Advancing Regolith Simulants for High-Temperature Applications:

Rethinking Regolith Simulants Through Melt Behavior & Material Outcomes

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Rethinking Simulant Fidelity: Context Matters

There's a common misconception that current regolith simulants behave closely enough to lunar material that melt-based results can be directly applied. Most simulants were built for geotechnical tasks—not thermal fidelity. Instead of assuming one simulant fits all, we must consider experimental context.

Biomedical research offers a parallel: different animal models are used based on the system being studied. A mouse may be ideal for immunology, a pig for surgical testing. Likewise, no single simulant can serve every ISRU process.

Just as animal models are tailored for purpose, so too should regolith simulants be. A modular suite—each designed for specific thermal, mechanical, or chemical goals—offers the fidelity needed for meaningful ISRU results.

(See Figure 1: Animal Models Analogy, adapted from Altamirano-Lagos et al., 2019)

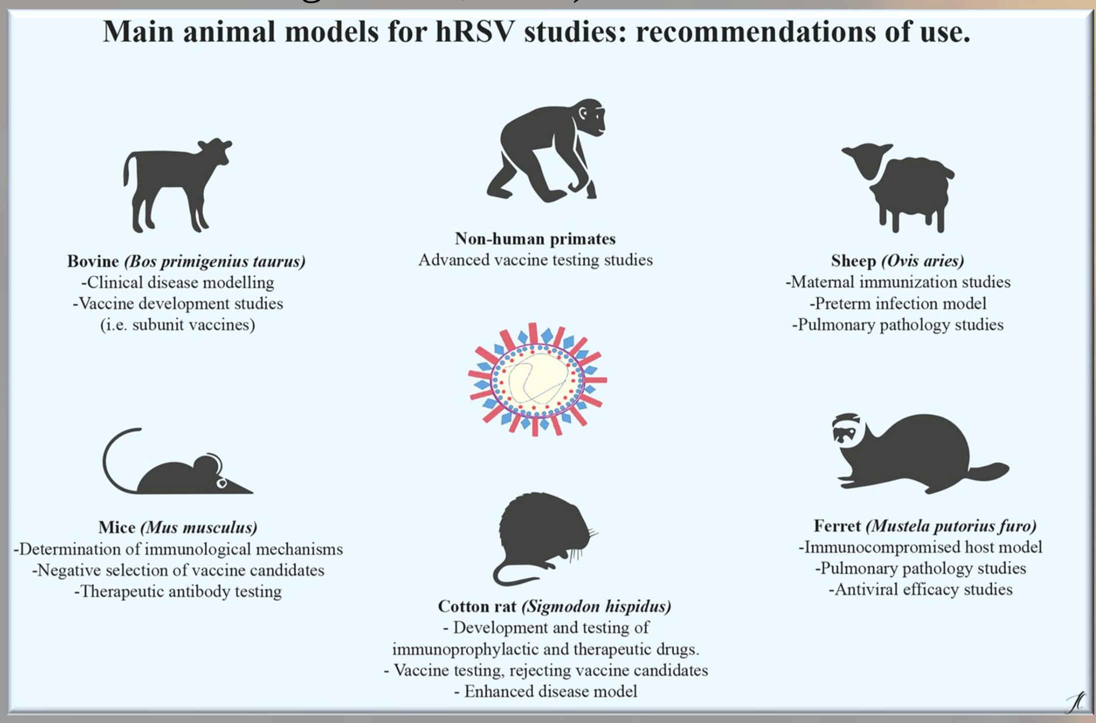

Figure 1: Animal Models Analogy, adapted from Altamirano-Lagos et al., 2019

Parent Material Characteristics: Greenspar Anorthosite

Thin section analysis of **Greenspar anorthosite** reveals hydrated minerals such as clinozoisite, mica, and amphiboles—phases not found in true lunar anorthosite. These introduce:

•Lower melting points

•Significant off-gassing during heating, likely from Na_2O, H_2O, and alteration products

•Foaming and porosity in melt products

These effects reduce thermal stability and complicate ISRU processes like casting, sintering, or vapor-phase extraction.

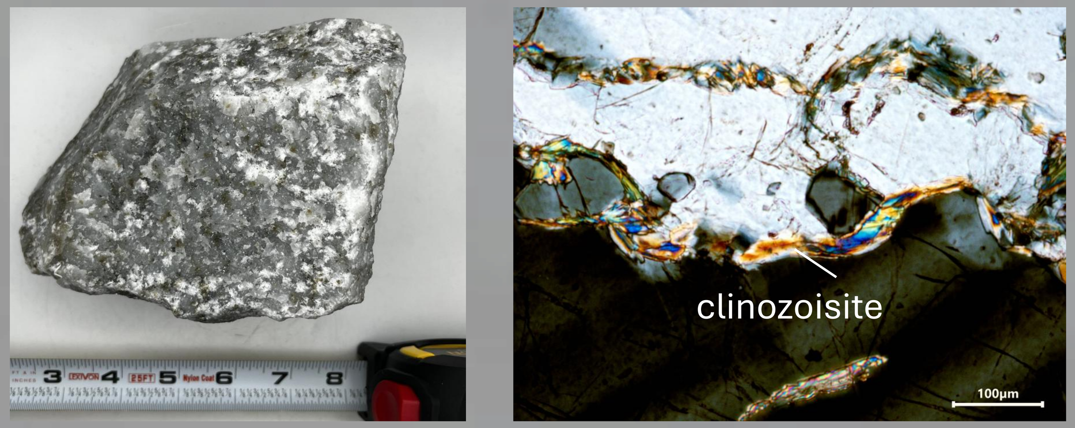

Figure 2: Greenspar anorthosite hand sample (left) and thin sections (right) showing the abundance of plagioclase, polysynthetic twinning and the presence of clinozoisite a hydrous mineral.

Parent Material Characteristics: Merriam Crater Basalt

Merriam Crater, a common source material for lunar mare simulants, is often referred to as "basalt." However, it is more accurately classified as a basaltic scoria—a highly vesicular, gas-rich volcanic ejecta formed by explosive eruption. This material differs substantially from the microcrystalline basalts found in lunar mare terrains. The scoriaceous nature of Merriam Crater introduces several melt-related challenges:

• High vesicularity contributes to foaming during melting and sintering

• Textural heterogeneity results in inconsistent melt behavior across grain sizes

• Oxidized phases and weathered surfaces introduce impurities not present in lunar samples.

These characteristics affect not only melting performance but also post-solidification phase stability, making Merriam Crater a potentially unreliable analog for thermal processing studies intended to simulate lunar basalt melt behavior.

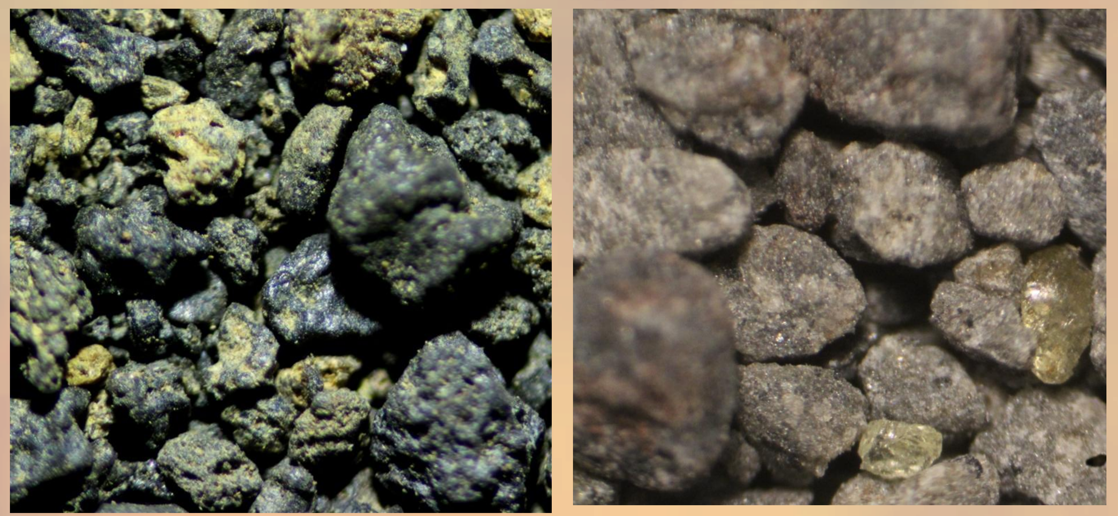

Figure 3: These representative samples illustrate the textural differences between vesicular basaltic scoria and dense crystalline basalt. Scoria, like that from Merriam Crater, is porous and inconsistent—leading to foaming and variable melt behavior.

Thermal Processing Challenges: Foaming Behavior

The CSM-LHT-1 simulant—a blend of Merriam Crater scoria and Greenspar anorthosite—was not designed for high-temperature melt processing. When heated, it exhibits vigorous foaming and volatile-driven bubbling, likely due to Na_2O, H_2O, and hydrated alteration phases.

In addition to melt instability, we observed violent outward spalling during heating, suggesting pressure buildup and structural failure inconsistent with lunar materials, which are dry and devolatilized.

These results highlight the risk of using geotechnical simulants in melt-focused ISRU studies without first validating their thermal behavior.

Figure 4: displays an image taken at Outward Tech. of a laser sintering CSM-LHT-1 in vacuum. The image shows how when heated in vacuum the regolith begins to spall, a red flag for volatile release upon heating.

Compositional Divergence Among Simulants in the SiO_2–Al_2O_3–FeO System

Although current lunar regolith simulants were primarily developed for geotechnical and mechanical testing, they are frequently used in high-temperature ISRU processes such as casting, sintering, and molten regolith electrolysis (MRE). To evaluate their suitability for melt-based applications, representative simulants were plotted in the SiO_2–Al_2O_3–FeO ternary space alongside Apollo samples A-15 mare and A-16 highlands. This comparison reveals several key trends:

• Merriam Crater basalt and Greenspar anorthosite, common source materials, deviate significantly from lunar compositions—often over-representing FeO or SiO_2.

• CSM-LHT-1, though developed as a highland's analog, occupies a composition prone to devitrification and mullite formation when melted.

•ORPH3N and NU-LHT-5M closely align with Apollo 16 highlands composition, suggesting stronger fidelity for feldspathic terrain melting behavior.

•JSC-1A, while broadly mare-like, does not reflect melt fidelity and often exhibits foaming or unstable crystallization.

These results highlight the limitations of assuming universal simulant applicability. Even simulants with similar bulk chemistry can behave differently in melt regimes, due to subtle variations in oxide ratios.

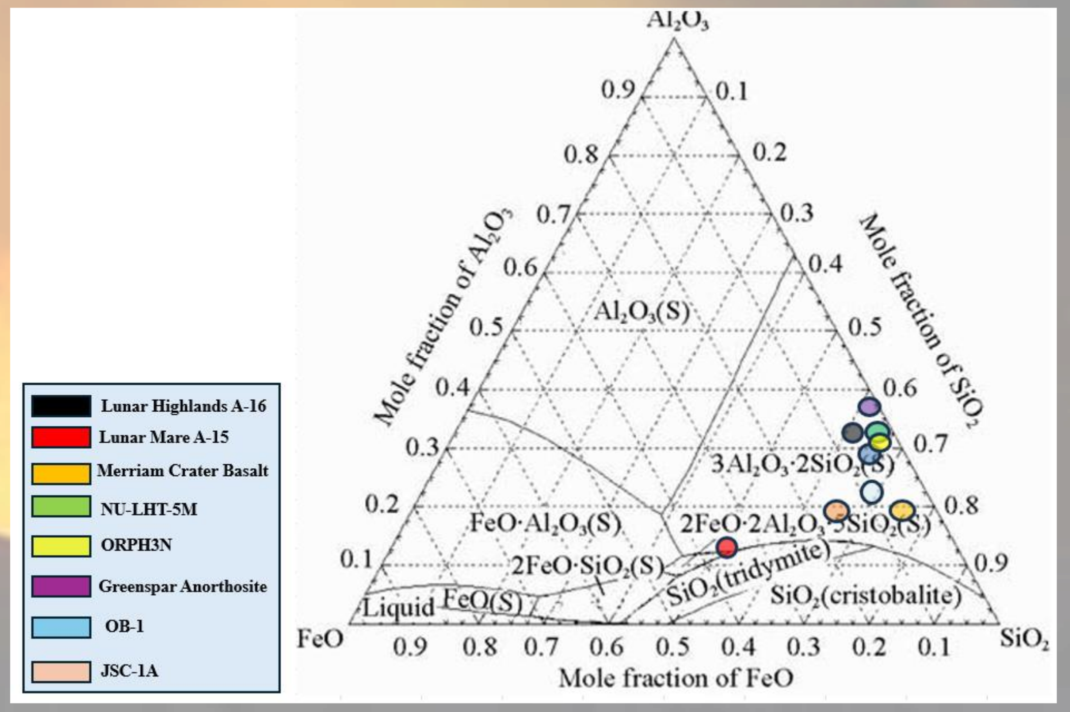

Figure 5: Ternary plot of normalized SiO_2–Al_2O_3–FeO compositions for common lunar simulants and Apollo reference materials. Most simulants cluster in Al-rich, FeO-poor regions associated with mullite, cristobalite, and other devitrification-prone phases. In contrast, Apollo 15 (mare) and Apollo 16 (highlands) compositions occupy distinct, melt-relevant phase fields, underscoring the need for composition-specific simulant selection.

Acknowledgements

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Viscosity Differences Reveal Melt Behavior Gaps

Viscosity plays a critical role in melt-based ISRU processes, influencing how materials flow, spread, and solidify. Using the Giordano, Russell, Dingwell (GRD) model, we calculated viscosity trends for Merriam Crater basalt and a representative lunar mare composition. Despite both being classified as "basalt," Merriam Crater exhibits significantly higher viscosities across the same temperature range, indicating more sluggish flow and potential challenges during casting or sintering. This may stem from scoria vesicularity, alteration phases, or chemical deviation from true lunar basalt.

Highlands-derived simulants could not be modeled using GRD due to their extremely high Al_2O_3 and low FeO content, placing them outside the model's calibration range. This further highlights the need for regolith-specific viscosity models, especially for feldspathic terrains.

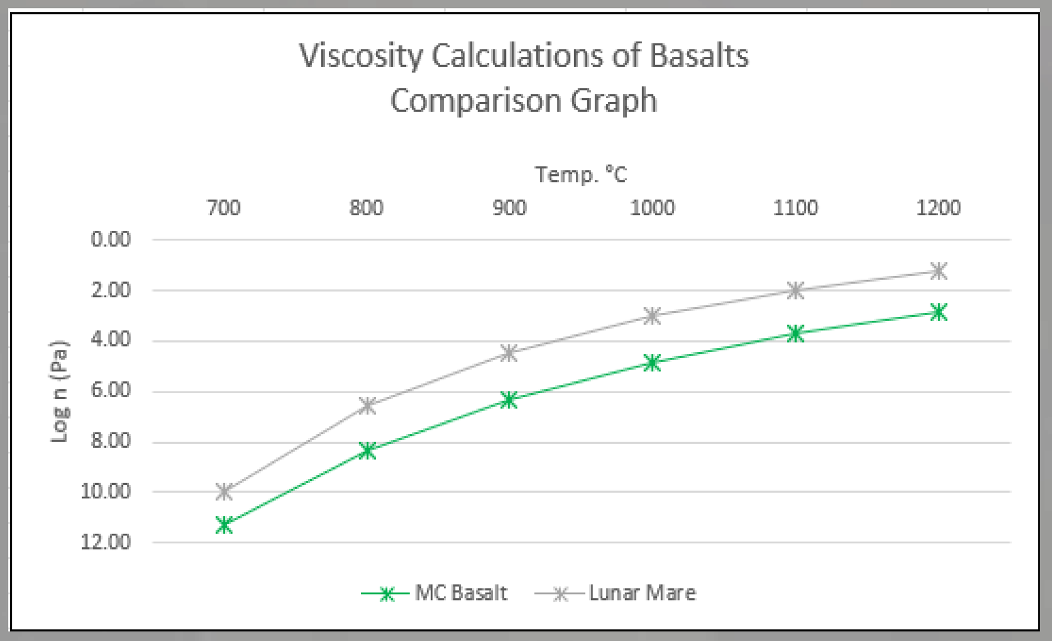

Figure 6: Viscosity comparison of Merriam Crater basalt and lunar mare analog using the GRD model. Despite similar classifications, MC exhibits higher viscosities and lower flow potential at all temperatures modeled.

Crystallization Issues in Cast Simulants

Cast parts made from the Merriam Crater + Greenspar blend appeared durable until sectioned. Upon cutting, the cross section revealed large, clustered cristobalite phases—a brittle silica polymorph not expected in lunar materials. Cracks were consistently observed to propagate from these cristobalite-rich zones, indicating that crystallization behavior—driven by melt chemistry and cooling—can severely compromise material integrity.

This highlights the risk of using simulants that deviate from lunar thermal behavior, even if initial mechanical strength appears acceptable.

Figure 7. Cristobalite "blobs" in cast CSM-LHT-1 material. Cracks (dark lines) originate from these silica-rich regions, reducing structural integrity post-cooling