Lunar Iron Reduction System:
Track 2

Metal Maniacs
Missouri University of Science and Technology

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Abstract:

Statement that places your work in context :

Within a few short years, humanity will be returning to the surface of the Moon, and there is a need for resources, infrastructure, and systems to be in-place prior to our manned return. The COSMIC Capstone Challenge (C3) competition invites students to develop conceptual missions and designs for spacecraft operations in-orbit or on the lunar surface.

The Lunar Iron Reduction System (LIRS), initially consisting of four subsystems: Rover, Collection, Processing, and Electronics, was originally conceived as an ambitious “all-in-one” system for autonomously or remotely collecting and producing iron aggregates via non-carbon reduction of bulk lunar iron-bearing materials (LIBMs), including those found within regolith. In accordance with the mission requirements of the system being expected to run autonomously, without intervention for up to 3 years, we avoided pursuing any processes which required consumable materials, such as the externally supplied reduction agents found in traditional carbothermal reduction. These iron aggregates would be suitable for creating cast iron structures or providing a higher-purity source of iron for future lunar ferrous alloying or steelmaking.

Due to time, budgetary, and experiential constraints, the LIRS system was condensed from the rover, processing unit, and navigation base station systems, narrowing our focus to production and testing of only the stationary processing unit. This requires external collection and initial size reduction of LIBMs prior to depositing in the LIRS. Additionally, due to unforeseen complications regarding the processing of regolith-bound LIBMs, the processing unit’s purpose shifted to the reduction of iron oxides, discarding the concept of liberating iron in regolith-bound minerals from the project entirely. Testing was conducted, but results of these experiments are inconclusive as the samples did not reach critical temperatures for desired phase transformations or reduction.

The prototyped LIRS processing unit is intended to first receive LIBMs in the form of nanophase iron (npFe) or oxides in the form of hematite (Fe2O3) or magnetite (Fe3O4). A predetermined amount of these materials will be fed by the auger into an inner graphite crucible, surrounded by a fireclay sleeve. The charge is inductively heated to 1250°C and permitted to “soak” for a period of time, undergoing thermal reduction until only the desired elemental iron and processing byproducts remain. The produced material is then removed from the system, at which point the process may begin again.

Wüstite (FeO), according to analysis of the Ellingham diagram, possesses the most restrictive thermodynamic requirements and is the penultimate state reached in iron reduction. As such, we considered successful reduction of wüstite as the final indicator of prototype viability. The primary roadblock faced in this pursuit was reproducing lunar atmospheric conditions for the purposes of testing the prototype. As the Moon possesses an approximate atmospheric pressure of $2.96\text{x}10^{-15}$ atm and predominantly consists of helium, neon, and hydrogen (Williams), conflict arose when we realized we were unable to locate a testing environment with a suitably low partial pressure of oxygen (pO2), estimated to be a minimum of $1\text{x}10^{-13}$ atm, though the actual required value is likely much lower as oxygen is only a trace element of the lunar atmosphere. It would be another several weeks before we realized that the partial pressure of hydrogen (pH2) would be far more relevant to the scenario, but given our inability to create an enclosure, we operated off the principle that the primary reducing gas would be oxygen. Initially, it was presumed we could achieve this pressure by using a continuous flow of purge gas, such as argon, to displace any atmospheric oxygen present in the crucible

during the reaction. It was later discovered that it would not be viable to reduce pO2 to any less than 1×10^{-8} atm using commercially available "ultra-high purity" argon gas, and that we did not possess access to any vacuum chambers capable of reaching such low oxygen concentrations.

Given the project's time constraints, we considered this an insurmountable obstacle to testing the prototype, and shifted focus to showing our system would be capable of wüstite synthesis under atmospheric conditions as part one of a two-part processing regime. However, due to wüstite's metastable nature and the difficulties presented in liberating it from regolith-bound minerals, we discovered the system needed to be capable of producing the oxide from available lunar materials prior to reduction. Testing of the system's wüstite synthesis capabilities consisted of attempts to mix, heat, and ideally prompt a peritectoid transformation in a mixture of predetermined ratios of magnetite and hydrogen-reduced iron powders so as to produce free wüstite.

The concept, as implemented in our prototype, is not viable; all samples tested failed to achieve thermodynamic conditions necessary for phase transformation of wüstite, and even under lunar atmospheric conditions, the unenclosed nature of the processing unit prevents the creation of an adequately pressurized (approx. 1×10^{-3} atm) hydrogen-rich environment required for non-carbon thermal reduction of wüstite. We found that due to limitations within the electronic control board of the coil assembly, the induction system's power use was constrained to ¼ of its operating capacity. As a result, the LIRS was unable to reach critical temperatures required for practical formation of wüstite.

Introduction:

The LIRS attempts to produce iron aggregates suitable for the creation of structural components or use in downstream resource production processes, such as lunar steelmaking. Transportation of materials to the Moon is an extremely costly venture, with a general estimate of $100,000/lb of transported material. Even as advancements in rocketry anticipate cutting that figure by as much as 55% (Visionary), these costs remain extremely significant. We believe that *in-situ* resource utilization (ISRU) of lunar iron presents a largely unexplored avenue suitable for creation.

Prior work, including the Utah State Carbonyl Gas iron Reduction System, has demonstrated a few attempts demonstrating iron reduction systems. With the plethora of attempts to develop landing and travel infrastructure or produce "spaceflight materials" from the processing of lunar resources. There is comparatively little modern information or research on extraterrestrial iron production. With even less focus on the viability of non-carbon production methods. We set out to explore this niche, with the hopes that we may develop a system which doesn't require complex and resource-intensive processing methods.
n of aggregates fit for use in the manufacturing of structures, such as habitation, or a preliminary resource required for more complex material production on the Moon.

On Earth, the primary method of iron production is through the direct reduction of iron-bearing materials. This requires an expendable supply of carbon, often in the form of graphite or charcoal added to a blast furnace. Due to the costs associated with transporting these consumable materials from Earth to the Moon, it is beneficial to interrogate the feasibility of non-carbon reduction methods utilizing ISRU of LIBMs.

Design Evolution

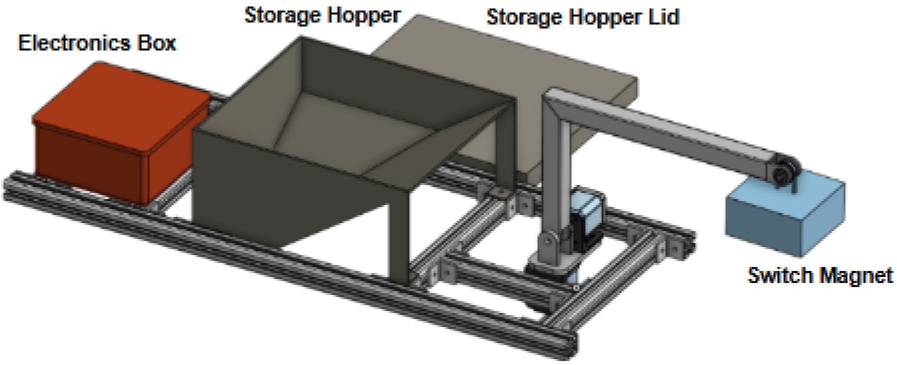
The current design of the LIRS evolved over three distinct generations.

Concept Revision #1:

I. "All-In-One" Rover and Base Station Design

The initial system consisted of a quad-wheeled autonomous rover which would collect and process lunar regolith to extract iron-rich materials from bulk lunar iron-bearing materials (LIBMs). The original design consisted of a rover and communication base station. The rover was equipped with a robotic arm-mounted magnetic material collection/separation system, 4 independently driven wheels for lunar traversal, electronic communication and hybrid autonomous/remote manual control subsystems, an attached solar panel and battery array providing power generation and storage, an onboard processing unit intended to thermally reduce LIBMs to elemental iron aggregates, and an onboard storage system for produced aggregates.

The system would be able to autonomously or manually navigate to iron-dense areas of the lunar surface, use the collection arm to separate and remove iron-bearing materials from surface regolith, and deposit these materials into the processing unit. The processing unit then transports, compresses, and heats the materials until reduction and agglomeration has completed, at which point the process begins again. These agglomerates are stored onboard the rover until such time as they can be deposited into a long-term storage area.



II. Rover System Breakdowns:

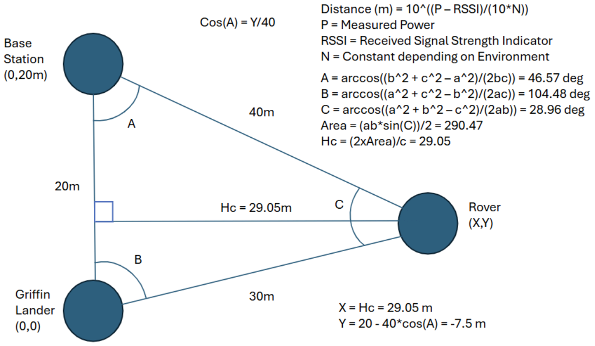
A. Material Collection:

The rover chassis, consisting of some form of extruded 80x20 metal framing, was initially meant to be equipped with a two-axis collection arm driven by a pair of NEMA 17 2A stepper motors. This arm possessed a switchable electromagnet intended to gather iron-bearing materials from the lunar surface. The arm, in addition to collecting the materials, would be used to move them to and from the processing unit and onboard storage vessels.

B. Electronics Subsystems

1. Rover Locomotion and Navigation Systems

In order to effectively and safely traverse the lunar surface, a navigation and collection subsystem was planned and conceptually developed for the December midpoint showcase. Each of the rover's 4 wheels would be driven by a NEMA 17 2A stepper motor. The navigation



subsystem would have used two stationary points of reference (the communications base station and the Griffin Lander) or the communication system of the rover to ping off of in order to determine the relative location of the rover, to the Griffin Lander.

The electronics subsystem was planned to have an expandable solar array for energy generation, a dual battery system on the rover, and a custom radiation hardened and shielded electronics board.

1. Electronic Communication and Control:

The electronics board was planned to receive Wi-Fi and midrange radio signals for communication and navigation. The board was planned to control the drive system through electronic speed controllers, control the induction coil through a relay, control the linear actuator through a relay, control the solar array expansion through a linear actuator through a relay, and have antennas for communication and navigation. This would enable the rover to autonomously navigate to chosen destinations or be remotely driven through wireless communication.

2. Power Generation and Storage:

- **LIRS has an estimated total energy consumption of 724W**
- **The system stores power in twin LiFePO4 336Wh batteries, powered by the Griffin Landers' solar array**
- **The system switches between the batteries regularly as to allow cooling**
- **Twin batteries also offer additional redundancy**

C. Onboard Thermal Processing Unit:

The rover's initial design included the processing unit being integrated into the rover itself. The processing unit would use a material feed transport system to deposit a measured charge of suitably-sized LIBM into the feed hopper, which in turn deposits the charge into the crucible. The unit then utilized a linearly-actuated compression mechanism and onboard induction coil to lightly compress and heat the charge, thus prompting the iron-bearing materials to undergo reduction and agglomeration, ultimately resulting in decomposition to elemental iron, oxygen gas, and reduction byproducts.

These byproducts and gas would be discarded before the produced agglomerate was stored onboard the rover. Once the rover's onboard storage was full or it was required to return to the base station, the produced agglomerates would be removed from the storage system by the magnetic arm and deposited in a long-term storage receptacle for eventual retrieval and use by other systems or astronauts.

This iteration of the processing system relied on a crucible chamber in which the reduction occurs. Initial designs suggested using a fused quartz tube as a crucible. However, it was determined that the temperatures required for reduction, alongside repeated thermal cycling would result in devitrification upon cooling, likely causing the tube to shatter. This rendered the crucible's design unsuitable for the project.

1. Oxide Reduction Thermal Chemistry

Initially, only the requirement of partial pressures of oxygen was considered to determine if and at what temperatures the reactions would be favorable. Per the Ellingham diagram provided below, at an ambient partial hydrogen pressure of approximately 2.45×10^{-16} atm, there is no minimum temperature at which any iron oxides will undergo reduction, thus the partial pressure of hydrogen in the reaction crucible must be raised to make the reaction favorable. A preliminary target soak temperature of 1250℃ was chosen to begin determining our experimental procedures, as that would be sufficient to cause reduction of all three primary iron oxides. However, there is extremely little variance in the required pressure with respect to temperature when reducing wüstite.

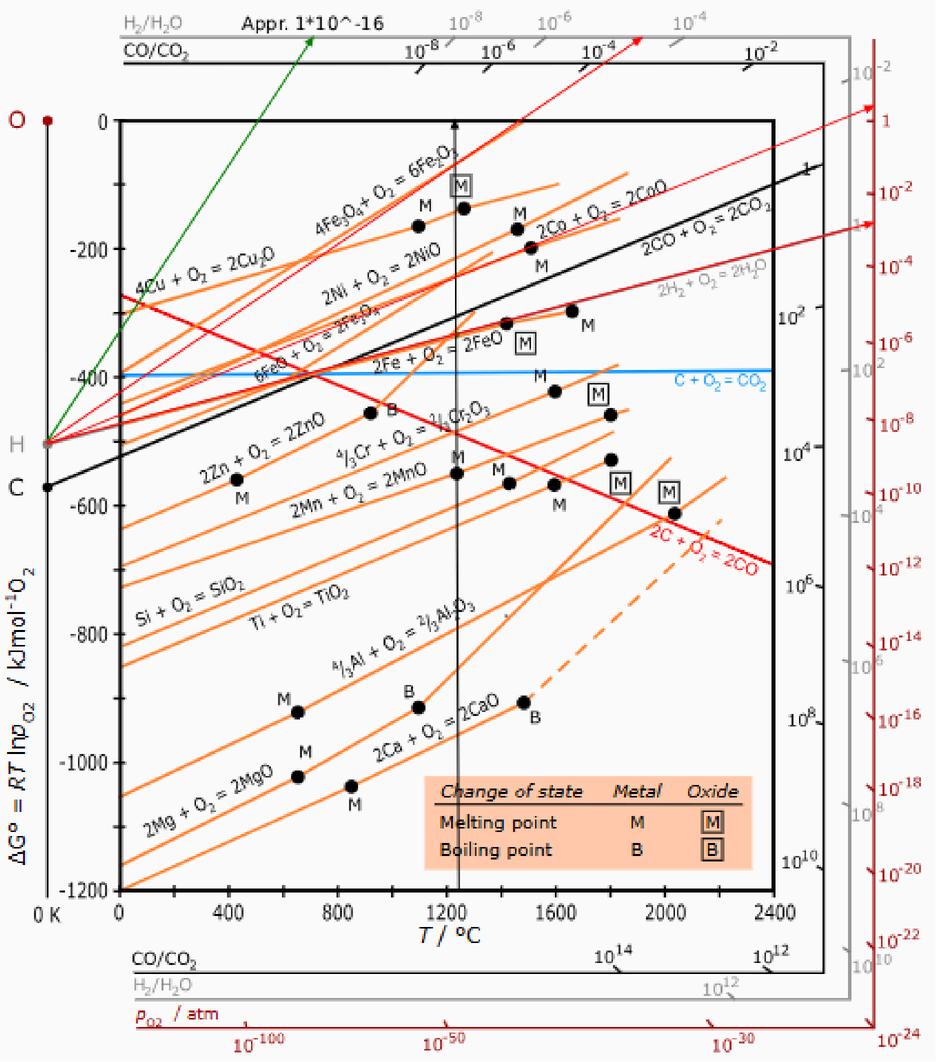


Fig 1. Annotated Ellingham Diagram [1]

In accordance with the diagram, the required partial pressure of hydrogen to conduct wüstite reduction at 1250℃ is approximately 1 atm. With adequate containment, this environment could be maintained, though there are logistical discrepancies with our present design and implementation of such a containment system.

The following reduction pathway was envisioned for this revision of the project:

$$3Fe_2O_{3(s)} \xrightarrow{\Delta} 2Fe_3O_{4(s)} + \frac{1}{2}O_{2(g)} \qquad (1$$

$$2Fe_3O_{4(s)} + \frac{1}{2}O_{2(g)} \xrightarrow{\Delta} 6FeO_{(s)} + \frac{3}{2}O_{2(g)} \xrightarrow{\Delta} 6Fe_{(s)} + 2O_{2(g)} \qquad (2$$

$$6FeO_{(s)} + \frac{3}{2}O_{2(g)} \xrightarrow{\Delta} 6Fe_{(s)} + 2O_{2(g)} \qquad (3$$

It is now understood that this pathway was invalid from the start, and a hydrogen or carbon-based reduction system would have been a more well-founded point to begin working from.

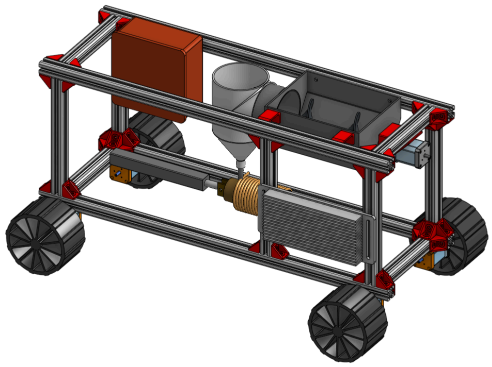
III. Problems with the Revision 1 Rover Concept

The "all-in-one" design philosophy of the Concept 1 rover led to a plethora of technical, logistical, and conceptual issues. Having the processing unit integrated into the chassis required additional thermal shielding.due to concerns of systemic damage due to excessive radiant heat while performing reduction. Concerns were raised with regard to the potential energy efficiency and battery life of a combined collection and processing system. Additionally, the nature of the processing unit being constantly mobile led to a host of complications regarding avoidance of damage due to the lunar environment. Finally, in the event that the rover was lost during an expedition, the associated loss of the processing unit presented too great a risk to justify the benefits of having the system integrated into the rover itself.

There were also unresolved processing issues that required additional development before the processing unit could be considered feasible. One key aspect which went unaddressed is the issue of deslagging the reduced materials. The thermal reduction process naturally generates unwanted byproducts requiring downstream separation, including unwanted oxides, such as alumina and silicates. During this project, we were unable to determine a reliable method of slag removal which did not include use of consumable materials or complex separation and treatment systems beyond the scope of our capabilities.

As a result of these conflicts, and with the understanding that our initial concept was overly ambitious, we made the decision to abandon the rover concept entirely, and focus on processing of bulk regolith by a dedicated stationary thermal processing unit.

Concept Revision 2:



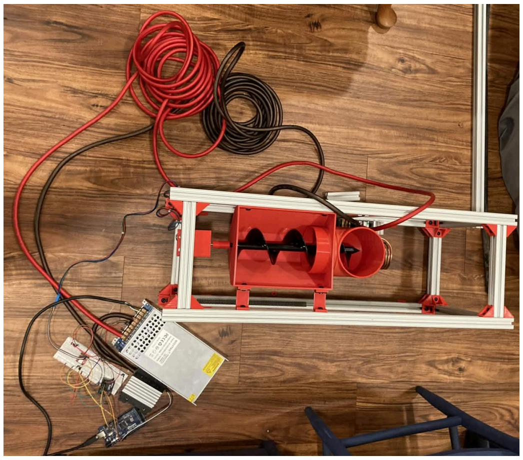
I. Shifting Focus to the Processing Unit

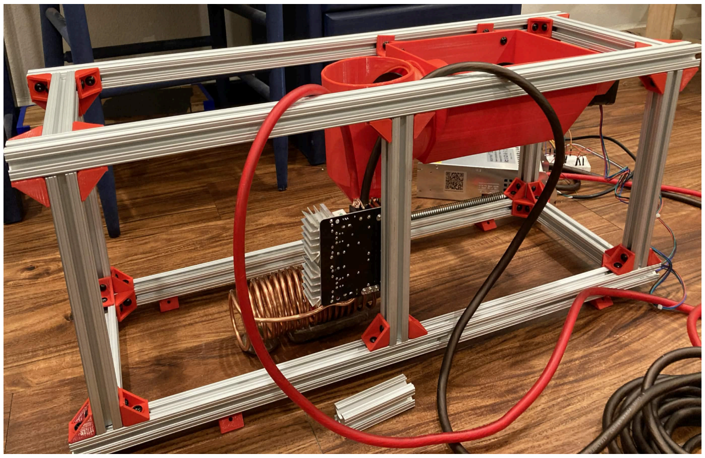
In lieu of a dedicated collection system, we opted to continue development and testing of the thermal processing unit. We began this portion of the project presupposing that an external system would be supplying iron-bearing materials, and that the only purpose of our prototype was to reduce and agglomerate the materials into a usable iron-rich substrate.

II. Thermal Processing Unit Developments:

A. Unit Structure and Assembly:

At this point, prototyping began. 80x20 extrusion aluminum was chosen as the structural framing material of the unit, and was connected and reinforced through use of custom 3d printed corner brackets affixed with T-slot hardware. This enabled the various components of the processing unit to be repositioned with relative ease during development. The material feed system remained relatively unchanged.



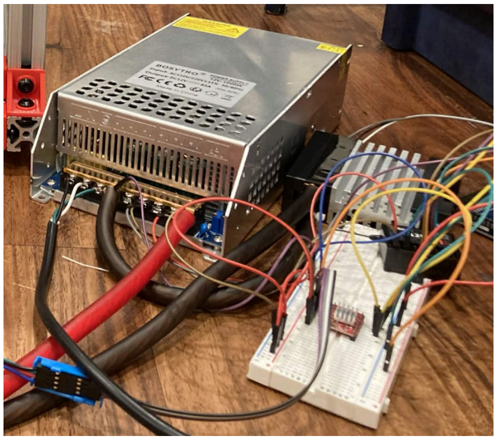


B. Induction Coil Heating Assembly

The coil assembly purchased for testing operates via a 20 amp, 50V (1kW) control board and includes a 6 turn coil consisting of ⅛“ copper tubing with an internal diameter of 55 mm.

C. Power Supply and Electronic Control

The coil is driven by a *BOSYTRO* 12V, 83A DC (1kW) switching power supply, which itself runs off of a standard 120v AC outlet. This supply delivers power to the induction coil, auger stepper motor, a custom PCB, an ESP32 bluetooth/wifi power module, and an rf remote control transmitter/receiver.



D. Crucible Material Improvements:

Due to the anticipated failure of the fused quartz crucible, we began looking into alternative materials. Initially, we settled on alumina due to its high thermal resistance and durability. However, sourcing an adequately sized partially capped alumina tube proved overly difficult. It was at this point that we decided to simply create our own out of *Aardvark* high-fire wet clay. This clay was sculpted into tube and disk forms and fired in a cone-10 kiln.

III. Problems with the Revision 2 Processing Unit

Since the project’s conception, the intent was to take lunar materials, primarily in the form of regolith-bound iron-bearing minerals, and thermally process them to produce iron. Initially, it was assumed that wüstite could be easily isolated from regolith. However, further analysis showed that the iron in lunar regolith is bound between silicates such as fayalite and ferrosilite, both of which require significant additional processing beyond the scope of the project to liberate.

Changing the feasibility of the assumed reduction pathway to liberate iron from these structures before reduction could occur was difficult. As reduction of wustite derived from regolith was no longer valid, it became necessary to identify a secondary means of collection or production of the material.

Environmental testing conditions made verifying the concept difficult. Due to reduction reactions requiring low oxygen partial pressure to occur. Testing under ambient Earth atmospheric conditions introduced excess oxygen inhibiting reduction. The use and test of inert gases such as argon was considered, successfully achieving low oxygen concentration is near impossible with the materials that were provided.

The system assumptions regarding the heating element were not fully validated. Assumptions that the induction heading would inductively couple with the feedstock material and provide sufficient energy for transformation, however do to multiple different iterations of testing this.

Concept Revision 3:

I. The Current Prototype

In this stage, focus was shifted from processing regolith due to the issues with the olvaines and pyroxenes to synthesizing semipure wüstite from lunar materials (nanophase, iron, magnetite, meteorite ejecta) for later reduction. The system was intended to thermally drive phase transformation, vent produced oxygen, and retain the remaining wustite product. Revision 3 directly

Methods:

The material was introduced into the ceramic crucible positioned by an stepper motor actuated auger controlled by a signal from a radio receiver interpreted by an arduino and run through an AR4988 stepper motor driver within a multi-turn copper induction coil. The coil was connected to a low-voltage supply and controlled through an 80 amp solid state relay activated by a signal from a radio receiver interpreted by an Arduino Mega 2560. The induction system operated at a maximum input of 12 V and 20 A, total power input of about 240 W.

Testing was conducted using a mixture of iron powder and magnetite powder, as an alternative to attempting to liberate wustite from lunar regolith. The powder was introduced into the crucible without compaction. Each test was ultimately unsuccessful as no configuration of the coil heating assembly was capable of heating the sample to the 580-700C wustite transition temperature. Crucible temperatures were monitored by handheld infrared pyrometers.

Results

As the maximum recorded temperature of approximately 400ºC was below the threshold for wüstite formation and reduction, the system did not achieve thermodynamic conditions required to initiate the intended reaction pathway. No measurable phase transformation or metallic iron production was observed.

The samples of the mixed powder exhibited a much lower heating response than anticipated. Temperature increases within the sample were not properly measured due to minimal relative steel control. There is no recorded evidence of sintering, melting, or any phase transformation.

Modifications to the electrical system such as increased wire gauge and relay adjustments did not result in improvements of heating performance. In fact, the opposite was observed and the peak of 400C was not reached again. The system remained constrained by the maximum power input of 240 W.

Post-test inspection of samples did not indicate formation of wüstite or metallic iron. The planned analysis of material characterization via X-ray diffraction (XRD) did not produce conclusive evidence of phase transformation. And no measurable reaction progression was observed during any trial, and no quantifiable reaction rates were observed and recorded.

Discussion

The system has demonstrated that thermal conditions required to achieve the reduction pathway were not achieved. Across multiple heating configurations, the testing material failed to reach the temperature threshold necessary for wüstite formation. This prevented analysis that could have occurred. While the present outcome should not be interpreted as the rejection of the processing concept, but rather further evidence that the prototype is heavily constrained by implementation and testing-environment issues. As the prototype had insufficient power delivery, poor inductive coupling with the fine-grained feedstocker that occurred with uneven sample heating and oxidation during testing.

The maximum observed threshold that was recorded with a University coil reached 400ºC, while significantly higher was not the threshold for a proper heat reaction to start. Due to further analysis and previous tests the same coil had previously melted steel. A possible limitation was not due to the heating method itself, but rather the interaction with the powder. It is possibly due to the size of the powder being much more fine and thus much more difficult to change due to lack of continuous conductive pathways between the particles which reduces the electromagnetic energy absorption in the heating system. Another avenue we could have discussed is focused light/Laser/Plasma pyrolysis of iron oxides.

Conclusion

Although the prototype did not achieve the required thermodynamic conditions for iron reduction, the results directly clarify the practical constraints of in-situ lunar iron production systems. The study demonstrated that the limiting factors are not only chemical feasibility, but also engineering implementation challenges such as power delivery, thermal efficiency, and environmental control. The system was limited to a maximum input of 240 W (12 V, 20 A) and had a temperature of 400°C, which is significantly below the temperature required for wüstite formation and reduction. Highlighting that the non-carbon iron reduction is significantly more complex than theoretical thermodynamics alone suggest and identifying the gaps between theoretical reduction pathways and physically deployable lunar hardware. These findings help refine the future design approaches by emphasizing that the successful lunar resources processing will require integrated solutions that combine thermal systems, atmospheric control, and material handling rather than isolated subsystems.

These findings relate directly to the challenges of building sustainable lunar infrastructure. Lunar iron production is often treated as thermodynamically achievable; this project shows that translating those reactions into a working system has additional constraints that dominate overall feasibility. The primary limitations of this work including insufficient power output, lack of environmental control, poor inductive, fine grained materials, and time and resources constraints prevented the system from reaching the temperatures and conditions required for reduction. However, these limitations are valuable results as they identify the key barriers that must be addressed in future designs and provide a realistic understanding of what is required to use ISRU technologies on the moon.

Possible iterations changes for the future might be through improvements in power delivery thermal efficiency and environmental control. This includes developing higher capacity heating systems, improving material coupling through preprocessing methods such as compaction and designing sealed reaction chambers that are capable of maintaining appropriate atmospheric conditions. Additionally heating methods such as microwave heating could be explored as they may offer for more efficient energy transfer for fine grained materials, though microwave heating has significant safety and control challenges especially on the lunar surface that must be managed carefully. The success of iron production from lunar regolith depends on a system that is able to reliably create and sustain the physical conditions that are needed for the reactions to occur rather than whether the chemistry is theoretically possible.

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