NASA/TM–2020-5008219
NESC-RP-19-01469

Lunar Dust and Its Impact on Human Exploration: A NASA Engineering and Safety Center (NESC) Workshop

Daniel Winterhalter (retired)
Jet Propulsion Laboratory, Pasadena, California

Joel S. Levine (retired)
Langley Research Center, Hampton, Virginia

Russell L. Kerschmann (retired)
Ames Research Center, Moffett Field, California

Timothy K. Brady/NESC
Langley Research Center, Hampton, Virginia

September 2020

NASA STI Program . . . in Profile

Since its founding, NASA has been dedicated to the advancement of aeronautics and space science. The NASA scientific and technical information (STI) program plays a key part in helping NASA maintain this important role.

The NASA STI program operates under the auspices of the Agency Chief Information Officer. It collects, organizes, provides for archiving, and disseminates NASA's STI. The NASA STI program provides access to the NTRS Registered and its public interface, the NASA Technical Reports Server, thus providing one of the largest collections of aeronautical and space science STI in the world. Results are published in both non-NASA channels and by NASA in the NASA STI Report Series, which includes the following report types:

- TECHNICAL PUBLICATION. Reports of completed research or a major significant phase of research that present the results of NASA Programs and include extensive data or theoretical analysis. Includes compilations of significant scientific and technical data and information deemed to be of continuing reference value. NASA counter-part of peer-reviewed formal professional papers but has less stringent limitations on manuscript length and extent of graphic presentations.

- TECHNICAL MEMORANDUM. Scientific and technical findings that are preliminary or of specialized interest, e.g., quick release reports, working papers, and bibliographies that contain minimal annotation. Does not contain extensive analysis.

- CONTRACTOR REPORT. Scientific and technical findings by NASA-sponsored contractors and grantees.

- CONFERENCE PUBLICATION. Collected papers from scientific and technical conferences, symposia, seminars, or other meetings sponsored or co-sponsored by NASA.

- SPECIAL PUBLICATION. Scientific, technical, or historical information from NASA programs, projects, and missions, often concerned with subjects having substantial public interest.

- TECHNICAL TRANSLATION. English-language translations of foreign scientific and technical material pertinent to NASA's mission.

Specialized services also include organizing and publishing research results, distributing specialized research announcements and feeds, providing information desk and personal search support, and enabling data exchange services.

For more information about the NASA STI program, see the following:

- Access the NASA STI program home page at *http://www.sti.nasa.gov*

- E-mail your question to help@sti.nasa.gov

- Phone the NASA STI Information Desk at 757-864-9658

- Write to:
  NASA STI Information Desk
  Mail Stop 148
  NASA Langley Research Center
  Hampton, VA 23681-2199

NASA/TM–2020-5008219
NESC-RP-19-01469

Lunar Dust and Its Impact on Human Exploration: A NASA Engineering and Safety Center (NESC) Workshop

Daniel Winterhalter (retired)
Jet Propulsion Laboratory, Pasadena, California

Joel S. Levine (retired)
Langley Research Center, Hampton, Virginia

Russell L. Kerschmann (retired)
Ames Research Center, Moffett Field, California

Timothy K. Brady/NESC
Langley Research Center, Hampton, Virginia

National Aeronautics and
Space Administration

Langley Research Center
Hampton, Virginia 23681-2199

September 2020

The use of trademarks or names of manufacturers in the report is for accurate reporting and does not constitute an official endorsement, either expressed or implied, of such products or manufacturers by the National Aeronautics and Space Administration.

Available from:

NASA STI Program / Mail Stop 148
NASA Langley Research Center
Hampton, VA 23681-2199
Fax: 757-864-6500

NASA Engineering and Safety Center
Technical Assessment Report

Lunar Dust and Its Impact on Human Exploration:
A NASA Engineering and Safety Center (NESC) Workshop

September 24, 2020

Report Approval and Revision History

NOTE: This document was approved at the September 24, 2020, NRB. This document was submitted to the NESC Director on September 25, 2020, for configuration control.

Approved:	*Original Signature on File*	9/28/20
	NESC Director	Date

Version	Description of Revision	Office of Primary Responsibility	Effective Date
1.0	Initial Release	Tim Brady, NESC Integration Office, JSC	9/24/2020

Table of Contents

Technical Support Report

1.0 Notification and Authorization

The NASA Engineering and Safety Center (NESC) former Chief Scientist provided support to produce an NESC final report on the " Lunar Dust and Its Impact on Human Exploration" workshop held February 11 - 13, 2020, in Houston, Texas. This report follows the standard NESC report format to describe the findings, observations, and NESC recommendations developed by the workshop participants.

The key stakeholders for the final report are the lunar mission designers and engineers for the precursor missions and the crewed mission, and the NESC. Further stakeholders are the mission planners deciding on the payload selections for future lunar missions.

2.0 Signature Page

Submitted by:

Team Signature Page on File – 9/30/20

Mr. Timothy K. Brady Date

Significant Contributors:

Dr. Daniel Winterhalter Date

Dr. Joel S. Levine Date

Dr. Russell L. Kerschmann Date

Signatories declare the findings, observations, and NESC recommendations compiled in the report are factually based from data extracted from program/project documents, contractor reports, and open literature, and/or generated from independently conducted tests, analyses, and inspections.

3.0 Team List

Name	Discipline	Organization
Core Team		
Tim Brady	NESC Lead	JSC
Daniel Winterhalter	Technical Lead and former NESC Chief Scientist	JPL (ret.)
Joel Levine	Basic Science	LaRC (ret.)
Russell Kerschmann	Medical and Life Science	ARC (ret.)
Business Management		
John LaNeave	Program Analyst	LaRC/MTSO
Assessment Support		
Pam Sparks	Project Coordinator	LaRC/AMA
Erin Moran	Technical Editor	LaRC/AMA

4.0 Executive Summary

With the United States (U.S.) planning a new series of human missions to the Moon in the near future, a NASA Engineering and Safety Center (NESC) workshop focusing on “Lunar Dust and its Impact on Human Exploration” was hosted at the Universities Space Research Association (USRA) Lunar and Planetary Institute (LPI) in Houston, Texas, on February 11–13, 2020. Quoting Apollo 17 Astronauts Eugene Cernan and Harrison Schmitt:

*“I think dust is probably one of our greatest inhibitors to a nominal operation on the Moon. I think that we can overcome other physiological or physical or mechanical problems except dust.” (*Eugene Cernan)

“One of the most aggravating, restricting facets of lunar surface exploration is the dust and its adherence to everything no matter what kind of material, whether it be skin, suit material, metal, no matter what it be and its restrictive friction-like action to everything it gets on.” (Harrison Schmitt)

The workshop followed the successful first NESC Lunar Dust Workshop held January 30 – February 1, 2007 at the NASA Ames Research Center (ARC), and NESC Mars Dust Workshop at LPI, held June 13 – 15, 2017. Much work needs to be done to mitigate the lunar dust problems, and the workshop addressed/highlighted concerns about the physical nature of the dust, and its impact on human health, surface systems, and surface operations. Specifically, workshop attendees participated in one of three panels:

- Panel 1 – Lunar Dust: Nature and Characteristics, covering the structure, chemistry, properties and distribution of lunar dust.
- Panel 2 – The Impact of Lunar Dust on Human Health, considering the impact of lunar dust on the health of astronauts.
- Panel 3 – The Impact of Lunar Dust on Human Surface Systems and Surface Operations, discussing the likely impact on surface operations and surface equipment (e.g., space suits, habitats, etc.) and the techniques/technologies to reduce/mitigate the lunar dust problem.

The product from these panels are a set of findings, observations, and recommendations (FORs) following the guidelines for Technical Reports of the NESC, published herein. Of the 37 FORs, eight are considered **“Very High Priority”**, summarized below (see Section 7 for the complete list):

- Characteristics of the finest fraction (<45 microns) of the lunar soil are not well understood. The knowledge gap increases with decreasing particle size. Further, there is insufficient knowledge of the variation in dust characteristics (e.g., chemical composition and mineralogy) and other characteristics of particles < 45 µm across lunar geological regions. It is recommended that future robotic and human lunar missions carry instrumentation to measure particle size and shape distribution from 45 to 0.1 micron on the lunar surface. Further, useful data on dust characteristics in this size range (e.g., chemical composition, mineralogy, chemical reactivity, mobilization, migration and deposition, etc.) across the lunar geological regions should be obtained.

- There is uncertainty in the electrical charging properties of the lunar surface and individual particles. It is recommended that future robotic and human lunar missions carry instrumentation to measure electrical particle charging across dust grain sizes on the lunar surface.
- Little knowledge exists about the electrical charge characteristics of regolith particles on and above the lunar surface due to the interactions with the solar wind plasma, photoemission, and secondary electron emissions. It is recommended that measurements of the electrical charge characteristics are performed using Apollo samples to simulated interactions with solar wind plasma, photoemissions, and secondary electrons.
- There has been little discussion of cabin and spacesuit (e.g., Lunar lander, Gateway) air cleaning systems. It is recommended that various routine technologies (e.g., filtration, external stowage platform (ESPs,) etc.) and innovative, integrated systems (e.g., photoionizers, enhanced ESPs, electret filters, etc.) are discussed, developed and selected for deployment. Selection should be based on important metrics to be identified (high removal efficiency, operability in environment under consideration, low-pressure drop, operating simplicity, etc.) by the responsible NASA technical teams.
- There is insufficient information with regard to the effect of lunar dust deposition on optical or thermal surface performance. It is recommended that the appropriate NASA Mission Directorate (MD) initiates/supports laboratory tests.
- While gaps exist, NASA's Lunar Airborne Dust Toxicity Assessment Group (LADTAG) provided significant toxicological data to guide setting a crew permissible exposure limit (PEL) for dust exposure on short-term lunar missions. It is recommended that studies are supported, including those using return materials from Artemis 1, to better inform potential risks for exposure on the longer-duration Artemis 2 missions.
- There appears to be little coordinated discussions across the agency to identify the impact of lunar dust on mechanisms, seals, connectors, and solar panels, nor are there cleaning systems identified. It is recommended that NASA organizes an Agency-wide, coordinated effort (working groups, technical discipline teams, etc.) to discuss, develop, and select for deployment, device cleaning technologies. Selection should be based on important metrics to be identified (high removal efficiency, operability in environment under consideration, low-pressure drop, operating simplicity, etc.).
- No industry-standard set of NASA requirements and oversight mechanisms exist for the manufacturing, quality control, and validation of lunar dust simulants. It is recommended that NASA identify the most qualified group within the agency and/or other agencies to address this issue. This group should oversee quality and manufacture of a consistent simulant product for toxicologic and engineering applications.

In summary, the assembled experts concluded the dust problem is an agency and industry concern affecting most mission subsystems, and it must be addressed. In particular, measurements and experiments need to be taken and conducted on the lunar surface by precursor landers to ascertain dust characteristics that will influence hardware design, and provide toxicology data to safeguard crew health.

5.0 Workshop Motivation and Description

On July 20, 1969, as Apollo 11 Astronaut Neil Armstrong was making his historic first step onto the surface on the Moon, he observed that the lunar module was kicking up such large amounts of lunar dust that the landing site was being significantly obscured. Fortunately, Apollo 11 successfully made the landing. As Armstrong was climbing down the Lunar Module ladder for humankind's very first step on another world, Armstrong observed that the surface of the Moon was covered with several inches of very fine dust, similar to talcum powder. A major discovery of Apollo 11, and the succeeding Apollo missions was that the surface of the Moon was covered by a several inch layer of fine dust. This dust layer had a negative impact on the health and well-being of the astronauts, and on their lunar equipment and instruments, including their spacesuits, helmets, and habitats. Surface operations and crew health were impeded by the ever present and intrusive dust.

Starting in 2024, the Artemis Program, the U.S. will return astronauts to the Moon and this time they will spend considerably more time outside of the lunar module exploring and working on the lunar surface than the Apollo astronauts, thus providing the Artemis astronauts increased exposure to lunar dust. Hence, the lunar dust problem will become a problem for human exploration of the Moon.

To address the impact of lunar dust on the human exploration of the Moon, the NESC sponsored a workshop entitled, "Lunar Dust and Its Impact on Human Exploration" at LPI, adjacent to the NASA Johnson Space Center (JSC), Houston, Texas, from February 11-13, 2020 (https://www.hou.usra.edu/lunardust/2020/). The other workshop sponsors were the USRA, LPI, the Jet Propulsion Laboratory (JPL), and The College of William and Mary. More than 150 people participated in the workshop representing diverse interests and backgrounds, including lunar scientists, mission engineers, mission architects and planners, human health researchers, and medical doctors. The list of workshop participants and their affiliation is provided in Appendix A.

The workshop attendees participated in one of three panels covering the following topics: (1) The structure, chemistry, properties and distribution of lunar dust (Joel Levine, Panel Moderator), (2) The impact of lunar dust on the health of astronauts (Russell Kerschmann, Panel Moderator), and (3) The impact of lunar dust on human surface operations and surface equipment (e.g., space suits, habitats, etc.) and the techniques/technologies to reduce/mitigate the lunar dust problem (Daniel Winterhalter and Michael Johansen, Panel Moderators). On day 1, the workshop began with a welcome by Tim Wilson, NESC Director. Following the welcome, nine invited plenary speakers addressed the subjects of the three panels. In their plenary addresses, the speakers identified what is known and the knowledge gaps in the subject area of each panel. Days 2 and 3 of the workshop were spent in panel discussions followed by a late afternoon plenary session where each panel reported their progress to the full workshop.

On the eve of the workshop, space reporter and author, Leonard David, wrote an online article on the lunar dust problem, human exploration of the Moon and the NESC Lunar Dust Workshop, entitled, "Dusting Off an Old Problem: Impact of Lunar Dust on Human Exploration" (http://www.leonarddavid.com/dusting-off-an-old-problem-impact-of-lunar-dust-on-human-exploration/).

6.0 Panel Discussion-Point Summaries

6.1 Lunar Dust: Structure, Composition, Chemistry and Distribution - Panel 1

Panel 1 was comprised of experts from NASA, industry, and academia. Some of the organizations represented on the panel included NASA JSC, NASA Langley Research Center (LaRC), NASA Glenn Research Center (GRC), NASA Goddard Space Flight Center (GSFC), the Planetary Science Institute, The College of William and Mary, Auburn University, University of Central Florida, University of Arkansas, University of Maryland, Colorado School of Mines, University of Western Australia, and Fibernetics Corporation.

Panel 1 considered the physical and chemical properties of lunar dust, how surface dust is transported and the surface and atmospheric distribution of lunar dust. These lunar dust characteristics are needed to better assess the impact of lunar dust on human health and surface systems and surface operations (e.g., spacesuits, helmets, habitats, mobility systems, etc.), and lunar dust reduction and mitigation techniques and technologies.

6.1.1 The Origin of Lunar Dust Particles

The lunar regolith is the unconsolidated covering of material on top of the primordial lunar bedrock and contains a mixture of crystalline rock fragments, mineral fragments, breccias, agglutinates, and dust particles. The relative proportion of each particle type varies by location, and is dependent on the mineralogy of the source rocks and the geologic processes that the rocks have undergone (Heiken, Vaniman and French, 1991).

Over billions of years, the lunar regolith has been constantly bombarded by micro-meteoroids. The Moon is continually bombarded by on the order of 10^6 kg/y of interplanetary dust particles (IDP) of cometary and asteroidal origin. Most of these projectiles range from 10 nm to about 1 mm in size and impact the Moon with speeds in the range of 10 to 72 km/s. On Earth, the entry and traverse of these projectiles are referred to as "shooting stars." When the micrometeoroids hit the lunar surface regolith, they create a miniature shockwave in the soil, which causes some of the soil to melt and form secondary ejecta particles, and some to vaporize (Heiken, Vaniman and French, 1991). The molten soil immediately freezes forming tiny pieces of glass shards, which are jagged and sharp. Most of the ejecta particles have initial speeds below the escape velocity of the Moon (i.e., 2.4 km/s) and they return to the lunar surface, blanketing the lunar surface with a highly pulverized and impact gardened regolith. Micron and sub-micron size secondary particles that are ejected at speeds up to the escape velocity form a highly variable, but permanently present, dust cloud around the Moon (Horanyi et al., 2020). Due to the absence of wind or rain on the Moon, the glass shards remain jagged and sharp over time. As a result of the constant "hammering" by micro-meteoroids over billions of years, the lunar surface dust is extraordinary fine, similar to flour, which makes it sticky and causes it to cling to everything (e.g., spacesuits, helmets, surface equipment and instruments, etc.). On the lunar surface, continual exposure of dust to solar ultraviolet (UV) radiation and the solar wind plasma have been hypothesized to explain a number of unusual observations that indicate processes related to dust charging and subsequent electrostatic mobilization of lunar dust (Horanyi et al., 2020). LADEE measured surface-born dust particles from near surface to 250 km altitude (Gateway will be at 1000 km). The number density decays rapidly with altitude. Particle speed distribution ranges from 0 to 1,500 m/s peaking around 500 m/s.

6.1.2 Sources of Information About Lunar Dust

Sources of information about lunar dust include:

- Observations of lunar dust made by the Apollo astronauts on the lunar surface. Two comprehensive reports by (Gaier, 2005) and (Wagner, 2006) on lunar dust and its impact on the Apollo astronauts, their health and equipment based on the Apollo mission reports, Apollo technical debriefings and the transcripts of the voice traffic between the astronauts on the lunar surface and Mission Control (These Apollo documents are available on line at http://www.hq.nasa.gov/aldsj/).
- Measurements of lunar dust obtained by the Apollo Dust Detector Experiment (DDE) developed and built by Brian J. O'Brien and placed on the lunar surface as an experiment on the Apollo Lunar Science Experiment Package (ALSEP) on Apollo 11, 12, 14 and 15 and left on the Moon to obtain dust data after the astronauts returned to Earth (O'Brien, 2018). The DDEs have provided a unique dataset and a wealth of information about the transport of dust on the lunar surface.
- Samples of lunar dust collected by the astronauts and brought back to Earth for detailed chemical and physical analyses (Greenberg et al., 2007).
- Measurements of dust from the Lunar Atmosphere and Dust Experiment (LADEE) (Elphic et al., 2014). This experiment was launched on September 7, 2013, and during its seven-month mission, it orbited the Moon's equator using instruments to study the lunar exosphere and dust in the Moon's vicinity. Instruments included a dust detector, neutral mass spectrometer, and ultraviolet-visible spectrometer. The mission ended on April 18, 2014, when the spacecraft's controllers intentionally crashed it into the far side of the Moon, which was determined to be near the eastern rim of Sundman V crater.
- Laboratory experiments with lunar simulants (Wallace et al., 2015).

6.1.3 Gaps in our Current Knowledge of Lunar Dust

Based on the discussions in Panel 1, the knowledge gaps include:

- The particle size distribution and characteristics of the finest fraction of lunar dust (<45 microns) of lunar dust are not known and this knowledge gap increases with decreasing particle size. This includes the mobilization, migration and deposition within this size range. Also, how dust characteristics and depositions vary across different geological regions is not known.
- The chemical composition and mineralogy of lunar dust particles smaller than 45 microns is inadequately known.
- The mechanism controlling cohesion (particle-to-particle interactions) is not understood.
- The mechanism controlling adhesion (particle-to-material interactions) is not understood.
- Thermal conductivity and thermal insulative properties of lunar dust is not adequately known.
- The magnetic properties as particle size decreases and the nanophase iron content increase is not known.

- The electrical charging properties of lunar dust particles and the lunar surface is not adequately known.
- The impact of solar ultraviolet radiation and solar wind, magnetosheath and magnetotail plasmas on lunar surface dust are not adequately known.
- The triboelectric charging of lunar dust particle is not adequately known.
- The electrical properties of lunar dust particles, including electrical conductivity, dielectric properties and dielectric breakdown are not well understood.
- The optical constants and spectral properties of lunar dust from the ultraviolet to far-infrared are not known.
- The bonding and adsorption of lunar dust particles with volatiles under lunar environmental conditions are not known.
- The impact of volatiles on the properties and behavior of lunar dust particles is not known.
- The packing, porosity and permeability, and other bulk surface properties (e.g., shear strength, angle of repose, coefficient of friction, etc.) of lunar soil and its variations with geographic location and depth are not known.
- The particle size distribution and movement of exospheric dust particles are not known at all altitudes.

6.2 The Impact of Lunar Dust on Human Health - Panel 2

6.2.1 Panel Summary

The HHE panel was comprised of experts from NASA, industry, and academia. Some of the organizations represented on the panel included NASA JSC, NASA GRC, NASA ARC, NASA GSFC, the Sierra Nevada Corporation, the European Space Agency, and the University of California at San Diego.

After a review of the state of current knowledge about lunar dust through discussions and individual presentations by the panel members, the group determined that current exposure standards, as determined in 2005 by LADTAG[1] (James, 2013; Lam, 2013), are sufficient to protect crew during the initial short-term Artemis landings on the Moon. It is recommended to understand the long-term effects of lunar dust on the human body and to build effective dust mitigation technologies, further research and development should be conducted into the properties of lunar dust across three broad areas:

- Increase our scientific knowledge for a more accurate physiochemical description of lunar dust in its native environment and subsequent alterations as the dust enters mission spaces: Lunar dust is in equilibrium with a native lunar environment not replicated in laboratories Earth, comprising a hard vacuum and constant bombardment by micrometeorites and radiation. Once dust has been carried from this environment and entered the drastically different crewed space environment, it will seek a new equilibrium point. This process requires further study and could include significant alteration of surface chemistry, physical changes in the morphology of dust particles, and the emission

[1] https://www.nasa.gov/centers/johnson/pdf/486003main_LADTAG15Sep05MtgMinutes.pdf

of potentially toxic or allergenic volatiles and elements into mission atmosphere and water compartments.

- Develop new technologies to monitor lunar dust transport within mission spaces and the human body: Develop technologies to monitor the transport of lunar dust particles and potentially toxic products into and through the crewed vehicle and habitat environments and within physiological systems. Focus particularly on the behavior of airborne particles within the lung, but include other less-studied exposure routes in the human body. Develop technologies to measure crew pulmonary and other physiological responses to dust.
- The definition and manufacture of authentic lunar dust simulants as an important enabling tool to further lunar science and technology: Because of the current and projected scarcity of returned lunar dust samples, the panel recommended the expansion within NASA of a formal industry-standard process for the manufacture, quality control, and distribution of toxicologically relevant lunar dust simulants to researchers. Because dust toxicology is dependent on physiochemical and micromorphologic properties of dust particles, toxicological simulants will likely not be the same as simulants developed for in situ resource utilization (ISRU), and other non-health lunar mission research. To qualify such simulants, mission planners will need to obtain more data on the relevant features of native lunar dusts and to use that data to validate such high-fidelity simulants. The data required to meet the recommendations of the panel should be collected during initial Artemis missions and analyzed so that high-fidelity simulants can be produced followed by short- and long-term toxicology studies, which are essential to assure crew health on the Moon during later, more prolonged stays. The health standards developed by these studies will impact the design of critical environmental control and other engineered systems.

6.2.2 Toxicologically Relevant Features of Lunar Dust

The six Apollo lunar missions took place between 1969 and 1972, during which the crews brought back a total of 382 kg of lunar surface materials, including core samples collected to a depth of three meters[2]. All materials from the Moon, including soil returned by the Luna Soviet robotic missions, were regolith (i.e., no bedrock was sampled).

The Apollo materials included 92 kg of soil, as defined by grains of <1 cm in diameter (Heiken, 1991), and of this about 20% was composed of dust <20 microns in diameter (Park, 2008).

This means that lunar dust was only a small fraction of the total sample payload returned to Earth during Apollo, placing significant limitations on the amount that was available for pulmonary toxicology studies (McKay 2015). Members of the panel asked if it was possible that there could be enough existing well-preserved respirable dust from Apollo still held by NASA sufficient to conduct some of these additional studies. Roughly estimated, there could be kilograms of finer dust mixed with the larger regolith samples at the Lunar Sample Laboratory. The JSC Environmental Sciences Branch team on the panel agreed to investigate.

Regardless, some of the Apollo samples were inadvertently exposed to crew cabin and Earth atmosphere due to failure of collection canisters and other issues. This exposure likely

[2] https://www.hq.nasa.gov/alsj/a17/A17DeepCore.pdf

disproportionately altered the dust as compared to lunar rocks because of the higher surface to volume ratio of dust and consequent chemical alteration of toxicologically-relevant surface chemistry (Wallace, 2009).

Yet, considering the high barrier-penetration potential due to dust's ability to adhere to suits and equipment taken into crew cabins, as well as its capacity for lofting in cabin atmospheres and the demonstrated tendency to penetrate seals and joints, there is a consequent increased risk of health hazard and equipment contamination compared to larger regolith components.

In planning for future lunar missions, more focus on specialized collection of kilogram-quantities of dust for testing of human health and artificial systems will be beneficial. There is no published utilization analysis of the quantities of lunar dust needed for future human health research, however, kilogram-scale quantities of Mars dust simulant were thought necessary by the HHE panel in a prior NESC workshop on Mars dust in order to conduct full toxicological examination, including chronic exposure studies (Winterhalter, 2018).

While all size dust grains could affect human health by exposure to the eyes, skin, upper respiratory and gastrointestinal tracts, it is the < 10 micron dust that is of particular focus for toxicology research, since these are the "respirable" fraction that can travel on inspired air into the most sensitive parts of the lung. This includes the respiratory bronchioles and alveoli, where gas exchange with the blood occurs. At these dust particle sizes, electrostatic and aerodynamic forces are more influential than inertial forces and the dust particles start to act as if they are not dominated by mass, which is important for their behavior in the airways of the lung especially in fractional gravity environments (e.g., the Moon and Mars) (Darquenne, 2013).

This has implications for human health beyond lunar exploration. On the Earth, how dust particles behave in the lungs has been studied by the pharmaceutical industry to address the respiratory delivery of powder-based pharmaceuticals, and in the general terrestrial dust toxicology literature (Crowder, 2002, W.H.O., 1999). Although it is known that lunar dust contains significant proportions of such respirable particles, more needs to be known about the possibility for entry of this particle size range into crew cabins and EVA suits, and how they migrate in various types of atmospheres.

6.2.3 Lessons Learned from Apollo

The Apollo astronauts did not stay on the Moon's surface long enough for serious and irreversible health issues to result from their exposure to lunar dust, at least so far as is known from the subsequent health profiles of the Apollo crews. However, it became apparent that the effects of the dust on the human body, and on safety-critical equipment had been underestimated prior to the Apollo missions. In the future, these problems may become amplified over longer stays and any health and safety effects of lunar dust could be intensified by handling and recycling of dust in habitat life support systems, or through ISRU water extraction or other operational processes, to the detriment of the crews. An important outcome of new investigations will be an understanding of acute versus chronic dust exposures, and establishing safe levels of exposure for long-term stays.

Now that decades have passed since the last Apollo mission during which time many studies on lunar dust have been performed, we can re-evaluate the impact of lunar dust on the health of the Apollo crew and draw some valuable insights.

The impact of lunar dust exposure on crew health could come from two general directions: direct toxicity and degradation of the safety environment causing increased accidents.

6.2.3.1 Direct Toxicity:

As was seen in Apollo, through differential transport fine dusts may accumulate in the pressurized crew spaces and ancillary systems. This will be a constant challenge in future lunar missions.

Lunar soil, which is the component of the lunar surface that future lunar crews are most likely to move about and to mine, manipulate and transport for use in ISRU processes and other activities, contains in its native form approximately 0.5% respirable particles. The proportion of dust transported into crew habitation spaces that is toxicologically relevant is likely to be disproportionately high since the Apollo experience indicates smaller particles more readily adhere to surfaces and get trapped in fabrics, suit joints and other equipment surfaces and will more easily be transported through environmental barriers and into cabin atmospheres. As direct evidence, dust cleaned from Apollo suits was measured to be as much as 50% respirable dust (Christoffersen, 2008); and it is known from Apollo that the process of handling suits and other equipment can cause exposure and what appears to be a clinically measurable allergic response (Scheuring, 2007). The nature of this allergen is not known, but lunar dust contains some nickel, which although present in lower concentrations than on Earth (Taylor, 1979), might still be capable of causing reactions in sensitized individuals.

The anecdotal report of an immune response to lunar dust brings up the possibility of some complex interaction between dust and the documented immune dysregulation in crew members seen during space flight, which can persist throughout an entire mission and can include exaggerated hypersensitivity reactions (Makedonas, 2018).

The major concern for human health will be transport of dust into the human body through the air. Fortunately, the human lung has efficient mechanisms for limiting dust transport into the sensitive parts of the respiratory system. On Earth, most inhaled particles are trapped in the upper respiratory system or the major airways and removed by mucociliary clearance. Only about 1% of inhaled dust <10 micron in diameter will make it to the periphery of the lung and enter the respiratory bronchioles and alveoli, where gas exchange occurs and where significant pathology is known to occur for terrestrial dusts (W.H.O., 1999). However, depending on the nature of the dust and its interaction in the body, even this amount may cause health issues.

Complicating this situation, as a result of human and animal studies since Apollo it has been appreciated that this transport is subject to considerable modulation by partial gravities and in the fractional atmospheres that will be the norm in habitation spaces and in extravehicular activity (EVA) suits on the Moon, so a significant factor of doubt remains about the potential for toxicity. For example, studies show that particles of approximately 1 micron are more heavily deposited in the lung in fractional gravity environments (Prisk, 2018).

Since the 2007 NESC-sponsored NASA ARC lunar dust workshop, the implications of the unusual chemistry and potential effects of lunar dust on the health of crew have been extensively studied and reviewed (Loftus, 2010, Linnarsson, 2012, Scully 2013).

Any health risk for such exposure will ultimately be dependent on the innate toxicity of the dust, including its physical properties such chemical composition, surface area and other micromorphologic properties, and the release of gas volatiles and water-soluble elements, particularly those that can distribute in biological tissue.

Measuring the content of low molecular-weight gas volatiles (e.g., H2O, CO, CO2, H2, H2S, NH3, SO2, CH4, C2H4) in lunar soil will be the focus of the planned NASA Volatiles Investigating Polar Exploration Rover (VIPER) mission. This rover will explore the permanently-shadowed craters of the lunar south pole and directly analyze the regolith at various depths to provide important ground-truth data for design of sample preservation and return containment systems for Artemis and other lunar missions where samples could be returned to Earth (Ennico-Smith, 2020).

Regarding release of elements from lunar dust into liquid water, only limited studies have been conducted (Keller 2012, Wallace 2010). Those studies were restricted in time-spans addressed and in measuring the number of elements released during dissolution, but they indicate that when native lunar dust is suspended in an aqueous solution, a variety of metals and other elements will leach into the water. This release has implications for future lunar missions, ranging from concern about effects on mission hardware, effects on life support systems, possible direct effects on human health, and effects on research experiments such as plant growth experiments, space biology experiments and any activities that may involve the use of water sourced from the lunar poles. Furthermore, such contaminants could become concentrated or chemically altered to a more hazardous form during a variety of lunar mission activities, including everything from space suit cleaning to lunar industrial materials extraction. The exact profile of the release of ions from lunar dust and the fate of the remnant particles has not been explored. Any model of this dissolution must be based on an understanding of the unique micromorphology of lunar dust, including its predominant agglutinate features, morphology and nanophase iron content. Dust has a very high surface area available for interaction with water. For this reason, on first exposure to water, an immediate pulsed release of ions could occur, with more prolonged release taking place over months or years. Basic information on this important process is lacking. A reproducible method to measure this dissolution has been published (Kerschmann, 2020).

Finally, with regard to the toxic potential of lunar dust, much has been made of its distinctive, pungent smell, which the first Apollo astronauts compared to gunpowder. The implication is that this odor may be evidence of a significant chemical reactivity, which could in turn suggest toxicity. However, a similar smell was reported in the absence of dust on the International Space Station (ISS) at the conclusion of EVAs, and this has been termed “the smell of space” and thought to be due to the creation of ozone. According to astronaut Tom Jones: “To me, the odor was like ozone, hot electrical insulation, or gunpowder. I think the odor is probably ozone-related.” [3]

6.2.3.2 Health and Safety Impacts:

Judging from transcripts of Apollo surface operations, degradation of crew safety due to lunar dust contamination of equipment and habitats was significant.

Effects on equipment and mission systems are addressed in detail by other workshop panels and described elsewhere in this report. However, it may be worth pointing out that in some circumstances, safety impacts, on crew equipment and the direct toxicological effects of dust

[3] https://www.airspacemag.com/ask-astronaut/ask-astronaut-what-does-space-smell-180958670/#XeWxG2rbsY7Qw0Tq.99

may combine to worsen a hazard. For example, an accidental mass exposure of both crew and equipment to a large dose of dust may simultaneously degrade visibility due to eye/cornea injury and coincident coating and abrasion of EVA suit visors, camera lenses, etc. The astronaut's eyes are part of a visibility system, and physical and medical mitigations (e.g., emergency cleaning/eyewash systems) should be designed to be deployed together in emergency situations.

Another example of such deleterious is that during Apollo, dust damaged the EVA suits, infiltrating into mechanical joints making suit articulations difficult to operate (Slane, 1994, Wagner, 2006). This caused impaired mobility in the suit and additional musculoskeletal stress on the astronauts with increased fatigue. It is known from subsequent studies on crew after EVA on the ISS, and even during pre-flight training in suits, that trauma from interactions with even a fully functional suit can cause significant injury to hands, shoulders, and nails (Ramachandran, 2018).

It is known there was heavy contamination of astronaut's skin during the Apollo missions, and from subsequent experimental work that lunar dust is abrasive to skin (Jones, 2008). Over high mechanical pressure points in a dirty suit interior, dust could cause breakdown of the stratum corneum[4], the outermost water-proofing layer of the skin. This could increase evaporative water loss through the skin into the EVA suit interior. To the extent that lunar dust exacerbates any of these known mechanical difficulties with suits, there could be significant secondary effects on crew safety and health.

6.2.4 Apollo Post-Mission Quarantine Biohazard and Toxicity Testing

During the quarantine period extending 30 days after the return of crews of Apollo 11, 12, and 14, lunar regolith samples from these missions were extensively tested for evidence of living organisms and cellular toxicity on a wide variety of plant, animal, and microorganism species. Except for one or two unexplained findings that may have been errors of methodology, there was no evidence of a significant immediate biohazard in the samples. After Apollo 14, these examinations were significantly reduced (Taylor, 1975). The absence of living organisms was not unexpected, as no one in the 20th Century thought there was much chance of life on the Moon. As stated in the quarantine report:

"… findings are consistent with the generally accepted hypothesis that the lunar surface is now, and has always been, sterile."

The Apollo quarantine program established that there are no lunar life-forms and there is no possibility of infection. Furthermore, there has been no evidence since that time that the Apollo investigations, based as they were on technologies now considered outdated, were in error or missed any type of living organism, much less one dangerous to human health. Therefore, all returned lunar specimens may not need to be biologically quarantined and selected amounts can be optimally and rapidly be transported to terrestrial experimental facilities for toxicology and other studies.

[4] Outermost water-proofing layer of the skin

6.2.5 Special Cases of Respirable Particles: Lunar Nanoparticles and Volcanic Spheroidal Dusts

6.2.5.1 Lunar Nanoparticles

Another poorly quantified component of lunar dust is that fraction from 1 to 100 nanometers in diameter, which usually defines nanoparticles (Vert, 2012). It is known the smaller the grain size of lunar dust, the more that impact-melt glass and vapor-deposited elemental or nano-phase iron oxide (FeO) dominates the chemical composition ((McKay 2015, Thompson, 2010).

It is known from research on terrestrial nanoparticles that their toxicity is dependent on physical and chemical properties (Sukhanova, 2018), but size can cause a qualitatively different toxicological response in the human body. It is also known from the behavior of nanoparticles terrestrial that they can directly enter the bloodstream through the pulmonary capillary vessels, and can migrate into the central nervous system along olfactory and other nerve fibers (Oberdörster, 2005).

Analysis of the Apollo samples shows that the amount of FeO in the soils is about 10 times greater than that in the rocks from which they were derived. The majority of this FeO comes from the reduction of $Fe2+$ as a result of condensation of vapors produced by iron-rich micrometeorite impacts. The latter produces iron-containing coatings on the regolith grain surface. FeO is potentially toxic in the aqueous tissue environment of the lung due to production of ROS. However, these particles are magnetic, which provides a potential means of removing them from crew environments using magnetic fields (Liu, 2006). The iron particles interact strongly with microwaves to cause oxygen and other element release and will likely be handled during ISRU (Meek, 1984).

More research needs to be conducted into characterizing the presence and physiochemical characteristics of lunar dust nanoparticles, and their behavior in lunar mission environments. Any crew cabin monitoring technologies should be designed to detect and characterize this type of particle.

6.2.5.2 Volcanic Particles

While micrometeorite-impact generated agglutinates dominate the composition of lunar dust, the second important component is volcanic glass. Although there is no known current volcanism on the Moon, much evidence points to widespread eruptions within the past 100 million years (Braden, 2014), a relatively short time on the geological scale. Volcanic grains are present in lunar dust in detectible amounts, but are of a fundamentally different origin than the predominant glassy impact-related agglutinates. Volcanic dusts have not been studied separately for their toxicology, even though they are present in concentrations on the lunar surface. Volcanic eruptions most likely contributed to a wide distribution this type of lunar fines due the energy imparted during an eruption. Extended time of flight can be inferred from the shape of these particles as they solidified from the molten form into spheres (Tolansky, 1970).

It might be expected that because of the micro-morphological differences between lunar dust volcanic particles and the agglutinate impact products (e.g., the large difference in surface-to-volume ratio) the potential for biological toxicity of these fractions could be different. These particles are chemically distinct from agglutinates, and may be a significant source of volatiles. For example, the pyroclastics at the sites of Apollo 15 and 17 were golf-ball sized and contained condensed toxic volatiles of sulfur, zinc, and probably lead and mercury (Renggli, 2017). Pyroclastic sources on the Moon are large and may be resources for ISRU. (Heiken, 1974)

This could be important for future lunar exploration since the two types of particles may have significantly differing transport and physical behavior in human tissue, lunar vehicle, habitat environmental, and other systems. The same may be true of the other minor components of lunar dust (e.g., mineral rock chips).

6.2.6 Toxicologically Relevant Simulants

Since the supply of lunar soil will be restricted even from the Artemis lunar missions, and the fraction of human health-relevant dust is further limited, authentic simulants are required to provide material for the testing of crew environment mechanical systems and mitigation strategies, and for certain aspects of determining toxicity and other health effects (e.g., testing of instruments in the toxicology laboratory prior to using lunar material).

In 2005, a NASA-sponsored workshop on Lunar Regolith Simulant Materials was held at NASA Marshall Space Flight Center (MSFC) to establish requirements for the production and distribution of terrestrial analogues of lunar regolith. One of the early workshops on simulants of lunar dust was held in 2007 at LPI. This included discussion on simulant requirements, the simulants that were available at that time and what simulants were needed. This information contributed to the production of JSC-1 (the first official lunar dust simulant). In 2005 a NASA-sponsored workshop on Lunar Regolith Simulant Materials was held at NASA Marshall Space Flight Center (MSFC) to establish requirements for the production and distribution of terrestrial analogues of lunar regolith. Copies of the papers and abstracts from this meeting are available online [5].

Simulants such as JSC-1 and some others being developed are designed to provide a reasonable simulation of the bulk chemical properties and the grain size distribution of lunar soils, with approximately the correct mixture of minerals and glasses. They have some jagged shapes similar to lunar soils. However, lunar dust simulants produced to date do not fully reproduce agglutinate morphology. Neither do they contain reduced iron, have the same reflectance spectral properties, implanted species from solar wind, solar flares and cosmic rays. They do not have reactive radiative damaged surfaces, or reactive vapor deposits. All of these and other micromorphological features could have significant impacts on toxicity (Liu, 2008, Park, 2008). Consequently, there is a need for more authentic lunar dust simulants for toxicological studies, and such simulants may have to be manufactured de-novo since they are not likely available from natural terrestrial sources such as volcanic dust.

6.2.7 The LADTAG: A Historical Summary

To characterize the toxicological effects of the lunar dust, under the authority of the Chief Health and Medical Officer and soon after the 2007 NESC Lunar Dust Workshop, NASA formed LADTAG to set health standards and risk criteria for use by mission design engineers, operations planners, and astronauts during lunar missions. The group comprised experts in space toxicology and medicine, lunar geology, dust toxicity and biomedical research. LADTAG developed a guide

---

[5] http://est.msfc.nasa.gov/workshops/lrsm2005_program.html

to the research required to fill the gaps in knowledge about lunar dust, and to set a PEL for lunar dust.

LADTAG directed several research groups to undertake particular projects. The Lunar Geology group characterized the dust recovered from the Apollo hardware, characterize the lunar dust from pristine unfractionated Apollo soils, made early estimates of the size distribution for major representative lunar soils, and activated simulants with hydrogen/proton bombardment and UV to compare surface reactivity with non-activated soils. The Chemistry group worked with the Geology group to perform lunar dust dissolution studies and to determine the properties of lunar activation and determining the rate of passivation. The Chemistry group investigated the how reactive oxygen species (ROS) interact with lung tissue. The Biology group evaluated the effects of dust on the skin and determine the potential for dust to cause abrasion, irritation and sensitization. This group also studied eye toxicology in a standard animal model.

The research studies sponsored by LADTAG were geared towards reducing the uncertainties in the factors (e.g., size distribution, time exposure, activity, dose, dust species) contributing to the medical and health effects of dust. LADTAG determined that any research should first be tested on simulants since supplies of lunar dust will be limited. LADTAG determined that testing should be carried out on highland mature and immature dusts, since they most closely resemble what the crews will be exposed to at a south polar landing site.

6.3 The Impact of Lunar Dust on Surface Mechanical Systems and Surface Operations - Panel 3

6.3.1 Summary

Panel 3 included experts from NASA, industry, and academia. Some of the organizations represented on the panel included seven of the ten NASA Centers (Headquarters, JSC, LaRC, GRC, GSFC, Kennedy Space Center (KSC), MSFC, the JPL/California Institute of Technology, and the NESC), the Canadian Space Agency, Korea Institute of Civil Engineering (KICT), Korea Aerospace Research Institute (KARI), the Planetary Science Institute, Lockheed Martin, Barrios Technologies, Bechtel Corporation, Blue Origin, Maxar Technologies, Michigan Technological University, Sierra Nevada Corporation, The Aerospace Corporation, University of Colorado, University of Central Florida, University of Southern California, LPI/USRA, Washington University in St. Louis, WEX Foundation, Campos Technical Services, University of Maryland, and the Colorado School of Mines.

The purpose of the mechanical systems and surface operations panel was to determine the key issues associated with operating mechanical systems, including life support systems, successfully in the lunar environment. The panel believes that any risks associated with the presence of dust can be managed within the context of sound engineering design and practice, even for a long duration presence on the lunar surface. The need for lunar dust-like material for testing the mechanical systems will be extensive and can only realistically be managed by the use of appropriate simulants. This creates a need for an early characterization of simulants that are appropriate for mechanical testing and a categorization of the required mechanical systems and their dust-related issues. In addition, it will be crucial to establish standards for testing and qualification of mechanical systems.

6.3.2 An Integrated Approach to Dust Management

The issue of how to deal with dust will form a part of the design and development of all aspects of future lunar missions. For effective contamination control dust characteristics, including its size distribution, chemical composition and the shapes of the dust particles must be quantified. Samples of the lunar dust and rock are available and techniques (e.g., optical and electron microscopy, X-ray photoelectron spectroscopy (XPS), and neutron holography) could be used. These could also be adapted for use in in-situ studies. The panels noted that Earth-based communities (e.g., NASA, aerosol scientists, others) have comprehensive approaches to contamination study and control – integrating satellite measurements with ground-based sensors; use of low cost but robust sensor networks, machine learning concepts to aid understanding and interpretation, etc. It would be prudent to learn from this community to develop a more comprehensive approach to a lunar dust mitigation strategy.

In addition to experimental data, theoretical investigations are required. These can be used to understand particle transport and deposition processes which can be modeled using coupled transport, diffusion, gravitational settling, and thermophoresis and electrophoresis models. Studies should be completed for turbulent and non-turbulent flows. Pressure effects can also be important – low pressure has no effect on the deposition of dust on surfaces, but at higher pressures deposition rates increase. Also, modest temperature gradients can lead to dramatic differences in deposition.

It is known from Apollo that every time a suit used for an EVA is brought into the habitat it will bring dust with it. Limiting the amount of dust tracked into the habitat must be part of the design of all aspects of the lunar lander, habitat, and EVA systems. The lunar lander and EVA systems must be designed to provide barriers to minimize the amount of dust entering the habitat (the acceptable amount, the Permissible Exposure Limit (PEL) is still to be determined by the agency). Subsystems and components must be designed to include barriers, an integrated design between the vehicle layout, Life Support System (LSS), and EVA systems are required. Dust barrier and lander system design considerations for dust exclusion should be communicated to all elements of the lunar program. The dust control philosophy should be communicated to the subsystem development and design teams.

It is most important to emphasize that an efficient plan is needed for removing dust from the suits and equipment before entering the airlock. For cleaning and maintenance, the effect on the crew's time is important. The Apollo astronauts spent hours dealing with dust, removing it from their suits and equipment, cleaning cameras, hoses, zippers, seals and bearing mechanisms. They also had to spend time troubleshooting and repairing equipment damaged by dust. Mitigation technology could reduce the amount of time the crew spends on these tasks by minimizing an accumulation of dust both inside and outside of the habitat.

A dust cleaning technology workshop was held in May 2005 (Gaier, J.R., 2005). Its focus was on cleaning methods that were electrochemical or electromagnetic, and methods that used advanced textiles or materials. The easiest methods to remove dust particles are rolling, sliding, or lifting. Mechanical, physical, chemical, electrical and thermal forces can remove particles. Terrestrial dust removal processes using aqueous, semi-aqueous, solvents and non-aqueous methods may be relevant to the problem of lunar dust.

Strippable coatings are easy to apply (by painting and brushing) and are easy to remove by peeling. These would allow for the removal of fine particles and are a low -cost solution. On the negative side they tend to degrade, they have long drying times and they have a large volume per application. On the Moon there would also be issues of how to dispose of the waste.

Other possible cleaning methods include the use of lasers, plasma cleaning (films and inorganic films, use reactive plasma), and electrostatic cleaning (can be used to remove dry particles from dry substrates).

Water was reported by the Apollo crews to be an effective cleaning agent in low gravity. Water management is critical though, because of its weight and because of the need to treat it for re-use. The water treatment capability will depend on the chemistry resulting from mixing lunar dust with water.

An internal air circulating system needs to be created within the suit to clean the air the astronauts are breathing. Operational procedures needed to be developed to prevent dust from getting into the suit and further to prevent abrasion from contact on the skin.

Requirements need to be established for human habitability (e.g., how much dust is acceptable in the air, water, and food).

Crewed spaceflight hardware requirements include functional performance requirements which are impacted by dust. Safety requirements address the hazard and risk assessment. Certification is a criticality level and demands quality and reliability. There are certain fixed requirements of contamination control which impact delivering hardware. Building quality into the design must be part of the certification and qualification process.

6.3.3 How Much More Must Be Known About Dust?

When Apollo flew, little was known about the nature of lunar dust, and the missions were not designed with dust mitigation in mind. The goal for future missions is to design spacecraft hardware that will operate properly and able to mitigate dust so that the crew members stay productive and healthy.

Lessons can be learned from previous programs. Apollo demonstrated the need for good housekeeping and showed that a major source of contamination is the bringing of EVA suits into the crew module. The missions also provide experience of some cleaning methods. Some work has been done with the Apollo vehicle and EVA equipment to determine the dust loads and its effects on components and systems. Further inspection and analysis of the Apollo equipment is required to determine the dust penetration, the impact on the filters, its reaction to materials, and the system degradation.

The Space Shuttle Program (SSP) can provide us with information on debris control during ground operations, and the ISS experience provides filtration capabilities that can work for particles down to 0.3 microns. Testing of technologies in the relevant environments is critical.

Some work has been done with the Apollo vehicle and EVA equipment to determine the dust loads and its effects on components and systems. Further inspection and analysis of the Apollo equipment is required to determine the dust penetration, the impact on the filters, its reaction to materials and the system degradation. However, it cannot be assumed the data from Apollo will be applicable to the materials and designs selected for the Artemis Program.

A review of current technologies used in industries (e.g., pharmaceutical, military, nuclear, and warfare protection) that use personal protective equipment and/or reusable equipment should be considered. This interaction could stimulate or invigorate new ideas.

For development and testing of mechanical systems, the basic properties of the lunar dust and regolith, especially of that fraction smaller than 20 microns, must be characterized. An understanding of the dust properties and their effects must be known before effective testing can be completed. Information on a variety of properties, as a function of particle size, will be required including:

- Particle morphology, including size and shape distributions.
- Chemical composition and mineralogical structure of the regolith.
- Physical properties including hardness and abrasiveness.
- Electrostatic and magnetic properties.
- Thermal and optical properties.
- Dust dynamics – How much and what size of particles will be lofted (electrostatically, tribo-mechanically) to become potential hazards to mechanisms and/or deposited on surfaces? At what altitude does the plume become an issue for the sensors?
- Chemical absorption composition.
-
- Particle flux and size distribution. Should the flux be appreciable, small-sized particles will enter the astronauts' environments (suit, habitat, etc.) in significant quantity, unless the habitats are engineered with impractical and expensive constraints. Also, other mechanical and electrical/electronic systems, as well as concept of operations (CONOPS) and ISRU, will be affected. Laboratory tests (e.g., with simulants) will be necessary, but are not sufficient. All environments and systems will experience the potentially detrimental effects of the dust.
- Also, it is important to know the behavior of the electric field near the lunar surface, and the charge characteristics of the dust particles. Measurements of this type should be included in the design of one of the robotic missions.
- The properties of the lunar dust can be used to develop a detailed specification of lunar dust simulants. These could be specified for individual mechanical components and environments. Work done at NASA MSFC on simulants has resulted in the development of a method to evaluate the quality of any simulant of the regolith.

6.3.4 What Types of Mechanical Systems and Operational Scenarios are Envisioned in the Lunar Environment?

Problematic during the short-duration Apollo missions, lunar dust will critically affect technical systems with mission timelines that may span months, years, or even decades. It is important to understand which systems and components are affected and how. It has been hypothesized that a small number of crucial components will be affected by dust, in which case mitigation efforts can be concentrated on this subset.

Since testing will be an important part of developing dust-resistant mechanical systems, it will also be important to develop an appropriate simulant. The physical and chemical reactivity of the dust will be application and location specific, and the different chemical characteristics of the dust will have different effects on the mechanical systems. Some components of lunar dust could have long-term effects, which may necessitate the design of materials that are able to tolerate direct interaction with the lunar soil.

The design of the mechanical systems must take into account operation, maintenance, and repair in the lunar dust environment. Dust accumulation on the surfaces of components will affect their properties (e.g., power generation and the thermal/optical properties necessary for heat retention/rejection). Dust will also affect exposed connectors, seals, and sealing surfaces of umbilicals. The suggestion of the panel is that systems should to be designed to be maintenance free. Designs should be modular for easy replacement of components and to allow for redundancy.

The mechanical components that require study are bearings, bushings, gears, ball-screws, seals, lubricants, rotating surfaces, and fasteners (latches, clamps, bolts etc.). To test the components, there must first be an understanding of the dust attributes. The different components must be designed to mitigate the extent to which the lunar dust environment impacts the performance and operation of the lunar mechanical systems. It was suggested that there could be a multitude of design mitigations. For example, there are many coatings that can be tailored for a particular application, but there is not one single coating appropriate for every application. Mitigation suggestions included:

- Surface coatings that repel the dust
- Removal of the dust
- Altering the local lunar surface environment
- Charged brushes
- Systems that are designed to be tolerant of the dust
- Redundant systems that use a combination of these approaches
- The impact of the dust will depend on the basic CONOPS needs to be developed with consideration of operations within a dusty environment. In particular, there is a need to be conscious of anthropogenic dust generation. There will be an additional set of requirements for components depending on where they are to be located.

The impact of the dust will depend on the basic CONOPS needs to be developed with consideration of operations within a dusty environment. In particular, there is a need to be conscious of anthropogenic dust generation. There will be an additional set of requirements for components depending on where they are to be located.

Lunar dust could also act as a means of transporting other contaminants. For example, radioactivity could be transported on dust from a nuclear reactor or radioisotope thermal generators (RTG). Berms can be built as barriers for nuclear systems, but over time, the beams will become radioactive.

The impact of the dust will depend on the basic operations concept and therefore CONOPS needs to be developed with consideration of operations within a dusty environment. In particular there is a need to be conscious of anthropogenic dust generation. There will be an additional set of requirements for components depending on where they are to be located.

Dust could affect vibrating surfaces and environments, in unknown ways. This could have positive and/or negative effects, since dust could damp the vibration. Any consideration of the effects of dust on vibration needs to take into account gravitational influences.

Information about the effects of dust on short-stay lunar missions is available from Apollo, and for longer-term missions from Lunokhod (series of Soviet robotic lunar rovers designed to land on the Moon between 1969 and 1977), NASA's Surveyor Program lunar landers, China's Chang'e 3 and 4 rovers, and from scientific instruments deployed on the lunar surface by the Apollo crews. In addition, information could be gained from missions on other planets (e.g., from the NASA Mars rovers). If some of the failures of these rovers have been dust-related, then this could help identify areas of concern for the lunar mission

A crucial question is what are the effects of the ISRU and the plume? One of the goals of these studies is to find ways to reduce the effects of the launch and landing plume. Surveyor 3 and its cameras show the effects of the impact of lunar dust. One of the cameras brought back by the crew was darkened by dust and showed evidence of pitting from particle impacts. In every pit that was identified, lunar dust was present. Fine grain lunar dust accumulated in the most exposed areas. In the aluminum tube, the brown contamination, due to unburned chemicals from the thrusters, was found to peak where the craters peaked. A population study needs to be done on the pits and their contents to make some estimate of the impacting velocity.

6.3.5 What is the Appropriate Set of Development and Qualification Tests Necessary for the Demonstration of Successful Mechanical Systems Operations in the Lunar Dust Environment?

An Agency-wide methodology and approach for design and testing needs to be developed for mechanical systems operations in the lunar dust environment. There is a need to identify the effects of the dust on the functionality of the system components so that the testing can be done on the individual components. For example, what effect does the dust have on the function of electrical connection? How does rubbing by dust affect the components?

Relatively simple test techniques can be employed to understand the sensitivity of the operation and performance of mechanical systems to dust. There are standard testing techniques available, but these need to be used in the relevant environment. The problem with emulating the lunar environment on Earth is that one cannot create plasma environments with a sufficiently large Debye length and there is an element of risk in simulating lunar plasma environments associated with it. Tests have to be done on the Moon to verify the results from simulations on Earth. A review of the simulated environments (e.g., plasma and radiation) is required. A thermal/ vacuum dust chamber with simulants would be a good example. There is a list of facilities available for prototype system testing for ISRU demonstrations across the U.S. Testing may or may not need to include a combination of multiple properties of the lunar environment to account for synergistic effects. Developmental testing is required, and standard techniques may need to be modified.

Based on the Apollo experience, and testing that has been conducted, the panel hypothesized that once the sensitivities are better understood, and mitigation strategies defined, a robust qualification test program can be developed to verify mechanical system performance in the lunar dust environment.

7.0 Findings, Observations, and NESC Recommendations

The main product from the three panels are the set of findings, observations, and NESC recommendations in this section, which are intended to follow the guidelines for technical reports of the NESC. The pertinent definitions are:

- A Finding is a technical fact statement about the topic.
- An Observation is a refinement of, or extraction from a Finding, or a noteworthy fact, issue, and/or risk, which may not be directly within the assessment scope, but could generate a separate issue or concern if not addressed. Alternatively, an observation can be a positive acknowledgement of a Center/Program/Project/Organization’s operational structure, tools, and/or support provided.

- A Recommendation identifies "**what**" is to be done and "**when"** (if appropriate). It should refrain from providing direction on "**how**" actions are to be accomplished. Also, it should be directed to a specific Center/Program/Project/Organization ("**who**"). ***Note***: In contrast to an assessment dealing with a specific technical issue in a Center/Program/Project/Organization, the workshop output is difficult to direct towards a specific organization since the lunar dust problem will touch many NASA organizations yet to be defined.

Even though the three panels operated mostly independently, their FORs showed a significant amount of overlap. This is not surprising, since all three depend significantly on the dust's basic properties and characteristics. Many are largely unknown and prompt similar investigation requirements in all panels.

The FORs listed in Sections 7.1, 7.2, and 7.3 have the overlap removed, but the information of which panel contributed to a particular finding was maintained by noting the contributing panel(s) in the list of NESC recommendations (Section 7.3). The observations represent the discussion points entertained by the respective panels and are useful here in supporting their findings and recommendations. Also, the NESC recommendations include their priority as determined by the panels: Very High, High, Medium, and Low. The recommendations are directed towards NASA and/or other entities encased in square brackets [].

7.1 Findings

The following findings were identified:

F-1. Characteristics of the finest fraction (<45 microns size) of the lunar soil are not well understood. The knowledge gap increases with decreasing particle size. Further, there is insufficient knowledge of the variation in dust characteristics (e.g., chemical composition, mineralogy, etc.) of particles < 45 microns size across lunar geological regions.

F-2. Apollo and LADEE have obtained particle size distributions, but the work/analyses are not widely known in the lunar dust community.

F-3. There is uncertainty in the electrical charging properties of the lunar surface and individual particles.

F-4. Little knowledge exists on the electrical charge of regolith particles on and above the lunar surface due to the interactions with the solar wind, and magnetospheric plasmas, and photoemission and secondary electron emissions.

F-5. The triboelectric charging of regolith particles in contact with other particles is not well understood. Also, the effects of triboelectric charged particles in contact with human made materials is unknown.

F-6. There is uncertainty about electrical conductivity, dielectric properties and dielectric breakdown of lunar soil under lunar environmental conditions (e.g., temperature, vacuum conditions).

F-7. There is limited knowledge about the physics of astronaut/spacesuit charging and discharging in the lunar surface plasma environment, as well as its potential consequences to astronaut and equipment safety during surface operations.

F-8. Identification and mitigation of electric potential interactions (compatibilities) between suits and hardware in the lunar dust environment need to be considered.

F-9. There is limited knowledge on the effects from the "operation/design factors" on arcing and arcing consequences. Specific guidelines for mitigating dusty spacesuit electrostatic charging are not readily available.

F-10. Adhesion and cohesion properties of lunar dust are not well understood.

F-11. Passive solutions to dust mitigation are system dependent. There is information lacking with regard to how lunar dust will interact with materials being considered for lunar operations.

F-12. There is no comprehensive plan to set up a network of dust measurement instruments in future missions to obtain a spatio-temporal distribution of particle concentrations.

F-13. Thermal conductivity and thermal insulative properties of lunar dust in the lunar environment are not adequately known.

F-14. There is uncertainty in the packing, porosity and permeability and other bulk properties (e.g., shear strength, angle of repose, coefficient of friction, etc.) of lunar soil and its variation with geographic location and depth are not known.

F-15. A full description of in-situ lunar dust surface chemistry will be necessary in order to build accurate toxicological models and to create authentic simulants, but will require in-situ measurement of equilibrium surface chemistry due to the difficulty of replicating the lunar environment in terrestrial laboratories.

F-16. Real-time monitoring of airborne particulates, including lunar dust, in lunar habitats and vehicles is required to assess and mitigate crew health risk.

F-17. There has been little discussion and work, coordinated agency-wide, of cabin (Lunar lander, Gateway, even spacesuit – if needed) air cleaning systems.

F-18. Our knowledge of collateral dust transfer is insufficient to effectively design mitigation strategies. Also, the physics of natural dust transfer, particularly across the day/night terminator and at the edges of permanently shadowed regions, is not known with sufficient fidelity to determine whether mitigation efforts need to be focused in that direction.

F-19. Multiple landing vehicles in close proximity will create dust layers on neighboring vehicles.

F-20. There is insufficient information with regard to the effect of lunar dust deposition on optical, or thermal surface performance.

F-21. The bristle brush used during Apollo did not adequately clean critical surfaces such as lenses and radiator panels, leading to equipment failures.

F-22. Optical constants and spectral properties of dust-sized particles from UV through far-IR under relevant lunar temperature and vacuum conditions are needed for measuring the local dust environment.

F-23. While gaps exist, LADTAG provided significant toxicological data to guide setting permissible exposure limit for spaceflight.

F-24. The presence and nature of specific allergens and irritants in lunar dust has not been established.

F-25. It is unclear whether there is sufficient pristine respirable dust fraction in the NASA JSC Lunar Sample Laboratory Facility to perform additional animal toxicology studies for landing sites relevant to upcoming missions.

F-26. Lunar dust dissolves in aqueous solutions, such as those found in the human body, and in that process releases a variety of materials, including potentially reactive metals, the extent to which this represents a risk warrants further evaluation.

F-27. It is known fine particulates (PM 2.5) are deposited predominately in lung periphery in reduced gravity.

F-28. Inclusion of a capability for respiratory monitoring and diagnosis would be beneficial for medical operations to monitor the impact of lunar dust exposure.

F-29. There appears to be little coordinated discussions across the agency to identify the impact of lunar dust on mechanisms, seals, connectors, and solar panels. Nor are there cleaning systems identified.

F-30. There is uncertainty in the magnetic properties of the dust as particle size decreases and nanophase iron content increases.

F-31. There is uncertainty concerning the behavior of volatiles on controlling the properties of dust particles.

F-32. There is uncertainty concerning the bonding and adsorption of regolith particles with volatiles under lunar conditions.

F-33. Volatile materials are present in permanently shadowed areas at the lunar poles and may present a hazard to crews and their equipment or valuable resources.

F-34. No industry-standard set of NASA requirements and oversight mechanisms exist for the manufacturing, quality control, and validation of lunar dust simulants.

7.2 Observations

The following observations were made:

O-1. The general characteristics and distribution of lunar dust particles have not been well characterized for the smallest fraction of particles (<10 microns) that impacts human health and well-being (e.g., respiration and eye irritations). Additionally, particle size distributions <45 microns, which will affect hardware performance, have not been well characterized. ***(F-1)***

O-2. Measurements of the electrical charging properties of the lunar surface and individual particles have not been sufficiently examined to support human surface operations of increasing frequency or duration. ***(F-3)***

O-3. While charging/electrostatic discharging has been studied extensively for spacecraft on-orbit, the charging situation on lunar surface is different because of the lunar dust environment. Dust accumulation and the wear and tear of spacesuit by dust will enhance the severity of differential charging on spacesuit surface. This increases the probability of electrostatic discharge and arcing on spacesuit.

O-4. Concerns were expressed by panel members regarding how the agency will address the change from mechanical systems used during Apollo to ubiquitous modern electronics today in vehicles, suits, and habitats, etc. The dusty environment will surely provide a challenge. ***(F-3, F-4, F-7, F-8)***

O-5. Change from mechanical systems to modern electronics since Apollo.

O-6. Initial studies have demonstrated that electrostatic/dielectric breakdown are likely occur to dusty spacesuits under many of the space plasma conditions on lunar surface.

However, the consequences of arcing/breakdown on spacesuit and astronaut have not been investigated. There has been no “quantitative” assessment of the risks associated with charging/arcing. ***(F-7, F-9)***

O-7. Initial study shows, in addition to plasma environment, charging, and dust coverage, arcing onset are also influenced by many operation/design factors, such as material property, material outgassing, seal/suit leakage, leakage during the opening/closing of the hatch, water sublimation and other details of spacesuit design, etc. Such operation/design factors need to be carefully considered during the quantitative assessment of the risks. Current design guidelines on spacecraft charging/arcing are developed for “clean” spacecraft on-orbit (e.g., make the spacecraft surface uniformly conductive, etc.) ***(F-9)***

O-8. Thermal conductivity and thermal insulative properties of lunar dust in the lunar environment have only been detected at a few sites where missions have landed. ***(F-13)***

O-9. The packing, porosity and permeability and other bulk properties (e.g., shear strength, angle of repose, coefficient of friction, etc.) of lunar soil has only been measured at a few Apollo landing sites. ***(F-14)***

O-10. Surface physiochemical activation is a significant factor in determining particulate Surface physiochemical activation is a significant factor in determining particulate toxicology in terrestrial materials. Chemical reduction of simulant raises oxidative damage markers in in vitro studies. This is not involved in LADTAG results; direct dry dust exposure to trachea in rodents is the preferable exposure route. ***(F-15)***

O-11. ROS toxicity studies of individual mineral phases show that slight chemical differences in individual mineral phases can strongly affect toxicity. ***(F-15)***.

O-12. While mass-based particulate load measurement is necessary at a minimum to protect crew health, a means to identify in real time the nature of particle types (cabin vs. lunar dust) contaminating the cabin air would be desirable.

O-13. The impact of aerosols resulting from dust particles-liquid interactions (e.g., cleaning fluids, breath, etc.) in enclosures (cabins, spacesuits) has not been estimated.

O-14. Although much was learned about collateral dust transfer during the Apollo Program, the flux of dust transfer during different surface operations, the role of dust cohesion, and how human activities affect the cohesive and adhesive properties of the surface layer of regolith, and the mechanisms by which lunar surface operations will transfer dust are poorly understood (all operational environments - zero g/inside/outside, etc.)

O-15. A campaign of landing vehicles on the lunar surface is planned to establish a human presence on the Moon. As described in the Lunar Dust Workshop, vehicle landing activities will produce significant dust from propulsion ejecta.

O-16. Although from the Apollo excursions into permanently shadowed regions and analysis of rover and foot tracks the flux of natural dust transfer is thought to be insignificant compared to collateral transfer, its magnitude has not been quantified so natural dust transfer could pose a risk to extended missions.

O-17. Surfaces may look optically clean but are dirty, leading to equipment failure.

O-18. Early Artemis landings are planned at 6.5 days, whereas later Artemis missions will be in the range of 30-180 days on surface. The LADTAG PEL is appropriate for the short-stay Artemis missions but gaps in toxicological analysis may pertain to long-stay Artemis missions

O-19. Nickel is a cause of allergic contact dermatitis and has known toxicological effects via inhalation and oral route. It is present on the Moon in lower concentrations than on Earth, however, allergic reactions are more dependent on host sensitivity than on allergen concentrations. Irritant reactions may resemble allergic reactions, but are more dependent on irritant concentrations and less specific to an individual.

O-20. 2% of the airborne particulate contamination on the ISS is composed of nickel-bearing material.

O-21. It is possible to separate in situ and transport to Earth sufficient quantities of lunar dust in the <100-micron size.

O-22. Materials given off by lunar dust in aqueous solution may be released in a concentrated burst, due to the high surface area of dust agglutinates and mostly glass adherent nanoparticles that dissolve rapidly due to their small size and high surface to volume ratio.

O-23. Most animal studies looking at dust toxicity did not control for deep lung deposition. There is evidence of weakened immune system during long-duration spaceflight. There are no studies looking at combined effect of lunar dust and a weakened immune system.

O-24. Magnetic properties as particle size decreases and nanophase iron content increases have not been well characterized.

O-25. Measurements on the behavior of volatiles on controlling the properties of dust particles do not exist.

O-26. Measurements on the bonding and adsorption of regolith particles with volatiles under all lunar conditions do not exist.

O-27. Volatile materials detected in cold-traps on the Moon [AGU report], especially in permanently shadowed polar craters, may include ammonia, mercury, hydrogen sulfide, methane, carbon monoxide, as well as resources such as water and carbon dioxide. The VIPER mission will analyze volatiles at the south lunar pole.

7.3 NESC Recommendations

The following NESC recommendations are directed towards lunar mission designers and engineers for the precursor and the crewed missions, and payload selections:

R-1. Measure lunar dust particle size and shape distribution, chemical composition, mineralogy, chemical reactivity, electrical charge, mobilization, migration, and deposition from 45 to 0.1 micron across lunar geological regions. ***(F-1 to F-4, F-6, F-9)*** [SMD, HEOMD, STMD] PRIORITY: Very High. (Panels 1, 2, 3)

R-2. Produce a review article that integrates the LADEE particle size distribution (0.3 -10 μm) near the lunar surface to altitude with Apollo data. ***(F-2)*** [NESC] PRIORITY: High. (Panel 3)

R-3. Measure electrical charge using Apollo samples to simulated interactions with solar wind plasma, photoemissions, and secondary electrons. ***(F-4)*** [HEOMD, SMD] PRIORITY: Very High. (Panel 1)

R-4. Measure tribocharging for particle-particle and particle-material charging using Apollo samples. ***(F-5)*** [SMD, HEOMD] PRIORITY: High. (Panel 1)

R-5. Measure electrical conductivity and dielectric properties of Apollo samples under lunar environmental conditions. ***(F-6)*** [SMD, HEOMD] PRIORITY: High. (Panel 1)

R-6. Investigate spacesuit charging/discharging by physics-based modeling and laboratory experiments. ***(F-7)*** [HEOMD] PRIORITY: Medium. (Panel 3)

R-7. Produce guidelines delineating and mitigating electric potential interactions between space suits and hardware in the lunar dust environment. ***(F-8)*** [HEOMD, Industry] PRIORITY: Medium. (Panel 3)

R-8. Initiate experiments to characterize lunar dust cohesion as well as adhesion to relevant materials (e.g., metals, fabrics, plastics, electronics, filters, etc.). Establish adhesion testing procedures for the materials and a data base containing the results. ***(F-10)*** [HEOMD, Universities] PRIORITY: High. (Panel 1, 3)

R-9. Measure lunar dust thermal conductivity using Apollo samples and future in situ measurements on the lunar surface. ***(F-13)*** [HEOMD] PRIORITY: Medium. (Panel 1)

R-10. Perform laboratory experiments and measurements to quantify the bulk lunar dust properties under lunar environmental conditions (e.g., hard vacuum, lunar surface temperature, and reduced gravity conditions). ***(F-14)*** [HEOMD, SMD) PRIORITY: Medium. (Panel 1)

R-11. Support studies on the characterization of the surface physiochemical activation of lunar dust and generation of ROS and other potentially toxic products. ***(F-15)*** [HEOMD] PRIORITY: High. (Panel 2)

R-12. Ensure that real-time dust monitoring solutions relevant to human health exist in Gateway and Human Lander System requirements. ***(F-16)*** [HEOMD] PRIORITY: High. (Panel 2)

R-13. Develop routine and innovative dust remediation systems (e.g., as filtration, ESPs, photo-ionizers, enhanced ESPs, electret filters, etc.) for lunar application. ***(F-17)*** [STMD, HEOMD] PRIORITY: Very High. (Panel 3)

R-14. Perform laboratory experiments, model and simulation on dust transfer, in-situ measurements (validation and iteration). ***(F-18)*** [STMD, SMD, Universities] PRIORITY: High. (Panel 3)

R-15. A strategy for distributing landing vehicles on the lunar surface must address ejecta effects on/from neighboring vehicles. ***(F-18, F-19)*** [HEOMD] PRIORITY: Medium. (Panel 3)

R-16. Initiate/support a laboratory program to characterize the effect of lunar dust deposition on optical and thermal surfaces. ***(F-11, F-13, F-20, F-21)*** [HEOMD, STMD] PRIORITY: Very High. (Panel 3)

R-17. Perform refractive index measurements of mare and highlands mineral components from the far-UV through the far-IR using Apollo samples. ***(F-22)*** [SMD, HEOMD] PRIORITY: Low. (Panel 1)

R-18. Support studies including those using return materials from short-stay Artemis missions to better inform potential risks for exposure on the longer-duration Artemis missions. ***(F-23)*** [HEOMD and OCHMO] PRIORITY: Very High. (Panel 2)

R-19. Support studies on characterization of lunar dust to address potential allergens, including metal allergens such as nickel. ***(F-24)*** [HEOMD and OCHMO] PRIORITY: Medium. (Panel 2)

R-20. Consult with the NASA Astromaterials Research and Exploration Science Division and report on the amount and accessibility of respirable-size lunar dust for studies of chronic toxicity, and make recommendations for such studies. ***(F-25)*** [HEOMD] PRIORITY: Medium. (Panel 2)

R-21. Support analytical studies on dissolution of lunar dust in aqueous environments. ***(F-26)*** [HEOMD] PRIORITY: Medium. (Panel 2)

R-22. Support toxicological studies to address deep pulmonary deposition of particles in fractional gravity. ***(F-27)*** [HEOMD] PRIORITY: Medium. (Panel 2)

R-23. Support studies to address the development of respiratory health monitoring focused on lunar dust and other particulate deposition in the respiratory system. ***(F-28)*** [HEOMD and OCHMO] PRIORITY: Medium. (Panel 2)

R-24. Organize an Agency-wide, coordinated effort (working groups, technical discipline teams, etc.) to discuss, develop, and select for deployment, device (including suits) cleaning technologies. ***(F-17, F-20, F-29)*** [STMD] PRIORITY: Very High. (Panel 3)

R-25. Measure the magnetic properties and how they vary with particle size and composition using existing Apollo and future in situ measurements on the lunar surface. ***(F-31)*** [STMD, SMD, Universities] PRIORITY: Low. (Panel 1)

R-26. Perform laboratory experiments to quantify how the presence of volatiles impact the bulk characteristics of regolith and dust under relevant environmental conditions. Also, quantify the nature of volatile bonding with particular emphasis on water. ***(F-31, F-32)*** [STMD, SMD, Universities] PRIORITY: High. (Panel 1)

R-27. Assess the results from the VIPER mission for remaining gaps in knowledge relevant to the Artemis program, and to the preservation of gas volatiles in samples. ***(F-33)*** [HEOMD] PRIORITY: Medium. (Panel 2)

R-28. Identify the most qualified group within NASA and/or other agencies that will develop an industry-standard set of NASA requirements and oversight mechanisms for the manufacturing, quality control, and validation of lunar dust simulants. ***(F-34)*** [HEOMD and OCHMO] PRIORITY: Very High. (Panel 2).

8.0 Alternative Viewpoint(s)

There were no alternative viewpoints identified during the course of this support by the NESC team or the NRB quorum.

9.0 Other Deliverables

No unique hardware, software, or data packages, outside those contained in this report, were disseminated to other parties outside this support.

10.0 Recommendations for NASA Standards and Specifications

- An Agency-level standard for the manufacture and quality control of lunar dust simulants specifically designed for toxicological studies should be developed by the NASA Office of the Chief Health and Medical Officer.
- An Agency-level standard for testing and qualification of mechanical systems in the lunar dust environment should be developed by NASA's HEOMD or STMD.

11.0 Acronyms List

ALSEP	Apollo Lunar Science Experiment Package
AOD	Aerosol Optical Depth
ARC	Ames Research Center
CONOPS	Concept of Operations
COSPAR	Committee on Space Research
CSA	Canadian Space Agency
DDE	Dust Detector Experiment
EVA	Extravehicular Activity
ESP	External Stowage Platform
FeO	Iron Oxide
FOR	Findings, Observations, and NESC Recommendations
GRC	Glenn Research Center
GSFC	Goddard Space Flight Center
HEOMD	Human Exploration and Operations Mission Directorate
HHE	Human Health Effects
IDP	Interplanetary Dust Particle
ISRU	In-situ Resource Utilization
ISS	International Space Stations
JSC	Johnson Space Center
JPL	Jet Propulsion Laboratory
KARI	Korea Aerospace Research Institute
KICT	Korea Institute of Civil Engineering
KSC	Kennedy Space Center
LADEE	Lunar Atmosphere and Dust Experiment
LADTAG	Lunar Airborne Dust Toxicity Assessment Group
LaRC	Langley Research Center
LPI	Lunar and Planetary Institute
LSS	Life Support System
MD	Mission Directorate
MGS/TES	Mars Global Surveyor Surveyor/Thermal Emission Spectrometer
MSFC	Marshall Space Flight Center
NESC	NASA Engineering and Safety Center
OCHMO	Office of the Chief Health and Medical Officer
PEL	Permissible Exposure Limit
PSD	Particle Size Distribution
ROS	Reactive Oxygen Species
RTG	Radioisotope Thermal Generator
SNC	Sierra Nevada Corporation
SSP	Space Shuttle Program
STMD	Space Technology Mission Directorate
TDT	Technical Discipline Team
U.S.	United States
USRA	Universities Space Research Association
UV	Ultraviolet
VIPER	Volatiles Investigating Polar Exploration Rover

WHO World Health Organization
XPS X-ray photoelectron spectroscopy

12.0 References

Braden, S.E., Stopar, J.D., Robinson, M.S., Lawrence, S.J., van der Bogert, C.H., Hiesinger, H. Evidence for basaltic volcanism on the Moon within the past 100 million years Nature Geoscience volume7, pages787–791 (2014) Letter | Published: 12 October 2014

Christoffersen, R., Lindsay, J.F., Noble, S. K., Meador, M.A. Kosmo J.J., Lawrence, A. Brostoff, L., Young, A, McCue, T. (2008) Lunar Dust Effects on Spacesuit Systems Insights from the Apollo Spacesuits NASA/TP 2008-000000 Library of Congress, Washington, D.C. Enter Month 2008 https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20090015239.pdf

Crowder, T.M., Rosati, J.A., Schroeter, J.D., Hickey, A.J. and Martonen, T.B. (2002) Review Article Fundamental Effects of Particle Morphology on Lung Delivery: Predictions of Stokes' Law and the Particular Relevance to Dry Powder Inhaler Formulation and Development Pharmaceutical Research, Vol. 19, No. 3, March 2002 http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.471.7262&rep=rep1&type=pdf

Darquenne, C. and Prisk, G.K. Particulate Deposition in the Human Lung Under Lunar Habitat Conditions (2013) Aviation Space and Environmental Medicine 84(3):190-5

Elphic, R.C., G. T. Delory, B. Hines, P.R. Mahaffy, M. Horanyi, A, Colaprete, M. Benna and S.K. Noble, 2014: The Lunar Atmosphere and Dust Environment Explorer Mission, Space Science Review, 185 (1-4): 3-25, doi: 10.1007/s11214-0113-z.

Ennico-Smith, K., Colaprete, A., Elphic, R., Captain, J., Quinn, J., and Zachny, K. (2020) The Volatiles Investigating Polar Exploration Rover payload. [abstract] 51st Lunar and Planetary Science Conference, Houston, TX https://www.hou.usra.edu/meetings/lpsc2020/pdf/2898.pdf

Gaier, J. R., 2005, *The Effects of Lunar Dust on EVA Systems During the Apollo Missions*, NASA/TM-2005-213610/REV 1, 65 pages

Geant H. Heiken, David S. McKay, R.W. Brown (1974) Lunar deposits of possible pyroclastic origin Geochimica et Cosmochimica Acta Volume 38, Issue 11, November 1974, Pages 1703-1704, IN3-IN9, 1705-1718

Heiken G. H., Vanniman, D. T., and French, B. M. (1991). Lunar Sourcebook. Cambridge University Press. *p. 756.* ISBN 978-0-521-33444-0. *https://www.lpi.usra.edu/publications/books/lunar_sourcebook/pdf/LunarSourceBook.pdf*

Heiken, G. H., Vaniman, D. T. and French, B. M., 1991: Lunar Sourcebook: A User's Guide to the Moon, Cambridge University Press and Lunar and Planetary Institute.

Horanyi, M. et al., 2020: The Dust Environment of the Moon, Abstract 5032, The Impact of Lunar Dust on Human Exploration, The Lunar and Planetary Institute, Houston, TX, Feb. 2020.

James, John T., Chiu-Wing Lam, Patricia A. Santana, and Robert R. Scully. (2013). "Estimate of Safe Human Exposure Levels for Lunar Dust Based on Comparative Benchmark Dose Modeling." Inhalation Toxicology 25 (5): 243–56. (https://doi.org/10.3109/08958378.2013.777821).

Jones, L., Jacques, S., Tranfield, E., Rask, J., Kerschmann, R. Loftus, D. (2008) Skin Abrasion Effects of Lunar Dust Relevant to Astronauts. 39th Lunar and Planetary Science Conference, (Lunar and Planetary Science XXXIX), held March 10-14, 2008 in League City, Texas. LPI Contribution No. 1391, p.2541

Keller W.D., Huang, W.H. (1971) Response of Apollo 12 lunar dust to reagents simulative of those in the weathering environment of Earth. Proceedings of the Second Lunar Science Conference, 1:973-981. MIT Press

Kerschmann, R., Winterhalter, D., Scheiderich, K., Damby, D. Loftus, D. (2020) Profiling lunar dust dissolution in aqueous environments: The design concept. Acta Astronautica [in press] www.sciencedirect.com/science/article/abs/pii/S0094576520305294

Lam, C., Scully, R.R., Zhang, Y., Renne, R.A., Hunter, R.L., McCluskey, R.A., Chen, B.T., Castranova, V., Driscoll, K.E., Gardner, D.E., McClellan, R.O., Cooper, B.L., McKay, D.S., Marshall, L., James, J.T. (2013) Toxicity of lunar dust assessed in inhalation-exposed rats. Inhal Toxicol, 25(12): 661-678

Linnarsson, D., Carpenter J., Fubini, B., Gerde, P., Karisson, L.L., Loftus, D.J., Prisk, G.K., Staufer, U., Tranfield, E.M., van Westrenen, W., (2012) Toxicity of Lunar Dust. Planetary and Space Science 74:57-71

Liu, Y, Thompson, J.R., Taylor, L.A.; Park, J., (2006) Magnetic Properties of Apollo 17 Soil Sample 70051 Lunar and Planetary Science XXXVII (2006)

Liu, Y., Park, J., Schnare, D., Hill, E. Taylor, L.A. (2008) Characterization of Lunar Dust for Toxicological Studies. II: Texture and Shape Characteristics Journal of Aerospace Engineering Vol. 21, Issue 4 (October 2008)

Loftus, D.J., Rask, J.C., McCrossin, C.G., Tranfield, E.M. (2010) 7.0 The Chemical Reactivity of Lunar Dust: From Toxicity to Astrobiology. Earth, Moon, and Planets, 107(1): 95-105

Martin, S., 2006: The Apollo Experience Lessons Learned for Constellation Lunar Dust Management, NASA TP-2006-213726, 71 pages.

McKay, D., Cooper, B.L., Taylor, L.A., James, J.T., Thomas-Keprta, K., Pieters, C.M., Wentworth, S.J., Wallace, W.T., Lee T.S. (2015) Physicochemical properties of respirable-size lunar dust. Acta Astronautica 107:163-176

Meek, T T., Cocks, F H, Vaniman, D T, and Wright, R A. Microwave processing of lunar materials: potential applications. United States: N. p., 1984. Web.

NASA/TM–2007–214755 National Aeronautics and Space Administration, Lyndon B. Johnson Space Center, Texas 77058

O'Brien, B. J., 2018: Paradigm Shifts About Dust on the Moon: From Apollo 11 to Chang'e-4, Planetary and Space Science, 156, pp. 47-56.

Oberdörster, G., Oberdörster, E., and Oberdörster, J. (2005)3 Nanotoxicology: An Emerging Discipline Evolving from Studies of Ultrafine Particles Environ Health Perspect 113:823–839 (2005). doi:10.1289/ehp.7339 (available via http://dx.doi.org/)

Park, J., Liu, Y., Kihm, K.D., Taylor, L.A. (2008) Characterization of Lunar Dust for Toxicological Studies. I: Particle Size Distribution, Journal of Aerospace Engineering, Vol. 21, Issue 4 (October 2008)

Park, J., Liu, Y., Kihm, K.D., Taylor, L.A. (2008) Characterization of Lunar Dust for Toxicological Studies I: Particle Size Distribution. Journal of Aerospace Engineering. 21:266-271

Prisk, G.K. (2018) Effects of Partial Gravity on the Function and Particle Handling of the Human Lung. Current Pathobiology Reports 6:159–166, Springer-Nature pub, https://doi.org/10.1007/s40139-018-0174-x

Ramachandran, V. Dalal, S., Scheuring, R.A., and Jones, J.A. (2018) Musculoskeletal Injuries in Astronauts: Review of Pre-flight, In-flight, Post-flight, and Extravehicular Activity Injuries. In: Effects of the Space Environment on Human Pathobiology (R Kerschmann, Section Editor). Published online: 28 July 2018. Current Pathobiology Reports (2018) 6:149–158 (available at https://doi.org/10.1007/s40139-018-0172-z)

Renggli, C.J., King, P.L., Henley, R.W. , Norman, M.D. (2017) Volcanic gas composition, metal dispersion and deposition during explosive volcanic eruptions on the Moon Geochimica et Cosmochimica Acta Volume 206, 1 June 2017, Pages 296-311 https://doi.org/10.1016/j.gca.2017.03.012

Scheuring, R.A. Jones, J.A., Polk, J.D. , Gillis, D.B., Schmidt, J. , Duncan, J.M., Davis, J.R., Novak, J.D. (2007) The Apollo Medical Operations Project: Recommendations to Improve Crew Health and Performance for Future Exploration Missions and Lunar Surface Operations

Scully, R.R., Lam, C.W., James, J.T. (2013) Estimating Safe Human Exposure Levels for Lunar Dust Using Benchmark Does Modeling of Data from Inhalation Studies in Rats. Inhalation Toxicology 25(14): 785-793

Slane, F. A. (1994) In Engineering, construction, and operations in space IV, R. G. Galloway, S. Lokaj, eds, ASCE, New York, 1097–1105

Sukhanova, A, Bozrova, S, Sokolov, P, Berestovoy, M, Karaulov, A. (2018) Dependence of Nanoparticle Toxicity on their Physical and Chemical Properties. Nanoscale Research Letters 13:44 1-21 https://doi.org/10.1186/s11671-018-2457-x

Taylor, G.R., Mieszkuc B.J., Simmonds, R.C. Walkinshaw, C.H., (1975) Quarantine Testing and Biocharacterization of Lunar Materials. Biomedical Results of Apollo, ed. Richard S. Johnston, Lawrence F. Deitlein, MD, and Charles A. Berry, MD. Scientific and Technical Information Office, NASA https://www.hq.nasa.gov/alsj/NASA-SP-368.pdf

Taylor, S.R. (1979) Nickel Abundances in Lunar Mare Basalts, Lunar and Planetary Science X 1215-1216 [abstract] http://adsabs.harvard.edu/full/1979LPI....10.1215T

Thompson, M., Christoffersen, R. (2010) The smallest lunar grains: Analytical TEM characterization of the sub-micron size fraction of mare soil. [extended abstract] 41st Lunar and Planetary Science Conference; The Woodlands, TX

Tolansky, S. (1970) Interferometric examination of small glassy spherules and related objects in a 5-gram lunar dust sample. Proceedings, Apollo 11 Lunar Science Conference, 3:2463-2466

Vert, M.; Doi, Y.; Hellwich, K. H.; Hess, M.; Hodge, P.; Kubisa, P.; Rinaudo, M.; Schué, F. O. (2012). "Terminology for biorelated polymers and applications (IUPAC Recommendations 2012)". Pure and Applied Chemistry. 84 (2): 377 410. doi:10.1351/PAC-REC-10-12-04.

Wagner, S. (2006) The Apollo Experience: Lessons learned for Constellation dust management NASA/TP-2006-213726, September 2006

Wallace, W. T. and A. S. Jeevarajan, 2008: Lunar Dust and Lunar Simulant Activation and Monitoring, NLSI Lunar Science Conference, 2015

Wallace, W.T., (2010) Dissolution Properties of Lunar Dust and Lunar Dust Simulant. Presented at the annual meeting of the Lunar Airborne Dust Toxicity Advisory Group (LADTAG) https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20090007462.pdf

Wallace, W.T., Taylor, L.A., Liu, Y., Cooper, B.L., McKay, D.S., Chen, B., Jeevarajan, A.S. (2009) Lunar dust and lunar simulant activation and monitoring. Meteorites & Planetary Science 44, 7:962-970

Winterhalter, D., Levine, J.S., Kerschmann, R. (2018) The Dust in the Atmosphere of Mars and Its Impact on the Human Exploration of Mars: A NESC Workshop. NASA/TM—2018-220084/NESC-RP-17-01263 https://ntrs.nasa.gov/citations/20180006321

World Health Organization, (1999): Hazard prevention and control in the work environment: Airborne dust (https://www.who.int/occupational_health/publications/airdust/en/)

Appendices

Appendix A. 2020 Lunar Dust Workshop Participants

Appendix A. 2020 Lunar Dust Workshop Participants

Name	Affiliation	Panel
Abel, Phillip B.	NASA Glenn Research Center	3
Agui, Juan H	NASA Glenn Research Center	3
Ballard, Jason D	ICON	3
Barker, Donald C.	NASA Johnson Space Center	1
Bell, Mary Sue	Jacobs, NASA Johnson Space Center	3
Beltran, Esther	University of Central Florida	3
Bergman, Heather	NASA Johnson Space Center	3
Beveridge, Iain C	Blue Origin	3
Biswas, Pratim	Washington University in St. Louis	3
Brady, Timothy	NASA Engineering and Safety Center	3
Brisset, Julie	University of Central Florida	1
Brown, Gary L	Barrios Technologies / NASA Gateway	3
Buhler, Charles Raymond	NASA Kennedy Space Center	3
Carrato, Peter J	Bechtel Corp	3
Chang, Hsing-Ming	Stony Brook University	2
Chung, Taeil	Korea Institute of Civil Engineering (KICT)	3
Collier, Paul Jason	NASA Johnson Space Center	3
Collins, Jacob	NASA Johnson Space Center	3
Connolly, John	NASA Johnson Space Center	1 Plenary Speaker
Cruz, Santana Frank	NASA Johnson Space Center	2
Danque, Hunter A	Colorado School of Mines	1
Darquenne, Chantal J	University of California, San Diego	2 Plenary Speaker
Deitrick, Sarah Rebekah	NASA Johnson Space Center	3
Diamond, Michael A	MICC	2
Dove, Adrienne	University of Central Florida	1
Evernden, Brent A	NASA Johnson Space Center	3
Folta, Blake A	Missouri S&T	3
Gaier, James R	NASA Glenn Research Center (Retired)	1 Plenary Speaker
Glenar, David Alan	University Maryland Baltimore County	1
Gustafson, Robert	Sierra Nevada Corporation	3
Hagen, Jeffrey David	NASA Johnson Space Center	3
Haggerty, Nathan	Sierra Nevada Corporation	3
Hartzell, Christine M	University of Maryland	1
Heath, Lauren M	KBR	2
Hendricks, James E	Campos Technical Services	3
Hendricks, Terry J	NASA Jet Propulsion Laboratory	3
Hendrix, Amanda R	SSERVI/TREX, Planetary Science Institute	1
Hendrix, Donald	Stony Brook University	2
Henninger, Donald L	NASA Johnson Space Center	3
Hirabayashi, Masatoshi	Auburn University	1
Horanyi, Mihaly	U. of Colorado	3 Plenary Speaker
Hoyle, Andrew	NASA Johnson Space Center	3

Hurowitz, Joel	Stony Brook University	2	
Israelsson, Ulf E	NASA Jet Propulsion Laboratory	3	
Jacobson, Howard	Healthcare Consultant	3	
Johansen, Michael R	NASA Headquarters	3	Plenary Speaker
John, Kristen Kathleen	NASA Johnson Space Center	3	
Johnson, Matthew E.	NASA Johnson Space Center	3	
Ju, Gwanghyeok	Korea Aerospace Research Institute (KARI)	3	
Keprta, Sean R.	NASA Johnson Space Center	2	
Kerschmann, Russell	NASA Ames Research Center	2	Moderator
Kim, Kyeong Ja	Korea Inst. of Geoscience and Mineral Resource	3	
Kirkland, Joel A	Lockheed Martin	3	
Klaus, Kurt	Lunar and Planetary Institute	3	
Kleinhenz, Julie E	NASA Glenn Research Center	3	
Kramer, Georgiana Y	Planetary Science Institute	1	
Kring, David A	USRA - LPI	3	
Lane, Melissa D	Fibernetics Corp.	1	
Lee, Kevin W	NASA Johnson Space Center	3	
Lee, Steve Anthony	NASA Johnson Space Center	3	
Levine, Joel S	The College of William and Mary	1	Moderator
Lewis, James Lyn	NASA Johnson Space Center	3	
Linnarsson, Dag	Karolina Institute, Sweden	2	
McBryan, Emily	NASA Johnson Space Center	3	
McCoy, James Torin	NASA Johnson Space Center	3	Plenary Speaker
McGarvey, Terence W	Missouri University of Science and Technology.	3	
Mendell, Christopher N.	NASA Johnson Space Center	3	
Metzger, Philip T.	University of Central Florida	3	Plenary Speaker
Meyer, Marit E	NASA Glenn Research Center	2	
Michel, Jeffrey	NASA Johnson Space Center	3	
Miller, Sharon K.R.	NASA Glenn Research Center	3	
Moeller, Chad Robert	NASA Johnson Space Center	3	
Moghbeli, Samuel Wald	NASA Johnson Space Center	3	
Munk, Michelle M	NASA-Langley Research Center	1	
Nekvasil, Hanna	Stony Brook University	2	
Noorani, Naina	NASA Johnson Space Center	3	
O'Brien, Brian J.	Brian J. O'Brien & Assoc	1	Plenary Speaker
O’Brien, Rosalind Anne	Brian J. O'Brien & Assoc	1	
Orndoff, Evelyne S	NASA Johnson Space Center	3	
Patterson, Ruby V	University of Arkansas	1	
Paz, Aaron J	NASA Johnson Space Center	2	
Peters, Todd A	NASA Johnson Space Center	3	
Picard, Martin	Canadian Space Agency (CSA)	3	
Prisk, Gordon K	University of California, San Diego	2	
Robertson, Brandan	NASA Johnson Space Center	3	
Robinson, Willie	NASA Marshall Space Flight Center	3	
Royce, Ashley J	University of Central Florida	3	
Runyon, Kirby D	Johns Hopkins APL	3	

Sanders, Gerald	NASA Headquarters	3
Schuler, Jason M	NASA Kennedy Space Center	3
Searcy, Brittani Renee	NASA Marshall Space Flight Center	3
Seibert, Michael	Maxar Technologies	3
Shin, Hyu-Soung	Korea Institute of Civil Engineering (KICT)	3
Sim, Peter Alan	Riverside Regional Medical Center	2 Recorder
Song, Hee Jong	NASA Johnson Space Center	3
Stambaugh, Imelda C	NASA Johnson Space Center	3
Stubbs, Timothy J	NASA Goddard Space Flight Center	1 Plenary Speaker
Surdyk, Robert	Sierra Nevada Corporation (SNC)	2
Swatkowski, John Charles	The Aerospace Corporation	3
Tan, Ernest	Canadian Space Agency	3
Thompson, Moriah S	NASA Johnson Space Center	2
Trevino, Robert Campos	NASA Johnson Space Center	3
Troutman, Brian	NASA Johnson Space Center	3
Tucker, Susan R.	MTS	3
Turci, Francesco	University of Torino, Italy	2
van Susante, Paulus J.	Michigan Technological University	3
Walker, Mary Lyn	NASA Johnson Space Center	3
Wang, Joseph	University of Southern California	3
Wang, Xu	University of Colorado	3
Weinhold, Maximilian S	The College of William and Mary	1 Recorder
Wilson, Timothy	NASA Engineering & Safety Center	Keynote/Welcome
Winterhalter, Daniel	NASA Jet Propulsion Laboratory	3 Moderator
Wohl, Christopher J	NASA Langley Research Center	3
Ximenes, Samuel W	WEX Foundation	3
Zinecker, Abigail	NASA Johnson Space Center	3

REPORT DOCUMENTATION PAGE	*Form Approved OMB No. 0704-0188*

The public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing the burden, to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.
PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.

1. REPORT DATE *(DD-MM-YYYY)*
09/30/2020

2. REPORT TYPE
Technical Memorandum

3. DATES COVERED *(From - To)*

4. TITLE AND SUBTITLE
Lunar Dust and Its Impact on Human Exploration: A NASA Engineering and Safety Center (NESC) Workshop

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Brady, Timothy K.; Winterhalter, Daniel; Levine, Joel S.;
Kerschmann, Russell L.

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER
860921.01.07.01.01

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
NASA Langley Research Center
Hampton, VA 23681-2199

8. PERFORMING ORGANIZATION REPORT NUMBER
NESC-RP-19-01469

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
Washington, DC 20546-0001

10. SPONSOR/MONITOR'S ACRONYM(S)
NASA

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
NASA/TM-2020-5008219

12. DISTRIBUTION/AVAILABILITY STATEMENT
Unclassified - Unlimited
Subject Category Space Transportation and Safety
Availability: NASA STI Program (757) 864-9658

13. SUPPLEMENTARY NOTES

14. ABSTRACT
The NASA Engineering and Safety Center (NESC) former Chief Scientist provided support to produce an NESC final report on the " Lunar Dust and Its Impact on Human Exploration" workshop held February 11 - 13, 2020, in Houston, Texas. This report follows the standard NESC report format to describe the findings, observations, and NESC recommendations developed by the workshop participants.

15. SUBJECT TERMS
Lunar Dust; Human Exploration; NASA Engineering and Safety Center

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
					STI Help Desk (email: help@sti.nasa.gov)
					19b. TELEPHONE NUMBER *(Include area code)*
U	U	U	UU	45	(443) 757-5802

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39.18