MICRO-MORPHOLOGY AND TOXICOLOGICAL EFFECTS OF LUNAR DUST.

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Introduction: The Moon is being considered as an effective test-bed and fueling station for future space missions to Mars and beyond, with In-Situ Resource Utilization (ISRU) of lunar materials [1]. From the Apollo missions, however, it is well known that dust on the Moon can cause serious problems for human's exploration activities [2]. One of the paramount problems is the potential for a toxic nature of lunar dust, the <20 μm fraction of the regolith.

In 1972, two astronauts Harrison Schmitt and Gene Cernan, commander of Apollo 17, reported that the air in their Lunar Module (LM), the *Challenger*, smelled like "gun-powder". The two astronauts had just returned from their first EVA (Extra-Vehicular Activity) with dusty spacesuits. In the LM, the dust became airborne and was breathed by them. Later, Schmidt complained of congestion and fever, although his symptoms went away shortly.

Armed with our knowledge of the chemical and physical properties of the lunar dust [3], it has become apparent that there may be acute toxicological effects to humans with breathing of the lunar dust. An important first step in dealing with dust toxicity is to fully characterize the morphology, size distribution, and reactivation surface area of dust particles.

We shall briefly describe about the possible toxicity and particle size and shape of lunar dust, and explain the detailed experimental methods of particle-size measurement, and report on the particle-size distribution (PSD) and reactivation surface areas.

Toxicity: With terrestrial interests in dust toxicity, there have been numerous studies in PSDs and health effects of dust particulates in air pollution [4,5]. In fact, dust particles on Earth have been shown to result in pulmonary diseases such as silicosis, asbestosis, and black lung disease with miners, in general. In the case of ultra-fine (<0.1μm) particulates, they could be easily inhaled and deposited in alveolar sacs and ducts of human lungs, and might be a cause of a progressive lung failure or cancer by a fibrogenic reaction, and pass into the blood stream, or enter into the lymphatic system [2].

Particle Size (Granulometry): The sizes of inhalable particles are distinguished with different ranges of particle diameters: coarse (D >2.5μm), fine (2.5μm > D > 0.1μm), and ultra-fine (D <0.1μm) [6]. The granulometry of particles can be determined by different methods such as sieve analysis, image analysis, laser analysis, etc. In this study, the microscopic imaging method using scanning electron microscopy (SEM) was used to measure the PSD of lunar dust particles in Apollo 17 soil, 70051.

Particle Shape (Morphology): Figure 1 shows SEM images of lunar dust particles in Apollo 17 soil, 70051. Most of particles show sub-angular to angular shapes with sharp edges. There are four prominent shapes: 1) spherical; 2) angular blocks; 3) glass shards; and 4) irregular (ropey or Swiss-cheese). In particular, submicron bubbles and cracks are present in most grains. This causes a multiplication of the reactivation surface area. In case of lunar soil simulant (JSC-1), the similar morphology of grains was observed [7], minus the submicron bubbles and the swiss-cheese morphology. It is obvious that considerations for lunar dust mitigation must factor in the sharp edges of the glass fragments and unique morphological characteristics of lunar dust particles [8].

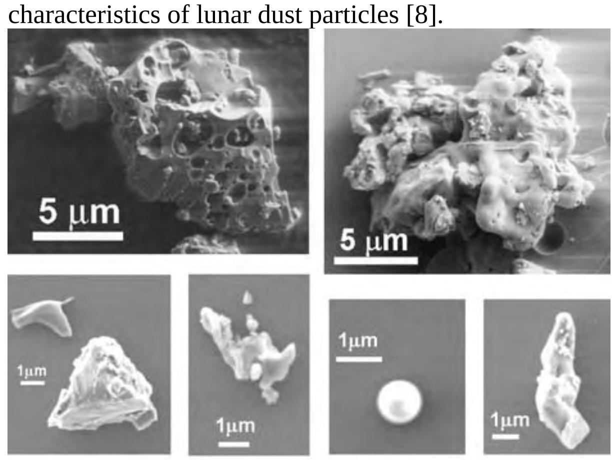


Figure 1. SEM images of Apollo 17 lunar dust 70051.

Experiment Methods

SEM sample preparation: The sample for the SEM was prepared with a method that was experimentally determined to give the best degree of dispersion of the grains; this involved a surfactant solution, with sonication, and deposition on a silicon wafer under influence of a magnet. In order to prevent dust particles from agglomerating, we used a dispersive surfactant-solution that was made of poly N-vinylpyrrolidone with a concentration of 0.02 % wt/v dissolved in 100 % isopropyl alcohol. A small fraction (~10 mg) of lunar particles was dispersed in the surfactant solution of 10 ml. The particle dispersion was treated with a bath-type ultrasonic cleaner for ~ 30 minutes.

After sonication, the lunar particle dispersion was immediately taken with a micro-pipet and a small fraction (~ 5 μl) of the dispersion was dropped on a pre-cleaned silicon wafer. A single drop of the particle-alcohol dispersion expanded gradually up to 2 cm diameter on the silicon wafer and began to evaporate. However, it was obvious that dispersion particles aggregated during the alcohol evaporation. The ferromagnetic nature of lunar dust was then considered in solving the aggregation problem [2]. A cylindrical magnet (D = 1 cm) was placed under the silicon wafer, which greatly aided sticking of the dust grains to the silicon surface, thereby preventing aggregation.

SEM imaging: A series of images was taken along the radial direction of the circular-shaped dispersion specimen (i.e., from center to periphery). Since the field of view of the SEM is considerably smaller than the entire area of dispersion specimen, selected sections were scanned at different radial distances and directions from the center, like spokes on a bicycle wheel. The number of particles in each section was multiplied by a differential in order to properly "weigh" the respective areas relative to their positions from the center. These data manipulations compensated for the low statistics of measurement data.

In the image processing, we used a commercial program 'Scion image' to measure the areas and perimeters of particles. The diameters of particles were obtained from the measured areas based on the assumption that all particles are circular.

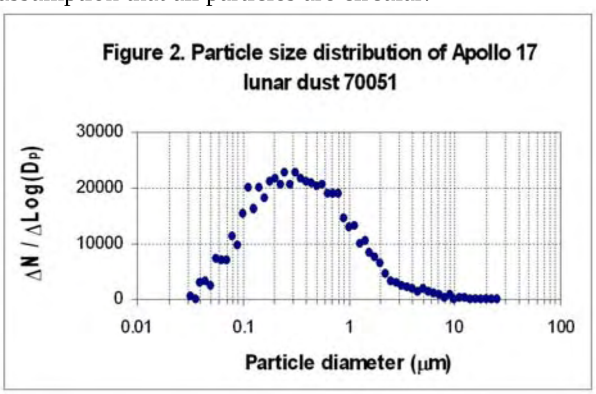
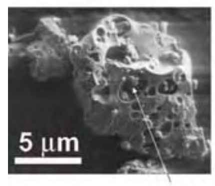


Figure 2. Particle size distribution of Apollo 17 lunar dust 70051

Particle Size Distribution (PSD): The SEM measurements captured about 1000 images with two different magnifications and counted more than 5000 particles of a size range from 30 nm to 25 µm. Figure 2 presents the PSD of Apollo 17 lunar dust particles. The measured PSD data show a peak near 300-nm and can be represented as a simple Gaussian distribution having a single mode. In the SEM sample the area of sections scanned with the 1000 images corresponds to ~0.8% of entire dispersion-area of dust particles. The total number of the dispersion particles might be about 6.5 $\times 10^5$.

The weaknesses of this SEM measurement are in the extremely time-consuming process and the low statistics of the measured particles comparing with millions of particles dispersed on the entire area of specimen. In addition, there are uncertainties of size distribution due to the small fraction of measurement area and a measurement resolution corresponding to an image-pixel size of ~20 nm.

Reactivation Surface Area: Due to the unique features of lunar soil, with the "Swiss-cheese" texture and the presence of porous agglutinate particles, the reactivation surface areas of a grain can be considerably larger than that of a purely spherical particle of the same diameter. Figure 3 illustrates a 26% increase in surface area caused by vesicles of the "Swiss-cheese" morphology. Depending on the textile of the particle, the ratio of the reactivation surface area to the volume of particle may increase up to 10 times higher than a sphere.



	Vesicles [a]	Particle [b]	Ratio (a/b)
Area (µm²)	20.33	79.63	0.26
Perimeter (µm)	85.64	38.46	2.23

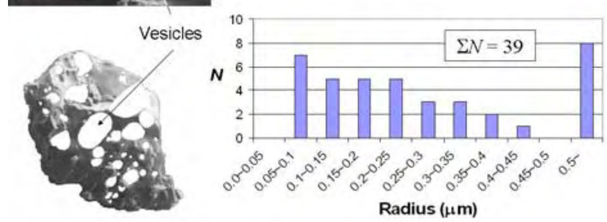


Figure 3. Reactivation surface area of "Swiss-cheese" lunar particles

Conclusive Remarks: The particle size distribution of the lunar dust from Apollo 17 sample 77051 has been determined using SEM imaging analysis. The size-distribution data features an approximate Gaussian distribution with a single mode at around 300-nm. The reactivation surface area of highly porous "Swiss-cheese" particles is about 26% higher than a sphere. The morphologies of dust grains have been classified based upon their four types: 1) spherical; 2) angular blocks; 3) glass shards; and 4) irregular (ropey or Swiss-cheese). These data will assist the medical researchers in their studies of the toxicological effects of inhalation of lunar dust by humans.

References: [1] Taylor L.A. and Meek T.T. (2005) *J. Aerosp. Engr. 18*, No.3, 188-196; [2] Taylor L.A. et al. (2005) *AIAA-1st Space Explor. Conf.*, CD-ROM, 2005-2501; [3] Heiken G.H. et al. (1991) *Lunar sourcebook a user's guide to the Moon*; [4] Christopher C.D. et al. (2003) *Inhalation Toxicology, 15*, 539-552; [5] Gunter O. (2001) *Int. Arch. Occup. Environ. Health., 74*, 1-8; [6] Banfield J.F. and Navrotsky A. (2001) *Reviews in mineralogy and geochemistry*, *44*, pp. 293; [7] Liu Y. et al (2005) *68th Annual Meteoritical Society Meeting*, 5207; [8] Liu Y. et al. (2006) *ASCE 2006.*