50th International Conference on Environmental Systems
12-15 July 2021 ICES-2021-433

# A Ground Testing Program to Verify Lunar Dust-Tolerant Hardware for the Artemis Mission

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**In preparation for NASA's Artemis Mission that will return humans to the surface of moon by 2024, an extensive test campaign will be undertaken to understand the effects of lunar dust contamination on equipment. Historically, early Apollo astronauts were affected by lunar dust that entered the cabin after their extravehicular activities, and subsequent missions had various cleaning protocols to reduce the impact of the contamination. The longest stays on the lunar surface were Apollo 15, 16, and 17 (just over three days), so equipment and suits were required to operate reliably for a relatively short duration. The ultimate goal of Artemis is a sustained human presence on the lunar surface, beginning with Artemis 3 which targets a six-and-a-half day surface deployment. This requires the design and testing of dust-tolerant infrastructure. Ground testing with aerosolized lunar dust simulants in a specialized chamber is an inexpensive way to verify the performance of equipment. Chambers equipped with various powder dispersers and analysis instrumentation can explore a variety of realistic scenarios relevant to lunar surface missions, from the interaction of dust with sensitive surfaces such as solar panels, textiles, radiators, and scientific equipment, to the effects of dust as it intrudes into habitable areas. These experiments require careful consideration of the expected mass concentrations, aerosolization methods, and transport properties of dust. Instruments that use light-scattering techniques to measure mass concentrations require calibration against lunar simulants for improved accuracy, and different simulants may have different calibration factors. Test facilities, laboratory setup and test methods for aerosolizing lunar simulant will be described along with relevant aerosol instruments and calibration efforts.**

## Nomenclature

| | | |
|---|---|---|
| Aerosol | = | a system of a solid or liquid particle suspended in a gas, inclusive of the gas |
| Coarse | = | dust particles with aerodynamic mobility diameter larger than 2.5 µm |
| COTS | = | Commercially-available Off-The-Shelf |
| $d_a$ | = | aerodynamic diameter (m) |
| $d_{em}$ | = | electrical mobility diameter (m) |
| $d_p$ | = | particle diameter (m) |
| $dve$ | = | Volume-equivalent diameter (m) |
| $C_S$ | = | Slip correction |
| e | = | Euler's number |
| EVA | = | Extra-Vehicular Activity |
| Fine | = | dust particles with aerodynamic mobility diameter between 0.1 and 2.5 µm |
| $g$ | = | Gravitational acceleration (m s$^{-2}$) |
| GASP | = | Gasses and Aerosols from Smoldering Polymers Laboratory |
| GRC | = | Glenn Research Center |
| JSC | = | Johnson Space Center |
| JSC-1 | = | Johnson Space Center Lunar Simulant 1 |
| JSC-1Ax | = | Johnson Space Center Lunar Simulant 1A, where x is a subset with a specific property |

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$l$ = mean free path (m)
LHS-1(D) = Lunar Highlands Simulant 1; LHS-1D is the fraction of LHS-1 below 30 µm
OEM = Original Equipment Manufacturer
$PM_X$ = cumulative mass concentration for particles with $d_p \leq$ X µm
PSD = particle size distribution
psi = Pounds per square inch
RH = relative humidity (%)
Ti = titanium
$TiO_2$ = titanium dioxide
$T_S$ = settling time
Ultrafine = dust particles with aerodynamic mobility diameter below 0.1 µm
$V_{TS}$ = terminal settling velocity (m $s^{-1}$)
$\eta$ = viscosity of air, $1.84\times10^{-5}$ kg $m^{-1}$ $s^{-1}$
$\rho_A$ = air density (kg $m^{-3}$)
$\rho_B$ = bulk material density (kg $m^{-3}$)
$\rho_P$ = particle density (kg $m^{-3}$)
$\tau$ = relaxation time (s)
$\chi$ = dynamic shape factor

# I. Introduction and Historical Perspective from the Apollo Program

LUNAR dust is a significant obstacle in establishing a long-term human presence on the moon. Lunar dust affects all aspects of human activity, and infrastructure must be designed with this in mind. Dust can, for example, affect the thermal performance of radiators[1], degrade the performance of optical sensors and solar panels[2], damage mechanical joints and seals[3], weaken spacesuit material[4], and deteriorate filtration efficacy[5]. Lunar dust is also a potential toxicant, able to penetrate deep into the respiratory system and damage the lung alveoli[5].

The lack of an atmosphere and the reduced gravity on the lunar surface present unique challenges to characterizing the transport properties of dust and confound efforts to mimic dust behavior in a terrestrial research laboratory. Furthermore, with target cabin pressures of 70.3 or 56.5 kPa (10.2 or 8.2 psi), aerosol behavior is markedly different than at mean sea level pressure, and the equations which govern their transport properties must be modified to account for reduced pressure and gravity.

The Apollo Program landed twelve astronauts on the Moon between 1969 and 1972. Without exception, the astronauts decried the insidious nature of lunar dust[6]. All aspects of the missions were affected in some way. Lunar dust obscured vision, inhibited experiment deployment, restricted motion, and caused acute respiratory problems. The degree to which dust impacted the missions was inconsistent. For example, Apollo 12 and 15 experienced dust problems starting at initial descent, with the descent rockets lofting enough lunar material into the exosphere that they both had to land by instruments alone. By contrast, Apollo 14, 16 and 17 noted the presence of dust upon descent, but not so much that the procedure was impaired.

Apollo 15, 16, and 17 included three-day lunar surface deployments, and while dust was already known to be a significant issue, hardware only needed to be resilient for this relatively short timescale. The Artemis Program, NASA's mission to land the first humans on the moon since Apollo, is targeting six and a half days starting with Artemis 3, with the ultimate goal of a sustained lunar presence in the Artemis Base Station. A permanent installation on the Moon requires a new approach to mitigating the detrimental effects of lunar dust, which necessitates a thorough understanding of the properties and behavior of dust, supported by a concerted ground testing effort to consider how dust will impact all aspects of Artemis.

# II. Ground Testing

Ground testing can help prove performance of space hardware via carefully tailored environments and equipment, thus reducing risk. Different aspects of airborne lunar simulant testing are described here, including detailed descriptions from an aerosol science and technology point of view.

## A. Simulant Selection

The Apollo missions returned approximately 360 kg of lunar material from six landing sites. Though the samples were sealed in vacuum bottles, fine lunar dust abraded the sealing edges of the containers, and the samples have become contaminated by Earth's atmosphere. Lunar material is especially susceptible to oxidation reactions. Lunar surface material exists in a chemically reduced state, due to the constant bombardment by high-energy protons in the solar wind without the benefit of a protective magnetic field. Actual regolith samples in their native state are nonexistent, and although some sample return is expected prior to Artemis, acquiring quantities needed for ground testing is economically prohibitive.

For ground testing, it is desirable to have a simulant that best represents the expected landing region. Lunar material can be broadly divided into two categories based on its origin: mare and highlands. Mare regions are the dark, basaltic features that were formed by lava flows, whereas the highlands are the brighter, predominantly anorthositic regions. Also present in lunar soil to varying degrees are various trace elements and pyroclastic glasses which contain between 1 and 14% $TiO_2$. The Artemis 3 landing site at the lunar south pole is a highlands region, and so ground testing efforts are focused on the effects of high-anorthosite dusts.

A variety of simulants have been developed with different levels of fidelity, which are reasonable substitutes for different testing needs. As of this writing, there are some 40 lunar simulants known to NASA, though some are discontinued, and others are of limited availability. The JSC-1 simulant, along with its clones and size-subsets is likely the most well-known simulant. It was developed at Johnson Space Center in the early 1990s to mimic the low-Ti mare soil samples returned by Apollo. However, for Artemis 3, the JSC-1 simulant family is unsuitable for ground testing for a highlands mission. Distinct highlands chemistry and particulate microphysical properties will affect equipment and operations differently. A new class of simulants is currently being developed at JSC using products with high anorthosite content as the base, which, when mixed with various minerals and processed, allows researchers to fine-tune the simulant properties to more closely mimic lunar highlands dust.

The JSC simulants are by no means the only options, and new simulants are being continually developed. Ultimately, the choice of simulant is informed by the assumed properties of a lunar region of interest, and a variety of simulants may be used to span a range of expected parameters. For example, the analysis in section II-C is done with JSC-1A and LHS-1D from The Exolith Lab. These simulants are chosen to span a wide range of bulk density, which informs transport properties. The LHS-1D simulant closely mimics the expected mineralogy and morphology of highlands-derived dust near the Artemis 3 planned landing site and has a stated maximum particle diameter of 30 µm and a mean diameter of 7 µm.[*]

### B. Testing Matrix for Expected Environments

A full-fidelity testing program for airborne lunar dust should ideally replicate the expected environmental conditions, which, for space travel, includes the effects of cabin pressure, air composition, relative humidity, and gravity. Chambers and reactors can simulate all but the effects of low- or zero-gravity. Short periods of microgravity can be simulated using specialized drop towers or aircraft flying parabolic trajectories, but for most hardware needs, designing such dust exposure experiments is unnecessary.

At the most basic level, a ground testing program can control expected ambient pressure, temperature, and relative humidity experienced by the article being tested. This will vary between internal and external environments and can range from essentially zero to typical indoor quantities specified by various industrial standards. Furthermore, the reactivity of lunar dust as it will be encountered during Artemis ground operations is difficult to achieve and maintain unless the dust is specifically prepared in the chamber where it will be used for testing. For example, the Lunar Dust Adhesion Bell Jar incorporates high-temperature bake-out followed by reduction in a plasma environment in order to prepare the simulant for testing.[7] Reactivity aside, during surface operations it is certain that dust will find its way into equipment and onto surfaces that are designed to operate nominally dust-free, for example mechanical joints, solar panels, and thermal radiators. Upon the conclusion of an EVA, a conservative estimate of 50 grams of dust per crewmember per EVA is expected to infiltrate the interior of lunar infrastructure, which necessitates the development and testing of dust mitigation strategies such as specialized vacuum cleaners, brushes, wipes, and airlock designs that take dust intrusion into consideration.

A test matrix (Table 1) categorizes the expected environments and provides guidance for developing testing protocols. Dust tolerance testing should be considered for all points of a lunar mission, including the orbiting Gateway habitat, which is susceptible to dust lofted by ascent and descent rockets, as well as any dust brought back into the Gateway cabin by surface crews. The combination of gravity and pressure alone are sufficient to define a testing framework capable of capturing the entirety of a lunar mission.[8]

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[*] Certain commercial equipment, instruments, or simulant materials are identified in this paper to foster understanding. Such identification does not imply recommendation or endorsement by the National Aeronautics and Space Administration (NASA), nor does it imply that the materials or equipment identified are necessarily the best available for the purpose.

**Table 1. Basic parameters for defining a test matrix for ground testing.**

| | Gateway* | Lunar Surface (interior) | Earth (reference) |
|---|---|---|---|
| Temperature (°C) | 18.3 to 26.7 | TBD | 0.0 |
| RH (%) | 60 (approx.) | TBD | 20-80 (varies by standard) |
| Pressure (kPa (psi)) | 70.3 (10.2) | 56.5 (8.2) | 101.4 (14.7) |
| g (m $s^{-2}$) | 0.00 | 1.62 | 9.81 |

### C. Transport Properties of Dust Aerosol

The transport properties of dust are markedly different in space and on the Moon than here on Earth. On Earth, a given aerosol particle size distribution (PSD) can be expected to behave in predictable ways, governed by particle properties such as material density and dynamic shape factor, and ambient properties such as pressure, gravity, temperature and humidity. In particular, ambient pressure affects the mean free path $l$, which is the average distance an aerosol particle will travel before impacting a gas molecule. This in turn affects transport parameters such as relaxation time $\tau$, terminal settling velocity $V_{TS}$, and settling time $T_S$. From a mitigation perspective, knowing these parameters for a broad size range will inform where efforts must be directed. For example, the largest dust grains on the order of 100 µm may be expected to settle under lunar lander conditions in less than a minute, regardless of material density, while grains on the order of 1 µm can remain aerosolized between one and seven days. Smaller particles, including those most threatening to respiratory health, can remain suspended indefinitely. The implications of these parameters are discussed below. Dust particles on the order of nanometers to tens of microns can be expected to migrate into lunar infrastructure, and the fundamental construct for understanding aerosol behavior is the PSD. The ultimate goal is to understand the PSD that will interact with lunar hardware and infrastructure. If the PSD is known, then replicating exact lunar surface conditions is unnecessary. In a pressurized environment, a given PSD will typically behave predictably once external forces and interaction kernels (functions that describe how the PSD changes according to agglomeration, evaporation, and other mechanisms) are accounted for, and the PSD will evolve according to the Aerosol General Dynamic Equation.[9,10] This modeling approach will support any experimental results to help inform predictions of dust behavior.

Testing typically begins by size-selecting a fraction of a batch of simulant based on the expected maximum and mean particle sizes. It is aerosolized into a chamber where it will settle onto a test article where any manner of tests can then be performed, and results will directly inform how that test article can be expected to withstand the expected dusty environment.

The PSDs required for comprehensive testing are informed by fundamental transport properties described above, assuming a pressurized environment where the dust particles behave as an aerosol. A given PSD generated by external surface activity is not considered an aerosol until it interacts with a gaseous environment, and in the lunar exosphere, the term *lofted dust* is preferred. Lofted dust does not conform to the equations of aerosol transport and instead must be modelled ballistically. Lofted dust can be treated from first principles as a ballistic object in free-molecular flow motivated by some force, which will travel without resistance until it settles due to gravity. Dust is lofted by meteorite impacts, sputtering by solar wind, ascent/descent rocket thrust, and EVA operations, and interacts with itself to form agglomerates via ballistic collisions and Van Der Waals forces. Gravitational settling on the lunar surface is modified by electrophoresis, or motion in an electric field, given that lunar dust exists in a reduced state and can be lofted by sudden changes in external electric fields. This typically occurs during the transition from night to day.

Upon intrusion into airlock and cabin environments, however, lofted dust is treated as an aerosol. The sudden change in flow regime from free-molecular to continuum will affect particle stopping distance, settling time, and agglomeration mechanisms. Upon intrusion into a habitable area, dust removal strategies must consider fundamental aerosol transport mechanisms, which can inform where to direct mitigation efforts.

To illustrate these basic transport properties in the lunar environment, Figures 1, 2, and 3 compare the settling time of several substances on Earth at sea level and on the Moon under planned Artemis 3 lander conditions. Considered here are the LHS-1D and JSC-1A simulants (0.7 g $cm^{-3}$ and 2.02 g $cm^{-3}$, respectively), the extreme values of samples returned by various Apollo missions (1.6 g $cm^{-3}$ and 1.8 g $cm^{-3}$) and water droplets (1 g $cm^{-3}$), which is included as a typical reference aerosol. $T_S$ is given by

$$T_S = \frac{h}{V_{TS}} \tag{1}$$

Here, $h$ = 1.6 m is used as an average height to the human respirable zone about the nose and mouth, though for infrastructure mitigation purposes, the total height of the habitable areas should be considered. $V_{TS}$ is calculated by

$$V_{TS} = \tau g \tag{2}$$

where $g$ is the acceleration due to gravity, and $\tau$, the relaxation time, is calculated by

$$\tau = \frac{\rho_B d_{ve}^2 C_S}{18\eta\chi} \tag{3}$$

where $\rho_B$ is the bulk density of the aerosolized material, $d_{ve}$ is the volume equivalent diameter (the diameter of a sphere with the same volume as the dust particle), $C_S$ is the Cunningham slip correction factor which models the drag force due to the gaseous medium, $\eta$ is the viscosity of air, and $\chi$ is the dynamic shape factor, which broadly accounts for the shape and orientation of the dust particle.

$\tau$ is useful for illustrating how quickly an aerosol reaches $V_{TS}$. $\tau$ is an e-folding time, which is the amount of time required for a particle released from rest to reach $V_{TS}/e$, or approximately $0.37V_{TS}$, where $e$ is Euler's number. A particle released from rest reaches $V_{TS}$ in approximately $3\tau$. At 56.5 kPa (8.2 psi), $\tau$ ranges from $5.67\times10^{-5}$ to $1.63\times10^{-4}$ s (0.06 to 0.16 ms) for a 10 µm particle, depending on the material density.

In Figures 1, 2, and 3, a value of $\chi$ = 1.7 is used as the average shape factor of observed terrestrial mineral dusts[i] and may not be ultimately representative of lunar materials for which $\chi$ has not yet been measured. The slip correction factor $C_S$ is required whenever $l$ is on the order of or larger than the diameter of the dust particle, and the surrounding gas can no longer be seen as a continuum. It is calculated from an empirical function of $l$ and the particle diameter[11]:

$$C_S = 1 + \frac{l}{d_{ve}}\left[2.34 + 1.05\exp\left\{-0.39\frac{d_{ve}}{l}\right\}\right] \tag{4}$$

Mean free path, however, is not constant across varying ambient pressure, and scales as

$$l = \frac{P_0}{P} l_0 \tag{5}$$

where $P$ is the ambient pressure under consideration, $P_0$ is a standard reference pressure (101.4 kPa, 14.7 psi) and $l_0$ is the mean free path at $P_0$ (0.066 µm), calculated from kinetic theory of gases. Mean free path is also a function of temperature, but this can be assumed negligible in a climate-controlled environment where humans reside.

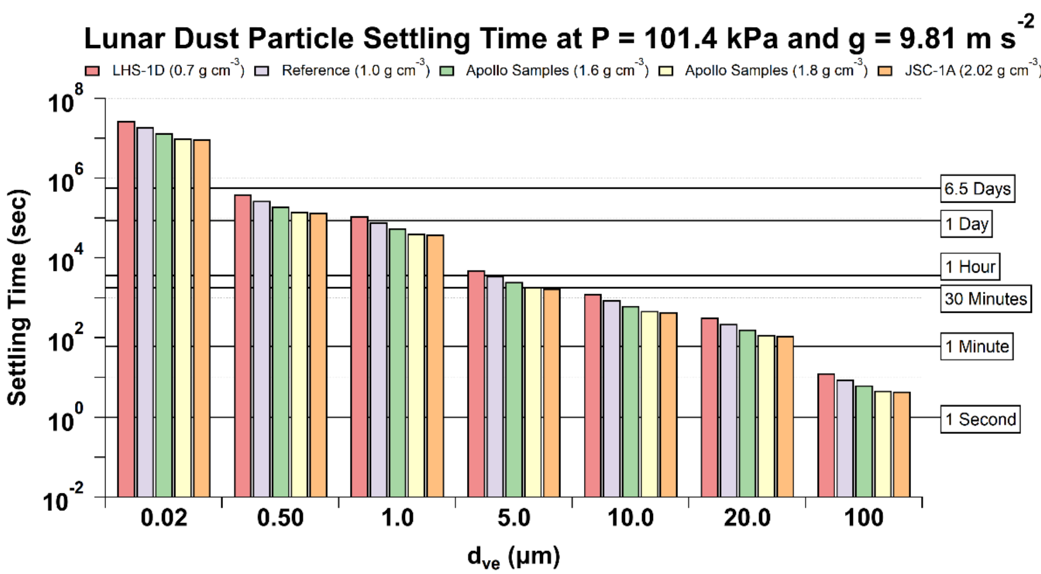


**Figure 1. Settling time of various substances under Earth conditions in still air.**

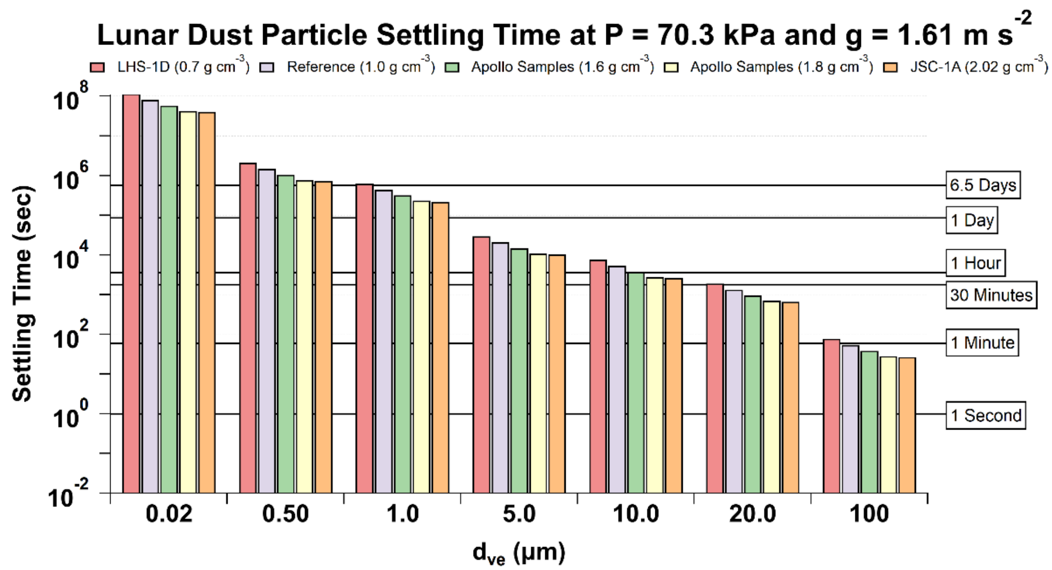


**Figure 2. Settling times of various substances at 70.3 kPa (10.2 psi) and lunar gravity in still air.**

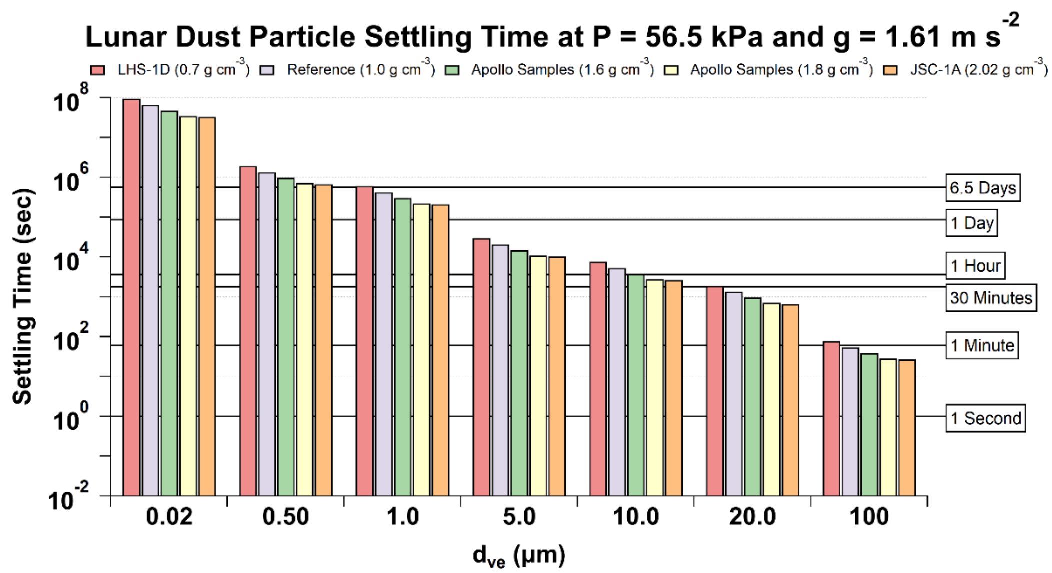


**Figure 3. Settling time of various substances at 56.6 kPa (8.2 psi) and lunar gravity in still air.**

This analysis demonstrates that $PM_{10}$ contamination in habitable areas can be expected to pose problems on long time scales, absent any active mitigation efforts like vacuuming or filtration. Bulk density is an important factor to understand – consider that at 56.5 kPa (8.2 psi) on the Moon, $T_S$ for a 1 µm aerosol ranges from 2.5 to 7.1 days given $\rho_B$ from 0.7 to 2.02 g cm$^{-3}$.The smallest particles ($PM_1$ and $PM_{0.2}$) that pose the greatest risk to human health will remain airborne essentially indefinitely. 0.02 µm aerosols (20 nm) will remain lofted for 1 to 3 *years*. Relying on lunar gravitational settling without active mitigation is not effective and these small particles will remain a threat for the duration of the mission.

This analysis is a best-case scenario of particles settling in quiescent air where there is no gas movement, and implies that after $T_S$, the concentration of particles released from respirable height will be zero. The opposite extreme is that of a continuously-stirred room (a reasonable analog to a room with human activity or active ventilation, where air is assumed to be instantaneously, completely, and continuously mixed), where the particle concentration at any given time is decreasing exponentially but will never reach zero:

$$n(t) = n_0 \exp\left\{\frac{-V_{ST}t}{H}\right\} \tag{6}$$

where $n(t)$ is the particle number concentration at time $t$, $n_0$ is the initial concentration, and $H$ is the height of the room under consideration. Here, $V_{ST}$ can be considered the average terminal settling velocity once higher-frequency velocity components due to the stirring motion are averaged out over time. The reality during Artemis missions will be somewhere between the quiescent and stirred extremes, and additional effects of diffusion, resuspension, and continuous generation of dust particles while crewmembers perform activities further confound the analysis.

### D. Chambers

Isolated chambers are the centerpiece of any ground-based dust testing campaign for safety and for accurate measurements of airborne lunar simulant. The facilities at the Gases and Aerosols from Smoldering Polymers (GASP) lab at NASA GRC are designed to isolate experiments in a double-ventilated chamber. The chamber is large enough that instruments can be placed inside the chamber to sample directly, or can sample from various ports via tubing. This facility was created for NASA's Spacecraft Fire Safety program but has been used for several aerosol projects for the Life Support Systems program. The chamber is a repurposed 326-liter glovebox with internal dimensions 0.7 m × 0.5 m × 0.7 m with 0.2 m diameter glove holes in the event that something should be manipulated as part of the experiment. All the safety permits and protocols for working with hazardous aerosols and gases are followed. This chamber can be purged with HEPA filtered air down to 5 particles per $cm^3$ (virtually zero concentration) to eliminate background laboratory aerosols. It is suitable for dust testing at ambient pressures, which is sufficient when testing hardware response to dust loading.

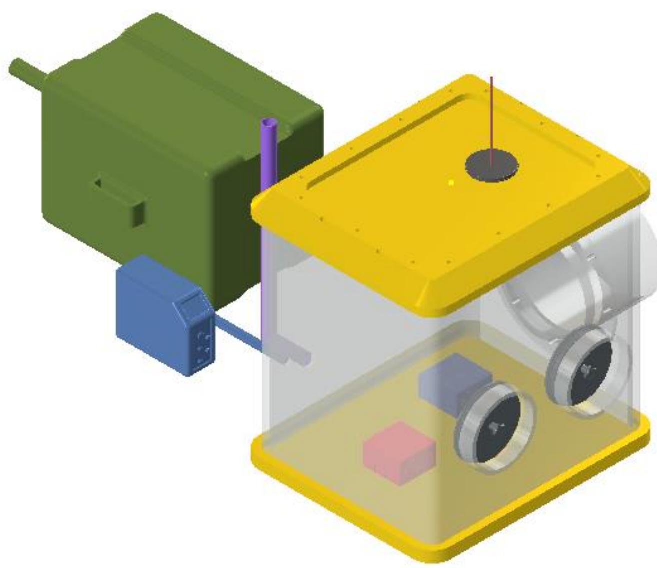

**Figure 4: a 3D render of the chamber at GASP lab.**

### E. Aerosol Testing Challenges

An aerosolization technique that most closely mimics the expected behavior of lunar dust is a major focus of current ground testing. The specific transport behavior of dust from source to the surface under test does not need to be replicated, rather, it is the way dust loads onto the test surface that matters most. For experiments that test the consequences of settling dust, the results are ultimately a function of simulant selection, particle size segregation, and aerosolization technique.

Depending on the test being performed, active or passive aerosolization techniques may be desired. An example of a passive technique would be to load a sieve tray with some mass of simulant and then shake it so the dust falls into the chamber. An active option would be a device designed to aerosolize wet or dry powders using pumps, blowers, ultrasonic membranes, or other means. COTS options exist for passive and active techniques. Because of the varied nature of dust testing, there is no single best method for aerosolization, and the ideal solution depends on the desired size distribution and loading.

Beyond aerosolization and simulant selection, there are many guidelines to consider, such as experiment layout, dilution, environmental conditions, and analysis instrument selection and configuration based on the specific key performance parameter to be reported as a result of the test. Experiment chambers that use sampling ports should be designed with tubing that minimizes loss mechanisms, such as using short lengths of conductive tubing with a minimum of bends to eliminate electrostatic, diffusive, and inertial losses. When dispersing a large size range, gravitational settling in a tall chamber is preferred over actively pumping or blowing the simulant in through a port to mitigate the effects of ballistic transport preferentially loading one side of the chamber with a larger particle size. When considering analysis instruments, it is crucial to be aware of the maximum concentration they are specified to measure, and dilute accordingly. The expected amount of dust intrusion during lunar missions is far beyond what any laboratory instrument can safely and accurately measure, and to protect equipment and data fidelity, the sample streams must be diluted with dry, filtered air.

### F. Analysis Instrumentation and Specialized Calibration

Guidelines for acceptable aerosol concentration in habitable spaces are commonly given in mass concentration (aerosol mass per unit volume of air) or number concentration (total number of particles per unit volume of air). A common method for measuring these parameters is by measuring its light scattering behavior or the aerosolized substances. The typical instrument for measuring light scattering is the nephelometer. Nephelometers utilize a monochromatic or narrow-band light source such as a laser or a light-emitting diode and measure either the angular-dependent or total integrated light scattering signal from an ensemble of particles in a known volume. Light scattering is commonly reported in units of inverse distance, which is material-independent. To derive a mass concentration from such readings, a material-dependent calibration factor must be used. Research-grade instruments commonly produce a histogram by reporting the mass concentration in multiple size bins, with more expensive options providing lower detection limits and more size bins across a wider range of particle diameters. On the other end of the spectrum is the fantasy of the low-cost sensor. Such devices are typically OEM modules with basic light sources and detectors coupled with a simple linear calibration scheme for deriving a mass concentration. While the per-unit cost of such devices is attractive, they require special care in their calibration and application, and still may have poor performance for airborne lunar simulant testing[12-16]. These devices are usually only valid over an extremely limited size range and a low number concentration. With high concentrations of aerosol (on the order expected during lunar missions, and therefore expected in ground testing), the instrument response is highly nonlinear, and the calibration factors are all but invalid. Furthermore, their noise floors may be too high for accurate diagnostics. When using multiple units, the variations may require extensive intercalibration routines and clever data inversion algorithms.

Regardless of the choice of instrument, it must be carefully calibrated to lunar material before the results can be correctly interpreted. For ground testing, a reference-quality instrument with a history of peer-reviewed publications and independent verification should be used. Such instruments are carefully designed according to theoretical aerosol transport models and have several features that distinguish them from the low-cost options. Reference-quality instruments are designed to minimize particle losses due to diffusion or inertial impaction on tubing walls by incorporating a laminar sheath flow and minimizing number of bends and bend radii in internal tubing. Reference-grade instruments also feature inlets that are optimized for the particle sizes one wishes to measure and can be swapped out with different inlet geometries for different aerosol size ranges. Additionally, instrument maintenance is a concern in ensuring fidelity across tests. Low-cost sensors are typically difficult to maintain, while reference-quality instruments can be easily serviced by the end-user. This usually involves replacing filters, cleaning optics, and recalibrating.

When these instruments are applied on Earth, they are typically used in a complex environment where multiple aerosol types can be expected. Such systems make interpretation of reported mass concentrations difficult. Since these instruments work via light scattering, the material's refractive index is necessarily a parameter in the retrieval algorithms. However, for a complex system with many aerosolized substances, the refractive index is not constrained. The aerosol system will instead have an *effective* refractive index, but this will change rapidly as the constituents of the aerosol change. Instruments are therefore calibrated to a standard substance such as Arizona Road Dust. This choice of calibration would be perfect if one were to study a system containing only Arizona Road Dust. Fortunately, when studying lunar material, it can broadly be thought of as monolithic (e.g., mare or highlands) despite occasional impurities, and when aerosolized and treated as a single analyte, it behaves as if it has a constant effective refractive index and therefore a constant calibration factor. However, different simulants will require separate calibrations, and ultimately the choice of calibration factor will be determined by the mineralogy of the landing site.

## G. Conclusions

This presents a strong case for a coordinated ground testing program. By isolating specific variables applicable to lunar missions writ large, such as pressure and gravitational acceleration, a framework can be defined in which to design tests for specific hardware and activities. Within this framework, individual transport variables can be further isolated and lunar simulant can be applied directly to a system and its effects studied. These laboratory studies will provide data to understand the consequences of crewmember activities and active mitigation strategies which will invariably resuspend some amount of dust. Additionally, these results can serve as the entry point for numerical modeling or Multiphysics simulations of predicted dust loadings and behaviors during lunar missions.

# References

[1]Keller, J. R. and Ewert, M. K., "Lunar Dust Contamination Effects on Lunar Base Thermal Control Systems," *SAE Transactions* 109, 1, pp 571-579, 2000.

[2]Kawamoto, H., Uchiyama, M., Cooper, B.L., and McKay, D.S., "Mitigation of lunar dust on solar panels and optical elements utilizing electrostatic traveling-wave," *Journal of Electrostatics* 69 (2011) pp. 370-379, doi:10.1016/j.elstat.2011.04.016

[3]Kruzelecky, R. V., et al., "Project MoonDust: Characterization and Mitigation of Lunar Dust," *41st International Conference on Environmental Systems*, Portland, Oregon, 17-21 July, 2011, AIAA-2011-5184.

[4]Christoffersen, R., et al., "Lunar Dust Effects on Spacesuit Systems – Insights from the Apollo Spacesuits," NASA/TP-2009-214786, NASA Technical Information Service, 2009.

[5]Cain, J. (2010), "Lunar dust: The Hazard and Astronaut Exposure Risks." *Earth, Moon, and Planets* **107**, 107-125

[6]Wagner, S. A., "The Apollo Experience: Lessons Learned for Constellation Lunar Dust Management," NASA/TP-213729, NASA Technical Information Service, 2006.

[7]Gaier, J. R. and Sechkar, E. A., "Lunar Simulation in the Lunar Dust Adhesion Bell Jar," NASA/TM-2007-214704, NASA Technical Information Service, 2007.

[8]"Classifications and Requirements for Testing Systems and Hardware to be Exposed to Dust in Planetary Environments", NASA-STD-1008, 2021.

[9]Gelbard, F. and Seinfeld, J. H., "The General Dynamic Equation for Aerosols – Theory and Application to Aerosol Formation and Growth," *Journal of Colloid and Interface Science* **68**, 2, 1979.

[10]Friedlander, S. K., *Smoke, Dust, and Haze: Fundamentals of Aerosol Behavior*, Oxford University Press, 2000.

[11]Hinds, W., *Aerosol Technology: Properties, Behavior, and Measurement of Airborne Particles, 2nd Edition*, John Wiley and Sons, Inc., 1999.

[12]Froyd et al., "A New Method to Quantify Mineral Dust and Other Aerosol Species from Aircraft Platforms Using Single-Particle Mass Spectrometry," Atmospheric Measurement Technology **12**, pp. 6209–6239, 2019.

[13]He et al., "Evaluation of Two Low-Cost PM Monitors under Different Laboratory and Indoor Conditions," *Aerosol Science and Technology* **55**, 2021.

[14]Jerrett et al., "Validating Novel Air Pollution Sensors to Improve Exposure Estimates for Epidemiological Analyses and Citizen Science," *Environmental Research* **158,** pp. 286-294, 2017.

[15]Kelly et al., "Ambient and Laboratory Evaluation of a Low-Cost Particulate Matter Sensor," *Environmental Pollution* **221,** pp. 491-500, 2017.

[16]Rai et al., "End-User Perspective of Low-Cost Sensors for Outdoor Air Pollution Monitoring" *Science of the Total Environment* **607-608**, pp. 691-705, 2017.