Lunar Dust Characteristics and the Health Consequences of Human Exposure. Peter A. Sim, MD, FACEP, Emergency Department, Riverside Regional Medical Center, 500 J. Clyde Morris Blvd, Newport News, VA 23601 peteralansim@gmail.com

Introduction: Lunar dust is powdery and very fine. Individual grains are jagged, sharp, abrasive and stick electrostatically to most everything. Human contact with lunar dust has only occurred briefly, during the Apollo missions. Apollo 17 LM pilot Harrison Schmitt's exposure resulted in symptoms he described as "lunar hay fever" [1]. NASA's return to the moon under the Artemis program is scheduled for 2024. In the 47 years since Apollo 17, returned samples of lunar regolith and dust have been exhaustively analyzed, but there are still important gaps in our knowledge. This discussion will focus primarily on what we currently do know about dust on the moon, and the deducible potential toxic health effects of exposure. The respiratory system is most at-risk, but the eyes and skin will also be affected. Obviously, prevention of exposure should be the primary objective, but plans to minimize and mitigate inevitable exposures must be in place. Keeping habitats dust-free will be a major challenge.

Determinants of Lunar Dust Toxicity: Key characteristics to consider are: 1) particle size; 2) particle morphology/surface reactivity; and 3) chemical composition.

Particle Size. The median particle size of lunar dust averages 70 µm, and 10%-20% of the soil is finer than 20 µm [2]. Particle size is a key factor in toxicity studies because it defines transport pathways into the lung. The total inhalable dust fraction is that portion of airborne material which enters the nose and mouth during breathing, and is therefore available for deposition in the respiratory tract. The respirable dust fraction is that smaller-sized portion (considered to be < 5 µm) which penetrates deepest, to the gas exchange region of the lung (the alveoli) [3].

A comprehensive study of the properties and composition of the very small size fraction of lunar dust (particles < 1 µm) is missing [4]. Such a study will be required to bridge the current gap between size fractions relevant to toxicity studies and the currently state-of-the-art work by Taylor and co-workers, that groups all particles < 10 µm as the smallest fraction [5].

The only published study of aerosol transport in lunar gravity [6] showed that while lunar gravity reduced overall deposition, for a given deposition fraction deposition occurred much more peripherally than in 1 G. The same study also showed that the unexpectedly high deposition of small particles (0.5 and 1.0µm) seen in microgravity was still present in a lunar-gravity environment. It must also be kept in mind that the samples of lunar material that were brought back from the moon during the Apollo era were not optimized for studies of their dust component [7].

Morphology/Surface Reactivity. The shapes of individual lunar soil particles are highly variable, ranging from spherical to extremely angular. In general, the particles are somewhat elongated and are subangular to angular [8]. Imaging of lunar dust particles by scanning electron microscopy reveals convoluted surfaces, with sharp edges and microcraters. Although surface shape and surface area are key aspects in dust toxicity research, the surface morphology of lunar dust grains is at present still poorly characterized [9]. Size reduction may lead to an increase in surface reactivity [10].

Environmental conditions that produce reactive sites on lunar dust are diverse, and some examples are solar radiation fluxes, micro-meteoroid impacts, and plasma charging at the terminator [11]. "From what we know about lunar dust, it's fairly reactive and it has properties that are quite similar to fresh fractured quartz here on Earth. And fresh fractured quartz is known to be very toxic" [12].

Because they have not been exposed to radiation and micrometeoroid impacts for the last 46 years, and have not been kept under vacuum, the chemical reactivity of Apollo era lunar samples is not likely to mirror that of lunar material in situ [13]. In 2015, McKay et al separated the respirable dust and other size fractions from an Apollo 14 bulk sample in a dry nitrogen environment. At the end of their study they concluded: "Uncertainty remains as to how well we have simulated the physical and chemical state of fresh lunar dust, which cannot be addressed without fresh lunar soil tested immediately after collection. Such studies must await future lunar sample return missions or in-situ measurements on the lunar surface" [14].

Chemical Composition. It is important to remember that the Apollo samples studied to date are of near-equatorial origin, and their mineralogy and physical properties may not be representative of other areas on the lunar surface including the South Polar region and the floor of the South Pole – Aitken basin, where future landing sites are proposed [15].

Taylor and colleagues suggest that the respirable size fraction of lunar dust is likely dominated by impact glass ($SiO2$, crystalline silica) and rich in metallic (nanophase) iron [5]. A study by Thompson and Christoffersen confirmed that approximately 80 % of submicron dust particles consists of glass [16]. This dominance of extremely small particles, coupled with their abundant np-Fe0 spheres, make lunar dust unique among any dusts breathed by humans during their evolution [14].

Pneumoconiosis Related to Significant Inhalation of Lunar Dust: Pneumoconiosis is irritation and inflammation of the lungs caused by inhalation of dust or other particulate matter, generally over an extended period. Silicosis is a specific pneumoconiosis due to the deposition in the lungs of fine respirable dust containing crystalline silicon dioxide. Silicosis presents as a nodular pulmonary fibrosis, and the most common form of the disorder only develops after decades of exposure, however accelerated silicosis can develop after several months or years of high-level silica dust exposure. The end result is respiratory impairment characterized by dyspnea, hypoxemia, and pulmonary hypertension.

The respirable portion (< 5 µm) of lunar dust is primarily composed of SiO_2, and it will be deposited more peripherally, i.e., more in the alveoli, in lunar gravity (0.166 G) than on Earth. If, as stated above, about 80% of the very smallest (submicron) particles consist of glass, then it follows that development of silicosis would be a definite, and likely increased, hazard compared to a similar exposure on Earth.

Long-term inhalation of silica dust also increases the risk of COPD, lung cancer, autoimmune disease, chronic kidney disease, nocardiosis, systemic sclerosis, rheumatoid arthritis, and tuberculosis [17]. The total silica dose one person accumulates over time is expressed as “mg/m3 years," calculated by multiplying the average exposure each year in mg/m3 by the number of years with that exposure, or by an estimated average for each year. As the total dose increases, so does the likelihood of developing silicosis, lung cancer, or (COPD) [18].

Ocular Toxicity of Lunar Dust: During Apollo missions, lunar dust adherent to spacesuits became airborne when the lunar module left the lunar surface and returned to microgravity on the return trip to Earth, and it was reported to be irritating to the eyes [19]. Crew simply put on their helmets while the dust was cleared by filters in the environmental control and life support system. No injuries were reported in the available NASA records [20].

Corneal abrasions could result from larger dust particles, especially in contact lens wearers. Ready access to goggles, as a preventive measure, and eye irrigation when symptoms occur, will certainly be necessary.

Skin Abrasions: Because of its abrasiveness, lunar dust in contact with the skin may cause abrasions, especially at pressure points inside a spacesuit. Hopefully the new xEMU will minimize this potential. To keep the dust at bay, the xEMU doesn’t have zippers or cables, and its main components are sealed.

Conclusion: Because of its physical and chemical characteristics, lunar dust, in sufficient doses, represents a toxic threat to human health when we return to the moon and establish a long-term presence. The respiratory system is particularly at risk. Prevention of exposure should be our primary goal.

References: [1] NASA, 01.30.06 Apollo Chronicles: The Mysterious Smell of Moondust. [2] Heiken, G. H., Vaniman, D. T., and French, B. M. (1991) *Lunar Sourcebook,* 478. [3] (2004) https://www.proz.com/kudoz/english/science/629936-respirable-dust-inhalable-dust.html [4] Linnarsson, D. et al. (2012) Toxicity of Lunar Dust, *Planetary and Space Science*, 272-273. [5] Taylor, L.A. et al. (2010). Mineralogical and chemical characterization of lunar highland soils: Insights into the space weathering of soils on airless bodies. *J. Geophys. Res.* 115, p.2. [6] Darquenne, C. and Prisk, G. (2008) Deposition of inhaled particles in the human lung is more peripheral in lunar than in normal gravity. *Eur. J. Appl. Physiol.* 103, 687-695. [7] Linnarsson, D. et al. (2012) Toxicity of Lunar Dust, *Planetary and Space Science*, 806-810. [8] Heiken, G. H., Vaniman, D. T., and French, B. M. (1991) *Lunar Sourcebook,* 478. [9] Liu, Y., et al. (2008) Characterization of lunar dust for toxicological studies. II: Morphology and physical characteristics. *J. 1076 Aerosp. Eng.* 21. [10] Fubini, B., et al. (2010) Physicochemical features of engineered nanoparticles relevant to their toxicity. *Nanotoxicology* 4, 347-363. [11] James, J. T. and Kerschmann, R. L. (2008) *NLSI Lunar Science Conference.* [12] Prisk, G. K. (2013) *Courtesy of EarthSky Communications.* [13] Linnarsson, D. et al. (2012) Toxicity of Lunar Dust, *Planetary and Space Science*, 806-810. [14] McKay, D. S. et al (2015) *Acta Astronautica* 107, 174. [15] Linnarsson, D. et al. (2012) Toxicity of Lunar Dust, *Planetary and Space Science*, 277-280. [16] Thompson, M., Christoffersen, R. (2010) The smallest lunar grains: analytical TEM characterization of the sub-micron size fraction of a mare soil. *Lunar Planet. Sci.* 1257 Conf. 41, 2191. [17] Lara A. R. (2018) https://www.merckmanuals.com/professional/pulmonary-disorders/environmental-pulmonary-diseases/silicosis. [18] https://www.silica-safe.org/know-the-hazard/whats-the-risk (2019) The Center for Construction Research and Training. [19] Gaier J. R. (NASA. 2005-213610. The Effects of Lunar Dust on EVA Systems: Lessons Learned from Apollo. [20] Meyers V. E. et al (2012) *BMC Ophthalmology* 12, 26. [21] Grush, L. (2019) NASA unveils future Moon spacesuits that should be ready by 2024. theverge.com