National Aeronautics and Space Administration

FY23 Topic Areas Research and Technology Development (TRTD)

High-temperature Batch Reactor for the fabrication of Lunar Simulants

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Strategic Focus Area: Lunar science

Objectives: The objective for this research is the develop the capabilities to fabricate a new JPL lunar simulant based on the Apollo-14 Lunar sample composition. This new simulants will enable crucial first step towards understanding the geologic history, origin, and processes that were and/or are active on lunar surfaces. NASA already has several proposed missions to the moon, which will require new process engineering frameworks. This is an important need for detailed characterization of lunar regolith compositions and physical properties critical to many applied areas in lunar science, ISRU, space engineering, and to the operational success of all future science missions involving surface or near surface contact. Present simulants do not adequately represent the presence of this glass fraction because it is very difficult to recreate, especially in the quantities needed for adequate testing of flight hardware.

Background: There are presently two viable methods for producing lunar simulants: 1) through the collection of analog rock materials from terrestrial field sites, and 2) synthetic production, using base materials in the lab. For example, FJS-1 and MKS-1 were both fabricated in Japan and designed specifically for engineering use but do not represent the strong glass component. JSC-1 was derived from volcanic ashes and crushed to proper grain sizes for laboratory and engineering use; this simulant closely matched the geomechanical regolith properties of lunar regolith but does not contain a bonding glass component. However, availability for distribution to the lunar scientific and engineering community was limited and none is available today. Finally, the lunar simulant CAS-1 was recently created in northeast China, but its geomechanical properties have not been fully characterized, and it is not available. Therefore, there is a great strategic need for NASA to develop the domestic capabilities of fabricating a new JPL lunar simulant based on the geomechanical properties of lunar regolith for use in the NASA community. We will optimize yields in excess of 2% of feedstock as well as further enhance production rate by fine-tuning operational parameters such as temperature, feedstock materials, and reaction times

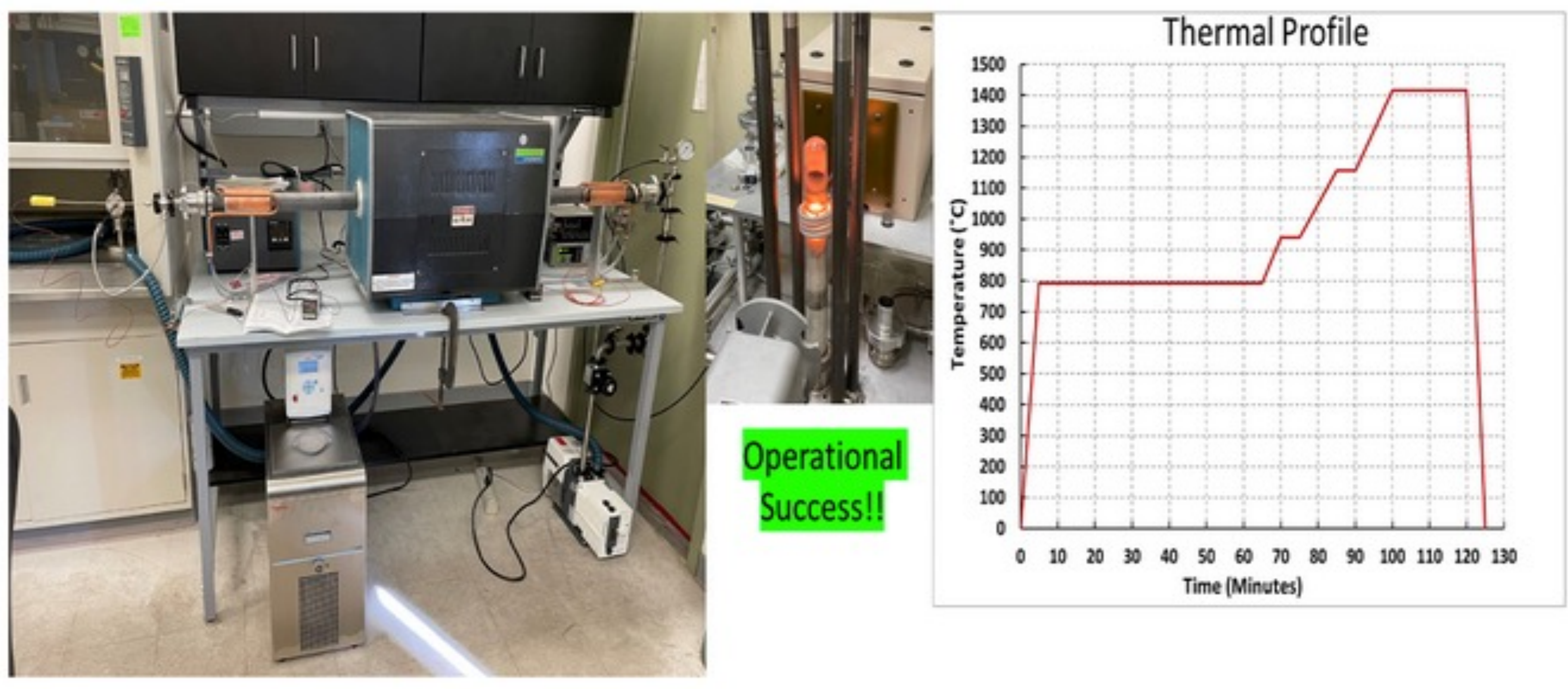

Figure 1 Operational Lunar Simulant Reactor

Approach: Currently, the two most viable methods of producing lunar simulants are either mined from the field or synthetically produced in the lab. FJS-1 and MKS-1 were fabricated in Japan and designed specifically for engineering use only due to differences from actual lunar regolith. JSC-1 was mined from volcanic ashes and crushed to proper grain sizes for laboratory and engineering use; this simulant exhibited the approximate geotechnical soil properties of lunar soils. However, availability for distribution to the lunar scientific and engineering community was obviously limited and none is available today. Finally, the lunar simulant CAS-1 was recently discovered in northeast China, but is obviously not available for NASA use due to reasons associated with political and economic rivalry. Our fabrication method develops a new (more optimized) lunar simulant with similar chemical compositions in-house at JPL by the method of microwave sintering process using the most advanced "custom-made" hardware (induction furnace + reduction reactor system). This process includes critical steps of ball milling to refine feedstock materials homogeneity, induction melting at about 1100 o C to produce raw simulants, and hydrogen reduction step at about 1000 o C to remove further impurities and/or chemical volatiles.

	JPL-Stock-01	JPL-LF1Silica-01	JPL-WS-01
Mixture	Stock materials purchased from Sigma-Aldrich	LF1 sample + stock SiO_2 powder	Slag + fly ash
Sample weight (g)	~2.5	~2.5	~2.5
Equipment	RF reactor	RF reactor	RF reactor
Sintering temperature (°C)	~1400	~1400	~1400
Powder particle size (microns)	>100	>100	~0.1*

*powder particle size can be manipulated by ball-milling time

Table 1: Laboratory Results

Results: The dedicated lunar simulant reactor was successfully assembled, and functionally tested (Figure 1). Figure 2 highlights test runs on lunar simulants for morphological, micro-structural, and chemical comparisons to those produced at JPL by XRD and microscopy imaging techniques, including JSC-1 for benchmarking purposes; the SEM image provides indications on the presence of Olivine [(Mg, Fe) 2 SiO 4], Pyroxene [(Ca, Mg, Fe) 2 Si 2 O 6], and Ilmenite (FeTiO 3). We optimized the chemical composition with particular emphasis on infusing glassy materials into the lunar simulant matrix. Table 1 highlights the increasing glassy phase materials on later production runs (#27 to #31) in terms of atomic percentage (%) using Enegy Desperive X-ray Analysis (EDAX). In Figure 3, a high-resolution electronic image confirms the fine-grained lunar simulant was infused with SiO 2 producing a desirable amorphous material highly more suitable for geotechnical applications. The new lunar simulant reactor testbed produce a rate of 5-10 mg/run (run = 2-4 hours). Figure 4 shows our simulation results of the chemical reactions between an g-Fe 2 O 3 nanoparticle (NP) of lunar simulant materials and water at room temperature (298.15 K) using the atomistic reactive force field molecular dynamics (ReaxFF MD) simulations. To understand the initial stage of iron oxide NP surface's hydrothermal reactions, we solvated a bare iron oxide NP, which was directly cut from the g-Fe 2 O crystal lattice. Our simulations revealed that the Fe atom with dangling bonds on the particle's surface is oxidized by water, forming a chemical bond between an Fe atom and an O atom or H atom of water (i.e., chemical adsorption of water) within 220 ps. As the temperature increases up to 800 K, the structure iron oxide NP becomes disordered and the NP surfaces are more oxidized by surrounding water molecules.

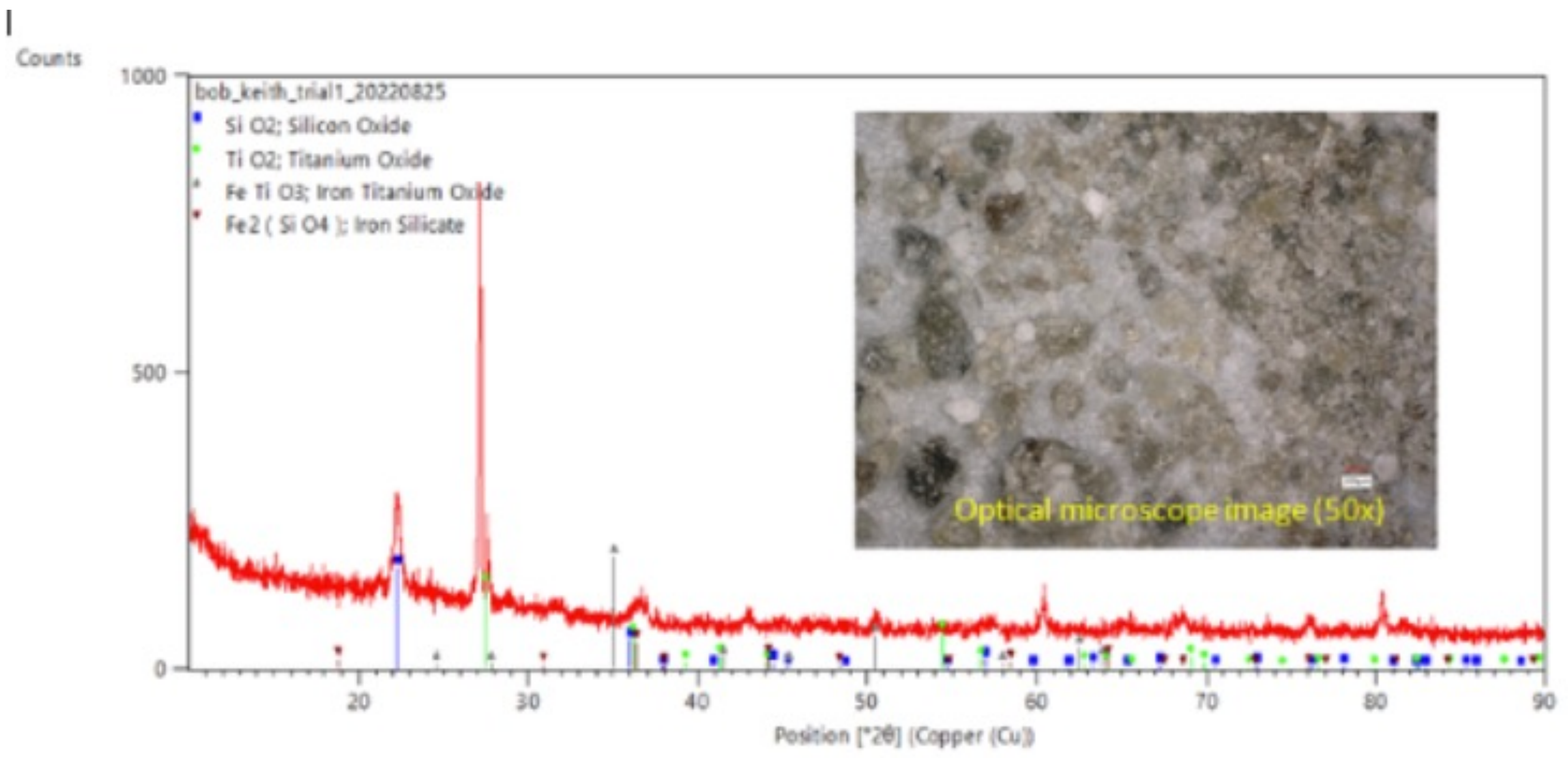

Figure 2. XRD compositional analysis of baseline lunar simulant sample from JPL's reactor testbed. The SEM image highlights the amorphous nature of sintered materials on simulant production runs.

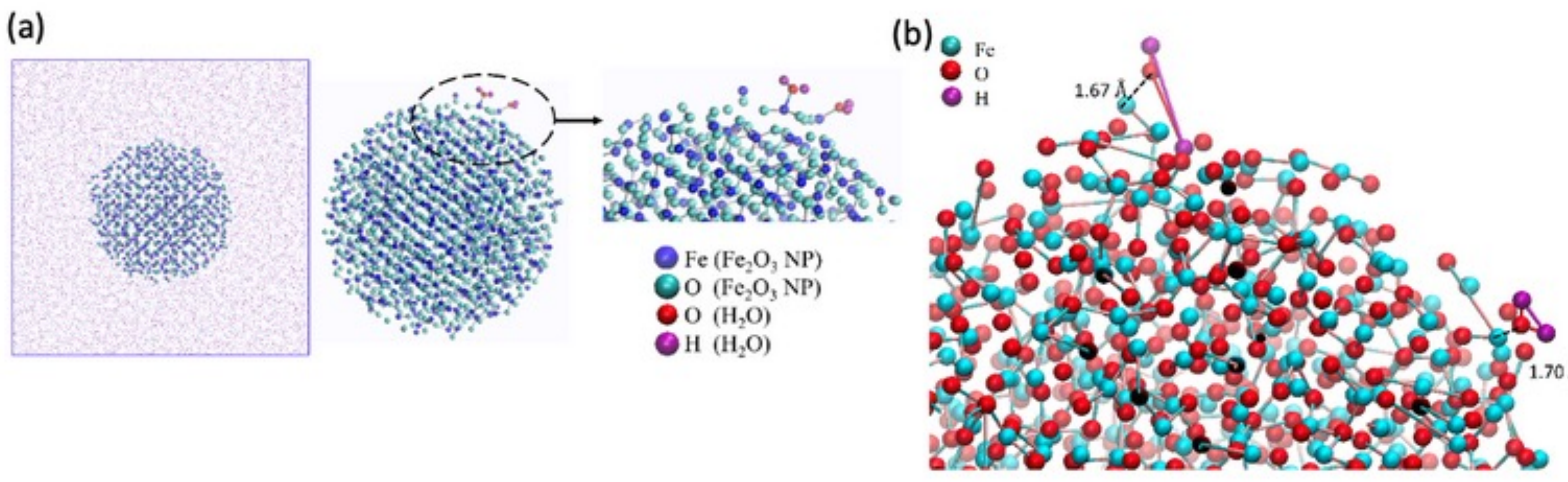

Figure 4. Atomistic ReaxFF MD simulations of the g-Fe2O3 NP (3.2 nm) of a baseline soil analog material interacting with water at 298.15 K. Chemical adsorption of water is observed on the NP surfaces. This type of molecular modeling technique provides crucial details on water/soil geological systems emanating at the quantum and molecular levels which not achievable by macroscopic measurement techniques.

Mission relevance: NASA already has several proposed missions to the moon, and our work will fulfill an important need of detailed characterization of lunar regolith compositions and physical properties critical to many applied areas in lunar science, ISRU, space engineering, and all future science missions involving surface or near surface contact. In addition, the validation of future rover concepts and operations will rely on a comprehensive determination of the strength and deformation behavior of soil-like lunar materials within its many localized environments.

Significance: At the same time, protection of moving parts against fine-grained regolith (dust) is a major challenge for hardware on the lunar surface. Such factors involving detailed understanding the mechanical and physical properties of the regolith are part of geo-technical interrogation critically needed for future lunar missions, and will also be fulfilled as part of our proposed work.

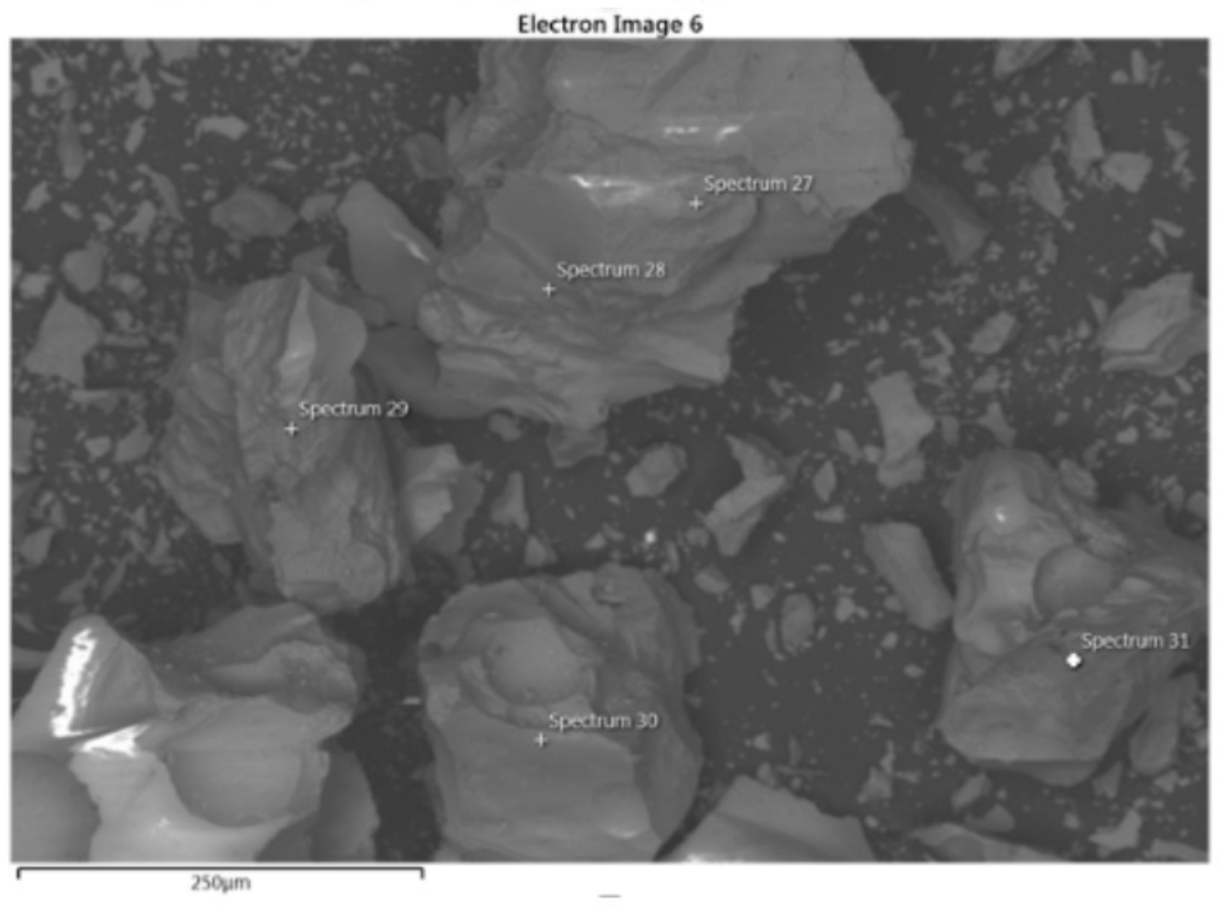

Figure 3. EDAX image validates the presence of glassy phase infused within the lunar simulants developed at JPL

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Clearance Number: CL#00-0000
Poster Number: RPC#