IMPLICATIONS OF PHENOMENA OBSERVED DURING MOLTEN REGOLITH ELECTROLYSIS.
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Introduction: Molten regolith electrolysis (MRE) is the process by which oxygen is evolved from regolith using an electric potential difference, after the regolith has been heated above its melting point. Space resource derived oxygen has been identified as a valuable asset as a consumable for satellite refueling in low earth orbit, for permanent Lunar surface operations, and for enabling human spaceflight to Mars [1]. MRE is different from other types of regolith oxygen production processes because it does not use electrolytes, additives, or other consumables; it only requires electrodes, regolith, and a heat source to pre-melt the regolith. Though the necessary MRE reactor equipment list is short, the physical environment and dynamics of the MRE process have an astounding number of confounding variables. These include complex interactions between molten material chemistry, electrodynamics and the interplay between joule heating (the process of directly heating through applied voltage), electrolysis, and obstruction from evolved oxygen, microgravity bubble behavior under (potentially) low ambient pressure, electrode geometry, solid mineral behavior in a molten material slurry, density separation and its prevention as evolved gas mixes pre and post electrolyzed materials, and a variety of other variables.

We will discuss anticipated and observed effects from some of these variable interactions during some of our early MRE technology development efforts.

Test Setup: Honeybee Robotics has been building an MRE test bed for the last two years to develop MRE specific technologies such as electrodes, regolith introduction systems, and reactor bed designs. For these experiments we used an 8 kW solar simulating xenon arc lamp for a heat introduction system, platinum plated niobium for electrodes, and a 10” CF flange vacuum chamber T-section with an electrode-embedded cup of regolith simulant placed inside for the reactor bed. The electrolysis process does not require vacuum, but heat retention in the melt pool is higher without free convection and the pressure will be set starting from vacuum in many flight reactor configurations for airless celestial bodies such as the Moon. This test setup and specifics of the solar simulator and electrode designs are more fully described in our 2021 SRR talk [2].

Test Procedures: Initial electrolysis tests were brief (under 20 minutes), low-mid temperature (1200-1500°C), and exploratory in nature. Rather than testing at steady voltages, tests were performed to discover

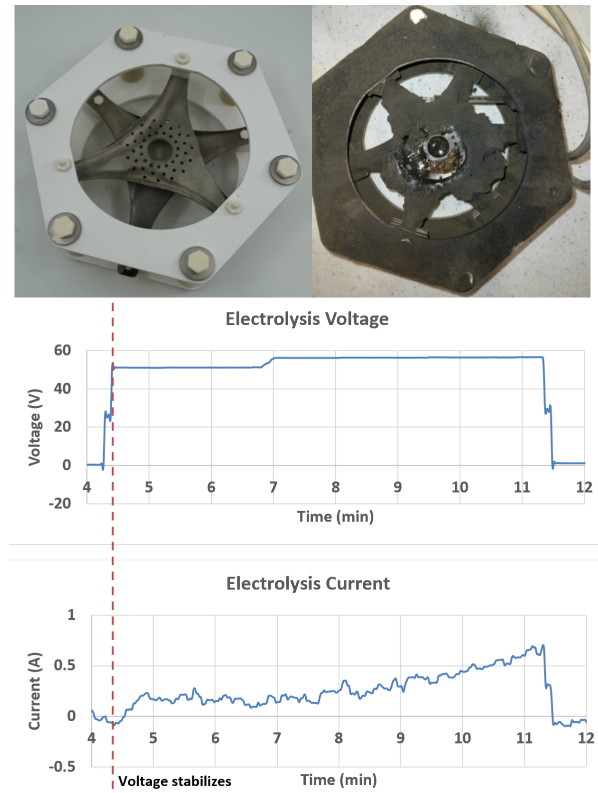

Figure 1: First electrolysis test. Top: electrodes before and after electrolysis. Bottom: voltage and current in an initial test.

where joule heating is necessary and how amperage changes at different voltages as a function of time. The short time periods were a function of the lamp’s cooling necessities. Temperatures and electrolysis voltages/currents (Figure 1) were kept low to find realistic joule heating transition points in a melt pool of a size relevant for a reactor designed to fly in the near term on a CLPS lander. Pressure levels were kept to 10-100 Torr. Oxygen flow rate was measured with a mass flow meter and modified oxygen sensor, but because of the non-oxygen volatiles and potential for solid micro-droplets of electrolyzed material to be carried in the offgassing, oxygen measurements remain too uncertain to report.

Results: Differences in current behavior between tests illustrated some of the aforementioned complex interactions within the melt pool. Stable current trailed stable voltage by 40 seconds in one test. This is likely evidence for joule heating of the melt pool, and possibly of this process thickening the melt pool to grow fully between the electrodes. The size of the heat affected zone being enlarged and differently colored between electrolysis tests and control melting tests support this idea. The current fluctuated and steadily increased throughout this test until electrolysis ended. Current fluctuation was observed in every test. There are two theorized mechanisms for this fluctuation. One is that oxygen bubbles forming and remaining between the electrodes cause temporary air gaps that reduce effective surface area until they move out of the melt pool. Another is that melt pools are potentially non-homogeneous, with paths of least resistance forming in certain materials while less conductive materials are concentrated through dynamic processes away from the conductive fluid paths. Though the first theory is less complicated, the second has supporting evidence in later tests from other amperage behavior. In later, longer tests, voltage was driven up until 1 amp was achieved, and then allowed to stabilize. These tests would show opposite behavior to that of the first test shown in Figure 1; the amperage would go down with time rather than go up. Tests with alternative electrode configurations (to more easily allow gas to flow from between the electrodes) did not prove conclusive; with the same electrode gap in a horizontal configuration, electrolysis could not be started at the same low voltages.

Discussion: *Potential Implications* As a front-runner technology for early space resource utilization on the Lunar surface, MRE still requires significant development. Process parameters will not be statically set, but likely will require a PID controller to maintain steady oxygen production and power consumption. Reliance on density separation in CLPS scale reactors on the Lunar surface may prove to be a mistake as other forces such as gas dynamic forces come into dominance. Larger reactors working at higher temperatures and voltages will likely produce smoother results, but will require exponentially more launch mass for both the larger equipment needed to supply it and the additional cooling hardware and thermal isolation material necessary to run at such higher energy inputs. Indeed, most of the energy put into the MRE reactor, whether from the heat source or the joule heating/electrolysis system, will eventually need to be radiated out of the system.

Future work: To study these confounding variables individualy, Honeybee continues to perform fundamental investigations using the test bed reactor. Future work will include testing at higher voltages and temperatures as well as alternative pressures to change bubble dynamics. Additionally, Honeybee will be launching the Honey Bubble Excitation Experiment aboard a Blue Origin Lunar gravity simulating suborbital flight to study bubble behavior and growth within a viscous substance (simulating oxygen production in molten regolith at various temperatures).

In addition to the complex variable interation within an MRE reactor, there is significant complexity in the required *accompanying* technology to handle the raw and molten regolith and make useable end products out of the output materials. These include excavators, material transport mechanisms, preheating subsystems, temperature control subsystems for various phases of matter, molten material handlers, molten material separators (for products such as silicon and aluminum), purification subsystems, oxygen capture subsystems, sensors, power, avionics, and a host of other subsystems for processing the products provided by the MRE reactor. Honeybee and Blue Origin are working together to develop a variety of these technologies through internal research and development funding. A CLPS demonstration flight unit is currently under development (Figure 2).

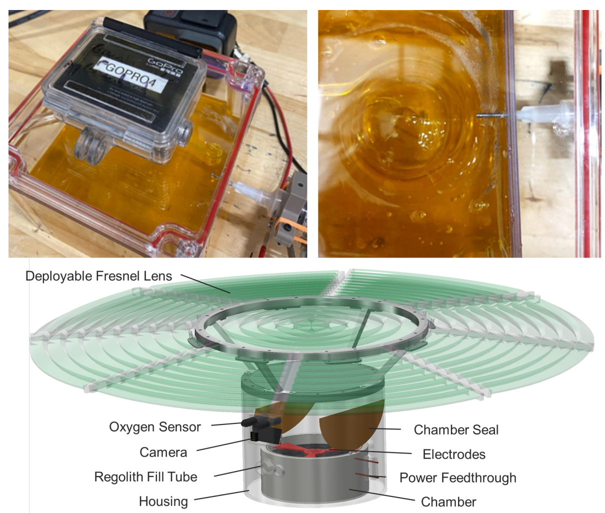

Figure 2: Ongoing work. Top: early model of H-BEE experiment, flying through NASA Tech Flights. Bottom: early CLPS flight MRE reactor design.

References:

[1] D. Kornuta, et al. (2019) "Commercial lunar propellant architecture: A collaborative study of lunar propellant production." *Reach 13*

[2] T. Newbold II et al (2021) “Concentrated Solar Simulator for Molten Regolith Electrolysis.” *Space Resources Roundtable*