} = \frac{2.18x10^{-3} mol*e^-}{s} \quad [3]$$

Then convert into moles of O_2 molecules, assuming 4 electrons: $5.44 * 10^{-4} \frac{O_2}{s}$

Next, convert to moles/s to kg/hr: $0.0627 \frac{kg\ of O_2}{hr}$

Fluctuations in oxygen production were observed during the test. A quasi-steady section of the oxygen production plot (green line on Figure 6) was utilized as a representative sample for further calculations. For the period during the electrolysis from 12:32-12:40, oxygen production rate was around 0.065 – 0.072 kg/hr. An average of 0.07 kg/hr was selected for KPP2. This number is within 3-10% of the theoretical oxygen production for the given 210 amps of current provided to the melt. An average oxygen mass produced over the 9-hr. period in which electrolysis took place yielded 2.3%(w/w) O_2. This KPP1 is calculated considering a total regolith starting mass of 25 kg.

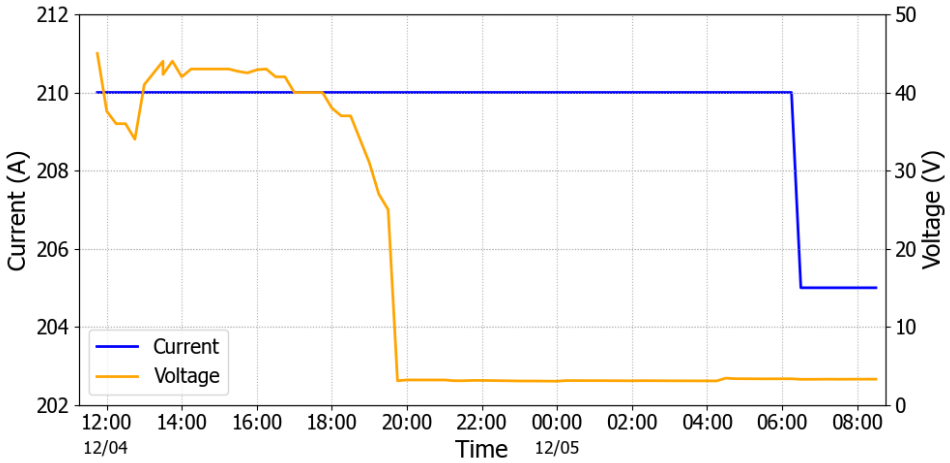

Figure 7. Electrolysis phase over time.

Voltage fluctuations were observed during electrolysis (Figure 7). These fluctuations are likely due to gas entrapment ("bubble formation") within the melt. Core sample pictures provide a visual indication of these non-homogenous areas in a later section of the paper. In addition, a sharp decline is observed close to the 20:00 hour mark. At this point, the melt has been depleted of its oxygen, and the temperature started to decrease. Once this occurs, the melt starts to rapidly solidify and iron dendrites might form allowing for a conductive path at a low voltage, but no oxygen production. This is commonly known as "the melt freezes". The system was maintained at this state for observation until the power supplies were turned off at around 09:00 of 12/05.

The energy efficiency of the oxygen electrolytic production phase of the MRE process is a measure of how the electrical power is used to produce oxygen (KPP3). This relies on measurement of how much oxygen is produced per energy unit (kW-hr) used in the electrolysis process. The energy efficiency may vary during a long test as it depends on the overall electrical resistance of the electrolytic circuit, and this will change as the composition of the regolith melt changes. Values for this KPP were calculated for different times during the test and an average KPP value was also calculated for the entire test. It does not include the amount of energy expended for initial melting of the regolith.

For the measured value of KPP3, during the electrolysis phase, the same quasi-steady period used for oxygen production indicated that the power draw was constant at 7.25 kW. Energy efficiency during the quasi-steady period of electrolysis was found to be in the range of 0.23-0.29 moles/kW-hr. These conditions varied during the total duration of the test execution thus the numbers for average energy efficiency are lower. Joule-heating increases the temperature of the melt, which increases its electrical conductivity. The behavior of the process indicates it is possible that at a higher current and oxygen production rate, the system efficiency can improve. However, the non-linear behavior of

this electrochemical process at high temperature makes it difficult to predict an extrapolated result beyond 1973 K based on the current data.

The heating phase duration was recorded to be 1 day, 16 hours, and 48 minutes (see Figure 8).

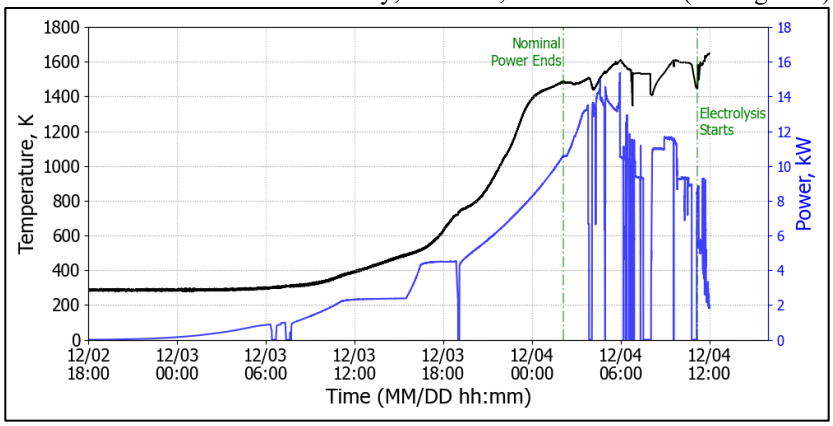

Figure 8. Heating Profile for MRE LR Reactor

For the total energy calculations, the power data was integrated over time as follows:

$$Q\ (Total) = \int_{heating\ start}^{heating\ end} P(time)dt$$

Where, Q is energy and P is power. This integration represents the area under the power curve over time. To integrate this discrete data set, the trapezoid rule was used.

$$Q = 617{,}788\ \text{kJ}$$

The measured mass of regolith (M_{reg}) added to the reactor was 25.0196 kg.

$$\frac{Q}{M_{reg}} = 24{,}692\,\frac{kJ}{kg}$$

KPP4 was designed to capture the energy required to melt the regolith prior to electrolysis. This was meant to be verified by a thermocouple in the regolith melt vicinity. However, given the initial parameters of the test, the nominal heating condition of the heater system reached its planned target with a melt temperature of 1473 K. The team decided to increase the power delivered to the heaters beyond its nominal rating. This phase is marked as "Nominal Phase Ends". From this point forward the modifications of the heaters system can be observed by the discontinuities on the power curve. These modifications allowed the temperature to achieve values beyond 1573 K. This change combined with enabling higher voltage power supplies to go beyond 12V was enough to start electrolysis noted in Figure 8 ("Electrolysis Starts"). An energy calculation was performed to determine the energy that was required to increase the temperature of the melt to 1473 K.

$$Q\ (Total) = \int_{heating\ start}^{nomial\ heating\ ends} P(time)dt$$

$$Q = 297{,}171\ \text{kJ}$$

Assuming a mass of regolith added to the reactors of 25 kg.

$$\frac{Q}{M_{reg}} = 11{,}877\,\frac{kJ}{kg}$$

Theoretical calculations for the lowest amount of energy needed to take 1 kg of LHT-1G from room temperature to the molten state can be estimated using the following formula:

$$E_{total} = M_{reg}(\Delta T * c_{LTH_1} + Lv_{melt})$$

Where M_{reg} is the mass of the regolith, ΔT is the temperature increase from ambient up to 1673.15 K, c_{LTH_1} is the specific heat of LHT-1G, and Lv_{melt} is the latent heat of melting. The project goal for KPP 4 (Table 5) estimates that 3,100 kJ could be achieved for a 100% efficient heating system to melt 1 kg of regolith. The thermal modeling performed by NASA for the MRE project was informative but primarily used as a design tool for safety factors. This thermal work could be strengthened by including accurate reactor design and multiphysics for the updated reactor model. The proprietary nature of the reactor design limited the authors' knowledge to accurately calculate a KPP4. If one is to assume that a system could be designed at 70% efficiency of the updated potential limit, the goal would become 4,030 kJ/kg. Due to the complexity of thermal loads and heat loss in the vacuum environment, losses to the reactor body itself, and other heat sinks, this value was experimentally measured to be much higher at 11, 877 kJ/hr for 1473 K and 24,692 kJ/hr at 1573 K.

C. Core Sample

A post-test sample of the reduced melt was retrieved from the core of the reactor for further analysis. The core sample specimen extracted was approximately 3 in. in diameter, 4 in. tall that included the anode, solidified magma melt, and metal cathode materials (see Figure 9).

Figure 9. Core sample from MRE post-test

A computer tomography (CT) scan was performed to provide internal images of the core. These images were used to estimate the porosity and total density of the reduced melt. Several other analyses such as X-Day Diffraction (XRD), Scanning Electron Microscopy (SEM), Elemental Dispersive Spectroscopy (EDS) were performed on the sample. Preliminary results of these tests can be found in Meier, et al. [13].

IV. Conclusions

The MRE team at KSC, in collaboration with the Lunar Resources, Inc. team, performed a series of tasks that culminated in the successful production of oxygen by means of the Molten Regolith Electrolysis (MRE) chemical process. This is the largest known reactor system that has demonstrated direct, quantified oxygen production from 25 kg of regolith. The 2-year project aimed to prove the feasibility of producing oxygen directly from regolith via a dedicated reactor that transitions granular regolith into a molten state and then applies a high current to produce molecular oxygen from the regolith compounds. Technology maturation work is needed to scale oxygen production rate to address several metric tons in a year of a lunar mission. However, the MRE test results presented here represent a significant stepping-stone in the technology maturation of this system and a step forward toward achieving a scalable solution that can produce sustainable oxygen production system in the amounts that align with NASA strategic goals. Future work will address a technology assessment of the subsystems that addresses a more integrated approach toward an ISRU oxygen production plant that will include delivery and extraction of regolith along with purification of exhaust gases for direct consumption for applications such as life support and cryogenic propellants.

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