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A Systems-Level Approach to Extracting Oxygen from Lunar Regolith via Molten Regolith Electrolysis.

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Abstract

We present a top-level architecture for extracting up to 10 metric tonnes per year of oxygen from lunar regolith by means of Molten Regolith Electrolysis (MRE) using less than 30 kW from vertical solar arrays and a regolith excavator. This System Integration Study identifies specific technology which could be engineered together in the near term into a single system and lander provided focused funding.
Keywords: ISRU, oxygen, Moon, electrolysis, sustainability

0. Executive Summary

Molten Regolith Electrolysis (MRE) refers to the process by which lunar regolith is melted, and then the molten regolith is directly electrolyzed to produce oxygen (O2) gas and metals, such as iron and silicon (Schreiner 2015). MRE therefore requires no consumables beyond regolith, and it can accommodate many silicate mineralogies, including those present at both lunar mare and highland locations (such as the lunar polar regions). MRE works by electrochemically separating molten metal oxides into two components, pure oxygen at one electrode and a plurality of liquid metals at the other electrode (Sibille et al. 2019, Sadoway et al. 2019). MRE is a technology that has not received as much attention as other in-situ resource utilization (ISRU) technologies, such as carbothermal or hydrogen reduction.

Water is a precious life support consumable, but experience using nearly closed life support systems on the International Space Station has reduced the need for water resupply. Rocket propellant, however, which is 80% oxygen by mass, is a large resource mass that cannot be recaptured after use. The primary use of extracted oxygen would therefore likely be rocket propellant, enabling spacecraft refuelling, and thus lowering overall program costs by demonstrating the ability to "live-off-the-land." Several space-based companies have indicated that each return mission from the Moon may require between 30 and 100 tonnes of propellant. The architecture that we have put forward represents a system-level design approach, on a single lander. NASA could choose to develop this lander to accomplish ISRU using MRE on the Moon by the mid-late 2020s (c.2027), given a focused funding mechanism.

This report outlines an investigation to identify the architecture and potential limitations associated with a scalable MRE Pilot Plant that could be built and remotely operated on the Moon. Where technology or capability gaps or "black boxes" have been identified, we describe the driving engineering requirements and suggest possible developments to close the gaps (i.e., to mature the technology or process). We developed a concept for a ~1 metric ton (tonne) MRE ISRU pilot plant that is capable of extracting oxygen from lunar regolith up to a rate of 10 tonnes of oxygen per year. Because performance metrics (e.g., voltage, current, speed, scale, volume, etc.) change as a result of technology development, our aim is to present such performance metrics to within approximately a factor of two.

An overview of our suggested architecture is as follows: 1) An excavation rover (such as the Regolith Advanced Surface Systems Operations Robot [RASSOR; pronounced "razor"]) collects regolith, hauling it and dumping it into a hopper at the base of the plant. 2) A spiral vibratory elevator then lifts the regolith from the hopper to the inlet of the reaction cell that is located at the top of a lander. 3) The regolith is poured either periodically or continually into a reservoir at the top of the cell. Subsequently, a specialized airlock periodically opens to allow the regolith to fall into the reaction chamber and then closes. 4) An MRE reactor (with a mass of several hundred kg for this pilot plant) melts and further heats the molten regolith as it separates the oxygen from the metals through electrolysis. The released oxygen bubbles up through the melt to pressurize the chamber to several bars, and passes through a purifier located adjacent to the MRE reactor cell. 5) The oxygen is then cryogenically condensed into a liquid and stored in a tank; other elements and slag may also be removed during this process. The molten waste is extracted through a tap and can be disposed or distributed as desired, such as by being centrifugally flung onto the Moon's surface to cool as spherules for RASSOR to scoop and dump into a proper disposal area. 6) The RASSOR excavator continues delivering regolith to the system, wirelessly recharging intermittently, and the process continues its cycle. Figure 1 provides an illustrative interpretation of this system.

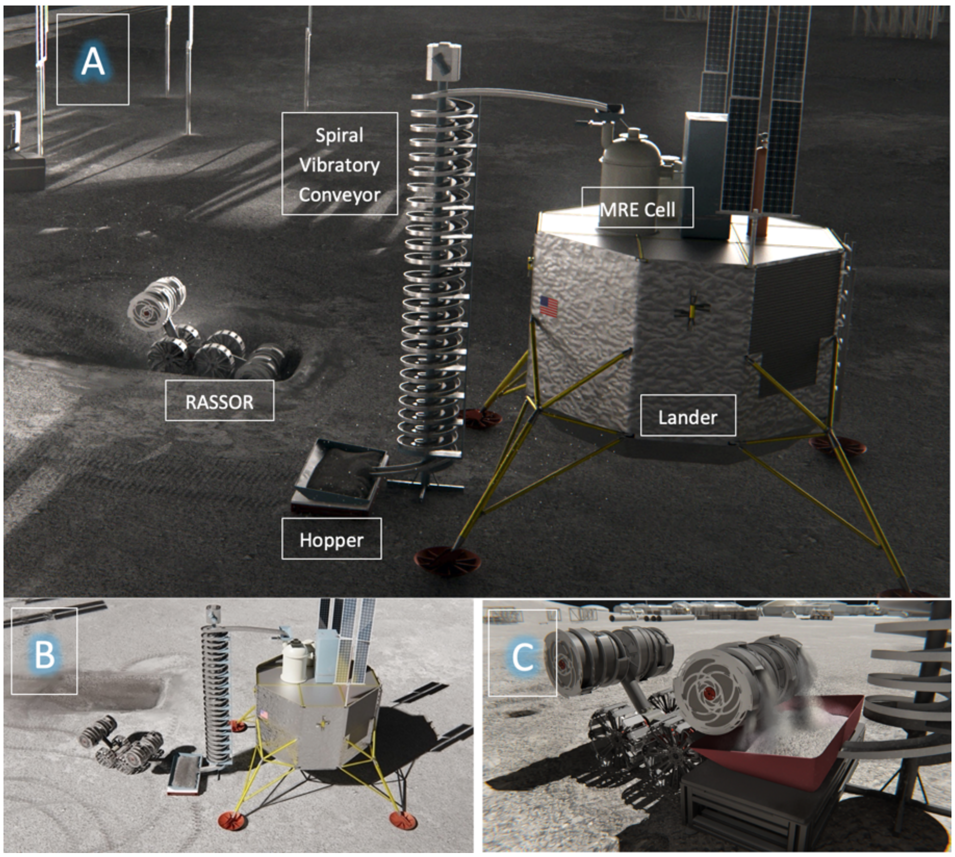

Figure 1. Illustrative interpretation of regolith excavation, dumping, and processing into an MRE reactor cell to produce oxygen and metal. In panels A and B, the RASSOR excavating rover scoops regolith and transports it to the MRE site. The rover dumps the regolith into the hopper (panel C). The rover then repeats the process. Once unloaded, the excavator rover can be recharged if necessary, or do other tasks. The spiral vibratory conveyor then lifts the regolith and allows it to fall into the reactor where it is metered in, then melted and electrolyzed. Evolved oxygen is purified and stored. **The illustration is intended as a notional interpretation only and is not necessarily to scale, nor is it intended for technical analysis.**

1. Introduction

1.1 MRE Pilot Plant Description (Lunar Resources)

Molten regolith electrolysis (MRE) is a promising but less studied technology for ISRU; MRE requires no consumables beyond regolith and can accommodate many silicate mineralogies, though challenges include very high temperatures and melt containment. Previous studies have considered water ice mining (Sowers & Dreyer 2019; van Susante & Zacny 2019), carbothermal reduction of regolith (Linne et al. 2021), and hydrogen reduction (Hegde et al. 2011; Sargeant et al. 2021).

The MRE Pilot Objective aims to design a Pilot Plant on the Moon that uses lunar regolith (specifically anorthositic highlands regolith of the type found in the Moon's polar regions) to produce breathable oxygen as well as oxygen suitable for use as a rocket propellant oxidizer. The MRE Pilot Plant project, if implemented, would transport, assemble, operate, and evaluate a scalable MRE oxygen and metal production facility on the Moon. This study addresses the architecture and operation of the Pilot Plant in a manner similar to previous studies, such as a recent study for carbothermal reduction of lunar regolith (Linne et al., 2021). The Pilot Plant will include all needed system elements to operate, including the excavator, hopper/feed subsystem, reactor, oxygen purification and storage, control, power, and communications.

At the heart of the architecture is the MRE reactor cell. Around this, we have architected solutions for power, regolith excavation, slag removal, communications, thermal management, and the concept of operations (ConOps) for all the above. We have elected to not mass-constrain the study nor to be overly concerned with the system's delivery to the Moon; we simply assume a single lander with a capacity to deliver >500 kg landed mass. We have elected to use the same landing site as the Linne et al. (2019; 2021) NASA COMPASS carbothermal reduction study (Spudis Ridge; 89.439˚S, -137.145˚W) due to the maturity of the illumination analysis.

We have used proprietary or otherwise non-public technology and designs from two providers: Lunar Resources for their MRE reactor cell, and the Kennedy Space Center Regolith Advanced Surface Systems Operations Robot (RASSOR; pronounced, "razor") excavator, with the specifics redacted in this public document; a non-redacted version was shared with NASA's Space Technology Mission Directorate in January of 2022. Our approach has been to use as much existing technology as possible and to invoke "black boxes" only where processes, technology, or technology interfaces do not readily exist. These "black boxes," or gaps, are opportunities to define the engineering requirements for a piece of technology or technology interface needed for a solution to close. The overall MRE process flow is captured in **Figure 2.**

1.2 Objectives

The Pilot Plant needs to be able to operate in the lunar environment, with its combination of one-sixth Earth gravity, vacuum, and wide temperature range, and must use lunar highlands regolith, with its unique physical characteristics and composition. The objectives of this study are 1) to demonstrate a potential design solution that NASA could choose to accomplish by the mid-late 2020s, and 2) provide a technically feasible solution for each of the steps in **Figure 2**, or to define the requirements. Accomplishing these objectives will set the stage for future analysis, beyond the current scope, of a specific flight system to:

1. Characterize and evaluate the acquisition and delivery of regolith to the reactor. **Addressed, §2-4.**
2. Characterize and evaluate sustained electrolysis of the molten regolith, assuming appropriate (highlands) regolith composition. **Addressed, §5.**
3. Evaluate evolution of performance and process control as reactor cell consumes the feedstock and new feedstock is provided. Not addressed.
4. Determine optimum strategy to remove O_2, waste products, and to replace feedstock. **Addressed, §5.**
5. Evaluate continuous process flow vs. batch processing. Not addressed.
6. Determine the quantity of oxygen produced per unit of feedstock, of power, and of production efficiency. **Addressed, §5.1, 7.1.**
7. Determine how to remove, purify, and store the oxygen produced. **Addressed, §5.1.**
8. Characterize the ability to produce potentially useful metals and other byproducts of oxygen production. **Addressed, §5.2-5.3.**
9. Determine how to remove and dispose of unwanted byproducts including slag. **Addressed, §5.3.**
10. Assess MRE performance with un-beneficiated regolith feedstock. **Not Addressed.**
11. Identify methods for delivering power to the reactor, such as using Vertical Solar Array Technology (VSAT). **Addressed, §7.**
12. Characterize the power consumption of the reactor when operating. **Addressed, §7.**

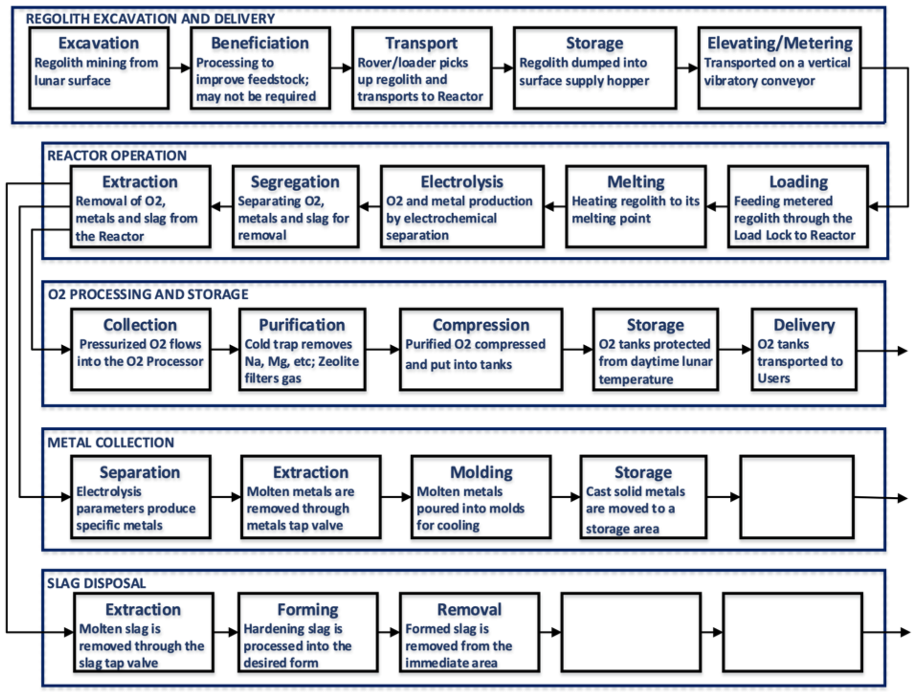

Figure 2. Process flow describing top-level beginning-to-end from regolith excavation to oxygen and metal production and storage. More advanced stages are increasingly notional for O_2 processing and storage, metal collection, and slag disposal. Not included in this flow diagram are power generation, distribution, and thermal management.

The main purpose of this Systems Integration Study (SIS) is to demonstrate just one possible instantiation for how a complete oxygen processing facility based around the MRE reactor could be accomplished. In order to demonstrate this, we will first introduce how regolith will be excavated and delivered to the MRE reactor, then focus on describing the MRE reactor process, including its system power requirements (realistically within a factor of ~two), and finally, we will discuss oxygen (and other materials such as slag) removal and storage.

2. Regolith Excavator

2.1 RASSOR Excavator Rover Concept of Operations (NASA KSC)

The RASSOR excavator (current TRL = 4) is being developed at the NASA Kennedy Space Center Swamp Works as a robotic regolith excavator, specifically for use on extraterrestrial surfaces, such as the Moon and Mars. Applications of the RASSOR Excavator include In-Situ Resource Utilization (ISRU), facility construction, and mining operations. RASSOR will operate in low gravity conditions and under varying bulk densities of regolith. It therefore utilizes an excavation approach that is not reliant on weight nor traction to counteract the force of excavation. RASSOR uses counter-rotating bucket drums to scoop material, then hauls the material to the destination or system requiring regolith, and is capable of dumping material into a vessel such as a hopper.

RASSOR's main actions in this study will consist of the following activities:

- Scooping, hauling, and dumping regolith to the MRE reactor;
    - The size of the scoops on RASSOR's bucket drums limits the size of regolith acquired (to on the order of ~1 cm or more), thus intrinsically beneficiating (size-sorting) the regolith.
- Scooping, hauling, and dumping slag waste products away from the MRE reactor;
- Possibly digging a trench and building a berm to create an artificial permanently shadowed region (PSR) for O_2 storage; and
- Recharging its batteries near the regolith dump.

2.2 RASSOR Single Cycle

Here, we consider a "day in the life" of RASSOR. The following Concept of Operations ("ConOps") will reflect the RASSOR 2.0 breadboard unit. The RASSOR excavator starts at its collection/landing site (e.g., Spudis Ridge in this study) and begins its excavation process. It collects 90 kg (Schuler et al., 2019; Schuler, personal comm.) of dry regolith mass into its rotating drums (see **Figure 3**). RASSOR has a cited excavation efficiency of 2720 kg/hr, indicating that a single load of 90 kg will take 1.98 minutes to collect [*]; however, communication with Jason Schuler (NASA KSC) indicates that the drum fill time is 127 seconds, or 2.12 minutes, which we will use for this study. During excavation, RASSOR can move at a roving speed of 0.05-0.1 m/s.

Figure 3. RASSOR uses counter-rotating bucket drums to scoop regolith. Reversing the rotation direction on the drums causes regolith to dump out. The relatively narrow openings in the bucket drums prevent large rocks from being collected; thus, beneficiation is inherent to its operation. Credit: NASA/KSC/Mueller et al., 2019.

After scooping, RASSOR will traverse at a speed of 0.44 m/s toward the MRE reactor, notionally 100 m driving distance away, which for simplicity we assume to be the distance for every trip. This results in a travel time of 3.8 minutes[†]. Once arriving at the MRE reactor, RASSOR will dump its contents into a hopper (§3.1) that will feed the regolith load into the MRE reactor via a spiral vibratory conveyor (§3.2). RASSOR's design features four bucket drums, two on each end of the vehicle. Dumping takes 67 seconds, or 1.12 minutes, and this must happen twice with RASSOR spinning 180˚ in place between dumps; we therefore schedule 154 seconds (134 seconds for dumping and 20 seconds for turning in place) or 2.57 minutes. Upon emptying its contents into the hopper for MRE processing, RASSOR will return to its excavation site (or a location adjacent to it) at the same 0.44 m/s speed, resulting in a return travel time of 3.8 minutes. This completes one cycle of the RASSOR delivery process, for a total elapsed time of 12.29 minutes[‡]. A single cycle will consume 68.5 Whr of battery power (justification described in §2.3). If the regolith hopper is sized similarly to the amount of

[*] (2720 kg/hr)/90 kg = 0.033 hr, * 60 min/hour = 1.98 minutes.

[†] 100 m/0.44 m/s = 227.3 seconds, * 1 min/60 sec = 3.8 minutes.

[‡] 2.12 (drum fill time) + 3.8 + 3.8 (travel time to and from) + 2.57 (dumping and turning) = 12.29 minutes

regolith the MRE cell can process in an Earth day, RASSOR can fill the hopper once a day with two trips.

2.3 RASSOR Long-Term

We expect the following quantitative analysis on RASSOR battery and regolith capacity to be accurate to within a factor of ~two. The stated numbers may change as technology matures and the ConOps evolve.

RASSOR has a beginning-of-life (BOL) battery capacity of 1410 Whr (Schuler et al., 2019). While this battery capacity will degrade with time, we performed the analysis using its BOL performance. For every 2430 kg of regolith that is excavated, RASSOR requires two hours for a full battery charge. This implies that during a single cycle (90 kg; 12.29 min), RASSOR will use 52.2 Whr[§] of its battery power. However, a table from a 2019 conference proceeding on RASSOR (Schuler et al. 2019) indicated that delivering 90 kg of regolith would consume 68.5 Whr of battery[**]. We will use the cited value from that conference proceeding in this study.

Schuler et al. (2019) also quotes an energy-per-delivered-regolith of 0.761 Whr/kg. If we assume RASSOR excavates 90 kg per trip, and makes 20 trips before roving to a recharge station (Schuler et al. 2019), it would consume 1369.8 Whr per charge. It therefore would be unable to make another trip (68.5 Whr) before reaching its total battery capacity of 1410 Whr. These small discrepancies in electrical usage could result from rounding down to 20 trips from 20.6 trips.

RASSOR is capable of excavating 1000 tonnes (Schuler, personal comm.) in 153 Earth days, or 6536 kg per day[††]. The number of maximum charges per Earth day is therefore (6536 kg/2430 kg =) 2.69 charges per Earth day, so RASSOR spends 5.38 hr per Earth day[‡‡] inoperable while it charges, leaving 18.62 hr to excavate. This would imply that it can excavate 8181 kg per Earth day[§§], which is inconsistent with the derived value of 6536 kg/day based on the 1000 tonnes/153 days. The cited value of 6536 kg may include reserve time between tasks, whereas 8181 kg is the optimal maximal efficiency in an ideal scenario. Therefore, it is more conservative to use the derived cited value of 6536 kg per Earth day.

2.4 Other Tasks for RASSOR

RASSOR is capable of delivering regolith far faster than the reactor will use it, freeing it for other tasks. While we do not consider needing trenches in our current architecture, RASSOR could create artificial PSRs for cryogenic storage tanks (ostensibly liquid oxygen). This would consist of digging down several meters below the surface and dumping the scooped regolith near the rim of the trench in order to build a berm for additional shade. For the 10-tonne O_2/year pilot plant, and assuming a liquid oxygen density of 1141 kg/m^3, we assume a spherical tank at least 8.8 m^3 in internal volume, implying a diameter of 2.56 m. RASSOR would thus need to dig down ~1.5 m and build a berm at least 1.5 m tall around the trench in which RASSOR drives up the sides of the partially completed berm to dump subsequent loads. If the sides of the berm slope are 20°, this implies a berm width of almost 9 m; if the ramps are positioned on the ends of the berms instead of the sides, a narrower berm would be possible.

3. Regolith Conveyance

We envision a ground-level regolith hopper for RASSOR to deliver regolith up to the load lock and metering system atop the MRE reactor via a spiral vibratory conveyor. The reactor loads regolith from the top; a hopper above it (with adequate capacity) would likely be unwieldy to assemble and difficult to fill from the ground. The approach is to put the hopper on the surface, and use a vertical spiral vibratory conveyor to lift regolith to the load lock at the top of the reactor. We chose a spiral vibratory conveyor due to simplicity (two enclosed unbalanced flywheels), effectiveness with over decades of terrestrial experience, near-imperviousness to degradation from dust, and its "plug-and-play" interoperability with any regolith-related system. The spiral vibratory conveyor raises regolith from the hopper to the height of the load lock atop the MRE cell; there is no vertical limit to the height of the spiral vibratory conveyor. The hopper (**Figure 1C**) is large enough to accommodate one Earth days' worth of processing and will be sized accordingly to de-couple the MRE reaction rate with the supply of regolith from RASSOR. The trough is longer than the RASSOR drum, about 90 cm, and the boom that supports the drum, when lowered, positions the drum over the trough so the regolith is not spilled when dumped. The front face that RASSOR approaches is steeply sloped, so the regolith will slide to the trough bottom. (The steeper the slope the less the RASSOR wheels can come in under the upper trough edge to extend the drum over the trough.) The baseline is to allow RASSOR to keep all four wheels on the surface, and extend the drum over the hopper side to dump.

3.1 Hopper

[§] 1410 Whr / 27 cyles = 52.2 Whr.

[**] 68.5 Whr is based on operations on Earth; the total energy used will be less on the Moon because of the reduced gravity. (This savings is mostly seen in the driving energies.) The estimated energy per trip on the Moon for this system will likely be closer to 37.4 Whr, however, we maintain the conservative value of 68.5 Whr for this study.

[††] 1,000,000 kg/153 days = 6535.95 kg/day

[‡‡] 2.69 charges x 2 hours = 5.38

[§§] (18.62 hr/ day * 60 min/hr) / 12.29 min/cycle * 90 kg/cycle = 8181.29 kg/day

We expect the following quantitative analysis to be accurate to within a factor of ~two. The stated numbers will change as technology matures and the specific behavior of lunar regolith under MRE conditions is better characterized.

The MRE cell processes between 109 kg to 168 kg (16 kg O_2, 14 kg of partially or totally reduced Si, 79 kg Al-Ca slag, at a production rate of 7 kg/hr) of regolith per 24 hr, which is a small fraction of the multiple-tonnes of regolith delivery capability of RASSOR. Scaling for the upper mass range, 168 kg of regolith per day with a bulk density of 1,660 kg/m^3 (Mitchell et al. 1974), the hopper should have a volume of 0.101 m^3, or 101 liters.

At a 45° drum boom angle to the surface, the lower edge of the RASSOR drum is about 45 cm above the surface. Making the top edge of the hopper 44 cm high, RASSOR can drive up to hopper edge and the center of the drum will be 11 cm inside the front wall. RASSOR dumps by turning the drum in the opposite direction from excavation, so regolith comes out when the drum openings pass through nadir; the 11 cm clearance keeps the dumped regolith inside the hopper. Lowering the boom after clearing the hopper side will increase the overhang. RASSOR (and the drum) is about 85 cm wide, so the hopper width is 90 cm. The hopper depth is at least half the drum diameter plus the overhang, at least 11.0 + 21.5 = 32.5 cm. The back of the trough can be vertical. If the hopper is rectangular, the 44.0 x 90.0 x 32.5 cm volume is 128.6 L, which provides significant margin for the above suggested volume of 101 liters. The hopper must funnel the regolith to the center portal, so the sides must have some slope. If the bottom halves of the hopper slope upward at 45° to the hopper ends, about 50% of the hopper volume is lost. If the depth is extended to 44 cm, the net volume increases from about 64 L to about 87 L, which provides capacity margin. The outlet port is about 10 cm diameter, to make sure it does not clog with regolith. When not moving regolith into the spiral vibratory elevator (see §3.2), a door closes off the port so regolith does not spill.

Anorthite is 46.01% oxygen by mass; assuming a conservative 70% efficiency of extracting oxygen, we arrive at 32.2% useable oxygen by mass. This implies 31 tonnes of regolith per year would need to be processed. However, if the reactor processes 109 kg of regolith per Earth day and operates for 153 Earth days per Earth year, then the reactor processes 16.677 tonnes of regolith, or half of what is needed for 10 tonnes/O_2 per year. **A potential black box is to ~double the operating time per year of the MRE reactor and/or improve oxygen extraction efficiency to reach 10 tonnes/year.**

3.2 Vertical Spiral Vibratory Conveyor

The vertical vibratory conveyor elevates dry granular materials with a vibrating trough which moves the particles upward with vibratory motion. The vibration lifts the particles, imparting a periodic forward and upward motion to them. Each cycle imparts forward motion, in this case up a spiral ramp, which continues indefinitely until they reach the top, where they are diverted into an "off ramp." An alternative motion is to vibrate the ramp around its long axis, using particle inertia. The ramp is rotated slowly in the upward direction, then quickly rotates in the other direction while particle inertia leaves it in place. The waveform, amplitude, and frequency would require tuning for operation in lunar gravity.

Vibratory conveyors are operationally simple and readily available for industrial applications. For instance, Vibra Screw Inc. of Totowa, NJ, sells commercial spiral vibratory conveyors capable of granular fluxes of 8 to 54 m^3/hr (https://www.vibrascrew.com/bulk-material-handling-products/spiral-conveyors/), though this flux could be reduced in lunar gravity. For the MRE cell, the needed flux, assuming a regolith density of 1,660 kg/m^3, is only 0.0042 m^3/hr (assuming 7 kg/hr), well within conveyor capabilities. The proposed conveyor extends from the back of the hopper on the surface to several meters high, alongside the MRE reactor and extending down the side of the lander.

The amplitude and frequency of the vibrations determine the material feed rate, and the required drive power is low, particularly when compared with other power usage within the system. While a conveyor for regolith transport on the Moon would need to be developed, it is mature technology that is particularly suitable for vacuum operation. No matter the approach, the result is that particles advance upward as long as they are being vibrated. This makes the conveyor work effectively independently of height.

The ramp itself has sides to contain the regolith and has an upward pitch (at least for terrestrial applications) of about 15°. The size of the ramp, width and sidewalls, for the required material flow, can be calculated for operation at 1/6 *g*; models for these, along with spiral pitch, must being determined for lunar application and tested in a simulated laboratory environment. The driver for conveyor performance is the flow rate that is needed to fill the load lock as often as needed -- a 30 cm diameter conveyor will be adequate. Note that the ramp can be enclosed without affecting operation; this could mitigate dust and allow higher transport velocities as free-flying particles will go much further on the Moon than in Earth's gravity. At the top, the regolith is diverted to an off-ramp by the conveyor side wall. This ramp carries the regolith to the load lock, which is mounted on top of the MRE reactor. This linear ramp may also require vibration to control regolith flow.

Spiral vibratory conveyors are robust against dust infiltration and degradation as the vibratory motor can be completely enclosed. Other than the whole apparatus vibrating, there are no external moving parts. The power to operate a lower end model is under 800 W (e.g., http://plastic-process.com/1-1-bulk-material-vibrating-spiral-conveyor.html).

4. Load Lock/Regolith Metering System (*APL Patent Pending*)

Transferring regolith from the spiral vibratory conveyor in the lunar vacuum to the MRE reactor operating at pressure requires a dust-resistant airlock system to minimize oxygen loss. We suggest a "dual cloche" load lock system to prevent dust contamination of seals in which the large, bell-shaped covers (cloches) close over an inner funnel (Figure 4). By using over-sized cloches, the pressure seals are removed from the vicinity of most of the regolith. To load regolith, the outer cloche lock is opened (and the inner cloche closed) and the spiral vibratory conveyor starts. The linear horizontal ramp—outside the operating envelope of the outer cloche—can dump regolith directly into the top of the funnel without spilling around the edges near the pressure seals. The funnel size is determined by the maximum regolith needed per load, and the acceptable frequency of loading. The load lock must deposit the requisite amount of regolith per hour from the conveyor into the reaction cell. To stop the loading of regolith once a desired amount has been metered in, the spiral vibratory conveyor simply needs to power off. Because the conveyor carries regolith at a known rate, the metering system can include a timer that shuts off the vibration after a time corresponding to the desired regolith amount, though a built-in scale or an optical metering system consisting of a strobe light and camera could provide redundancy by imaging and measuring each regolith grain.

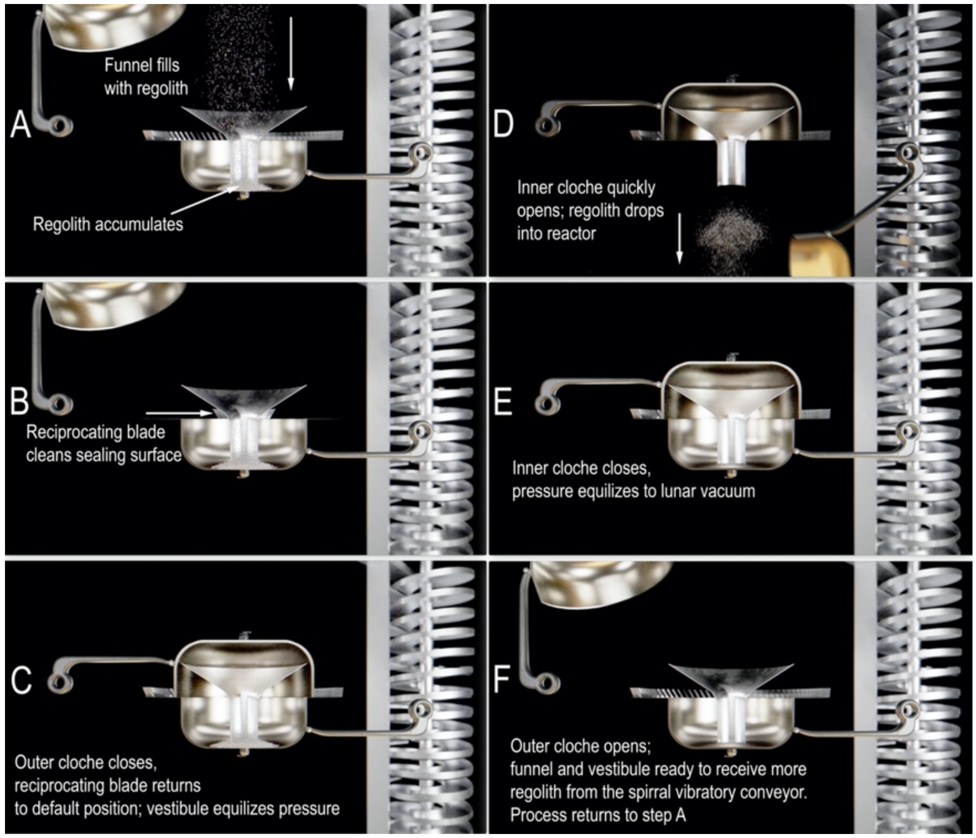

Figure 4. *APL PATENT PENDING.* Cut-away illustration of a dual-cloche regolith load lock system that minimizes dust contamination on pressure seals. Step A: The outer cloche opens up and regolith is metered directly inside the load lock from the spiral vibratory conveyor. Some of the regolith will spill into the inner cloche, and the vibratory conveyor will shut off after the requisite amount of regolith has been metered into the outer cloche. Step B: A metal reciprocating blade will scrape across outer seal to remove any dust. Step C: The outer cloche closes onto the top of the load lock and vents (not shown) will equalize pressure with the inside of the MRE reactor cell, which is nominally at a pressure of ~2 bars. Step D:

Inner cloche (located inside the reactor) opens quickly and allows regolith in load lock to fall into MRE reactor cell. Step E: The inner cloche swings back closed, and the oxygen in the load lock is either vented to space or captured. Step F: The outer cloche reopens, ready to accept more regolith from the vibratory conveyor and the process repeats. The spiral conveyor is incidental and is not connected to the dual-cloche system. This figure is for illustrative purposes only and is not intended for technical analysis.

Once the load lock is filled with regolith, the outer cloche on the top of the load lock would close in order to hold pressure, and the inner cloche on the bottom must open quickly (relative to the slow falling speed of the regolith) to allow the regolith to drop into the reaction cell. A vibrating mechanism on the load lock may be needed to promote regolith flow in low lunar gravity. The inner cloche is placed so the dry regolith falls directly into the center of the molten regolith already in the reactor. Due to the relatively high atmospheric pressure inside the cell, this opening of the bottom load lock cloche would result in a sudden pressure drop in the cell and pressure spike in the load lock. Cloche actuators should be strong enough to act against the high pressure, and valves should be considered for a more gradual pressure equalization. **Black Box: Care should be taken that the O_2 pressure change is not able to disrupt the reaction or O_2 reclamation system**. Oxygen in the load lock could be vented to space as an acceptable loss as the load lock resets to receive more regolith from the spiral vibratory conveyor, or the oxygen reclamation system could also be plumbed to the load lock. Following the regolith dump into the reaction cell, the load lock seals the bottom opening and the load lock must vent its pressure to space or the oxygen reclamation system. Once evacuated, the load lock can receive another regolith delivery. The load lock must operate many 100s of times over the life of the reactor, and be reliable despite the presence of lunar dust. Between openings and closings, a metal blade would scrape across the upper cloche seal to remove any stray dust without scratching the seal; a blower system using a small amount of O_2 could likewise remove dust.

5. Reactor Cell

Overview: Upon first start and subsequent re-starts, the regolith will be heated to incipient melting at 1100˚C with various types of heaters, then joule heating from the anode will take over and continue heating the molten regolith to 1800˚C. **Black Box: We note a possible design challenge of creating resistive heaters that are not destroyed in the heating process.** Oxygen released from the electrolysis process will pressurize the reaction cell to several bars and be drawn off and captured by the oxygen purification and storage system (§5.1). The melt becomes density-stratified with the metal (ferro silicon) on the bottom and the slag (mostly alumina, magnesia, and calcium) floating on top; taps will draw each off for occasional removal (see subsection on slag removal). More information is needed regarding the behavior of melts and bubbles in lunar gravity.

Bubbles: Currently unknown is the behavior of oxygen bubbles in a regolith melt under ~2 bars of pressure at lunar gravity (1.62 m/s^2). **Black Box: We suggest further testing in reduced gravity (e.g., parabolic aircraft flight) to verify the behavior of oxygen bubbles in silicate melt (or an analog) next to an anode.**

Oxygen bubbles will likely pop at the melt surface in unexpected ways and may coat the interior of the reactor cell with melt. However, the low viscosity of the regolith melt (at 1800˚C, approximately that of glycerin) may preclude significant splashing. **Black Box: Bubble popping and splashing of regolith melt requires characterization via testing in a relevant facility.**

Active Cooling and Temperature Management (Black Box): This is required for, among other things, managing mineral and solid-liquid phase transitions (that could cause unanticipated temperature, pressure, and volume changes), which can be detrimental if not properly addressed.

5.1 Oxygen Purification System

The main requirement for oxygen purity is based on safety measures; hydrocarbons (and potentially dust/regolith) in the oxygen could be potentially hazardous (Forbes 1967). Industrial filters exist which can be cleaned by simply exposing them to the lunar vacuum at sufficiently high temperatures. An oxygen fugacity sensor downstream of the filter will quantify purity. Ideally, inert impurities should be limited to 3 – 5% by weight, however, for cryogenic propellants, condensable materials could be controlled to 0.5% by weight or lower (Forbes 1967).

We suggest storing oxygen cryogenically in liquid phase versus high pressure gas cylinders. Ten tonnes of liquid oxygen correspond to 8.8 m^3, whereas 10 tonnes of gaseous oxygen at 0˚C and 2000 psi (1.379 x 10^7 pascals) corresponds to 103 m^3. A zeolite-based purification system could require 2-2.5 kW of power.

5.2 Metal Recovery

The first demonstrator MRE processor should produce metal as a proof of concept. We consider further metal recovery, processing, forging into sheet and bar stock, etc., to be largely outside the scope of this study. However, we note the rising attention drawn to, and importance of, metal as an integral piece of lunar ISRU and lunar permanence. It suffices to say that a metal foundry could likely connect to the metal tap to draw off and process molten-reduced metal oxides, notably Al and Fe, and perhaps Mg and Ti.

5.3 Slag Removal

In addition to delivering regolith to the reactor, the excavator rover must also collect, carry, and dump the slag and metallic/metalloid by-products from the reactor cell; this represents nearly the same mass as the delivered regolith, less the extracted oxygen (and/or metal). To first order, this will have the effect of doubling the time needed for the rover to recharge its batteries. Slag (mostly Ca and Si) is considered a waste product and can be tapped in its molten form from the side of the reactor, such as by automated drilling into the frozen slag plug in the drainage port with an externally deployable drill. We consider a situation in which the molten slag and metal drain onto a rough, rapidly spinning surface and are centrifugally sprayed above the lunar surface away from any infrastructure, quenching into glassy spherules, and subsequently allowed to fall to the ground. These granular glassy beads can then be excavated by the excavation rover. Additional trade-offs for waste removal could include:

- Pouring molten waste into another furnace to be stored as a liquid and formed into paving and constructing tiles and bricks.
- Pouring melt onto a sled that would be periodically towed by the excavation rover and dumped into a small, nearby crater. The top of the sled would be dusted with regolith to prevent the molten waste from adhering to the sled.

6. Deployment and Maintenance (Black Box)

We envision delivering the entire system for the MRE oxygen pilot plant on one high-capacity (>500 kg) lander, such as Blue Origin's Blue Moon, SpaceX's Lunar Starship, or similar. The MRE reactor and solar arrays would be on the top deck of the lander. The spiral vibratory conveyor rotates and is lowered (with RASSOR attached) down to the Moon's surface. Vertical solar arrays (e.g., VSATs) would deploy upward from the deck and track the Sun.

6.1 Communications, Interoperability, and Maintenance

We assume a lunar communications network would be in place and we do not architect out such a system here. However, some form of monitoring of the reactor cell, and the system as a whole, will be required to capture the efficiency of oxygen production, ensure that the vitals of the system are tracked, and assess the success of the power-up and power-down processes during periods of darkness. Communication with RASSOR will also be required in order to relay activity commands.

We notably highlight the need for common interfaces across subsystems (e.g., plumbing, electrical, communications, mechanical) and the need for repairability and maintainability of the systems. It is currently unknown how replacement parts and/or robotic servicing would access the site, if at all. Ideally, the system would be outfitted with parts that adhere to a defined Modularity and Open Systems Approach (MOSA), such that servicing and replacement of broken parts may ensure that the system's lifetime is extended as much as possible.

7. Powering the MRE Pilot Plant from VSAT Solar Power

7.1 Power Requirements for MRE Reactor Cell, RASSOR, and Cryogenic Storage

Power Requirements for MRE: In total, the system requires ~25 kW for operation, with ~20 kW being used for extracting the O_2 and compressing the gas to a liquid (plus ~10% margin). Several of the other smaller components of the system, including intermittent charging of RASSOR and cryogenic storage, will require ~3-5 kW. Power is provided by three 10 kW solar photovoltaic sources, operating ~292-314 days of the year (depending on the exact location near the South Pole), augmented with regenerative fuel cells or batteries for surviving the night. We expect 70% efficiency in the extraction of O_2 from regolith. Factoring in the fact that 40% of the regolith is O_2, for every 500 kg of regolith processed (containing 200 kg of oxygen), 140 kg O_2 will be successfully extracted, and 60 kg of O_2 will remain in the slag. **Challenges and future work should include understanding melts and regolith dynamic behavior in lunar gravity; understanding the power requirements of cryogenic storage of O_2; and the duration, timing, and power needs for surviving the lunar night.**

Power Requirements for RASSOR: The excavation rover should be capable of completing ~20 excavating-and-dumping trips per battery charge, though we note that the hopper only needs to be filled once a day, or two excavation rover dumps. RASSOR will take roughly 2 hours to fully charge; it is powered by batteries that will be recharged at the lander. Solar panels are not currently being designed for integration on most excavation rovers, due to the fact that they would get covered in regolith from the excavation and dumping process. Therefore, this will likely require power from the same VSATs that will provide power to the MRE reactor. A dust tolerant thermal management system, as well as the integration of a dust tolerant charging port (such as an inductive charger) will need to be incorporated into the excavation rover.

Power Requirements for O_2 Storage: Lunar Resources' design for the MRE reactor will not utilize cryogenic storage, but rather will use water-cooled compressed gas. Each of the two planned storage containers can store ~3 kg of O_2, and will need to be changed out every lunar day. **As stated previously, we recommend cryogenic storage; however, power requirements for cryogenic storage have not yet been computed.**

Numerous other components also require power, such as the spiral vibrator for the regolith loading system, the actuators for the metal and slag removal system, the anode jackscrew, various gates, locks, and valves, charging the RASSOR excavator battery, and power for the reactor control and communication systems.

7.2 NASA VSAT

The MRE Pilot Plant is located near the lunar South Pole at a location that is sunlit more than 50% of the time. The plant operates when sunlight is available, suspending operation during the short periods of darkness, both due to self-shading and landscape/horizon shading. A solar array power system, using the Vertical Solar Array Technology (VSAT), is co-located with the Pilot Plant, to power it during operation.

VSAT is a NASA Game Changing Development (GCD) project "focused on the development of relocatable 10 kW solar array technologies" (Lunar VSAT Appendix, 2020). It is planned for deployment near the lunar South Pole, where sunlight has a low grazing angle. The VSAT mast is extended, and the solar array deployed. An internal battery provides power for these activities until the array begins producing power. To minimize sunlight blockage, the VSAT uses a ~8-10 m mast to elevate the solar array above blocking terrain features. The mast rotates through 360° to track the sun during the lunar day.

From an initial proposal phase, with proposals submitted on December 14, 2020, five companies were selected for fixed price 12-month Base phase contracts. In this Base phase, the "offerors shall perform design and analysis in order to demonstrate the expected performance of the proposed Lunar VSAT system" (Lunar VSAT Appendix, 2020). These contracts were awarded in September 2021. The contracts include a provision that NASA can exercise an option to "build and test a prototype of the Lunar VSAT system designed during the Base [phase]" (Lunar VSAT Appendix, 2020). The optional phase duration is up to two years. At the end of the Option phase, up to two offerors will be selected to produce VSAT solar arrays. That said, Honeybee Robotics stated in the 2022 LSIC Spring Meeting (https://lsic.jhuapl.edu/Events/Agenda/index.php?id=200) that they intend to pursue development of VSAT regardless of Phase Two awards, potentially indicating an emerging market for VSATs on an accelerated timeline.

7.3 VSAT Concept of Operations

The VSAT project is in Base phase with five competitors, so the details of their designs are not yet known. The concept of operations and performance will be that described for the NASA reference mission and concept of operations (Lunar VSAT Appendix, 2020). While our architecture uses VSATs atop a lunar lander, VSATs are more generally designed to be transportable, which we describe here. After transporting the VSAT to the Moon on a lunar lander, offloading it to a lunar rover, and transporting it to the operating location, it is deployed in the following steps: 1) Unload it with a crane on the lander; 2) While the crane supports the VSAT, deploy the support legs; 3) Set the VSAT on the lunar surface and auto level the VSAT base, then deploy the mast, with the undeployed solar array at its top; 4) Extend the solar array "blanket" housings horizontally; 5) Deploy the solar array blankets extending down from the top of the mast; 6) Secure the deployed blankets and begin operation. **Figure 5** provides an artist's illustration that steps through this process.

The VSAT operates continuously when sunlit, and is designed to survive the lunar night; the VSAT may roll up during darkness, however, the teams competing in the VSAT challenge may determine methods for surviving the night. It has a battery that provides the power for its internal use, "such as array deploy/retract motors, heaters, array tracking, avionics, sensors, and communications" (Lunar VSAT Appendix, 2020). Radio frequency (RF) communication allows the VSAT "to transmit health status information, and to receive commands remotely." VSATs are intended to survive for at least 5 years.

The VSAT should be located as close to the MRE reactor as feasible, to minimize power loss in the power cable; considerations include the radiated heat from the reactor, excavation operations around the reactor base, protection from potential slag spray, and shadowing of the solar array by the reactor. The latter should not be a problem, as the reactor is about 2 m tall, and with a ~10 m boom (8 m threshold, 16 m goal) the base of the solar blankets is about 5 m above the lunar surface.

7.4 VSAT Performance

The solar flux at the lunar surface is ~1370 W/m^2 in vacuum. There are several types of photovoltaic solar cells available, designed to produce power from that illumination, optimized for the AM0 ("zero atmospheres") spectral response and the radiation environment. The VSAT is specified to produce 10 kW at beginning of life, with the choice of cell up to the offeror. Since the Sun at the lunar South Pole is always at a low elevation angle, a single axis azimuth gimbal can track it.

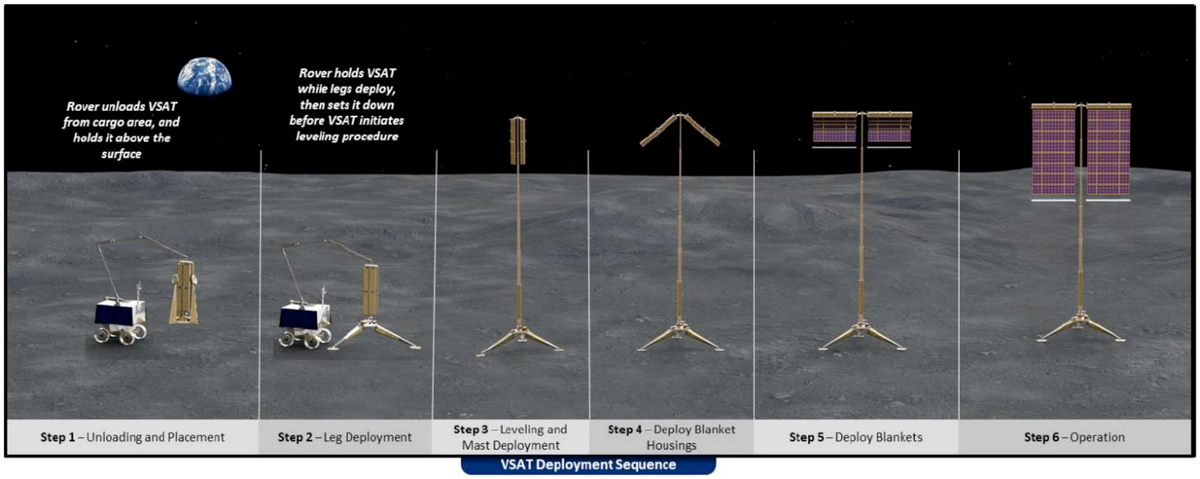

Figure 5. Notional graphical overview of the major stages of the relocatable VSAT deployment sequence. Note that our concept uses singly-deployed VSATs atop a lander deck. Image credit: NASA/VSAT solicitation (Lunar VSAT Appendix, 2020).

The unregulated primary power is specified to vary from 90 to 150 V, and the electrical interface regulates primary power to 120 V; these voltages are to be reviewed, and may change. The threshold system specific volume is 40 kW/m^3 at beginning-of-life (BOL), and threshold system specific power is 40 W/kg BOL. It should be noted that degradation throughout its lifetime will certainly occur and will need to be accounted for when assessing power capabilities toward end-of-life (EOL).

7.5 VSAT Utilization for MRE

It is assumed that three VSATs are dedicated to support the MRE Pilot Plant, since the electrolysis alone (~20 kW) uses all of the power available from two VSATs. Note that the VSAT's available power is not precisely defined, i.e., whether the 10 kW is unregulated or regulated. If it is unregulated, outstanding questions include what the regulator (converter) power loss will be. Assuming conversion is 90% efficient, the net power is 9 kW. If there is 3% loss in the interconnect between the VSAT and the MRE Pilot Plant, power delivered is 8.73 kW. In this case, three VSATs would indeed be enough to sustain the plant, but with very limited margin.

No matter whether the VSAT provides unregulated or regulated power, the various power-consuming elements require different types of conditioned power, which must be provided to the MRE Pilot Plant. We summarize these here:

- **MRE electrolysis power** requires a high-power converter. It is likely this could be designed to operate from the VSAT unregulated 90 to 150 V output, saving the inefficiency of regulation to 120 V.
- **Regolith melt heaters** heat up the regolith to its melting point, so that electrolysis can begin. They can possibly be designed to operate directly from the VSAT input, regulated or unregulated. If they cannot, a high-power converter will be needed. The heaters have to withstand a highly corrosive environment (immersed in molten regolith), which may be a significant design constraint. The required power is not known, but it is assumed that they would require no more power than electrolysis, and would only operate before electrolysis begins.
- **Vibration transfers (hopper-to-spiral conveyor, spiral conveyor, spiral conveyor-to-load lock, and load lock),** all require power to drive the vibratory actuators. Further design is needed to determine the driver and power requirements, and whether individual drivers can share a common power converter.
- **Slag valve drill** removes slag from the slag valve so molten slag can be removed from the reactor. A motor driver is probably required, but it might be able to operate from a 28 V bus.
- **Gates (hopper), Locks (outer and inner load lock cloches), and valves (metal tap, slag tap, O_2 gas port, and reactor vent)** can probably use drivers that all operate from 28 V bus power.
- **MRE Pilot Plant controller** can probably operate from 28 V bus power.
- **MRE Pilot Plant communications** can probably operate from 28 V bus power.

As with the VSAT, internal battery power may be required to sustain the MRE Pilot Plant during the lunar night, and bring it back into operation when sunlight returns.

7.6 Recharging the RASSOR Excavation Rover with VSAT

RASSOR requires periodic recharging of its battery in order maintain its operations. It presently has a 1410 Whr capacity (C) battery and its calculated recharge rate is 0.44 C, about 627 W (Mueller et al. 2019). The MRE system will have to periodically supply this power from the VSAT for recharge. The obvious time to do this is after dumping a regolith load, and it could be done whenever convenient. Discharging of RASSOR would not occur beyond 70% of full battery capacity, and smaller recharges will extend the battery life. The charging station should be accessible, but protected from the regolith dust coming from MRE loading activities. Plugging RASSOR into a charger or using inductive power transfer (IPT) are both options.

7.7 Surviving the Lunar Night (Black Box)

VSAT operation will likely occur ~292-314 days out of the year, depending on the exact location near the South Pole (Noda et al. 2008), and MRE operation will occur ~250 days out of the year. At locations of interest for lunar exploration near the South Pole, the longest continuous periods of darkness are typically 3-5 days (Gläser et al. 2014).

Most of the components of this architecture can be hibernated during periods of darkness, including RASSOR, the vertical spiral vibratory conveyor, and the load lock/metering system. However, the MRE reactor should not drop too low in temperature, to avoid potential difficulties and power-draw during the start-up process. Fortunately, the reactor is well-insulated and does not lose internal heat very quickly. Even in scenarios where the MRE must be powered down for 14 days (significantly longer than the typical periods of darkness near the South Pole), the temperature of the reactor will drop to ~700˚C, and will not require additional waste heat or liquid pumps to stay warm during that time. The reactor will take roughly 24 hours to warm back up to its operating temperature of 1800˚C. At the pole, assuming a nominal 4 days of darkness, the temperature of the reactor will be reduced only to ~1200˚C, resulting in maintenance of the liquid state of the reactor regolith. As a result, additional auxiliary heating would not be needed, and internal anode-cathode Joule heating would be used to initiate electrolysis after the dark period ends.

Nevertheless, a more detailed analysis regarding the duration of, and timing for, power needs during and surrounding the lunar night is still needed. Additionally, the specifics surrounding the duration of continuous on/off power at specific times will be required in order to identify how the power requirements change with the lunar night and general equipment survival.

8. Conclusions and Takeaways

We have demonstrated a systems-level architectural approach for acquiring 10 tonnes (10 metric tons) per year of oxygen from lunar highlands regolith using near-term technology based upon molten regolith electrolysis. Our architecture assumes delivery by a multi-tonne robotic lander of a molten regolith electrolysis reactor, such as the reactor designed by Lunar Resources. An excavation rover, such as the RASSOR excavator designed by the NASA Kennedy Space Center, would scoop regolith into a hopper, which would then feed regolith into the base of a spiral vibratory conveyor to raise the regolith to the top of the reactor. A dual-cloche load lock design would permit a dust-tolerant regolith loading mechanism across an atmospheric pressure gradient while maintaining pressure seal integrity. Our efforts to quantify performance should be interpreted to be within a factor of ~two.

While MRE technology can extract oxygen and metal without using Earth-based consumables, it does require more electrical power than other options, such as carbothermal reduction. The inclusion of multiple VSATs in this demo power plant will increase both the mass and overall cost of the system. The nature of bubbles in viscous silicate melt in lunar gravity is currently unknown, and will require characterization via testing in a relevant facility. Reduced power availability during periods of darkness, such as the lunar night, might also present a challenge. Further modeling of the minimum electrical and thermal power required to maintain a hibernation state for each component of the system will be necessary prior to identifying whether or not enough power will be available to keep the system alive.

This architecture we have put forward represents a potential design solution that NASA could choose to act on and accomplish on the Moon by the mid-late 2020s (c. 2027), given a focused funding mechanism.

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