# Lunar Regolith Mitigation through Emission of Laser Technology, *MELT*

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# 1. Quad Chart

## *Lunar Regolith Mitigation through Emission of Laser Technology*

### Objectives & Technical Approach:

**Project Objectives**

- Provide a long-term, in-situ solution to lunar dust interference by creating a dust-reduced area in regions of high traffic.
- Provide autonomous and non-autonomous deployment methods on the lunar surface.

**Technical Approach**

- Use a laser device mounted on an adjustable vantage point to allow the laser to cover a large area.
- Tripod system electronics are insulated to survive harsh lunar conditions.
- Concept feasibility will be tested with regolith simulant in order to predict successful implementation on lunar surface

### Key Team Leads:

**Anna Pedersen**, Team Lead
**Chris Crews-Holloway**, Mechanical Design and Integration Lead
**Sean Chu**, CAD Lead
**Nathan Jordan**, Theoretical Analysis Lead
**Ian Burke**, Concept Feasibility Lead

### Schedule:

- **Feb.:** Terrestrial-based proof of concept test with 200W laser
- **Mar.:** Terrestrial-based testing with 200 W laser, comparing maria and highland regolith.
- **May:** Finalize optics and CAD design for concept.
- **Jun.:** Fabrication of laser tripod system and optical periscope
- **Jul.:** Preliminary terrestrial testing of laser tripod system
- **Aug.:** Materials testing to determine sintered regolith structural properties
- **Sept.:** Lunar environment concept testing (temperature, no atmosphere, and low-gravity simulation)
- **Oct.:** Finalize concept with necessary design modifications from environmental testing.

### Cost:

- Total Budget: $101,122

## 2. Summary Statement

This team is addressing the challenges of exterior dust prevention, tolerance and mitigation. Our group aims at solving this problem by using a stationary high power laser to sinter slabs of regolith to modify a thin layer of lunar surface. Dust particulate on the lunar surface has been a significant concern since the Apollo missions since the fine particles would adhere to exterior areas of the lunar lander and other modules necessary for lunar exploration. This dust, abrasive in nature, will significantly degrade sensitive electronics and optics present in the environment, causing technical problems for the astronauts and limiting opportunities to explore the lunar surface [4]. This solution, MELT (Mitigation through Emission of Laser Technology) offers a method of dust prevention through sintering lunar regolith into glassified surfaces on the moon. This lunar surface modification will create a dust free environment which lunar vehicles can explore without being exposed to the dangers of abrasive lunar dust adhering to exterior surfaces. In addition to prolonging the lifetime and functionality of mobility platforms, solidified dust particulates will not be prone to agitation or clouding from mechanical surface motions, vastly reducing the amount of dust in the air and local environment. The substantial reduction of local dust particles would help protect lunar surface systems from contamination and buildup, with the resulting dust free environment mitigating particulate entry of human habitations or landers.

While our main focus is upon exterior dust prevention, there are also additional implications for landing dust tolerance. When retrorockets engage on the lunar landing module upon surface touchdown, a significant amount of dust is kicked up posing problems for astronauts and technical equipment on board. The high power laser could also sinter slabs of regolith for the creation of landing pads [5]. These landing pads would be sufficient in minimizing the amount of dust kicked up during landing and takeoff, reducing dust interference with nearby surface assets.

MELT offers a solution to the adverse problems caused by lunar regolith using an easily-implemented and time sustainable technology of high power laser sintering. Our payload design entails a laser mounted on a tall tripod with extendable legs for maximum efficiency and a larger target area. To deliver energy to the surface, the high powered beam is collimated and controlled through a periscope to enable solidification of the surrounding regolith. The technology solution proposed by this group will passively mitigate the dust by sintering dust particles into slabs of usable material.

Verification testing will be done in the University of Santa Barbara's Experimental Cosmology lab. The high power laser sintering device will be built and operated in the lab to fuse samples of lunar regolith simulant [20]. Initially, the team will successfully sinter thin lines of regolith together before moving on to larger and larger samples until we successfully reach our goal of 1 m by 1 m by 1 mm slabs. Our testing includes design optimization to determine sizing of specific optical elements for sintering efficiency and validation of thermal management systems to support widespread usage of a laser sintering device on the lunar surface. Measurements will be made on the efficiency and accuracy of our laser with increasing amounts of simulant. Theory for our experimentation tells us that if our experimentation proves effective in Earth-based verification, it will work better in the vacuum of space.

The proposition of MELT has tremendous implications for reducing lunar regolith accumulation on the exterior surfaces and in the local environment. Incorporating laser sintering technology would glassify the surface providing dust free zones for landers, surface subsystems, and roads. Implementation of this lunar surface modification promotes travel and vehicular exploration while reducing contamination or degradation of surface assets from lunar dust particulate. This increases amounts of research able to be completed on the lunar surface, furthering goals of Project Artemis and future NASA programs.

## 3. Problem Statement and Background

Our group utilizes laser sintering technology to mitigate exterior lunar dust from interference with surface assets (and additionally could create solid landing pads) for supporting long term human presence on the moon [7]. During the Apollo missions, astronauts learned about the dangers associated with lunar regolith. The fine powdery dust is electrostatically charged, due to the influx of cosmic rays through the moon's exosphere, which makes it stick and coalesce onto electronic equipment and spacesuits. Without significant weathering and erosion on the moon, the fine particles of lunar dust remain as sharp, abrasive shards. This causes many health-related risks for astronauts, damaging visors and other optical devices necessary for a human colony to survive on the lunar surface. With these challenges in mind, our group aims to actively mitigate the fine electrostatically charged dust particles by sintering them into a cohesive surface both to limit the number of dust particles in a habitation zone and build foundations for habitation systems, roads, and landing pads.

There are two approaches to lunar dust mitigation: active and passive [1]. Active technology utilizes external forces to mitigate dust, whereas passive methods generally refer to the selection and treatment materials to discourage dust from adhering to the surface. Much research has gone into active strategies, varying from fluidal, mechanical, and electrostatic/electrodynamic methods [22].

One method of passively mitigating lunar dust, for example, is through specially-made dust repellent coating developed using nano-phase silica, titania, and other oxides designed to work in a vacuum environment under a large array of temperatures. These coatings are made with dielectric properties for strong repulsion of charged particles that develop on target surfaces.

In contrast, an active electrostatic/electrodynamic dust removal technique optimal for protecting solar cells and optical devices is called the Electrostatic Lunar Dust Collector (ELDC). With this technique, parallel plate capacitors are lined on the device to be protected such that the charged moon dust is redirected by Coulomb forces away from said device. Another notable technology is the Electrodynamic Dust Shield (EDS) which utilizes embedded conducting electrodes to shift dust particles away from the surface. Other examples of active technologies include mechanical brushes and incompressible fluid jet sprays.

This group is approaching dust mitigation by examining the use of lasers instead of the other techniques stated. Literature exists on utilizing selective laser sintering [23], microwave, and solar sintering to concentrate electromagnetic waves and transform the powdery regolith into a cohesive surface [10]. Solar sintering takes the longest to fully sinter regolith and uses solar reflectors to direct and concentrate sunlight on the target area [16]. Sintering via microwave radiation is faster than solar melting due to the higher energy per photon of microwaves. Some models place microwave sintering technology on the underside of rovers so as the rover moves along its path it creates a road for future human and rover use [9]. The process requires the rover to be stopped while sintering for maximum efficiency similar to commercial microwaves here on Earth. There are also stationary techniques for microwave sintering similar in function to that of the rover technique but utilizes a fixed device to sinter regolith in the surrounding area.

The combination of laser sintering with other sintering techniques will give us the desired results of lunar surface modification in the local environment. For example, the use of microwave sintering technology could be employed to create a centralized patch of sintered regolith then followed by laser sintering the surrounding exterior regions would enable creation of a dust free zone. If laser sintering were the only immediate sintering technique available, our lasing technology could be scaled for incorporation in the design of early landers to sinter their surroundings. This would establish dust free zones that human habitations and surface assets could occupy while humans established their presence on the lunar surface. It is important to account for the conditions of the environment and the resulting effect that it will have on our sintered regolith. Based on our research, the subzero temperatures of the moon will aid in the structural strength of the sintered regolith.

Furthermore, previous testing in the UCSB Experimental Cosmology lab has been completed to show this concept's feasibility on a small scale. Using a 40W carbon dioxide laser at 50% efficiency, the group was able to sinter 1 mm wide lines of simulated regolith in a laboratory setting. This experimental work is the proof of concept that our group will be able to sinter slabs of lunar regolith using a high power laser.

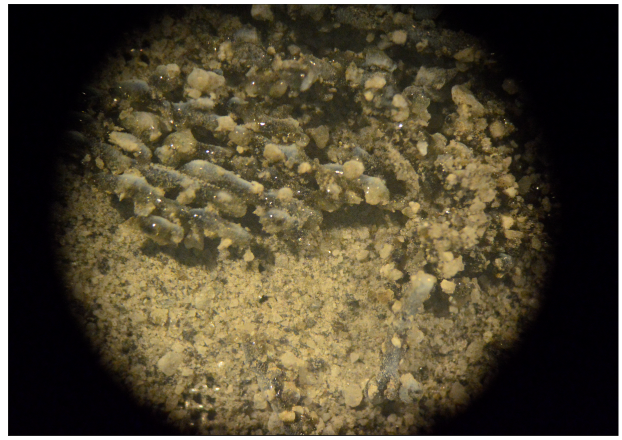


*Photo courtesy of Dr. Philip Lubin*

Future research would preferably utilize multiple techniques for dust mitigation. Having solar sintering devices placed in a target area coupled with our group's design would allow for more regolith to be sintered while using less power [26]. Optimally, electrostatic mitigation should be used for protecting electronics, optics, and solar panels on our devices, as well as telescopes and other systems. Dust repellent coating and foils will also be used to cover sensitive technology on microwave sintering rovers, lasers, and solar deflectors.

## 4. Project Description

4.1 Proposed Technology and Importance

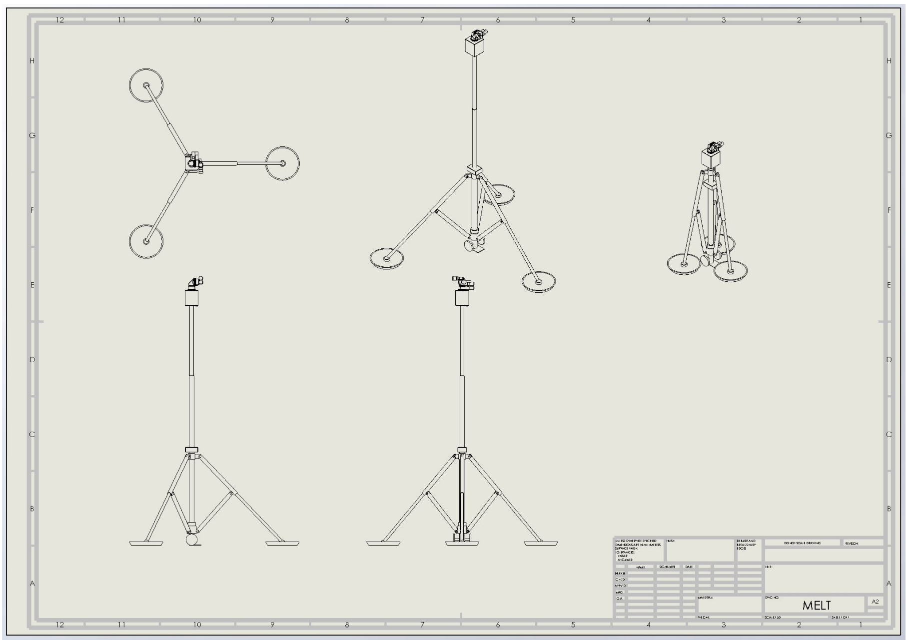
Many technologies propose active or passive mitigation mechanisms, such as electrostatic surfaces or dust-resistant coatings, designed to resist the harsh conditions of the lunar environment [1]. Although other previous technologies have their own merits, they perpetuate the harsh environment on the Moon. For example, electrostatics, as well as dust repellent coatings, displace the dust into surrounding areas which causes more localized dust. The localized dust can then be kicked up by rovers and astronauts which then shorts electronics and causes health problems. Laser sintering of lunar regolith intends to tackle this problem at its source, proactively transforming the environment into a more suitable area. We envision a near dust-free zone, where the lunar environment will be a safer and easier place to work in, utilizing the inconvenient dust and converting it into a positive resource.

Thoughts for the design of a laser sintering device initially took the form of a rover fashioned with a laser, which allowed for a vast surface to be covered and enabled device mobility. The rover would strategically work its way around a designated area, sintering the regolith as it traverses across the surface. However, after further discussion, it was decided that the rover portion of the project would significantly complicate the process. While device mobility is significantly increased, the movement of the rover would agitate the lunar regolith, exciting the loose particulate into the air and on the already solidified regolith. The lifetime of our design would be reduced significantly in traversing the local surface area; excessive movement through loose regolith would contaminate the rovers' mechanical joints and electronics limiting extensive implementation of lunar surface modification. Additionally, the rover's powertrain would require more energy usage to enable functionality of the laser sintering device. Energy is a vital resource that will be sparse in this inhospitable environment; it will already be in high demand for this sintering mitigation technique to be widespread and ultimately effective for comprehensive exterior dust prevention. These concerns led the team to pursue a static solution that would not require excessive energy for mobility purposes, as well as require significantly less complexity in the form of sensors and electronics for device functionality.

The static design, MELT, is a tall telescoping tripod supporting a laser diode and optical beam system at the top. MELT can be designed to function either autonomously or non-autonomously, depending on how it is chosen to be utilized during lunar exploration. The length of the three tripod legs are adjustable, independent of one another so that they can provide robust stability on uneven surfaces. The extensibility of the legs allow for the height of the tower to be adjustable, and autonomously, adjustments are made with linear actuators [13,19] to enable laser operation at more elevated heights. Using Fresnel's equations, we predict that energy transmission from the laser to the regolith will be highly efficient below an angle of 65 degrees, but for angles larger than 65 degrees the energy transmission sharply falls off. This relation causes the height of the output beam to constrain the radial area of regolith MELT is able to sinter, making its tall, extendable

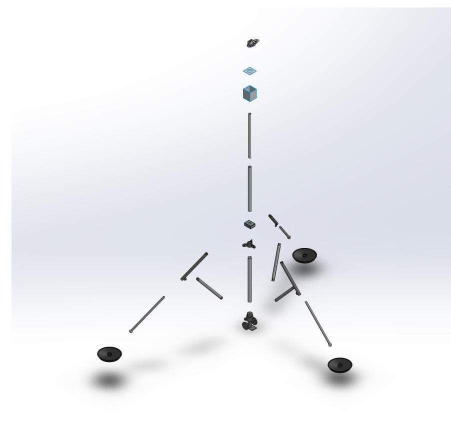
Above: *MELT in its fully extended form* design vital for more widespread usage. We will verify our calculations experimentally to optimize the effective radius desired for sintering.

The group plans to develop regolith-sintering into a more refined process with a major goal being to increase its efficiency and understand the tensile strength of regolith as a function of its depth so excessive energy is not wasted while sintering localized areas. Optimizing both efficiency and energy usage in the laboratory setting will enable its operation in lunar environments, providing a promising solution to the lunar dust problem with in-situ resource utilization. Testing the feasibility of this technology is quite important because if widespread implementation of regolith sintering is possible, it could significantly resolve the dust problem for the exterior regions of the local lunar surface.




Left: *Multiple views of MELT design concept along with its collapsed form*

Below: *Exploded view*



4.2 Adherence to Planned Lunar Architecture

In order to establish key infrastructure for sustained habitation in the lunar environment, humans must be able to successfully mitigate the lunar dust problem. By using this passive dust mitigation technology, the regolith on the lunar surface would be fused together into larger pieces until extensive areas of the surface would become vitrified. While no single technology can solve this lunar dust problem, regolith sintering would significantly decrease the presence of dust in the local environment so that it is manageable by active mitigation techniques. In solidifying the top portion of the surface, large regions of the lunar surface would become dust free zones, significantly reducing the need for active mitigation techniques for lunar surface assets, rovers, and landers necessary for prolonged lunar habitation.

If our technology were to be implemented in the Artemis missions, it would have significant impacts for the development of a sustainable Artemis base camp. In order to establish a lasting, long term presence at the lunar south pole, the lunar dust in the local base camp environment must be manageable. While comprehensive active mitigation techniques will be vital to this process and necessary for the initial establishment of a lunar outpost, extensive passive mitigation to create dust free zones will better enable sustained durability for activities in the local environment.

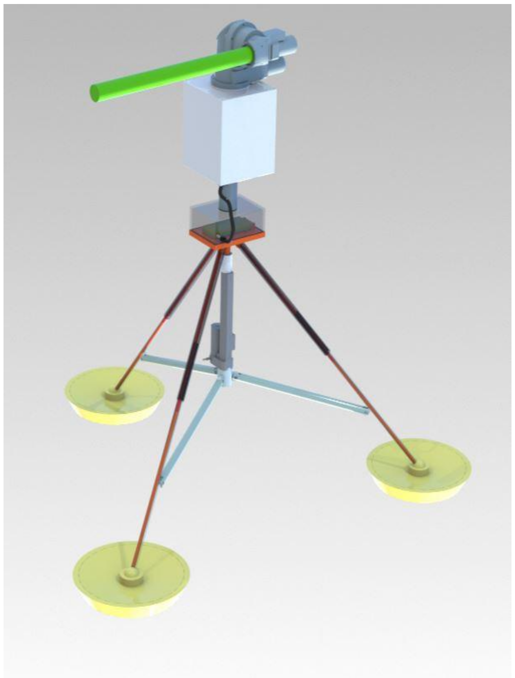
In early robotic missions [17], MELT could be deployed autonomously by a lander or rover to begin preparing for the arrival of necessary large cargo elements to later support human habitation. If provided enough energy and time, MELT could establish large sintered regions of surface upon which landers could continually dock upon. This solidified surface modification would enable them to unload their cargo without excessive dust being cast into the surrounding environment. Furthermore, it would limit the surface interactions and buildup of dust particulate with the cargo while it's waiting to be utilized by astronauts in coming missions. Continual sintering in the local region could expand this dust-free zone to large regions capable of supporting additional habitations, lander pads, and roads for mobility platforms such as the LTV. In terms of design scalability, MELT's lasing system and optic technology could be modified for mounting upon tall lunar landers or could be transported by a mobility platform for widespread surface modification if provided enough energy for sintering processes.

If the implementation were non-autonomous or after Artemis III, MELT still would be a valuable resource for sustaining lunar surface presence. For the prolonged survival of the Artemis Base Camp, robust solutions will be needed to keep the dust from compromising mission [8] longevity in the unwelcoming environment. Sintering technology enables the creation of a dust free workspace, solidifying vast areas of surface regolith to handle mechanical impacts and motions without kicking up exorbitant amounts of the abrasive dust. During base camp development, this amenadity to the lunar surface would significantly reduce dust in the local environment and surrounding air, being extremely beneficial to all subsystems supporting habitations. The massive reductions in dust particulate levels through surface modification will inherently reduce the amount of dust sticking to space suits of astronauts and contamination of in-cabin spaces. Lunar surface sections could be sintered before the expansion of habitation systems, ensuring minimal dust build up upon the new components and subsystems. MELT could also significantly impact the performance of mobility platforms; these entities could travel on roads or large regions of solidified lunar surface. Consequently, the sintered dust would not be able accumulate as rapidly upon all of their mechanical parts and joints, significantly increasing their lifetime and performance. Also, dust particulates will not be expelled into the air during the operation of these platforms, minimizing clouding and contamination of surface assets. This directed energy approach could be a pivotal solution that mitigates dust from most of the local environment, making extensive lunar exploration and habitation seem much more feasible.

### 4.3 Adherence to the Design Constraints and Guidelines

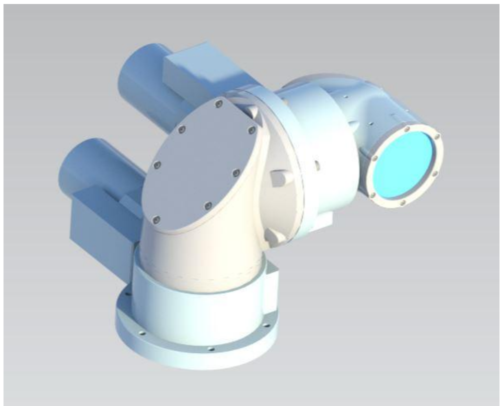
To adhere to outlined design constraints, MELT design has been carefully optimized for usage in the extreme lunar environment. As stated earlier, our design consists of a compact telescoping tripod, equipped with a laser, thermal supports, and an optical system. The optimal height of our design is roughly three meters tall (due to angle constraints of beam energy emission efficiency) to allow for an efficient radial sintering area of approximately six meters around the tripod legs. For ease of transportation, the payload's telescoping legs enable MELT to condense to a much smaller size—less than half of its operational length. If wanted for autonomous implementation, linear actuator(s) will be responsible for this extension after deployment on the lunar surface.

For early widespread use, MELT could be placed in a cart or have protractible wheels for rovers or other mobility platforms to reposition the device. Large, circular feet will support the tripod legs on the uneven lunar surface, ensuring MELT the structural stability to support the laser optics system for proper beam control. The 200 W laser diode will be situated atop the legs, enclosed in a thermal chassis to support the removal of waste heat [11]. With an energy efficiency of 50%, the 100 W thermal load will be routed away from the laser diode with heat pipes [3,12] connected to the chassis, dissipating waste heat to a high emissivity heat sink with a large surface area. If necessary, the team will utilize flexible heat pipes provided by the Boyd Corporation [6] to keep the design of MELT extremely compact for payload transportation. This would enable the heat pipes to pass through the interior section of the extendable tripod legs, and foot pads would double as radiators. Wrapping the foot pads with a high emissivity material like foil would improve radiation heat transfer to the environment as well as prevent dust from contaminating mechanical joints. Additionally, shutters could be fashioned around the laser compartment and electronics box improving radiation transfer to the environment during lunar day operation to prevent overheating if the thermal management plan is deemed not sufficient enough for continual sintering during relevant environmental testing.



Above: *Thermal design of MELT*

Resting directly above the thermal compartment holding the laser is a warm electronics box insulating vital electronic components and the optical system [18] required for beam control and direction. A fiber optic cable is connected between the laser and a fiber port, pumping the beam into the optical assembly. After leaving the fiber, the beam is collimated to a specific width to enable efficient sintering of the lunar environment. Beam width after collimation does not affect the overall efficiency of the sintering process, so the actual spot size of the design will be determined via laboratory testing. The collimated beam will be directed out of the top of the electronics box, entering a periscope with two motorized mirrors that will enable omni-directional beam control of the laser. The beam leaves the periscope through an optical window, allowing the directed energy from the laser to modify the physical state of the regolith particulate upon the lunar surface. All electronic components, motors, and external wiring will be space rated and protected by tubing or housing units to provide insulation from harsh environmental temperatures and abrasive lunar dust. Additionally, flexible thin film kapton heaters would be mounted to the insulated electronics boxes or placed upon specific electronic components. While minimal heat would escape from the insulated box, this ensures the fundamental components for device operation will remain at or above their operational temperatures to survive the extreme temperature gradient of the lunar environment.



Above: *Closeup view of the periscope*

MELT's design enables it to be tolerant of the lunar night if provided additional power or equipped with extra batteries. In instances where MELT could not be stored inside a habitation or lander during the 14 day period, lunar night survivability would still be possible. The external housing protecting the electronics would be equipped with multiple thin layers of mylar to limit radiation heat loss to the surrounding environment. Vital electronics would still be functional in a low power mode, enabling the device to utilize its heaters and warm the small insulated areas before temperatures dropped below operational levels of components. Fine element analysis will be used to verify the insulation supporting electronic component survivability and optimize the thermal architecture of the design for the relevant lunar environment.

Through regolith vitrification, MELT will be able to successfully manage and mitigate all sizes of abrasive dust particles. Smaller dust fragments (in the micron range) resting atop the lunar surface will be conjoined during this mitigation process, melted together with the adjacent particulate. This systematic solidification of lunar surface regions will create a thin surface layer where no clouds of dust particles can be discharged in the surrounding air or environment. MELT's approach to lunar surface modification is nontoxic, employing continuous beamed energy transfer to a small spot of regolith at a time. The spot of dust will increase in temperature until it begins to change phase due to the energy flux of the laser; flammability also is not an issue since the surrounding regolith and the device's fabricated components are non flammable. While the sintering process could release fumes into the environment, this will occur outside of the habitation and will not pose immediate risks to lunar astronauts or surface assets.

However, a laser this powerful could pose significant danger to astronauts if the beam comes into contact with a human. In order to promote safety during operation of MELT, the finalized device will be equipped with a motion sensor. This sensor is intended to detect the presence of motion in the area and will subsequently shut the laser off and end the sintering process. This will therefore ensure no human is close enough to the laser to be in danger of injury.

MELT's mechanical design will be relatively low mass and cost effective. The tripod legs and electronic housings will be made of cheap, lightweight 6061 Aluminum alloy. Mylar insulation will be used to protect heat loss of electrical components so minimal power can be allotted to heating and electronics survival. Minimal electronic and optical components are needed for functionality of the design; these integral elements have low mass and are of relative affordability. The most expensive physical components of our device will be the laser and its thermal chassis to ensure its temperature remains in an operational range. A more specific breakdown of the pricing of these components can be seen below in our team's budget. Furthermore, our concept may prove to be very cost effective for lunar exploration and human developments if implementation of widespread usage is possible. This technology greatly reduces the overall dust in the environment, hence minimizing the need for other costly dust mitigation strategies and practices. Additionally the operational lifetime of surface assets and mobility platforms functioning in the solidified local regions will significantly help improve overall mission expenditures. The largest expense of MELT's technology will be the immense power supply needed to successfully sinter large portions of the lunar surface.

The power requirements for sintering is the only adverse constraint we find with our technology, potentially limiting MELT's widespread adoption of dust mitigation in lunar exploration. The team did its initial calculations analyzing the energy requirements to sinter low titanium mare regolith [20], which is most commonly found in the lunar south pole. To sinter a general surface area of one square meter with a depth of one centimeter, our calculations have shown roughly 3 kW of continuous power would need to be provided to sinter this area in an hour. On a larger scale, this sintering process is also feasible. In order to sinter an area of 25 meters by 10 meters with a thickness of 2 centimeters in the lunar day period (14 days), around 43 kW of continuous power would need to be provided. In order to achieve a continuous power draw of 12.5 kW, it would take 48 days to complete the sintering of this area.

**Energy needed to sinter from specific heat:**

$$C_p = \sum_i \chi_i c_{f,i} + T \sum_i \chi_i c_{g,i} + T^{-2} \sum_i \chi_i c_{h,i}, \quad (1)$$

$$Q_1 = mC_p\Delta T = m\int_{260K}^{1500K} C_p\,dT \quad (2)$$

$$\frac{Q_1}{m} = \int_{260K}^{1500K} C_p\,dT \quad (3)$$

$$\frac{Q_1}{m} = \int_{260K}^{1500K} 9.093x10^2 + 2.87x10^{-1}T - 2.46x10^7T^{-2}\,dT = 1,440.71\frac{kJ}{kg} \quad (4)$$

**Energy needed to sinter from latent heat:**

$$\frac{Q_2}{m} = L = 457.7\frac{kJ}{kg} \quad (5)$$

**Total energy needed to sinter regolith:**

$$\frac{Q}{m} = \frac{Q_1}{m} + \frac{Q_2}{m} = 1,898.41\frac{kJ}{kg} \quad (6)$$

Still, these numbers seem to be a sizable request and do not optimally adhere to the desired constraint of a low power technology. If a solar array were to be installed for the implementation of our device, this could greatly offset the power consumption requirements from alternative energy sources provided by NASA (such as batteries or generators). Further advancements in solar technology in the near future may significantly lower costs, enabling a photovoltaic array to be a potential cost effective solution for the entirety of MELT's power generation. Additionally, further laboratory research would enable our team to optimize energy efficiency of the systematic melting process. Tensile strengths of sintered regolith would be analyzed to help determine the required thickness of the solid regolith surface, which is dependent on its application in the relevant environment. Sintering lunar surface regions not utilized for supporting surface assets, landers, or mobility platforms may still be a useful technique for dust mitigation in the local surrounding area [28]. If a considerably smaller surface depth were required, a much larger surface area encompassing the lunar base could be solidified with the same amount of power supplied to our device.

Furthermore, the concept will also be modified with solar arrays to help augment the power consumption required for laser sintering. These solar arrays will need to be treated to withstand the harsh lunar environment and will need to be further tested to ensure proper deployment and expansion. Backup electronic components will also need to be added to the electronics box to ensure that a technical failure will not cause overall failure of the laser tripod system. While this will add some extra mass, it will ensure the tripod system can maintain functionality even with failed electronics.

## 4.4 Proposed Verification on Earth

The overall goal of the project will be to demonstrate a prototype of the tripod mounted laser system to sinter a large area of regolith in a lunar environment. The laser sintering technology that MELT employs is currently at a TRL of 3 [27]. Previously, regolith has been successfully sintered in basic experimental testing of concept feasibility in our on campus laboratory. To increase TRL levels of our design, there are two major areas in which testing must be conducted. The first is testing the properties of sintered regolith to better understand them and optimize sintering techniques. The second is the testing and verification of our prototype hardware. This will allow us to achieve a TRL of 4 or higher with our hardware systems.

Due to the high cost and rarity of large vacuum chambers, this testing will be conducted in earth standard atmospheric (1 atm) and temperature conditions (~24℃) in a lab setting. We will perform testing on component subsystems in order to confirm viability in the lunar environment, we will attempt to simulate a realistic environment which complies as closely as possible to the NASA DSNE design specifications [21]. The two most important factors in this will be simulating the thermal and vacuum environment of the lunar surface. Vacuum conditions will be replicated using a small scale vacuum chamber available to the lab. Temperature conditions will be replicated using liquid nitrogen to simulate the lowest temperatures at the lower limit of what could be encountered on the moon. In addition, regolith simulants will be used on mock-ups of external components to test their resistance to abrasion.

Because actual regolith samples are extremely valuable, we will test using a regolith simulant which possesses a similar composition to lunar regolith; the simulant [20] contains mainly aluminum oxide, calcium oxide, and silicon dioxide whereas lunar regolith contains silicon, calcium, and aluminum. The simulant is readily available and relatively cheap, but provides a realistic simulacrum in terms of thermal conductivity and diffusivity, as well as heat capacity which are the most important factors for our testing. The MELT Team acknowledges that regolith simulants do not have the same mineralogy as actual lunar soil. Furthermore, lunar regolith includes nano-phase iron particles that directly affect its magnetic and chemical properties [15]. While regolith simulants are able to mimic much of the lunar regolith composition, most do not include any components of nano-phase iron. In order to increase the TRL of the sintering process, testing using actual lunar regolith or nanophase iron-treated simulant is necessary. Some of the methods currently being used for nano-phase iron treatment include the use of porous silica gel powders permeated with ferric nitrate. Another technique utilizes the method of combining mixed-metal oxides with other metals in order to produce nano-phase iron. This would offer insight into how the nano-phase iron particulate impacts the sintering process; design modifications may need to be made in order to accommodate for any new findings when sintering actual lunar regolith [25].

The team will sinter small samples of regolith simulant using our 200W laser on the lab bench in order to test its sintering capabilities. The goal of this testing program will be to determine the time taken to sinter a unit area for a given depth. We will determine how the angle of the laser to the surface, as well as the temperature of the surface itself affect sintering in order to optimize and ensure the viability of our sintering techniques. In order to test the physical properties of large areas of sintered regolith the team's laser cutter could be used to create large uniform patches of sintered regolith simulant. This technique using a laser cutter has been demonstrated on similar compounds by hobbyists [14] and seems promising for our application. We will test the strength of this sintered surface in the lab to determine its ability to support weight and calculate how that translates to the lunar gravity environment. We will also test its ability to mitigate dust from wheeled vehicles by performing tests using the lab's small scale rover chassis. We will compare the amount of dust thrown up by the rover's passage through unsintered regolith to its passage over sintered regolith.

Our next priority will be the testing and verification of our hardware component subsystems. We will examine both the functionality and the ability to function in a simulated lunar environment. First we will test the lasers optical system in our lab to ensure proper collimation and focus of the beam on the regolith surface. Next, accuracy testing of the beam aiming optics will take place through the periscope assembly using a low powered laser to illuminate targets of known position in a lab setting. The basic operational plan entails MELT's computer software or microcontroller to establish a local coordinate grid around the fixed position of the tripod. This grid enables our device to execute a program with proper beam control to systematically sinter the radial surroundings of the tripod. Finally the control electronics will be assembled and tested, first on a breadboard, then on a custom designed PCB. Both the optical and electronic components will then be subjected to lunar temperature and vacuum conditions in order to test them in a realistic environment. Once the design is deployed in a relevant environment, these components will be further protected by the insulation of the warm electronics box.

Because of the large size of the tripod we won't be able to test the deployment and heat management systems integrated into it in a simulated lunar environment. Stress testing will be performed to ensure the moving parts are sufficiently robust to survive the stresses placed upon them. The team will also test the thermal dissipation systems to ensure that they are sufficient to allow for continuous operation of the 200W laser. As this testing will take place in an atmosphere we will need to account for the role that convective heat transfer plays in order to factor it out during testing. To accomplish this we will subject the system to higher than expected thermal loads as well as monitoring the purely radiative components of heat transfer in the system using an infrared camera. This will be supplemented by computer simulations. This should allow us to verify the performance of the tripod systems despite being unable to put it in a simulated lunar environment.

Finally all of the subsystems will be assembled and tested together for final verification. Each subsystem will be tested individually after final assembly to ensure overall functionality. The prototype's abilities will then be tested, first on a small patch of regolith simulant then on a much larger area. We will then repeat our earlier testing of the sintered regolith samples in order to verify it has the desired properties and dust mitigation capabilities. This will allow us to demonstrate our concept fully in a terrestrial environment.

In the event that our access to the lab is limited due to external factors, our testing will need to be much more limited. Because we cannot use high energy lasers outside the lab, it will be much more difficult to test the sintering of regolith and create samples of sintered regolith. In addition, environment testing outside the context of the lab will need to be much more limited, possibly testing only the electronics and laser components after they have been fully assembled. However, assembly of the prototype components would be able to proceed at only a slightly reduced pace working outside the lab. In addition more in depth simulations could be substituted for some of the testing. This should allow us to proceed with meeting many if not all of our objectives, albeit with somewhat reduced testing.

### 4.5 Path To Flight

In order to ensure this concept is operational for use on the lunar surface by 2026, significant testing and modifications will need to be made. While environmental testing is planned, this concept will still need modifications in order to withstand the lunar conditions. Additional more rigorous environment testing will need to be conducted in higher fidelity simulated environments. Radiation can potentially degrade electronic components [24], so radiation hardened components may need to be considered as replacements for electronics used in the terrestrial prototype. Vibrational testing will be conducted to ensure the design is robust enough to withstand a launch on the selected launch vehicle.

Mechanically, the device will also be configured to meet the payload requirements of the CLPS lander being used for the mission. The tripod system will need to be fitted with a proper attachment and deployment system for the specific CLPS lander in order to ensure safe transport. Also, the device will need to be finalized with either autonomous or non-autonomous deployment; this is dependent on the current infrastructure currently existing on the lunar surface. Human return to the lunar surface will take place in 2024 [2]; by 2026 (when implementation of this concept is most likely to take place) it will be possible to use both the autonomous and non-autonomous methods of deployment.

If the laser tripod system is non-autonomously deployed, astronauts will need to be trained in how to properly deploy and place the laser tripod systems. This is critical as increasing the number of laser tripod sintering systems will increase the total area that can be sintered. However, if these are not placed at an optimal distance apart, then two lasers may sinter the same areas, which is inefficient. Proper care and training need to be taken then to ensure the systems are deployed correctly and spaced on the lunar surface adequately.

Software will also need to be developed for implementation on the lunar surface. For autonomous deployment, systems will be improved for smooth and steady operation even over uneven terrain. Furthermore, programming will still allow laser sintering to occur even if the legs cannot fully extend due to environmental factors. The operating process will provide an option for the laser to be "shut-off" - this is vital for powering down the laser when not in use or if the tripod system tips over on the lunar surface. This is intended as a safeguard for transit and to ensure the laser does not fire randomly if the tripod tips over, preventing the possibility of damage to other tripod systems or surface assets. Beam control will be regulated by a motion sensor to ensure laser operations switch off when human or vehicle motions are detected in the sintering region. This implementation ensures the laser does not pose dangers to any humans and mobility devices on the moon.

## 5. Capabilities Statement

5.1 Team Capabilities

Anna Pedersen, Chris Crews-Holloway, Sean Chu, Nathan Jordan, and Ian Burke have all conducted previous research on a directed energy lunar rover concept to explore permanently shadowed regions on the lunar poles. Furthermore, they have also researched methods to ensure onboard electronics can survive the lunar night. Chris and Sean have previous experience with mechanical design and integration. They have designed a CAD model for the lunar rover concept and have proposed various models used to protect electronics from harsh lunar temperatures. Dylan Vu has further experience in CAD modeling, as does Chris Ewasiuk. Chris Ewasiuk also has experience with materials testing and optical integration. Furthermore, as part of the lunar rover project, Chris Crews-Holloway has previous work with optical systems, as well as thermal management and electrical integration of design components. Jason Barrios has experience working with robotics and electrical integration, as well as with optical equipment in a laboratory setting. Jason Allen and Rickey Kenneybrew have previously worked with Blender and Maya animation software and have utilized these skills to provide concept videos, animations, and images.

5.2 Advisor Capabilities

Dr. Philip Lubin has extensive experience working with directed energy power systems, especially high-flux lasers. He has overseen numerous laser beaming experiments in the laboratory setting to prove that optical laser systems are a feasible option for delivering heat and power. As head of the UCSB Experimental Cosmology Lab, he has helped design experiments to beam power over the lunar surface and to the lunar surface from Earth. Furthermore, Dr. Lubin oversees projects including DESTAR, a directed energy program designed to use laser power to eliminate asteroids or other space debris to keep it from impacting earth. He also is currently researching methods to survive and sustain electronics during the lunar night.

Dr. van der Veen is part of the UCSB Experimental Cosmology Lab and has conducted research on spectroscopy of lunar regolith samples. Furthermore, she has conducted research on the Search for Extra-Terrestrial Intelligence (SETI). She also teaches courses on astronomy, especially on lunar exploration and colonization, at Santa Barbara City College (SBCC). Dr. van der Veen has also conducted research in physics education and has published numerous papers about linking mathematical and physical properties to real-world situations.

Alexander (Sasha) Cohen graduated from UCSB in 2019 with a B.S. in Physics. He currently is a Junior Specialist in the UCSB Experimental Cosmology lab and specializes in optics. He has extensive experience in CAD and FEA modeling and has designed several optical systems for laboratory use. Additionally, he has published extensive research on optical systems and phased laser arrays.

Bryan Phillips received his B.S. degree in Physics from UCSB and now is a Jr. Specialist in the UCSB Experimental Cosmology lab. He is experienced in mechanical and electrical integration and has experience in CAD design as well as optical integration. Furthermore, he has helped to design and craft an optical bench used for laser testing in the laboratory and has fabricated numerous parts for laboratory experiments and testing.

The team is also grateful for the expertise from Mr. Rajat Sewal and Dr. Lars Borg, both from Lawrence Livermore National Laboratory. Mr. Rajat Sewal is a Design Engineer; he specializes in radar and image system architecture in FPGAs. Furthermore, his work also encompasses space mission analysis and design and laser systems design. He has a background in Physics and is highly familiar with electronics and processing. He has helped the team consider how electronic elements will behave in different lunar conditions. Dr. Lars Borg received his Ph.D in Isotope Geochemistry and currently researches geochemistry and geochronology of Martian, lunar, and asteroid samples. Furthermore, he has conversed with Harrison (Jack) Schmidt (Apollo 17) and can provide the team a unique perspective on the problems of lunar dust. Dr. Borg also has advised the team on the geochemical properties of regolith and how this may impact sintering capabilities. Furthermore, he is serving on several NASA committees, including the Curation and Analysis Planning Team for Extraterrestrial Materials (CAPTEM) and the Mars Exploration Program and Analysis Group (MEPAG).

5.3 Facilities Capabilities

The UCSB Experimental Cosmology lab has a designated space for laser testing and has designed an optical bench as well. This area will provide a space large enough for a stationary laser to sinter lunar regolith simulant placed on a metal sheet. The lab owns several lasers of different powers; these can be used to test the sintering process. Furthermore, device fabrication can be completed using the laser cutter and the 3D printers as part of the lab. Other components of the device can be fabricated using the Physics Machine Shop, which includes mills, lathes, and CNC machines. Relevant structural testing on the sintered regolith can be performed in the UCSB Materials Research Laboratory; this will allow us to determine the maximum compressive stress the sintered regolith can withstand. The lab's Pololu chassis and Husarion rover can also be used to test the yield strength of the sintered regolith simulant samples.

## 6. Concept Timeline

| Month | Key Dates and Deliverables |
|---|---|
| January | ● Make final modifications to the optical periscope and finalize optical components used on the periscope. |
| February | ● Design of a sample sintering environment will be made and constructed in the laboratory. |
| March | ● Conduct terrestrial testing using the 200W laser to determine proof of concept feasibility. A comparison of highland and maria regolith will be made as well. |
| April | ● Complete mid-project report and report on any anomalies. |
| May | ● Following terrestrial testing, necessary modifications will be made to the optics and mechanical design. Modifications will be added to the CAD design and a finalized version will be created. |
| June | ● Fabrication of optical periscope and tripod system will be completed.<br>● System will be assembled and any necessary modifications to ensure accuracy following machining. |
| July | ● Preliminary laser sintering will be conducted in a terrestrial setting using the laser tripod system and a 200W laser. Numerous sintered regolith samples will be taken using both highland and maria regolith. |
| August | ● Conduct material and structural testing at UCSB Mechanical Test Lab on the sintered regolith from terrestrial testing on the laser tripod system. |
| September | ● Conduct no atmosphere, low-gravity, variable temperature environmental testing with the laser tripod system utilizing both highland and maria regolith.<br>● Evaluate structural/material properties of sintered regolith and compare to terrestrial sintered regolith simulant to determine commonalities and differences. |
| October | ● Finalize concept design with necessary changes obtained from environmental testing. Finish relevant technical paper and poster for BIG Ideas conference.<br>● Prepare technical demonstration and video it as proof of concept demonstration. |
| November | ● Finalize details on the technical paper and prepare presentation.<br>● Attend BIG Ideas conference. |

**7. Concept Budget**

| | | | | Phase 1 | Phase 2 |
|---|---|---|---|---|---|
| Domestic Travel | | | | | |
| | | Travelers | Days | | |
| | Registration | 5 | 4 | | $2,500 |
| | Lodging | 5 | 4 | | $2,240 |
| | Transportation | 5 | 4 | | $200 |
| | Food Stipends | 5 | 4 | | $1240 |
| Materials and Supplies | | | | | |
| | Metal Sheet | | | $100 | |
| | Aluminum 6061 | | | $400 | |
| | High Emissivity Foil | | | $200 | |
| | Fasteners | | | $400 | |
| | Mylar Insulation | | | $200 | |
| | Computer | | | $500 | |
| | Linear Actuators | | | $600 | |
| | Battery | | | $500 | |
| | Thermal Sensors/PRT | | | $250 | |
| | Kapton Thin-Film Heaters | | | $100 | |
| | Thermal Chassis | | | $10,000 | |
| | Fiber Holder/Port | | | $600 | |
| | Lens Tube | | | $300 | |
| | Collimating and Focus Lens | | | $200 | |
| | Mirrors | | | $400 | |

| | | | | | |
|---|---|---|---|---|---|
| | **Periscope Chassis** | | | **$300** | |
| | **Optical Window** | | | **$200** | |
| | **Motion Sensor** | | | **$700** | |
| | **Fiber Optic Cable** | | | **$100** | |
| | **Nano-Phase Iron** | | | **$1,000** | |
| | **Miscellaneous/Unforseen Costs** | | | **$1,000** | |
| | **Parts for Design Modifications** | | | | **$800** |
| **Environmental Testing** | | | | | **$10,000** |
| **Materials Testing** | | | | | **$1,000** |
| **Construction** | | | | | |
| | **Fabrication (Machining)** | | | **$2,000** | |
| | **CAD Fabrication** | | | **$1,000** | |
| | **Fabrication (Design Modifications)** | | | | **$1,000** |
| **Stipends** | | | | **$9000** | **$16000** |
| **TOTAL DIRECT COSTS** | | | | **$30,050** | **$34,980** |
| **TOTAL INDIRECT COSTS** | **55.5% of Modified Total Direct Costs** | | | **$16,677.75** | **$19,414** |
| **TOTAL PHASE COST** | | | | **$46,728** | **$54,394** |
| | | | | | |
| **TOTAL COST** | **$101,122** | | | | |

**8. References**

[1] Afshar-Mohajer, N., Wu, C., Curtis, J., & Gaier, J. (2015). Review of Dust Transport and Mitigation Technologies in Lunar and Martian Atmospheres. *Advances in Space Research, 56*(6), 1222-1241, https://doi.org/10.1016/j.asr.2015.06.007

[2] Artemis: Humanity's Return to the Moon. (n.d.). Retrieved December 4, 2020, from https://www.nasa.gov/specials/artemis/

[3] *ATS Engineering eBook: Collection of Technical Articles on Heat Pipes and Their Roles in the Thermal Management of Electronics*. Advanced Thermal Solutions. https://www.qats.com/cms/wp-content/uploads/Heat-Pipe-Engineering-eBook.pdf

[4] Clark, P.E., Calle, C.I., Curtis, S.A., Keler, J.F., Minetto, F., & Mantovani, J. G. (2007). Electrostatic Dust Control on Planetary Surfaces. AIP Conference Proceedings 880, 400, https://doi.org/10.1063/1.2437479

[5] Fateri, M., Gebhardt, F., & Khosravi, M. (2013) Experimental Investigation of Selective Laser Melting of Lunar Regolith for In-Situ Application. *ASME International Mechanical Engineering Congress and Exposition*, https://doi.org/10.1115/IMECE2013-64334

[6] *Flexible Heat Pipe Assemblies*. (n.d.). Retrieved December 12, 2020, from https://www.boydcorp.com/thermal/two-phase-cooling/flexible-heat-pipe-assemblies.html

[7] Hintze, P. E. (2010). Building A Vertical Take Off and Landing Pad using in situ Materials. *Materials Science Division, NE-L2, NASA Kennedy Space Center*.

[8] Hyatt, M, & Feighery, J. (2008). Lunar Dust Mitigation Technology Development. 1–25.

[9] Imhof, B., Urbina, D., Weiss, P., Sperl, M., Hoheneder, W., Waclavicek, R., Madakashira, H., Salini, J., Govindaraj, S., Gancet, J., Mohamed, M., Gobert, T., Fateri, M., Meurisse, A., Lopez, O., & Preisinger, C. (2017). Robotic Prototypes for the Solar Sintering of Regolith on the Lunar Surface Developed within the Regolight Project. *International Astronautical Congress.* https://www.researchgate.net/publication/321036142_Robotic_prototypes_for_the_solar_sintering_of_regolith_on_the_lunar_surface_developed_within_the_Regolight_project

[10] International Agency Working Group. (2016). Dust Mitigation Gap Assessment Report. pp. 24-34.

[11] Jafari, D., & Wessel, W.. (2018). The Utilization of Selective Laser Melting Technology on Heat Transfer Devices for Thermal Energy Conversion Applications: A Review. *Renewable and Sustainable Energy Reviews, 91*, 420-442, https://doi.org/10.1016/j.rser.2018.03.109

[12] Jouhara H., Chauhan, A., Nannou, T., Almahmoud, S., Delpech, B., & Wrobel, L.C. (2017). Heat pipe based systems - Advances and applications. *Energy, 128*, 729-754, https://doi.org/10.1016/j.energy.2017.04.028

[13] *Linear Actuators 101 - Everything You Need to Know About Linear Actuator*s. (2018, November 16) Retrieved December 12, 2020, from https://www.firgelliauto.com/blogs/news/linear-actuators-101

[14] List, Jenny (2016, December 7). *SINTERING SAND WITH A LASER CUTTER*. Hackaday. https://hackaday.com/2016/12/07/sintering-sand-with-a-laser-cutter

[15] Meurisse, A., Beltzung, J., Kolbe, M., & Cowley, A. (2017) Influence of Mineral Composition on Sintering Lunar Regolith. *Journal of Aerospace Engineering*, *30*(4), https://doi.org/10.1061/(ASCE)AS.1943-5525.0000721

[16] Meurissea, A., Makaya, A., Willsch, C., Sperla, M. (2018). Solar 3D Printing of Lunar Regolith. *Acta Astronautica*. *152*, 800–810. https://doi.org/10.1016/j.actaastro.2018.06.063

[17] *NASA's Plan for Sustained Lunar Exploration and Development*. NASA. https://www.nasa.gov/sites/default/files/atoms/files/a_sustained_lunar_presence_nspc_report4220final.pdf

[18] *Optical Systems*. (n.d.). Retrieved December 13, 2020, from https://www.thorlabs.com/navigation.cfm?guide_id=10

[19] *PA-08*. (2020, August 19). Retrieved December 13, 2020, from https://progressiveactuators.com/products/linear-actuators-pa-08/

[20] *Planetary Simulant Database: LHS-1 Lunar Highlands Simulant*. (2020, March 24). Retrieved December 13, 2020, from https://sciences.ucf.edu/class/simulant_lunarhighlands/

[21] Roberts, Barry C. (2019). Cross-Program Design Specification for Natural Environments (DSNE) Revision G. NASA. https://ntrs.nasa.gov/citations/20200000867

[22] Schreiner, S., Dominguez, J., Sibille, L., & Hoffman, J. (2016). Thermophysical Property Models for Lunar Regolith. *Advances in Space Research*, *57*(5), 1209-1222. https://doi.org/10.1016/j.asr.2015.12.035.

[23] *Sintered Regolith*. Lunarpedia, 10 Apr. 2019, 14:16, lunarpedia.org/w/Sintered_Regolith.

[24] *Space Radiation Effects on Electronic Components in Low-Earth Orbit*. (n.d.). Retrieved December 4, 2020, from https://llis.nasa.gov/lesson/824

[25] Tang, H., Wang, S., & Li, X. (2011). Simulation of Nanophase Iron Production in Lunar Space Weathering. *Planetary and Space Science*, *60*(1), 1-5. https://doi.org/10.1016/j.pss.2011.10.006

[26] Taylor, L., & Meek, T. (2005). Microwave Sintering of Lunar Soil: Properties, Theory, and Practice. *Journal of Aerospace Engineering*, *18*(3), 188–196. https://doi.org/10.1061/(ASCE)0893-1321(2005)18:3(188)

[27] *Technology Readiness Level Definitions*. NASA. https://www.nasa.gov/pdf/458490main_TRL_Definitions.pdf

[28] Vijayan, S., Mohan, S., Murty, S. (2015). Lunar Regolith Thickness Estimation Using Dual Frequency Microwave Brightness Temperature and Influence of Vertical Variation of FeO + TiO2. *Physical Research Laboratory, 105*, 123-132. https://doi.org/10.1016/j.pss.2014.11.017