Developing Lunar Dust Simulants: Current Status and Plans

Robert (Bob) Gustafson
Principal Aerospace Engineer
Orbital Technologies Corporation
gustafsonr@orbitec.com

Phase 1 SBIR Project Objectives

- Demonstrate the technical feasibility of manufacturing a new high-fidelity lunar dust simulant that better matches the unique properties of lunar dust than existing simulant materials
- There are three primary characteristics that a high-fidelity lunar dust simulant should attempt to reproduce
  - Particle Size Distribution (at least the range of particle sizes)
  - Composition
  - Morphology
- If a lunar dust simulant matches the primary characteristics, it should also match many of the important secondary characteristics, including electrostatic, magnetic, abrasion, and toxicity properties

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Characteristics of Lunar Dust

(Requirements for a Lunar Dust Simulant)

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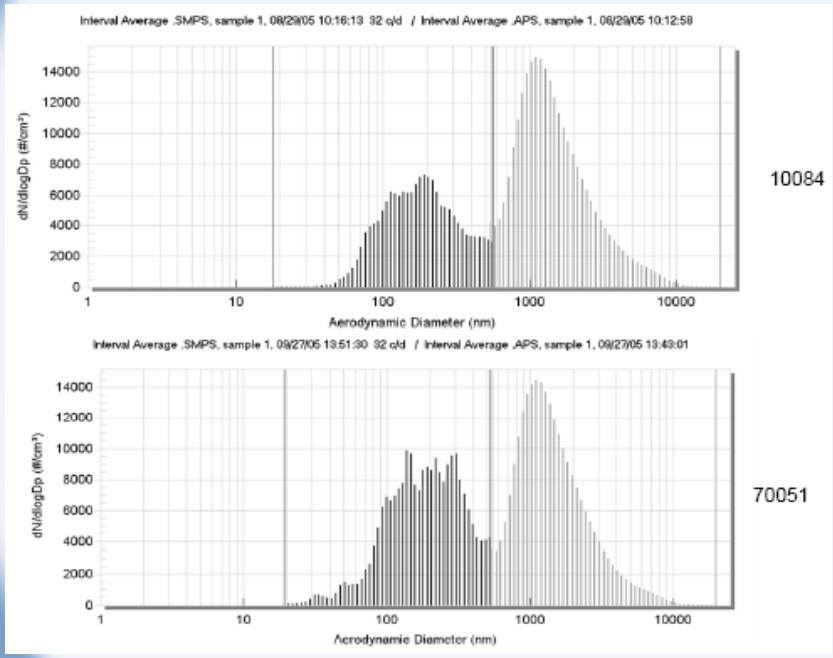
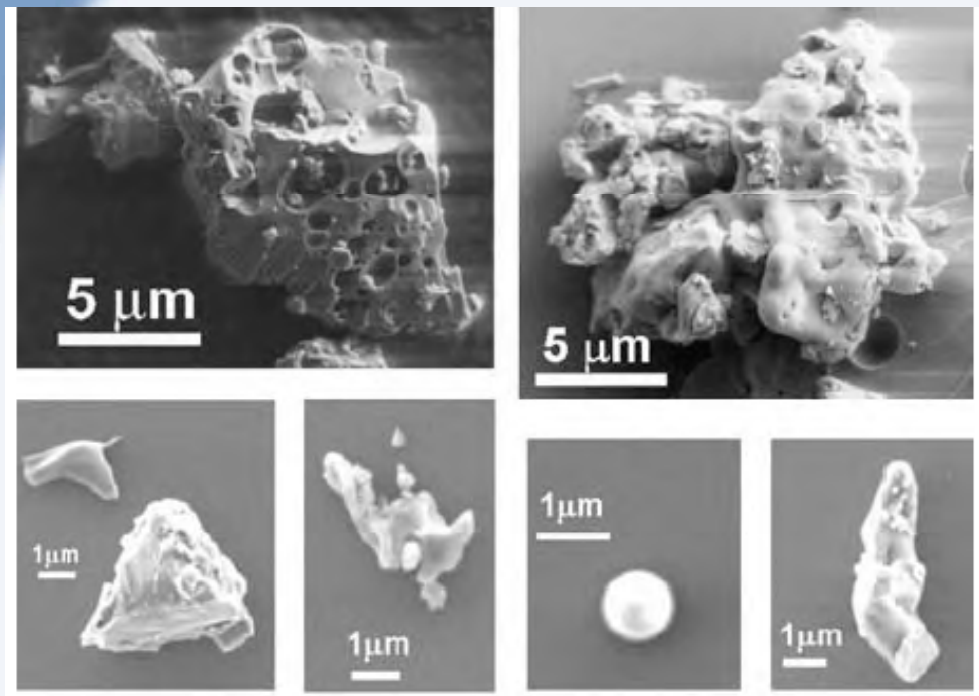
Particle Size Distribution of Lunar Dust

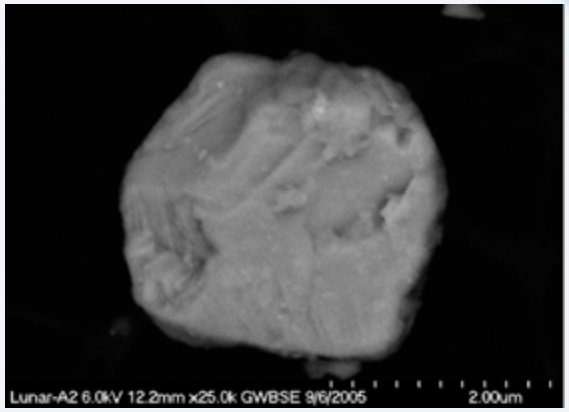


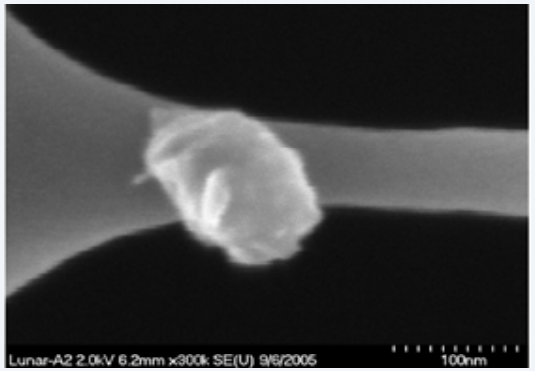
- The particle size distributions for two Apollo samples (<20µm) were measured using gas phase dispersal and aerosol measurement techniques (Greenberg et al., 2007)
  - Most of the particles in the Apollo samples were found to be in the 40 nm – 5 µm range
  - A significant number of ultrafine (20 – 100 nm) and fine (100 nm – 20 um) particles are present in the regolith

Morphology of Lunar Dust Grains



SEM images of Apollo 17 Lunar Dust 70051
(Park et al., 2006)





Typical Shapes of 2.5 μm (top) and 100 nm (bottom) Lunar Dust Particles
(Greenberg et al., 2007)

- The shapes of lunar dust grains are variable, ranging from spherical to extremely angular
- Typical lunar dust grains in the smallest size fractions are slightly elongated, but not highly complex

Composition of Lunar Dust

- Broken pieces of agglutinitic glass make up 70-90% of the lunar dust (Taylor and James, 2006)
- The glassy portion of lunar agglutinates contains numerous metallic iron (Fe^0) globules
  - Single domain iron globules ~3 – 30 nm in diameter (nanophase iron)
  - Multi-domain iron globules 30 nm – 1 μm in diameter

Process to Create a Lunar Dust Simulant

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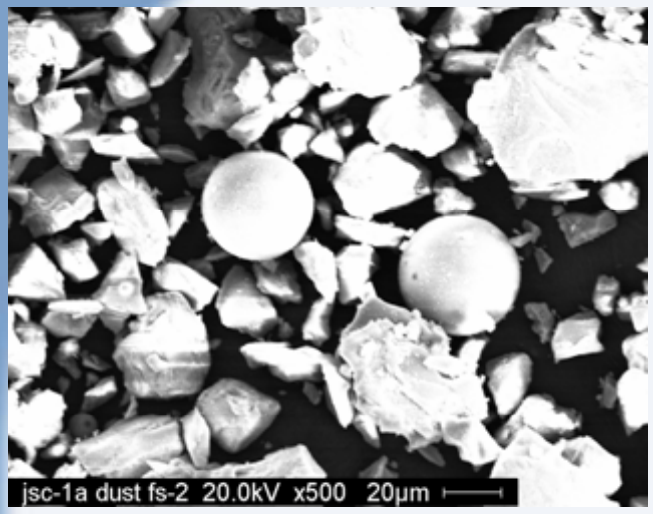
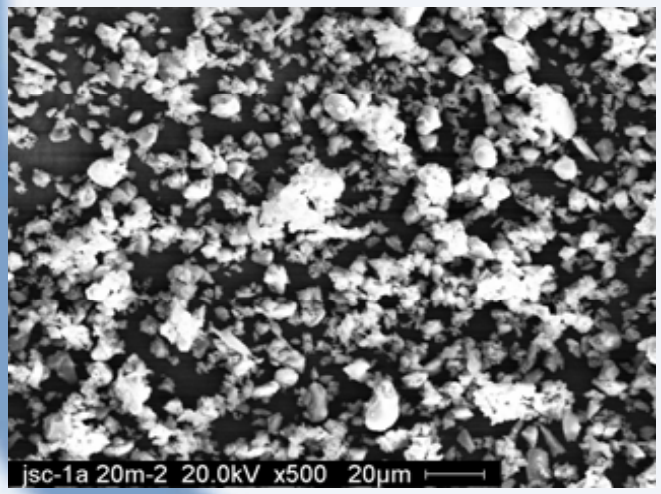
Two-Step Process to Create a Lunar Dust Simulant



Processed JSC-1A Before Grinding



Processed JSC-1A After Grinding

- Step 1. Create feedstock material that contains simulated agglutinates and glass spherules containing Fe-rich globules
- Step 2. Grind the feedstock material to the desired particle size distribution

SEM Images of the Processed JSC-1A Simulant Before and After Grinding
(Images courtesy of the NASA Glenn Research Center)

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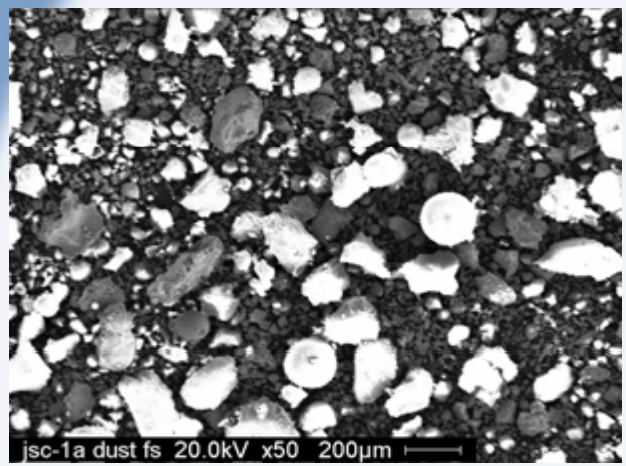
Characteristics of the Feedstock Material



SEM Images of the Processed JSC-1A Simulant
(Images courtesy of the NASA Glenn Research Center)

- The feedstock material for the first two lunar dust prototypes was made with JSC-1A lunar regolith simulant
- The processed JSC-1A simulant contains numerous glass spherules 20-50 µm in diameter, as well as more irregular glassy particles with admixures of un-melted grains
- Glass spherules as small as 5 microns in diameter were also observed
- The processed JSC-1A simulant also contains sub-spherical glassy grains and glass shards

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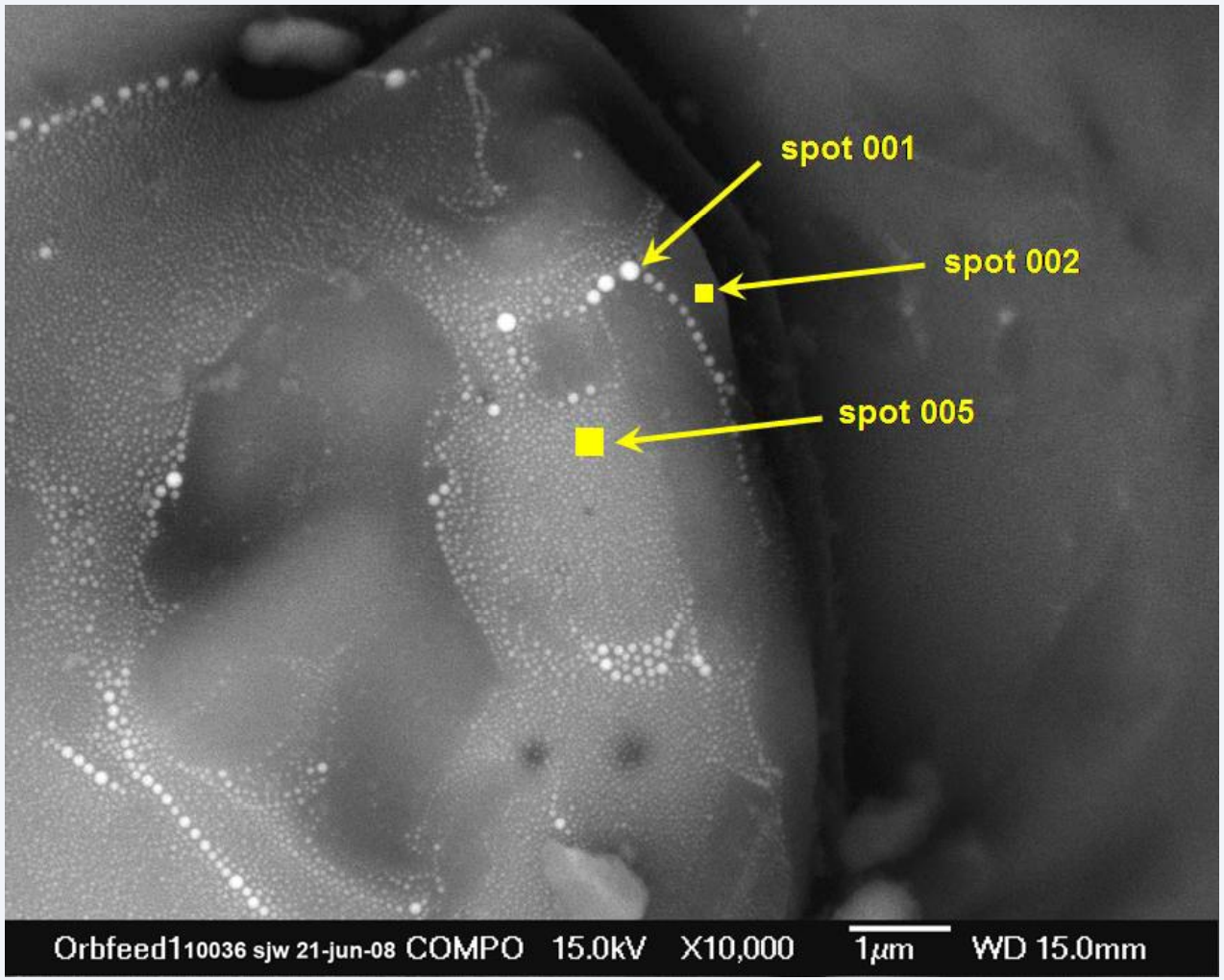
Fe-Rich Globules on Feedstock Material



Fe-SEM Image of the Numerous Fe-rich Globules Present in the JSC-1A-5000-2X Feedstock Material
[Image courtesy of the NASA Johnson Space Center]

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Step 2. Grind Feedstock Material

- ~2 kg of processed JSC-1A was sent to a toll processing facility to perform a grinding feasibility test
- ~900 g of feedstock material was used under different conditions to produce ~675 g of prototype lunar dust simulants

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Characteristics of the Prototype Lunar Dust Simulants

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Analyses of Prototype Lunar Dust Simulants

- Two different lunar dust simulants produced from JSC-1A were selected for analysis
- Samples of the processed JSC-1A and the two prototype lunar dust simulants were sent to several NASA centers for analysis
  - Particle size distribution via laser diffraction and aerosol measurement techniques (analysis completed)
  - Optical, SEM, TEM images to evaluate particle morphology and the presence of metallic iron globules (some analysis completed)
  - Total iron content measurement via destructive Inductively Coupled Plasma (analysis completed)
  - Mossbauer Spectroscopy and magnetic susceptibility measurements to help quantify the amount of metallic iron present (analysis not performed)
  - X-ray Diffraction to measure mineral composition (analysis completed)
  - X-Ray Fluorescence to measure the amount of contamination introduced by the milling process (analysis completed)
  - Dielectric, resistivity, and charge decay tests on the samples under vacuum conditions (10^{-5} torr) (analysis not completed)

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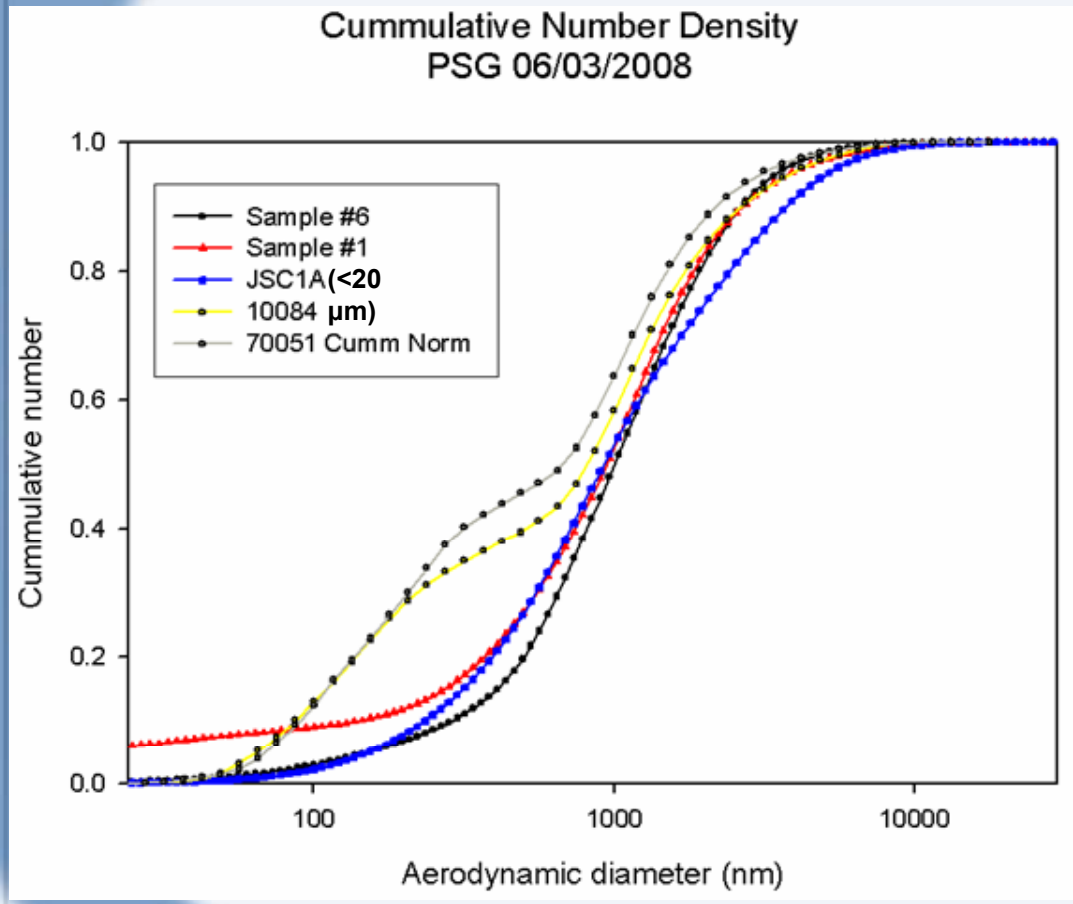
Lunar Dust Simulant vs. Apollo Samples



Courtesy of Paul Greenberg, NASA Glenn Research Center

- The cumulative number densities of the dust simulants were compared with JSC-1A and two Apollo samples (10084 and 70051)
  - JSC-1A and Apollo samples sieved below 20 µm
- Particles >1 µm
  - Similar cumulative number densities
- Particles 100 nm to 1 µm
  - Number densities in the dust simulants are significantly lower than the Apollo samples
- Particles <100 nm
  - Number densities in dust simulant #1 are higher than the Apollo samples

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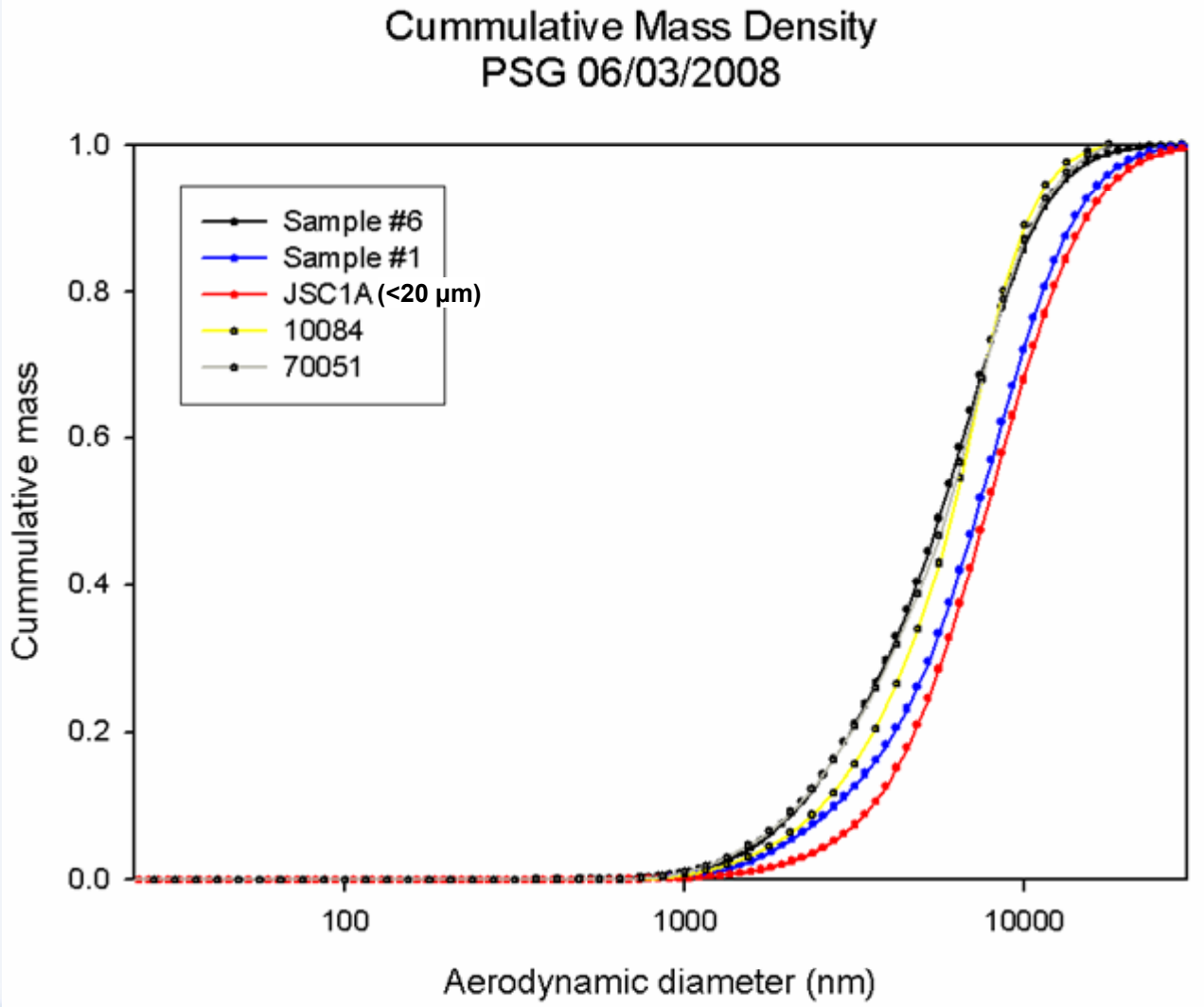
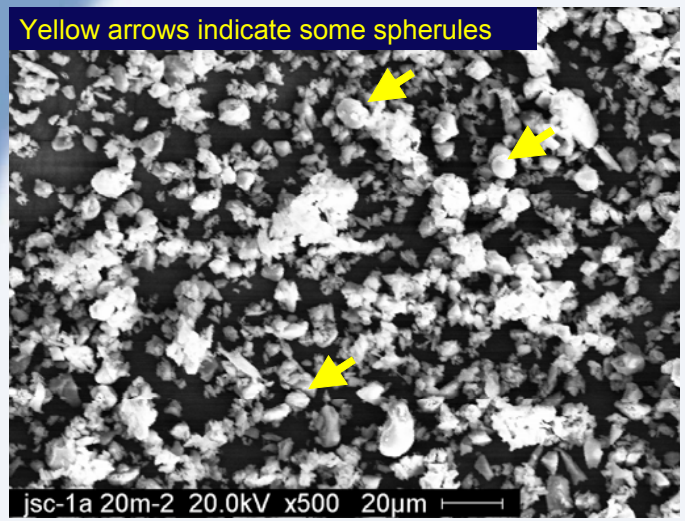
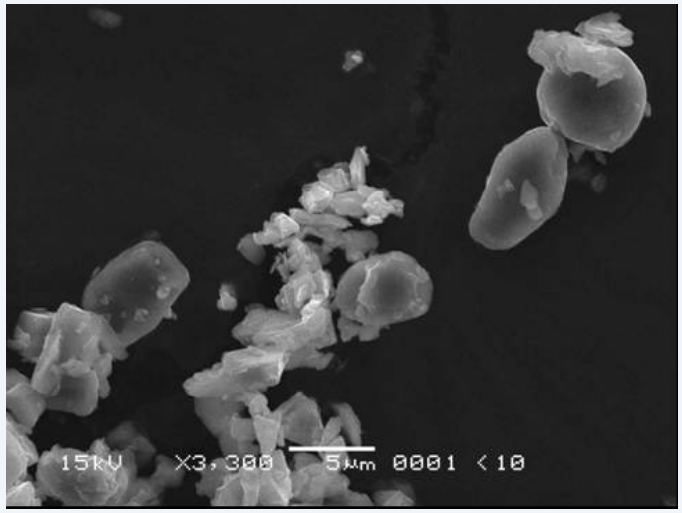
Lunar Dust Simulant vs. Apollo Samples

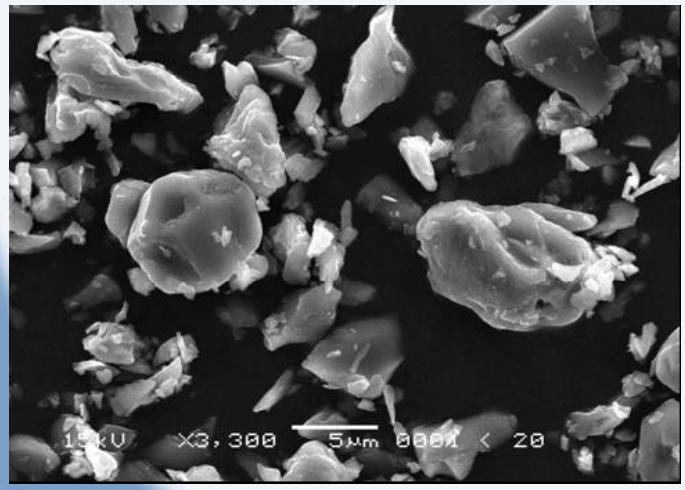


Courtesy of Paul Greenberg, NASA Glenn Research Center

Dust Simulant Particle Morphology







- Some of the very small glass spherules (~5 µm) in the feedstock material remain intact after the grinding process
- The dust simulants contain a variety of shapes, ranging from spherical to very angular
- The same range of particle shapes have been observed in the lunar dust

SEM Images of the Prototype Dust Simulant #6
(courtesy of the NASA Glenn Research Center and Johnson Space Center)

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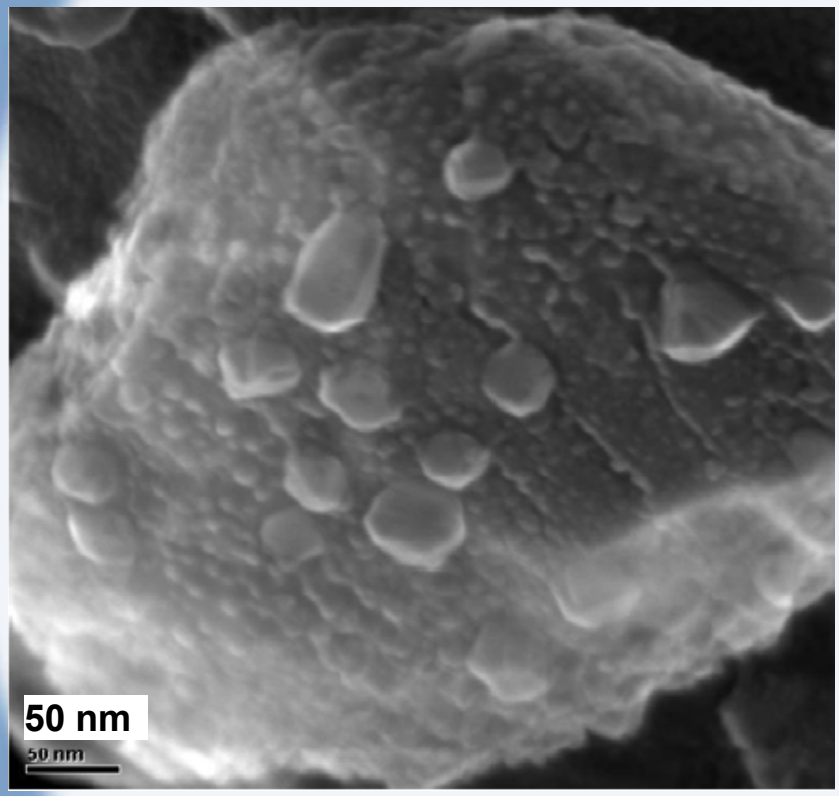
Evidence of Nanophase Fe^0



SEM Image of a Grain of the Dust Simulant #6
(Image courtesy of R. Christoffersen, NASA Lyndon B. Johnson Space Center)

- Preliminary scanning electron microscope (SEM) backscattered electron images resolved droplet-shaped Fe-rich globules that appear to be nanophase Fe^0 on the surface of the larger glass particles
- The sub-micron grain shown appears to be covered with relatively large nanophase iron droplets (25-40 nm) and very small droplets (5-10 nm)
- Preliminary analytical scanning transmission electron microscope (STEM) observations indicate that the relative amount of glass with Fe-rich globules is lower for the finest size fractions
- Probably indicates that the unmelted portion of the feedstock is preferentially being ground into the smallest size fraction

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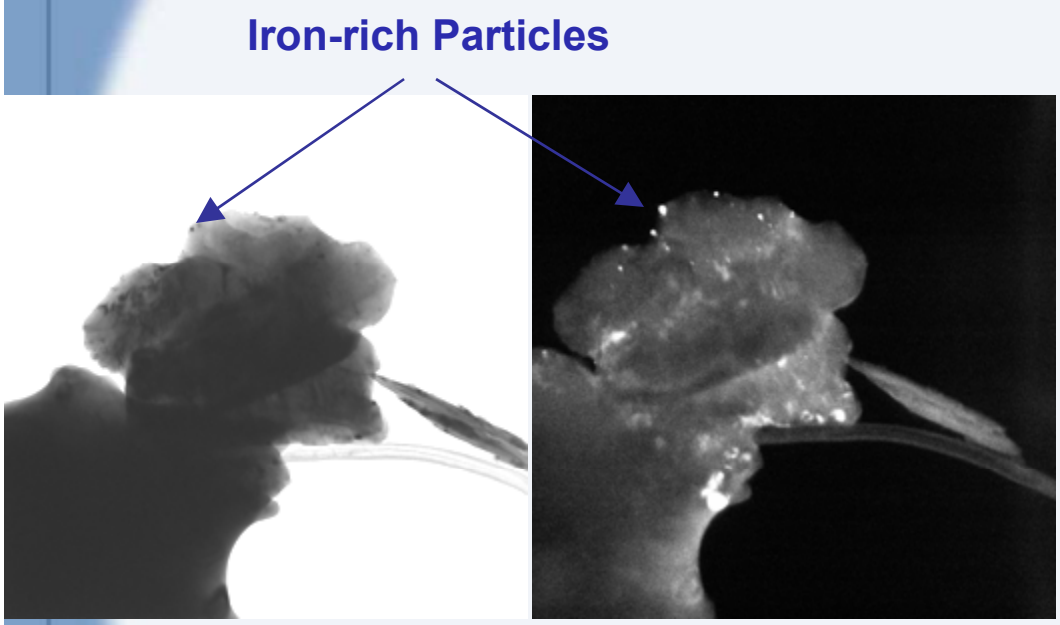
Evidence of Nanophase Fe^0

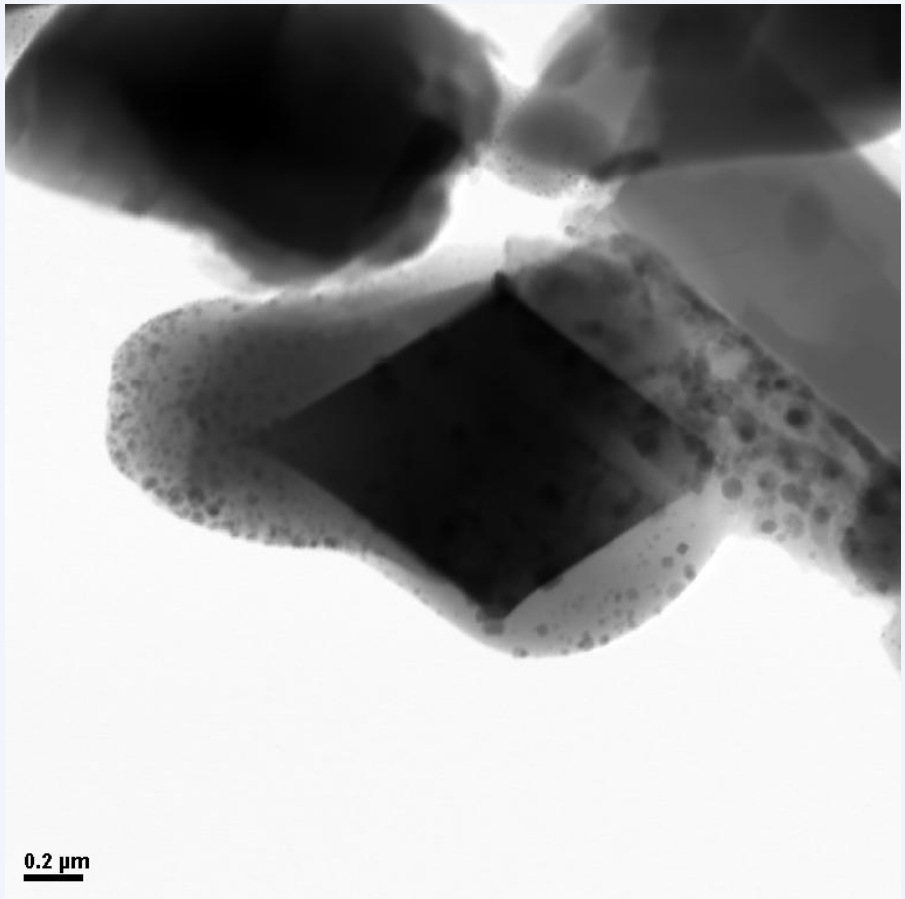


Bright Field **Dark Field**

TEM Image of a Grain of the Dust Simulant #6
(Image courtesy of the NASA Glenn Research Center)

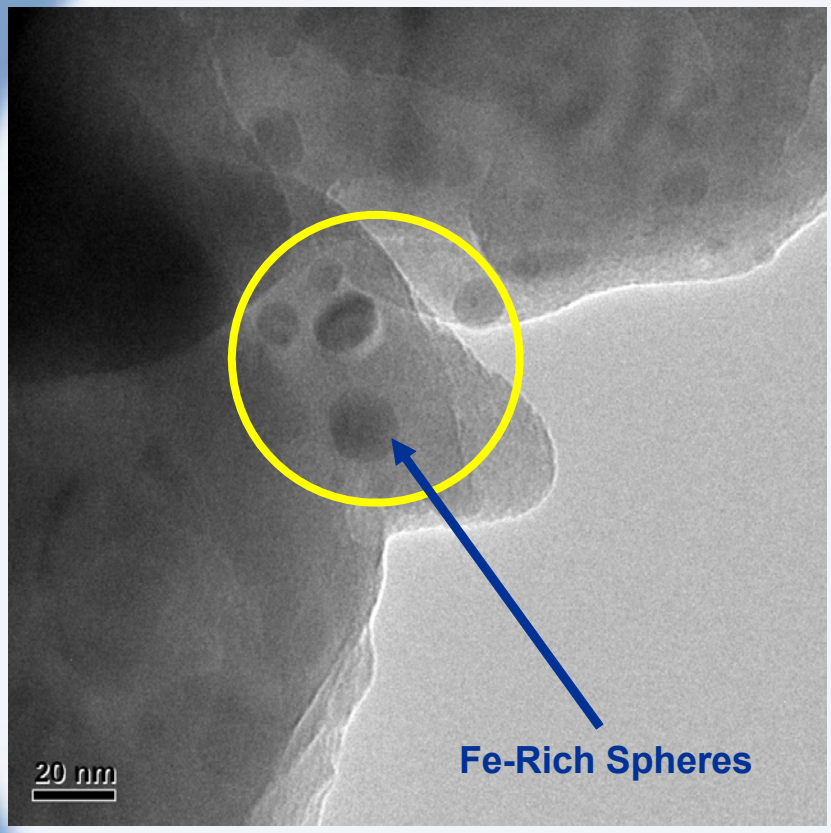
- Transmission electron microscopy (TEM) analyses were performed on the dust simulants to investigate the presence of nanophase Fe^0
- Fe-rich particles <20 nm were observed in the lunar dust simulant grains, very similar to previous observations in simulated agglutinate particles
- The most likely form of the Fe-rich particles is Fe^0 located on and within glassy grains, but the exact composition of the Fe-rich particles has not yet been determined
  - Attempts to measure the electron diffraction pattern of the Fe-rich particles caused the grains to melt

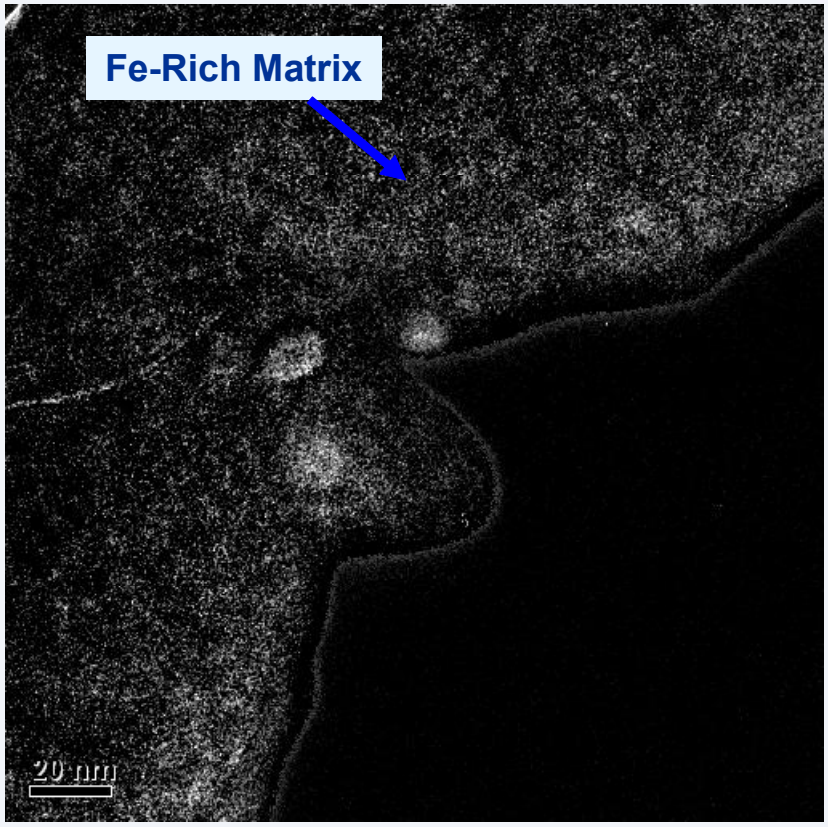
Evidence of Nanophase Fe^0



STEM Bright-Field Image of Euhedral Fe-oxide Crystal enclosed in Silicate glass with Nanophase Grains (EDS analyses indicate nanophase grains are primarily Fe^0 mixed with some Fe-oxide)
[Image courtesy of the NASA Johnson Space Center]

Evidence of Nanophase Fe^0





Bright Field TEM

Fe Map – Gatan Image Filter

TEM Image and Iron Map of Iron-Rich Nanophase Spheres in the JSC-1A-DUST-06 Prototype Lunar Dust Simulant (Image courtesy of the NASA Glenn Research Center)

Conclusions from Phase 1 Work

- Based on the analytical data received to date, it appears to be technically feasible to create a high-fidelity lunar dust simulant
- The prototype lunar dust simulants that were created from JSC-1A lunar regolith simulant have some important similarities to lunar dust
  - The range of particles sizes in the dust simulants is similar to those observed in lunar dust, although the PSD is different
  - The dust simulants contain particles with shapes ranging from spherical to angular, similar to lunar dust particles
  - The glassy particles in the lunar dust simulant contain Fe-rich globules (ranging from ~5 nm – 1 μm), similar to those observed in lunar agglutinates
- Additional analyses are required to help refine the manufacturing process in Phase 2
  - Mossbauer spectroscopy and/or ferromagnetic resonance is needed to quantify the metallic iron content and compare to lunar dust

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HLDS Phase 2 Objectives

- Determine the requirements for the high-fidelity lunar dust simulant that will be delivered to NASA during the Phase 2 effort;
- Refine the manufacturing process for the high-fidelity lunar dust simulant;
- Create an improved prototype lunar dust simulant based on the knowledge gained during Phase 1;
- Distribute samples of the improved prototype lunar dust simulant to lunar dust experts for characterization and evaluation;
- Finalize the manufacturing process for the high-fidelity lunar dust simulant;
- Produce a significant amount of high-fidelity lunar dust simulant;
- Characterize and evaluate the high-fidelity lunar dust simulant;
- Distribute allocations of the high-fidelity lunar dust simulant to users approved by NASA and deliver any unallocated amount to NASA for future applications.

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HLDS Phase 2 Project Schedule

Work Task	Project Quarter							
	1	2	3	4	5	6	7	8
Task 1. Requirements for the Deliverable Lunar Dust Simulant								
Task 2. Refine the Manufacturing Process								
Task 3. Create an Improved Prototype Lunar Dust Simulant								
Task 4. Characterize the Improved Prototype Lunar Dust Simulant								
Task 5. Finalize the Manufacturing Process								
Task 6. Produce the Deliverable Lunar Dust Simulant								
Task 7. Characterize the Deliverable Lunar Dust Simulant								
Task 8. Distribute the High-Fidelity Lunar Dust Simulant								
Task 9. Project Management/Reporting								

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