FORGE C3 Final Report

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LIST OF ABBREVIATIONS

FORGE	Facility for On-surface Refining, Gathering, and Extraction
FTD	FORGE Technology Demonstrator
LSP-2	Lunar South Pole Regolith Simulant
MRE	Molten Regolith Electrolysis
ANSYS	Analysis System (Engineering Simulation Software)
DAQ	Data Acquisition
NASA	National Aeronautics and Space Administration
NIST	National Institute of Standards and Technology
CAD	Computer-Aided Design

1.0 INTRODUCTION

As NASA progresses towards Mars through the Artemis Program, it has been made clear that establishing permanent settlements on the surface of the moon is a priority for extended interplanetary travel. However, given the high costs required to deliver materials to the sites[1], the ability to produce materials in-situ proves to be a necessary initiative. The Facility for On-surface Refining, Gathering, and Extraction (FORGE) aims to lower the cost of sending material to the moon by using the elements already present on the lunar surface.

Astrobotics advertises the delivery of payloads to the lunar surface as $1.2M per kilogram[2]. FORGE intends to bypass the reliance on Earth-based materials altogether by producing usable construction resources directly from lunar regolith. Lunar regolith is rich in key oxidized materials, such as silica, alumina, iron oxide, and titanium oxide (titania). By leveraging in-situ resource utilization, FORGE seeks to supply materials for building lunar bases and infrastructure without the financial burden of transporting them from Earth.

FORGE intends to operate in tandem with the initial landscaping and digging stages when developing the lunar sites, utilizing excess regolith as intake for material production. The FORGE Technology Demonstrator (FTD) will therefore join a critical mission in the development of lunar settlements, refining the lunar regolith to create more materials for the settlement.

1.1 Lunar Regolith Analysis

NASA is targeting the lunar south pole as one of the primary locations for potential lunar bases. Due to this, FORGE analyzed the composition of LSP-2 regolith simulant [3] due to its similarity to the regolith present on the lunar south pole. The composition of LSP-2 can be seen in Fig 1 below.

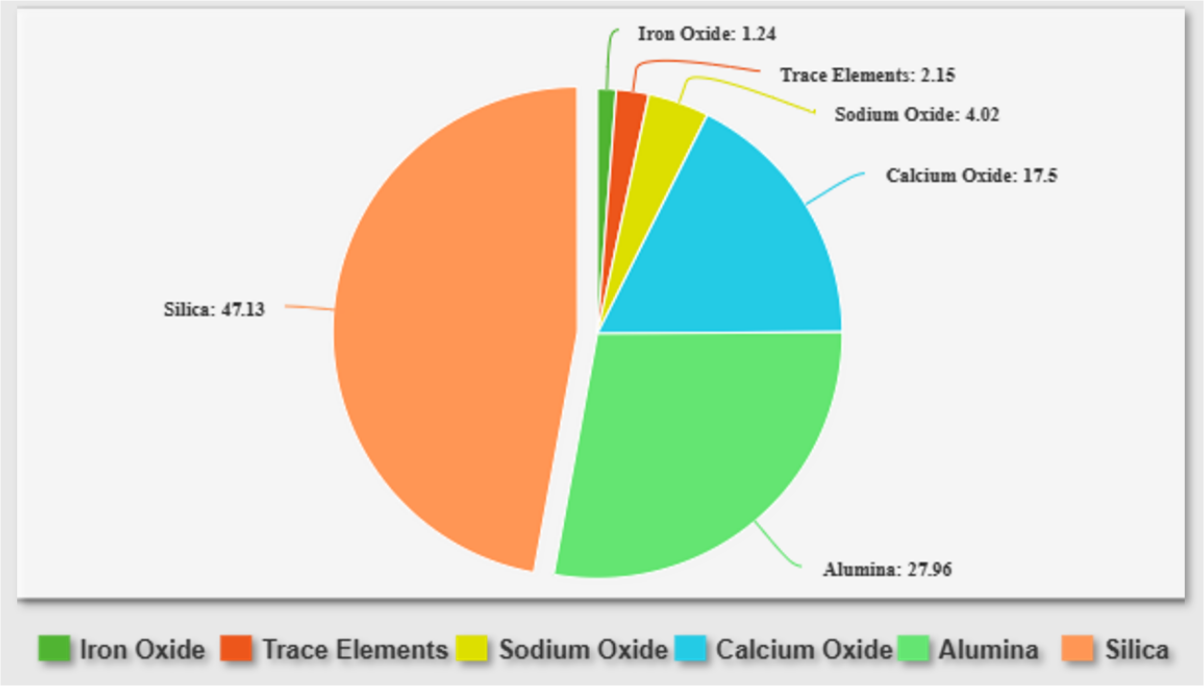

Figure 1: LSP-2 Composition by Element

Shown in the chart above, LSP-2 has a silica composition of 47.13 percent and an alumina composition of 27.96 percent. Silica and alumina are both very common materials and notably used in alloys and aerospace structures. Some refining is still required for the materials to be ready for use, however the elements can still be extracted using the FTD.

To separate individual materials, FORGE will use a process known as Molten Regolith Electrolysis (MRE) [4]. This process leverages the differing Gibb's free energy of various oxides to separate them within the FTD. After fully melting the simulant, it is used as an electrolyte while a current is passed between electrodes two submerged within the melt [5]. This strips oxygen atoms from the liquidus oxide molecules, producing oxygen gas and pure elemental remnants.

1.2 Molten Regolith Electrolysis

On Earth, electrolysis is most commonly used in the context of desalination plants. These turn saltwater into freshwater by passing a current through water, which separates into gaseous hydrogen and oxygen as well as salt crystals. These gasses are then condensed into purified drinking water [6]. The concept of electrolysis is not limited to water; any oxidized liquid can be separated into oxygen gas and pure elements by passing a current through it. This is the conceptual basis for MRE. The lunar regolith is composed entirely of various oxides, including alumina, titania, silica, and iron oxide [7]. By heating lunar regolith to its liquidus temperature and passing a current through the resultant melt, it is feasible to extract oxygen gas and other materials. This is how FORGE can assist the creation of a lunar settlement while lowering the cost significantly [8].

Electrolysis cannot begin until the oxide melt is in a liquidus phase. Therefore, FORGE elected to use an induction heater to heat the regolith simulant within a crucible to 2000 °C, well above the liquidus temperature of LSP-2. After liquidus phase is achieved, the MRE process will maintain the temperature of the melt via joule heating [4] [9].

Fig. 2 below was developed with data from the Slag Atlas [10]. The phase diagrams in the Slag Atlas describe the temperatures necessary to electrolyze the materials listed along the top of the chart. To achieve sufficient material separation, FORGE determined that the temperature must exceed 1830°C. This leaves a 170°C margin of safety for the 2000°C design goal of the furnace.

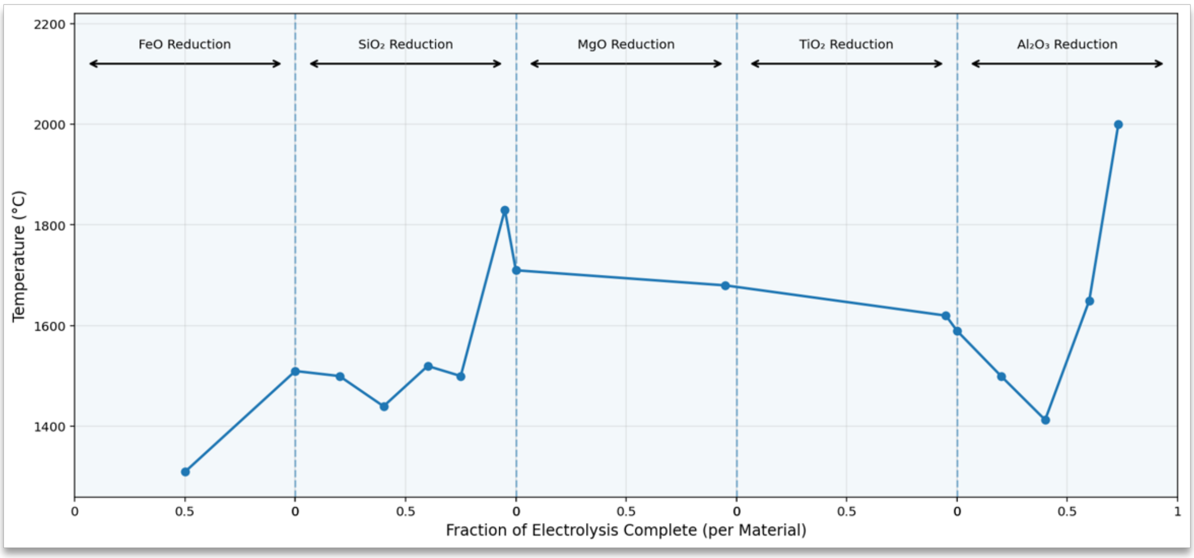

Figure 2: LSP-2 Liquidus Temperature Curve.

To determine how far the MRE process has progressed during testing of the FTD, measurements of the voltage drop across the electrodes will be taken regularly. This voltage drop is a function of 3 different factors: the Gibb's free energy of the oxide being electrolyzed, the activation overpotential, and the electrical resistivity of the melt [11]. Via data from the slag atlas [10] FORGE can predict the voltage drop due to resistivity. To analyze the Gibb's free energy of decomposition, values were taken from the NIST JANAF tables [12] and altered for the partial pressures of each component in vacuum [13]. Finally, the overpotential voltage due to boundary effects was addressed with the Tafel equation [14]. Summing the 3 terms outlined above for various oxides and comparing them to measured voltages during testing will allow FORGE to determine the stage of progression of electrolysis inside the FTD.

1.3 Concept of Operations

Over the course of the de-scoped operation of FORGE, the entire system can be broken down into seven steps as shown in Fig. 3. The mission begins with the launch of the Griffin Lander from Earth for the Moon, likely aboard a Falcon Heavy rocket as the payload. Upon arrival and descent onto the Moon's surface at the lunar south pole, the Griffin Lander will deploy on the site of the prospective lunar base. Next, powered by the systems onboard the lander, FORGE will begin inputting excess lunar regolith from simultaneous construction efforts so that it can begin MRE. The MRE process occupies the final four steps of FORGE's operation. The process starts as the induction furnace will melt the regolith within the crucible. In the next phase, a current will pass between the anode and the cathode, using the now molten regolith as an electrolyte. As the process occurs, the oxide ions from the silicon, iron, and titanium oxides will separate and gather at the top of the crucible around the anode. The pure silicon, iron, and titanium will gather in a molten alloy on the cathode, as shown in the subsequent phase. Finally, a progressive, stepped temperature decrease will crystallize the metals on the cathode, fully separating them from each other, forming either layers or distinguishable groups of pure materials that can then be extracted.

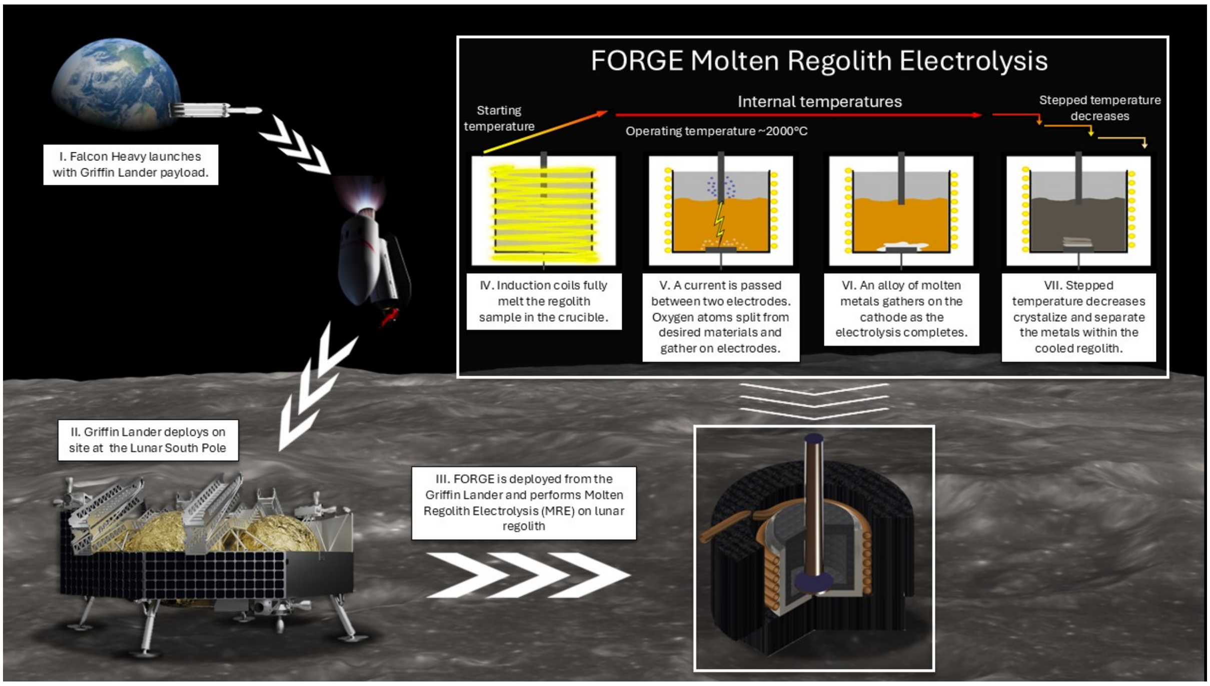

Figure 3: FORGE Concept of Operations

Within the scope of FORGE, the FTD will not have a mechanism to extract any materials from the crucible after separation. After testing, the crucible will be sectioned and analyzed using a scanning electron microscope (SEM) where FORGE will observe the cooled regolith to verify the results of the MRE process.

2.0 RESEARCH

In order for MRE to be performed, the lunar regolith within the FTD must reach above 1830 °C, which requires a furnace subsystem. The furnace subsystem contains an induction heater. An induction heater uses helical coils known as induction coils which are fed a high current that forms eddy currents, which rapidly heat a workpiece within the coils through resistive losses. In the induction heater of the FTD, the workpiece is a graphite crucible and will be heated to 2000°C. The high current requirement of the induction heater necessitates a heater board to supply power to the coils, and the crucible requires it's own individual insulation to ensure the heating from the coils will stay within the crucible. This collection of parts composes the furnace subsystem.

Induction heating for the furnace subsystem was chosen through a trade study. The other options considered were a plasma arc furnace, joule heating, and the use of a gas torch. A plasma arc furnace uses a jet of gas or ambient inert gas in a chamber to create a jet of plasma that would heat a workpiece through heat transfer. This option was eliminated because it requires a working fluid, which would make the FTD's lifetime limited by a tank of working fluid; and requires more power compared to an induction furnace. Joule heating is a heating method in which an electric current is passed through and resistively heats a workpiece. This method would reduce the part count as it would require components of an MRE only. However, the power required to joule heat the workpiece within the FTD would be far too high, damaging the equipment that FORGE is borrowing. The final heating option of a gas torch was a last resort option if FORGE did not receive the funds necessary for a furnace. This option would quickly oxidize the graphite crucible, as graphite will break down into carbon dioxide and carbon monoxide at high temperatures if exposed to oxygen from the torch.

Within the scope of the FTD, testing will be performed in a vacuum chamber to ensure that the FTD will function in the vacuum environment of the lunar surface as well as to protect components from oxidation at high temperatures. Although no air will be present, insulation is still necessary to mitigate radiative energy loss within the furnace and to prevent excess heat from damaging components outside of it. FORGE selected a graphite felt insulation to encapsulate the furnace, which will ensure that the heat loss from the crucible is limited. This will reduce the external temperature of the FTD to around 100°C. The graphite felt and it's subsequent assembly requirements will be referred to as the insulation subsystem.

The graphite felt was selected after conducting a trade study. Other options that were considered include mullite foam, alumina foam, silicon carbide foam, and low density graphite foam. Originally, low density graphite foam was selected due to its high temperature resistance, high emissivity, and lower thermal conductivity (due to its lower density in comparison to the options available for the other materials [15]). A concern with the low density graphite foam was coupling with the induction coil and directly heating up the insulation. This concern was dismissed as the majority of power consumed by the insulation would be emitted back at the crucible due to the high emissivity of the low density graphite foam. Ultimately, problems with finding a supplier for such a small quantity of low density graphite foam led to the final selection of graphite felt as the insulation. The graphite felt had nearly identical thermal properties as the low density graphite foam but could no longer support components such as the anode and thermal-couple due to its malleable nature. A steel plate was used on the exterior of the felt insulation to support these components.

2.1 Electrode Selection

As described earlier, electrolysis will be performed within the molten regolith by passing a current through two electrodes that will be submerged within the LSP-2 melt. The electrodes must satisfy a few key requirements. They must have a melting point above 2000°C (the maximum operating temperature of the FTD) in vacuum, high electrical conductivity, and adequate resistance to oxidation. Failing to meet any of the above requirements would result in the electrodes being rapidly degraded and unable to supply current to the LSP-2 melt.

To satisfy the above requirements, the list of viable materials for electrodes is limited to refractory metals with very high melting points: tungsten, niobium, iridium, hafnium, osmium, ruthenium, molybdenum, and tantalum [16]. Among these metals, the only economically realistic options for FORGE are tungsten, tantalum, niobium, and molybdenum [17].

The next most significant consideration is how each element performs as either an anode or cathode. Due to the direction of current flow and only the cathode being completely submerged in the melt, the electrodes cannot be identical [18]. The anode must be more resistant to oxidation, as it will be continuously exposed to the O_2 gas produced by electrolysis. The layer around the cathode is where electrolysis will occur, so it should be machinable in a way that maximizes its surface area. Additionally, the cathode should have a melting point well above 2000 °C to leave a safety margin for the varying temperature of the melt.

Niobium offers a unique advantage among the 4 metals, in that it can form a thin oxidized layer around itself without losing significant mechanical strength or electrical conductivity [19]. Additionally, this layer can mitigate further oxidation at certain temperature ranges [20]. Due to the above reasons, niobium was selected as the anode material for the FTD. For the cathode, FORGE elected to avoid tungsten due to it being extremely brittle at low temperatures and therefore very challenging to machine [21].

Of the two remaining options for use as cathode, FORGE decided to use tantalum due to the melting point of molybdenum in a vacuum being below 2100°C; thus leaving a relatively small margin of safety from the desired testing temperature [16]. FORGE ultimately decided to use molybdenum for another purpose within the furnace. Since it has the highest electrical conductivity among the refractory metals discussed above, it is uniquely suited for use as a high-temperature resistant wire [22]. The FTD will utilize molybdenum wire directly interfacing with the electrodes inside the furnace and connecting to copper wires outside the furnace. Analysis shows that this setup will be capable of supplying sufficient power to electrolyze all desired oxides in approximately 5 hours while minimizing transmission loss[23]. All components related to material separation discussed above will be designated the separation subsystem.

2.2 Assembly

Given all project requirements to ensure the FTD operates, FORGE has designed the FTD to incorporate the furnace, insulation, and separation subsystems using the CATIA V5 program. The measurement subsystem was not included in the CAD as none of the components of the measurement subsystem were fabricated by FORGE. The final CAD assembly is shown below in Fig. 4.

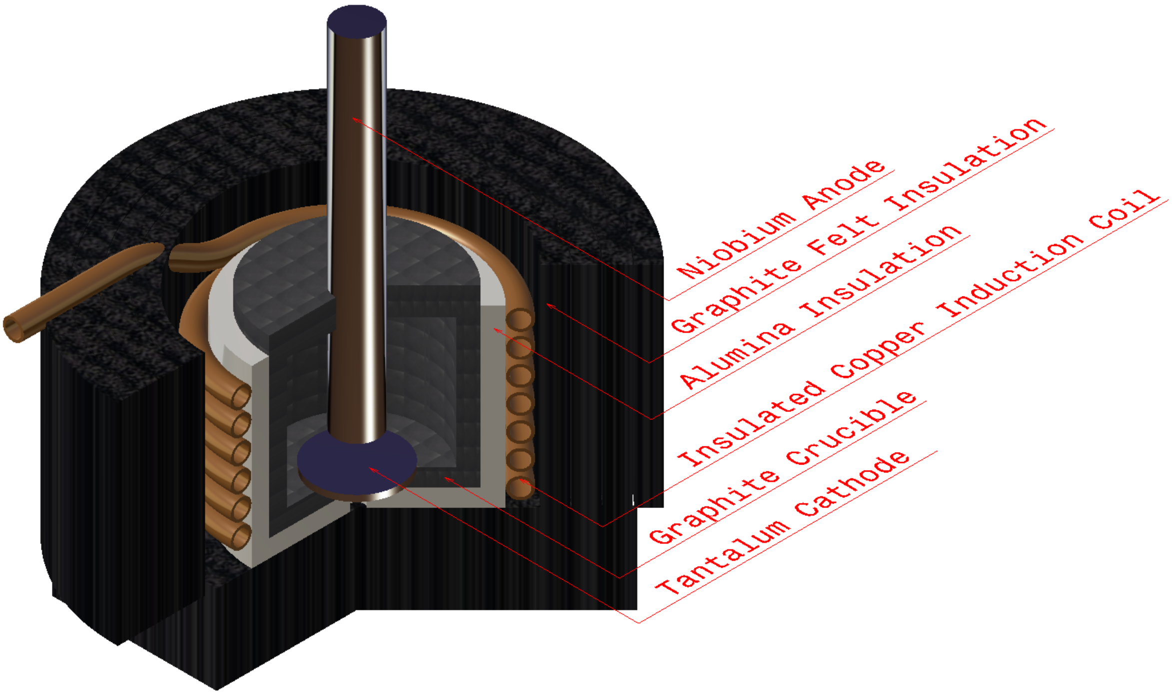

Figure 4: Digital Assembly of the FTD

Within the furnace subsystem, there are the insulated copper induction coils, the graphite crucible, and the crucible lid. The insulated copper induction coils are hollow copper tubes with fiber-glass sleeves around them to reduce heat transfer and prevent shorting. The induction coils are wrapped around the alumina refractory ceramic crucible insulation. The copper coils will have water pumped through them to prevent overheating which will reduce the conductivity of the copper and thus the melting power of the induction furnace. The graphite crucible is the workpiece that the induction furnace will heat directly using induction heating. The crucible lid is placed on top of the graphite crucible. The crucible is inserted into the alumina refractory ceramic crucible insulation.

The insulation subsystem contains the graphite felt insulation and alumina refractory ceramic crucible insulation. Graphite felt insulation, which is formed by wrapping a long felt strip around a cylinder and stitching it together with carbon fiber, then stitching caps for the top and bottom of the insulation. The graphite felt insulation wraps around the coils. Alumina refractory ceramic crucible insulation contains the crucible and prevents heat transfer from overheating the induction coils.

The separation subsystem contains the niobium anode and tantalum cathode. The niobium anode will be suspended above the cathode. The tantalum cathode is placed onto the bottom of the graphite crucible's interior. The cathode will be wired through a hole in the bottom of the graphite crucible and crucible insulation.

The measurement subsystem, as previously mentioned, was not included in the CAD. The measurement subsystem includes a type c thermocouple, an infrared radiative thermometer, a DAQ system, and a computer running software compatible with the output of the DAQ system (LabView). The type c thermocouple is inserted through the top of the graphite felt insulation and the crucible lid and is submerged in the material within the graphite crucible. The leads of the type c thermocouple are wired to the DAQ system. The infrared radiative thermometer is affixed to the exterior of the FTD and is pointed at the exterior surface of the graphite felt insulation. The output wires are wired to the DAQ system and power supply wires are attached to a DC power source. The DAQ system is connected to the computer running LabView.

3.0 Prototype

FORGE has thus constructed a prototype, the FORGE Technology Demonstrator (FTD), using our allocated budget of $2505 provided by Embry-Riddle Aeronautical University. The FTD has thus been constructed as a result of the furnace, separation, and insulation subsystems. In order to test the operation of the FTD, FORGE will conduct a total of four tests.

The following is a summary of the four tests that will be performed at both the system and subsystem levels on the FTD. The safety and electronics, temperature control, and regolith simulant melting tests are subsystem-level tests, and will ensure adequate function of the electronics, furnace and temperature control, and regolith melting. The full-scale test will be a comprehensive, system-level test that will evaluate the functionality of the FTD as a whole. Given the nature of the separation subsystem, it requires all other subsystems to operate. Thus, the separation subsystem will be tested in the full assembly during the full-scale test. All tests will be conducted within or around the vacuum chamber located on the Prescott campus of Embry-Riddle Aeronautical University within the Space Systems lab in Building 75 (AXFAB). Table 1 describes all the tests that will be performed by the FTD.

Table 1: Summary of FTD Tests

Test Name	**Purpose**	**Pass Criteria**
Test 1: Safety and Electronics	Ensure that electronics are connected and that all components can be powered safely.	Pass if all components are operational and can be powered safely.

Test 2: Temperature Control	Ensure that thermocouple can make accurate measurements, which can be used to control temperature at 1000°C.	Pass if temperature within the crucible is measured within ± 50°C
Test 3: Regolith Simulant Melting	Ensure that the FTD can melt LSP-2 at 2000°C.	Pass if at end time of melting that the regolith shows solidification into one mass.
Test 4: Full-Scale Test	Ensure that the FTD can use MRE separate pure elements from LSP-2 and maintain internal temperatures at 2000°C.	System produces clearly defined layers of separate raw materials after inspection.

Table 1 outlines how the 4 tests that FORGE will carry out will verify every requirement. Testing of the FTD will begin with the safety and electronics test before proceeding with temperature control and regolith simulant melting in subsequent tests. The testing will conclude with a final Full-Scale Test with all subsystems integrated. Table 2 outlines the key parameters for each of the FTD's 4 tests below.

Table 2: Test Descriptions

Test	**Max Temp. (°C)**	**Pressure (atm)**	**In Crucible**	**Crucible #**	**Time (min)**
1	200	0.2	Empty	1	30
2	1000	0.02	Silica Sand	2	–
3	2000	Near vacuum	LSP-2	2	180
4	2000	Near vacuum	LSP-2	1	490

Note that the test 2 time requirement in Table 2 has been left blank since the test will be carried out until the desired temperature is achieved. The ”Crucible #” column refers to either the first or second crucible. Since FORGE only has 1 set of electrodes, they need to be preserved for test 4. As such, a different crucible setup will be used for tests 2 and 3, the tests which would carry a risk of damaging the electrodes.

3.1 Testing Results

FORGE has currently conducted 3 of the 4 planned tests for the FTD, these being tests 1 through 3. This section thus reviews each of the tests conducted and reviews the results for each test.

3.1.1 Test 1 - Safety & Electronics

Test 1 was conducted progressively as components arrived and were assembled. FORGE tested each subsystem of the FTD to ensure proper operation and initial compliance with system requirements.

The first portion of Test 1 involved testing the induction heater board to verify that the induction heater can be powered and cooled. FORGE determined that the heater board did not include an integrated pump; therefore, an external water pump was acquired and incorporated to enable active cooling. With the cooling loop established, the heater board was powered on and monitored for nominal operation. A small-scale heating test was then conducted, successfully demonstrating the inductive heating of the graphite crucible and confirming that the system was capable of exceeding the required 3 kW output. This verified both adequate induction performance and functional water-based coil cooling.

The second portion of Test 1 involved validation of the measurement subsystem. Accurate temperature measurement was required for both system safety and operational control. External temperature readings ensured that the vacuum chamber and surrounding environment remained within safe limits, while internal temperature readings were necessary to detect regolith melting and support controlled temperature stepping during future separation processes. The data acquisition system successfully read values from both the infrared (IR) sensor and thermocouple, confirming accurate temperature output. Following this, lead wires were routed through a bulkhead interface, and both sensors were fully integrated with the FTD.

During Test 1, the only remaining testing procedure was testing of the separation subsystem's power supply. While power was successfully supplied to the furnace subsystem, the separation subsystem (MRE) was not powered due to a missing structural component—specifically, a sleeve required around the anode. This prevented safe and complete electrical integration of the MRE system. This issue is not a design limitation but a temporary hardware deficiency and is planned to be resolved in Test 4 once the required component is installed.

In addition, safety power shut-off was verified through the implementation of multiple shutdown conditions, ensuring that power to the system could be safely terminated under fault or unsafe operating scenarios.

3.1.2 Test 2 - Temperature Control

Test 2 involved validation of the measurement subsystem and thermal performance of the FTD. This was accomplished by heating a non-toxic substance (silica sand) to temperatures exceeding 1000 °C, while simultaneously monitoring internal temperature using a thermocouple and external temperature using an infrared (IR) sensor.

The expected outcome included initial signs of material transformation indicative of elevated temperatures. Following the test, the sand exhibited clear evidence of partial melting, including the formation of a large consolidated clump adhered to the bottom of the crucible. This clump required mechanical scraping for removal while remaining structurally intact (see Fig. 5), confirming that temperatures above 1000 °C were achieved.

Figure 5: Clump of melted sand on crucible

Looking at Fig. 5, the sand on the right was the ”top soil” inside of the crucible and consists primarily of individual grains with minor clumping. This indicates that the top section of the crucible did not reach as high a temperature as the bottom, as evidenced by the large clump in the center of the image, which was originally located at the bottom of the crucible.

3.1.3 Test 3 - Regolith Simulant Melting

This test followed the previous procedure, with the primary differences being the material heated and the operating temperature of the heater board. The material used was LSP-2 Lunar Regolith Simulant, heated to approximately 2000°C. The following observations were recorded:

1. Operation amperage was required to remain below approximately 300 amps on the heater board to prevent tripping the 20 amp room breaker. This constraint resulted in longer heating durations to limit overall current draw by the FTD.

2. The water circulating through the induction coils increased in temperature more rapidly than expected. To mitigate this, the cooling system was expanded from one to two five-gallon buckets of tap water.

3. The fiberglass insulation surrounding the coil degraded and ultimately melted, exposing bare copper by the end of the test. Additionally, the alumina crucible insulaion containing the crucible exhibited signs of melting, indicating that the bottom of the crucible exceeded the solidus temperature of alumina at approximately 2100°C as shown in the following figures.

The crucible remained structurally intact throughout testing with no evidence of cracking or oxidation. The furnace melted the regolith within a reasonable time frame, with peak thermocouple temperature readings achieved approximately 9 minutes into testing, demonstrating effective heating performance.

Precise temperature control was successfully demonstrated, as the induction heater board allowed for precise and responsive control of LSP-2 temperature throughout the test. Demonstrating this proved the possibility of the stepped temperature decreases necessary for mineral separation.

The thermocouple did not read 2000°C during the test. The thermocouple maintained structural integrity and continued to return consistent readings; however, it lost direct contact with the LSP-2 during testing. As a result, accurate internal temperature verification within the material could not be confirmed, and true internal measurements were not obtained. Future testing will require improved thermocouple placement or securing methods to ensure sustained contact with the regolith simulant.

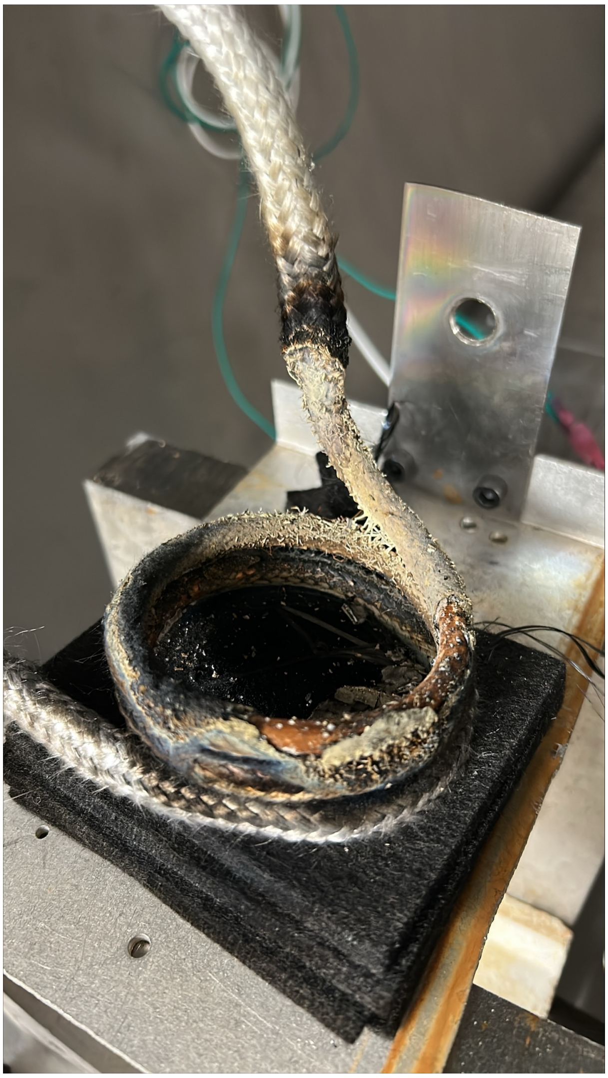

Figure 6: Melted Fiberglass insulation around the coil

In Fig. 6, the coils are visible through the fiber-glass insulation. Despite the insulation being burned through, the coils remained fully operational, were not close to melting, and the water flowing through them was well below boiling and safe to touch, indicating the coils would not melt. Additionally, the heater-board includes a safety feature that monitors amperage; an increase in amperage indicates excessive coil temperature, prompting the system to shut off automatically.

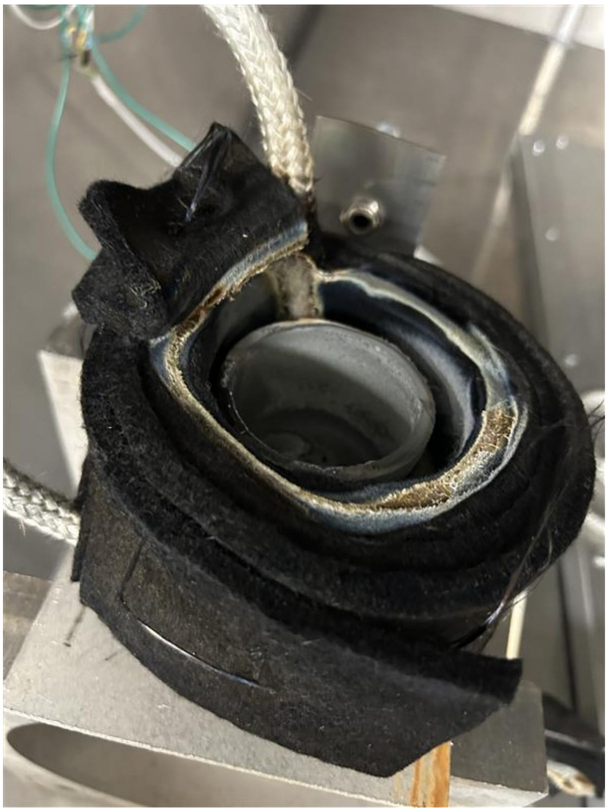

Figure 7: Graphite insulation showing scorched markings

Fig. 7 shows the aftermath of heating within the graphite felt insulation. The insulation effectively limited heat transfer to the IR sensor, with the external temperature remaining below 300°C. The external temperature remained below the safe material limit of the structural of the vacuum chamber, which is approximately 500°C, and FORGE considers the results acceptable.

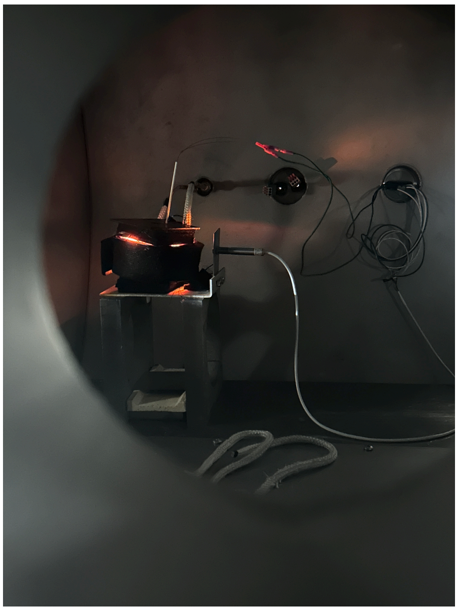

Figure 8: FTD inside the vacuum chamber

Fig. 8 shows the inside of the vacuum chamber at approximately .5 torr, with the FTD conducting test three. The visible glow indicates that the insulation did not fully encapsulate the heated components, allowing energy to escape radiatively and likely raising the external insulation temperature above 100°C but below 300°C.

As a result of these three tests, FORGE has confirmed the FTD can melt lunar regolith in a safe environment. Test 1, ensured that the FTD operates correctly and that the assembly can support the power supply in the system. Test 2 ensured that the measurement and furnace subsystems operate with material within the crucible. Lastly, Test 3 ensured that the FTD can reach 2000°C within the crucible and successfully melted the regolith. The final test of the prototype is scheduled for the 10th of April 2026 and will ensure that the separation subsystem operates with the molten regolith within the crucible.

4.0 CONCLUSION

The FORGE Technology Demonstrator (FTD) has been tested three times, as summarized in Table 1, with a fourth and final test scheduled. Across these trials, the FTD has demonstrated promising performance with minimal setbacks, allowing FORGE to remain on schedule. While some requirements were not fully met, the degree of deviation was minor and correctable and does not impede continued development or overall project viability.

On April 10th, 2026, FORGE will conduct the fourth and final test, which will serve as the primary validation of system performance. During this test, the furnace will be maintained at approximately 2000°C for a duration of 3 to 5 hours. This extended high-temperature operation will enable the full integration of Molten Regolith Electrolysis within the crucible to deoxidize the LSP-2 lunar regolith simulant, representing the central objective of the capstone project.

Upon completion of the test, FORGE expects to observe distinct layers or clusters of titanium, aluminum, silicon, and iron formed through controlled thermal processing. Successful separation of these materials would validate the proposed stepped cooling methodology and demonstrate the feasibility of producing usable construction materials through integrated In-Situ Resource Utilization processes.

As this paper is submitted prior to the final test, detailed results and analysis will be presented during the FORGE formal presentation.

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