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The Effects of Microgravity in Sintering Lunar Regolith Simulant

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Abstract

The RockSat X mission's primary objective is to evaluate the durability and structural applications of sintered lunar regolith and to investigate how microgravity affects the sintering process. Launching supplies into space is extremely difficult and expensive. As space exploration advances, the need for using in-situ resources becomes critical. The ability to sinter regolith will give humanity the unique advantage to create construction material on remote celestial bodies. There were several methods of sintering that the team considered, but the final method chosen was induction. An induction heating unit, copper coil, and a graphite crucible filled with lunar simulant will be flown on a rocket in microgravity during the sintering process. Initial testing consisted of sintering our simulant in a kiln as a proof of concept. Temperatures of 1200 C are required to sinter lunar regolith and finding a power source capable of sintering and being flown in a rocket was one of the biggest hurdles. Two RC car batteries in series provided the necessary voltage required for the induction system. After acquiring sufficient battery power, the team performed a dry run test to determine the functionality of the system without water cooling, an insulation test to see if our materials could handle 1200C, and finally, an induction sintering test to show we could sinter our simulant with this method. Strength testing as well as microscopic analysis will be conducted on control simulants sintered on earth and compared to simulants sintered on the rocket. We expect these differences including lack of unified sintering, densification rate, grain size distribution, pore formation, and overall structural deformation. The ability to sinter lunar regolith simulant in a microgravity environment will pose valuable data for humanity. Understanding how this in-situ resource will be affected in these environments during the sintering process gives us vital information for future missions.

Introduction

The primary mission for RockSat X is to evaluate how sintering lunar regolith simulant (LRS) in a microgravity environment affects the sintering process. As well as testing the structural integrity and durability of sintered LRS after exposure to a suborbital environment. Launching supplies into space is extremely difficult and expensive. As humanity begins its mission to conquer the cosmos it will need structural material to do so. Taking advantage of in situ resources is vital for the ability to explore our solar system efficiently. The ability to sinter regolith of any kind will give humanity the unique advantage of creating construction material on celestial bodies without wasting excess fuel, money, and time.

Lunar Regolith

Lunar regolith, or regolith of any sorts, is a fascinating material that can be found on many celestial bodies. The composition of regolith can vary drastically depending on where it is taken from. Martian regolith is very different from Lunar regolith. Even different parts of the moon will have different compositions for its regolith depending on if it is from the highlands or the lunar mare (Isachenkov *et al.* 2022). Though the spectrum of its composition is quite vast, how regolith is made is universal. There are several conditions necessary for regolith to form. No active planetary processes such as weathering, tectonics or volcanism, combined with a lack of an atmosphere. Planets and moons that lack atmospheres have no cosmological shield to burn up meteorites ("Lunar Soil", Wikipedia). After billions of years of bombardment the crust has been pulverized into extremely fine dust. This lack of protection coupled with the fact that there is no weathering, active tectonics or volcanism to resurface the celestial body leaves a barren, desolate, and dusty environment (Nobel). This regolith, under the right conditions can be sintered (Han *et al.* 2022). Having material that can be used on site poses serious hope for the future of humanity's ability to create structures on planets other than Earth.

Why is it bad? Beautiful but deadly, this ancient moon dust is horrific for life, electronics, structures, and anything that interacts with it ("Lunar Soil", Wikipedia). The dust is so incredibly fine that it is electrostatically charged. This poses several issues. The opposing charges will cause the finest of particles to levitate and cling to whatever object has an opposite charge. This has serious consequences for electronics, drones, rovers, space stations, astronaut suits, and humans ("Lunar Soil", Wikipedia). The dust causes electronic malfunctions after an inevitable buildup. It also clings to and destroys the joints of anything that moves including door hinges, wheel axles, and more. Phenomena such as Plume Surface Interaction (PSI) also cause serious issues not only for satellites and other orbitals but for any structure within the proximity of its effects (Plume Surface Interaction, 2020). PSI occurs when rockets land on surfaces that contain regolith. The plumes of the rocket throw ejecta violently into the air and because the dust is so fine, it can get up to orbital speeds and interfere with reconnaissance satellites. It can also travel great distances and cause issues for ground structures and electronics. Additionally it can get into the airways of astronauts causing health issues and irritation. Ultimately regolith dust will have to be dealt with before humans colonize the moon. ("Lunar Soil", Wikipedia). One way to eliminate dust and create building material is to sinter (or fuse) the lunar regolith into building material (Han *et al.* 2022). As this project developed to investigate lunar building material, several ways to sinter regolith were considered. This paper explicitly investigates sintering methods that are feasible for use in microgravity (ie the surface of the moon or moon orbiting satellite) to pre-sinter building material prior to human colonization of the moon. Humanity will benefit from mastering sintering when they leave Earth. Learning how the sintering process is affected by gravitational forces on different worlds poses valuable data for the future of our missions.

Sintering

Sintering is a process in which materials are heated up to their melting point allowing the particles to bond together. The combination of heat and pressure forces particles across grain boundaries which results in a stronger, denser, and more durable substance. Think of it this way, when you take a pottery class and are done making your creation you put it in the kiln. This kiln reaches very high temperatures (up to 1300 C!) and causes the clay to sinter together. This leaves you with a denser, stronger, and more durable clay creation that you can take home. Now if this process can be done to lunar dust or regolith, it would open up a world of in situ materials that can be used to benefit humanity. When sintered properly, the lunar regolith becomes strong enough to provide shielding from radiation and even micrometeorite damage. Oxygen as well as water can be extracted during the process providing vital elements for human survival. Building material for labs, outposts, landing pads, and maybe eventually homes exists in abundance on the lunar surface. It just has to be utilized efficiently.

Additive manufacturing, more commonly known as 3D printing, is widely recognized for its versatility and creative applications. When this technology is combined with in-situ resource utilization, it becomes a potent tool for space exploration, extending our reach within the solar system and potentially even into the galaxy. This is where sintering comes back into play. NASA proposed a method in which microwaves are used to sinter large portions of the lunar surface at once. This would be a practical way to make landing pads, roads, and foundations for much larger constructions that will eventually be put in place. Other methods such as heating the lunar regolith up to its melting point and then extruding the molten regolith out a tip, much like a 3d printer, can be used to make more complicated structures such as buildings. Missions such as the Artemis mission will eventually depend on humanity's ability to perfect this process. There are many different methods of sintering and each comes with its own unique strengths and weaknesses. (Han, et al. 2022)

Induction

This was the chosen method of sintering the LRS on the rocket. It was the most energy efficient process that still allowed the payload to fit into the 12 inch diameter deck. Induction heating uses alternating electromagnetic fields to create thermal energy. This is done by flowing an alternating current through the coils to induce eddy currents in ferromagnetic materials between them due to Lenz's law. As the current is flipped back and forth extremely quickly these eddy currents build up and their resistance to the change in the field converts electromagnetic energy into thermal energy. This process can get things very hot very quickly.

Microwave

Microwave sintering is similar in the sense that you are still converting electromagnetic energy into thermal energy just in a different way. Dielectric heating is the primary method for microwave heating polar material, but it only works if the material is polar in the first place (Xu 2019). Ionic conduction is necessary because the majority of lunar regolith is not polar. That means as opposed to the polar molecules aligning with the field and switching rapidly to create heat, the microwaves agitate ions or electrons within the material leading to resistive heating much like induction heating. One of the bigger issues we ran into during experimentation was the fact that the dielectric constant of our lunar regolith simulant was not high enough at room temperature to absorb microwaves. After much more research it was concluded that the dielectric constant of most materials including regolith goes up as the material gets hotter. In order to get most regoliths to the temperature where their dielectric constant is high enough to absorb microwaves a SiC receptor is used. The receptor can absorb microwaves at room temperature and bring the regolith up to the appropriate heat needed to initiate sintering with microwaves (Gholami *et al.*2022 &Kim *et al.* 2021).

Others Methods

Spark plasma and C02 laser sintering were considered, but they were too power hungry and expensive. Solar sintering, the process of magnifying the sun to concentrate the solar power and melt/sinter regolith, was ruled out due to not having enough time to expose the regolith to the sun. Chemical reaction sintering was also ruled out due to the complications of how they react in space and how it might affect the rocket/payload.

Materials and Methods:

Materials pertaining to the sintering mission:

Key components of the structural and power materials required for the RockSat X launch are described below. Table 1 lists the primary components pertaining to the sintering of the Lunar Regolith.

The simulant was one of the most important materials to select. It is a high fidelity simulant produced by Exolith Labs and is used by universities, research centers, and even NASA to conduct testing on. The lunar mare regolith simulant was chosen due to the fact that the lunar mare has higher levels of iron. It was selected with the hope that it would have increased ferromagnetic properties and could more efficiently utilize the alternating current and heat up quicker. Graphite crucibles were chosen because they are incredible at conducting currents. This allows them to heat up extremely quickly in an induction heating system. Heat was one of the major concerns for the team but was mitigated with the ceramic fiber blanket. Testing showed the material was more than up to the job of insulating the temperatures required to sinter. Copper coils were necessary to transfer the alternating current into the crucible. Several designs were made and tested. Decreasing the amount of turns in the coil while increasing the diameter of the coil itself increased the frequency of the current, but might have also increased the load. Ceramic fiber boards were used to secure the crucible on the bottom and top. The ⅛ inch aluminum housing is also critical to the design. Acting as a shield both to keep the heat in, and the elements out, this aluminum shielding will serve its purpose.

Table 1. List of primary materials.

Part Type	Part Name
Lunar Regolith Simulant LRS	Lunar Mare (LMS-1) High-Fidelity Moon Dust Simulant
Graphite Crucible	Smelting Lab Graphite Crucible with Cover Lab Supply 40MM X 40MM
Ceramic Fiber Blanket	Ceramic Fiber Insulation: Aluminum Silicate, 5 ft Lg, 4 ft W, 1/2 in Thick, 10 lb Wt, 0.75 R-Value
Copper Coils	Copper Coils
Ceramic Fiber Board	BXI Ceramic Fiber Thermal Insulation Board
Aluminum	2024 T3 Aluminum Sheet 24" x 48", 1/8" thickness

Electrical/Power

Power was the most crucial and difficult part of this mission. The induction system needed at least 10 but pulled 40 amps and had a range of 12 - 48V. Obtaining a power source capable of this demand was extremely difficult. The only power sources used for such systems are plug into the wall kinds of power sources. Typically step down converters plugged into a 120V outlet that converted the voltage down to usable levels. These were typically put in series to be brought up to the 48V the system required, but these power sources were not feasible for a sounding rocket mission. After extensive research and consultation with electrical aerospace engineers the team found a solution. RC car batteries were found to be incredibly energy dense, storing up to 8000 Mah at 22.2V with discharge rates up to 120C. The selection were two 1800 Mah 22.2V batteries with a discharge rate of 25C. The two batteries were put in series to achieve the 44.4V required for the induction system to fully power on. Multiplying the discharge rate times the capacity of the battery gives you the amount of amperage a battery can supply. They were chosen because they had the capacity to get the crucible up to temperature and were only capable of supplying 45 amps to the system making it safer. At 22.2V and the system pulling 40 amps, the coils pump out 1776 watts of energy into the crucible and LRS.

Electrical includes what is shown below. The two main sensors used for the regolith experiment are the TMP36 and the atmospheric sensor. The TMP36 temperature sensors that were selected are standard SpaceGrant hardware and used to determine that the crucible got to the required temperature. The atmospheric sensor also has a temperature gauge but is primarily being used for its ability to track altitude so that we can confirm that the LRS was sintered in a microgravity environment (Table 2).

Table 2. List of primary electronic components.

Part Type	Part Name
Microcontroller	Raspberry Pi 4B
Temperature Sensor	TMP36 Temperature Sensor
Atmospheric/Altitude Sensor	SparkFun Atmospheric Sensor Breakout - BME280
Solid State Relay	Solid State Relay RM1D060D50
5v Voltage Regulator	LM2596
LED	Blue LED
Battery	6S Lipo Battery 1800Mah 25C 22.2V Lipo Battery Pack
Induction Heating System	1800W ZVS Induction Heater Induction Heating Board Module Tesla Coil

Results:

Pre-launch testing

Bunsen Burner

To see if the Lunar Regolith Simulant (LRS) we chose was capable of sintering, the team filled up a ceramic crucible with LRS and put it on top of a burner for 30 minutes. The bunsen burner failed to get to the appropriate temperatures required for sintering and the only measurable result was a change in color (Fig 1 & 2).

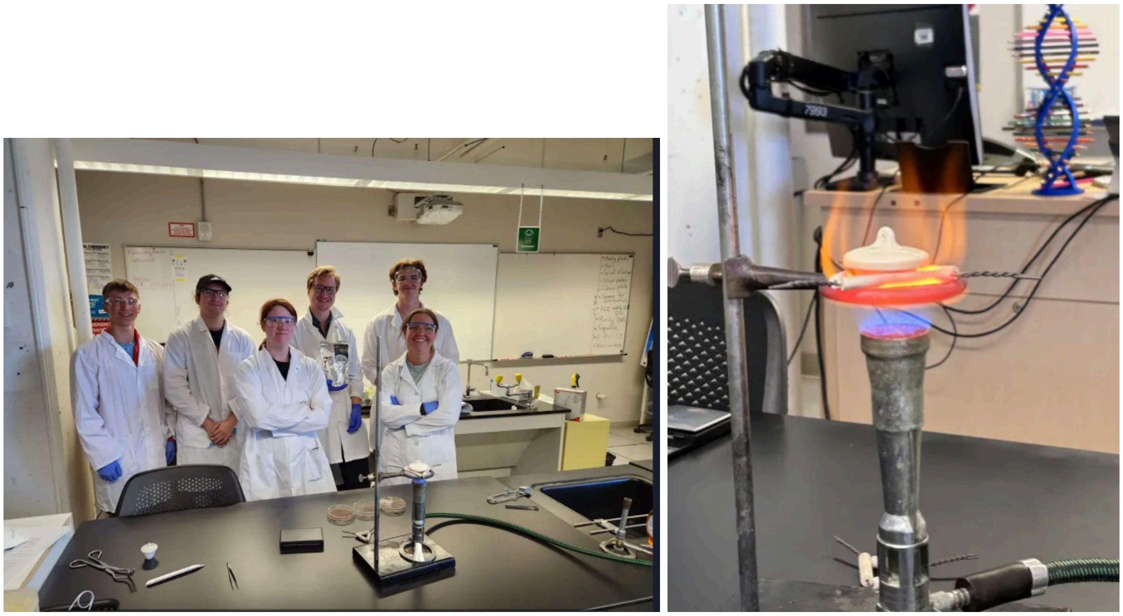


Figure 1 & 2. The RRCC and ACC RockSat team attempt to sinter regolith with a Bunsen Burner

Kiln Sintering Test

Kiln sintering was used as a proof of concept to ensure that our simulant was capable of sintering. Four graphite crucibles with varying amounts of simulant were placed inside a Red Rocks kiln. The kiln was brought to a temperature of 1200 degrees celsius for 180 seconds to replicate conditions that would be on the rocket. The graphite crucibles were destroyed but left behind three beautifully sintered pucks of lunar simulant. Each puck showed clear signs of sintering and the test was deemed successful (Fig. 3 & 4).

Figure 3 & 4. A fully sintered puck of LRS can be seen on the left. The picture on the right shows the crucibles after the kiln sintering experiment.

Induction Test And Water Cooled Induction Test

Knowing our LRS was capable of sintering. Due to size constraints, weight constraints, cost and power considerations we selected induction heating as the method of sintering on the rocket. Finding a power source small and light enough to fit on a sounding rocket proved to be an incredibly difficult task. After securing a method of power, an induction test was necessary to prove that the batteries could supply ample wattage. The first test was run without water to see if the system would even work. Results were very promising with a linear trend that suggested that the crucible would easily reach 1200 degrees Celsius in 180 seconds (Fig 5). For the next test an aquarium pump was attached to some tubing which was secured to the hollow copper coil. The crucible was placed in the center and the system was turned on. The graphite crucible reached temperatures of 900 degrees Celsius and glowed a dull red. The outer layer started to oxidize and the test was halted due the newly observed behavior.

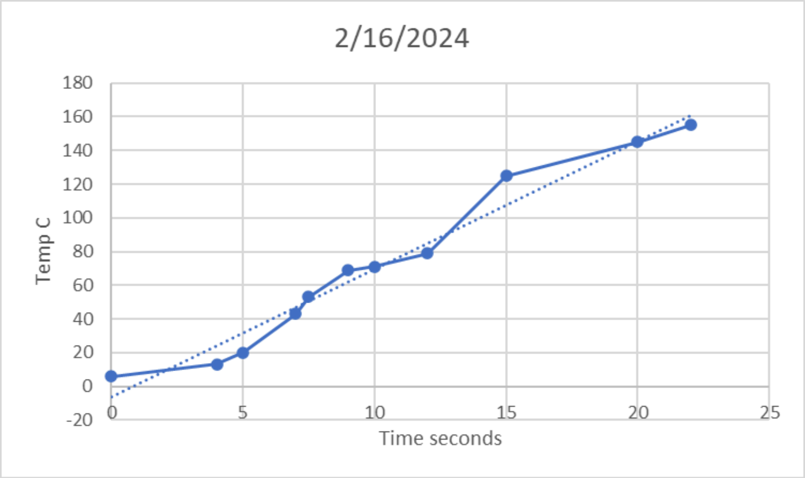


Figure 5. The first induction test powered with the new batteries showed promising results. The trend was essentially linear and lined up with 1200 degrees Celsius at 180 seconds.

Dry Run/Insulation Test

To prove that the induction system would run without water cooling the copper coil a dry run test was performed. The system showed no signs of overheating and the coils were undamaged after a full run. We also needed to confirm that the insulation material used to make the payload safe could withstand the necessary temperatures. The material chosen for insulation was a ceramic fiber blanket capable of withstanding temperatures up to 1200 degrees Celsius for extended periods of time. The graphite crucible's temperature exceeded 1200 degrees Celsius during testing, but the outer coils only reached 350 degrees Celsius (Fig. 6 & 7). It should be noted that this test was done with about half the amount of ceramic fiber blanket that will be used in flight to ensure thermal isolation. The blanket remarkably showed no signs of damage.

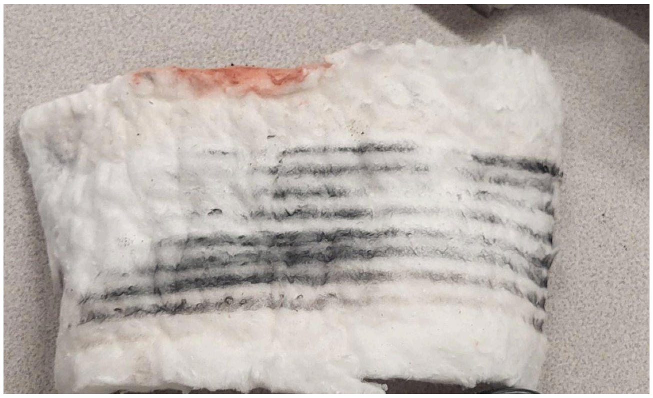


Figure 6 & 7. The graphite crucible on the left can be seen glowing a yellow-orange at 1200 degrees Celsius. The right shows the undamaged ceramic fiber blanket. The red discoloration is due to asbestos.

Induction Sintering/ Solid State Relay Test

1776 watts of AC current pulsed through the coils and induced eddy currents in ferromagnetic/conductive materials between them due to Lenz's law. The chosen lunar regolith simulate was selected because it replicated the lunar mare giving it a higher iron content which in turn gave it higher ferromagnetic properties. And the graphite crucible in which it was placed was selected for its highly conductive properties. Properties that allow the graphite crucible to heat up rapidly due to the eddy currents produced via induction that then transfer that thermal energy into the simulant. In 180 seconds temperatures exceeded 1200 degrees centigrade allowing the crucible to glow yellowish orange. The simulant was then collected and after inspection appears to be fully sintered, possibly having gone past dry state sintering temperatures into liquid state sintering territory (Fig 9).

In order to ensure that this process would not happen anywhere but in space the team devised a technique to inhibit power. A solid state relay switch was integrated into the system. Its purpose was to inhibit power until the Raspberry Pi gave the commands to fire. The solid state switch did not perform correctly in this test. It was later discovered that the solid state switches were duds and did not function correctly (Fig 8).

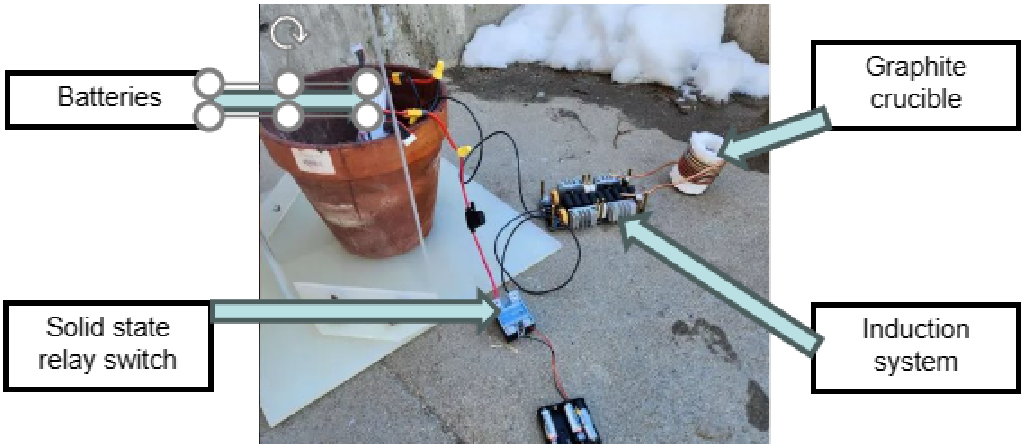


Figure 8. This image shows the almost fully integrated system. The batteries are in a bucket behind a blast shield. They are connected to the solid state relay switch which is wired to the induction heating system. The graphite crucible is hidden in the ceramic fiber blanket inside the copper coils.

Figure 9. The LRS in the crucible from the induction sintering experiment appears to be black and glossy. This implies that it went past solid state sintering and became molten.

Voltage Reduction LED Test

Visual proof that the solid state relay system was functioning and correctly inhibiting power to the induction system was critical. This need was met by integrating an LED into the design that would power on if the system failed. The batteries in series provide 44.4 V which needs to be reduced down to the point of not blowing up an LED. Several resistors were soldered in series to reduce the voltage and the test was a success (Fig. 10).

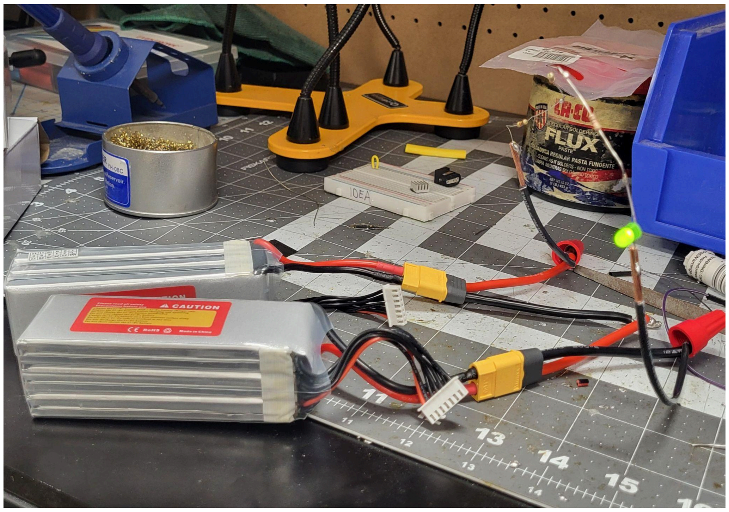


Figure 10. Two batteries in series provided 44.4V. Resistors were soldered in series to reduce this voltage and power the LED to prove that the solid state relay is functioning properly.

Fully Integrated Test

Power has to flow in a specific order from the rocket to the payload and the team wanted assurance that a fully simulated test would function correctly. This was done via a fully integrated test of the regolith subsystems while using simulated rocket power. A power supply was set to 28V to simulate the power we would be receiving from the rocket. This was then fed into a voltage converter that reduced the voltage down to a usable 5V for the Raspberry Pi. The Raspberry pi was then wired to the solid state relay switch that was inhibiting the 44.4V supplied by the batteries. To further replicate conditions on the rocket the team removed the fans from the system and used a homemade copper coil. The test was running well and the graphite crucible reached temperatures of 850 degrees Celsius before the fuse broke (Fig 11). The homemade coil had a thicker diameter and less loops with the intent of increasing the frequency of the alternating current to decrease the time to get to sintering temperatures. This was believed to pull more power than the system could handle breaking the fuse. Other explanations could be the multiple re-uses of the same circuit and fuse which could wear down the system. The LRS did not reach sintering temperatures in this test.

Figure 11. The team designed a fully integrated test with simulated rocket power. In the far back is the white box with the blue screen. This is the power supply that replicates rocket power at 28V. It is then wired to the voltage converter, Ras Pi, solid state relay switch, and then finally to the induction system.

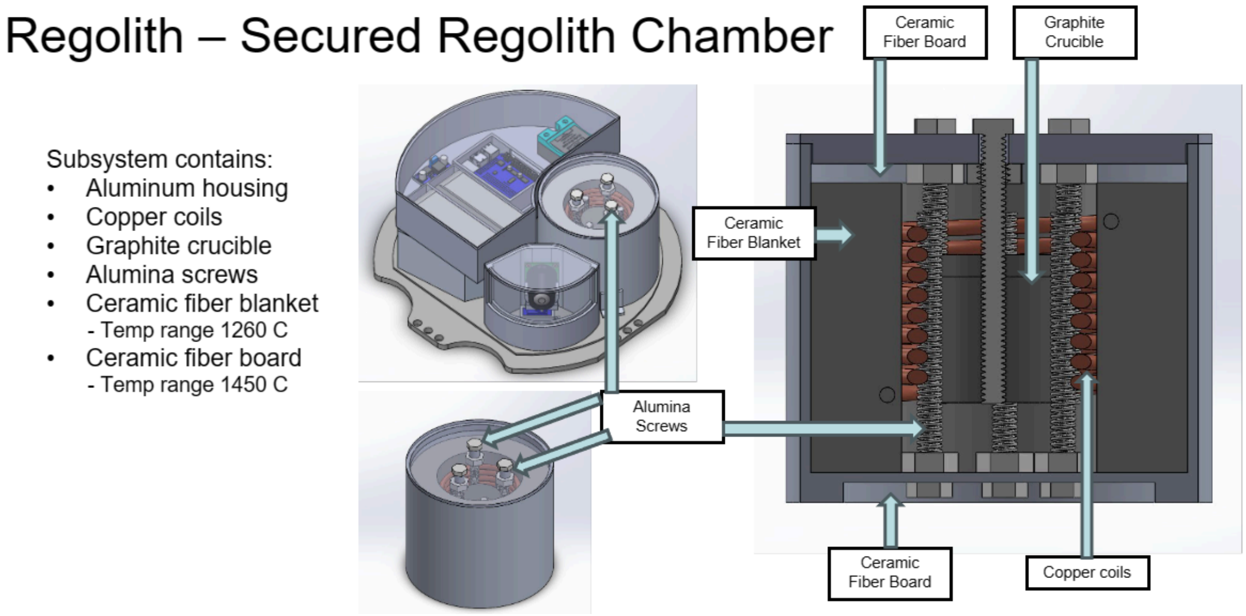
Payload Structure and Design

Goals

The RockSat X's primary objective is to evaluate how sintering lunar regolith simulant (LRS) in a microgravity environment affects the sintering process. As well as testing the structural integrity and durability of sintered LRS after exposure to a suborbital environment. One of the other primary goals is overall mission safety. In order to achieve these goals the structure, power, coding, and materials were carefully constructed or selected.

Structure

The payload was designed with the intent of maintaining and trapping the heat produced by the graphite crucible and possibly molten lunar regolith simulant. The graphite crucible will be securely wrapped in a ceramic fiber blanket and placed in the coil. More ceramic fiber blanket will be wrapped around the outside of the coil and on the bottom and top completely encasing it. An ⅛ thick aluminum shell will fully enclose the experiment providing ample thermal isolation and securement. The rest of the housing is designed for other components including: Batteries, wiring, Raspberry Pi, a star tracker used for spacecraft navigation, the induction system, and room for a ballast to reach the required 15lbs (Fig. 12).



Regolith – Secured Regolith Chamber

Subsystem contains:
- Aluminum housing
- Copper coils
- Graphite crucible
- Alumina screws
- Ceramic fiber blanket
  - Temp range 1260 C
- Ceramic fiber board
  - Temp range 1450 C

Figure 12. Containment for the graphite crucible and isolation of its thermal activities was crucial. This was achieved via wrapping the graphite crucible in a ceramic fiber blanket, placing it in the coils, and then surrounding it with more blanket material. The Alumina screws were taken out from the initial design after testing. Ceramic fiber board protects the bottom and top of the containment which is housed in aluminum.

Discussion

During pre-flight testing the lunar regolith selected was effectively sintered both in tests using a ceramics kiln (~1200C) and while using the induction heating system (~1500C). The sintered solid material is sufficient for construction.

Kiln testing provided a clear example of solid state sintered LRS while the induction sintering test pushed into liquid state sintering or “melting” territory. Timing adjustments will be made to the induction sintering method in order to stay below the threshold for melting. While these observations and measurements are fine, they are from samples that have undergone the process on Earth. We expect very different results for LRS that has been sintered in a microgravity environment.

It is expected that terrestrially sintered LRS will show promising results with clear signs of densification, compaction and overall hardening of the material. LRS that has been sintered during flight will be extremely altered compared to simulants that have sintered in gravity. We expect them to be altered in various ways including: The densification rate, grain size distribution, pore formation, and overall structural deformation. For Densification rate, in the absence of gravity, the rate at which particles compact and fill empty spaces slows down. In microgravity, the densification rate should be slower. The control LRS that has been sintered on Earth should be denser in comparison. Grain size and distribution will be different due to gravitational forces causing denser objects to settle while liger particles float on top. We expect to see a more uniform grain distribution. Pore formation is affected by buoyancy which migrates the pores to certain areas. In the absence of gravity this buoyancy driven pore migration will create different patterns. Finally we expect the overall structural deformation of the simulant to take place. Without the sculpting force of gravity, deformation in sintered material is to be expected. It will likely be less uniform.

As humans start to explore and expand into our solar system, they will need resources to do so. The ability to utilize local resources will allow us to do so efficiently. Our team aims to help with future space missions by collecting valuable data and learning how regolith simulants sinter in a microgravity environment.

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