



Building the Future: A Blueprint for Martian Self-Sufficiency Laying the Groundwork for In-Situ Resource Utilization Through Microwave-Based Regolith Fabrication

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Abstract

This manuscript details specific operational aspects for DEIMOS (Developing & Evaluating In-Situ Martian Operations), a future analog astronaut mission facilitated by Habitat Marte, focusing on the critical role of in-situ resource utilization (ISRU) for Martian sustainability. We lay the groundwork for utilizing Martian regolith to 3D print essential tools and components, outlining the associated procedures from material acquisition to fabrication. Our methodology, constrained by current technology, involves using a standard 3D printer to create tools for simulated Extravehicular Activity (EVA) soil collection, enabling evaluation of tool and glove efficacy for future design improvements. It's important to note that the soil collected during these EVAs will not be used in our 3D printing experiments, as its composition does not sufficiently resemble Martian regolith. Instead, upon returning to the simulated habitat, we will combine a Martian regolith simulant (MGS) with two distinct binding agents/polymers, followed by microwave heating to produce and analyze microwave-fired ceramic/pottery. Anticipated findings include the demonstration of the potential for robust regolith structures through sintering and the identification of a more durable binding agent. The overall significance of this research is to advance human preparedness for long-term, self-sufficient habitation on Mars by validating fundamental ISRU processes and material properties in an analog environment.

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Introduction

Since the dawn of humanity, exploration has been an intrinsic part of our nature, driving us to push beyond known boundaries. Our journey into space began with the earliest forms of rocketry, evolving from simple fireworks to sophisticated vectored rockets. A pivotal moment arrived with the Soviet Union's launch of Sputnik in 1957, commencing the Space Race. In response, the United States launched Explorer 1, its first satellite, and established NASA, setting the stage for an intense period of innovation [16]. Following the Soviet Union's historic achievement of putting the first man, Yuri Gagarin, into space, and soon after, the first woman, Valentina Tereshkova, the U.S. responded with its own pioneering flights, sending Americans Alan Shepard

into space and John Glenn into orbit [16]. This monumental competition culminated in the United States achieving the unparalleled feat of landing a man on the Moon, a distinction it still holds to this day [16].

After the lunar landing, the U.S. transitioned to a new era of orbital exploration with the launch of the Space Shuttle program [16]. This initiative not only broadened access to space but also saw groundbreaking milestones like Sally Ride becoming the first American woman in space and Guion Bluford becoming the first African American in space [2,15]. These missions, in combination with international partners, led to the establishment of the International Space Station (ISS) [16]. As a unique microgravity laboratory, the ISS enables scientific experiments across various disciplines ranging from human physiology and material science to astrophysics and Earth observation—contributing to advancements not possible in terrestrial settings [11]. The ISS remains a vital orbiting laboratory, and the space landscape has further evolved with the widespread acceptance of commercial entities assisting and carrying out their own ambitious missions, opening new avenues for space access and innovation [11].

Today, entities, both governmental and commercial, are setting their sights on an even more distant frontier; Mars. However, greater distance results in greater challenges related to telecommunications, payload mass, and resupply. For instance, the round-trip light time to Mars varies from several minutes to over an hour, implying that an emergency communication and response from Earth could span days. Furthermore, spacecraft weight and balance constraints prevent crews from carrying all potential necessities. Since a resupply mission from Earth typically takes six to nine months, these delays are unacceptable in critical scenarios, thus highlighting the crucial importance of astronaut self-sufficiency for extended durations.

To adequately prepare humans for these long-duration missions and cultivate self-sufficiency, analog astronaut missions are a must-have. These Earth-based simulations replicate the conditions, challenges, and operational environments of spaceflight, allowing for the testing of technologies, procedures, and human factors in a controlled yet realistic setting. This approach is crucial because the inherent challenges of deep-space missions, especially to destinations like Mars, fundamentally shift the paradigm of mission planning from Earth-reliant to self-sufficient. This vital transition is largely predicated on the successful implementation of In-Situ Resource Utilization (ISRU).

According to NASA, “ISRU is the practice of collecting, processing, and storing materials found or generated on other celestial bodies to support astronaut missions”[19]. ISRU is absolutely necessary for a sustainable Martian presence because, simply put, astronauts cannot bring everything with them. Even if we could pack every conceivable item, it is impossible to foresee every broken part or the need for new, revamped equipment during long-duration missions. Things will break, and new needs will arise. Instead of having to “make do” with limited supplies or non-ideal solutions, ISRU offers the potential to fabricate what is needed, when it is needed, directly on Mars. Moreover, by leveraging Martian resources, the amount of mass needed to be launched from Earth can be reduced significantly. This not only saves tremendous costs but also frees up valuable space within the spacecraft, creating a more comfortable voyage for the astronauts involved.

One key example of ISRU involves using Martian regolith as a primary material for 3D printing. This capability will be a transformative technology, enabling astronauts to fabricate a wide array of necessary items on demand. This manuscript details specific aspects of a future analog astronaut mission, DEIMOS (Developing & Evaluating In-Situ Martian Operations), facilitated by Habitat Marte. One of the mission’s primary objectives is to lay the groundwork for utilizing Martian regolith to 3D print essential tools and components, outlining the entire associated procedure from material acquisition to fabrication, thereby advancing the capabilities required for sustainable human presence on Mars.

The manuscript is structured to cover: background information on the Martian environment and ISRU potential; the analog mission concept and its justification; a dedicated research focus on 3D printing with Martian regolith (including methodology, materials, preparation, and expected outcomes); the integration of this technology into analog and real missions (covering operational scenarios and challenges with mitigation strategies); followed by sections on future work and next steps, and a conclusion.

Background: Martian Environment and ISRU Potential

Martian Surface and Atmosphere

The Martian environment presents a fascinating and complex landscape. Key geological features, such as volcanic regions like Olympus Mons (the largest volcano in the solar system), offer insights into the planet's internal processes and a diverse array of materials [3]. Impact craters dot the surface, showing evidence of hydrothermal activity, which can lead to the formation of unique mineral deposits [5]. Similarly, canyon edges expose rock stratigraphy, revealing the planet's layered history and providing accessible areas for geological study and the possibility of identifying various mineral types [5].

Regarding the overall composition of the Martian surface, the regolith—the layer of unconsolidated rock and dust covering bedrock—is primarily basaltic [18]. It is rich in key elements like silicon dioxide, aluminum oxide, calcium oxide, and sulfur oxide, along with other notable elements such as iron, titanium, magnesium, potassium, and chlorine [5]. The high concentration of ferric oxide (iron oxide), commonly known as rust, is what gives Mars its distinctive red color [3].

A defining characteristic of the regolith is the presence of perchlorates, a type of salt that can influence its chemical properties and potential interactions with any introduced biological systems [10].

Beyond the regolith's composition, a critical aspect of Mars that has drawn significant research focus is the presence of volatiles [24]. These are elements or compounds that transition from solid or liquid states into vapor at relatively low temperatures. Water is particularly significant among these, especially given its importance for the emergence of life. On the red planet, water ice is found in polar caps and potentially in subsurface deposits [1]. Beyond ice, bound water also exists within some of the various mineral types that may be identified in the previously highlighted geological features and beyond, representing a significant volatile reserve [22]. These water sources are fundamental not only for understanding Mars's past climate but also for its potential to sustain future human and robotic exploration.

Finally, the Martian atmosphere itself is a defining characteristic. Composed predominantly of carbon dioxide (~95%), nitrogen (~2.8%), argon (~1.6%), and oxygen (~0.13%), it shapes the planet's weather patterns and plays a role in its broader geological cycles [1].

Overview of ISRU Technologies and Additive Manufacturing (3D Printing) in Space Exploration

In an effort to leverage Mars's natural resources, various ISRU approaches are being explored. This includes processing the volatiles mentioned earlier, where water can be extracted for life support (e.g., using Water Vapor Adsorption Reactors (WAVAR) or heating regolith to sublime ice) and then split into oxygen and hydrogen for propellant via electrolysis [26]. The Martian atmosphere, with its high carbon dioxide content, also offers a direct source for producing oxygen (e.g., through Solid Oxide Electrolysis Cells (SOECs) like MOXIE) and even methane through processes like the Sabatier reaction, essential for breathable air and rocket fuel [20].

However, regolith utilization stands out for its versatility in manufacturing and construction on Mars. The regolith's abundant basaltic composition, rich in silicon dioxide, iron, titanium, and magnesium, makes it an exceptionally feasible material for producing a wide array of items [17]. One key application for producing these items is 3D printing.

This promising application for Martian construction draws heavily from 3D printing's already transformative role in the terrestrial space industry. Companies such as Relativity Space are 3D printing entire rockets, while SpaceX leverages it for rapid prototyping and manufacturing complex, lightweight components such as rocket engine parts [21,23]. The extensive lessons learned from these existing applications directly accelerate the development of reliable 3D printing systems for the harsh Martian environment.

With this foundation, 3D printing using Martian regolith can potentially fabricate essential infrastructure like habitats, landing pads, crucial radiation shields, and even everyday tools. This additive manufacturing approach offers profound advantages for space exploration, enabling on-demand manufacturing. This means astronauts can produce spare parts or custom tools precisely when and where needed, drastically reducing reliance on Earth-based resupply missions. Such capability fundamentally transforms mission logistics from a "launch everything" model to a more agile "print what you need" paradigm, thereby saving immense mass and cost.

Furthermore, 3D printing enables the creation of highly customized parts, optimizing designs for specific functions, unique astronaut needs (like custom-fit tools), or the challenging Martian environment, often with complex geometries impossible via traditional methods.

However, challenges do exist. For instance, structures made from 100% pure regolith might be brittle [27]. This necessitates further research into developing composite materials or optimizing printing techniques. Despite this setback, pure regolith remains incredibly valuable for applications where structural load is less critical, such as protective coatings [27]. Another pertinent challenge is managing the perchlorates present in the regolith, as they can influence material properties and even impact potential agricultural endeavors [10]. Lastly, a thorough understanding of the regolith's particle size and shape is imperative, as these factors directly affect its interaction with various processing and manufacturing equipment.

Analog Mission Concept and Justification

Rationale for an Analog Mission and Proposed Analog Mission Location

Analog environments are crucial for validating ISRU techniques. They provide an effective and controlled platform to test technologies and operational procedures in conditions that closely mimic those of the target extraterrestrial environment, all without the immense cost, risk, and logistical challenges of an actual space mission. These Earth-based simulations allow researchers to identify and resolve potential issues before they become critical problems on Mars.



Figure 1: Habitat Marte and Aerospace Complex Facility [9].

Through these missions, specific objectives such as testing hardware, evaluating human factors, and refining protocols can be achieved. To effectively pursue these goals, careful selection of the test environment is paramount. An ideal terrestrial analog site is typically one that is isolated and has geological similarities to the extraterrestrial location. For instance, Mission DEIMOS will be held at Habitat Marte in the semi-arid region of Brazil, offering such a relevant analog setting due to its extreme dryness, basaltic soil composition, wind-driven erosion, and significant temperature variations, all of which closely mimic key aspects of the Martian environment. Figure 1 depicts the overall layout of the facility.

Mission Phases and Objectives



Figure 2: DEIMOS Mission Patch [25].

The premise of 5-day Mission DEIMOS will advance the viability of long-term Martian habitation by investigating key technologies and human factors critical to survival. Our objectives include pioneering in-situ additive manufacturing using Martian regolith, optimizing ergonomic designs for tools and spacesuits in low-gravity conditions, assessing the efficiency of extraterrestrial energy systems, and monitoring the sustainability of life support and food production systems. By integrating engineering, psychology, and resource management, this mission aims to lay the groundwork for future innovations and Martian settlements.

The success of any Martian mission (real or analog) hinges on a carefully planned series of phases, each with distinct objectives and operational considerations. For Mission DEIMOS, the proposed activities are structured into several key stages as follows (*Note: These mission phases, represented by Figure 2, are subject to change as research evolves and as we gain further insights*):

In-Situ Resource Utilization (ISRU) & Additive Manufacturing (3D Printing)

- **Objective:** Pioneer in-situ additive manufacturing using Martian regolith simulants, specifically focusing on tool fabrication and material property evaluation for construction.
- **Direct Support to Mission Premise:** Addresses "pioneering in-situ additive manufacturing using Martian regolith" and lays "groundwork for future innovations and Martian settlements" by validating on-demand manufacturing of essential tools and construction materials.

Days 1-2 (Focus: Tool Production & Initial Material Prep)

- **Activity:** 3D Printing of Tools (Shovels) using a selected material/simulant.
 - **Purpose:** To demonstrate the rapid, on-demand fabrication of essential equipment using additive manufacturing, reducing reliance on Earth-supplied tools.

- **Activity:** Evaluation of 3D-printed shovels' usability during simulated soil collection (note: actual Martian regolith simulant used later for binding tests).
- **Purpose:** Direct assessment of the ergonomic design and functional effectiveness of 3D-printed tools under operational conditions.
- **Activity:** Preparation of simulated Martian regolith for material binding experiments.

Days 3-4 (Focus: Regolith Construction Material Evaluation)

- **Activity:** Combine simulated Martian regolith with different binding agents.
- **Activity:** Pour regolith-binder mixtures into a series of molds of varying depths.
- **Activity:** Begin curing and initial observational evaluation of the binding agent effectiveness.
 - **Purpose:** To identify optimal binding agents for potential regolith-based construction (e.g., radiation shielding, structural components), directly contributing to "pioneering in-situ additive manufacturing."

Human Factors Engineering (HFE)

- **Objective:** Optimize ergonomic designs for tools and spacesuits in simulated low-gravity conditions and assess psychological factors.
- **Direct Support to Mission Premise:** Addresses "optimizing ergonomic designs for tools and spacesuits in low gravity conditions" and integrates "psychology."

Days 1-5, (During EVAs)

- **Activity:** Completion of Extravehicular Activities (EVAs).
- **During EVAs, specifically focus on:**
 - Evaluation of spacesuit design for ergonomics (mobility, dexterity, comfort).
 - Evaluation of tool design for ergonomics (ease of use, grip, reach), especially the 3D-printed shovels.
 - Observation and assessment of crew psychological factors (stress, teamwork, isolation response) in an analog environment.
- **Purpose:** To ensure future Martian tools and suits enhance crew efficiency and well-being, directly benefiting long-term habitation.

Life Support Systems (LSS) & Energy Systems

- **Objective:** Assess the efficiency of energy systems (solar panels) in terms of production and storage.
- **Direct Support to Mission Premise:** Addresses "assessing the efficiency of extraterrestrial energy systems" to ensure sustainable power for settlements.

Days 1-5 (Continuous Monitoring)

- **Activity:** Monitor energy production from solar panels.
- **Activity:** Evaluate energy storage efficiency (e.g., battery systems).
- **Purpose:** To understand and optimize power generation and storage for continuous operation of Martian habitats and ISRU processes, including future 3D printing operations.

Sustainability & Food Production Systems

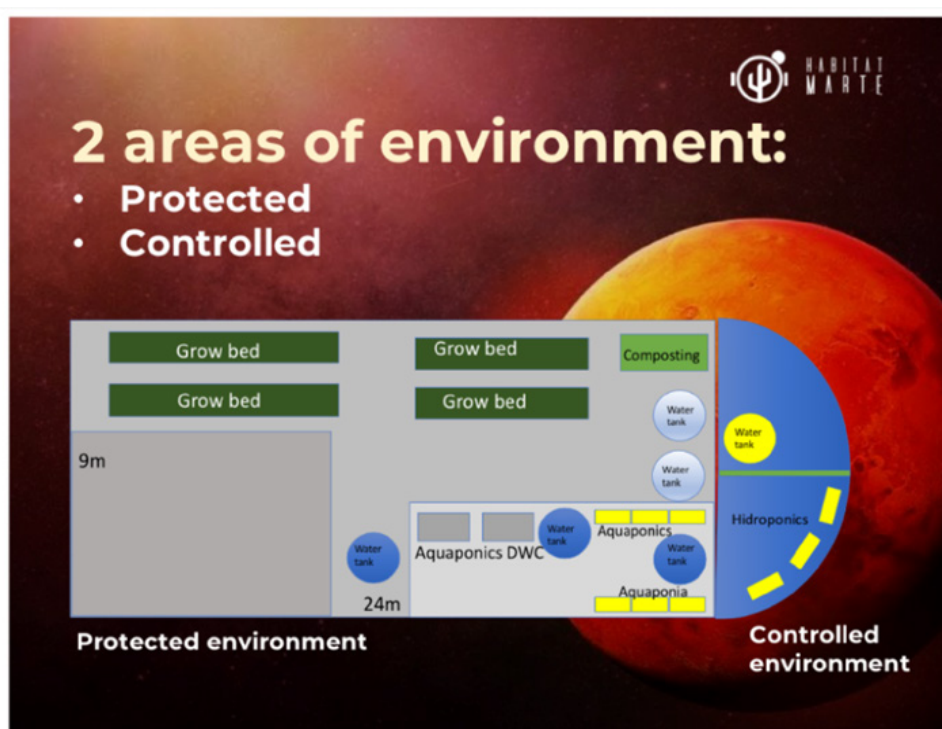


Figure-3 Habitat Marte Hydroponics & Aquaponics System Layout [9].

- **Objective:** Monitor the sustainability of life support and food production, leveraging existing analog infrastructure (Figure 3).
- **Direct Support to Mission Premise:** Addresses "monitoring the sustainability of life support and food production" for long-term survival.

Days 1-5 (Observation & Data Collection)

- **Activity:** Evaluate food production systems within Habitat Marte's large greenhouse.
- **Activity:** Assess and manage hydroponic/aquaponic systems for efficiency and yield.
- **Purpose:** To identify effective methods for sustainable food generation, reducing reliance on resupply and supporting permanent Martian settlements.

Research Focus: 3D Printing with Martian Regolith Materials and Methods

Comparing Analog Soils MMS1, MMS2 and RVAS: Composition, percent by weight

ID	MMS-1	MMS-2	Mars Average	RVAS
SiO ₂	49,40%	43,80%	43,20%	46,08%
Fe ₂ O ₃	10,87%	18,37%	18,28%	17,64%
Al ₂ O ₃	17,10%	13,07%	8,64%	17,48%
CaO	10,45%	7,98%	6,09%	4,16%
MgO	6,08%	6,66%	6,54%	1,86%
SO ₃	0,10%	6,11%	6,42%	2,10%
Na ₂ O	3,28%	2,51%	2,57%	
P ₂ O ₅	0,17%	0,13%	0,79%	1,10%
TiO ₂	1,09%	0,83%	0,78%	3,73%
K ₂ O	0,48%	0,37%	0,35%	5,21%
MnO	0,17%	0,13%	0,32%	0,28%
Cr ₂ O ₃	0,05%	0,04%	0,37%	
ZrO ₂				0,16%
SrO				0,09%
Total	99%	100%	94%	100%

Figure 4: Comparison of Analog Soils (Rezende, 2025).

Regolith Simulant Selection

As displayed in Figure 4, Habitat Marte CEO Julio Rezende conducted a detailed analysis of the Rio do Vento Analog Soil (RVAS) composition, comparing it with NASA's well-established Martian regolith simulants, MMS1 and MMS2. His assessment, which determined that RVAS ultimately does not meet the criteria for use in a high-fidelity Martian mission simulation, highlighted several key points:

"While RVAS possesses some similarities to Martian regolith, it doesn't quite make the cut to be used during a Martian mission. The primary discrepancy lies in its chemical composition: it is significantly too rich in potassium (K₂O) and aluminum oxide (Al₂O₃) compared to anything observed on Mars, which typically lacks such high concentrations of feldspar. Conversely, RVAS is notably deficient in magnesium (MgO); Martian regolith generally has a more mafic composition. Furthermore, while RVAS contains some sulfate, its concentration is far from sufficient to accurately match the sulfate-rich Martian terrains, such as those investigated by the Curiosity rover.

The most critical unknown factor, however, is RVAS's geotechnical properties. Without understanding its cohesiveness or whether it accurately mimics the grain size distribution of actual Martian dust, it presents a significant limitation for any serious physical or mechanical simulations. This makes RVAS unsuitable for applications requiring accurate physical interaction, like In-Situ Resource Utilization (ISRU) or detailed mechanical studies. While RVAS might be acceptable for some basic chemical experiments, more accurate Martian regolith simulants like MGS-1C (designed for clay-heavy regions) or JEZ-1 (for Jezero-like sediment) are better options for research due to their overall chemical and, crucially, geotechnical similarities to the Martian environment" (Rezende, personal communication, July 15, 2025).

Regolith Processing and Solid Casting

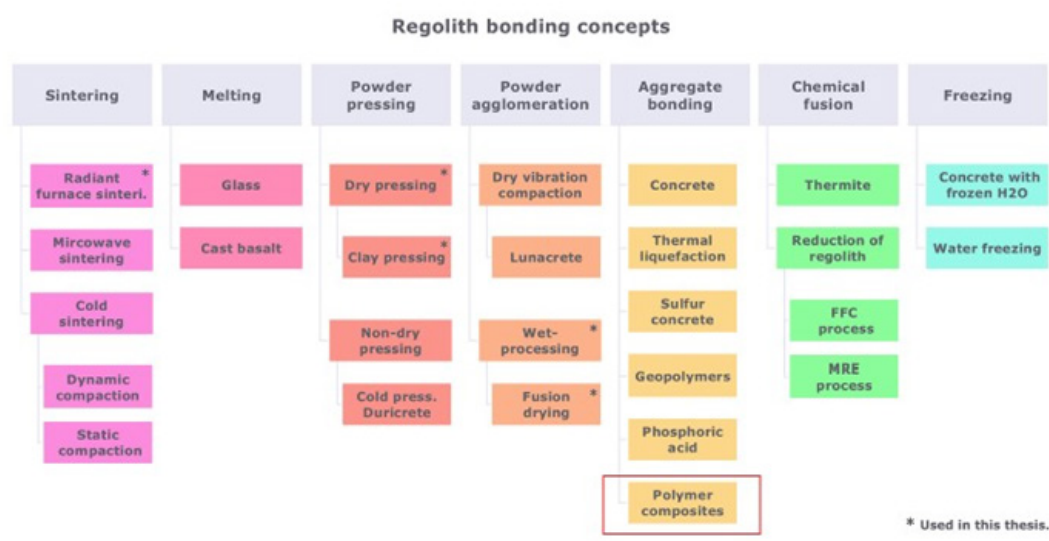


Figure 5: Regolith Bonding using aggregate bonding [12].

The method for processing the regolith will begin with sifting to ensure a consistent particle size distribution. This will be followed by an aggregate bonding process involving two different slurries (watery mixtures of insoluble matter). Each sample set, consisting of a total of three samples, will contain 60% by weight (wt%) of Martian Global Simulant (MGS) [12]. One slurry (sample set 1) will use deionized water as the liquid component, while the other (sample set 2) will incorporate 0.26–8 wt% of Dolapix PC67, an electrosteric sodium polyelectrolyte dispersant [12]. This dispersant prevents clumping and ensures a uniform, stable suspension, essentially acting as a "cement" for the regolith [6].

The mixing will be executed by hand. Once prepared, the mixes will undergo solid casting, in which they will be poured into hollow molds to form simple geometries and art pieces.

Microwave Sintering and Thermodynamics

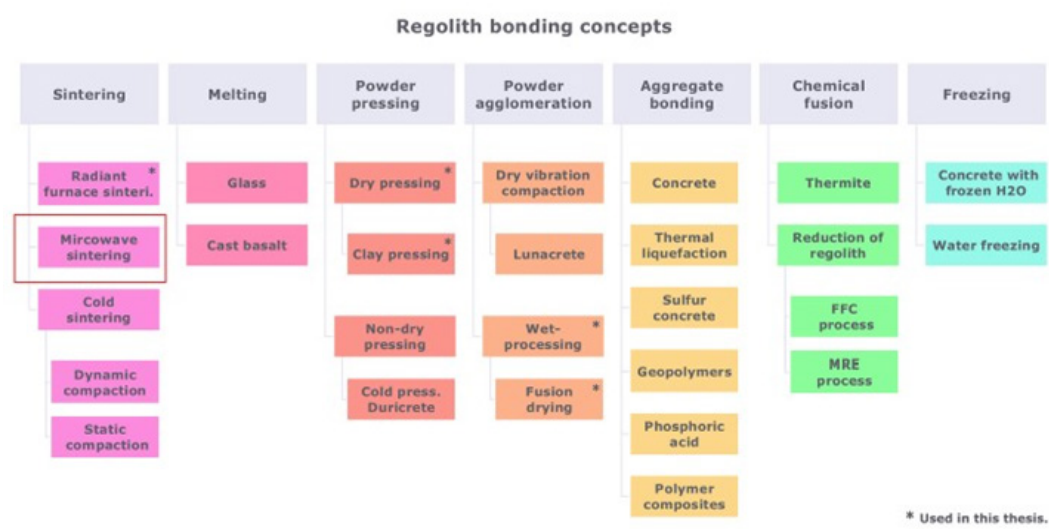


Figure 6: Regolith Bonding using sintering [12].

The prepared molds will then be placed in a microwave-safe, ceramic kiln and subjected to microwave sintering (Figure 6). This approach serves as a crucial first step for understanding how a microwave-based 3D printer may work in the future, despite current resource limitations like the absence of a regolith-capable 3D printer. This method allows us to effectively evaluate binding agents for future systems that will process and consolidate both the regolith and the bonding agents, and to establish key performance characteristics and processing parameters prior to determining future system design requirements.

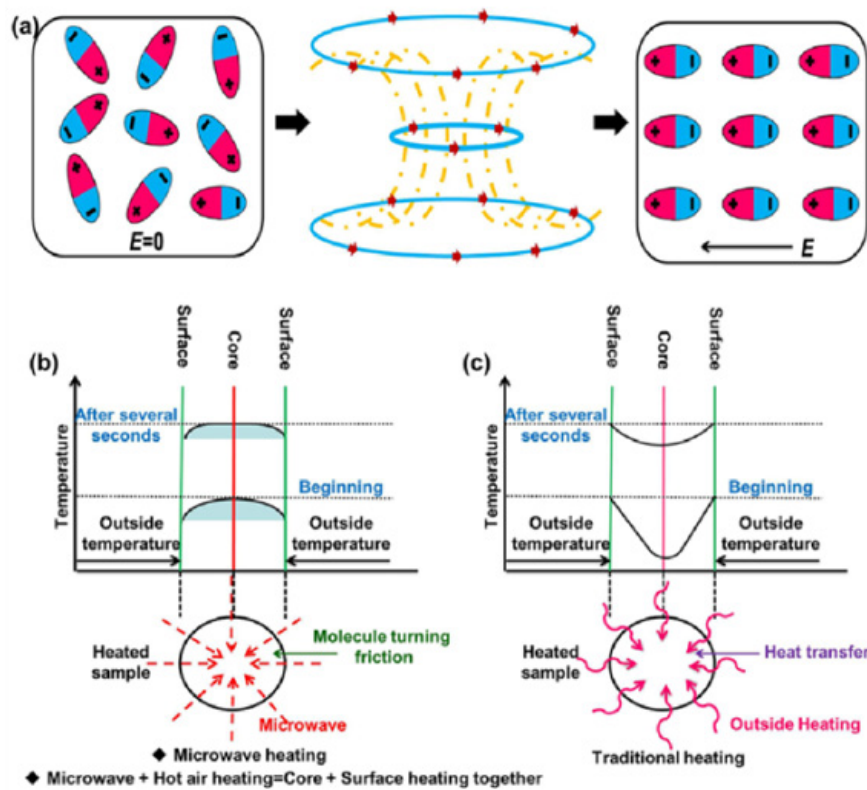


Figure 7: Microwave heating principle vs. Traditional heating methods [28].

The core concept behind this process is microwave volumetric heating. As depicted in Figure 7, unlike conventional ovens that heat from the outside-in, microwave energy penetrates the material, causing molecules within it (like water and certain regolith minerals) to vibrate rapidly [7]. This molecular friction generates heat from the inside-out, allowing for rapid and efficient heating of the entire material volume at once [7].

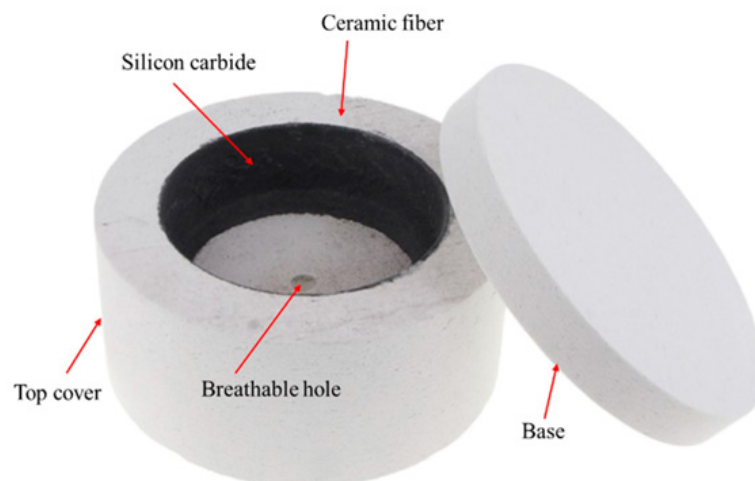


Figure 8: Microwave kiln [4].

The kiln, as depicted in Figure 8, "...made of a white insulating material... is generally composed of a porous ceramic body with an inside coating of high temperature susceptor material... which absorbs microwave energy" [14]. This setup is particularly effective for heating regolith, as regolith on its own may be difficult to penetrate with microwaves and would require very high temperatures to fuse without the aid of a susceptor. The insulation of the kiln is the main reason for it reaching high temperature. "The small hole helps it in increasing the temperature because once the microwave gets in it is a-kind-of-impossible to get out" [14].

This internal heating drives the sintering process, where a powdered material is compacted and formed into a solid mass. The process differs slightly between the two sample sets:

- For **sample set 1 (regolith + deionized water only)**, microwave energy will initially heat the water, causing it to evaporate—an endothermic phase change that requires significant energy. Once the water largely evaporates, the remaining microwave energy will transfer more efficiently to the regolith particles, increasing their temperature to the point where they can fuse together. This fusion relies solely on the intrinsic properties of the regolith simulant.
- For **sample set 2 (regolith + deionized water + Dolapix PC67)**, the process begins the same way with water evaporation. However, once the water is gone, the microwave energy will transfer to both the regolith and the binder particles, facilitating enhanced fusion due to the binding agent.

This microwave-based sintering actually proves useful and offers several advantages for Martian applications [13]. It is energy efficient, which is critical where power is a limited resource [13]. Additionally, it allows for faster processing of materials, leading to accelerated construction, and offers material versatility since microwaves can penetrate opaque materials [13]. This allows for the processing of a wide range of regolith compositions, unlike some laser- or light-based methods [13].

After sintering is complete, the material cools. Heat dissipates from the hot ceramic piece via conduction (into the mold), convection (to the air), and radiation, which is key for minimizing cracks and upholding the final product's structural integrity.

Analysis and Evaluation

The resulting samples will be evaluated based on their compressive strength, apparent density, and apparent porosity. To rigorously analyze the performance of the two slurries, the data will be quantified using a confidence interval.

This statistical approach is crucial for comparing the performance of the samples with different bonding agents. By calculating a confidence interval for each property (e.g., compressive strength) for both the deionized water slurry (Sample set 1) and the Dolapix PC67 slurry (Sample set 2), the measured difference between them can be determined for statistical significance. This rigorous analysis will allow for:

- The determination of the baseline properties achievable with water alone, helping to assess if it's a sufficient binding agent for specific, less-demanding builds.
- The precise quantification of how much stronger the Dolapix PC67 material is, providing a reliable range for the maximum strength achievable with this bonding agent.

Ultimately, the confidence interval provides the necessary statistical rigor to make informed decisions about which slurry is most suitable for builds with varying toughness requirements.

Expected Outcomes and Hypotheses

It is anticipated that the Dolapix PC67 slurry will yield a more durable and structurally sound ceramic product due to its properties as a dispersant and binder. Additionally, the ceramics made with the Dolapix PC67 slurry are expected to exhibit higher compressive strength, increased apparent density, and lower apparent porosity

(indicating a more solid structure).

Expected Challenges During Experimentation

Some potential challenges that may be faced throughout the process include, but are not limited to:

Material Preparation and Casting:

- **Challenges:** Achieving uniform mixing of regolith simulant and binders through hand-mixing can lead to inconsistent final products.
- **Mitigations:** Use standardized mixing protocols and precise component weighing.

Microwave Sintering Process:

- **Challenges:** Microwaves can create uneven heating, leading to hot or cold spots within samples and non-uniform sintering.
- **Mitigations:** Use a turntable for better heating distribution.

Post-Sintering Evaluation and Translational Aspects:

- **Challenges:** Variability in final sample properties can arise from process inconsistencies, affecting the reliability of strength, density, and porosity data.
- **Mitigations:** Produce multiple replicate samples and use statistical analysis for robust conclusions.

Integration into the Analog and Real Missions

Operational Scenarios for 3D Printing ISRU

During an analog or real mission, 3D printing with regolith would be a central part of daily operations. Astronauts would receive digital schematics from mission control or a local server for necessary tools or replacement parts. The process would involve collecting simulated regolith during EVAs, processing it into a printable slurry, and then using a specialized 3D printer and sintering method to fabricate the desired object. This allows the crew to practice resource management and on-demand manufacturing. In a real Martian mission, this process becomes even more critical for self-sufficiency. Rather than relying on a long-distance resupply chain, astronauts could autonomously create tools, equipment, and even structural elements. This shifts the focus from being a passive consumer of resources to an active manufacturer.

Based on the ratio of bonding agent to regolith and the sintering process employed, the resulting prints can exhibit a wide range of strengths, allowing for the creation of items tailored to specific demands. For example:

- **Flexible/Low-Strength Items:** Items like gaskets, coatings, seals, or flexible tool grips could be created by using a different binder to produce a more pliable material.
- **Medium-Strength Items:** This category includes replacement parts for equipment, brackets, or simple handles. These would require a stronger, more rigid material that can withstand moderate forces, achievable through a standard sintering process.
- **High-Strength/Structural Items:** This includes building materials or radiation shielding. These would require high-temperature sintering and a bonding agent such as Dolapix PC67.

Potential Human Factors and Logistical Challenges

Integrating 3D printing into daily operations also introduces unique human factors and potential issues like:

- **Resource Management:** The crew must carefully manage their binder materials. An error in one print could exhaust resources needed for a more critical item, leading to a mission-critical failure.
- **Health and Safety:** The process of sifting and mixing regolith could expose the crew to fine, abrasive dust, which is a known health hazard. Additionally, the sintering process itself could also release vapors or gases from the binder, requiring a robust air filtration system.
- **Cost:** Although this high-power microwave system could save millions of dollars in the grand scheme of things, technology will be costly upfront.

Future Work and Next Steps

Short-Term Goals:

- Refine the current process by experimenting with and optimizing the ratio of MGS to Dolapix PC67 to achieve the highest possible compressive strength and density while minimizing porosity.
- Standardize microwave sintering protocol by pinpointing the ideal power level and duration to produce the most consistent results.
- Explore new binding agents and corresponding ratios to see if others yield better results in relation to evaluation criteria, including use of metal alloys.
- Conduct thermal analysis to determine how different temperatures affect the end product.
- Determine a reliable and consistent mixing process for creating homogenous mixtures.

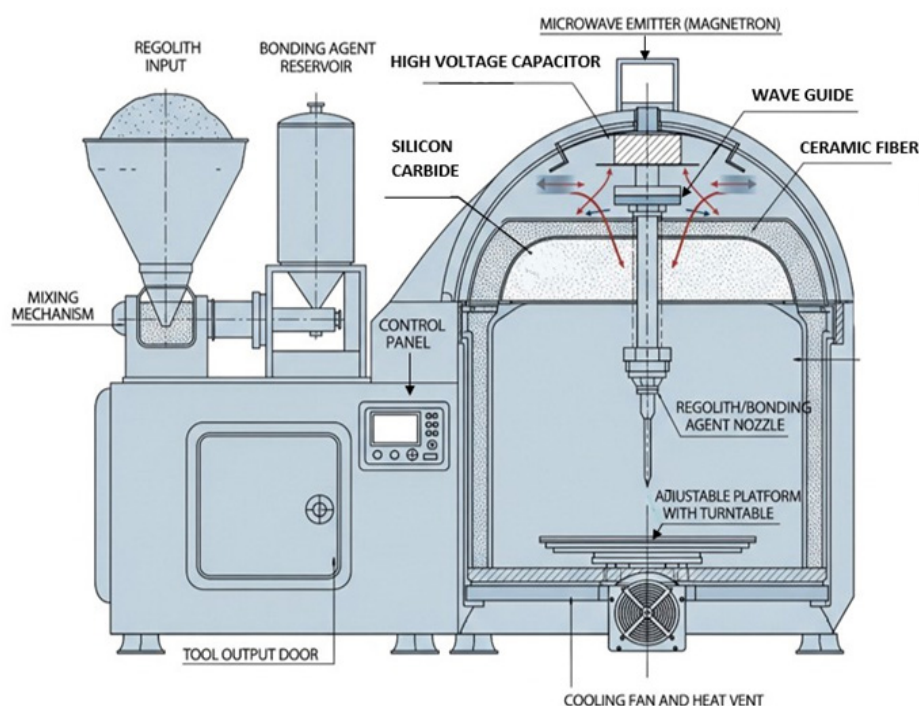


Figure 9: Potential Design Concept [8].

Long-Term Vision

- Develop means to make regolith and bonding agents safe for long-term human exposure.
- Develop an automated, closed-loop fabrication system capable of processing Martian regolith into a final product (E.g., Figure 9).
- Move beyond simple tools and art pieces to constructing complex habitats and infrastructure.
- Establish a recycling system that allows for broken or obsolete tools and parts to be ground down and re-sintered or re-printed.
- Explore organic compounds native to Mars that can act in the absence of Dolapix PC67.

Conclusion

In closing, as the human race moves towards less Earth-dependent endeavors, it is crucial to start thinking of ways to implement ISRU into technology. Microwave-based 3D printing of Martian regolith can contribute to on-demand manufacturing and the accelerated construction of critical infrastructure, as well as save on costs and be energy and time efficient in comparison to other methods of printing. Though there is much research to be done in terms of temperature gradients, aggregate bonding selections, and ratios, it is a promising way to allow astronauts to construct what they need, when they need it, without the sole reliance of resupply missions.

The described procedures in this manuscript will be conducted at Habitat Marte in November 2025, with the detailed results of the investigation to be presented in a subsequent report.

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Disclosures

During the preparation of this work, the author used Google Gemini [8] to enhance clarity and fluency of expression. After using the tool/service, the author reviewed and edited the content as needed and takes full responsibility for the content of the publication.

Conflict of Interest

None declared.

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