## University of California San Diego

# Microwave-Sintering Operations Of Nanophase-Iron Pads (MOON Pads)

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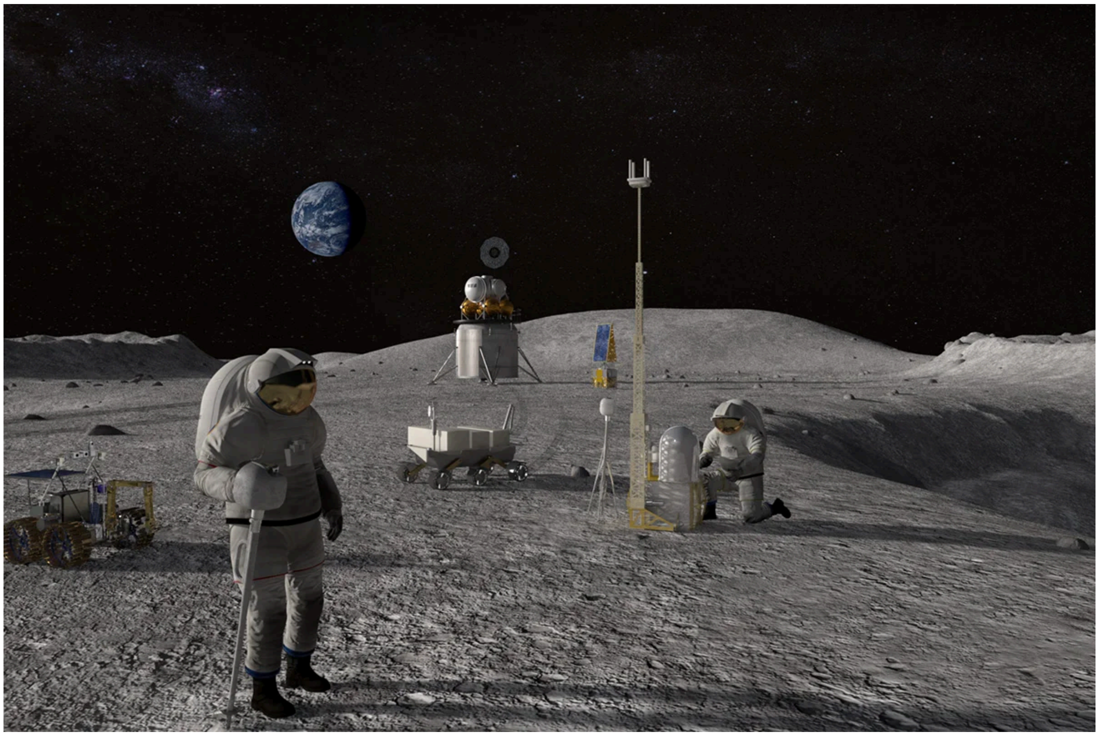

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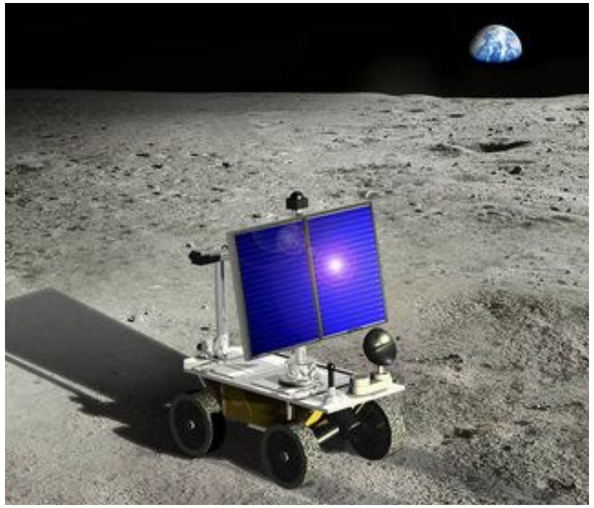
## Major Objectives & Technical Approach

- Objectives
  - Develop a method to help a human lander manage the Plume Surface Interaction (PSI) from the impact of lander
- Technical Approach
  - Uses microwave sintering to create landing pads in before lunar landings from lunar regolith
  - Sintering technology is placed on a rover that can drive around to different landing sites to make a landing pad for future lunar landings



## Key Design Details & Innovations of the Concept

- Design Details
  - The rover is roughly 200 cm x 60 cm x 35 cm in size (L, W, H), weighing approximately 42 kg.
  - Solar Array 1 meter by 2 meters, generating 862W.
- Innovations
  - Microwave Sintering: 800 W Microwave with a titanium box (30 cm x 6 cm x 20 cm integrated onto the back of the rover to sinter the landing pad.
  - Magnetic collector to gather nanophase iron for enrichment of soil.

## Schedule & Costs

- Timeline for deployment
  - Tested with new nanophase-iron based simulant by January of 2025.
  - Rover to be launched by June 2025
  - Sintering process starts July 2025
  - Sintering process completed by September 2026 before the launch of Artemis 3
- Costs
  - The total cost of the construction of the rover is $7.6 million
  - Launching costs of $5.85 million at $130,000 per kilogram

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## 1. Introduction and Technical Background

Lunar exploration is a gateway for human exploration and development of the solar system, due to its location and resources. Departing from the Moon, spacecrafts will have to expend half as much impulse to reach Mars, and significantly increase the payload capacity of missions to mars. In concurrence, NASA has implemented the Artemis program, a series of missions within the next five years designed to establish a permanent base at the Moon for future space operations, expecting the first manned landing to occur in 2026 [1]. However, the lunar environment is dramatically different from Earth's environment. The lack of atmosphere results in extreme temperature gradients, especially near the poles, which can cause systematic failure in rovers and spacecraft. The lack of an effective magnetosphere results in large amounts of charged particles which causes dust to easily attach to any and every surface on the Moon [2].

One of these main issues of lunar development is Plume-Surface Interaction (PSI), a phenomenon where "clouds" of dust can arise when spacecraft are landing and taking off. Lunar PSI is composed of micro and nano sized, electrically charged, sharp dust fragments flying around at thousands of meters per second, causing significant damage to spacecraft and lunar rovers hundreds of meters away.

Falling under the category of "Reduction / Mitigation of Erosion (Cratering) and Ejecta during Descent, Landing, and Ascent," our solution to PSI-related damage is the construction of a landing pad via microwave sintering. This acts as a physical barrier separating exhaust gasses from dust particles during take-off and landings, directly limiting damage caused by dust particles. Furthermore, total failure of such a physical barrier is limited because of the mechanical nature of our solution. In the event of partial completion of the landing pad, there will still be some protection from PSI threats.

Microwave sintering is chosen as our method of landing pad construction because of how conductive lunar regolith is to microwaves. Nanophase iron, whose grain sizes are on the nanoscale, is extremely conductive to sintering. Experiments by Lawrence Taylor have shown that sintering nanophase iron compared to popular lunar simulant JSC-1 is approximately two and a half times faster and requires half the power [1]. Furthermore, since the process is controlled by the microwave sintering unit, the sintering process can be controlled, limiting defects in the landing pad and ensuring reliability of the sintering process. By sintering the nanophase iron with the use of microwaves, we can turn the dusty lunar surface into a solid ceramic surface capable of withstanding the launches and landings of space vehicles.

## 2. Technological Readiness and Path to Adoption of Unique Features

Creating a landing pad is an energy intensive process that will require new technologies that have yet to be tested in a lunar environment. Refining these technologies until they are suitable for use requires both funds and a path to technological readiness so that they may be used.

### 2.1 Microwave Sintering

The first technology we require is a microwave sintering capable of sintering lunar regolith into a hardened surface. It has already been shown that lunar simulants such as JSC-1 are capable of being effectively sintered by commercial microwaves (2.45GHz frequency) within minutes. At final temperatures above 1350°K with total input powers of 900kJ, sintered lunar simulant JSC-1 displays compressive strength of the order of 20MPa (12 - 37 MPa) and hardness of the order of 5GPa (5.04 - 7.74 GPa) scaling proportionally to the input power-to-mass ratios of 4 W/g to 16 W/g [3]. A sintered layer 5 mm thick, should be capable of resisting the 162,500 N of force or estimated 10 kPa of pressure applied by the Starship HLS as well as the heat from Starship HLS's landing thrusters, due to the low thermal and electrical conductivity of the material and high melting point.

One of the variable factors in microwave sintering of known lunar simulants is olivine content. The melting point of the sintered regolith can vary with olivine content, even on small scales, which can ultimately affect the mechanical strength [3][4]. However, work by Lawrence Taylor has shown that the dominant source of heating within lunar regolith is Nanophase Iron, iron grains on the scale of nanometers [5]. Unlike lunar simulants, lunar regolith contains significant concentrations of nanophase-iron which acts as conductors for microwave energy rather than reflectors. When comparing Apollo 17 samples to JSC-1 Lunar Simulant, for small samples of the same size, the Apollo 17 samples sintered 2.5 times faster with half the power, for an overall 5x increase in sintering efficiency [6]. As olivine contains significant amounts of iron, we cannot assume that olivine silicates in earth based simulants are the same as olivine silicates in lunar regolith. As a result, we suspect that nanophase iron is a more significant factor than olivine content.

Advancing the technological readiness of microwave sintering of lunar regolith will require several steps. First the development of a lunar simulant incorporating both nanophase iron and crushed glass aggregates, focused on making it suitable for representing the electromagnetic, thermal, and physical properties of surface level lunar regolith. The cost may be significantly more expensive due to the need for nano-sized grains. Next, testing microwave sintering with the newly developed simulant in a cold (180°K) vacuum and analyzing the resultant's compressive strength and hardness for particular power densities will prepare the process of microwave sintering for the system component. We expect this next stage . Finally testing microwave sintering with the rover with lunar simulants will require prototyping the rover and testing with low temperatures and low pressures.

One of the potential challenges of using microwave sintering is the possibility of runaway thermal heating and extreme temperature gradients within lunar soil [3]. This could damage any part lying on its surface, as well as the microwave cavity which will sinter the regolith. To mitigate this risk, we propose to have the sintering module at the back of the rover to avoid heating of the rover directly, as well as having the tires on the sides of sintered paths, preventing direct contact with hot sintered regolith. For the walls of the microwave cavity, we plan on using heat resistant materials such as titanium or tungsten to prevent heat related damage.

Additionally, microwave radiation in the presence of living beings is potentially dangerous with side effects including cataracts and skin burns [7]. However, the expected risk is minimal since landing pads are created prior to human settlement and sintering is done in an enclosed space. Furthermore, microwaves will be pointed into the ground, limiting exposure to other humans.

### 2.2 Solar Power Generation and Power Management System

Because Sintering is an energy intensive operation, large amounts of power is needed to power the sintering module. We plan on using a 1 meter high, 2 meters long triple-junction solar panel from Azure Space [8] to supply approximately 862 W to our sintering rover [9].

Backing the solar panels, we plan on using a series of nitinol wires in parallel. Nitinol has been shown to retain shape-memory alloy properties between -321°F and 1200-1300°F [10], allowing for the solar panel to deploy under temperatures of up to -250°F on the moon. Furthermore, Nitinol has the advantage of being a lightweight alloy, allowing weight to be saved.

Under pre-deployment conditions, the solar panel array can be rolled together so that the solar array takes up less space. Upon deployment to the Moon, the nitinol mesh can be released from its retained state, to extend the solar panel array to its upright position. Once extended, the elastic properties of the nitinol will keep the array panel extended. Solar panels can then be rotated in the transverse direction by a motor attached to the base of the solar panel configuration. This allows the solar panel to rotate to ensure that the rover will be receiving maximum power during its mission.

Although each of these technologies are individually used in space related environments for commercial and scientific satellites and rovers, including solar panel deployment reaching, the complexity of using Nitinol wire to extend against the force of gravity as combined with the working of a delicate solar array has not been tested. However, Nitinol wire has been tested in environments such as Curiosity's chainmail wheels, or ball bearings. Deploying such an extensive solar panel array using Nitinol wires will require further testing in lunar (cold and vacuum) conditions, leading to a TRL 7.

There are two risks that need to be addressed. The first is night-time conditions with cold temperatures. However, the solar panels may be able to be undeployed, minimizing surface area, while the nitinol wires are heated until just below the critical temperature to ensure that the wires do not accidentally extend. Gold foil can then be expanded from a panel on the back of the solar panel to reduce the radiative emission. The second risk is the possibility of premature deployment of the solar panels if the wires become too hot during transit. This can be mitigated by using a relatively high temperature for the critical temperature of the nitinol wires as well as facing the solar panel component away from the sun.

### 2.2 Magnetic Concentrator of Lunar Iron

Due to the unique interaction between nanophase iron and microwave sintering, the concentration of nanophase iron in lunar soil is critical to the efficiency of sintering. By using metal detectors and electromagnets, we can identify nanophase iron rich regions suitable for creating a landing pad. We can also extract nanophase iron rich particles from the lunar soil, which can then be added into our sintering process, enriching the soil and potentially increasing the efficiency and uniformity of the heating process.

Magnetic filtering has previously been used to extract metals from heterogeneous mixtures and to purify metals in large factories [11]. However, magnetic filtering has yet to be used in space, placing this technology at TRL 4. Advancing the technological readiness of a Magnetic concentrator requires similar steps to advancing the technological readiness of Microwave sintering meaning that the cost can be shared between the two development phases. First a lunar simulant including nanophase iron and glass aggregates that reflects the physical, thermal, and electromagnetic properties of lunar regolith. This iron rich simulant can then be tested on filtering of the lunar simulant to steady its effectiveness in extracting regolith. Then the magnetic concentrator can be examined with the sintering process to identify feasibility and conduct cost-benefit analysis of including a magnetic concentrator as a part of the sintering process. Once component testing has been completed, this technology can be incorporated into a test design with a microwave sintering test design.

### 2.3 Other Necessary Technologies

The sintering rover will be equipped with basic, well tested technologies used for other space rovers. Our rover will be designed to use lithium-ion batteries to store power for deployment as well as to buffer power usage for microwave sintering. It will also use basic movement software with both autonomous and manual intervention, as well as communication technologies used on other rovers. Our rover will be coated in a multi-layer insulation painted in a reflective coating to regulate radiative heat transfer as well as use a Plutonium-238 Radioisotope Heating Unit (RHU) for nighttime operation. All these technologies have already been demonstrated successfully for spacecraft, achieving TRL 9 [12] [13]. Below is a timeline of the technological maturation of sintering technologies.

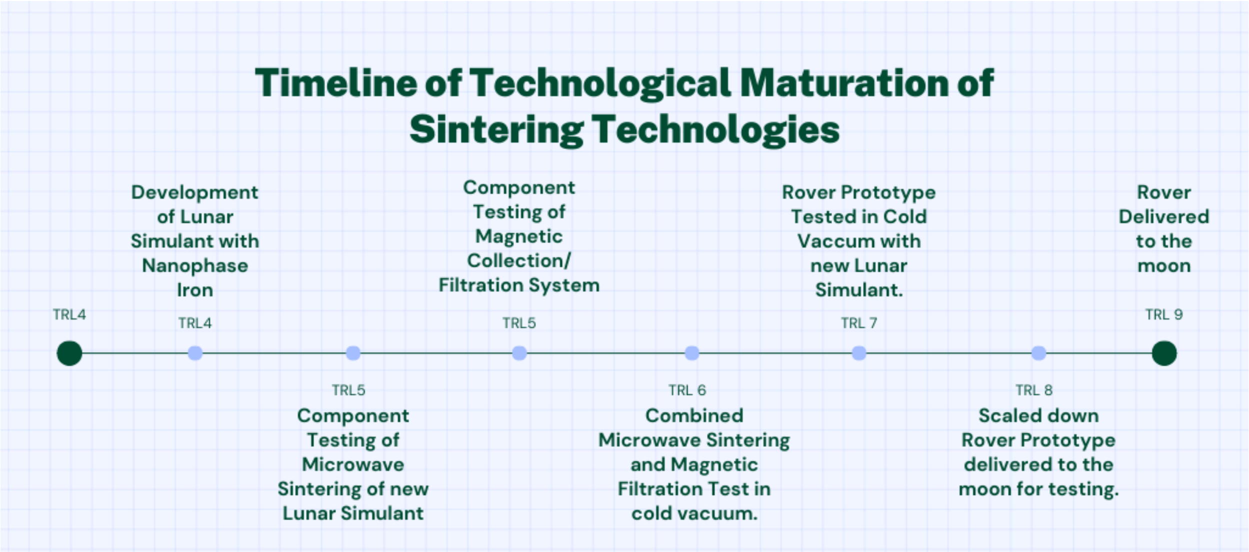

*Figure 1: Timeline of improvements and adjustments made to reach TRL 9*

## 3 Blueprint of a Sample Rover

### 3.1 Rover Design and Configuration (and changes from proposed design)

Our design of a sintering rover would be a six-wheeled rover in a box shape. The body will be rectangular in shape with wheels extending from the sides utilizing the rocker-bogie configuration. The design, deviating from our proposal design, will be larger at 200 cm long, with a body width of 40 cm and a total width of 60 cm. The height of the rover when its solar panels are undeployed will be 35 cm, with a total height of 120 cm when the solar panels are deployed. The estimated total weight of the rover will be approximately 60 kg with a stored size of approximately 200 cm by 40 cm by 60 cm, or 480,000 $cm^3$, making it lighter and smaller than mars scientific rovers, while still being capable of accomplishing sintering between the timings of Artemis 2 and Artemis 3. The wheels will be made of a zinc coated steel mesh with a spun woven aluminum center with titanium chevrons as done on the previous lunar rovers on Apollo to allow for efficient travel, as the loose lunar regolith will give normal wheels and treaded solid wheels issues of slipping [14]. As there are no special differences between our expected rover design and the designs of current and past rovers, we can expect this design to be at TRL9.

### 3.2 Weight, Size, and Cost Analysis

Weight and cost are major concerns that must be addressed in order to be an attractive option for PSI mitigation. The rover needs to be able to fit a sintering device and be capable of sintering the lunar surface over a long duration. Furthermore, the rover needs to be capable of producing significant amounts of power requiring significant vertical surface area. However, it does not need to fit many bulky instruments. Considering these constraints, a long rectangular prism shaped rover is optimal for allowing a large vertical solar fin while minimizing the required volume.

Previous rovers on Mars and Lunar rover vehicles were built using aluminum alloys, specifically ⅛ thick aluminum 6061-T6 for the body and rocker-bogie tubes due to its high strengths, corrosive resistance and ability to resist a non-atmospheric environment [15] [16]. Based on the configuration of our rover, its construction will require at least 7 panels of aluminum with the following dimensions.

*Table 1: Dimensions, weights, and costs of rover components*

| | Dimensions (cm) | Weight (kg) | Cost ($)** |
|---|---|---|---|
| Bottom | $150 \times 40 \times 0.3125$ | 5.0625 | 143.48 |
| Front | $40 \times 55.9 \times 0.3125$ | 1.8866 | 62.64 |
| Back | $25 \times 40 \times 0.3125$ | 0.8438 | 36.41 |
| Sides (x2)* | $200 \times 25 \times 0.3125$ | 2.7344 | 271.96 |
| Top (x2) | $400 \times 40 \times 0.3125$ | 13.5 | 426.13 |
| **Total** | **N/A** | **24.0273** | **940.62** |

* Side dimensions and costs are based upon the total metal area, but the weight is based upon the rectangle having a 50 cm x 25 cm triangle cut out of it.
** Total cost comes from [18]. Actual price may vary.

For the rocker-bogie configuration, 2 hollow 12.7 cm diameter 6061-T6 aluminum tubes will be used at 0.93 cm wall thickness for both sides. The tubes will be cut at a length of 210 cm, a bit longer than the body of the rover to compensate for the curving nature of the rocker–bogie configuration. This has a weight of 366 g per tube, costing about $271 per tube assuming 2.7 g/cm$^3$ [17][18].

For context on the microwave magnetron, a standard 1000 W microwave oven is about 15.75" deep x 20.19" wide x 12.09" high and weighs 14.5 kilograms, costing roughly $115 [19]. Conventional microwaves also use stainless steel for its interior, however this material is vulnerable to sustained high temperatures and corrodes quickly.

With this in mind, the microwave cavity will consist of a 6-4 Grade 5 Titanium box 30 cm wide, 6 cm long, 20 cm tall, and 0.3 cm thick (5400 cm$^3$), with 0.5 cm tall openings near the bottom to allow lunar regolith to enter and exit, building a sintered layer on the Moon. This box will weigh approximately 2.4338 kg assuming a density of 4.43 g/cc. This configuration may be cut from a single 61 cm by 84 cm sheet costing $554 [20]. Other metals and alloys with even higher melting points may be used in place of the titanium sheet at the bottom if deemed necessary.

Cameras which have been used on Mars will be used on this rover as well, weighing 250 grams and costing roughly $4,000 [21]. In order to keep 1200 wh in storage for safety, EaglePicher Technologies' lithium ion battery is suitable with its high specific energy at 153.5 wh/kg and a volumetric energy density of 271 wh/L [22]. The cells have a voltage range of 3.1 to 4 volts, costing about $139 per kwh on average [23]. Thus, for our purposes, the cost of the battery will be $166.8 with a volume of 4.42 L and a weight of 7.81 kg [22]. The Radioisotope Heating Unit, which generates 1 watt of heat energy weighs 0.2 kilograms and costs $6.56

million and the solar cells weigh 1.6512 kg total with a cost of $1,000,000 [24][25][26] . The wheels will weigh 0.975 kg each, scaled down 18.75% from 81.28 cm at 5.4 kg each wheel used on the Apollo Lunar Rover Vehicle to 15.24 cm [27]. Cost can vary for wheel manufacturing depending on specific amount of chevrons, so we estimate that the cost will be $2000 per wheel based on individual material costs. The multi-layer insulation costs $1313 total and weighs 1055.34 g [28][29].

With all things considered, the total weight of the rover with its instruments is 42 kilograms, estimated to cost about $7,575,447 per rover produced.

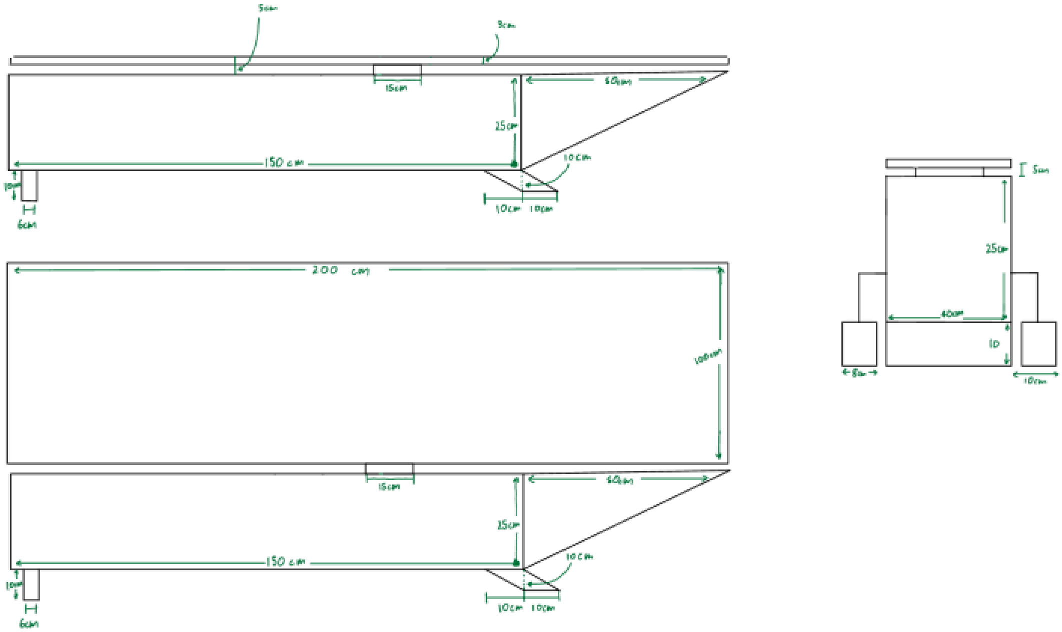

*Figure 2: Schematic diagram of the rover*

### 3.3 Power Analysis

Due to the similar size and expected momentum of motion, we expect power consumption of sensors, CPU, and Communications modules, and motors to be similar to the Indian Rover Pragyan, approximately 50 W. Adding this to the Solar Panel Power Generation will allow for approximately 12W of Power duration during solar daylight hours. During night time, we expect Internal Heat Generation to be 43 W to maintain a skin temperature of 200 °K. Because the internal components will be largely separated from the external components, we expect the temperature of those components to be even higher. If we want to maintain a higher skin temperature of 273 K, then we will need 106.21W.

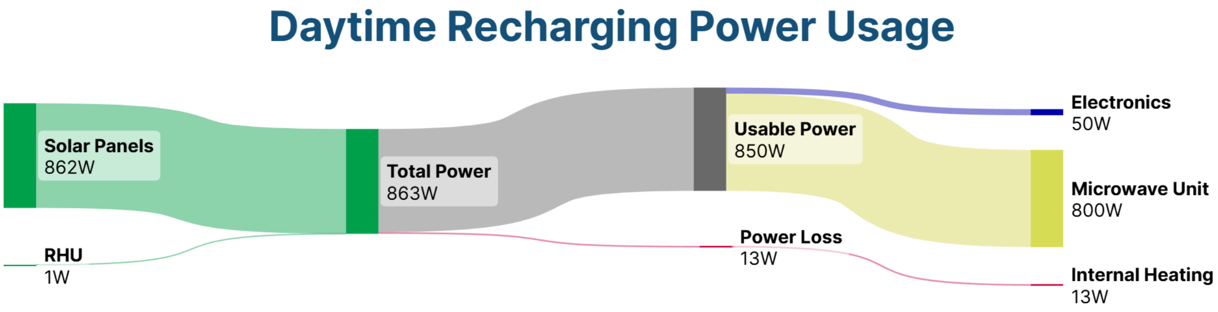

*Figure 3: Diagram demonstrating the energy and power flow in the system*

## 4. Technical Management (Implementation and Schedule)

### 4.1 Orbital Transfer from LEO into Lunar Orbit

There are two methods for delivering a sintering rover to the lunar surface that are being considered in this paper. The first is to include the rover and its landing module as a part of the Artemis II flyby with a separate descent stage, and the second is to have a completely separate launch for sintering purposes. Both of these methods have advantages and disadvantages that will be briefly discussed, however both will require a Translunar Injection burn in order to reach the Moon.

Delivering the rover as a part of Artemis II brings the benefit of only needing to include a landing device and a method to depart from the HLS in space. Occupying an approximate volume of 200 cm by 40 cm by 60 cm, and weighing 60 kg, the rover will be attached to a landing module which will also serve as a skycrane to bring the rover to touchdown. Another benefit is that it does not require a separate mission to launch and land the sintering rover. However, this takes up volume in the Artemis missions and would add a level of complexity to the missions, and something could go wrong with the sintering rover deployment while it is in the vicinity of the astronauts.

A separate launch system is advantageous because it does not risk the astronauts in Artemis 2. In addition, there is no exact time constraint as the mission does not need to align with Artemis 2, but rather be completed before Artemis 3. Furthermore, with a separate launch there is more available weight and volume in the Artemis missions for other NASA objectives and extra supplies for the astronauts.

Based on the above discussion, it is recommended to utilize a separate launch system for the deployment of the sintering rover. In general, the mission launch is estimated to cost $130,000 per kilogram [30]. To ensure a diversity of contracts, and to reduce costs and implementation time, we propose to use the United Launch Alliance Vulcan-Centaur Launch system to deliver the sintering rover to the south pole [31]. The Vulcan-Centaur Launch configuration is launched from CCSES (Cape Canaveral Space Force Station) and allows for payloads of 2,100 kg (VC0S - meaning no SRBs (solid rocket boosters) with an estimated cost between $100 and $200 million, with additional solid rocket boosts for up to 11,300 kg of thrust at additional costs. The Vulcan-Centaur configuration allows for multi-system capabilities, meaning we can share a launch weight, space, and costs with other customers, reducing the launch cost of our project. As with the first option, a separate launch will still need a deorbiting mechanism for the sintering rover. Since this mission has already proven to be successful in launching to the Moon, this launch mechanism is at a higher level of TRL 9.

### 4.2 Powered Deorbit and Landing Phase

After arriving in orbit, the skycrane along with its rover payload will be released from the spacecraft. Will then begin the deorbit maneuver costing a deltaV of 1.612 km/s (see appendix) The skycrane will reduce the speed of the rover as it reaches the ground and allow it to hover above the lunar surface long enough to drop the rover to the ground. Once completed, the skycrane will use its remaining fuel to lower itself to the ground away from the sintering unit. The skycrane can be retrieved in the future for analysis of PSI effects, or be left alone. Once the rover has successfully reached the surface, the sintering rover will deploy its solar panels and begin operations.

### 4.3 Landing Pad Creation Operation

Once settled at one of the 13 selected lunar landing sites, the rover will begin with the collection of nanophase iron. Once quantities, determined by future research, of nanophase iron have been collected, the lunar sintering rover will begin the process of sintering, adding nanophase iron to increase the efficiency and uniformity of the soil content when applicable.

#### 4.3.1 Landing Pad Orientation

The landing pad is 30 m by 30 m square, large enough to accommodate the 9 m diameter Starship HLS lander with 10 m accuracy that SpaceX has proven with Earth bound rockets [32]. Although the dynamics on the Moon are different due to the lack of an atmosphere, we believe that the principles behind accurate landings would be the same for both landers.

The lunar day-night cycle is important for our purposes due to our usage of solar panels for power generation. A Lunar synodic day takes about 29.5 Earth days [33]. While the Artemis mission is focused on exploring the permanently shadowed regions of the south pole of the Moon, the landing sites are exposed to sunlight at least 80% of the time due to their locations on mountainous terrain and crater rims, allowing ample time to complete sintering [34].

The landing pad will be constructed in a series of one hundred strips each 30 cm wide and 3000 cm long forming a square 3000 cm by 3000 cm. Each strip will take approximately 3.125 days to complete, allowing a maximum of 7 strips to be completed in each lunar day cycle with 1.5 hour breaks between for repositioning and recharging. At this rate of sintering, we expect our rover to take a minimum 15 lunar days (442 earth days), with some room for additional strips on the last lunar day if the rover falls behind schedule. To begin with, the rover will complete every other strip for the first 50 strips. After this, the rover will then complete the missing strips in a similar fashion. This will prevent the wheel from having to travel on hot lunar regolith which could cause changes in both the properties of the landing pad as well as potentially partially melt the wheels.

### 4.4 Post Landing Pad Utilization and Disposal

The rovers can be repurposed after the intended use is completed. Upon completion of sintering, the sintering rover can traverse to other nearby locations or landing pads that require sintering. Similar applications of horizontal lunar sintering include roads for lunar vehicles or soil beds for plant growth, which can be constructed similarly [35]. Alternatively, the sintering rover can await the arrival of the human lander and permanent human settlement where it can serve as a factory for producing bricks from lunar dust, which can be used for the construction of vertical infrastructure.

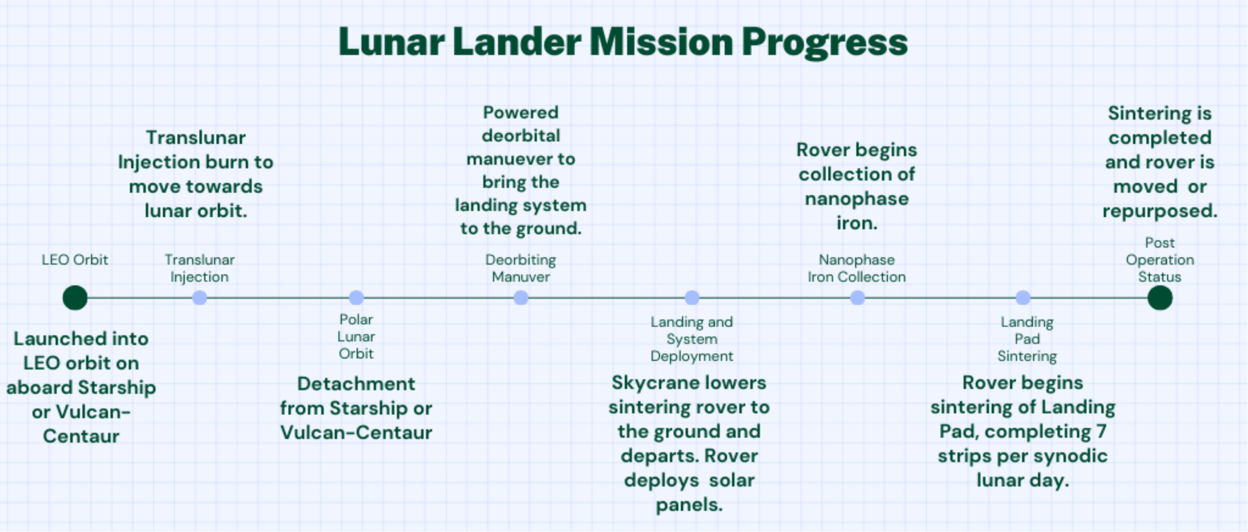

*Figure 4: Estimated timeline for the entire lunar lander mission*

## 5. Impacts and Effects

### 5.1 Technological/Engineering

Development of a lunar landing pad constructed from sintered materials is a unique technology that can assist in other areas of space exploration. One such area is to assist the further construction of space structures using lunar regolith without the additional costs of moving materials from Earth. In 2023, NASA selected 11 companies to complete a variety of lunar exploration technologies, one in particular was Redwire, selected to develop sustainable lunar landing pads and infrastructure, which could reduce operational risk for NASA and other lunar service providers [36][37].

Besides landing pads, regolith sintering has applications in lunar infrastructure construction. The Moon to Mars Planetary Autonomous Construction Technology's Microwave Structure Construction Capability team at Marshall Space Flight Center is developing the ability to densify lunar regolith into glass-ceramic landing pads and horizontal infrastructure, such as roads for lunar vehicles [35].

However, our solution reduces fabrication time and is more viable due to its ability to not entirely depend on the availability of solar. In addition, it uses 23% less energy compared to laser sintering, thus it can be argued microwave sintering is more affordable as it requires less power.

In addition, this can lead to developments in infrastructure using sintered dust on other Moons or planets with similar compositions.

### 5.2 Financial

The large development costs of implementing a lunar landing pad is largely due to optimizations of current earth based equipment and technologies for space use. Research has already been done to develop infrastructure manufacturing with lunar regolith from TRL 4 to TRL 6, as well as sending said equipment into space [36]. The estimated initial investment to develop and launch the rovers will be in the millions. A lunar landing pad can reduce costs for spacecraft maintenance due to its ability to reduce the risks associated with PSI leading to damage to nearby equipment and spacecraft. This can increase the number of missions to the Moon while keeping costs low, which will make the investment worthwhile in the long run.

### 5.3 Scientific

Because lunar regolith will be collected, research tools can be utilized to examine the effects of sintering lunar regolith for future development. Lunar regolith has demonstrated uses as solid-support substrates for plant growth, sources for extraction of plant-growth nutrients, substrates for microbial populations of degradation of wastes, and sources of O2 and H2, which could be used to produce water; all these functions aid in the life support systems needed during long-duration missions to the Moon [38]. In addition, using lunar regolith from Apollo 11, 12, 17, plants have been shown to germinate and grow in this diverse set of lunar regoliths [39].

Furthermore, the composition of the regolith and the concentrations of nanophase iron affects the efficiency of sintering; ideally, the concentration of nanophase iron is uniform through the sintering process. Furthermore, since the sintering process will heat lunar dust to 1350°K, the rover will be equipped with infrared sensors capable of analyzing the sinter process, which can be used to refine the sintering process for future microwave sintering processes, as well as to gain valuable information about lunar dust for varying temperatures and powers.

### 5.4 Social

NASA's Artemis Plan aims to achieve not only an initial human landing by 2024, but to work towards sustainable lunar exploration by the end of the 2020s [40]. The mitigation of Lunar Plume Surface Interaction via lunar landing pads would not only aid in achieving initial human landing, but is also sustainable - capable of supporting a growing amount of landings and launches to and from the Moon.

### 5.5 Risk Mitigation

While there is potential for the process of lunar sintering, there are risks associated with the engineering development, verification, and validations of the processes. One such risk is if the sintering process will work as ideally as we plan in an environment that is drastically different from Earth's. If not done at the desired rate, it may delay future launches, or not be able to protect spacecraft from PSI damages. However, proper and detailed experiments that can match the environment as best as possible will give us a margin of expectation that will allow for high confidence values that the process will be successful. Things may not be perfect when in the real environment; however, if it is within the range of desired performance based on experimentation, it will be less of an issue.

Another risk may be that, during the development of the landing pad, there could be electrical malfunctions due to the sintering unit or other required instruments. To mitigate this, multiple rovers can be deployed to work on a single landing pad. The idea is that while one rover should be able to complete the landing pad before the upcoming landings, when multiple rovers are working at once, the process to create the landing pad can be completed ahead of schedule. Moreover, if one rover fails, the others can complete its tasks within the desired time frame.

Furthermore, there is a concern that because of the lunar regolith's statically charged environment, electronics and mechanical parts of the rover may be affected if electrically conductive. The critical parts of the rover are the sintering unit, wheels, and camera/sensors. The sintering unit is inside the body of the rover which is protected by an aluminum body sealed at any open joints. When operating, the body would be at high temperatures, which discourages shocks from static electrically charged rocks. The mesh wheels will be able to handle the charged regolith and the camera/sensors will be protected by an aluminum outer shell as well.

Finally, the first rover being deployed and its landing vehicle could run into issues with PSI mitigation. The first landing craft will possibly suffer damage from PSI, therefore previous data collected from PSI behaviors on landing must be analyzed and understood when landing the first rover to minimize as much damage as possible.

## 6. Conclusion

Our proposed solution to PSI is the creation of a lunar landing pad that will prevent the exhaust gasses from impinging on the surface which results in lunar dust plumes. By using microwave sintering, we achieve in-situ resource utilization, allowing sustainable PSI prevention without the continued addition of earth-based resources. With a secure landing pad, the establishment of future lunar bases for exploration can be realized. New technologies never tested outside of Earth can be tested on the Moon—such as life support and long term habitats—can give engineers a starting point on designs for these items on other alien worlds [41]. Technologies like these allow NASA to further not only the Artemis missions, but to achieve sustainable lunar exploration by the end of the decade.

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## Appendix

### Thermal Behavior of Solar Panels

The Temperature of a solar panel on the Moon is governed by the heat generated from solar radiation balanced by the heat lost from thermal radiation of the solar panel as well as heat lost from conduction to external surfaces. Here we will consider the radiation effects first.

The temperature at a steady state can be found through the energy balance of absorption against emission with the following equation:

$$A_{ab} s a = A_{em} \varepsilon \sigma T^4 \qquad a = 1 - r - \eta,\ \epsilon = 1 - r$$

Where ‘s’ is the Solar Irradiance , ‘α’ is the absorptivity, ‘ε’ is emissivity, ‘r’ is the reflectivity, ‘η’ is the solar panel efficiency and ‘σ’ is the Stefan-Boltzman Constant 5.670374419E-8 $\frac{W}{m^2K^4}$. The areas of absorption and emission are $A_{ab}$ and $A_{em}$ respectively. Calculating the Temperature of 31.5% efficient, 5% reflective solar panels gives us:

$$2m * 1361\frac{W}{m^2K^4} * 0.635 = 4m * 0.95 * 5.670374419 * 10^{-8}\frac{W}{m^2K^4}T^4$$

Giving T = 299.27°K or about 26.12°C, which is in line with real world experience of satellites exposed to sunlight.

### Sintering Rate Calculation

The sintering rate can be estimated from [1] data by taking the energy input of the sample and dividing it by the weight and size.From [1] it takes about 900,000J at 800W for 50g of lunar simulant to become sintered, meaning it takes about 18,000J/g. From Lawrence Taylor we can estimate that the efficiency of regolith with lunar sintering is about 5x, placing our energy required at 3600J/g. In between these values is the theoretical extrapolated value of 6531 J/g [42]. We can then convert these values to J/cm$^3$ by using 1.5g/cm$^3$ density, giving us 27,000J/cm$^3$, 9797J/cm$^3$, and 4800J/cm$^3$. For a strip of volume of 45,000cm$^3$, we need 1215 MJ, 440.865MJ, and 216MJ. At input powers of 800W, we estimate that the time it takes for a single strip to be sintered is between 3.125 and 17.517 days, with estimates being on the lower side of things. Assuming Taylor is right, this means 312.5 days of total sintering time is needed.

### Thermal Profile under night-time conditions:

Assuming that our heat transfer from the ground (conduction through the wheels is negligible) we can calculate the power needed for our systems to maintain 200°K temperatures by assuming we have multi-layered insulation with gold foil to minimize radiative heat loss. The radiation equation can be given by the following equations:

$$P_{loss} = A_{surf}\frac{\sigma\left(T_{internal}^{4} - T_{space}^{4}\right)}{\frac{1-\varepsilon_1}{\varepsilon_1} + 1 + \frac{2(1-\varepsilon_2)}{\varepsilon_2} + 1 + \frac{1-\varepsilon_3}{\varepsilon_3}} = A_{surf}\frac{5.67*10^{-8}\left(200^4 - 3^4\right)}{6.77777} = 43.5W$$

Where $\varepsilon_1$, $\varepsilon_2$, and $\varepsilon_3$ are the emissivities of our rover, the insulation, and of the vacuum of space.

$\varepsilon_1 = 0.90$ for white paint,

$\varepsilon_2 = 0.30$ for aluminum films

$\varepsilon_3 = 1$ for space.

$A_{surf} = 3.25m^2$

### Starship HLS Weight Analysis

The force Starship HLS is expected to exert on the lunar surface is given by:

$F_g = m \cdot g = 100,000kg \cdot 1.625\frac{m}{s} = 162,500N$, where g = 1.625 ± 0.025 m/s and m = 100,000 kg [43].

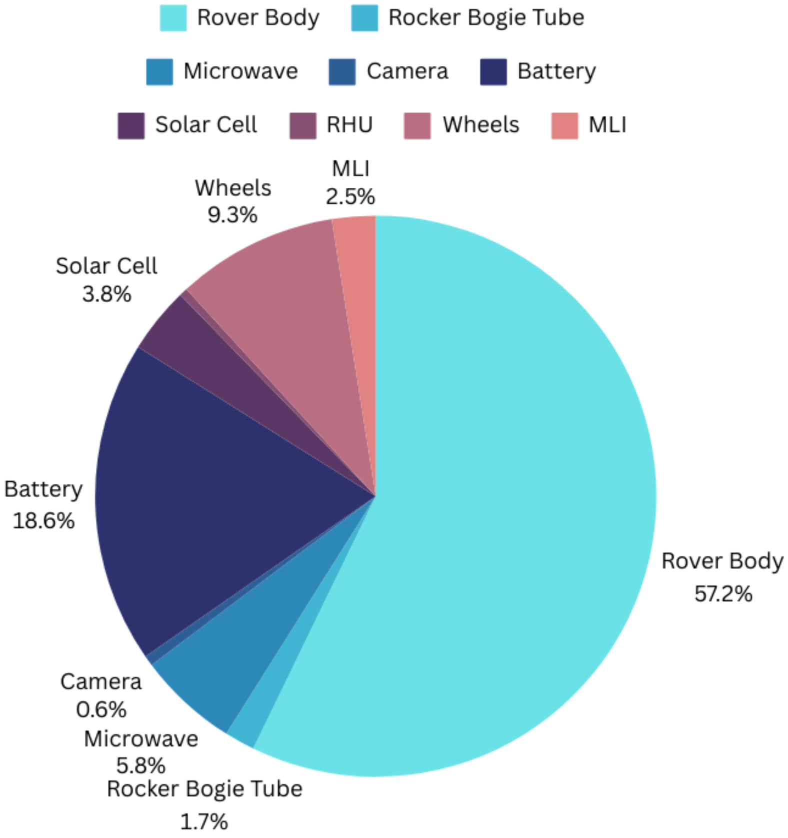


*Figure 5: Weight breakdown of the rover*

*Table 2: Weights of each rover component*

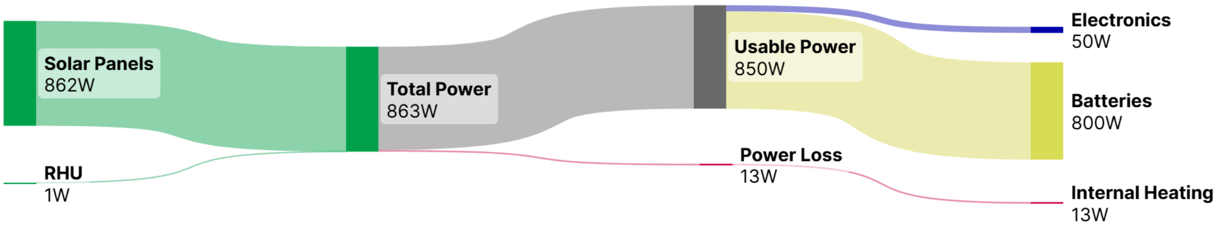
| Part | Weight (kg) |
|---|---:|
| Rover Body | 24.0273 |
| Rocker Bogie Tube (2) | 0.732 |
| Microwave | 2.4338 |
| Camera | 0.25 |
| Battery | 7.81 |
| Solar Cell | 1.6 |
| RHU | 0.2 |
| Wheels (4) | 3.9 |
| MLI | 1.055 |
| **Total** | **42.0081** |

*Table 3: Cost breakdown of the rover*

| Part | Cost (USD)* |
|---|---:|
| Rover Body | 871 |
| Rocker Bogie Tube (2) | 652 |
| Microwave | 554 |
| Camera | 4000 |
| Battery | 167 |
| Solar Cell | 1000000 |
| RHU | 6560000 |
| Wheels (4) | 8000 |
| MLI | 1313 |
| **Total** | **7575447** |

*rounded to the nearest dollar

Daytime Recharging Power Usage



Nighttime Power Usage