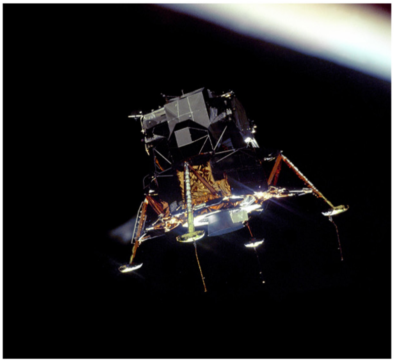
The Impact of Lunar Dust on Human Exploration






Edited by

Joel S. Levine

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Cambridge Scholars Publishing

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Dedicated to Dr. Brian J. O’Brien (1934-2020), the designer and builder of the Apollo Dust Detector Experiment (DDE) that obtained the first in situ measurements of dust on the Moon and to the Apollo astronauts who experienced the deleterious effects of lunar dust.

Dr. Brian O'Brien at the NASA Workshop on Lunar Dust and Its Impact on Human Exploration at the Lunar and Planetary Institute, Houston, Texas, on February 12, 2020. Dr. O'Brien is holding the Apollo Dust Detector (DDE) that he developed (Photograph by Joel S. Levine).

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PREFACE

As NASA is preparing to send humans back to the Moon under the Artemis Program, a major concern is the impact of lunar dust on the human exploration of the Moon. In their flights to the Moon from 1969-1972, the Apollo astronauts experienced numerous problems with lunar dust. Lunar dust blown up into the thin lunar atmosphere during the landing of the Lunar Module significantly impacted astronaut visibility. On the lunar surface, lunar dust kicked up by the astronauts walking and driving their lunar rover had deleterious effects on their space suits and helmets and surface equipment and instrumentation. The tiny, very sharp, glassy lunar dust particles eroded and deteriorated their space suits and their seals. On the flight back to Earth, free-floating lunar dust in the Command Module caused additional problems.

Apollo 17 astronaut Gene Cernan, one of the last two people to walk on the Moon, summarized the lunar dust problem during his post-flight briefing as follows:

> I think dust is probably one of the greatest inhibitors to a nominal operation on the Moon. I think we can overcome other physiological or physical or mechanical problems except dust… 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.

Apollo 12 astronaut Alan Bean reported:

> After lunar liftoff … a great quantity of dust floated free within the cabin. This dust made breathing without the helmet difficult, and enough particles were present in the cabin atmosphere to affect our vision… The use of a whiskbroom prior to ingress would probably not be satisfactory in solving the dust problem, because the dust tends to rub deeper into the garment rather than to brush off.

To discuss and address these concerns, the NASA Engineering and Safety Center (NESC) sponsored a workshop entitled “Lunar Dust and Its Impact on Human Exploration” at the Lunar and Planetary Institute (LPI), adjacent to the NASA Johnson Space Center in Houston, TX, the NASA center for human space exploration, on February 11-13, 2020. The sponsors of the workshop included the NESC, LPI, the Universities Space Research Association (USRA), the Jet Propulsion Laboratory, and the College of William and Mary in Williamsburg, VA.

The workshop was attended by approximately 125 participants, comprising a very diverse group of scientists and engineers, including lunar scientists, mission engineers, architects and planners, medical researchers, physicians and undergraduate and graduate students. In a series of invited plenary papers, experts in these areas of research reviewed both our current understanding of and our knowledge gaps in lunar dust and its impact on human exploration.

On the first day of the workshop, the invited plenary lectures were presented to the entire workshop. At the end of day 1 and on days 2 and 3, attendees participated in one of three panels of their choice. Contributed papers were presented by participants in each of the three panels. At the end of days 2 and 3, the entire workshop met in a plenary session to review and discuss the progress of each of the three panels.

The topics of the panels and their moderators and recorders were:

Panel 1. Lunar Dust: Composition, Structure, Movement and Distribution (Panel Moderator: Joel S. Levine; Panel Recorder: Max Weinhold).

Panel 2. The Impact of Lunar Dust on Human Health (Panel Moderator: Russell Kerschmann; Panel Recorder: Peter Alan Sim)

Panel 3. The Impact of Lunar Dust on Human Surface Systems and Operations and Techniques/Technologies to Reduce/Mitigate These Effects (Panel Moderators: Daniel Winterhalter and Michael Johansen; Panel Recorders: Michael Johansen and Daniel Winterhalter).

Abstracts of the invited plenary papers and contributed papers are available on the LPI website at https://www.hou.usra.edu/meetings/lunardust2020/pdf/lunardust2020_program.htm. A report on the workshop was prepared and released by NASA as "Lunar Dust and Its Impact on Human Exploration: A NASA Engineering and Safety Center (NESC) Workshop," NASA Technical Memorandum (NASA/TM-2020-5008219), 2020 at: https://ntrs.nasa.gov/citations/20205008219.

This book consists of 14 chapters in three sections based on talks presented and discussed at the workshop. The contributors to this book include a total of 50 researchers from NASA and the European Space Agency (ESA), universities and industry from the United States, Australia, Germany, Italy, the Netherlands, Portugal, and Sweden.

Chapter 1 was written by Brian J. O'Brien, the invited lead off plenary speaker at the workshop. Dr. O'Brien worked on the early Explorer satellites with Dr. James Van Allen at the University of Iowa. In 1963, he was appointed Professor of Space Science in the new Department of Space Science at Rice University. He proposed and was selected by NASA to build the Charged Particle Lunar Environment Experiment (CPLEE), one of the nine original experiments that NASA selected for the Apollo Lunar Surface Experiment Package (ALSEP). At an ALSEP investigator meeting, NASA informed Dr. O'Brien that he was required to develop a dust cover for his CPLEE experiment. On the airplane flight home from the meeting, Dr. O'Brien thought about lunar dust, a dust cover for CPLEE, and then designed a new separate, miniature instrument to measure lunar dust, the Dust Detector Experiment (DDE). Next, he convinced NASA to include the DDE on the ALSEP. The rest is history. The DDEs flew to the Moon on Apollo 11, 12, 13, and 14 and obtained the first measurements of dust on the surface of the Moon. Dr. O'Brien established the scientific discipline of lunar dust.

I invited Dr. O'Brien to present the opening plenary paper at the workshop on February 11, 2020. Dr. O'Brien, accompanied by his daughter, Ros, traveled from Western Australia to Houston to attend the workshop. Hence, the Lunar Dust Workshop opened with the researcher who established lunar dust as a scientific discipline. Dr. O'Brien participated in Panel 1 and was an active and enthusiastic contributor to the entire 3-day workshop. At the conclusion of the workshop, Dr. O'Brien, along with most plenary speakers, agreed to submit a written version of his plenary address for the workshop proceedings. I suggested to Dr. O'Brien that he include an autobiographical account of his development of the DDE, his interactions and training of the Apollo astronauts, as well as a discussion of the scientific results of the lunar dust measurements made with the DDEs. Dr. O'Brien liked this suggestion and subsequently submitted a 30-page manuscript for this proceedings volume. Unfortunately, Dr. O'Brien passed away in Australia on August 7, 2020 at the age of 86, shortly after he had completed and submitted his paper.

Dr. O'Brien's chapter is preceded by a brief remembrance of his life and career written by four of his former graduate students at Rice University, all now distinguished space scientists—Rick Chappell (Department of Physics and Astronomy, Vanderbilt University, and a former astronaut), Jim Burch (Space Sciences and Engineering Division, Southwest Research Institute), Patricia Reiff (Department of Physics and Astronomy and Rice Space Institute), and Jackie Reasoner (Alabama Space Grant Consortium, University of Alabama in Huntsville).

Section 1 contains nine papers covering the Apollo lunar dust experience, surface and exospheric dust, and preparations for the forthcoming Artemis human missions to the Moon. Following Chapter 1 written by Brian J. O'Brien, Chapter 2, written by Joel S. Levine, is an overview of lunar dust and its impact on human exploration and an introduction to the very thin lunar atmosphere, which is really a planetary surface exosphere. Chapter 3 by John Connolly deals with the lunar dust lessons learned from the Apollo missions and a look ahead to the return of humans to the Moon with the Artemis Program beginning in 2024. Chapter 4 by James Gaier is an assessment of the impact of lunar dust on surface equipment and surface operations during the Apollo missions. The transport of dust on the lunar surface due to the descent and ascent of the lunar module is the subject of Chapter 5 by Phil Metzger and James Mantovani. The dust environment of the Moon based on measurements of the Lunar Dust Experiment (LDX) on the Lunar Atmosphere and Dust Environment Explorer (LADEE) mission is discussed in Chapter 6 by Mihali Horanyi and nine co-authors. Don Barker discusses the lunar surface, its human modification and contamination, and lunar dust in Chapter 7.

Section 2 contains three papers dealing with lunar dust and human health. The toxicity of celestial dust prepared by members of the European Space Agency's Topical Team on the Toxicity of Celestial Dust (T3CD) is the subject of Chapter 8 prepared by Francesco Turci and Erin Tranfield, corresponding authors, and 12 co-authors. This report discusses the Apollo experience with lunar dust and looks to the future Artemis missions. Human exposure to lunar dust and its health effects is discussed in Chapter 9 by Peter Alan Sim, an emergency room physician. Dust inhalation in the Moon's reduced gravity environment is the subject of Chapter 10 by medical researchers Chantal Darquenne, Ellen Breen, and G. Kim Prisk.

Section 3 contains four papers dealing with lunar dust reduction and mitigation techniques and technologies. Chapter 11 covers aerosol science and engineering measurements and particle control aspects related to lunar dust by Pratim Biswas. Testing an integrated concept of operations through simulation and analogs with technology for dust quantification, characterization, and mitigation is discussed in Chapter 12 by Esther Beltran, Julie Brisset, and Ashley Royce. Lunar dust simulant particle adhesion on copolyimide alkyl ethers is discussed in Chapter 13 by Christopher Wohl and six co-authors. Chapter 14 is a summary of NASA's lunar dust mitigation strategy by Michael Johansen. A list of contributors to this book and their affiliation is given following the final chapter.

In 2017, the NASA Engineering and Safety Center sponsored another dust-related workshop that may be of interest to readers of this book entitled “Dust in the Atmosphere of Mars and Its Impact on Human Exploration.” The NESC report for this workshop was published as NASA Technical Memorandum TM-2018-220084, and it may be viewed at https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20180006321.pdf. The Mars dust workshop proceedings were published in a book, *Dust in the Atmosphere of Mars and Its Impact on Human Exploration* (edited by J. S. Levine, D. Winterhalter, and R. Kerschmann) by Cambridge Scholars Publishing, UK, in 2018.

The NASA Engineering and Safety Center

The mission of the NASA Engineering and Safety Center (NESC) is to perform value-added independent testing, analysis, and assessments of NASA’s high-risk projects to ensure safety and mission success. The NESC engages proactively to help NASA avoid future problems.

The NESC is dedicated to promoting safety through engineering excellence, unaffected and unbiased by the programs it is evaluating. It is a resource meant to benefit the programs and organizations within the Agency, the NASA Centers, and the people who work there.

At the core of the NESC is an established knowledge base of technical specialists. This ready group of engineering experts is organized into 15 discipline areas called Technical Discipline Teams (TDTs), formally known as Super Problem Resolution Teams (SPRTs). TDT members are from the NASA Centers, industry, academia, and other government agencies. By drawing on the recognized expertise of leading engineers from across the country, the NESC consistently optimizes its processes, deepens its knowledge base, strengthens its technical capabilities, and broadens its perspectives, thereby further executing its commitment to engineering excellence.

The NESC’s technical evaluation and consultation products are delivered in the form of written reports that include solution-driven, preventative, and corrective recommendations. The NESC strives to set the example for the Agency by providing full and appropriate documentation of every activity its teams perform. Along with each report, lessons learned are communicated to the Agency’s leadership and to engineers through avenues such as the NASA Lessons Learned system.

Another important function of the NESC is to engage its proactive investigations to identify and address potential concerns before they become major problems. To further this goal, the NESC is currently leading NASA's efforts in independent data mining and trend analysis. The NESC has established a Data Mining and Trending Group that includes representatives from all NASA Centers, as well as external experts. This group ensures that results are maximized and that the NESC comprehensively learns from previous efforts.

Joel S. Levine
Workshop Convener and Chair
Editor of Workshop Proceedings

Brian O'Brien

From the Earth to the Moon

Dr. Brian J. O'Brien, a space scientist whose career spanned the entire history of space exploration, died in Australia on August 7, 2020 at the age of 86. His space instruments were carried on spacecraft ranging from the original Explorer missions to the lunar landings and his scientific contributions covered a period of more than 60 years.

Brian was born in Australia and had the natural curiosity, motivation, creativity, perseverance, and determination that underpin the personalities of those who choose to become scientists and to understand the world and the universe around them. Brian's early scientific adventures began below the surface of the Earth when he began to explore underground caves in Australia. His curiosity led him to uncharted caves. As a 19-year-old explorer, he once became lost in a cave alone and had scratched out his will on the rock wall beside him before being found more than 3 days later. His determination in this early exploration was an annealing experience that established his life of exploring to understand places that humankind had never been to before.

Brian graduated in Physics from the University of Sydney in 1954 and received his PhD in Physics there in 1957. The dawning of the space program in the late 1950s captured his curiosity, and he and his wife, Avril, moved to the University of Iowa to work with Professor James Van Allen on the early Explorer satellites as first an Assistant then an Associate Professor. This experience honed his skills in spacecraft technology, and his interests moved to lower energy particles shifting from the MeV energies of the early Geiger counters on the Explorers to the KeV energies of the precipitating particles that caused the aurora.

The growth of interest in space exploration led to the creation of the Space Science department at Rice University, and Brian became a Professor in the new department beginning in 1963. His expertise in instruments and satellites led to multiple missions ranging from the Twins sounding rockets from Fort Churchill to the Aurora 1 satellite. These missions involved him and his new graduate students, Jim Burch, Larry Westerlund, Rick Chappell, David Reasoner, and, later, Patricia Reiff designing and building instruments to study the Earth's space environment. Brian also brought Stephen Mende, Bob Eather, and Bernt Maehlum to join the group at Rice. Brian's creativity, motivation, and persistence were passed on to his students for whom he was an outstanding teacher and mentor. He had a great sense of humor and cared about all of his students and colleagues who became his personal friends.

With President Kennedy's commitment to the nation to send astronauts to the moon, Brian broadened his space interests to exploring the more distant reaches of the Earth's magnetosphere in the geotail by pursuing the possibility of placing particle instruments on the surface of the moon on the Apollo Lunar Surface Experiments Package (ALSEP) mission. His success in this pursuit is illustrated by an occurrence leading up to the selection. NASA planned a pre-proposal conference at the Manned Spacecraft Center to solicit ideas for the scientific payload. Multiple scientists gathered in the room to talk about their ideas and concepts for the ALSEP, showing charts and sketches. When it became Brian's turn to speak, he reached down into his briefcase at his feet and pulled out an ion/electron instrument that had already flown successfully on his sounding rockets and Aurora 1 satellite and said, "I'd like to fly this to the moon!" It was selected by NASA and flew on three missions to the moon.

As the plans and technology were developing in the '60s for the Apollo missions, a concern was raised by Professor Tommy Gold at Cornell about the dust on the surface of the moon and whether it was so deep that the landing spacecraft would sink into the surface. There was evidence on both sides of the issue. In talking with Buzz Aldrin, Brian became interested in trying to measure the amount of the pervasive dust because it could affect the operation of the instruments on the lunar surface and might compromise the safe operation of many of the technical systems, including the astronauts' equipment and the interior of the lunar lander and from it to the Command Module with which the lander would later dock after the landing. The ALSEP had already been accepted and was being built. On a plane flight home after one of the ALSEP investigator meetings, Brian had an idea about how to easily measure the amount of floating dust that could be created by the astronauts' activities and by the launch of the upper portion of the Lunar Excursion Module rocket when it took the astronauts back up to the orbiting Command Module. His idea was to have a small solar cell mounted on the side of one of the instruments on the ALSEP and to measure the change in the solar cell current caused by the amount of dust that was floating around during different lunar conditions. NASA resisted this late addition to the payload, but finally agreed. The Lunar Dust Detectors were built and flown on

Apollo 11, 12, 13, and 14. The knowledge of the lunar environment that came from these detectors has been used continuously, and Brian's papers on this subject are still important. These results were most recently used by the Chinese space program in designing their lunar rover that is on the backside of the moon and will doubtlessly be used in the design of the new spacecraft that will take astronauts to the lunar surface as part of the Artemis program in the coming decade. He most recently gave the opening invited plenary address at the Workshop on Lunar Dust and Its Impact on Human Exploration at the Lunar and Planetary Institute on February 11, 2020 at the age of 86.

Brian returned to Australia in 1968 and became the Director of the Environmental Protection Authority for Western Australia and an Adjunct Professor at the University of Western Australia. He published more than 400 papers. He received the NASA Medal for Exceptional Scientific Achievement and was elected a Fellow of the Australian Academy of Technological Sciences and Engineering. His favorite quote was from Isidore Rabi, winner of the Nobel Prize in Physics in 1944—"I think physicists are the Peter Pans of the human race. They never grow up and they keep their curiosity."

Brian O'Brien was a quintessential scientist and explorer. His curiosity, intellect, clever creativity, and indefatigable persistence and optimism created an exciting life and an enduring legacy for his science and for those of us who had the privilege of having our careers shaped by his foresight and enthusiasm. He will be missed, but the new knowledge that he has left will be with us forever.

Rick Chappell
Department of Physics and Astronomy, Vanderbilt University, Nashville, Tennessee

Jim Burch
Southwest Research Institute, San Antonio, Texas

Patricia Reiff
Department of Physics and Astronomy and Rice Space Institute
Rice University, Houston, Texas

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NASA Space Grant Consortium (Retired)
University of Alabama in Huntsville
Huntsville, Alabama

SECTION ONE:

THE APOLLO EXPERIENCE AND PREPARING FOR THE ARTEMIS MISSIONS

CHAPTER ONE

MEASUREMENTS OF SURFACE MOONDUST AND ITS MOVEMENT ON THE APOLLO MISSIONS: A PERSONAL JOURNEY

BRIAN J. O'BRIEN

Summary

This chapter—written by the inventor and Principal Investigator (PI) of the four Apollo Dust Detector Experiments (DDEs) deployed by Apollo 11, 12, 14, and 15—will hopefully assist scientists, engineers, and administrators of NASA, and international and commercial expeditions to the Moon to achieve cost-effective risk management of Moondust problems categorised by Apollo astronauts as the number one environmental problem on the Moon. A dozen discoveries, unfunded, are shown and measurements and references provided. In addition, two out of three Apollo dust-related experiments and their discoveries passed unnoticed and unreferenced by the lunar science community in the brief but funded lunar renaissance under President George W Bush in 2004-2008. They did not come to notice again until O'Brien (2009).

Emphasis is given for the future planning of lunar expeditions of NASA, other international agencies, and commercial industries, human and robotic, to take a total systems approach and to open themselves and seek synergies of science and engineering such as were proven successful in the DDEs. Discoveries of movements of lunar dust to date by the Apollo 12 DDE have often been unexpected. But we also show that particular engineering value, including mining on the Moon, can be derived from scientific discoveries in the first place. Another end purpose here is not only to increase the numbers and values of such discoveries in cost-effective lunar risk management, but to extend them to Earth technologies in fields such as nanotechnology and exotic chemistry where the outermost 2 cm of Moondust provides a unique, rich, and multidisciplinary laboratory, still lying vacant and largely unused 50 years

after the magnificent Apollo 11 landing on the sea of knowledge foreshadowed by President Kennedy in 1962 on Rice University football field.

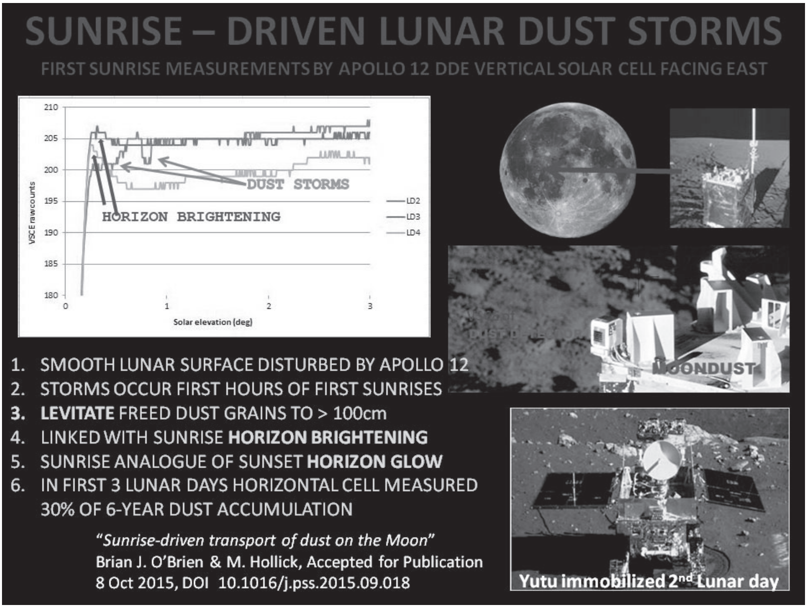

Figure 1-1. A “Nugget” showing Apollo 12 DDE discoveries important to mining on the Moon in one slide.

1. Introduction

As the oldest living Apollo scientist active in discussions with NASA about Moondust since January 1966, in this chapter I look forward to helping future expeditions such as Artemis and commercial voyages to the Moon, both human and robotic, to resolve the risk management of Moondust.

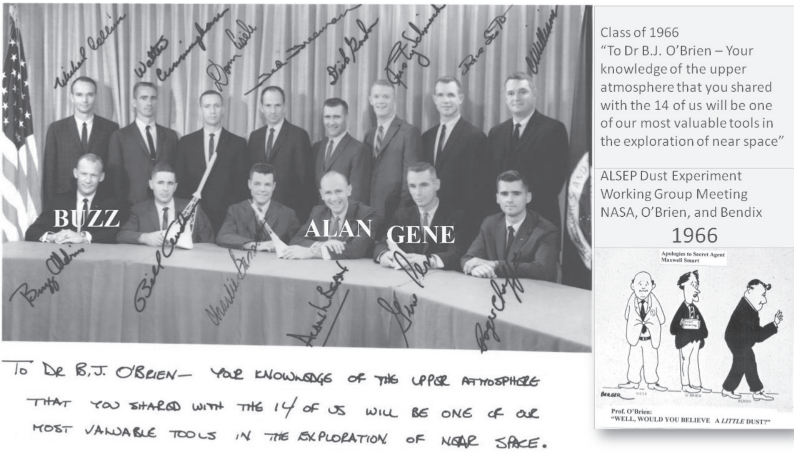

Figure 1-2. Paradox of Apollo astronauts. In 1964 they expressed thanks for my few hours of teaching about radiation hazards, the ionosphere, etc. which had been explored by satellites, including some of mine. But in 1966, as shown in the Get Smart cartoon, I had no champion to support my proposal for an Apollo DDE. As a consequence, each Apollo astronaut had to meet and overcome inescapable fine sticky Moondust with no training and reduced cost-effectiveness.

2. Goals and Objectives

The goals and objectives of this chapter are as follows:

1. To show the first measurements of rocket launches from the Moon and other material and to assist Artemis and human settlement of the Moon by documenting the strategic necessity of total systems analyses in pioneering payloads such as inventing, proposing, and using a DDE on every expedition to the Moon, human or robotic. That is what led to DDEs on the first four Apollo landings on the Moon, which led to the only existing archives of quantitative measurements of movements of Moondust, with potential operational benefit for knowledge-based risk management over a wide range to be discussed here, but which was not used during Apollo. Apollo left Moondust as unfinished business.
2. To assist Artemis and human settlement of the Moon by informing risk management plans for Moondust, the number one environmental problem, by describing a dozen peer-reviewed discoveries about movements of dust and relevant matters in the uppermost few cms

of fine Moondust. There could and should have been many more, but palpable opportunities were missed unnecessarily.

3. To encourage further analyses and uses of some tens of millions of Apollo 11, 12, 14, and 15 digital and formatted measurements supplied to the NASA Space Science Data Coordinated Archive (NSSDCA) in October 2009 as outcomes of a working partnership with Prof. Yosio Nakamura of Austin University.
4. By making use of #3, to help test the Figures of Merit (FoM) of critically important simulants of lunar dust against the actual behaviour of Moondust *in situ* on vertical and horizontal silicon covers of orthogonal solar cells of Apollo 12 DDE.
5. Making use of animated and original photographs of the Apollo 14 Thermal Degradation Sample (TDS) experiment as outlined on our website (https://www.brianjobrien.com/cohesive-studies), to analyse cohesive forces in the only structures ever built of Moondust and to stimulate STEM interest generally.
6. To outline a variety of other discoveries, including (1) opening the door to mining and *In Situ* Resource Utilization (ISRU) on the Moon; (2) helping to optimise Apollo dust legacies and pioneering work such as on solar cell arrays operating on the Moon for over 5 to 6 years at three Apollo sites, and to help assess relative contamination by dust and by radiation; and (3) providing significant new strategic arguments enhancing the priority of the Moon as the next target for human exploration and settlement, including use of the Moondust laboratories for advanced research in nanotechnology and chemistry that cannot yet be simulated on Earth or in Low Earth Orbits (LEOs).

It is not the purpose of this chapter to attempt an encyclopaedic summary of the known or unknown properties of Moondust particles or clumps. Peer-reviewed publications are referenced, grouped, and available free to all on our website (https://www.brianjobrien.com/publications).

To many, Apollo 11 demonstrated that the United States had clearly won the “space race” with the Soviet Union, which had been one of the space program’s major purposes. By the time that was done, other issues dominated the scene. National interests were not the same in mid-1969 as they had been in 1961. Of the public reaction after Apollo 11, a congressional historian has written,

> The high drama of the first landing on the Moon was over. The players and stagehands stood around waiting for more curtain calls, but the audience drifted away… The bloody carnage in Vietnam, the plight of the cities, the

> revolt on the campuses, the monetary woes of budget deficits and inflation, plus a widespread determination to reorder priorities pushed the manned space effort lower in national support. (Compton, 1989)

Now, sixty years after Apollo 11, two things are certain:

1. The USA will revisit the Moon with human and robotic expeditions.
2. Those expeditions must meet and manage inescapable sticky Moondust and include highly skilled risk management of this number one environmental problem on the surface of the Moon for humans and robotic equipment. In my opinion, this requires a paradigm change also in culture towards Moondust.

Again in context, the Apollo program ended with Moondust as unfinished business, despite an expenditure of $27 billion, a workforce some 400,000 strong, and six missions each of two astronauts working on the Moon half a century ago. The challenges from Moondust alone for the future are immense.

We suggest a number of strategies that NASA and commercial institutions will have to guard especially, and they must also cultivate a wide acceptance of total systems analyses to keep Moondust as an essential high priority issue. For some reasons, problems with Moondust arouse emotion and the issues are not always dealt with by simple linear issues of linear science and engineering. Emotion is a factor. High-level administration will have to deal with such emotional factors, even when in the midst of the scheduling and financial pressures which are inevitable. This chapter intends to assist by supplying historical facts whose provenance is certain.

3. ALSEP and the Genesis of the Apollo DDEs

I became involved with lunar dust by serendipity on January 12, 1966. In 1965-1966, our Charged Particle Lunar Environment Experiment (CPLEE) (O'Brien and Reasoner, 1971) was selected by NASA in the first group of seven experiments for the Apollo Lunar Surface Experiment Package (ALSEP), chosen from among 90 proposals.

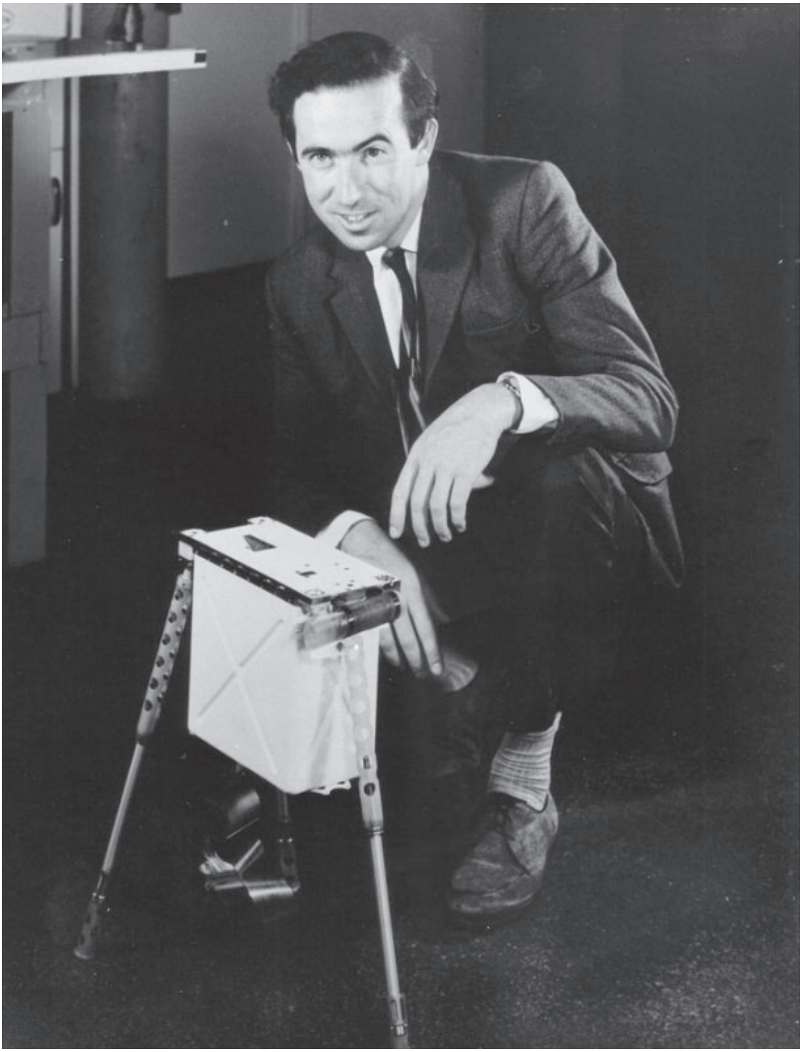

Figure 1-3. Brian O'Brien and the Apollo 13 CPLEE.

On 11 and 12 January 1966, NASA insisted that we add a removable dust cover to guard against hypothetical dust particles that might impact apertures of the CPLEE when rocket exhausts of the ascending Lunar Module (LM) disturbed surface Moondust. I readily favoured the modification, believing that lunar surface rocks, having been pulverised for some 4,000 million years by hypervelocity meteorites and cosmic dust, had probably resulted in extensive surface dust, which could cause dust problems. Indeed, in April 1965, at the International Astronomical Union (IAU)-NASA symposium on "The Nature of Lunar Dust", having examined Ranger photos of large rocks on the lunar surface, I agreed that the Moon was covered in fine dust, but it would bear the weight of an LM. I happily decided to put a Nickel 63 radioactive source underneath our retractable dust cover to calibrate the CPLEE on the Moon itself again before the astronauts left.

The dust issue was hypothetical for the ALSEP in January 1966 because at the time neither the Soviet Union Luna 9 nor the USA Surveyor 1 soft-landing spacecraft had obtained close-up photos of lunar soil. Nevertheless, NASA did not plan any dust detector among the seven ALSEP experiments, bringing to the two briefings on 11 and 12 January 1966 a mindset from 1964 that the importance of Moondust could be dismissed. When asked in the conference rooms to defend this position, they argued additionally that (1) astronauts would not have time to deploy a dust detector and (2) existing dust detectors weighed 2 to 3 kg, which was unacceptable. I regarded this strategy as both inconsistent and lacking common sense and total systems analyses for the historic Apollo 11 landing on the Moon, which the IAU-NASA symposium in 1964 had decided was covered in fine dust.

Accordingly, on the evening of January 12, 1966, on a National Airlines flight returning home to Houston, I invented an eighth experiment, the DDE, which overcame NASA's initial difficulties.

From the press kit for Apollo 11 in 1969 to the NSSDCA website for Apollo 11 DDE in May 2020, the word "dust" is avoided with regard to causing the possible and then the actual termination of the Apollo 11 active observatory Early Apollo Science Experiment Package (EASEP) and the Passive Seismometer.

Of great significance and in the majority of opinions about human expeditions to the Moon in the 20th century, the "dismissal" of dust in 1964 was valid at that time because it had a caveat limiting it to issues of the relative bearing strength of dust when the Ranger photos came in, for example: "*Let's see, that's a big rock sitting calmly on the surface and not sinking out of sight. So anybody in his right mind would conclude that the bearing strength of the lunar surface is not an issue. It could hold on to hundreds or thousands of pounds of rocks. What's the problem?*" Most of us dismissed that concern.

Figure 1-4. Left: Gene Cernan (left), the last man on the Moon on Apollo 17 in 1972, with the author (right) in 2017 in Perth, Australia. Right: Gene Cernan on the Moon covered with lunar dust.

Under the pressures of schedules and making many thousands of decisions, soon that caveat was neglected or ignored. By 1966, "dismissal" extended to the very notion of the need for a dust detector instrument. Such neglect of a caveat for a charismatic, simple culture of behaviour is not uncommon in large and complex organisations. It is still blatant on NASA's official website for the NSSDCA, which now admits that the historic Apollo 11 first observatory on the Moon "ended" but not that it was terminated, and it refuses to mention the dust that caused its overheating and then termination.

In my opinion, NASA's culture in the next several years must withstand and overcome such cultural pressures. I suggest a high-level announcement officially recognising the paradigm shift to the importance of Moondust. I suggest further that NASA formally cultivate and support total systems analyses for Moondust issues of any kind.

Ideally, they need to go beyond the Earthbound culture imposed by much of the Apollo-era geology. NASA and commercial firms must help inspire research and applications of the unique characteristics of the outermost 2 cm of dust in vacuum conditions such as nanostructures, nano-iron for medical tracking of dust toxicity, and the unique fresh and variable chemistry brought by the solar wind. There is no matching laboratory on Mars! The "Earthly" culture for Apollo needs updating to an "extraterrestrial" culture for future lunar expeditions, human or robotic.

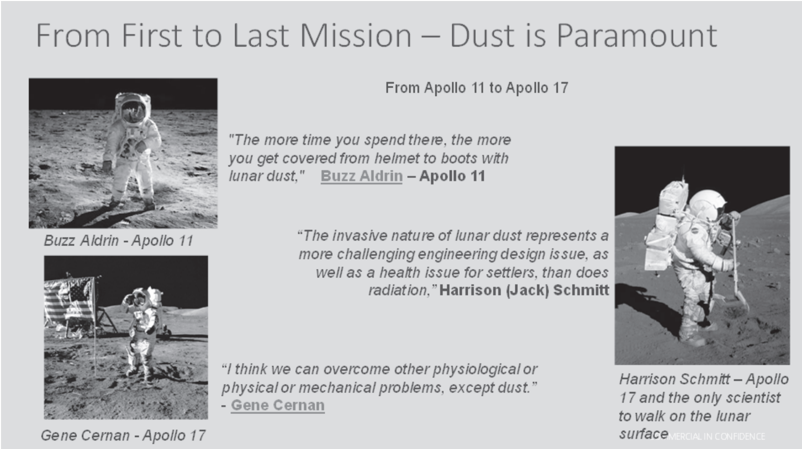

Figure 1-5. Comments about lunar dust from astronauts Buzz Aldrin (Apollo 11), Gene Cernan (Apollo 17), and Harrison Schmitt (Apollo 17).

4. Summary of Moondust Discoveries with DDEs To Date

My Apollo DDE was the only Apollo integrated minimalist scientific and engineering dust experiment flown as a risk-management and scientific tool on Apollo 11, 12, (13), 14, and 15 to measure what Apollo astronauts later concluded was the number one environmental problem on the Moon, and it made the following discoveries:

1. First quantitative measurements of (expected but officially denied) dust contamination and heating effects from rocket firing on the Moon (Apollo 11 LM ascent);
2. First quantitative measurements of (unexpected) dust cleansing and cooling effects from rocket firing on the Moon (Apollo 12 LM ascent);
3. First measurement of differentiation of dust adhesion on vertical and horizontal surfaces (Apollo 12);

4. First measurement of an increment of temperature change caused by an increment of lunar dust *in situ* (Apollo 12);
5. First analyses of collateral dust contamination of hardware, e.g. with (1) Surveyor 3 sampling by Apollo 12 astronauts and (2) showing photos of Apollo sites unreliable if pre-LM ascents;
6. First quantitative differentiation of long-term (6+ years) degradation of solar cells by radiation and dust at Apollo 12, 14, and 15 sites (O'Brien and Hollick, 2015), including effects of the August 1972 Coronal Mass Ejection (CME);
7. First measurements of long-term (6 years) upper limits to dust accumulation on the Moon;
8. First critiques of the possible causes of Apollo 17 ALSEP Lunar Ejecta and Meteorite Experiment (LEAM) data as ALSEP noise, not levitated dust;
9. First since 1971 to draw attention in 2011 to discoveries by long-forgotten and unreferenced Apollo 14 TDS experiment, including cohesive forces, and helping to stimulate the completion of adhesion studies (Gaier, 2012);
10. Published prediction in 2011 of two reasons it was unlikely that hypothetical dust causing "horizon glow" at high altitudes, the major objective of the LADEE lunar orbiter in 2013-14, would exist. Zsalay and Horanyi (2015) confirmed it had not been measured;
11. Analyses of Apollo 12 DDE revealing sunrise-drive dust storms on the first few lunar sunrises over the area disturbed by the Apollo 12 rocket descent (O'Brien and Hollick, 2015);
12. Development of minimalist 5-step model of sunrise-driven transport of Moondust. This suggests the first direct measurement of levitated dust (above 100 cm), the direct cause of "horizon glow", an explanation of smooth lunar surfaces, and opens the door to the naturally-occurring amelioration of dust from mining on the Moon and the use of ILSR (O'Brien and Hollick, 2015);
13. Discussion of long-term theoretical understanding of Moondust and Kuhn Cycles (O'Brien, 2018);
14. A 2009 white paper with Jim Gaier foreshadowing that lunar dust might become a substitute for geology as a primary scientific and technological reason for expeditions to the Moon (O'Brien and Gaier, 2009);

15. Most Apollo Moondust quantitative discoveries measured and analysed to date come from the Apollo DDEs deployed by Apollo 11, 12, 14, and 15, particularly Apollo 12. All their digital, formatted data at 54-second resolution were made available to the NSSDCA in October 2009 for public use. Other data about cohesive dust came from the Apollo 14 TDS experiment. Peer-reviewed publications are cited, and our website at https://www.brianjobrien.com/about-this-site contains much detail and previously unpublished material, together with links to references. The site also contains varied authentic information, including the secret agreement between Neil Armstrong and Buzz Aldrin about not revealing that the American flag had blown over during Apollo 11's LM ascent. The history of dust research would likely have been much more productive if they had decided otherwise, yet we too, in Sydney, shared their wish not to rain on the glorious parade of Apollo 11.

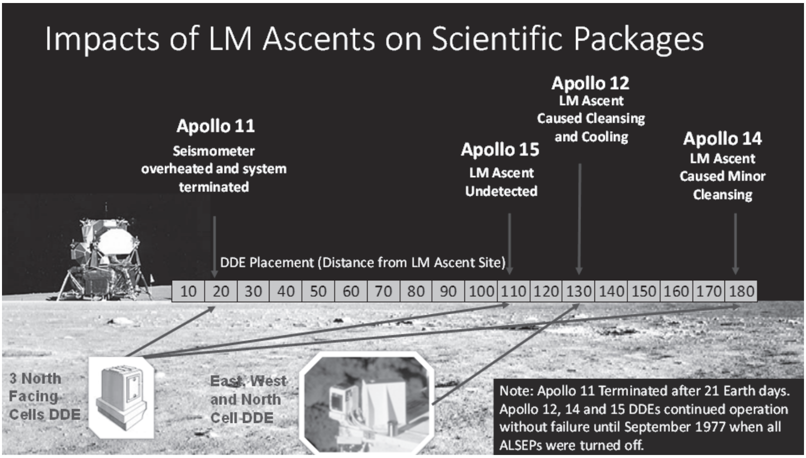

Figure 1-6. Impacts of LM ascents on scientific packages: Apollo 11, 12, 14 and 15.

Figure 1-7 (left). Brian and Sammy 1 rocket.
Figure 1-8 (right). Brian and Owl prototype payload for a Nike Cajun.

5. "Hitchhiker" Apollo DDEs

In 1965, NASA advertised for and received 90 proposals for scientific experiments for the ALSEP to be deployed on the Moon on each Apollo mission. My radiation experiment (CPLEE) was chosen on the basis of its many previous successes and discoveries. Indeed, the CPLEE was one of the few ALSEP experiments which could be deployed with confidence in its space-proven provenance.

I remember fondly the reaction of relief and laughter at a very early, closed, and frank meeting in a small Washington room with only NASA chiefs Homer Newell and John Naugle and five or six of the potential ALSEP PIs. Most of the other proposed experiments had no flight background in space. Discussions become fraught with fear of failures and/or schedule delays. I opened my briefcase and unwrapped a flight model of SPECS to display its flight readiness in 1965. It rattled loudly on the wooden conference table, breaking the tension, without a word but with much laughter. ALSEP became a reality.

But on January 12, 1966, after NASA insisted that the CPLEE had to have a roll-up dust cover, I invented an eighth and uninvited experiment for every ALSEP, a small DDE of three orthogonal solar cells, each with its own tiny thermometer (thermistor). I proposed it to NASA before either the American Surveyor or Russian Lunar spacecraft had made their successful soft landings that photographed the lunar soil for the first time. Four DDEs are now on the Moon. Apollo 12, 14, and 15 DDEs operated continuously from their deployment in 1969 and 1970 until NASA switched off all ALSEPs in September 1977.

The bolt-on DDE, weighing only 270g, was deliberately a minimalist experiment to enable hitchhiking on ALSEP with space-proven elementary sensors of shielded solar cells and small ball-shaped thermistors on the back of each solar cell, measuring both cause and effects on three orthogonal sensors. The electronics were also minimalist. The two wire leads of each solar cell were short-circuited every 54 seconds by the ALSEP telemetry encoder with a 1-ohm resistor, and the voltage sample varied according to sunlight penetrating into the solar cell. Calibration for an IJS simulant was of the order of a 10% decrease in voltage for about 0.5 mg/cm^2 of dust, assumed uniform over the cell (O'Brien, 2011). It measured basic factors making dust a threat to temperature controls, but as will be shown, enabled both science and engineering, carrying on our practice from Injun 1.

My strategic invention of such an unsolicited eighth experiment using solar cells came from my experience with Injun 1, where I used the multi-layer interference filters on solar cells for fine-tuning the temperature control of Injun 1, particularly to cool the auroral photometer to improve its signal-to-noise ratio. At the time (1961), thermal control by white paint was unreliable because of the possible yellowing of the paint in space under raw solar ultraviolet. The DDE proposal included vertical east-facing and west-facing solar cells to supplement a horizontal cell for long-term scientific studies of dust, particularly at lunar sunrise and sunset. Only Apollo 12 and 13 carried our original design with orthogonal cells. A small thermometer was attached on the back of each of the three solar cells on our original invention (and thus on Apollo 12 DDE) so that each would record both cause and effect.

The 1966 DDE was profoundly different from traditional dust detectors built for space use, which measured the momentum and direction of individual hypersonic cosmic dust, such as the "shooting stars" that burn brightly in the Earth's atmosphere but directly bombard the rocks of the lunar surface in its vacuum, without any shielding atmosphere. The DDE was designed to measure the movements of billions to trillions of very low-energy dust particles, which changed the brightness of the light getting into each solar cell. On other Apollo DDEs, the Apollo Handbook gives a misleading story about the temperature sensors, causing 2012-13 attempts to archive data to mistakenly correct measurements for temperature. Unfortunately, it omits the Apollo 12 DDE from its discussion.

The DDE experiments flown on Apollo 11, 14, and 15 were modified DDEs with three solar cells half the size, all horizontal and different from each other, with one bare and two with thinner silicon protective plates, 0.15 or 0.51 mm thick, with one pre-irradiated. They were spares from a development project of the Space Physics Division of the then NASA Manned Spacecraft Center (MSC), later renamed the NASA Johnson Space Center (JSC) in Houston (Bates and Fang, 2001). Bellcomm added a resistance thermometer to measure lunar temperature. The two versions of Apollo DDEs are photographed in Figure 1-9 and drawn in Figure 1-10. The main results of the Apollo 11 DDE are summarised in Figure 1-11.

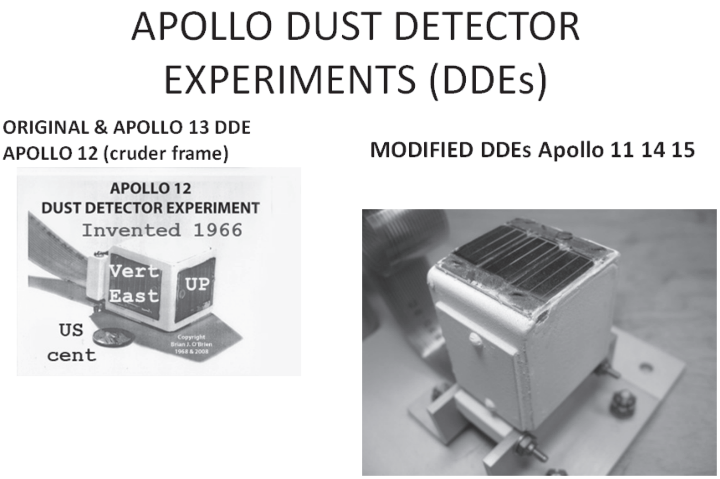

Figure 1-9. Apollo DDEs.

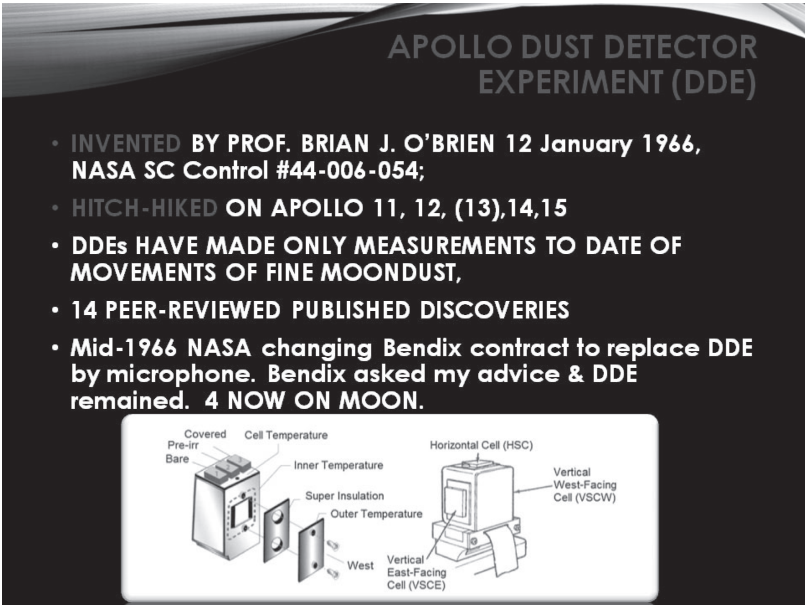

Figure 1-10. Modified (Apollo 11, 13, and 14) and a little unmodified (Apollo 12) original DDE.

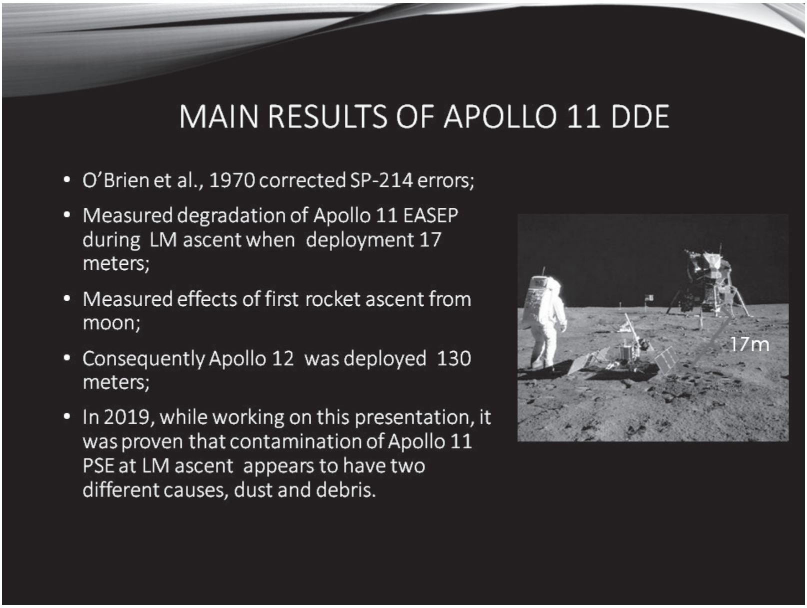

Figure 1-11. Main results of Apollo 11: 5 of 6 DDE sources show significant effects on the LM's ascent.

6. DDE Dust and Temperature Measurements on Apollo 11 on LM Ascent

The modifications to the DDEs were made four months before Apollo 11 in the mistaken belief by Bellcom and the NASA MSC (now JSC) that Jet Propulsion Laboratory (JPL) tests of rocket exhausts by Surveyors on the Moon had shown very little dust. Actually, in its 1967 Annual Report (JPL, 1967: 7), the JPL had shown photographs before and after severe dust contamination caused by a small vernier rocket on Surveyor 6. This was, in reality, a foreshadowing of what occurred later during the Lunar Module ascent of Apollo 11. In Figure 1-12, we show the dust measurements for Apollo 11.

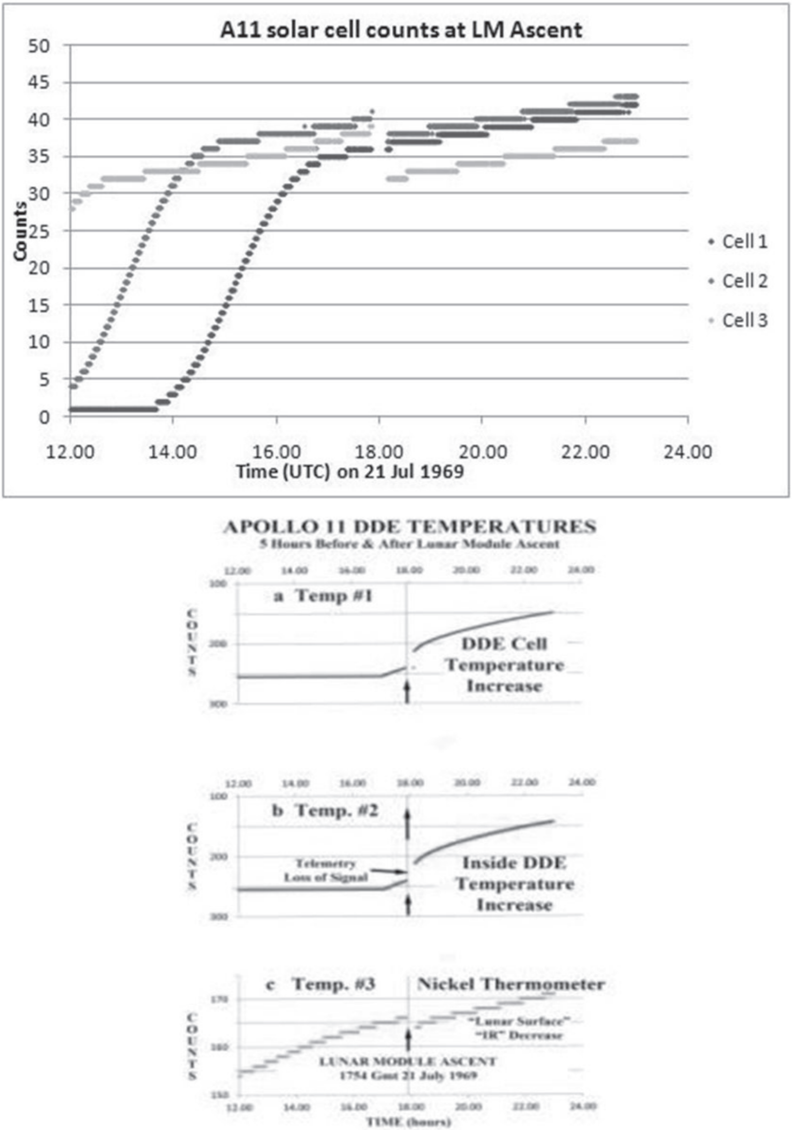

Figure 1-12. Responses of all six Apollo 11 DDE outputs five hours before and after the LM ascent. Data gaps were caused by the rolling plasma clouds of rocket exhausts around the transmitter/antenna 17 m from the LM on the Moon.

7. DDE Dust and Temperature Measurements on Apollo 12 on LM Ascent

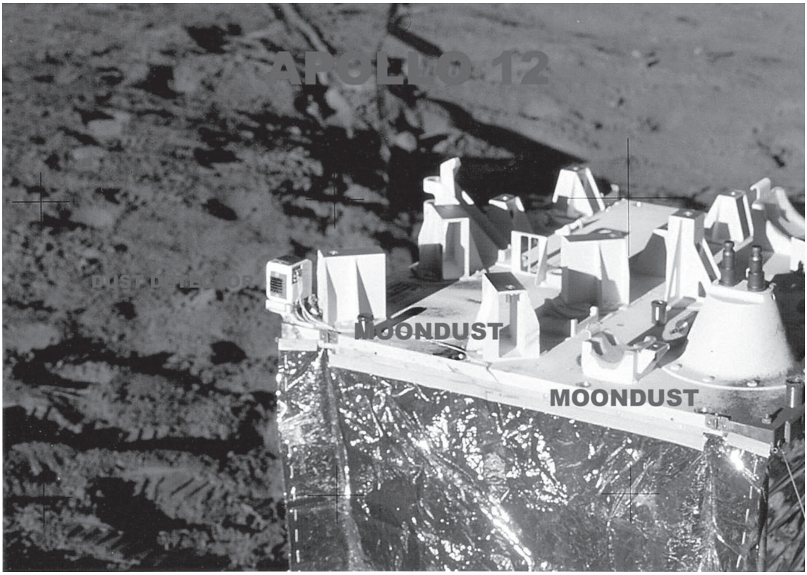

Figure 1-13. Apollo 12 DDE on the Moon, showing the full face of the vertical east-facing solar cell. Note that vertical west-facing cell has obstacles in its view.

The Apollo 12 DDE was originally built for Apollo 11 but, together with three of four large experiments, was offloaded when the ALSEP concept was replaced in four months by the EASEP for Apollo 11. It is useful to view the east-facing solar cell of Apollo 12, standing proud with a clear view of the eastern horizon and measuring the sunrise directly. As can be seen (Figure 1-13), the west-facing cell faced white objects, which spoiled its sunset views

From this point of view we focus on moving forward with discoveries about Moondust. Accordingly, no attempt is made here to discuss many errors in official reports about dust. The reader is instead suggested to refer to the website constructed by us for the celebration of the 50th Anniversary of Apollo 11 in 2019 (https://www.brianjobrien.com). Similarly, no discussion is included here on the significant reasons for the lapse of time before we resumed analyses of lunar dust in 2009. Again, such details and previously unpublished MSC documents from 1969 are given on our website.

In summary, here we show only a sample range of discoveries with Apollo 12 DDE, focussing on examples of possible practical use in risk management of Moondust for Moon villages and robotic expeditions.

The first are the only quantitative measurements of dust on vertical and horizontal surfaces, both silicon covers of solar cells.

8. Dust Effects from Four Apollo Lunar Modules Launched from the Moon

Table 1-1 summarises the effects of dust and deployment distances for Apollo 11, 12, 14, and 15. Detailed references are given in O'Brien (2011).

Apollo Mission	NASA photo DDE	LM to DDE (meters)	Effects of LM ascent	References	NASA preliminary science report
11	AS11-40-5948 and others	17 m	Contamination and overheating	O'Brien, Freden, and Bates (1970)	NASA SP-214: Bates, Freden, and O'Brien (1969) Incorrect re. LM effects
12	AS12-47-6927 and others	130 m	Cleansing and cooling	O'Brien (2009); Mission Report MSC-01855, Figs. 3-4	NASA SP-235: Report by O'Brien invited by NASA, submitted by O'Brien, omitted. No explanation
13	N/A	N/A	N/A	None	None
14	AS14-67-9381	180 m	Cleansing (small)	O'Brien (Unpublished); Mission Report MSC-04112 pp. 3-6 (incorrect re. LM ascent)	NASA SP-272: DDE omitted

15	AS15-86-11592	110 m	Undetected as yet	O'Brien (Unpublished)	NASA SP-289: DDE omitted *Summary Science* (pp. 2-11) incorrect re. LM effect

Table 1-1. Dust effects of rocket ascents from the surface of the Moon (O'Brien, 2011).

9. Review of DDE Measurements

A comprehensive review of the measurements of dust movements on the Moon by the DDEs is given by O'Brien and Hollick (2015). This includes movements of dust caused by human activities including the rocket ascents of Apollo LMs, human motion, and those caused by natural phenomena, including cohesive forces and sunrises over disturbed Apollo landing sites. Here, for the convenience of the reader, we give informative charts as well as references to their peer-reviewed references.

Apollo 11, 12, 14, and 15 deployed a DDE at different distances from their parent Lunar Module rocket. Figure 3 in O'Brien and Hollick (2015) provides the digital plot of three solar cells during the ascent of the Apollo 11 Lunar Module and shows beyond doubt the extensive contamination by dust. This led to the overheating of the passive seismometer by more than 50ºF above its nominal maximum and its deterioration to the point of failure to receive commands. The DDE solar cells also overheated (Fig. 11) (O'Brien and Hollick, 2015). The entire active Early Apollo Surface Experiments Package (EASAP) was terminated after 21 days.

Bates, Freden, and O'Brien (1969) reported there was no significant degradation. This fallacy was also carried on page 100 of NASA SP-214 with consequent misinformation given to the 142 PIs awaiting receipt of the invaluable samples from Apollo 11.[1] The misinformation could have involved either the spatial disturbance of samples, chemical contamination, or both. These issues are discussed on our website, which compares a Preliminary NASA/MSC Mission Report from August 14, 1969 containing, in blue, the effects on two solar cells with the Preliminary Science Report from August 21, 1969, which omits the measurements. This discrepancy was only part of the errors of NASA SP-214 (see Figs. 10-3 and 10-4). Those two plots began after Apollo 11's LM ascent.

[1] N.B. O'Brien's name was included in this publication without his agreement or knowledge. See O'Brien, Freden, and Bates 1970 for a corrected version.

10. Dust Movements on Horizontal and Vertical Surfaces (Apollo 12)

The Apollo 12 DDE was a bulkier copy of my original. A detailed analysis of the extensive discoveries with the Apollo 12 DDE is given in O'Brien et al. (2011, sections 4.4 and 4.5).

The Apollo 12 DDE was the only one of four on the Moon that almost replicated the orthogonal design originally proposed by O'Brien (1966). Consequently, extensive use was made of the horizontal solar cell (HSC) and the vertical solar cell east (VSCE). To our knowledge, the VSCE continues to have been the only source of measurements, on the Moon, of sunrise and the dawn Moonscape, although that seems incredible in 2020.

Structures on the Moon will have architectural needs to consider Moondust adhesion to vertical versus horizontal surfaces. We show some examples.

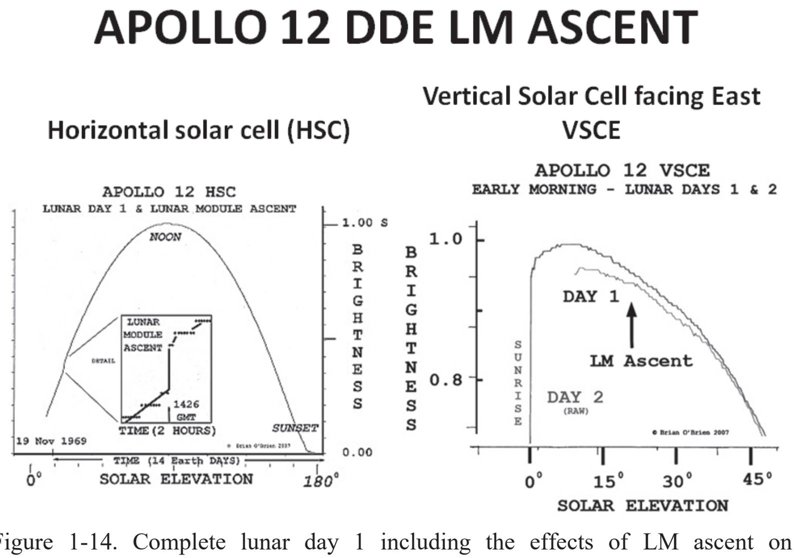

Figure 1-14. Complete lunar day 1 including the effects of LM ascent on orthogonal solar cells. An accurate comparison of VSCE measurements on the two days is given in the plotting of the ratio of the normalised brightness at every measurement at 54-second intervals.

As a senior NASA official commented to me in 2009 in Washington, DC, the trouble with my dust detectors was that they kept giving unexpected results. So it was with Apollo 12's DDE and the rocket ascent of the LM at a distance of 130 m, which cleansed the solar cells of dust (O'Brien, 2009). That had not been predicted (Phil Metzger, personal communication). Now it is understood as having been caused by a sandblasting effect. But then the effects at sunrise were not predicted formally. We discuss next what may have occurred. However, there is no consensus as yet on all the effects.

11. Moondust Falling Off a Vertical Surface In Situ on the Moon

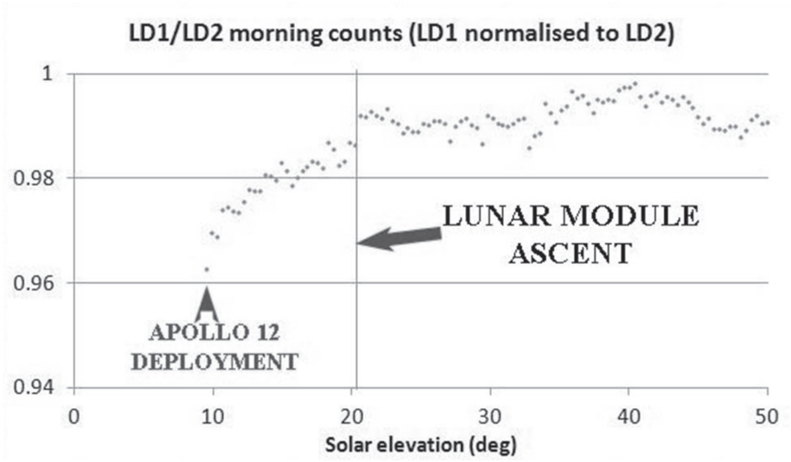

Figure 1-15. Collateral dust falling from the VSCE after deployment, before the LM ascent rocket exhausts cleansed it and the HSC. We recommend these normalised measurements to those seeking FoM or other checks on simulated dust samples. Does your simulated dust fall off a vertical silicon cell in a vacuum in this way?

The great analytical strength of the orthogonal design of Apollo 12 DDE is the fact that the HSC measures the accumulation of dust, whereas the VSCE measures dawn, the rising sun, and the scattering of early morning sunlight from dust particles levitated between its height of 100 cm and the sun. While I discovered the resultant effects in 1970, the submitted manuscript was withdrawn not for scientific reasons but because of the concern of Phil Abelson, editor of *Science*, that active advocates who contended that the Apollo missions were all fake could have seized upon such a manuscript to demean the reputation of the journal. The difficulty was that the Apollo 12 Preliminary Science Report did not include the report on the dust detector, which would have proved it was there. Although I was invited by Stan Freden of NASA/MSC and the editor of the NASA Apollo 12 Preliminary Science Report to submit a dust report and such a report was submitted on schedule, it was not published.

12. Accumulation of Moondust on a Horizontal Surface In Situ

Among the many detailed discoveries by the Apollo 12 DDE was the net rate of accumulation of dust on a solar cell. Once again, the unpredicted occurred. The rate of accumulation of dust on the HSC of the Apollo 12 DDE on the first three lunar days after landing was about 30% of the total accumulated over six years (Figure 1-16; see also Hollick and O'Brien, 2013).

Note, however, that a similar effect did not occur with the Apollo 14 and 15 covered cells. It did occur with the Apollo 14 bare cell, but none of the three horizontal cells of the Apollo 15 DDE. There is a possibility that the effect is linked to the brightness of the sun at the time, i.e. its location in its orbit, but nothing substantial has yet been established at this time. For the Apollo 14 and 15 DDEs with all three solar cells horizontal, there is no VSCE east-facing cell to validate changes in brightness of the dawn horizon, discussed below.

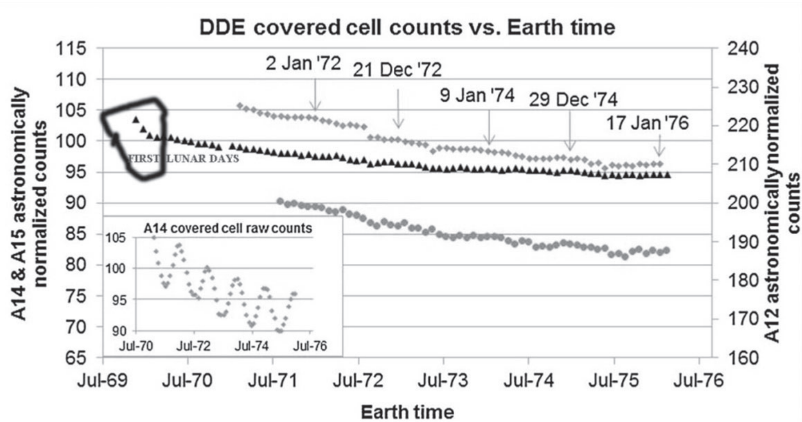

Figure 1-16. The heavily-marked boundary shows the rapid decrease in the output voltage of the Apollo 12 DDE HSC at noon in the first three or four lunar days of its exposure after deployment and departure by the astronauts.

A distinctive similar effect was also measured by the Apollo 14 DDE bare solar cell, but has not been detected in the analysis as yet of the other five horizontal solar cells of the Apollo 14 and 15 DDEs. However, the Apollo 12 DDE effect shown is consistent with our interpretation of the dawn measurements of Apollo 12's VSCE as being caused by sunrise-driven dust storms and dust levitated above the height of the Apollo 12 DDE of 100 cm (see below), subsequently falling under lunar gravity to fall on the HSC.

The temperature-controlled sticky quartz crystal microbalance (QCM) device used by Chang'e-3 to measure Moondust also reports (Figure 5B) high accumulation over the first three lunar daytimes compared to the subsequent seven lunar daytimes. Li et al. (2019) attribute the most probable causes for the high dust deposition rates in the first three daytimes to the activities of the Yutu rover and that two major meteor events occurred during that time period. For several reasons, we do not agree with their interpretation and analyses, and discussions will continue.

13. Apollo 12 DDE Sunrise Effects

The combination of the HSC and the VSCE on the Apollo 12 DDE provided a powerful tool for the investigation of sunrise effects on dust on the Moon. These are reported extensively and analysed by O'Brien and Hollick (2015). On Apollo 12, structures nearby obscure the views of the west-facing solar cell.

My interpretation of sunrise effects is that the Apollo 12 DDE measured levitated dust to a height above 100 cm, transported to that height by naturally-occurring transport mechanisms driven by the sunrise in the 5-step process described below. The VSCE measured the scattering of sunlight at sunrise, which we believe is the equivalent of the long-sought horizon glow photographed by Surveyor spacecraft on the Moon after sunset. The effects occur particularly over the first few sunrises, consistent with Figure 1-16 of the HSC (above) and Figure 1-18 of the VESC (below).

We show below the long-term effects of sunrise over approximately one and two years after the landing of Apollo 12, when the smooth surface of the primal Moon had been penetrated by the hypersonic exhaust gases of the rockets during both the landing and the LM's ascent. This gives us an operationally useful guideline for the natural rehabilitation of the lunar surface after disturbances such as rocket exhausts, mining, or excavation for resource utilisation. A rich library of other images is shown in O'Brien and Hollick (2015).

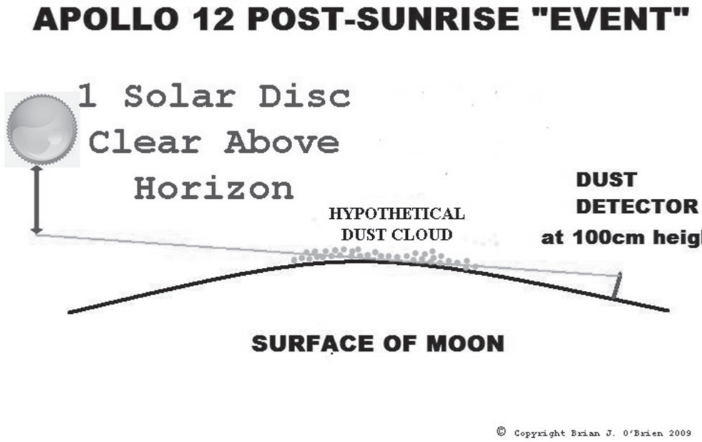

Figure 1-17. On a personal note, I have long believed that the Apollo astronauts probably waded through a "Ground Mist" of very fine Moondust not visible to them before the first lunar sunrise. The risk implications are not examined here. However, if our 5-step model of sunrise-driven dust transport (see below) is valid, then such effects could be palpable on the second lunar day of a future astronaut.

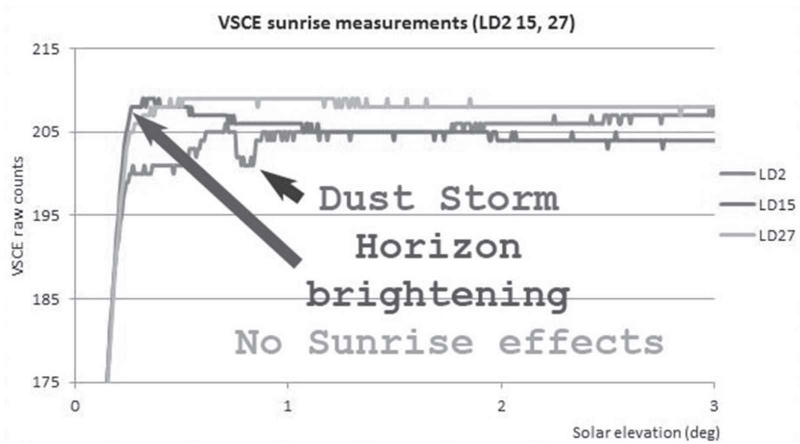

Figure 1-18. Comparison of the dawn brightness – including sunrise itself – measured by the VESC of the Apollo 12 DDE after the first sunrise (LD2 Blue), then about one year (LD15 Red) and about two years after the astronauts departed (LD27). We also speculate that the constant flat period after sunrise, occurring only after this first sunrise, may be a fairy castle effect.

14. Dust "Storms" After the First Few Sunrises from Apollo 12 DDEs

The original publication (O'Brien and Hollick, 2015) and its supplement show many plots of the variation of dawn brightness at both low and high solar elevation angles.

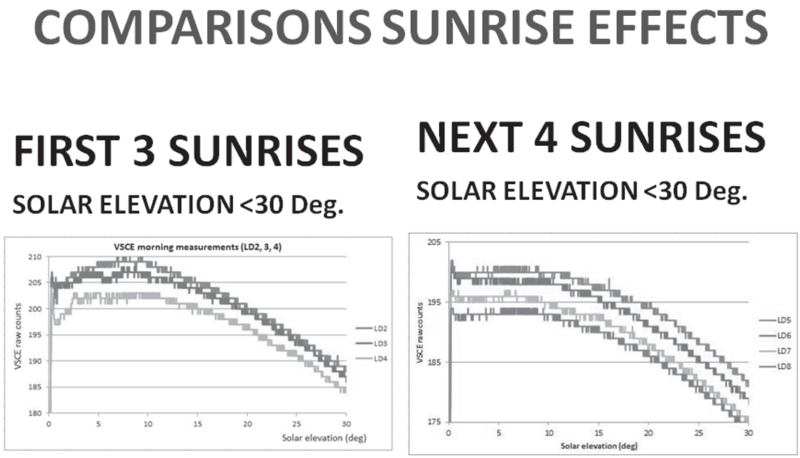

Figure 1-19. Comparison of the enhanced dawn brightness over seven lunar days. Changes to the brightness measured come from changes in the orbital location of the Moon.

I developed a 5-step minimalist model without equations to describe the transport of dust on the Moon, which we consider also explains the smoothness of the lunar surface, another long-sought mystery.

Our 5-step analysis begins with the acceptance of the strong cohesive forces of lunar dust as reported by Tommy Gold (1971), but which were then forgotten about and ignored for 40 years until O'Brien (2011).

Step 2 is that at the LM ascent, the rocket exhausts penetrate below the surface and free the previously bound dust particles.

Step 3 is that at sunrise, the blast of high-energy sunlight, including x-rays and ultraviolet, will create massive photoelectric effects causing free dust particles as well as the surface to be charged positively.

Step 4 is that there will be a mobilization and transport of the freed dust particles as a result of Coulomb forces of repulsion between like-charged particles.

Step 5 is that from one sunrise to the next, we assume that the population of free dust particles gradually reduces as more fall to the surface and are recaptured by the cohesive forces.

To date, we have received few significant comments, perhaps in part because our 5-step model does not have any equations. However, preliminary advice by Phil Metzger is that such a process may explain previously unexplained discolouration of the Surveyor 3 equipment sampled on the Moon by the Apollo 12 astronauts after 30 months' exposure.

If our 5-step model is valid, it presents solutions to a host of 50-year-old puzzles, including the cause of horizon glow, photographed by Surveyor spacecraft before Apollo.

Historically, horizon glow is thought of as a sunset forward scattering sunlight to an observer in the dark after sunset. The Apollo 12 DDE showed there was a forward scattering of sunlight from levitated dust to an observer (the DDE) just after dawn in the DDE's perspective (see Apollo 12 LD2 Blue in Figure 1-18 and Figure 1-20).

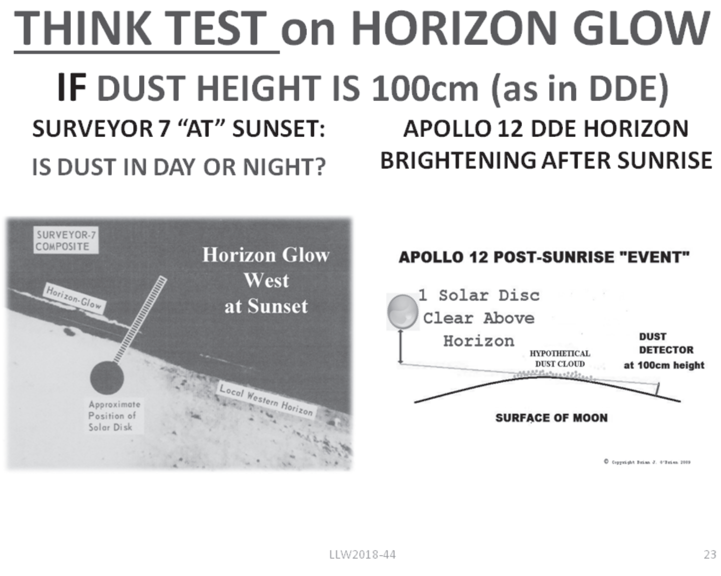

Figure 1-20. Popular view of horizon glow from Surveyor photos at sunset, compared with Apollo 12's DDE VSCE direct views of forward scattering by levitated dust on the dawn horizon.

The 5-step model (O’Brien and Hollick, 2015) also opens the door to mining on the Moon and to the natural amelioration of clouds of dust raised by excavation and the like.

15. Lunar Polar Stations Powered by Solar Cells

This and one other factor may be invaluable in consideration of proposals to equip polar bases on the Moon with solar-powered devices. The other consideration for such bases is that the Apollo 12 DDE has several years’ accumulation of information about sunlight intensity at very low elevation angles and its significant variation caused, we believe, by levitated dust. We are unaware whether such issue is taken into consideration in the current planning of polar bases on the Moon or for those matter analyses of volatiles at such stations. The variation of sunlight at low elevation angles can be several percent – see the numerous charts in O’Brien and Hollick (2015) and its supplement.

16. Apollo 16 and 17 Carried No DDEs

Apollo 16 and 17 carried no DDEs although they were the largest ALSEPs and carried out the most extended missions. We are advised (Jim Bates, personal communication, 2015) that Apollo 16 did have DDEs built for it but these were not flown for reasons unknown. Indeed, the only surviving accurate flight unit model of a modified dust detector is one found by Jim Bates in Houston. We have no idea why DDEs were not flown.

Apollo 17 did carry the Lunar Ejecta and Meteorite (LEAM) experiment, which encountered significant operational difficulties. Like most cosmic dust detectors at the time, it was designed to measure the impacts (momentum and direction) of hypervelocity cosmic dust particles individually. A strength of our DDEs and solar cells is that they measure the collective effects of millions to billions of low-energy dust particles, the inescapable Moondust.

17. Solar Cell Degradation by Radiation and/or Dust

Apollo 14 and 15 carried three horizontal solar cells, as did Apollo 11 DDE, and are the modified form of the DDE which focused, from an abandoned radiation experiment by MSC, on radiation damage. Analysis by Hollick and O’Brien (2013) made use of this capacity and the heavy shielding of the Apollo 12 DDE to make the first lunar weather measurements at three Apollo sites. In summary, this was the first study which enabled discrimination between the effects of lunar dust and radiation on the degradation of solar cells on the Moon.

We draw attention here to the reality that the Apollo 12, 14, and 15 DDEs may represent the greatest source of information at the present time of the degradation of solar cells over a long period (5-6 years) on the surface of the Moon (Hollick and O'Brien, 2013). Together they formed Lunar Weather Observatories. While much effort is expended on increasing the radiation resistance of solar cells, a coating of Moondust has been found to cause a greater downgrading of outputs (for details, see Hollick and O'Brien, 2013).

18. Recent Comments Regarding Apollo DDEs and Lunar Dust

I have carried analysis of movements of inescapable fine lunar dust through to the suggestion that the studies are now sufficiently mature that the Kuhn cycle can be used to describe the evolution of the movements of lunar dust from a pre-science stage through a paradigm shift into the 5-step cycle of the transport of dust on the Moon (O'Brien, 2018).

I have advocated and received significant support for the concept that an Apollo 12 DDE should be routinely flown on every lunar mission as a fungible bolt-on dust experiment with space-proven capabilities. Many arguments can be made in favour of having such a device on international payloads, such as the ready capability of comparison of dust at new sites to dust at Apollo 12, 14, and 15 sites.

Most recently, at the celebration of the 50th anniversary of Apollo 11 at the NASA Ames Research Center, my colleagues and I had the pleasure of announcing the pending publication of China's Chang'e-3's successful measurements of dust, using a new quartz crystal, which measured the weight of dust. We therefore update our recommendation for future payloads to the Moon to include both an Apollo 12 DDE and such a quartz crystal device, provided that its temperature control within the payload is very carefully stabilised.

19. 2010 Review of Three Apollo Dust-Related Experiments

At the Dust, Atmosphere and Dust Conference in Boulder in December 2010, I gave my second 21st-century address on Moondust by reviewing all the Apollo experiments associated with dust, though not necessarily measuring Moondust. This review was later published (O'Brien, 2011) after vigorous discussions with two (then three) referees about our critical comments of the popular 30-year-long Apollo 17 LEAM experiment. A summary table is reproduced here. Detailed references are given in O'Brien (2011).

Experiment	Description	PI* & Reports	Mission	Comments	Product
DDE Section 4 Minimalist; 270g; EASEP, ALSEP; 4 missions; Apollo 11 noisy TM at LM ascent; deployment at only 17 m	ACTIVE+: 3 solar cells: voltage output decreases proportionally to dust coating; 3 thermistors: measure temperature of each cell; height: 100 cm; continuous but only daytime gives useful outputs	O'Brien*; O'Brien, Freden, and Bates 1970; O'Brien 2009; Gaier and O'Brien 2009; O'Brien and Gaier 2009; White paper LEAG	Apollo 11, 12, 14, 15	A12 has 3 identical cells, 1.5 mm silicon cover, 2x2 cm orthogonal: East, West, Up; thermistor on back of each cell; A11, A14, A15: 3 cells, covers different: bare, 0.15 or 0.5 mm; 1x2 cm; all horizontal; thermistors scattered	6 digital words, 8 bits; 0-255 per 54 seconds. A11 ended in 21 Earth days; A12, A14, A15 operational at termination. 30 million measurements; only DDEs give direct quantitative measurements on surface; July 21, 1969-September 30, 1977
TDS Section 5 Carried on and off Moon by astronaut; astronaut sprinkled dust	PASSIVE: 2 sets of 12 panels, e.g. teflon, white cloth, alumina; 1 set brushed; photographed; back to Earth; lost	Gold* & NASA MSC*; Gold 1971; Jacobs et al. 1971	Apollo 14	Gold's analysis discusses electric fields on micro mm scale, unique; photos unique examples of cohesive grain-to-grain forces on surface of Moon (Fig. 1)	3D photos but clearer; Fig 1. mono to study cohesion; search re. last report TDS in quarantine prior to "radiative property measurements" (Jacobs et al.).

LEAM Section 6 Complex experiment; 7.5 kg, dust shield and overheating problems, many data uncertainties (Berg et al. 1973)	ACTIVE+: After Pioneer 8 and 9 cosmic dust detectors; agreed most events not cosmic dust; uncertainties previously unresolved; new analyses here carry past tipping point to rejection	Berg* et al 1973; 1976; Colwell et al. 2007 and refs; Bates et al. 1975; Wolf 1977; Bailey & Frantsvog, 1977	Apollo 17	Complex orthog sensors, Up, W, & 25^0N of E; West "smaller"; tapes and plots lost; workbooks copy with Horanyi (2009); new references include Wolf's (1977) analyses of 9-track tapes	Average 50 "events" per lunation from sunset-45 hrs to SR + 45 hrs; sunrise peak flux about $1x10^{-5}$ cm^{-2} sec^{-1} (see text); this review rejects use of LEAM data (Section 6)

Table 1-2. Apollo dust experiments on the surface of the Moon.
NOTE: "Active+" experiments were those powered by the ALSEP and their digitised outputs transmitted to Earth for recording giving two sets of computer tapes, one for the PI and one for NASA.

I was sceptical that the major purpose of the $250 million LADEE lunar orbiting satellite was to measure high-altitude fine dust, hypothetically the source of horizon glow photographed by several Surveyors (O'Brien, 2011). This scepticism had two independent bases. First, the theories of levitation which generated models of fine dust at high (LADEE satellite) altitudes were then assuming that cohesive forces of dust were negligible, contrary to Gold's (1971) discovery from Apollo Image AS14-77-10369, which, together with the Apollo DDE, had been forgotten and ignored for about 40 years. Second, I gave a set of reasons why (a) the electronics of LEAM differed from those of Pioneer 8 and its high-prestige forbear space probes, and (b) the "events" or outputs of the LEAM experiment were in bursts and generally consistent with and reminiscent of payload noise I had encountered in my work, being caused by electromagnetic noise from the ALSEP. I suggested that those using LEAM hypotheses should add a caveat that there was an alternative cause that levitated dust, namely electromagnetic noise pollution. Mikhail Horanyi publicised this caveat prior to the launch of the LADEE.

Two subsequent developments were Szalay and Horanyi's (2015) report that the LADEE high-altitude measurements had found no evidence of the hypothetical dust thought to cause horizon glow, and O'Brien and Hollick's (2015) report of evidence and many figures from Apollo 12 DDE that was consistent with the enhancement of dawn sunrise, which they attributed to an early morning sunlight scattering of fine dust levitated above the 100 cm height on the DDE. Their conclusion was strengthened because the horizontal cell of the Apollo 12 DDE suffered dust contamination after the first three sunrises, which amounted to about 30% of its degradation over six years.

But only one of the other horizontal cells of Apollo 14 and 15 showed this enhancement. Further analyses are required (Hollick and O'Brien, 2013).

20. Miscellaneous Dust Discoveries

Miscellaneous discoveries about movements of Moondust that can be relevant to the risk management and architecture of future missions are included in various publications, particularly O'Brien, Freden, and Bates (1970) and O'Brien (2009).

These discoveries include (1) different dust depositions on the horizontal and vertical silicon shields of relevant solar cells of the Apollo 12 DDE and (2) different rates of the cleansing of such dust by the sandblasting effect of the LM's ascent; only one measurement of the quantum of heating was caused by the movement of a quantum of lunar dust (O'Brien, 2009).

The powerful synergistic roles of the HSC and the VSCE (Apollo 12 DDE) proved extraordinarily fruitful (O'Brien and Hollick, 2015), answering puzzles left in Hollick and O'Brien (2013). But we had only one Apollo 12 DDE with orthogonal cells. The knowledge gap caused by the modifications of Apollo 14 and 15 and the lack of DDEs on Apollo 16 and 17 is immeasurable.

21. Challenge to Dust Simulants

I know little about simulated dust or the figures of merit (FoM) by which they are judged on a variety of properties thought to similar to rocks and rocks sampled by astronauts for the Moon. The commercial need for simulants is understood to help test various devices against what they may find in Moondust in the early morning sun, when the Apollo astronauts had visited, and later through each lunar day when the DDEs made measurements, including through sunrise.

I have suggested previously to the lunar community that it may attempt to test some simulants, for example, to see what properties would cause them to match, for example, the *in situ* falling of dust off a vertical silicon cover onto a solar cell as measured by Apollo 12 VSCE, as in Figure 1-21.

I repeat such offers here, together with renewed attempts for the NSSDCA to make the formatted digital tapes of all Apollo DDEs publicly available.

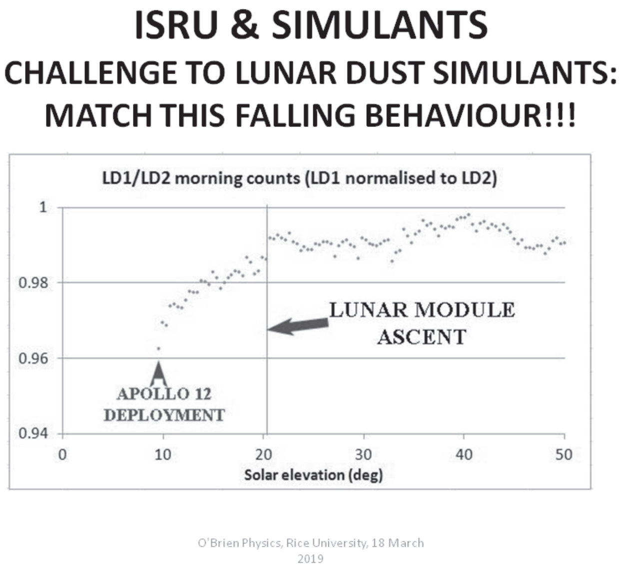

Figure 1-21. Normalised brightness of sunlight on the Apollo 12 VSCE from deployment through cleansing during LM ascent. In effect, the collateral dust fell off the vertical silicon cover over the solar cell. We can offer the raw data for those wishing to test a simulant.

22. Practical Distinctions between "Adhesion" and "Cohesion"

There has been some prolonged confusion about any distinctions between the forces of adhesion and cohesion. O'Brien and Gaier (2009) informally clarify the practical aspects, summarised in the following.

Once the topic of "adhesion" was identified via Gaier (2012), much engineering design and space suit stickiness, etc. became more clearly targeted for engineering designs and actions.

Similarly, once the vital starting point of "cohesive" forces is the starting point to understand the effects of Apollo rocket landings to "free" dust from the original cohesive forces that lead to smooth lunar surfaces, other stages of transport of dust follow, including opening the door to mining and the use of local resources (O'Brien and Hollick, 2015).

However, with little existing data and resultant research on cohesive forces, the extent to which "clumps" of dust occur in both *in situ* locations and laboratories requires additional research attention. We have only one identified example of cohesive forces from one TDS photo. It seems unlikely to me that Moondust would always behave cohesively in an identical way to the single sample from Apollo 14.

23. Concluding Discussions and Recommendations

Moondust research demands synergies of science and engineering. We suggest that groups of scientists working alone on scientific experiments they propose for the Moon may sometimes stray from reality in ignoring the engineering feasibility or practicalities of their aims. The reverse may often be true for engineers.

The Apollo DDE was classified by NASA as Engineering Experiment M515, presumably to escape the tunnel of scientific reviews that would have delayed its progress without the realistic awareness and appraisal that it is both science and engineering, which are synergistic in its design.

Who, for example, has proposed a lunar experiment that measures the lunar effects at sunrise? Surely there must have been some others than Surveyor before Apollo or VSCE on Apollo 12 DDE. Yet the Apollo 12 DDE east-facing solar cell of the original DDE design, by measuring two effects of Moondust, appears to our knowledge to be the first such study. The first is of scientific importance, measuring the scattering of dawn sunlight off levitated dust mobilised by the very processes of photoelectric effects caused by sunrise, observing directly levitated Moondust for the first time on the Moon and solving a suite of long-duration mysteries ranging from horizon glow to explaining naturally-occurring transport mechanisms that keep the surfaces of the Moon smooth despite frequent cratering by meteorites and ejecta. It also complements the horizontal cell, which measured a considerably quick accumulation of dust over the first few days after deployment.

To the extent our analyses are correct, the Apollo 12 east-facing cell measures the dawn forward scattering that is equivalent to the post-sunset horizon glow, the 50-year-old problem that was the prime goal of the $250 million LADEE lunar orbiter. The LADEE did not measure the fine dust predicted at high altitudes as the cause of horizon glow (Szalay and Horanyi, 2015). But the Apollo 12 DDE provided ground truth at a height of 100 cm as we also predicted.

In addition, important to engineering and operations on the Moon, these levitated particles explain the cause of the unusually heavy deposition of Moondust on the first few days after landing. For the Apollo 12 DDE, some 30% of dust deposited over six years was deposited in the first three lunar days (Hollick and O'Brien, 2013), a fact explained in O'Brien and Hollick (2015).

If our 5-step analysis of sunrise-driven dust "storms" is valid, this also opens the door to mining on the Moon and should ease environmental concerns about the persistence of dust clouds from excavations for local resources. The family of sources of dawn brightness give periods of 1 to 2 years before angular scattering resumes normal profiles.

The combination of vertical and horizontal cells in the Apollo 12 DDE also gives us the only quantitative information about the adhesion or otherwise of dust on vertical and horizontal surfaces on the Moon. This is surely a fundamental question to be asked by architects and engineers concerning designs of a Moon village or other significant structures.

A significant flaw in the Apollo 12 DDE exists even though it broadly follows the orthogonal design of our original invention and proposal. In order to accommodate the Bellcomm thermometer which was part of the modifications of the Apollo 11, 14, and 15 DDEs, NASA/MSC made the housing of the Apollo 12 DDE the same enlarged size as the others. They failed to note that the original design of the DDE was the size of the solar cells themselves, for very valid design reasons. The faces of the DDE facing the sun were completely solar cells, which measured their absorptivity. The additional structure and white paint on the structure remain unknown, consequently degrading the capability of the original, smaller DDE to make precise measurements of both absorptivity and the emissivity, the two essentials and designing heat properties of a device on the Moon. If an Apollo 12 orthogonal DDE is flown in future flights, the original Apollo 13 version shown in Figure 1-9 with a US one cent coin for scale is recommended.

We do not suggest that each scientific experiment necessarily requires sensitivity to its engineering implications. However, the loss of valuable information about thermal properties of dust *in situ* on the surface of the

Moon caused by such rushed modifications without consultation with the designer is only one example of the unnecessary absence of a range of valuable information about the thermal properties of dust caused by that single act. Synergies between scientists and engineers are both strongly recommended and potentially extremely valuable in the future.

The only other peer-reviewed publication about Moondust is by Li et al. (2019) on the use of a sticky QCM on Chang’e-3. Due to international cooperation, including our work in Beijing with the China Academy of Space Technology (CAST), we had the pleasure of announcing the pending publication of further results at the celebrations for the 50th anniversary of Apollo 11 at the NASA Ames Research Center.

We assume there is now general agreement by NASA, space scientists, and commercial lunar expeditions that “anyone who flies a payload to the Moon without a Dust Detector is dumb,” words spoken in the conclusion of Chairman Professor Jim Head in his address at Microsymposium 50. But readers should also note that my expression in January 1966 was even stronger, saying they would be “bloody stupid.” Readers should ask why the results of the Apollo 11 and 12 DDEs remained unknown even through the brief renaissance of lunar science in 2004-2008. Is there a deep-seated antagonism towards measuring Moondust on the Moon? But of course, the very existence of the DDE remained unknown during this brief renaissance.

In the celebrations of the 50th anniversary of Apollo 11 at NASA Ames in 2019, I suggested two basic dust detectors for future lunar expeditions. More sophisticated and powerful arrangements can be discussed.

We suggest a combination of an Apollo 12 DDE to measure dust movements and a sticky QCM to weigh Moondust such as flew on Chang’e-3 in 2013-2014 (Li et al., 2019). However, the payload of Chang’e-3 experienced significant temperature variations which significantly limited the end-point reliability of dust measurements. If a QCM is to be flown, the payload must provide high-quality control of temperature.

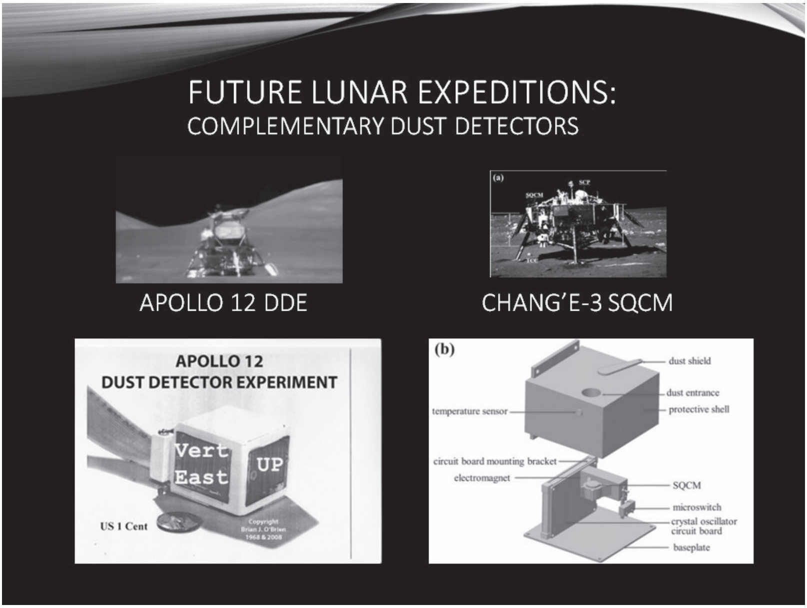

Figure 1-22. Suggested Moondust experiments for future human and robotic lunar expeditions.

Acknowledgements

Many colleagues have greatly assisted during this long quest, especially my first mentor, the late Harry Messel, then Jim Gaier and Guy Holmes, and most recently Joel Levine. The unique and most valuable polymath support from my beloved wife Avril ended on July 20, 2017 after 65 wondrous years. Our daughter Ros and our family now provide much-valued continuity, together with Jim and Guy and Joel. My enduring thanks!

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CHAPTER TWO

LUNAR DUST AND ITS IMPACT ON HUMAN EXPLORATION: IDENTIFYING THE PROBLEMS

JOEL S. LEVINE

Introduction: Lunar Dust and the Apollo Experience

Some historians have described the Apollo 11 landing of humans on another celestial body, the Moon, 50 years ago, as perhaps the most significant accomplishment in the history of the human species (Fishman, 2019).

On July 20, 1969, as he was about to become the first human to set foot on another world, Apollo 11 astronaut Neil Armstrong climbing down the ladder of the Lunar Module (LM) onto the lunar surface communicated with Mission Control at NASA Johnson Space Center in Houston and reported (Heiken, Vaniman, and French, 1991):

> I'm at the foot of the ladder. The LM footpads are only depressed in the surface about 1 or 2 inches, although the surface appears to be very, very fine-grained, as you get close to it, it's almost like a powder; down there, its very fine… I'm going to step off the LM now. That's one small step for [a] man: one giant leap for mankind. As the-The surface is fine and powdery. I can-I can pick it up loosely with my toe. It does adhere in fine layers like powdered charcoal to the sole and sides of my boots. I only go in a small fraction of an inch. Maybe an eighth of an inch, but I can see the footprints of my boots and the treads in the fine sandy particles.

The boot prints of the Apollo 11 astronauts are shown in Figures 2-1 and 2-2. Armstrong's first encounter with lunar dust came a little earlier in the mission during the landing of the LM on the lunar surface when the exhaust gas from the LM blew large amounts of surface dust into the very thin lunar atmosphere that significantly obscured the visibility of the lunar surface. Fortunately, Armstrong successfully landed the LM on the lunar surface even though visibility was reduced due to the large amount of lunar dust added to the lunar atmosphere.

Armstrong's observation that the surface of the Moon "appears to be very, very fine-grained… almost like a powder" was a very important discovery. The presence of very fine lunar dust over the surface of the Moon had a very significant negative impact on human lunar exploration, affecting human health, lunar surface equipment, and systems, including astronaut spacesuits and helmets and lunar surface operations.

Figure 2-1. Boot print of Apollo 11 astronaut Buzz Aldrin in lunar dust on the surface of the Moon.

During their extensive post-flight NASA technical debriefings, all of the Apollo astronauts commented on their experiences with lunar dust while on the Moon and during the return home to Earth in the Command Module. During his post-flight mission debriefing, Apollo 17 astronaut Eugene Cernan, one of the last two humans to walk on the Moon (the other was Harrison Schmidt), told NASA officials (NASA, 1973):

> I think dust is probably one of the greatest inhibitors to a nominal operation on the Moon. I think we can overcome other physiological or physical or mechanical problems except dust… 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.

Apollo 12 astronaut Alan Bean reported (Heiken, Vaniman, and French, 1991):

> After lunar liftoff … a great quantity of dust floated free within the cabin. This dust made breathing without the helmet difficult, and enough particles were present in the cabin atmosphere to affect our vision… The use of a whiskbroom prior to ingress would probably not be satisfactory in solving the dust problem, because the dust tends to rub deeper into the garment rather than to brush off.

Figure 2-2. Apollo 11 astronaut Buzz Aldrin on the surface of the Moon. Note the boot prints in lunar dust in the foreground.

Apollo 16 astronaut John Young concluded (Dovey, 2019):

> Dust is the number one concern in returning to the Moon.

Apollo 17 astronaut Harrison Schmitt stated (Asaravaka, 2005):

> Dust is the No. 1 environmental problem on the Moon.

The surface lunar dust is lifted into the very thin lunar atmosphere as the astronauts walk over the lunar surface or drive their Lunar Rover to explore the Moon's surface (Figures 2-3 and 2-4). The surface lunar dust released into the lunar atmosphere by the astronauts results in dust-covered equipment, including space suits, helmets, scientific instrumentation, etc. (Figures 2-5 and 2-6).

The Apollo Lunar Dust Experience

Two important and comprehensive reports were compiled by NASA engineers James R. Gaier (2005) and Sandra A. Wagner (2006) on the impact of lunar dust on the Apollo astronauts, their health, and their 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 documents are available online at http://www.hq.nasa.gov/aldsj/). Both of these reports should be required reading for the Artemis astronauts, mission planners, and engineers since, 50 years after the Apollo missions, there is a new generation of individuals in these professions, with little or no corporate memory of the devastating Apollo experience with lunar dust. The conclusions/recommendations of both studies are given below. It is interesting to note that the conclusions of both studies end with a quotation from Apollo 17 astronaut Eugene Cernan, the last human to walk on the Moon during the Apollo Program.

Figure 2-3. Lunar Rover pumping surface lunar dust into the thin lunar atmosphere.

Refering to the lunar dust, Gaier (2005) writes: “It obscured the astronauts’ vision on landing, clogged mechanisms, abraded the Extravehicular Mobility Suits (EMS), scratched the instrument covers, degraded the performance of radiators, compromised seals, irritated their eyes and lungs, and generally coated everything with surprising tenacity. Some of the EMS components were deteriorating at the end of the missions, which ranged from 21 to 75 hours on the lunar surface.”

Gaier divided the observed effects of lunar dust as described in the astronauts’ extensive post-mission NASA debriefings into nine categories: (1) Vision Obscuration, (2) False Instrument Readings, (3) Dust Coating and Contamination, (4) Loss of Traction, (5) Clogging of Mechanisms, (6) Abrasion, (7) Thermal Control Problems, (8) Seal Failures, and (9) Inhalation and Irritation. The conclusions and recommendations of the Gaier study are reproduced here:

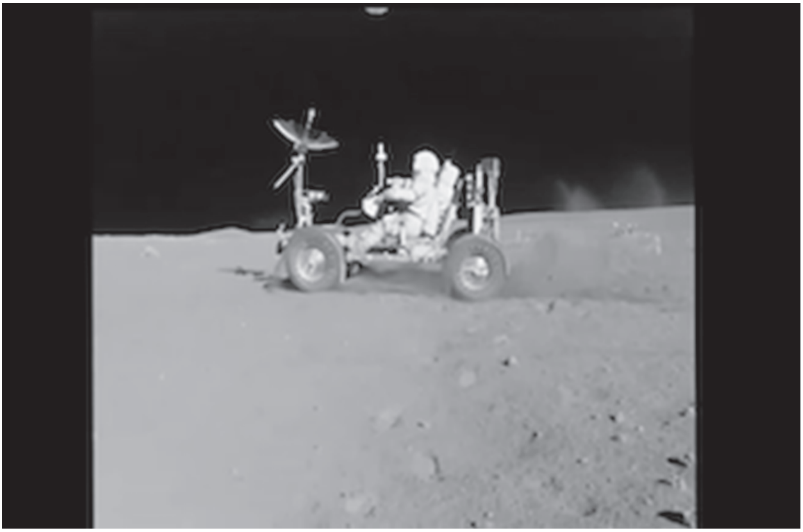

Figure 2-4. Lunar Rover pumping surface lunar dust into the thin lunar atmosphere.

Dust on the lunar surface proved to be more problematic than anyone had anticipated. Gene Cernan in the Apollo 17 Technical Debriefing remarked

"I think dust is probably one of our greatest inhibitors to a nominal operation on the Moon. I think we can overcome other physiological or physical or mechanical problems except dust."

All of the Apollo missions were adversely affected by the dust due to included visual obscuration, false instrument readings, dust coating and contamination, loss of traction, clogging of mechanisms, abrasion, thermal control problems, seal failures, and inhalation and irritation.

Simple dust mitigation measures were sufficient to mitigate some problems like loss of traction, but for many such as thermal control problems, adhesion, and abrasion, it is clear that new technologies must be developed. Some mitigation strategies, such as vibration have been tried and found lacking. Others, such as brushing appeared to work much better in ground tests than they did in the lunar environment. Clearly, an important area is the development of better simulation environments than were used in the Apollo era. This may include the use of better simulants, higher vacuum, correlated simulations, and more realistic thermal and illumination environments.

Figure 2-5. Apollo 17 astronaut Harrison Schmitt in a dust-covered space suit.

Finally, the pervasiveness of the dust and the problems it causes were summed up by Gene Cernan in his Technical Debrief

> Dust – I think probably 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 it's restrictive friction-like action to everything it gets on. For instance, the simple large tolerance mechanical devices on the Rover began to show the effect of dust as the EVAs went on. By the middle or end of the third EVA, simple things like bag locks and the lock which held the pallet on the Rover began not only to malfunction but to not function at all. They effectively froze. We tried to dust them and bang the dust off and clean them, and there was just no way. The effect of dust on mirrors, cameras, and checklists is phenomenal. You have to live with it but you're continually fighting the dust problem both outside and inside the spacecraft. Once you get inside the spacecraft, as much as you dust yourself, you start taking off the suits and you have dust on your hands and your face and you're walking in it. You can be as careful in cleaning up as you want to, but it just sort of inhabits every nook and cranny in the spacecraft and every pore in your skin.

Wagner (2006) summarized the lunar dust problems that the Apollo astronauts experienced by dividing the problems into the different phases of the mission journey: (1) Surface Obscuration During Descent, (2) Lunar Module Engine Regolith, (3) Lunar Module Contamination, (4) Contamination During Transfer Between Lunar Module and the Command Service Module, (5) Command Module Contamination, (6) Mechanisms for Lunar Module Contamination, (7) External Environment Lunar Dust Effects, and (8) Space Suits and Seals. The conclusions and recommendations of the Wagner (2006) study are reproduced below:

> Lunar dust will present significant challenges to NASA's Lunar Exploration Missions. The challenges can be overcome by using best practices in system engineering design.
>
> For successful lunar surface missions, all systems that come into contact with lunar dust must consider the effects throughout the entire design process. Interfaces between all these systems with other systems also must be considered.
>
> Incorporating dust management into Concept of Operations and Requirements development are the best place to begin to mitigate the risks presented by lunar dust. However, that is only the beginning. To be successful, every person who works on NASA's Constellation lunar missions must be mindful of this problem.
>
> Success will also require fiscal responsibility. NASA must learn from Apollo the root cause of problems caused by dust, and then find the most cost-effective solutions to address each challenge. This will require a combination of common sense existing technologies and promising, innovative technical solutions.

Wagner's conclusions end with the same quote from Apollo 17 astronaut Gene Cernan as Gaiers's report.

Figure 2-6. Apollo 17 astronaut Eugene (Gene) Cernan in the LM after EVA. Note lunar dust on the forehead.

The Formation 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 from place to place 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 micrometeoroids. 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 to a gas (Heiken, Vaniman, and French, 1991). The molten soil immediately freezes again, forming tiny pieces of glass—glass shards. These tiny glass shards are jagged and very sharp. Most of the ejecta particles have initial speeds below the escape velocity of the Moon (2.4 km/s), and they return to the lunar surface, blanketing the lunar crust 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 very sharp over time. As a result of the constant "hammering" by micrometeoroids over billions of years, the lunar surface dust is extraordinarily fine, similar to flour, which makes it very sticky and causes it to cling to everything, e.g., space suits, helmets, surface equipment and instruments, etc. On the lunar surface, the continual exposure of dust to solar ultraviolet radiation and the solar wind plasma has been hypothesized to explain a number of unusual observations that indicate processes related to dust charging and the subsequent electrostatic mobilization of lunar dust (Horanyi et al., 2020).

Lunar surface dust enters the very thin lunar atmosphere as the astronauts walk around and kick it up. In addition, the motion of wheels on the Lunar Rover is another mechanism of transferring surface dust to the atmosphere. The lunar atmosphere is much too thin to support the surface dust for any appreciable time and the dust quickly settles back on the surface of the Moon. If, somehow, the atmosphere of the Moon were to increase in mass, it could hold more dust for longer periods of time, and the lifetime for surface dust to remain in the atmosphere would also increase, making lunar dust even more dangerous to humans on the Moon. The possibility of the mass and density of the lunar atmosphere to increase as the result of human activities will be discussed in a later section.

The Atmosphere of the Moon: A Surface Boundary Exosphere

The atmospheric pressure on the Moon is only about $3x10^{-15}$ bar, which is equivalent to $2.96x10^{-15}$ atmosphere (atm). For comparison, the mean sea-level atmospheric pressure on Earth is 1 atm, which is equivalent to 1.013 bar. Hence, the surface pressure of the Moon's atmosphere is about 14 orders of magnitude less than the surface pressure of the Earth's atmosphere. The total mass of the very thin atmosphere of the Moon is only about 10^7 g and the lunar atmosphere's surface number density maximum is just below 10^6 particles cm^{-3} (Stern, 1999). The lunar nighttime atmosphere has a surface number density of about $2x10^5$ particles cm^{-3} and the lunar daytime atmosphere has a surface number density of about 10^4 particles cm^{-3} (Heiken, Vaniman, and French, 1991).

The Moon belongs to a class of planetary bodies with an atmosphere defined as a "surface boundary exosphere" (SBE) (Stern, 1999). Other celestial bodies possessing a surface boundary exosphere include the planet Mercury and three moons of Jupiter: Callisto, Europa, and Io (Stern, 1999). The number density at the bottom of an exosphere, called the exobase, is so low that any atmospheric atom or molecule traveling upward from the surface with a velocity greater than the planetary escape velocity (which for the Moon is 2.38 km s^{-1}) is unlikely to experience a collision with another atmospheric atom or molecule and can readily escape to space. The standard definition of an exosphere is the atmospheric region where the atmospheric scale height is less than the collisional mean free path. On Earth, the height of the exobase varies between 500 and 1000 km above the surface, depending on the level of solar activity. On Mars, the exosphere begins at about 225 km above the surface (Levine, 1985).

The Artemis Program: The Return of Humans to the Moon

NASA released its plan for the renewed human exploration of the Moon in April 2020 (NASA, 2020). Now, with the new Artemis Program, the U.S. will continue the sustained human exploration and development of the Moon beginning in as early as 2024. The NASA Artemis Program Plan (NASA, 2020) states: "*The first human mission to Mars will mark a transformative moment for human civilization. Establishing a sustained lunar presence and taking the initial steps toward the first human mission to Mars will be the greatest feat of engineering, and the greatest voyage of exploration and discovery, in human history*."

To accomplish the Artemis Program's goal of human exploration of the Moon, the U.S. is developing a new, very powerful launch vehicle, the Space Launch System (SLS), being built by the Boeing Company, and a new human spacecraft called Orion, being developed by Lockheed Martin. NASA has also invited industry, academic institutions, and international partners to assist the U.S. in the renewed human exploration of the Moon. To date, international partners on the Artemis Program include Canada, Japan, the European Space Agency (ESA), and Russia.

During the Artemis Program, humans will spend weeks to months on the Moon and will establish a permanent infrastructure for human colonization, as compared to the few days that the Apollo astronauts spent on the Moon. For comparison, the Apollo astronauts spent between 22.2 hours on the first Apollo lunar landing (Apollo 11: Armstrong and Aldrin) and 75 hours on the final Apollo lunar landing (Apollo 17: Cernan and Schmitt) on the surface of the Moon, mostly in the LM, rather than exploring the surface of the Moon itself (Johnston, Dietlein and Berry, 1975). The other Apollo astronauts spent the following times on the surface of the Moon: Apollo 12 (Conrad and Bean): 31.5 hours, Apollo 14 (Shepard and Mitchell): 33.5 hours, Apollo 15: 67 hours, and Apollo 16: 71 hours (Johnston, Dietlein and Berry, 1975).

Now that humans will return to the Moon and this time for considerably longer periods than the Apollo astronauts, we must learn more about the nature, composition, and structure of lunar dust and how to develop techniques/technologies to reduce/mitigate its negative impact on humans and human equipment.

Human Exploration and Activities: Perturbing the Mass of the Very Thin Lunar Atmosphere

Due to its very low mass, the atmosphere of the Moon is very susceptible to impact by activities associated with human presence and exploration, as first hypothesized by Vondrak (1974, 1988). During the Artemis Program, on each human mission to the Moon, astronauts will spend considerably more time exploring and working on the surface of the Moon than did the Apollo astronauts 50 years ago. Not only will the Artemis astronauts have considerably longer exposure to lunar dust than the Apollo astronauts did, but they will have a much greater time on the surface of the Moon to alter the very thin atmosphere of the Moon. Each Apollo landing mission added several tens of percent of additional gas to the mass of pre-Apollo lunar atmosphere resulting from descent and ascent rocket gaseous exhausts, leaked habitat gases from the LM, etc. (Vondrak, 1974, 1988; Heiken, Vaniman, and French, 1991).

During the Artemis Program's return to the Moon, currently being planned and set to begin in 2024, human presence on and exploration of the Moon will continue and at a greater pace than during the Apollo missions. A denser lunar atmosphere resulting from human presence and exploration will result in a longer atmospheric lifetime of surface dust in the atmosphere. The possibility of human activities and exploration increasing the mass of the lunar atmosphere and increasing the concentration of dust in the atmosphere of the Moon and the time that it resides in the atmosphere has previously been discussed (see, e.g., Vondrak, 1974, 1988; Stern, 1999; Levine and Zawodny, 2007; Weinhold and Levine, 2020; Barker, 2020).

Conclusions

The Apollo missions to the Moon led to the discovery that lunar dust has a very negative impact on the astronauts, their surface systems, including space suits and helmets, other surface equipment, and on lunar surface operations. The next phase of the human exploration of the Moon, the Artemis Project, will send humans back for longer visits and longer periods of time, during which the astronauts will walk and drive on the surface of the Moon and be exposed to the detrimental effects of the lunar dust. It is critical that we develop new techniques and technologies to reduce and mitigate the negative impact of lunar dust on the astronauts, their surface systems, and surface operations.

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Chapter Three

Lunar Dust: Lessons from Apollo and a Look Ahead to Artemis

John F. Connolly

Even before mankind journeyed to the Moon in the 1960s, artists had already begun to think about what the lunar dust situation would look like as the Apollo lunar module descended to the surface. Some of the artwork of the time (see Figure 3-1) show that these artists came pretty close to the reality of what the Apollo crews actually encountered. Some of this early conceptual artwork show descent engines raising plumes of dust and rays of ejecta extending from the lunar module's engine outward – consistent with the physics of lunar dust and soil seen during the actual Apollo missions. Images such as this give a good sense that the challenge of lunar dust was anticipated by the Apollo engineers.

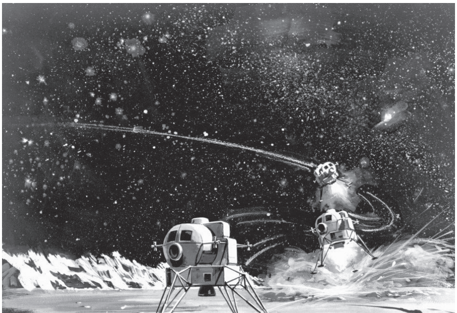

Figure 3-1. Early Apollo lunar lander concepts showing the artist's renditions of lunar landing soil and dust interaction.

Studying the Apollo experience is a useful starting point to understand the challenge awaiting future lunar explorers as they return to the lunar surface. The Apollo missions are well documented, and the lessons learned about lunar dust from Apollo landings, engine ejecta, extravehicular activity (EVA) suits, mechanisms and seals, optical surfaces, and mobility systems can greatly inform the next generation of engineers and explorers.

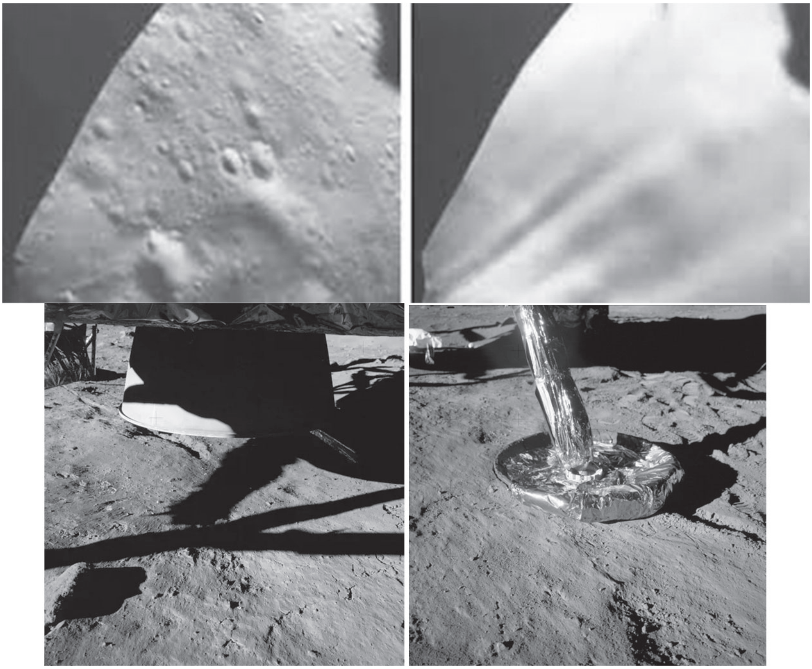

Figure 3-2. Apollo lunar descent imagery and lunar surface scouring.

A study of the lunar surface around the Apollo Lunar Modules reveals the scouring of the surface regolith due to the ejecta of the lunar module descent engine (Figure 3-2). While descending to the surface, 16 millimeter film cameras photographed increased dust obscuration as the lander descended below an altitude of 100 feet and increased with proximity down to the surface. This dust obscured the view of the final moments of the lunar landing and made an estimation of the actual distance to the surface somewhat uncertain for the Apollo crews. Apollo photography also shows the lunar module foot pads depressed in the surface only by fractions of an inch, indicating that the unconsolidated upper layers of the regolith were mostly removed from the area by engine exhaust, and the foot pads were left to depress the remaining soil, which was already compacted to some extent.

Perhaps the most notable effects of lunar dust were on the Apollo crew's lunar extravehicular garments themselves – the spacesuits. Following each Apollo mission, photographs taken of the crew members revealed extensive amounts of dust on each of the spacesuits, as evidenced in Figure 3-3 from Apollo 17. Videos of Apollo astronauts working on the lunar surface showed that with each step or hop, some quantity of dust was kicked up by the astronauts. As each mission's EVAs progressed, there is a noticeable buildup of lunar dust on the legs and lower torso of the EVA suit.

A great deal of effort was spent by the crew members on surface brushing, vacuuming, and minimizing the amount of dirt carried into the lunar module on their suits in an effort to minimize the amount of lunar dust carried back to lunar orbit with them. Photos of Apollo crews show noticeable coatings of lunar dust on their EVA suits. A comprehensive study of the effects of lunar dust on spacesuit systems was conducted in 2009 by a number of NASA engineers and is well documented in NASA/TP-2009-214786, "Lunar Dust Effects on Spacesuit Systems."

Figure 3-3. Apollo 17 Commander Gene Cernan (left) and Lunar Module Pilot Jack Schmitt (right) photographed each other following EVA number 3. The lunar dust on each EVA suit is pronounced.

Apollo EVA hardware involved a number of critical seals for gloves, helmet, and EMU zipper, and seals in general were an issue for the Apollo missions. Two sealing mechanisms in particular were of concern – the seal of the lunar module egress hatch, and the seals of the lunar sample containers. The lunar module front hatch was the crew members' primary egress and ingress route from the lunar surface, and each time the crew members entered the lunar module they brought with them quantities of lunar dust. This lunar dust settled on the seals of the external hatch and was brushed away by the crews before the hatch was engaged and the Ascent Module repressurized. The lunar sample containers also contained seals that were protected from lunar dust. The Apollo lunar “rock boxes” had knife-edge seals that were protected up until the point where the protective cover was taken away and the sample container closed by engaging the Indium seal. In total, the seals of four of the twelve Apollo Lunar Sample Return Containers failed due to pieces of equipment or dust interfering with the seals. Additionally, other pieces of equipment such as the Special Environment Sample Container and Gas Analysis Sample Container contain similar seals that were protected from lunar dust until the time that the sealing surface was exposed and the sample container closed.

Optical surfaces were equally affected by lunar dust. Apollo 12 astronauts removed components of the Surveyor 3 Lander for return to Earth, enabling testing of the dust coating on Surveyor’s television camera mirror. Astronaut Conrad’s thumbprint smear is clearly visible on Surveyor’s camera’s mirror, but this only highlights the glazing of fine-grained particulates adhering to the mirror surface, which degraded television images sent to Earth by the robotic lander. Apollo crewmembers were keenly aware of the degrading effects of lunar dust on optical surfaces and exhibited care when deploying optical instruments such as the Laser Ranging Reflectometer (LRR) not to kick up any local lunar dust onto those optical surfaces. Apollo missions 15 thru 17 featured the Apollo Lunar Roving Vehicle (LRV) and encountered significant challenges with dust kicked up by the rover wheels onto the camera television camera of the LRV.

Mobility systems such as the LRV were prime sources of lunar dust contamination, and the rover was well documented in its ability to kick up large plumes of dust as it traversed the surface. Videos of Apollo 16 astronauts testing the LRV’s performance documented the amount of dust that the LRV produced as it traversed the lunar surface, and Apollo 17 astronauts documented the large quantity of dust that the LRV coated them with when a wheel fender failed, prompting an in-flight maintenance procedure to fix the fender and gain some control of the dust. In addition to the dust kicked up onto the astronauts by the LRV, the dust also affected radiator surfaces on the rover, and as a result the LRV’s battery temperature approached its upper operating limit.

Dust Physics Hasn't Changed

The experiences of the Apollo lunar missions and the samples of dust, soil, and rock that were returned to Earth form the basis of our understanding of lunar dust, and future explorers will face many of the same challenges as did Apollo. The physics of lunar dust has not changed since Apollo – lunar dust particles are electrically charged, have irregular geometry which causes them to embed themselves within certain materials, and have abrasive properties that will challenge materials selection, mechanisms, and optics. Our understanding of lunar dust has improved, however. With actual lunar soil samples in the laboratory for the past 5 decades, NASA has been able to carefully catalog the characteristics of lunar dust in terms of its chemical, physical and electrical properties, and even its possible toxicity to future space explorers.

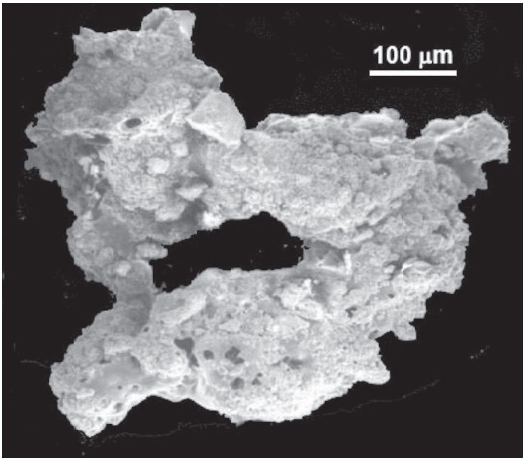

Figure 3-4. Lunar dust particle.

Our technologies to address lunar dust have improved, but not exponentially. In the years since Apollo, and with actual lunar dust to experiment with, engineers and technologists have been able to make progress in lunar dust mitigation techniques. For example, technologists at NASA's Kennedy Space Center have used the electrostatic property of lunar dust to their benefit by applying a small electrical field to create a repelling force that can clean certain surfaces of dust. Other NASA technologists have developed coatings that help dissipate the electrical charge of lunar dust, and others have studied mitigation techniques such as EVA outer garment materials that would be less susceptible to lunar dust adhesion. Recently, NASA's Space Technology Mission Directorate has established a Lunar Surface Innovation portfolio of technologies, which gives a new focus to lunar dust mitigation technology development and a pathway for combining the best of NASA, academia, and commercial expertise.

New Lunar Architecture, New Lunar Systems

Since the most recent Apollo mission returned from the Moon in 1972, NASA engineers and mission designers have been envisioning a return of human explorers to the lunar surface. Numerous studies have been conducted over the past 50 years, and a number of initiatives had promised a return to the lunar surface. In 1989 the George H.W. Bush administration proposed the Space Exploration Initiative (SEI) as its plan for returning human explorers to the Moon and then journeying to Mars. The SEI resulted in NASA's 90-day study and a brief acceleration of human exploration activity in the early 1990s. The SEI was ultimately unsuccessful in obtaining broad political support, and it would be a number of years before a human lunar exploration initiative was once again proposed. In 2004 the George W. Bush administration proposed the Vision for Space Exploration, which resulted in the creation of NASA's Constellation Program, which ran until 2010. We are now at the forefront of a new opportunity to push beyond Low Earth Orbit and continue our exploration of the Moon and beyond. With a new return to the Moon initiative, we are once more reminded of the challenge of lunar dust and lunar dust mitigation.

As of this writing, NASA is assembling the components of the Artemis lunar program to return human explorers to the Moon. Unlike previous exploration efforts under previous administrations, the Artemis program uses a different approach to lunar exploration – one that embraces commercial and international partners and begins in a unique lunar orbit known as a Near Rectilinear Halo Orbit (NRHO). Where many prior lunar mission designs had taken explorers from the Earth to the surface of the Moon by way of a Low Lunar Orbit (LLO), Artemis seeks to use the unique gravitational relationship between the Earth and the Moon to position a lunar transportation node in the NRHO, which could support multiple missions to the lunar surface. The NRHO is a unique potato chip-shaped orbit that can have a close approach to either the North or South Pole of the Moon with an elongated leg on the opposite side and orbits the Moon every 6.5 days. The NRHO provides unobstructed communication back to Earth and is unobstructed from eclipses of the sun. The NRHO allows a vehicle to be positioned on the Moon and serves as the transportation node where crew transport to and from Earth meets crew transport to and from the Moon. The vehicle placed in NRHO was named Gateway by NASA, a fitting name for a vehicle that could be the gateway for crews to visit the lunar surface or even for crews departing for Mars.

Phase One – Initial Return to the Moon

Phase One of NASA's Artemis plan began with tests of the Orion spacecraft and Space Launch System (SLS) launch vehicle, first without crew and then with a human crew orbiting the Moon. This would be accomplished at the same time that the first elements of the lunar Gateway were being assembled in NRHO. The first element of Gateway would be a high power solar electric propulsion system named the Propulsion and Power Element (PPE). This element would provide the propulsive and power backbone for the Gateway platform. The next element to be delivered to Gateway would be the Habitation and Logistics Outpost (HALO) module, which would provide habitable volume and docking interfaces. Future missions would deliver logistics modules to Gateway to support crews using Gateway for lunar orbital science as well as for crews using Gateway as a departure node to the lunar surface.

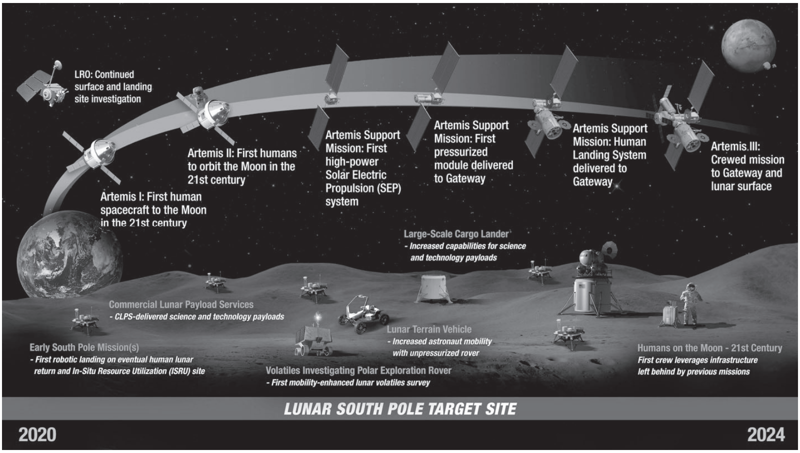

Figure 3-5. NASA Artemis Program Phase One.

In addition to Gateway orbiting the Moon, NASA would also begin a series of lunar science and exploration delivery missions made possible through Commercial Lunar Payload Services (CLPS). CLPS would make use of commercial landers and launch vehicles, enabling NASA to economically deliver science instruments and small equipment to the lunar surface. This could include experiments that better characterized the lunar environment, instruments to characterize specific lunar landing sites, and even delivery of equipment for the initial lunar crews. Ultimately CLPS missions could even be used for the delivery of larger cargo elements such as a next-generation unpressurized lunar rover or surface logistics necessary to extend the duration and range of lunar exploration. Phase One of NASA's Artemis plan is shown in Figure 3-5.

NASA's challenge is to merge the construction of the lunar orbiting Gateway, the delivery of science equipment and logistics via CLPS missions, and the initial human return to the lunar surface by the year 2024. In order to accomplish these compressed milestones, NASA has begun making use of increased commercial capabilities that were not available at the time of Apollo, or even during the previous attempts to re-start lunar exploration. Today, commercial contracts to build the elements of Gateway are progressing in parallel with commercial contracts to deliver science and technology payloads to the lunar surface as part of the CLPS program. Additionally, NASA has challenged the commercial spaceflight sector to provide commercial human lunar landing services that would take astronauts from lunar orbit down to the surface of the Moon, then return them back to lunar orbit. This accelerated program of returning to the Moon would challenge both NASA and commercial aerospace with rapidly developing both technologies and human spacecraft systems in a short period of time.

NASA envisioned a lunar program where a small orbital outpost, the lunar Gateway, would be orbiting the Moon in a Near Rectilinear Halo Orbit, commercial landers would be providing payload delivery services to the lunar surface via CLPS, NASA's Orion and SLS programs would be delivering crews to lunar orbit and returning them to Earth, and commercial landers would be transporting crews to the lunar surface and returning them back to lunar orbit by 2024. The Phase One missions would most likely be targeted at a landing site near the South Pole of the Moon and would consist of a crew complement of two astronauts living out of the lander for surface durations of up to 6.5 days. The South Pole landing site would enable missions entirely in daylight, and the missions would not rely on the aid of any pre-deployed surface assets. Lunar surface EVAs would be targeted for a minimum of four hours, with two to five EVAs scheduled for each mission. It is likely that the commercial lunar landers will have limited delivery capability ("down mass") for science or technology experiments, so care will be taken to select critical equipment to travel to the lunar surface with the crews. Additional science and technology equipment could be delivered via robotic CLPS missions. It is also possible that enhanced capabilities such as an unpressurized lunar rover could be pre-emplaced by robotic missions prior to the arrival of the first crew. The return mass of lunar samples will be critical to the science community, and current requirements call for a minimum of 35 kilograms, and a goal of 100 kilograms, of returned lunar samples for each mission.

As with the Apollo missions, dust will pose challenges to the Artemis program explorers. The landers that they pilot will likely be larger than the Apollo lunar module and will use larger descent engines for landing. This will create additional challenges with engine blast ejecta and scouring of the surface near the engines. Materials that will be chosen for lunar surface systems will need to be compatible with the lunar surface environment and with the properties of lunar dust. In particular the EVA systems will need to perform much better than the Apollo spacesuits in terms of dust abrasion and tolerance to lunar dust. Seals on the EVA systems, on lander hatches and mechanisms, and on rover mechanisms will need to be substantially enhanced from their Apollo counterparts. The electrostatic characteristic of lunar dust will need to be thoughtfully designed into each component that interacts with the lunar soil. The cleaning of dust will need to be taken into account from the very early stages of design – simple brushes as were used in the Apollo program will likely not be adequate for the length and breadth of exploration missions that are anticipated in the Artemis program. Most importantly, the cleanliness of the crew volumes and the possible health effects on astronauts must be taken into account for these extended missions. If future missions to the lunar surface involve multiple EVAs and multiple egress and ingress operations for the crew volumes, enhancements will need to be made to the complete EVA system to enhance the cleanliness of the crew volume and greatly decrease the amount of lunar dust transported into the crew volume. As was exhibited on Apollo missions, dust in the Ascent Module cabins, once the crew was in the zero gravity of lunar orbit, became a health concern due to inhaled dust in the lungs and dust in the eyes of crewmembers. Additionally, any dust returned from the lunar surface will contaminate the lunar Gateway once the returning lander has docked and the hatch opened between the two vehicles. Repeated sorties to the lunar surface will result in the accumulation of lunar dust in the Gateway unless successful mitigation techniques can be put into place.

Phase Two – Building Capabilities for Longer Lunar Surface Stays, and Preparing for Missions to Mars

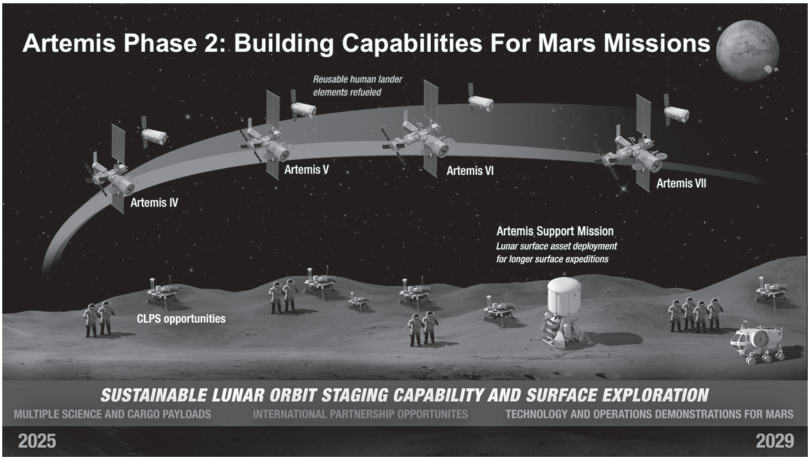

Figure 3-6. NASA Artemis Phase Two.

Following the initial return to the Moon, the next phase of lunar exploration will begin under NASA's Artemis program. Phase Two will involve longer duration stays on the lunar surface, emplacing permanent infrastructure on the lunar surface, and building capabilities to enable future missions to Mars. Commercial lunar payload deliveries will continue to deliver science and technology payloads to the lunar surface, as well as lunar logistics to support human operations. Cargo landers will begin to deliver foundational habitat elements as well as mobility elements such as pressurized rovers. By the close of the decade, missions will increase to four crew members and the length of surface explorations will increase. At the same time, the lunar Gateway, orbiting the Moon in NRHO, will continue to grow to support the lunar surface missions as well as more complex missions in lunar orbit.

Phase Two of the lunar program will be characterized by more sustainable lunar operations – lunar missions will evolve from polar missions to global access, from two- to four-member crews, and to extended surface stays which will include long eclipse or night periods. Commercial lunar lander services will continue, but in Phase Two crew members will no longer use the lander for habitation and will have surface assets such as habitats or pressurized rovers available to them on the lunar surface. Extravehicular activities will become more extensive and the number of crew hours spent on the lunar surface will increase. Power and communication systems to enable these longer missions will be emplaced, and the amount of payload delivery to the surface of the Moon will be greatly increased through the use of commercial lunar payload deliveries as well as large cargo missions. Phase Two is illustrated in Figure 3-6.

Lunar dust challenges will continue to increase with the growth of lunar surface activity. Larger lander blast ejecta will impact surface systems, and shielding techniques or geography will need to be employed to protect permanent surface assets. The reuse and cleanliness of crew volumes will need to be designed into surface habitats, pressurized rovers, and all systems that will be reused. EVA systems will need to be designed for longer lifetimes, with maintenance and resupply performed by surface crews. The long-term wear of mechanical systems such as rover drive mechanisms, hatches, and seals will need to be designed into systems and maintenance systems designed to address lunar dust. Dust accumulation and performance degradation on thermal radiators, solar panels, and other surfaces will need to be designed into those systems and mitigation techniques also designed into those systems. And importantly, the long-term health effects of dust exposure on lunar crews will also need to be well understood by this point, with mitigation measures in place.

Final Thoughts

Lunar missions to the South Pole and to Permanently Shadowed Regions (PSRs) will introduce additional challenges for understanding regolith and lunar volatile physics. The prospect of finding volatiles in the PSRs will create new challenges as the normally desiccated lunar dust may now be combined with lunar volatiles. Research will need to be undertaken on the physical properties, the chemistry, and the mitigation techniques necessary to address lunar dust/volatile mixtures.

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CHAPTER FOUR

THE IMPACT OF DUST ON LUNAR SURFACE EQUIPMENT DURING APOLLO

JAMES R. GAIER

Introduction

When Apollo astronauts began lunar surface operations they were surprised by the many great difficulties the lunar dust[1] caused (Gaier, 2005). Operations were hampered as the dust became elevated while setting up the experiment packages, obtaining core samples, and driving the lunar roving vehicle (LRV). O'Brien has suggested the term "collateral dust" for dust accidentally deposited on surfaces by the astronauts during operations (Gaier and O'Brien, 2009). Collateral dust is clearly visible on publically available photographs of many instruments deployed on the lunar surface, yet it has received little attention. The dust posed challenges not only to Extravehicular Activity (EVA) systems but also to the LRV (Gaier and Jaworske, 2007) and many of the Apollo science instruments.

It must first be acknowledged that most of the Apollo systems were robust to collateral dust effects. All agree that the lunar surface missions were astoundingly successful. The performances of the descent and ascent portions of the Lunar Excursion Module (LM), the subsystems of the spacesuit and portable life support system (PLSS), the LRV, and many of the science experiments were not substantially degraded by collateral dust. But the objective of this report is to highlight the ways that collateral dust did degrade the performance of many Apollo systems. Most of these sys-

[1] Although dust is formally defined as particulate matter smaller than a threshold size (typically 20 μm), for the purposes of this paper the definition is expanded to include all particles and aggregates small enough to be transported through normal lunar surface exploration operations, roughly up to a few mm in size.

tems were exposed to the lunar environment for only a few days, and yet many were already experiencing a decrease in their effectiveness. Since future lunar surface missions are projected to be of much longer duration, effective dust mitigation strategies will need to be developed.

Dust Effects on EVA Systems

Mission documents from the six Apollo missions that landed on the lunar surface have been studied in order to catalog the effects of lunar dust on EVA systems, primarily the Apollo surface space suit. The following discussion directly follows from the summary paper and its references (Gaier, 2005). It was found that the effects could be sorted into nine categories: vision obscuration, false instrument readings, dust coating and contamination, loss of traction, clogging of mechanisms, abrasion, thermal control problems, seal failures, and inhalation and irritation. Although simple dust mitigation measures were sufficient to mitigate some of the problems (e.g., loss of traction), it was found that these measures were ineffective in mitigating many of the more serious problems (e.g., clogging, abrasion, diminished heat rejection). The severity of the dust problems was consistently underestimated by ground tests, indicating a need to develop better simulation facilities and procedures.

Vision Obscuration: The first dust-related problem experienced by the Apollo astronauts occurred when they landed the LM. The Apollo 11 crew reported that *"Surface obscuration caused by blowing dust was apparent at 100 feet and became increasingly severe as the altitude decreased."* This was even more of a problem for Apollo 12 where there was total obscuration in the last seconds before touchdown to the extent that there was concern that one of the landing feet could have landed on a boulder or in a small crater. In Apollo 14 the landing profile was adjusted to be more steep, and the astronauts reported little difficulty in seeing the landing site. However, this may have been due in part to the Apollo 14 landing site being intrinsically less dusty, because Apollo 15 and Apollo 16 also used the steeper landing profile and both reported difficulties seeing the landing site in the critical last seconds. Apollo 17 experienced some vision obscuration in the landing of the LM, but they were able to see boulders and craters through the blowing dust all the way to touchdown.

The Apollo experience reveals that the extent to which vision obscuration is a problem on landing is dependent on the amount of loose dust in the specific landing zone. The record has far fewer references to dust-related problems in Apollo 14 and 17, where there was little obscuration on landing, than in the other missions. Thus, it will probably remain a variable as long as spacecraft are landing in unexplored territory. Since vision obscuration is dependent on the depth of loose dust in a particular area, crews may use this as an indicator of how much difficulty they can expect to have with dust during EVA activities.

A related observation is the discoloration of the Surveyor III spacecraft reported by the Apollo 12 crew. Apollo 12 landed about 163 meters from Surveyor III with the intent of determining the degradation experienced by the spacecraft after being in the lunar environment for 31 months. The crew expected to find a white spacecraft, but found instead that it was a brown color. Further investigation revealed that the brown color could be wiped off, and was in fact a fine coating of dust. The source of the dust coating was later determined to be largely from the dust kicked up when the LM landed.

In addition to vision obscuration on landing, the dust caused minor problems with photography. The Apollo 15 crew reported problems with a halo effect on the television camera transmission. This was remedied by cleaning the dust off of the lens with a soft bristle brush.

False Instrument Readings: In Apollo 12 the landing velocity trackers gave false readings when they locked onto moving dust and debris during descent. The Apollo 15 crew also noted that landing radar outputs were affected at an altitude of about 30 feet by moving dust and debris. But the Apollo 17 crew reported no lock-up onto moving dust or debris near the lunar surface. This again points out the differences in the amount of dust at the different landing sites, with it being high at the Apollo 12 and 15 sites, and low at the Apollo 17 site.

Dust Coating and Contamination: Dust was found to quickly and effectively coat all surfaces it came into contact with, including boots, gloves, suit legs, and hand tools. Consequences included the Apollo 11 astronauts repeatedly tripping over the dust-covered TV cable and a contrast chart on Apollo 12 becoming unusable after being dropped in the dust. This was particularly troublesome on Apollo 16 and 17 when rear fender extensions were knocked off of the LRV and dust "rooster tailed" and showered down on top of the astronauts. Dust coating is the precursor to other problems such as the clogging of mechanisms, seal failures, abrasion, and the compromising of thermal control surfaces. In addition, valuable astronaut time was spent on ordinary housekeeping chores like brushing off and wiping down equipment – which often proved ineffective.

Loss of Traction: Neil Armstrong reported material adhering to his boot soles caused some tendency to slip on the ladder during ingress back to the LM. However, this slipperiness was not reported by any of the other crew members, and there are specific references in the Apollo 12 record that this was not a problem for them. It became standard practice for the astronauts to kick the excess dust off of their boots on the ladder before they reentered the LM in an attempt to keep as much dust as possible out of the spacecraft, and it is likely that this measure was enough to keep slipping from happening.

Although there was concern about the surface being slippery, there are no incidences in the mission record of falling due to slips, though some of the astronauts tripped and fell. In the Apollo experience, loss of foot traction was not a major concern, as long as simple precautions and care were used.

Clogging of Mechanisms: There were reports of equipment being clogged and mechanisms jammed on every Apollo mission. These included the equipment conveyor, lock buttons, camera equipment, and even the vacuum cleaner designed to clean off the dust. Dust made Velcro® fasteners inoperable, and was a particular problem with some LRV indicator mechanisms. The dust also clogged Extravehicular Mobility Unit (EMU) mechanisms, including zippers, wrist and hose locks, faceplates, and sunshades. This was particularly troublesome on Apollo 16 and 17 when fender extensions were knocked off of the LRV and showered dust down on top of the astronauts.

The most alarming characteristic was how quickly and irreversibly dust problems could happen. One short ride on the LRV with a missing fender extension or standing where the equipment conveyor dumped dust on the EMU and difficulties began immediately. All of the astronauts experienced this to some degree, even those with the shortest stays on the surface. Several remarked that they could not have sustained surface activity much longer, or clogged joints would have frozen up completely.

Abrasion: Lunar dust also proved to be particularly abrasive. Pete Conrad noted that the suits were more worn after 8 hours of surface activity than their training suits were after 100 hours, and further reported that their EMUs had worn through the outer layer and into the Mylar multi-layer insulation above the boot. Gauge dials were so scratched up during the Apollo 16 mission as to be unreadable. Harrison Schmitt's sun shade on his face plate was so scratched that he could not see out in certain directions. Clearly, if mission times are to be significantly extended, these abrasion problems must be mitigated.

Thermal Control Problems: As described above, an insulating layer of dust on radiator surfaces could not be removed and caused serious thermal control problems. On Apollo 12, temperatures measured at five different locations in the magnetometer were approximately 68 °F higher than expected because of lunar dust on the thermal control surfaces. Similarly, on Apollo 16 and 17 the LRV batteries exceeded operational temperature limits because of dust accumulation and the inability to effectively brush off the dust. John Young remarked that he regretted the amount of time spent during Apollo 16 trying to brush the dust off of the batteries – an effort that was largely ineffective. This led him to remark recently that *"Dust is the number one concern in returning to the Moon."* In addition to the problems dust caused to the science instruments described previously, high temperatures caused difficulties with communications equipment and TV cameras.

Seal Failures: The ability of the pressure garment of the EMU to be resealed after EVAs was also compromised by dust on the suit seals. The Apollo 12 astronauts experienced higher than normal suit pressure decay due to dust in fittings. Pete Conrad's suit, which was tight before the first EVA, developed a leak rate of 0.15 psi/min after it, rising to 0.25 psi/min after the second EVA. Since the safety limit was set at 0.30 psi/min, it is doubtful whether a third EVA could have been performed, had it been scheduled. Another indicator is that all of the environmental and gas sample seals failed because of dust. By the time the gas samples reached Earth they were so contaminated as to be worthless.

This does not bode well for a long duration habitat where several astronauts will be passing through airlocks and unsealing and resealing their EMUs routinely. More attention must be directed at ways either to keep dust off of the seals, to better clean the seals, or to make more dust tolerant seals.

Inhalation and Irritation: Perhaps the most alarming possibility is the compromising of astronaut health from the irritation and inhalation of lunar dust. The Apollo crews reported that the dust gave off a distinctive, pungent odor (David Scott suggested it smelled a bit like gun powder), suggesting that there are reactive volatiles on the surface of the dust particles. Dust found its way into even the smallest openings, and when the Apollo 12 crew stripped off their clothes on the way back to Earth, they found that they were covered with it. Dust was also transferred to the Command Module during Apollo 12 and was an eye and lung irritant during the entire trip back. Given the potential toxicity of particle sizes less than about 5 μm, this points out the need to monitor the concentrations of dust particles within the EMU, the airlock, the habitat, and the spacecraft.

Later Apollo missions were more cognizant of the problem, and dust management strategies such as venting to space and using water to wash down the LM proved to be somewhat effective. But this experience points out that vigilant housekeeping will be required, and as crew sizes and mission durations increase, this will become more of a challenge.

EMU Modifications for Dust Abatement (Joe Kosmo, personal communication): The principal concern early on was abrasion caused by sharp rocks. The "super beta cloth" outer covering was not very abrasion resistant, so Chromel-R was woven into the lunar boots and gloves, which could expect to see the most abrasion. The boots and gloves also used the abrasion-resistant silicone RTV-630 for the soles and fingertips.

A nylon bristle brush was provided to dust off the suits and visors. This was effective for removing the coarse grain material, but not very effective for the fine grain. Since there was only a single brush, there is some thought that in the latter parts of the mission the brush might have transferred nearly as much dust as it removed. Wet wipes were provided for use inside the LM, and these reportedly were effective for cleaning skin and equipment. However, they could not be used outside in the lunar environment.

In between EVAs, the zippers and helmet and glove disconnect seals were cleaned and re-lubricated with Krytox® oil and grease. Although this helped, it was not completely effective either at keeping mechanisms from clogging or at keeping the seals from leaking. The wrist bearings and rotational hardware connectors only had a fabric covering to keep out the dust, and these were not totally effective. When rover operations started with Apollo 15, dust covers that were attached with Velcro® were added to the connectors on the front of the EMU (Michael Rouen, personal communication).

There was no concerted effort to keep dust out of the LM, and so the astronauts dragged a lot of dust in when they crawled through the hatch. Some of this dust was redistributed onto sensitive surfaces and even the astronauts' skin in the rest periods between EVAs. There was a small vacuum cleaner in the command module (CM) that was used to try to limit the dust transferred from the LM to the CM on docking, but it had limited effectiveness.

Dust Effects on the Lunar Roving Vehicle

Heat rejection from power systems will be necessary for human and robotic activity on the lunar surface. The functional operation of such heat rejection systems is at risk of degradation as a consequence of dust accumulation. Perhaps the most instructive lessons learned from Apollo on the effects of lunar dust on heat rejection system surfaces come from the radiators that cooled the batteries on the LRV.

The radiators were second surface mirrors with front surfaces composed of fused silica. The lunar dust has a high emittance (about 0.93), so there was little concern about the ability of the radiators to reject heat through a dust layer (Adams et al., 1967). However, the dust also has a relatively high absorptance (about 0.76), so there was concern that there would be an additional heat load from solar heating if there was a significant amount of dust on the radiators (Blair et al., 1971). The LRV batteries were rated for an operating range of 4 to 51 °C but operated in an environment that ranged from 10 °C at the beginning of the mission to 82 °C at its end.

The batteries were located on the front of the LRV, and so were expected to have a fair amount of dust impinging on them. Thus, the design for the battery radiators included dust covers. The plan was for the dust covers to be opened, exposing the second surface mirror radiators to cool the batteries between periods of EVA. It was anticipated that, despite the precaution of the dust covers, some dust would still find its way onto the radiators. However, a study by Jacobs, Durkee, and Harris (1971), which utilized lunar regolith returned by Apollo 12, concluded that removing lunar dust from fused silica second surface mirrors with a nylon brush would be effective. This was the strategy utilized to remove the dust from the radiators on all three LRVs for Apollo 15, 16, and 17.

However, the experience on the lunar surface was very different from that which was modeled and simulated beforehand. In Apollo 15 there was good battery cool down between EVA 1 and EVA 2, but after dust found its way onto the radiators, there was essentially no cool down between EVA 2 and EVA 3 (McKay, 1971). Both batteries warmed to about 47 °C, about 4 °C below their maximum rated operating temperature.

On Apollo 16 the batteries only cooled down 11 °C instead of the 28 °C expected, and reached their operating limit at the end of the second EVA. After the cool down period, at the beginning of the third EVA the batteries had only cooled about 2 °C. At the end of the third EVA the temperature had exceeded the maximum rated survival temperature, as shown in Figure 4-1 (McKay, 1972).

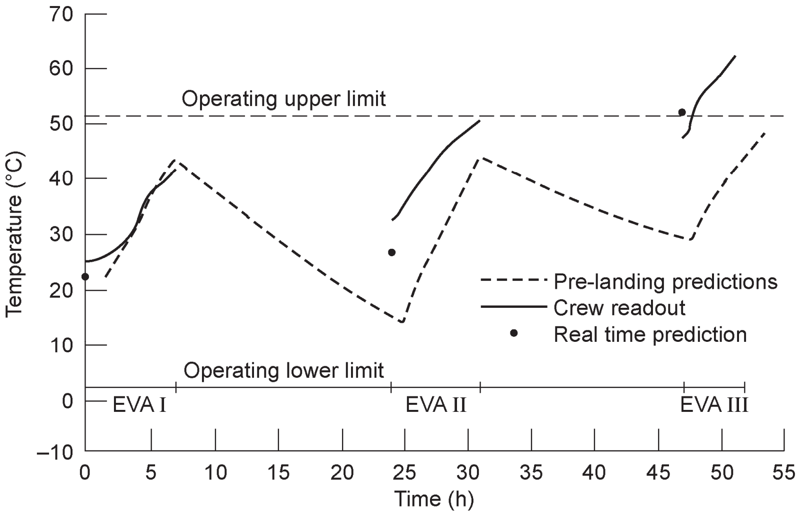

Figure 4-1. Plot of the LRV battery temperature for Apollo 16 (McKay, 1972). As shown in the plot, attempts to brush the dust off of the radiator between EVAs were largely ineffective in reducing the operating temperature.

The battery temperature profile on Apollo 17 was similar to that of Apollo 16, and after a little more than 4 hours into the third EVA, the batteries exceeded their maximum operating temperature. By 6 hours, the batteries had reached their maximum survival temperature (McKay, 1973). Apparently, lunar dust under lunar surface conditions is much more adherent than under the terrestrial simulation conditions chosen by Jacobs, Durkee, and Harris. This was especially true for the finest fraction of the dust, which was not removed at all by brushing. Since solar heat load is proportional to the fractional coverage, this fine fraction soon covered most of the surface and dominated heat transfer.

Experiments With No Reported Collateral Dust Issues

Although effects on the individual Apollo instruments have been reported, these have been systematically collected only sparsely (Gaier and O'Brien, 2009), and nowhere discussed in detail. It must be acknowledged that most of the instruments deployed on the surface during Apollo appeared to be robust to collateral dust effects. Listed below, and in Table 4-1, are the eleven instrument types on which the effects of collateral lunar dust were not reported in the mission debriefs or the preliminary science reports.

This was taken to mean that they were not significantly affected by collateral dust, either because the measurements were inherently insensitive to dust effects or because the mitigation measures were effective. The descriptions of the science instruments and their effects, unless otherwise noted, have been extracted from the 1994 review of Sullivan and the references therein (Sullivan, 1994). More recent analyses of the science results from these instruments were not surveyed, so it is possible that there were collateral dust effects on some of these instruments that were only later identified.

Table 4-1. Experiments with no reported collateral dust issues.

Instrument	Apollo Missions
Charged Particle Lunar Environment Experiment	14
Far UV Camera and Spectrograph	16
Heat Flow Experiment	14, 15, 16, 17
Lunar Mass Spectrometer	17
Lunar Portable Magnetometer	14, 16
Lunar Seismic Profiling	17
Lunar Surface Gravimeter	17
Lunar Surface Magnetometer Experiment	12, 15, 16
Neutron Flux Experiment	17
Solar Wind Spectrometer	12, 15
Traverse Gravimeter Experiment	17

Charged Particle Lunar Environment Experiment (CPLEE): The experiment was designed to measure the ambient fluxes of charged particles, both electrons and ions, with energies in the range of 50 to 50,000 eV. It was equipped with a dust cover that was not removed until after Lunar Module (LM) ascent, and so was not exposed to collateral dust.

Far UV Camera and Spectrograph: This was a miniature observatory that acquired imagery and spectra in the far UV range below 160 nm. The experiment was hand carried to its deployment position in the LM shadow and moved twice to maintain a shadowed position. Some scattering of far UV light in the photos of the Magellanic cloud was attributed to lunar dust electrostatically suspended above the surface, but the effect was not considered severe enough to affect the science return.

Heat Flow Experiment: The experiment was designed to make temperature and thermal-property measurements in the lunar subsurface in order to determine the rate at which heat flows out of the interior of the Moon. Since the instrument was designed to be deployed underneath the lunar surface, collateral dust was not an issue.

Lunar Mass Spectrometer: The instrument was a 3-channel mass spectrometer designed to identify the composition of, and variation in, the lunar exosphere. It was protected by a dust cover which was not commanded open until the last explosive charge of the Lunar Seismic Profiling Experiment was detonated, six days after deployment. The gas entrance was pointed upward and had a dust trap around the source region to prevent dust falling into the source itself.

An error in thermal design and temperature-sensitive components limited its operation to temperatures <325 K, which precluded operation during elevated lunar day temperatures when the atmosphere would have been most prevalent. So the experiment collected good data during the lunar night, but missed the time when exospheric pressure would be the highest. As operated, collateral dust did not appear to affect the experiment.

Lunar Portable Magnetometer: The experiment was designed to measure the magnetic field on the lunar surface and to determine from these measurements some of the deep-interior electrical properties of the Moon and the interaction between the solar plasma and the lunar surface. The measurement was not sensitive to the presence of collateral dust.

Lunar Seismic Profiling: Eight explosive charges were deployed at distances between 100 m and 3.5 km from an array of four identical geophones. These charges were later detonated by a timer after LM ascent stage liftoff, and seismic measurements were obtained. A concern was raised that the larger charges could conceivably throw debris to altitudes where the command module was still gathering orbital data two days later, but it was calculated that the risk was in the range of 10^{-5} to 10^{-6}, which was low enough to allow the experiment to proceed.

Lunar Surface Gravimeter: The experiment was designed to make very accurate measurements of lunar gravity and of its variation with time. Due to a design error no valid data were returned, but collateral dust played no part in its failure.

Lunar Surface Magnetometer Experiment: The purpose of the experiment was to measure the magnetic field on the lunar surface and to determine from the measurements some of the deep-interior electrical properties of the Moon and to elucidate the interaction between solar plasma and the lunar surface. The measurement was not sensitive to the presence of collateral dust.

Neutron Flux Experiment: Time-integrated fluxes of thermal neutrons as a function of depth in the regolith were measured using targets of ^{10}B and ^{235}U placed at intervals along a 2 m rod that was inserted into the hole left by the deep drill core. The measurement was not sensitive to the presence of collateral dust.

Solar Wind Spectrometer: The purpose of the experiment was to compare the solar wind properties at the lunar surface with those measured in space near the Moon and to characterize the magnetotail of the Earth. It was equipped with dust covers that were not removed until after LM ascent, and so was not exposed to collateral dust.

Traverse Gravimeter Experiment: The purpose of the experiment was to make relative gravity measurements at a number of locations and to use these to obtain information about the geological substructure. The measurement was not sensitive to the presence of collateral dust.

Experiments Designed to Study Dust and Regolith

Three Apollo experiments, discussed below and listed in Table 4-2, were designed to study the lunar regolith or the dust environment. They provide unique resources as they are the only experiments to date which directly measure properties of the lunar environment as humans interact with it.

Table 4-2. Experiments designed to study dust and regolith.

Instrument	Apollo Missions
Lunar Dust Detector	11, 12, 14, 15
Soil Mechanics Investigations	11, 12, 14, 15, 16, 17
Thermal Degradation Samples	14

Lunar Dust Detector: This instrument (DDE) was included on the central station of the Apollo Lunar Surface Instrument Packages (ALSEPs) to record the dust accumulation from LM ascent or from any long-term cause. As DDE designer and PI O'Brien has explained (O'Brien, 2009), the DDE was flown in two different configurations. On Apollo 12 it was flown in the original configuration with three identical solar cells on each facing the sunrise, zenith, and sunset directions. On the other missions the DDE was modified to measure radiation effects on the solar cells. In the modified DDEs three solar cells in the zenith orientation were used: one bare and two with protective cover glasses, 0.15 or 0.51 mm thick, with one pre-irradiated with 1×10^{15} electrons of 1 MeV energy. In both configurations the short circuit current was used to measure the dust occlusion due to its direct dependence on illumination.

Spurred by the re-emergence of original Apollo data tapes in 2007, O'Brien has more recently written a series of papers which extract much additional information from those measurements revealing surprising insights, some of which contradict the original mission science reports. Those results are detailed in the O'Brien article in this volume. It should be noted that all of the DDEs were functioning at the time they were turned off. So these instruments could also be listed under the category of "Instruments Not Affected by Collateral Dust."

Soil Mechanics Investigations: The purpose of the experiment was to enhance the scientific understanding of the nature and origin of the lunar regolith and to provide engineering data on the interaction of crewed systems and operations with the lunar surface.

The soil mechanics investigation included for Apollo 11, 12, and 14 utilized no special soil mechanics testing or sampling devices. The main sources from which data could be extracted included real-time astronaut observations, television and still camera images, flight mechanics telemetry, and various objects of known geometry and mass that came in contact with the lunar surface.

On Apollo 14, the geophone/thumper anchor was used as a penetrometer to obtain three two-stage penetrations into the lunar surface. It had a 30° cone tip on one end and a connection for the extension handle on the other. When so used, it was referred to as the Apollo Simple Penetrometer. After the completion of these tests, the device was used to anchor the geophone cable.

Apollo 15 included a self-recording penetrometer that could penetrate up to a 76 cm with a penetration force of up to 111 N. Three penetrating cones, each of 30° apex angle and base areas of 1.29, 3.22, and 6.45 cm^2, were available for attachment to the shaft, as well as a 2.54 × 12.7 cm bearing plate. During Apollo 16, eleven tests were performed during EVA 2. In addition to the penetrometer measurements, soil mechanics properties could be inferred from such activities as coring and trenching.

The soil mechanics experiment on Apollo 17 was passive and involved no apparatus or crew time unique to the experiment. The results were deduced from studies of EVA transcripts and kinescopes, mission photo graphs, data on the LRV performance, debriefings, and limited examination of returned lunar samples by the Lunar Sample Preliminary Examination Team.

Thermal Degradation Sample (TDS): The purpose of the experiment was to evaluate the effect of lunar dust on the optical properties (absorptivity and emissivity) of twelve candidate thermal coatings. Two duplicate arrays, each containing samples of the twelve coatings, were exposed to the lunar environment. After astronaut Shepard covered them with dust, one was tapped or perhaps shaken to remove the dust and the other was cleaned with a nylon-bristle brush. Before and after photographs taken on the lunar surface are the only data records from this experiment. The arrays were then packaged in a closed, but not vacuum-sealed, container (the hand tool carrier pouch) and returned to Earth.

Although records show that the TDS was brought back to Earth and placed in quarantine, there are no post-exposure measurements reported and the hardware has not been accounted for since. The photographs of that experiment, however, are extraordinary. After the TDS plates were dusted and tapped, some of the dust was dislodged from the serial numbers on the plates. As can be seen in Figure 4-2, the cohesion of the dust is such that the numbers can still be distinguished in the dislodged dust.

Astronaut Shepard commented that he was surprised by the low adherence of the dust to the array. A 2012 analysis reported by Gaier (Gaier,

2012) hypothesized that this was in part due to the short time that the samples were exposed to the full lunar environment – no more than 2.5 min. Tests in the ultrahigh vacuum Adhesion Rig at the NASA Glenn Research Center suggest that thermal control surfaces exposed to the solar wind for a longer period of time would likely have residual terrestrial contamination removed from their surfaces, likely resulting in substantially greater adhesion.

Figure 4-2. TDS showing the strong cohesion of lunar dust dislodged from the serial number on the mounting plate (Photo credit: NASA).

Experiments With Reported Collateral Dust Issues

Perhaps of most interest is to examine the impacts on the seven experiments that reported issues attributed to the accumulation of collateral dust, listed in Table 4-3.

Table 4-3. Experiments with reported collateral dust issues.

Experiment	Apollo Mission
Cold Cathode Gauge	12, 14, 15
Solar Wind Composition	11, 12, 14, 15, 16
Laser Ranging Retroreflector	11, 14, 15
Cosmic Ray Detector	11, 16, 17
Lunar Ejecta and Meteorites	17
Passive Seismic Experiment	11, 12, 14, 15, 16
Surface Electrical Properties	17

Cold Cathode Gauge: The purpose of the experiment was to measure the total pressure of the lunar exosphere. As designed, pressures between 10^{-6} and 10^{-12} Torr could be measured. The instrument featured a dust cover that was not vacuum-tight. The cover was removed by command. Because it was not evacuated, adsorbed gasses produced an elevated response when the gauge was initially turned on, but because it reached 350-400 K for more than a week each lunar day, those adsorbed gasses were driven off.

The Apollo 12 instrument failed after about 14 hours of operation when the 4500 V power supply shut off. This may have been due to dust getting into the unit when it repeatedly tipped over during deployment.

The Apollo 14 and 15 instruments appeared to operate nominally, and though there were a few unexplained anomalies, none were attributed to dust interactions.

Solar Wind Composition: The purpose of the experiment was to trap a sample of the solar wind so as to measure its ion types and energies on the lunar surface. The trap consisted of a 4000 cm^2 aluminum metal foil. The purity of the foil was critical to avoid contamination of the lunar samples and background contamination of the experiment itself. Once returned to Earth, the foil was ultrasonically cleaned before analysis. Part of the sheet was then melted in an ultra-high vacuum system and the gasses released were analyzed with a mass spectrometer.

On Apollo 12 there was difficulty rolling up the foil for stowage, so the astronauts used their hands to roll it, and as a result the foil was soiled by the dust adhering to their gloves. Dust on samples also released gas and so affected the composition measurements.

On Apollo 15, after exposure the foil was transferred to the LM via the equipment transfer bag and may have been kept separate from other samples to minimize dust contamination.

Finally, for Apollo 16 the foil was composed of both an aluminum and a platinum section. The platinum foil allowed for treatment with dilute hydrofluoric acid before sample analysis on Earth to remove dust contamination and the resulting uncertainties.

Laser Ranging Retro-reflector (LRRR): The purpose of the experiment was to measure lunar librations (both in latitude and longitude), the recession of the Moon from the Earth due to tidal dissipation, and the irregular motion of the Earth, including the Chandler wobble of the poles. This was accomplished using short-pulse laser ranging from the Earth onto corner-cube reflector arrays emplaced on the lunar surface.

The arrays were placed more than 500 feet from the LM to minimize the dust from LM ascent. Range measurements using the Apollo 14 array were successfully accomplished on the day it was deployed. Measurements taken after LM liftoff indicated that the ascent stage engine burn caused no serious degradation of the LRRR's reflective properties.

But recent analysis indicated that there has been a factor of 10 degradation in the reflected light intensity over the subsequent 40 years (Murphy et al., 2010). The most likely causes of the degradation were suggested to be dust, transported either by micrometeoroid impact or electrostatic levitation, or pitting from micrometeoroids.

Cosmic Ray Detector: The purpose of the experiment was to observe cosmic ray and solar wind nuclei and thermal neutrons, and also included metal foils to trap light solar wind gasses. On Apollo 11 the experiment was limited to post-mission analysis of the flight helmets. On Apollo 16 the experiment used a four-panel array of passive particle track detectors. A set of smaller detectors was used on Apollo 17, one solar facing and the other anti-sun facing. As the particles passed through the materials, they left tracks which could be observed after a preferential chemical attack, allowing the particles to be identified and counted.

At the end of EVA 1 on Apollo 16, the experiment was moved for thermal control. Astronauts reported that it was hot to the touch, even through gloves. Temperature labels, designed to sense the approach to the permitted upper limit of 328 K, located on the outboard face of the frame indicated that the temperature had exceeded 319 K. Although the clean equipment should not have overheated, it was calculated that a deposit of as little as 10 percent cover of dust would have produced excessive heating. It is not known if the degradation was due to lunar dust from landing or a residue from engine exhaust during transposition and docking. However, the crew felt that the experiment may have reached this temperature before landing due to the extra three revolutions before descent, though this should have been prevented by its covering with a perforated thermal control material.

Lunar Ejecta and Meteorites (LEAM): The objectives of the experiment were to detect secondary particles that had been ejected by meteorite impacts on the lunar surface and to detect primary micrometeorites themselves. The three classes of particles to be measured comprised lunar ejecta, interstellar grains, and cometary debris, and these were distinguished by particle speed, momentum, and kinetic energy as well as radiant direction. The particle detectors of the instrument were multi-layered arrays that were capable of measuring the velocity and energy of incident particles. It included three sensors, east, west, and up, with the east sensor directed 25° north of east to accommodate interstellar grains protected by two dust covers that were removed by ground command.

After deployment, it was commanded "on" from Earth for calibration, then turned off until after LM ascent and detonation of the surface charges of the Lunar Seismic Profiling Experiment. The dust covers over the sensors were commanded to release in the lunar night, but did not, perhaps because of the cold. They did release during the dawn of the second lunation.

The thermal control provisions for the unit did not maintain the operating temperature below the qualification test maximum level during the lunar day because the thermal conditions at the site were different than those at the design site (level plain at the equator). However, the unit operated during 100 percent of each lunar night and 30 percent of each lunar day.

Unusual data events followed by laboratory investigations with the spare LEAM unit were attributed to the transport of lunar surface fines (Rhee, Berg, and Wolf, 1976). Reported dust particle flux increased dramatically 10 hours before sunrise. However, this conclusion has recently been called into question, and the signal may be attributable to power switching of the thermal control heaters rather than dust motion (O'Brien, 2011).

Passive Seismic Experiment: The instrument consisted of a seismometer designed to detect moonquakes and impacts.

The Apollo 11 experiment was gold-covered and deployed 17 m from the LM. It got hotter than expected, perhaps because of dust coverage, and no longer accepted commands after near-noon of the second lunar day.

Later missions were redesigned with a Mylar skirt thermal shroud to reduce thermally induced tilts of the local surface around the apparatus. The thermal shroud was not deployed until late in the ALSEP's deployment so that dust would not accumulate on it. On Apollo 12, the thermal shroud would not lie flat. It was believed that it had been folded for so long that it had developed "elastic memory," though the problem could also have been caused by electrostatic effects. It was resolved by putting lunar soil and bolts along the skirt edges, though this degraded the skirt's function.

The temperature of the Apollo 16 experiment ran higher than planned. This was likely due to dust that was inadvertently kicked onto the skirt after deployment.

Thus, several of the stations exhibited thermal control problems. Limiting the instrument operation temperature to a band of ~1.1 K was required for resolving tidal data. This limitation was not achieved, partly because of problems with the deployment of the thermal shroud. Corrective actions included the addition of weights to the outer edges of the shroud, the use of a Teflon® layer as the outer shroud covering, and the stitching of the shroud to prevent layer separation. Even so, an optimum shroud deployment was not achieved. Thus, the heat loss during the lunar night and the solar input incurred during the lunar day limited the science return.

Surface Electrical Properties: This experiment measured the dielectric constant and loss tangent of the lunar regolith *in situ* and also provided information on the subsurface structure (electrical layering, discrete scattering bodies, and the possible presence of water) in the region covered by the geology traverses.

During the rest period between EVAs 1 and 2, the temperature of the receiver increased. This was due to dust kicked up by the LRV compounded by inadequate dust protection for the SEP radiators. (The LRV had a broken fender on EVA 1, but it was repaired before the second EVA.) The adhesive on the beta cloth cover for the radiator failed, allowing dust onto the radiator. Overheating hampered the operation until the data storage electronics assembly recorder was removed in the middle of EVA 3 to prevent the loss of data that had already been recorded. Despite the efforts of the crew to control the temperature, the receiver became too hot and was turned off by a thermally operated switch. The transmitter operated nominally throughout the mission. Data were obtained during EVA 2 on the traverses from the SEP transmitter site toward Station 2 and from Station 4 toward the transmitter. Data were not obtained during the early part of EVA 3 because the receiver switch was in the standby position rather than "on" as requested by Mission Control.

Way Forward

It is not the goal of this report to suggest that lunar dust poses intractable problems. However, it is the author's opinion that far too few resources have been devoted to studying the behavior of the dust in the lunar environment, its implications for exploration systems, and mitigation strategies. There has been far more study of natural dust transport processes than collateral ones. But in addition to the Apollo experience documented herein, even cursory studies (Katzan and Edwards, 1991) show that dust transport from exploration activities will be orders of magnitude higher than natural dust transport, and so a much greater threat to astronaut safety and mission success.

The first recommendation is that more work be funded to understand collateral dust transfer in the lunar environment. Simulations of the lunar environment, both numerical and physical, must be much more sophisticated than simply lower gravity and vacuum environments if useful results are to be obtained. Tied to this is the cohesion of the dust as well as its adhesion to spacecraft surfaces. The fact that dust is transported in aggregates rather than as individual grains is seen within Apollo photographs and has been duplicated in the lab (Marshall, Richard, and Davis, 2011), yet this has not been taken into account in most dust transport models to date.

The lunar environment is incredibly complex, with a vacuum harder than any that is routinely replicated on Earth, a constant barrage of solar wind and micrometeoroids, and complex plasma phenomena that depend on the time of lunar day, the position with respect to the Earth's magnetotail, and solar activity. It is not clear which of these environmental factors must be replicated in high fidelity to generate useful models and simulation data of collateral dust transport. If experiments and analyses could identify which of these factors are substantial contributors to dust transport and adhesion, this has the potential to substantially simplify the design of lunar environment test chambers while providing the high fidelity testing conditions needed to verify mitigation technologies.

The second recommendation is that much more coordinated work be funded to develop dust mitigation strategies. Work undertaken to date, for the most part, has been haphazard in the sense that the efforts have been uncoordinated and not systematically evaluated against one another. NASA should re-establish an organization within the lunar exploration program to coordinate, prioritize, and evaluate mitigation technologies. Funding should be available to all organizations on a competitive basis, but they should submit their technologies to one single evaluative body for apples-to-apples comparison for each potential application. It will require substantial funding to tackle the multi-headed task of dust mitigation for lunar exploration, but without it the costs, both monetarily and for mission success, will be much higher.

Acknowledgments

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CHAPTER FIVE

DUST TRANSPORT AND ITS EFFECTS DUE TO LANDING SPACECRAFT

PHILIP T. METZGER
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Introduction

Lunar lander engine exhaust blows dust, soil, gravel, and rocks at high velocity and will damage surrounding hardware such as lunar outposts, mining operations, or historic sites unless the ejecta are properly mitigated. Twenty years of research has developed a consistent picture of the physics of rocket exhaust blowing lunar soil, but significant gaps exist. No currently available modeling method can fully predict the effects. However, the basics are understood well enough to begin designing countermeasures.

Understanding the Basic Physics

Researchers have characterized several different regimes of gas/granular interaction that can occur when rocket exhaust impinges on planetary regolith. These include (1) *viscous erosion* (as it is called in the space literature) when the gas flows across the granular surface and entrains individual grains into the flow (Roberts, 1963; Land and Scholl, 1966; Metzger, Lane, and Immer, 2008; Metzger, Latta III et al., 2009; Metzger et al., 2010; Morris et al., 2015, 2016); (2) *bearing capacity failure* when the static, impingement pressure of gas under the centerline of the plume mechanically shoves the soil down so that it shears in bulk, forming a cup or crater (Metzger and Mueller, 2009; Metzger, Li et al., 2009; Immer and Metzger, 2010); (3) *diffused gas eruption* when the gas diffuses between the grains then erupts from the subsurface at another location or time carrying grains with it (Scott and Ko, 1968; Chambers and Metzger, 2016); (4) *diffusion-driven flow* when the gas flowing through the pore spaces of the soil drags the soil and causes it to flow in bulk, forming a crater (Metzger, Immer et al., 2009); (5) *shock impingement splashes* (Metzger, 2020); and (6) *repeated shocking of the soil* from a pulsed jet causing the soil to liquefy in bulk then flow easily (Mehta et al., 2011). Whether any of these occur in a particular situation depends on the friction, cohesion, and permeability of the soil, the particle size distribution, the gravity, the ambient atmospheric pressure to either collimate or not collimate the plume, the rarefaction of the plume in the region of interest, the thrust of the plume, the abruptness of application of the plume, and other factors. The parameter space has not been mapped, nor is it sure that all the possible phenomena have been cataloged, so we can discuss what will happen in particular cases only after we have done enough research into that case to be sure.

For the Martian case, rocket exhaust is far more likely to create a deep crater in the regolith (Metzger and Mueller, 2009) than in the lunar case. On the Moon with small landers up to the 5 t (landing mass) of the Lunar Module (LM), the phenomena are largely restricted to surface scouring of the top few centimeters of looser regolith. Figure 5-1 shows the stages of this soil erosion seen during the Apollo lunar landing looking out the window of the LM (Metzger, Smith, and Lane, 2011).

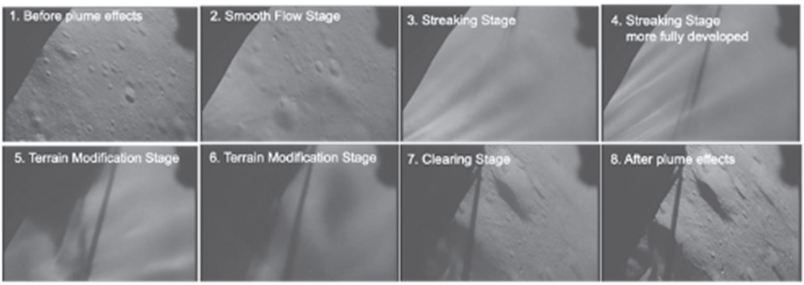

Figure 5-1. Stages of blowing dust and soil observed during Apollo lunar landings (Metzger et al., 2011).

The blowing dust in Figure 5-1 is traveling at very high velocity, typically 1000 to 3000 m/s, according to the best estimates (Lane, Metzger, and Immer, 2008; Lane, Metzger, and Carlson, 2010; Lane and Metzger, 2012). Sand, gravel, and rocks attain slower speeds than this due to their greater ballistic coefficient, causing them to speed up more slowly as they run out into the surrounding vacuum where the drag forces of the gas vanish, but they are still traveling very fast. The escape velocity of the Moon is only 2380 m/s, so the dust is distributed globally and some is ejected completely off the Moon. This is contrary to our common sense on Earth, where rocks travel the farthest, sand the next farthest, and dust travels hardly any distance at all because the drag force of the ambient atmosphere immediately stops it. On the Moon, it is the dust that can travel at extreme velocities and reach extreme distances, damaging whatever it impacts even many kilometers away.

The deeper forms of cratering were not observed in the Apollo landings. The surfaces under the LMs were only smoothed by the plume, as shown in Figure 5-2. The actual crater was a few centimeters deep, and somewhat deeper in a ring about a meter or two away from the centerline where the shear stress of the gas was at its maximum (Roberts, 1963; Metzger, Smith, and Lane, 2011). A deeper crater was not expected for a combination of reasons. First, the lunar regolith is highly compacted deeper than a few centimeters, so it is highly resistant to bulk shearing. Second, the absence of significant pressure in the lunar atmosphere means the plume will not be collimated but will instead spread out to fill the entire hemisphere below the lander, and even more than the hemisphere since some of the gas turns greater than 180 degrees after leaving the rocket nozzle. This broad plume prevents abrupt, high-pressure gradients from forming on the regolith's surface. Soil has a much higher bearing capacity for broad pressure gradients than abrupt ones. However, we cannot yet rule out the possibility that deeper cratering might occur in the permanently shadowed regions where soil may be looser (as suggested by several lines of evidence). Also, there is a major gap in our understanding about what will happen with NASA's proposed lunar lander for the Artemis program (20-40 t landing mass, estimated) and even larger commercial landers. It is unknown whether the vastly increased thrust will be adequate to induce bulk shearing, whether by bearing capacity failure, diffusion-driven flow, or another mechanism. If it does, then the changed shape of the hole under the lander will redirect ejecta into higher ejection angles, and the changed pattern of gas flow might enhance the erosion or turbulent mixing of the regolith with gas. Without more research, we cannot predict what will occur in these cases.

Figure 5-2. Smoothed soil beneath the Apollo 11 LM after landing. The engine bell is visible at the top of the image. Features indicative of soil erosion are visible in the image, including erosional remnants and a terrace where a natural lamination in the soil resisted erosion. The gouge in the soil at the top of the image is from the LM's soil contact probe (from NASA image no. AS11-40-5921HR).

Modeling Erosion Rate

If the primary phenomenon in lunar landings is viscous erosion, then we need to understand how much material is blown, how fast it travels and at what ejection angles so we can calculate where it will impact, and how much damage it will do on impact. Extensive experimental work has been performed in laboratories and reduced gravity flights to derive the rate of viscous erosion (Metzger, Immer et al., 2009; Metzger, Li et al., 2009, Metzger et al. 2010; Immer and Metzger, 2010). The experiments indicated that the volumetric erosion rate scales according to

$$\frac{\mathrm{dV}}{\mathrm{d}t} = K\frac{\rho v^2 A}{\rho_m g D + f(c)}$$

where $\mathrm{dV/dt}$ is the growth rate of the total volume of eroded soil in a small experiment, ρv^2 is gas density times gas velocity squared at the exit plane of the nozzle, A is the exit area of the nozzle, so overall the numerator is the total momentum flux into the experiment (indicating erosion is a momentum-driven rather than kinetic energy-driven process), $\rho_m g D$ is sand grain mineral density times gravity times average diameter of the sand grains, and $f(c)$ is a hypothesized function of soil cohesion that is invoked to explain behaviors seen in reduced gravity experiments. K is the proportionality constant and has units of velocity; its physical interpretation is still missing. The numerator is entirely a function of the rocket forcing erosion, and the denominator is entirely a function of the environment resisting erosion. According to Roberts (1963), the plume should be operating in rough turbulent flow conditions where erosion is occurring (this is questionable and subject to on-going research) so the shear stress on the soil σ at every location $\vec{R}$ and time t should be proportional to thrust, which is equal to the numerator. Therefore, the local erosion rate at each location on the soil may be written as

$$\frac{\mathrm{dm}}{\mathrm{d}t} = \kappa(\mathrm{soil}, g)\ \times \sigma(\vec{R}, t)$$

where $\mathrm{dm/dt}$ is the rate that soil mass is entrained into the gas flow per unit area from a particular location, and $\kappa(\mathrm{soil}, g)$ is a constant that combines all soil and environmental parameters for the landing site along with the unknown K. This form of the equation can be integrated over the regolith's surface in the region where erosion occurs (varying $\vec{R}$) and over the time t of descent during which the plume conditions over the soil are changing. This calculates the total mass of eroded soil as

$$M = \rho_m\, \kappa(\mathrm{soil}, g) \int \mathrm{d}t \iint \mathrm{d}\vec{R}\, \sigma(\vec{R}, t)$$

If the eroded mass during a lunar landing can be measured empirically, and computational fluid dynamics modeling can calculate $\sigma(\vec{R}, t)$ and each moment and location during the descent, this equation can be used to solve $\kappa(\text{soil}, g)$. Then the parameterized equation can predict the erosion rate for any other size lander or descent trajectory on the same type of soil on that same planet. This has been attempted (Immer, Metzger et al., 2011; Metzger et al., 2010), but the resulting equation was not accurate, predicting erosion rates that were apparently too high by an order of magnitude. A clue to the discrepancy came from erosion experiments in a vacuum chamber, which found that the erosion rate increases as the background pressure becomes more rarefied (Metzger, 2016). All the other experiments that derived the above erosion rate equation had been done in continuum conditions. This finding seems reasonable because erosion is a momentum-driven process, and gas viscosity is the diffusion-of-momentum parameter governing how the momentum of the gas diffuses through the boundary layer to impart motion to the soil, so in the rarefied limit where viscosity breaks down the momentum of the gas may more easily reach the soil.

Lane and Metzger (2015) developed a new method to make more accurate empirical measurements of erosion rates during lunar landings by performing statistical analyses of the optical density of dust seen in the Apollo landing videos. This produced a more accurate erosion rate equation which turned out to be a power law of the shear stress:

$$\frac{\mathrm{dm}}{\mathrm{d}t} = 0.0222\,\sigma^{2.52}\left(\vec{R}, t\right)\ \mathrm{kg/s/m^2}$$

The power index turned out to be about 2.5 instead of unity, as derived in the terrestrial experiments in continuum conditions described above. This potentially explains why the equation developed for continuum conditions was not accurate in predicting the eroded soil in the Apollo landings: erosion increases faster than linearly with shear stress.

It is difficult to understand how the physics results in this 2.5 power index, but it produces reasonable predictions for small landers such as the approximately 1 t Commercial Lunar Payload Services (CLPS) landers and the approximately 5 t LM. It is disconcerting, though, because it predicts extreme quantities of soil will be ejected for an approximately 40 t Artemis lunar lander or larger. Figure 5-3 shows the erosion equation integrated over the descent profile of an Artemis lander when naïvely applying this model. It predicts a crater over 50 m deep under the lander. We know this is unrealistic because of at least three considerations. First, the model was derived from empirical measurements of the Apollo landings, and in those cases the soil was approximately flat (very shallow craters only) where the gas was flowing and erosion was taking place. Very deep erosion would disrupt the gas flow, so the empirical results of the Apollo landings cannot be extrapolated that far. Second, the Apollo landings eroded soil by only a few centimeters where the soil was very loose on the lunar surface. After a lander scours away that loose material, the remaining soil should be more resistant to the plume and the erosion rate should slow. Third, when the lander is very large then the thrust is greater and the gas impacting the lunar surface is denser, so when it is sufficiently close to the surface the plume may reach the continuum regime where the unity power index seen in terrestrial experiments should apply. This should cause erosion to increase more slowly during the remaining descent of the vehicle.

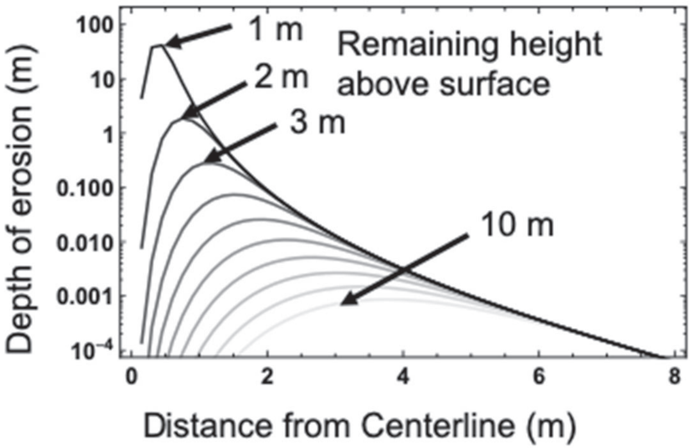

Figure 5-3. Prediction of naïve soil erosion model applied to a 40 t lunar lander as it descends from 10 m height down to 1 m height above the lunar surface.

The current working hypothesis is this: that the 2.5 power index observed in Apollo landings is valid in a lunar vacuum when the vehicle is small and/or high above the surface so the plume flowing across the surface is rarefied, but when the vehicle is low and/or large enough that the plume is denser and in continuum flow, then the erosion rate transitions to the unity power index. Figure 5-4 shows this transition for 5 t and 40 t landers.

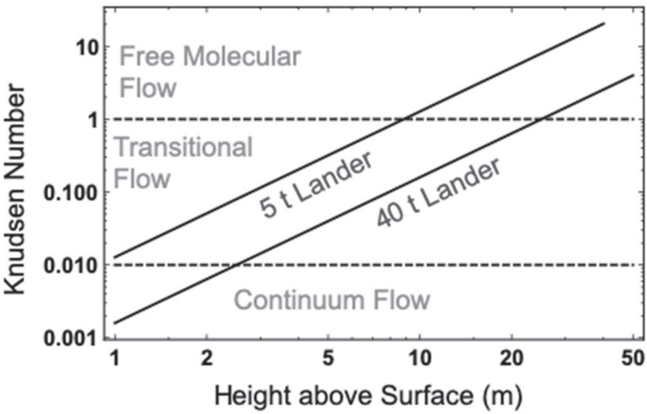

Figure 5-4. Knudsen number (calculated relative to the radius of an average lunar soil particle) along the centerline of the plume.

This suggests that the erosion rate may transition from the 2.5 index to the 1.0 index near the centerline of the plume when the 40 t lander is at 2.5 m height. It would transition at higher altitudes for more massive vehicles. (Note that this transition needs to be considered a function of radius from the centerline, as well.) Per Figure 5-3, the crater under a 40 t lander as it descends will be 0.5 m deep when it transitions to continuum flow (on the centerline), so the crater should grow more slowly beginning from that altitude. If the 2.5 power index prevailed through the entire landing of the vehicle, it would eject 470 t of ejecta (compared to 2.6 t measured for the Apollo LM). If the power index transitions to 1.0 at about 2.5 m height, then a rough estimate is that the vehicle will eject a total of 108 t of regolith during its descent, or 77% less. This still predicts a very deep crater under the lander and a huge amount of ejecta that could strike surrounding assets. Work is on-going to adapt the models to more quantitatively predict crater depths and ejecta masses based on this hypothesized transition of power indices and the other two considerations mentioned above. More experimental work and landings of larger lunar landers are needed to definitively solve the physics.

Trajectories of Ejecta

Analysis of LM ejecta trajectories was done by physics-based simulation (Lane, Metzger, and Immer, 2008; Lane, Metzger, and Carlson, 2010; Lane and Metzger, 2012) and validated as far as possible using Apollo video imagery (Immer, Lane et al., 2011; Metzger, Smith, and Lane, 2011). The results show that the finest dust particles can be accelerated up to the exit velocity of the rocket propellant, which is 3.1 km/s for the LM's Aerozine/N_2O_4 propellants. Larger particles generally go slower, with sand-size particles traveling 100-1000 m/s, gravel ~30 m/s, and fist-sized cobbles ~10 m/s (Metzger, Smith, and Lane, 2011). The detailed relationships are complicated because ejecta velocities depend on lander height, distance from the centerline at which the particle was eroded, terrain shape, scattering between particles of different sizes (Murray et al., 2012; Anand et al., 2013; Berger et al., 2015), and other factors. Extrapolating to larger landers, simulations show that ejecta velocities increase logarithmically with vehicle mass (Metzger and Britt, 2019), so a 40 t lander ejects the eroded material generally 50% faster than a 5 t lander. This is because the volume of the plume is larger, so the ejecta have more time to accelerate in the drag of the plume before running out into highly rarefied conditions then a vacuum. Accounting for changes in propellant, the CH_4/LOX favored by SpaceX has an exit velocity of 3.8 km/s, and the H_2/LOX favored by NASA and Blue Origin has an exit velocity of 4.5 km/s. This is another factor that may increase the velocities of the ejecta. On the other hand, a choice of propellant with higher exit velocity also results in lower gas density for a given thrust, so the factors are at least partially offsetting. A crude estimate of maximum particle velocities as a function of size for an H_2/LOX 40 t lander is provided in Figure 5-5. This is just a preliminary estimate while detailed simulations are on-going. It indicates that particles up to 10 μm can be ejected completely off the Moon.

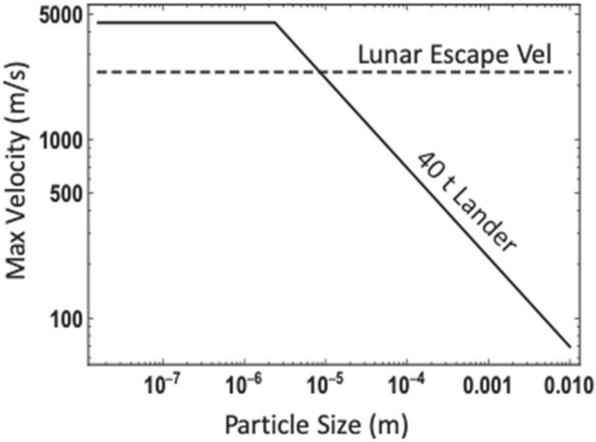

Figure 5-5. Model of maximum ejecta velocities as a function of lunar soil particle size.

In Apollo video images, the ejecta were seen traveling generally in a sheet close to the surface at 1 to 3 degrees above the local plane. Small craters affected gas flow locally and ejected denser streams of dust into higher angles than this, and during the final moments of landing the plume ejected some particles from nearer the centerline into much higher angles, about 15 degrees. These behaviors were seen both in physics-based computer simulations and in the video imagery (Immer, Lane et al., 2011; Lane and Metzger, 2012).

For now, global-scale modeling of ejecta trajectories has included only particles leaving the lander locale in the 1-3 degree sheet. The paths of these particles travel all the way around the Moon, with a significant fraction traveling higher than the Lunar Gateway orbit, as shown in Figure 5-6. This ejecta sheet slowly evolves in space for days or weeks. On-going analyses are currently assessing the effects of the solar wind and solar radiation pressure in possibly dispersing this ejecta sheet and the effects of the Earth's gravity and the non-inertial reference frame of the Moon causing particles to be captured in the Earth-Moon system. It is an open question whether heavy traffic to and from the Moon might build up orbiting belts of dust that could be of sufficiently significant density to affect spacecraft, astronomy, or other activities. The preliminary analysis indicates that after just one landing of a 40 t lander, the Gateway will sustain 10,000 impact/m^2 each time it passes through the ejecta sheet based on calculations using the 2.5 power index, or about 2,350 impact/m^2 based on the hypothesized transition to unity power index at 2.5 m altitude of the lander.

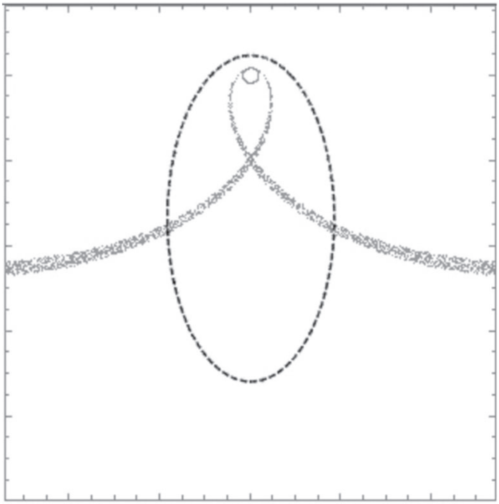

Figure 5-6. Cross-sectional view of lunar lander ejecta (blue dots) leaving the Moon (small circle) from the landing site (top of the circle). Ejecta cross the Lunar Gateway orbit (dashed ellipse).

Impact Damage

The best information about damage from the impact of these ejecta comes from the Surveyor 3 spacecraft, which was impacted by particles at much lower speeds than hypervelocity when the Apollo 12 LM landed nearby, and from experience with hypervelocity impacts on spacecraft in Low Earth Orbit. Surveyor 3 landed on the Moon and was visited by Apollo 12 two and a half years later, as shown in Figure 5-7. Pieces were cut off by the Apollo astronauts and brought back to Earth. They were re-analyzed recently using modern techniques by Immer, Metzger et al. (2011).

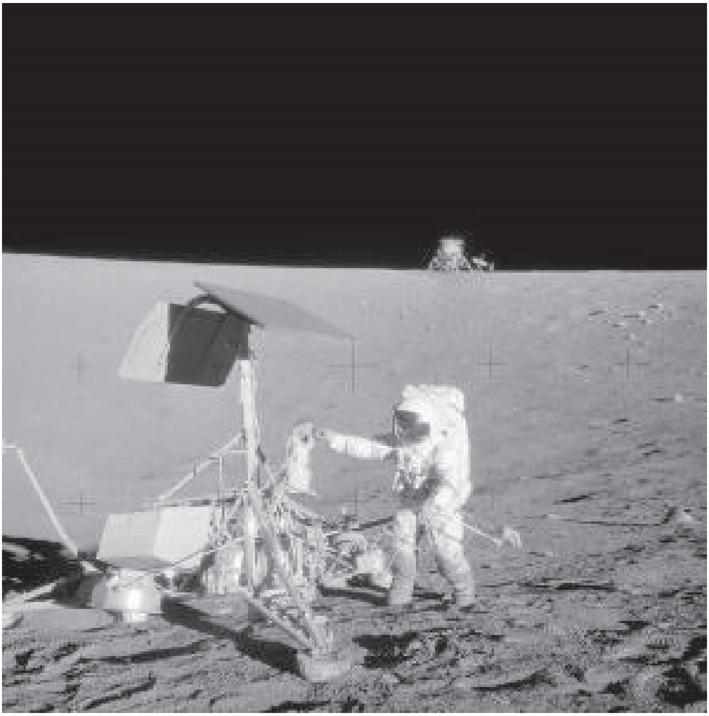

Figure 5-7. Apollo 12 commander Charles "Pete" Conrad Jr. visiting the Surveyor 3 spacecraft. The Apollo 12 LM is on the rim of the crater in the background (Photo credit: NASA).

The Surveyor's surface facing the Apollo LM had been sandblasted thoroughly, with more than 1 cm^2 of impacting dust per 1 cm^2 of target surface (probably at least 3 cm^2/cm^2 judging by the thoroughness of surface scouring). This indicates the number of dust particles impacting it was probably at least $10^{12}/m^2$. This is nine to twelve orders of magnitude more than will impact Gateway each time it passes through the ejecta sheet, but the particles impacting Surveyor were at much lower velocity and not in the hypervelocity regime as they will be at Gateway. On Surveyor, they crushed the paint pigment and mixed dust into the paint, as shown in Figure 5-8. The Surveyor was also impacted by sand-sized particles, about $10^6/m^2$. The sand penetrated the paint, causing cracks to radiate away, so the coupon had a "dried mud-cracking" appearance, as shown in Figure 5-9.

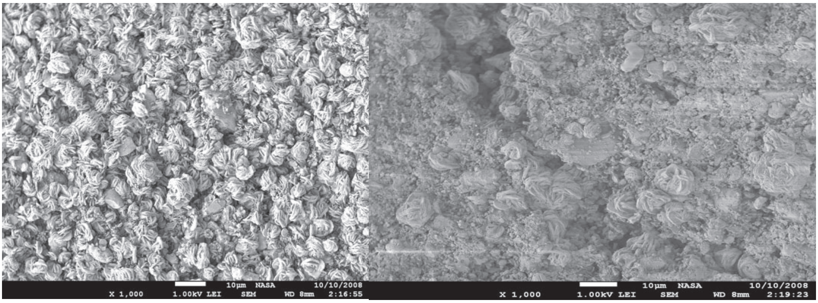

Figure 5-8. Scanning Electron Micrograph of Surveyor 3 paint. Left: before sandblasting by Apollo LM. Right: after sandblasting (Photo credit: NASA).

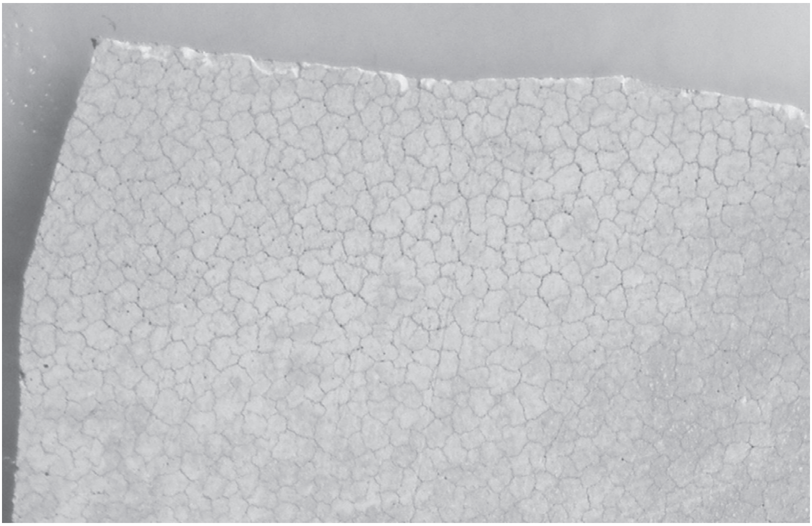

Figure 5-9. Mud-cracking pattern in the paint on a Surveyor 3 coupon.

Ejecta striking orbiting spacecraft will impact at the relative velocity, which includes orbital motion, so they will be in the hypervelocity regime. Experiments and analyses of micrometeoroid impacts in Low Earth Orbit show that the impactor and a portion of the target material both vaporize. Work is on-going to quantify the amount of damage that will occur on Gateway, on spacecraft orbiting the Moon at lower altitudes, and at surface assets on the Moon as a function of distance from the landing site.

Self-Damage During Landings

Not only can landers damage surrounding assets during a lunar landing, they can also damage themselves in certain conditions. If the lander is single-engine then there should be no plume recirculation, so all ejecta should travel away from the vehicle. Only the landing gear should be exposed to that spray. If there is more than one engine, and if they are still firing when the lander is low enough, then the plume will recirculate between engines, and this can bring ejecta back up to strike the bottom of the lander. In the case of the Surveyor 3 lander, there was no solid baseplate, so ejecta were able to travel up through the structure and impact equipment attached to the lander's frame. The lander had an off-nominal landing because the three Vernier engines were not shut off quickly enough so the spacecraft bounced twice before the final landing. After landing, the camera provided degraded imagery, and this was attributed to dust deposited on the camera during the off-nominal landing. After the camera was returned to Earth by the Apollo 12 astronauts, it was found to have two "shadow lines" drawn across its mirror, as shown in Figure 5-10. Nickle (1972) described these lines as either adhered dust or small pits caused by impacting dust, and that the shadow lines were an abrupt change in their density.

Nickle (1972) analyzed the pointing direction of the camera throughout the mission and possible locations on the surface from which dust must have been ejected to cause these two lines. He found that they were caused either during landing or toward the end of the mission as the Surveyor scoop was dropping soil on the surface for geotechnical testing. Because the drop test locations coincided with the possible sites for etching the near-exact shape of these curves, he concluded that this was the most likely explanation. Here, an argument is presented that the shadow lines were actually plume damage, instead. First, the lines are too sharp to have been caused by low-velocity ejecta. Second, analysis of the kinematics shows that low-velocity granular splashes would not be capable of reaching the camera from that distance. Third, there were far more than two drop tests so there should have been far more than two shadow lines, but the two

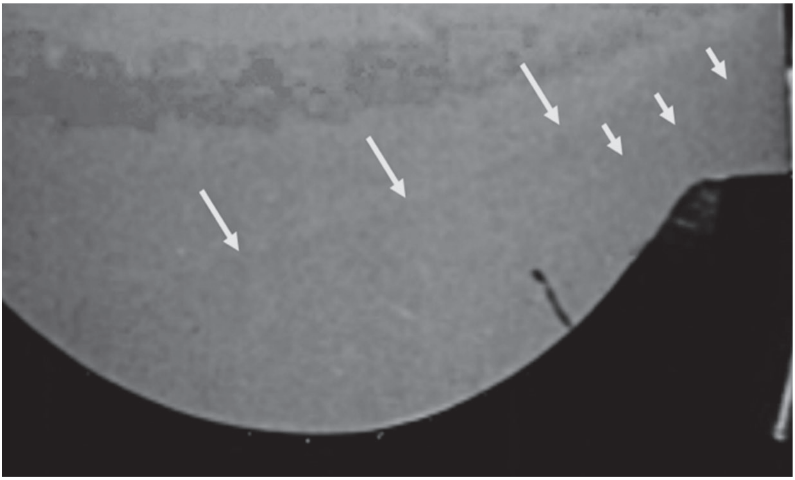

Figure 5-10. Shadow lines (annotated by yellow arrows) on the Surveyor 3 camera mirror. Detail enhanced from Nickle (1972).

bounces during landing with engines firing close to the ground correlates neatly to the two shadow lines if pluming is the explanation. Fourth, the quantity of splashed material on the mirror and additionally over 2 pi radians around the splash site would be an excessive quantity for a singular splash event, so this quantity must be from a continuous flow, not a splash. Fifth, the point sources analyzed by Nickle did not (apparently) provide perfect fits to the shadow lines. If they were from pluming, they would not be point sources but from line sources along the plume reflection planes. It is possible, although proof has not been attempted, that the exact shape may be fit by line sources. Plume reflection planes are not fixed in location but move according to the relative thrust of the engines. Because the Surveyor was bouncing on the sloped inner surface of a crater and was trying to maintain level flight, the engines would have been throttled differently from each other. Figure 5-11 shows the locations of the plume reflection planes for one hypothetical case of throttled engines.

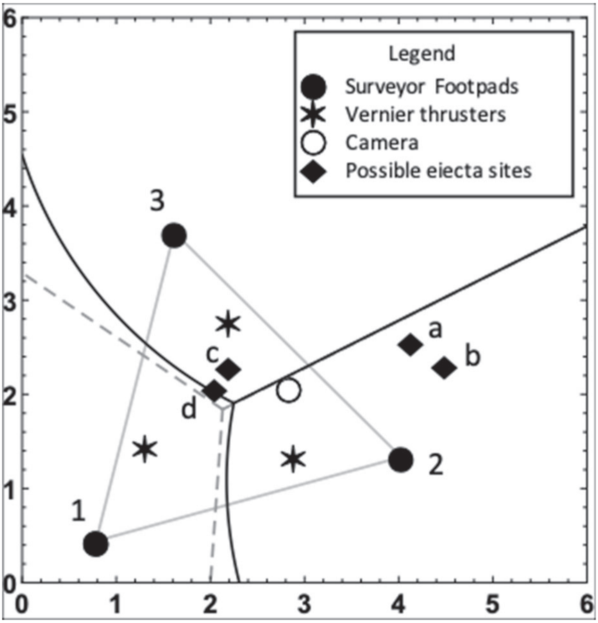

Figure 5-11. Location of the two pairs of possible ejecta sites per analysis of Nickle (1972), showing one pair (a, b) coinciding with robotic arm soil splash tests and another pair (c, d) coinciding closely with plume reflection planes under the lander. Dashed lines: ejecta planes with equal thrust. Solid lines: one possible case with unequal thrusts. The camera was pointed toward Footpad 3 during landing.

This re-analysis indicates the shadow lines were caused by direct sandblasting of the Surveyor's own engines during landing during the two bounces where the engines were still firing close to the surface, setting up strong fountain flow along the plume reflection planes. This also suggests the tan color all over the Surveyor noted by the Apollo 12 astronauts might have been caused by deposition from the fountain flow of that off-nominal landing. The mineral contents of adhered dust on the east and west sides of Surveyor were measured and found to be different (Lane et al., 2012). This may be due to the additional sandblasting on only one side of Surveyor by the Apollo 12 landing or to some other mechanism, such as passage of the terminator line (O'Brien and Hollick, 2015).

Shock Splash During Engine Shutdown

Another mystery is what caused the photometric disturbances to the lunar surface around each lunar landing site (Clegg et al., 2014; Clegg-Watkins et al., 2016). These disturbances are in a roughly 75 m radius from the LM. The high velocities of the ejecta do not predict abrupt discontinuities in surface effects at such short distance, or any distance, so the photometric disturbances cannot be attributed to the high-velocity sprays of ejecta. Another mystery is the observed dust clearing that takes place in the field of view out the LM windows for approximately 20 to 40 s after the engine shutdown (Metzger, Smith, and Lane, 2011; Lane et al., 2012). Earlier analysis did not find a plausible mechanism to keep the dust suspended for so long (Lane et al., 2012), so it was thought that electrical charge transfer by the rocket exhaust plume (Sabaroff, 1965; Aronowitz, 1968) may have been involved. A new model was written to include the physics of dust particles bouncing when they fall upon a much larger particle in the hope of explaining how dust stayed aloft for so long after engine cutoff (Metzger, 2020). Perhaps they stayed aloft by bouncing multiple times. The fraction of each particle size that should bounce when impacting the lunar surface is shown in Figure 5-12. In geomaterials at low velocity, it is generally estimated that 80% of the kinetic energy is retained with each bounce, so the bounced particles will retain about 90% of their original velocity. It was thought that the slow decay of their velocities might explain both the dust clearing time and the extent of photometric disturbance.

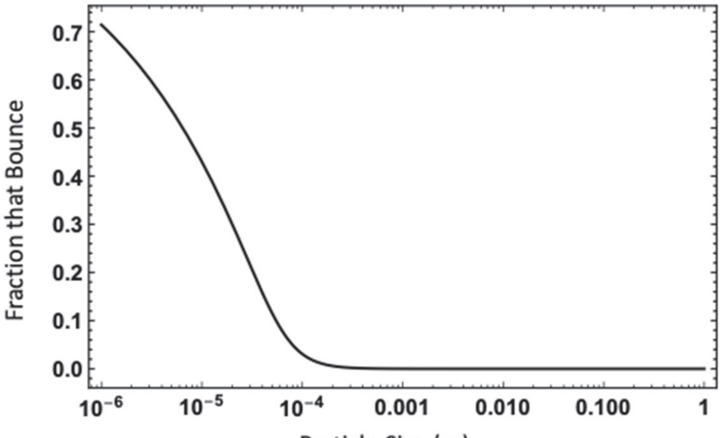

Figure 5-12. Fraction of each particle size that will bounce by randomly falling on a larger particle.

The model showed that even with bouncing, the dust should clear the view within just a fraction of a second because it will immediately disperse laterally, spreading over vast distances before it stops bouncing. The only way to reproduce the clearing time was to assume the dust started from much lower initial velocities than plume-induced ejection would cause. By assuming the particles start with only 3% of the velocities they would have obtained from standard plume ejection, the model matched the distance the particles would travel to the radius of the photometric disturbance. This tuning simultaneously predicted that the amount of dust in the field of view would decay away with the ~20 s time constant. In at least one of the Apollo landing videos, we can also see that the haziness in the field of view begins as soon as the engine is shut off (not before), and in at least one other landing video, we can see that the field of view clears closer to the LM first and then the region of clarity moves radially outward. All these clues suggest a common explanation: these are the results of a low-velocity splash event that occurs when the engine is shut off. It is known that shutting off a supersonic rocket engine causes shockwave collapse to slap the surface under the engine (Mehta et al., 2007), which indeed should cause a splash of soil. The model of particle ejection velocities derived from computer simulations (Lane and Metzger, 2012) evaluated at an engine height of 1.3 m is $v = (2{,}010)\ D^{-0.5}$ where ejection velocity v is in m/s and particle diameter D is in μm. In a splash, the distribution of velocities might have a different particle size-dependence than this, so we try $v = (3\% \cdot 2{,}010)\ D^{-b}$ where b is now an empirical parameter between 0 and 1. The resulting radius of the splash zone is shown in Figure 5-13. The zone still has the correct radius of 75 m, but its edge is more or less sharp depending on the value of b. The choice $b = 0.5$ that was derived from the high-velocity plume ejecta simulations produces a splash zone with boundaries that are more diffuse than the photometric disturbance seen at the landing sites (Clegg et al., 2014; Clegg-Watkins et al., 2016). A value of b that is smaller than 0.1 better matches the observations. This suggests the velocities in the splash do not vary as much with particle size as they do for the ejecta blown by viscous erosion, and that is physically plausible. The model also predicts the correct (approximate) 20 s exponential decay constant in optical density as seen out the LM window, but the curves have somewhat different shapes with choices of b. Better data measured during lunar landings is needed to make further progress. Overall, it seems likely the shock collapse of the engine shutting off causes a splash that drapes dust over about a 75 m radius around the landing site at low velocity. A similar but larger splash of dust likely occurs on engine ignition when a vehicle departs the lunar surface (perhaps mitigated by the descent stage acting as a launch pad, if it is left behind as was done in the Apollo program). This additional, shock splash-induced mode of dust transport should be considered when designing future lunar operations.

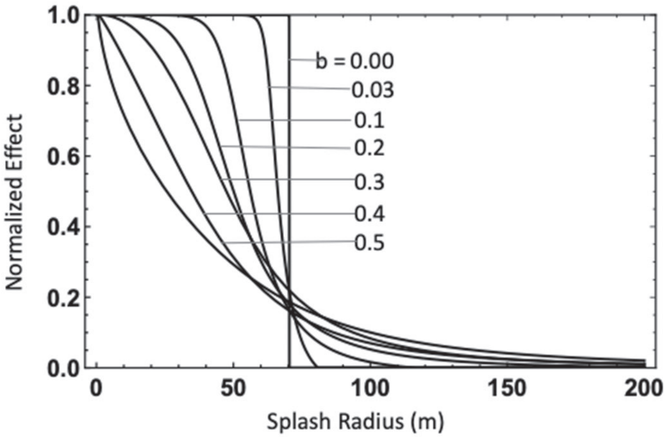

Figure 5-13. Normalized effect, showing how photometric disturbance might taper off with distance depending on initial velocity function.

Mitigating to Levels of Acceptable Damage

The damage that can be caused by the plume-induced transport of lunar dust can be severe or very mild, depending on how far away the affected assets are located and depending on the details of the physics that we still do not understand. Ideally, we would like to create mitigation strategies that will reduce the plume ejecta damage to an order of magnitude less than the damage caused by the natural in-fall of interplanetary dust to the lunar surface. That way, the cumulative damage of 10 to 100 spacecraft landings will only be about equal to or no more than ten times worse than what is caused by the natural environment over a similar amount of time. We do not yet know if this goal is achievable. Ultimately it will be a systems engineering decision on how much damage is acceptable. Spacecraft systems may be affected by the dust impacts in many ways: reduced radiator efficiency, reduced solar power generation, degradation of optical instruments, increased absorption of solar radiation on surfaces causing excess heating, etc. Systems engineering analysis will have to consider all these effects on various types of spacecraft to decide how much dust impingement is too much. This should lead to the selection of strategies to mitigate and manage the plume-induced transport.

Mitigation strategies include landing farther away from the sensitive assets, building landing pads, landing behind terrain features to block a large portion of the spray, mounting engines higher on a spacecraft instead of beneath the baseplate, moving assets behind protective barriers before a nearby landing occurs, hardening the assets to sustain less damage by the impacting dust, and simply planning to replace damaged assets more frequently. Examples of unacceptable outcomes include the failure of assets causing a threat to human life, excessive economic loss, or delays of critical mission timelines. International agreements to cooperatively manage these issues on the Moon will be needed because in the Moon's airless environment, the plume-induced ejection of dust is a planet-wide event and extends even beyond the Moon into cislunar space.

A Final Perspective

There are still major gaps in our understanding of the physics of dust transport caused by the interaction of spacecraft rocket exhaust with the lunar surface. To close these gaps, we need focused campaigns of laboratory experiments, computer modeling, and measurements taken from the lunar surface. One or two of these approaches by themselves will not be adequate; it will take all three. So far, solving the physics has been like peeling back the layers of an onion. With each layer of new understanding, we realize other unknowns in the physics that we did not previously recognize. We must begin operations on the Moon as soon as possible to obtain data to help solve the physics. Therefore, we must begin operations before the problem has been solved. This must be taken into account when planning the early missions. Ultimately, this problem should not stop us from scientific exploration and extending the economic activities of civilization to the Moon. The benefits of accessing the lunar surface are too great to let a technical challenge like this slow us down. We have already overcome amazingly great challenges to leave Earth's surface and reach the Moon, so this one can be overcome, too. Numerous plume mitigation concepts have been developed to various levels of technological maturity, and we believe they will prove sufficient when we have learned to apply them well.

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CHAPTER SIX

THE DUST ENVIRONMENT OF THE MOON

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Introduction

The Moon is continually bombarded by on the order of 10^6 kg/y of interplanetary dust particles (IDPs) that are micrometeoroids 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 characteristic range of 10 to 72 km/s. At Earth, the passage through the atmosphere ablates most of these particles, turning them into "shooting stars." However, they directly reach the surface of the Moon, generate secondary ejecta particles and leave a crater record on the surface from which the micrometeoroid size distribution has been deciphered (Grün et al., 1985). Most of the ejecta particles have initial speeds below the escape speed from the Moon (2.4 km/s) and following ballistic orbits return to the surface, blanketing the lunar crust with a highly pulverized and impact gardened regolith with >1 m thickness. Micron and sub-micron sized secondary particles that are ejected at speeds up to the escape speed form a highly variable, but permanently present, dust cloud around the Moon. Such tenuous clouds have been observed by the Galileo spacecraft around all lunar-sized Galilean satellites at Jupiter (Krüger et al., 2003). Our understanding of the lunar dust exosphere before NASA's Lunar Atmosphere and Dust Environment Explorer mission (Elphic et al., 2014) has been summarized elsewhere (Grün, Horányi, and Sternovsky, 2011), hence here we focus on the results of that mission greatly enhancing our understanding of the high-altitude (>1 km) lunar dust environment. These findings provide a unique opportunity to map the composition of the lunar surface from orbit (Postberg et al., 2011) and identify regions that are rich in volatiles, providing opportunities for future in situ resource utilization (ISRU).

Near the lunar surface (<1 km) the exposure to UV radiation and the solar wind plasma flow have been suggested to explain a number of unusual observations indicating processes related to dust charging and the subsequent electrostatic mobilization of lunar dust. Images taken by the television cameras on Surveyor 5, 6, and 7 showed a distinct glow just above the lunar horizon referred to as horizon glow (HG). This light was interpreted to be forward-scattered sunlight from a cloud of dust particles above the surface near the terminator. A photometer onboard the Lunokhod-2 rover also reported excess brightness, most likely due to HG. From the lunar orbit during sunrise the Apollo astronauts reported bright streamers high above the lunar surface, which were interpreted as dust phenomena. The Lunar Ejecta and Meteorites (LEAM) Experiment was deployed on the lunar surface by the Apollo 17 astronauts in order to characterize the lunar dust environment. Instead of the expected low impact rate from interplanetary and interstellar dust, LEAM registered hundreds of signals associated with the passage of the terminator, which swamped most signatures of primary impactors of interplanetary origin (Grün and Horányi, 2013). Currently no theoretical model fully explains the formation of a dust cloud just above the lunar surface, but the observations discussed above all indicate the role of charging, subsequent mobilization and transport of lunar fines (Grün, Horányi, and Sternovsky, 2011). Here we summarize the results of recent laboratory experiments indicating that the interaction of dust on the lunar surface with solar UV and plasma is more complex than previously thought, and can possibly offer an answer to many questions that have remained open since the Apollo era (Wang et al., 2016; Schwan et al., 2017).

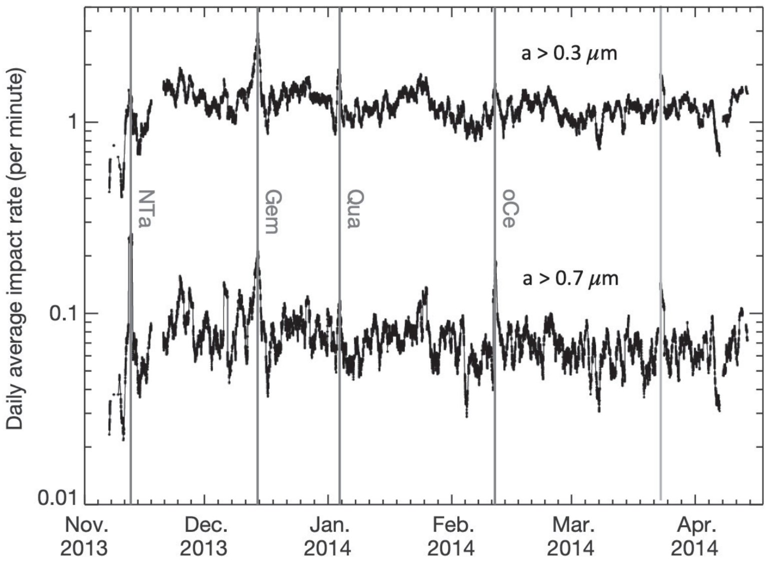


Figure 6-1. Impact rates observed by LDEX throughout the LADEE mission. The daily running average of impacts per minute of particles with radii >0.3 μm and *a* >0.7 μm recorded by LDEX. Four of the several annual meteoroid showers generated elevated impact rates lasting several days. The labeled annual meteor showers (blue vertical lines) are the Northern Taurids (NTa), the Geminids (Gem), the Quadrantids (Qua), and the Omicron Centaurids (oCe). Towards the end of March, LDEX data indicated a meteor shower that remained unidentified by ground-based observers.

The Lunar Dust Experiment

The Lunar Atmosphere and Dust Environment Explorer (LADEE) mission was launched in September 2013. It reached the Moon in about 30 days, continued with an instrument checkout period of about 40 days at an altitude of 220-260 km, followed by approximately 150 days of scientific observations at a typical altitude of 20-100 km. LADEE followed a near-equatorial retrograde orbit, with a characteristic orbital speed of 1.6 km/s. The Lunar Dust Experiment (LDEX) had detected a total of approximately 140,000 dust hits (Figure 6-1) during about 80 days of cumulative observation time by the end of the mission in April 2014.

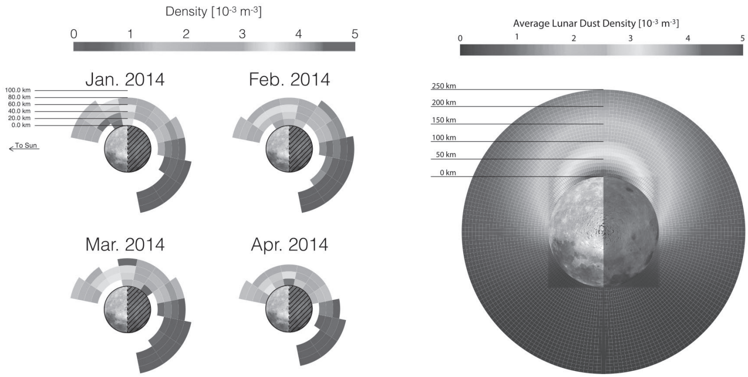


Figure 6-2. *Left*: The average dust ejecta cloud density observed by LDEX for each calendar month LADEE was operational in 2014. Each color ring corresponds to the density every 20 km. *Right*: The modeled annually averaged lunar dust density distribution for particles with a 0.3 μm. These plots are in a reference frame where the Sun is on the left (-x direction) and the apex motion of the Moon about the Sun is toward the top of the page (+y direction) (Szalay and Horányi, 2016).

LDEX was designed to explore the ejecta cloud generated by sporadic interplanetary dust impacts, including possible intermittent density enhancements during meteoroid showers, and to search for the putative regions with high densities of dust particles with radii <1 μm lofted above the terminators (Horányi et al., 2015). LDEX was an impact ionization dust detector, which measures both the positive and negative charges of the plasma cloud generated when a dust particle strikes its target. The amplitude and shape of the waveforms (signal versus time) recorded from each impact are used to estimate the mass of the dust particles. The instrument had a total sensitive area of 0.01 m^2, gradually decreasing to zero for particles arriving from outside its dust field-of-view of 68º off from the normal direction (Horányi, Sternovsky et al., 2014). The measured fluxes indicate that the Moon is engulfed in a permanently present but highly variable dust exosphere (Figure 6-2).

Compositional Mapping of the Lunar Surface

The dust particles comprising the lunar ejecta cloud are small samples from the surface and could be used to map the chemical composition of the Moon from orbit (Postberg et al., 2011) and to identify regions that could be most valuable for ISRU, a key element in establishing human habitats on the Moon. The expected availability of water ice, and other volatiles, in Permanently Shadowed Regions (PSRs) makes the lunar poles of prime interest. However, the relative strength of the various sources, sinks, and transport mechanisms of water into and out of PSRs remain largely unknown. At high latitudes, the lunar surface is exposed to continual bombardment from the northern and southern toroidal meteoroids as well as intermittent, intense meteoroid showers (Szalay et al., 2019). Impact bombardment produces transiently large quantities of lunar dust ejecta, which serves to re-blanket and cover the surrounding terrain, and also produces impact vapor from the volatile distribution at the surface.

Water is thought to be continually delivered to the Moon through geological timescales by water-bearing comets and asteroids and produced continuously in situ by the impacts of solar wind protons of oxygen-rich minerals exposed on the surface. IDPs are an unlikely source of water due to their long UV exposure in the inner solar system, but their high-speed impacts can mobilize secondary ejecta dust particles, atoms, and molecules, some with high enough speed to escape the Moon. Other surface processes that can lead to the mobilization, transport, and loss of water molecules and other volatiles include solar heating, photochemical processes, and solar wind sputtering. Since none of these are at work in PSRs, dust impacts remain the dominant process to dictate the evolution of volatiles in PSRs. The mobilized atoms and molecules can get trapped in PSRs, and the accumulation of water in these regions has been suggested since the early days of the space age (Watson, Murray, and Brown, 1961; Crotts, 2011). While there are several processes leading to the accumulation of volatiles in PSRs, the only recognized and possibly significant loss mechanism is due to IDP impacts. The competing effects of dust impacts are a) ejecta production leading to loss out of a PSR; b) gardening and overturning the regolith; and c) the possible accumulation of impact ejecta, leading to the burial of the volatiles. The competition between the volatile influx and these dust impact-induced processes determine the ability of a PSR to accumulate volatiles, as well as their accessibility for ISRU (Arnold, 1979). Hence, the measurement of the temporal and spatial variability of the dust influx and the characteristics of the impact-generated secondary dust particle plumes are critical to assess the availability of water in PSRs. A polar-orbiting spacecraft (Figure 6-3) could directly sample the lunar ejecta, providing the critical link between IDP bombardment and the evolution of water ice in PSRs (Postberg et al., 2011; Bernardoni, Szalay, and Horányi, 2019).

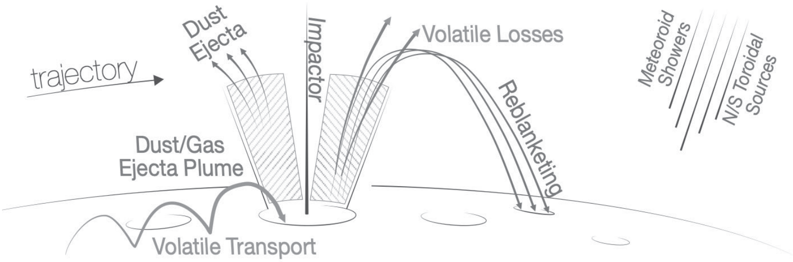


Figure 6-3. Depiction of IDP bombardment-related processes at the lunar polar regions. IDP impacts are important contributors to sustaining the dilute lunar exosphere, to mobilizing and transporting volatiles towards the lunar polar regions, and simultaneously to limiting their accumulation in PSRs through geological timescales.

Near-surface Dust Transport Observations

In addition to bombardment by interplanetary dust, the exposure of airless surfaces to ultraviolet radiation and solar wind plasma flow has been suggested to result in the lofting of small dust particles, owing to electrostatic charging and subsequent mobilization (Rennilson and Criswell, 1974; Berg, Wolf, and Rhee, 1976). Electrostatic dust mobilization on the lunar surface has remained a controversial topic since the Apollo era. In situ (Rennilson and Criswell, 1974; Berg, 1976; Berg, Wolf, and Rhee, 1976; Berg, 1978; Grün and Horányi, 2013) as well as remote sensing observations (McCoy, 1976; Glenar et al., 2011, 2014; Feldman et al., 2014) have potentially indicated the efficient lofting of charged dust particles near the lunar terminators.

High-altitude observations also indicated the existence of lofted dust at tens of km above the surface. The first high-altitude, remote sensing optical observations were made during the Apollo 15-17 missions, which took a series of calibrated images to analyze the zodiacal light and the solar corona. Some of these images indicated an excess brightness that has been interpreted as forward-scattered light from small grains with characteristic radii $a \sim 0.1\mu$m lofted over the terminator regions of the Moon by electrostatic effects. The density of such a dust population was first calculated to be on the order of 10^4 m^{-3} near the surface using Apollo data (McCoy, 1976; Glenar et al., 2011). Subsequent remote sensing surveys by Clementine (Glenar et al., 2014) and LRO/LAMP (Feldman et al., 2014) have significantly lowered the upper limit of the lofted dust density to ~1 m^{-3} near the surface. LDEX was designed to be able to identify the anticipated high density of small lofted particles (Horányi et al., 2014) but found no evidence of electrostatically lofted grains in the altitude range of 3-250 km above the lunar terminator (Szalay and Horányi, 2015a, 2015b). Contrary to the LDEX in situ and recent LRO/LAMP remote sensing observations (Feldman et al., 2014), the most recent analysis of the Ultraviolet/Visible Spectrometer (UVS) on board LADEE did observe a dense cloud of nanodust particles with radii in the range of 20-30 nm, driven from the surface by electrostatic charging and/or IDP impacts (Wooden et al., 2016). The accumulation, or ponding (Poppe et al., 2010) of nanodust in PSRs can offer an explanation for their low FUV surface albedo reported by LRO/LAMP (Gladstone et al., 2012) and is likely to alter their near-surface geotechnical properties, possibly reducing the production of secondary ejecta particles generated by IDP impacts and the accessibility of potential resources for ISRU.

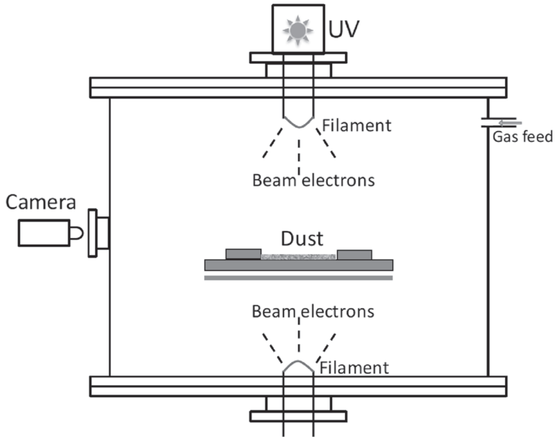


Figure 6-4. Schematic of an experimental setup to investigate charging under UV and plasma exposure of regolith surfaces (Wang et al., 2016).

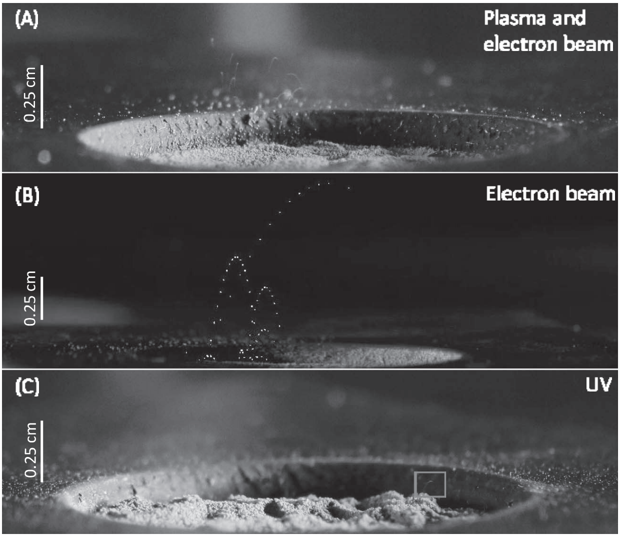


Figure 6-5. Images of dust transport and hopping trajectories in (a) plasma and electron beam, (b) electron beam, and (c) UV experiments. The blue square in (c) indicates a hopping trajectory captured under UV illumination. Deposits of dust particles on the surface outside the crater also indicate their hopping motions in all three images. Large aggregates up to 140 μm in diameter are lofted in addition to individual particles in the size range of 38-45 μm in diameter (Wang et al., 2016).

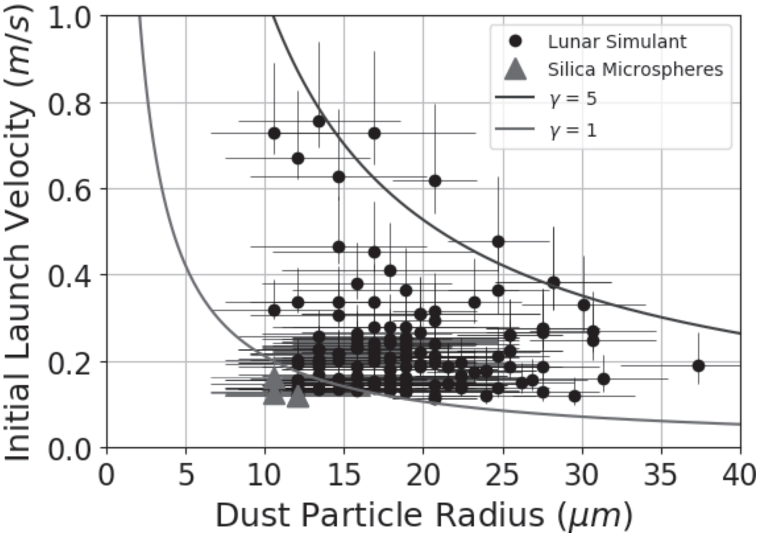
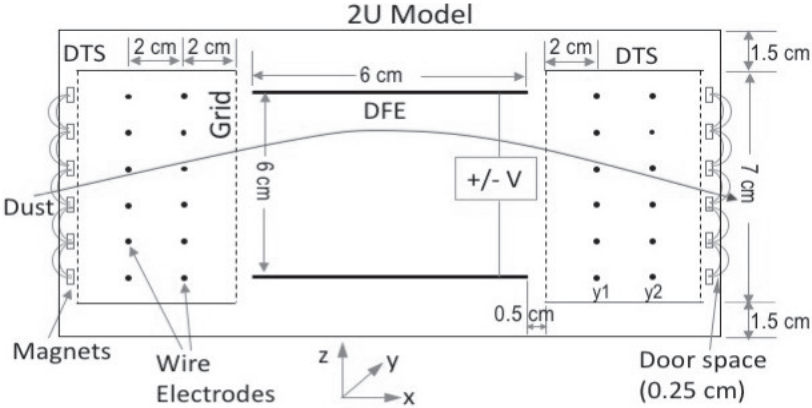


Figure 6-6. Initial launch velocity as a function of the radius of dust particles for both irregularly shaped Lunar Highland simulant (solid circles) and 10 *mu*m radius silica microspheres (solid triangles), respectively. The theoretical curves (solid lines) obtained from energy conservation involving the electrostatic energy before launch and the final kinetic energy of the particles are shown as γ = 1 and 5, respectively, a scaling factor to describe the effective cohesion between particles. The minimum velocity of about 0.1 m/s is limited by the cutoff in the data analysis of the available data (Carroll et al., 2020).



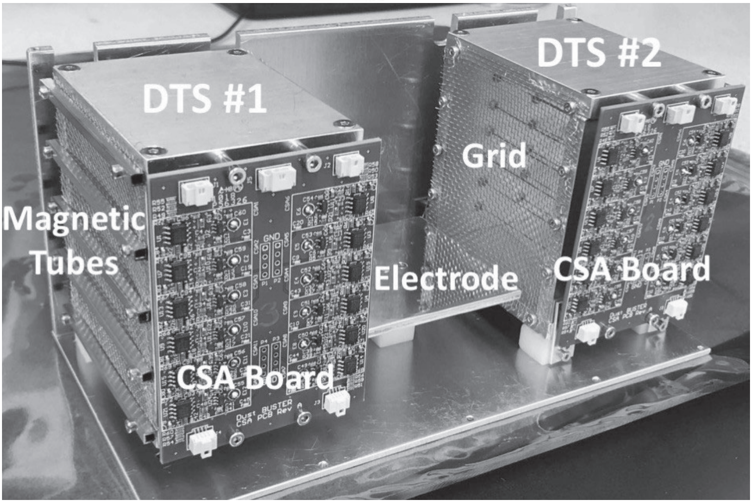


Figure 6-7. *Top:* Schematic of an EDA. *Bottom:* Photo of its fully integrated functional module. The magnitude of a particle's charge, Q, is measured by induced signals at the entry and exit of the EDA, and the charge-to-mass ratio, Q/m, is estimated by bending the dust trajectory by applied electric fields. Hence the measurement can provide the speed, mass, and charge of mobilized dust on the lunar surface (Wang et al., 2019).

Dust Transport Laboratory Experiments

Laboratory experiments cannot reproduce the conditions on the lunar surface, but have been invaluable to shed light on the microphysical processes that contribute, or even control, the properties of the regolith. Recent laboratory experiments (Figure 6-4) recorded micron-sized dust particles jumping to several centimeters high with an initial speed of ~0.5 m/s under ultraviolet illumination or exposure to plasmas (Figure 6-5), resulting in an equivalent height of ~0.1 m on the lunar surface, which is comparable to the height of the so-called lunar horizon glow (Wang et al., 2016). These experiments showed that the emission and re-absorption of photoelectrons and/or secondary electrons at the walls of micro-cavities formed between neighboring dust particles below the surface are responsible for generating unexpectedly large negative charges and intense particle-particle repulsive forces to mobilize and lift off dust particles (Wang et al., 2016, 2018; Schwan et al., 2017). The initial speed distribution of the particles (Figure 6-6) is on the order of 0.5 m/s, and it is expected to be inversely proportional to the size of the particles with a large scatter due to the somewhat stochastic effects of particle-particle cohesion (Carroll et al., 2020). These experiments indicate that electrostatic dust transport could be a surprisingly fast and efficient process to intermix lunar fines in the top layer of the lunar regolith, and indicate that these processes could indeed be responsible for delivering small particles to PSRs. Dust charging, mobilization, and transport observed in laboratory experiments could be verified by an Electrostatic Dust Analyzer (EDA) instrument (Figure 6-7) placed on the lunar surface (Duncan et al., 2011; Wang et al., 2019).

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CHAPTER SEVEN

THE LUNAR SURFACE: HUMAN MODIFICATION, CONTAMINATION, AND DUST

DONALD C. BARKER

Abstract

Humanity strives to reach out and explore new worlds, and the Moon is once again on the path. What will human activity impact on the Moon be, and are we responsible for mitigating such impacts? On Earth, the naming of a new epoch of geological time, the "Anthropocene," highlights just how pervasive humanity's influence is on the terrestrial biosphere and environment. On the Moon, an environment deprived of earthly weathering cycles, every human interaction will leave indelible marks and changes that will only grow with increased human activity over time. Implications regarding the fundamental reasons why we want or should go to the Moon are directly tied to our impacts on the lunar surface. Establishing correct early goals including infrastructure development and resource usage could mitigate environmental impacts. Examples from Apollo era landings are used to estimate human impacts regarding the movement of dust, and scarring from surface operations and trash accumulation. Much of this activity has the potential to directly confound planetary research by disrupting the pristine nature of lunar surfaces, which is in direct contradiction to commonly intended purposes for being there in the first place.

1. Introduction

Since the very beginning of human lunar exploration, researchers have been considering the impacts that human activities would have on the lunar surface and exospheric environments (Vondrak, 1974). The ability of human actions to induce and create surface and exospheric changes is proportional to their activity, duration, and location.

Human imprints on the environment are well known on Earth, and some of these last centuries or millennia, and now such effects outweigh many natural climatic and geological forces (Ellis and Ramankutty, 2008). But Earth has a dynamic, water-laden environment that washes away and erodes all but the most indelible of human creations and marks. Though those will eventually succumb through deep time. Survivability ultimately depends on surface materials, construction materials, and local environments and climate over time (see Figure 7-1).

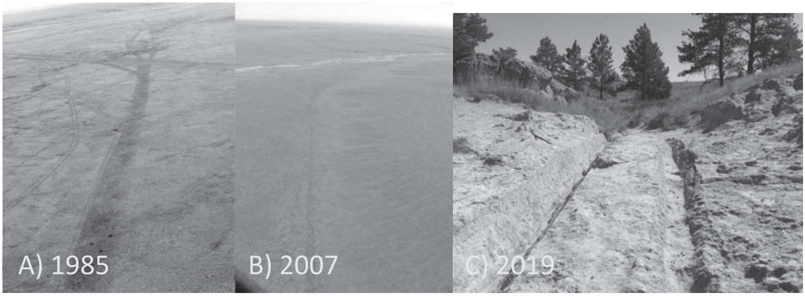

Figure 7-1. A & B) Scarred tundra, or "seismic trails," spanning 22 years after petroleum resource exploration (US Fish and Wildlife Service; Jorgenson, Ver Hof, and Jorgenson, 2010); C) Oregon trail ruts ca. 1850 in Wyoming (National Parks Service).

The question for humans now reaching out from our home world is how much do we want to alter and trash other destinations? What regulatory issues and organizations will there be to assure compliance and protection? How can clear definitions of goals,visions and designs play directly into the development of infrastructure, which will engender a philosophy of custodial management of the environment while enabling sustainable growth? To date, planetary protection efforts (Stern, 2019) have only really been concerned with the forward and backward spread of biological materials that could confound our search for life off Earth (e.g. on Mars), and offer little or nothing toward developing or assessing the mechanical and material interactions or environmental contamination and trash buildup.

The Moon does not have consistent or macroscale weathering processes as does the Earth that routinely modify and reform surface geological environments and geography (i.e. a water-driven process). An important and historically dominant form of lunar resurfacing comes from meteoroid impact and gardening processes (Szalay et al., 2019), which have been occurring since the formation of the Moon some 4.5 billion years ago. A process which has changed much over time, but left much of the surface blanketed in a fine powder laden regolith (Grün, Horanyi, and Sternovsky, 2011). Currently, programs such as Near-Earth object Lunar Impacts and Optical TrAnsients (NELIOTA) routinely monitor the surface for impacts and show that this process is alive and well, allowing for the understanding of meteoroid masses (ranging from g to kg), sizes (1-20 cm), energies, and impact frequency distributions (Liakos et al., 2019).

Plans for humans returning to the surface of the Moon to advance beyond humanity's first steps of Apollo, now nearly 50 years gone by, are being molded by various goals, hazards, tools, and methods. Ultimately human landing site selection would ideally be based on the collocation of easily extractable resources, which itself leads to other types and scales of human environmental modification. The tradeoff would be in our ability to sustainably support in situ human development and growth (Barker, 2020). Understanding our impacts on the lunar surface environment is both driven and guided by our stated purposes for being there, which includes a desire to understand the origin and evolution of our planet's nearest neighbor. It is that 'stated purpose' that needs to be thurohgly vetted going forward.

2. Signs That Humans Were There

Humans have long dreamt about exploring the surface of the Moon, and in the last half of the 20th century took those same first steps on that frontier. Those steps remain, nearly indelibly imprinted, on the lunar surface. The before and after effects of human activity remain clearly seen at the last location visited on the Moon (see Figure 7-2), the Taurus-Littrow Valley. The Apollo 17 surface crew, Gene Cernan and Harrison Schmitt, spent roughly 22 hours outside on the lunar surface and drove the lunar rover nearly 36 km. Operational concerns included terrain characterization, consumables usage, and the "walk-back distance" required to maintain crew safety. Burkhalter and Sharpe (1995) provide a good overview of the lunar rover vehicles (LRVs) and their history. All of these activities remain clearly etched onto the Apollo 17 landing site landscape (Figure 7-3). As can be clearly seen, at nearly all sun angles, in the Lunar Reconnaissance Orbiter Camera (LROC) imagery (Robinson et al., 2010), the impacts of anthropogenic activities have lasted nearly 50 years undisturbed and unchanged.

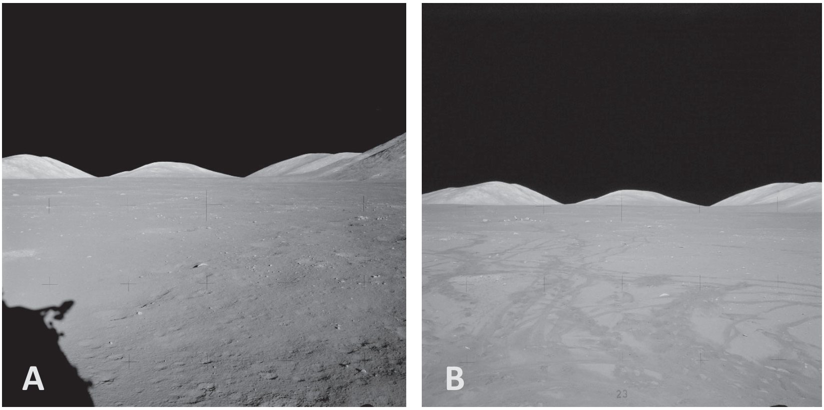

Figure 7-2. Apollo 17 landing site in the Taurus-Littrow Valley: A) just after landing (AS17-147-22470), B) just prior to leaving, after only 75 hours on the surface (AS17-145-22200).

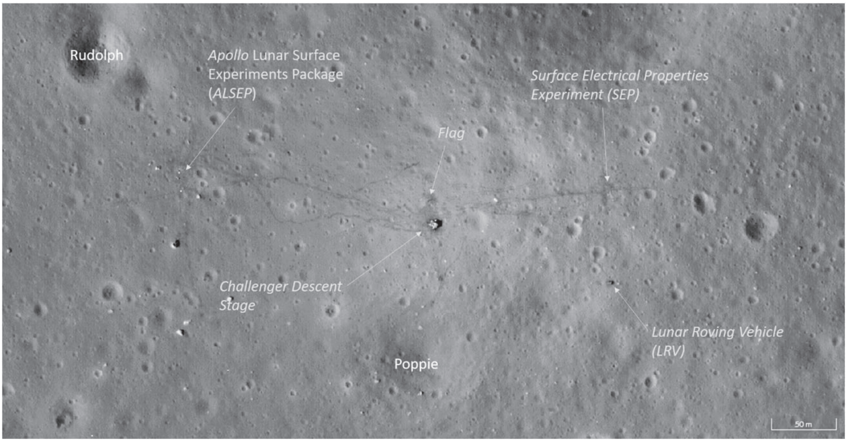

Figure 7-3. Lunar Reconnaissance Orbiter Camera (LROC) image of the Apollo 17 region showing traverses and hardware clearly visible after 47 years (M113758461R; NASA/GSFC/ASU).

Other less noticed perturbations of the Moon's environment are marked by sporadic impact sites across the surface where spacecraft and hardware have been sent to take measurements or spent propulsion stages to rest. Examples of the latter are expanded upon in Section 2.4 below, including spent Apollo transfer stages.

2.1 Dust Movement and Interactions

Dust movement in the lunar environment can be divided based on two sources, one that is natural to the physical processes in the lunar environment, and one that is induced by human activity (anthropogenic). Figure 7-4 is a schematic showing the relative interactions of each source, including potential areas of disturbance or contamination with regards to hardware or pristine geological surfaces. Many variables, some measured, interact to determine actual effects including geological setting, depth and age of regolith/soils, lunar day-night cycles, charging, and more (O'Brien, 2011, 2018). Each has a different effect, extent, and impact on lunar surfaces and human goals. Dust depths, distributions, and mineralogy vary depending on the location on the surface, and knowledge of this will help in site selection, creating infrastructures, designing dust tolerant hardware, and mitigating its movement and contamination during future human surface activities.

Micrometeoroid impacts and alteration of surface regolith is ongoing and has been modeled and observed on Apollo samples (Fechtig et al., 1975; Cremonese et al., 2013), and is estimated to regionally redistribute surface dust, depositing approximately 10 μg/cm^2/year (Katzan and Edwards, 1991). Another, extremely slow, natural process in which lunar surfaces are modified is the redistribution of dust through electrostatic levitation and lofting (Colwell et al., 2009), but estimates on yearly cover range from 100 to 3000 μg/cm^2/year (Rennilson and Criswell, 1974). Natural dust deposition at the Chang'E-3 site was determined to be approximately 21 μg/cm^2/year (Li et al., 2019), a value comparable to the measurements taken at the various Apollo sites.

Dust directly impacted all Apollo surface operations, including human activities both inside and outside the lunar module. Lunar rover dust excavation and lofting over several meters from wheel rotation has been examined and verified (Hsu and Horanyi, 2012). Both natural and anthropogenic dust movement processes, given current rates (e.g. no large impact events), are likely too slow to cover and therefore hide almost any human-induced effects or traces of surface operations. Repeated surface traffic in the same area will create a mélange of overlapping and indelible local material movement and contamination.

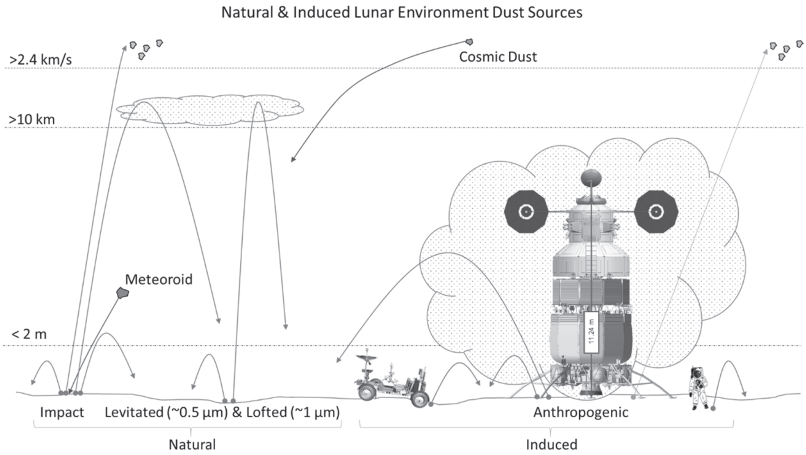

Figure 7-4. Schematic showing all potential sources of dust in the lunar environment.

2.2 Permanent Etching of the Surface

As already shown in Figures 7-2 and 7-3 above, human activities have marked the lunar surface for a very long time. In total, six human landings on the Moon have created over 95 km of surface traffic and subsequent dust mobilization (Orloff and Harland, 2006). Figure 7-5 demonstrates both rover and foot traffic, and dust mobilization from these activities. As seen in the Apollo slip and trip footage, dust was clearly moved up to a few meters by astronaut boot kicks, redistributing and splattering dusty materials (O'Brien, 2011, 2018). Walking and rover activity during the Apollo program induced surface dust movement that impacted an estimated 799 m^2 of surface area. An estimate conservatively arrived at by assuming a walking path disturbs a swath one meter wide, and an LRV disturbs a swath about three meters wide.

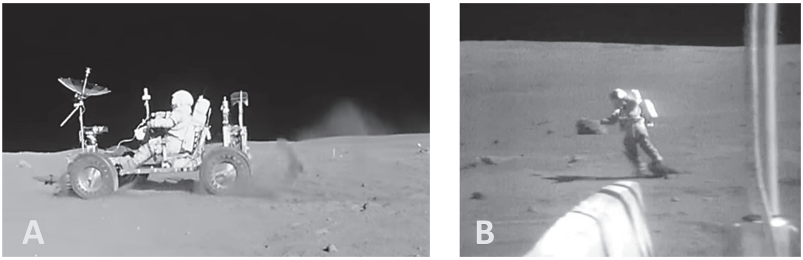

Figure 7-5. Video frames showing dust being moved during human surface activities: A) the Apollo 16 “Grand Prix” LRV rooster tail, B) an astronaut’s lunar gravity dusty gait.

How will future programs, missions, operations, and activities address this issue? When considering all forward going goals and activities, especially regarding the development of a single, evolving, and growing landing site, championed herein, the impacts to ongoing and future pristine scientific research will be significant, as well as resulting in the permanent scarring of the lunar surface. These will become prime areas of focus for human surface operations in the development of mitigating infrastructures.

Assessing the potential future impact of human surface operations can be seen by overlaying all Apollo landing traverses over a presumed lunar South Pole landing area (Figure 7-6) adjacent to Shackleton crater. The area of disturbance grows with each excursion and landing, especially when thruster plume effects are added to human surface operations. Ultimately, the effect of unrestrained activity or programs devoid of designed infrastructure that will help control dust movement will push the need to move surface excursions farther and farther afield in order to access pristine lunar surfaces for geological analysis. This will also push the need to enhance both rover and surface operations and technologies to heightened limits to account for the greater risks involved in such extended treks.

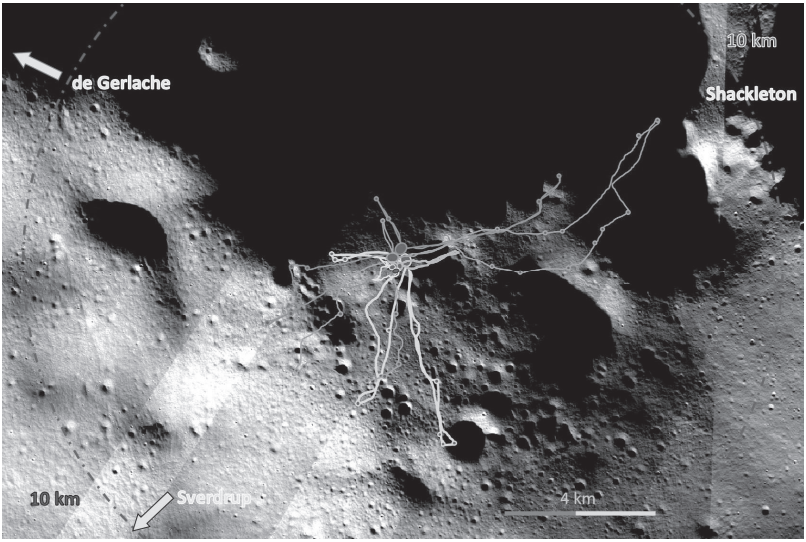

Figure 7-6. One proposed lunar South Pole landing site showing the stacking of all Apollo traverses (both foot and lunar rover). Dashed arcs demark a portion of the 10 km radius circle encompassing a region of potentially heightened thruster plume dusting (see section 2.3 for more details).

2.3 Contamination and Confounding of Pristine Science

The process of traveling to and from the surface induces dust movement that alters the lunar environment. Rocket engine landing plumes scour the surface, moving various amounts of dust and debris, depending on size, anywhere from a maximum of a few centimeters on the surface and all the way into lunar orbit (Metzger et al., 2008) for the smallest particles. Dust movement during the first lunar day of the Chang'E-3 mission was measured at 0.83 mg/cm^2 and was attributed to dust-induced movement during the landing process (Zhang et al., 2020).

It has been speculated that by comparing site-specific dust plume excavation and movement processes (e.g. Chang'E-3 to different Apollo sites) that such measurements may provide a basis for understanding geological properties such as age and possibly dust content distributions. Though some scientific information could be gleaned from such forceful mechanical surface impingement, it is more likely that plume ejecta will be a source of contamination to the surrounding terrain. Material ejected would blast or deposit on all near surfaces and regolith (top cm) through a radially thinning annulus (i.e. bull's eye) of displaced lithic and glass dust grains.

A region, potentially 10 km in radius, could be dusted by various amounts of ~100 µm or less debris and dust for low angle ejecta traveling at <400 m/s (see Figure 7-7) for moderately sized landing thrusters. The amount of particulate matter in that size range will be site-specific, and likely proportionally higher anywhere in the lunar highlands.

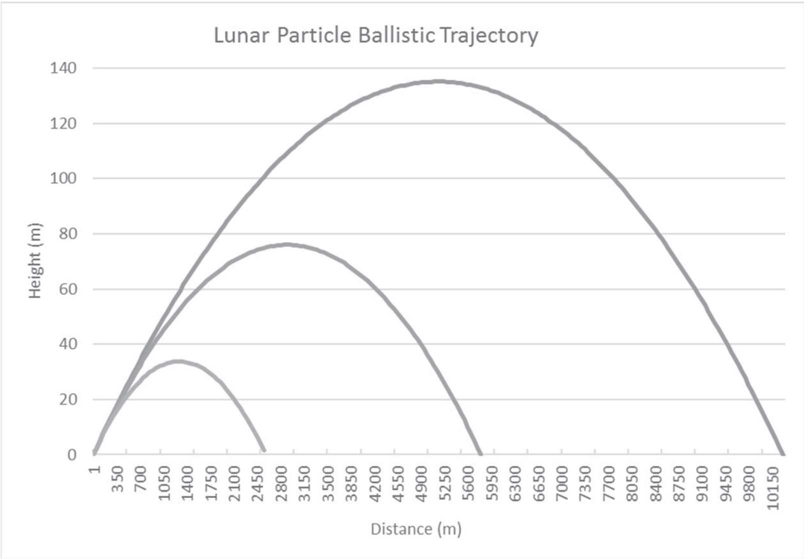

Figure 7-7. Simple ballistic trajectories calculated to demonstrate three ejection velocities: 400, 300, and 200 m/s at a 3° angle from a lunar landing site.

Given the current primary goals for why we are going to the Moon, the ultimate impact on the lunar surface would require transverses of ever greater distances from the landing area to avoid non-natural (impacts are natural) cross-contamination of surface materials. As demonstrated in the previous section (see Figure 7-6), there is also a cost to be incurred by repeated travels to the same location, and therefore, focusing efforts on developing an infrastructure based on a permanent and growing human settlement becomes paramount. Establishing this goal as the primary purpose for going to the Moon from the very beginning, rather than scientific exploration, will allow many of these problems to be controlled and mitigated early in favor of long-term growth and sustainability.

Controlling or mitigating the impacts of transportation thruster impacts during landing and launch from the lunar surface are topics that have gained momentum over the past several years. This conundrum resides in the "chicken vs. the egg" dilemma across several areas including, initial architecture and vehicle design, rate of accessing the lunar surface, intent for usage of the near landing site region, and sustained financial support for program goals. Many ideas are in the pipeline, but few cross much above a test readiness level (TRL) of 2 or 3, including regolith sintering, regolith brick construction and laying, lunar concretes, and alumina-injected thruster plumes (Lin, Skaar, and O'Gallagher, 1997; Davis, Montes, and Eklund, 2017; Meurisse et al., 2018; Fateri et al., 2019). Concepts and studies will only grow and evolve as fiscal support emerges in the future. Landing pads are probably the most important technical and civil engineering structure needed for any growth of human activity on the Moon. Yet, due to the unknowns and complexities regarding the ultra-high vacuum environment and limits to terrestrial testing, as well as other surface environmental conditions, costs associated with development, testing and standardization, and uncertainties in program commitments over the short and long term, the likelihood decreases across the board of substantial mitigation methods being user-ready in a timly manner.

2.4 Environmental Impacts and Trash

Without plans in place to control the amount or kind of environmental impacts, human activity on the Moon is increasingly changing it, as it has on Earth. Figure 7-8 shows a portion of the lunar near side and most of the major landing and impact sites for spacecraft from Earth. The best characterized sites, of course, are the Apollo landing sites, but most of the associated impact sites for that program and others have been well imaged over the past decade by the LROC spacecraft (Wagner et al., 2016). Lunar landing and impact sites now include, among others, the lunar far side (Chang'E 4), the north polar region (Grail-A), and the south polar region (Chandrayaan-2 Vikram lander). The Lunar Atmosphere and Dust Environment Explorer (LADEE) impacted on the eastern rim of Sundman V crater, and the Lunar Crater Observation and Sensing Satellite (LCROSS) mission was the first to have a concurrent orbital analysis of artificial ejecta products (including water) and related effects (Gladstone et al., 2010; Colaprete et al., 2010). The environmental impacts and contamination due to all these events have been little quantified; additionally, there could be a growing deterioration of the pristine near-surface regolith for geological assessments across ever-widening areas of the lunar surface. Each artificial impact distributes materials over varying ranges depending on impact energies, similar to the ballistic comments in the previous section. Questions regarding control and access may be forthcoming.

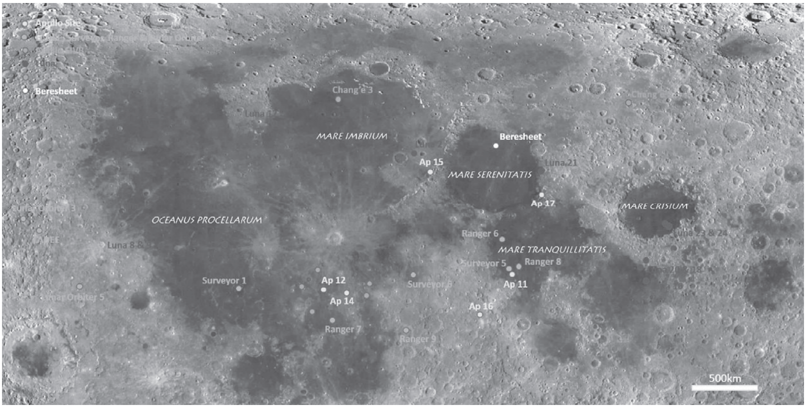

Figure 7-8. Examples of lunar near side spacecraft landing and impact sites.

Saturn S-IVB stages (Apollo 13 through Apollo 17; see four orange dots in Figure 7-8 above) were controlled crashes into the Moon in support of geological seismic measurements and investigations. The final S-IVB stage from Apollo 17 was directed to impact the Moon on December 10, 1972 (see Figure 7-9). Each stage had an empty weight of roughly 13,500 kg and was constructed of common rocketry materials of the day. These materials ranged from aluminum (*7075*), steel (*4135*), titanium dioxide-filled paint, and phenolic plastic laminates to nitrile (*Buna-N)* and silicon rubber, polychlorotrifluoroethylene (*Kel-F)*, Teflon FEP and TFE, polyurethane foam, and cyclotrimethylenetrinitramine (*RDX*) (MSFC-MAN-503, 1968). The list is expansive, and as the surviving impact remnants or their degradation are relatively unknown, we do not have a good understanding of the distribution and type of contamination layering the local impact sites.

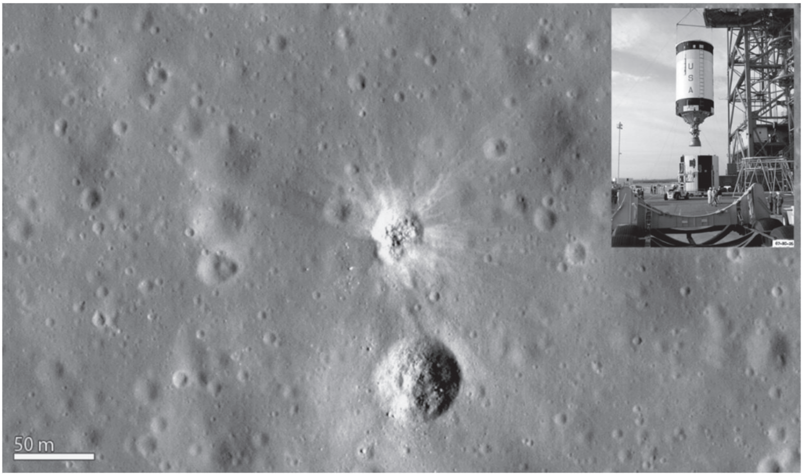

Figure 7-9. Apollo 17 SIV-B impact site. Inset: stage being assembled (NASA/GSFC/ASU).

All told, roughly 180,000 kg of manmade materials are on the lunar surface, including the aforementioned rocket stages (see Figure 7-9). Another interesting list of lunar trash comes from the Apollo sites themselves. The most complete list of lunar surface trash items currently includes hundreds of individual items, including experiment packages (Figure 7-10), lunar descent stages, flags, golf balls and memorabilia, and all the actual waste and trash materials discarded by the Apollo crews (NASA History Program Office, 2012).

Many of these sites will remain intact for a very long time, while some items will be degraded by radiation and even potentially buried by exospheric dust deposition or thruster plume dusting, as discussed previously, though actual deposition rates at any given site will vary. This invokes an interesting problem for those interested in saving and establishing historical sites (NASA, 2011; Spennemann and Murphy, 2020).

Ideally, answers will need to be found if humans are to continue to visit the lunar surface, especially for the long term. As one approaches the lunar module descent stage of each Apollo site, the incidence of trash items increases. The amount of individual trash items also generally increased for each Apollo landing, and this trend is expected to increase further with future Artemis landings (Table 7-1).

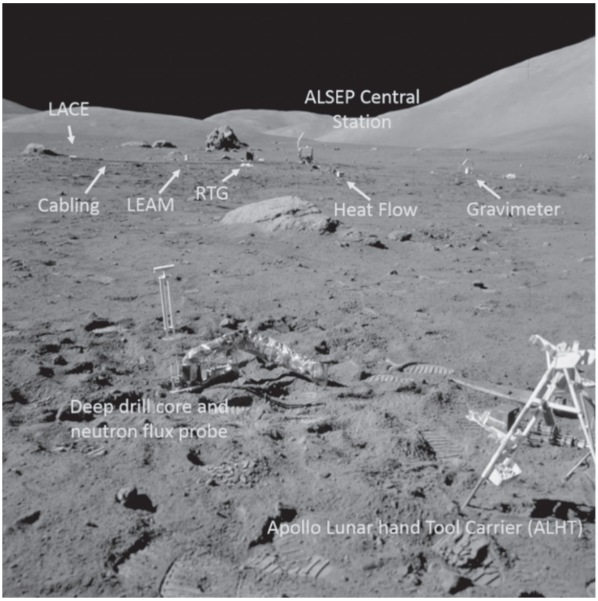

Figure 7-10. Annotated view showing Apollo 17 instruments left on the lunar surface (AS17-134-20505).

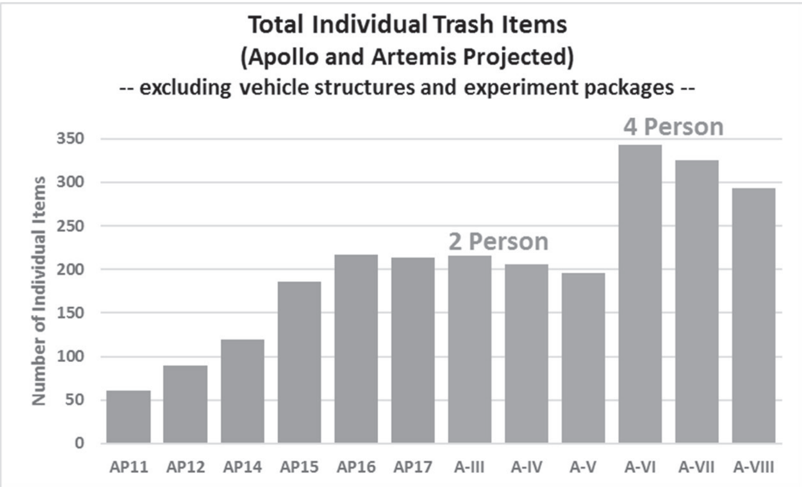

Table 7-1. Derived trash history and near-term projections for the future missions.

Currently there are no formal plans, under Artemis, to implement direct preservation of the lunar surface for long-term operations or habitation. On the contrary, current operational plans include discarding many trash and hardware items, e.g. lunar suit components and tools, prior to liftoff from the surface. Artemis lunar return architectures include a lunar surface lander and transitional interactions at the lunar Gateway station (Figure 7-11), with a continuing bombardment and cluttering of the surface with spent transfer and descent stages. Ultimately, any presumed landing areas, especially sites that are reused, will rapidly fill with a multitude of dust collecting debris, from derelict landing stages to discarded biological trash.

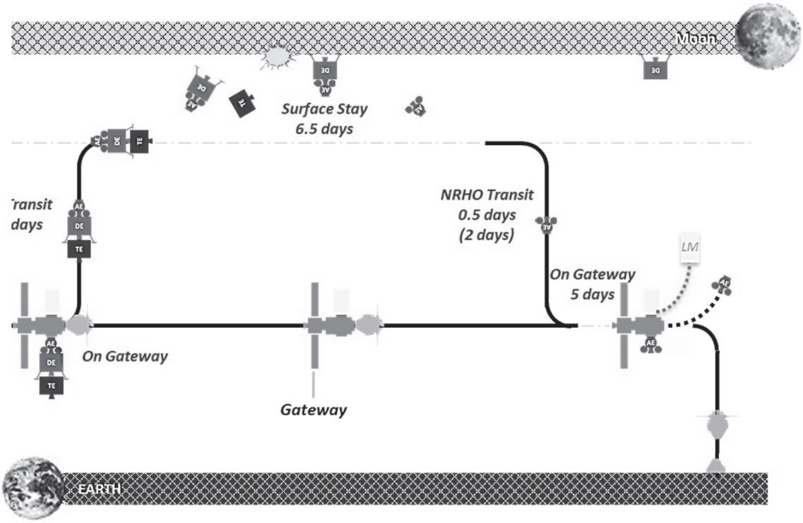

Figure 7-11. Artemis and Gateway single flight profile with stage discarding (NASA modified).

There is a "chicken vs. the egg" quandary here with regards to funding, architectural design, timing, program inertia, and precedent mindsets. Allowing the easy discarding of trash from the beginning dissuades the development of robust, easily repairable, reusable, and storable hardware. This directly affects long-term sustainability, and early decisions between "exploration vs. settlement" need to be answered in the overarching purpose of going to the Moon. There is a distinct difference between overall architectures directed at going to individual isolated sites versus going to a single site deemed a planned and growing settlement. The first inherently increases the amount of surface trash, whereas the second, from the beginning, should have the mindset of reusability and maintainability. A prime example is the design of airlocks, access ways to the lunar surface. Designs that incorporate robust "mud-room" type facilities can support their continuous long-term use, storage, dust-mitigation, maintenance, and ultimately easy access to perform lunar surface excursions and operations. Addressing the multifaceted question of why directly affects the how, and ultimately the design and efficiency of the architecture over time.

3. Conclusion

The repercussions of not planning and preparing the surface from the very beginning will cycle far into the future regarding use, preservation, and scientific results from the lunar surface. If humans are to actually develop any viable and growing lunar surface endeavor, then dust mitigation and trash (directly, plus the indirect emphasis on designing for reuse and in situ maintenance) may be the two most important problems to address from the very beginning. The likely choice for efficiency in future endeavors directly depends on the purpose for being there, be it scientific return and/or settlement. Therefore, the question as to what do we do remains alive and unanswered. A set of suggested forward looking paths and steps are outlined below.

The top five observations and recommendations are:

1) Precisely define why we are going there in the format of settlement and permanence,
2) Implement standardization in designs for all hardware for reuse and refurbishment in situ,
3) Landing pads and controlled roadways and surface traffic being the first permanent structures,
4) Keep increasing our understanding of mining impacts, needs, and abilities,
5) Increase our understanding of exospheric dust interactions.

The following ideal steps are proposed for establishing a sustainable and growing settlement in a timely manner and should look something like this:

1) Unwavering financial subsidizing, policy, and organizational commitments to the single purpose of developing a sustainable and growing lunar settlement,
2) Large-scale, parallel robotic prospecting missions to canvas sights of potential in situ resources for building settlement infrastructure,

3) Settlement landing site to be chosen from the best confluence and collocation of the greatest amount of useful and extractible resources (Barker 2020),
4) Begin landing pad construction followed by settlement construction; from the very first human landing, every flight must keep preparing some portion of the infrastructure rolling forward,
5) Develop a growing and sustainable foothold, protect the environment, and conduct scientific and engineering research.

To ensure a sustained human presence on the Moon, the previously mentioned infrastructure emplacement and trash efforts must be elevated to the level of a program goal and stand on their own. If humans are ever to travel in mass, e.g. true settlement and tourism, to the lunar surface, then our ability to construct structures out of local resources will be of utmost importance in growing and operating efficiently, and protecting the Moon. We sit at the crossroads of another path in human evolution that affords the opportunity to learn from history and begin correctly, or play catchup as a result of hasty and reckless decisions and actions as has happened so much in human history. Ultimately, these goals and lessons should feed forward, if done correctly, to all future human space exploration, travel, and settlement endeavors.

Acknowledgments

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SECTION TWO:

LUNAR DUST AND HUMAN HEALTH

CHAPTER EIGHT

HISTORY AND FUTURE PERSPECTIVES FOR THE EVALUATION OF THE TOXICITY OF CELESTIAL DUST

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The Apollo Experience

In 1969 the crew of Apollo 11 successfully landed on the Moon and then returned safely to Earth. The success of Apollo 11 was followed by five more crewed landings (Apollo 12, 14, 15, 16, and 17). Although the missions had slightly different individual objectives, they shared some common objectives, including exploring features on the Moon, examining the lunar environment, and assessing the feasibility of establishing a lunar outpost (Naser, 2019).

All of these Apollo missions were adversely affected by the lunar dust, which established itself early on as a nuisance because of its physico-chemical properties and the associated difficulties in its control and cleanup. With the lack of an atmosphere and in reduced gravity conditions (1/6 g), lunar dust is easily lifted from the lunar surface. There are two general classes of dust transport mechanisms: natural (e.g. secondary ejecta from meteor and micrometeoroid collisions with the surface, and electrostatic levitation of dust) and anthropogenic (e.g. astronaut ambulation, rover wheels lifting dust, landing and take-off of spacecraft (Katzan et al., 1991), astronaut falls (Gaier, 2005), or intentional kneeling to better observe the surface). None of the natural transport mechanisms are expected to transport significant amounts of dust and only the anthropogenic mechanisms seem to have a significant impact on astronaut exposure.

All spaceflight evidence pertaining to the effect of lunar dust on astronauts is anecdotal (Scully et al., 2015) and mission documents have been studied to catalog the possible adverse effects of lunar dust. Some of the adverse effects included visual obscuration, false instrument readings, dust coating and contamination, loss of traction of the rover during an extravehicular activity (EVA), clogging of mechanisms, abrasion of suits, especially gloves, thermal control problems, and seal failures. More specifically, regarding health effects, which is the topic of the present work, astronauts reported that when they returned to the lunar module after EVAs and removed their spacesuits, dust exposure occurred causing eye, throat, and lung irritation. Dust adhered "to everything, no matter what kind of material" with "restrictive, friction-like action" (Cernan et al., 1973). After leaving the lunar surface, any dust in the vehicles began to float in microgravity. Dust found its way into even the smallest openings, and when the Apollo 12 crew stripped off their clothes on the way back to Earth, they found that they were covered with dust. Dust was also transferred from the Lunar Module to the Command Module and caused upper respiratory irritation during the entire trip back to Earth (Gaier, 2005). There was continual inhalation exposure to airborne dust, as well as skin exposure and eye contact from surface contamination on the return journey to Earth (Cain, 2010a). Moreover, the Apollo crews reported that the dust gave off a distinctive, pungent odor, suggesting the presence of reactive volatiles or reactive surfaces on dust particles. Lunar dust induced symptoms of respiratory irritation in some crew members (Cernan et al., 1973) who used expectorants to facilitate clearance of the particles from the upper airways. These effects may be attributed to acute, albeit mild, reactions to dust particles deposited in and cleared from the upper airways (Barratt, 2019). The health effects experienced were heterogeneous and differed in severity and duration. In all cases, the observed symptoms were transient, and no lasting respiratory effects were observed in returning Apollo crew members.

The Need to Investigate the Toxicity of Celestial Dusts

The Future of Space Exploration Will Entail a Dusty Journey into the Unknown

The Apollo lunar flights ended in 1972, but the Moon has remained of great interest to space agencies and scientists worldwide. In 1989, the Space Exploration Initiative (SEI) was announced by the United States and committed NASA to returning to the Moon as well as to exploring Mars. This ambitious program slowed, but it regained momentum in 2017 when NASA refocused exploration efforts on the Moon as the starting point to reach Mars and even go beyond (Dunbar, 2018).

This new phase includes the involvement of international and commercial partners. Since transportation to (and from) the Moon requires less energy, time, and cost than that required to reach Mars, the Moon represents the ideal destination to establish a convenient outpost for further space exploration and a test site for examining the human capability to live beyond low earth orbit. Through its current Artemis program (Figure 8-1), NASA envisions sending astronauts to the lunar south pole by 2024 and eventually establishing a permanent presence on the Moon. NASA gained broad international support for the Artemis program from several national agencies and private companies (Potter, 2019). Artemis is now an ongoing crewed spaceflight program carried out by NASA, commercial spaceflight companies, and international partners such as the European Space Agency (ESA), the Japan Aerospace Exploration Agency (JAXA), the Canadian Space Agency (CSA), and the Australian Space Agency (ASA). The Global Exploration Roadmap (ISECG, 2018), with active participation by ESA, represents a blueprint for the next steps for the current and future generation of explorers involving governments, the private sector, and academia.

Long-duration missions and planetary operations entail numerous risks that must be understood and mitigated to maintain the health and productivity of crew members. Several human spaceflight hazards need to be considered for any exploration mission. A central health concern for future crewed missions is represented by the fraction of lunar soil with a diameter smaller than 20 μm, which is described by the term “lunar dust” (McKay et al., 1991). Based on the Apollo experience, lunar dust caused a plethora of problems for both mechanical systems and crew members, as described above. Thanks to the short time exposure, these symptoms were not long-lasting and did not cause any long-term effects (Scully et al., 2015).

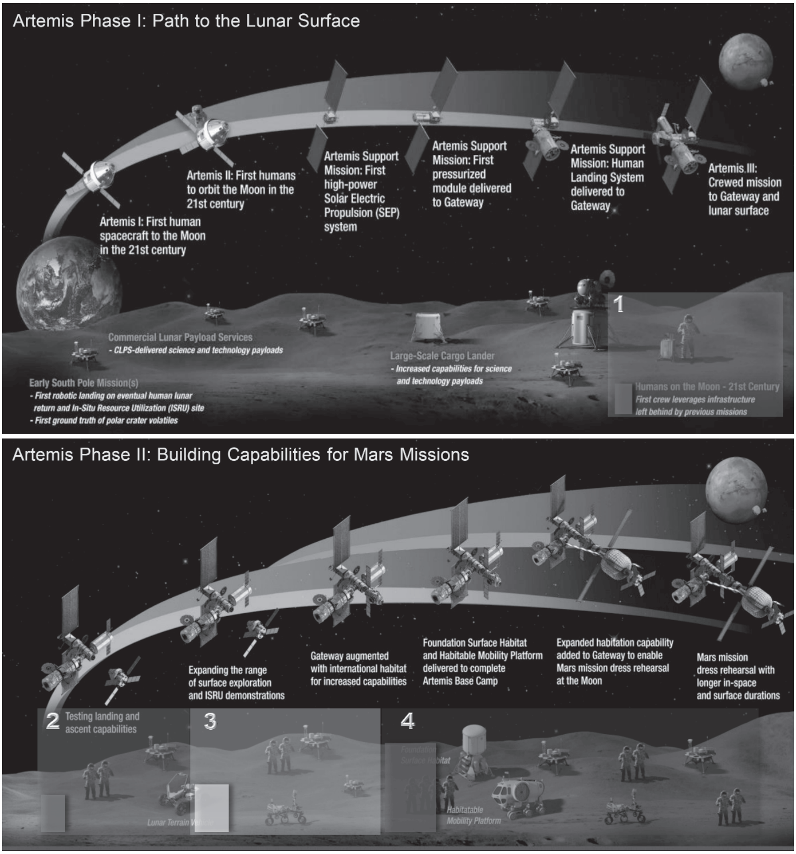


Figure 8-1. Qualitative estimation of lunar dust exposure during the Artemis program, as color-coded intensity bars. Limited crewed activities are expected to occur in Phase I (targeted for 2024) and are destined to increase in Phase II with prolonged human missions (in the period 2025-2029). Phase I activities are planned to use infrastructure left on the Moon's surface by previous uncrewed missions. The first step of Phase II will lead to limited permanent human presence. The degree and duration of exposure to lunar dust is expected to increase as the project matures. Furthermore, the dustiness of the lunar vehicles will significantly increase with the expansion of surface exploration and ISRU demonstrations. With the establishment of surface habitats and the expansion of habitation capability, the astronauts will have to cope with the ubiquitous presence of dust. Adapted from "America to the Moon 2024" (NASA, 2019).

In the context of future exploration, the astronauts' presence on the lunar surface will initially be limited to missions lasting up to 6.5 days during Phase I of the Artemis program. With the transition to Phase II, the duration of the missions and the number of astronauts involved are destined to increase as well as the duration of their exposure to lunar dust. Figure 8-1 reports ESA's Topical Team on the Toxicity of Celestial Dust's (T3CD) qualitative estimation of lunar dust exposure for each step of the crewed activities during the Artemis program. During the early crewed activities of Phase I that consist of the use of infrastructure left on the Moon's surface by preliminary uncrewed missions (1), exposure is expected to be limited. The first steps (2) of Phase II will be characterized by a limited presence of humans on the Moon, but the extent of their exposure is expected to increase with respect to Phase I due to the spread of dust from landing and ascent activities. Dust exposure will significantly increase at the later stages of Phase II when the residence time of astronauts will increase to potentially beyond one month and the number of EVAs will be significantly higher than during the Apollo program. Moreover, the creation of sustainable infrastructure to explore and sustain human life on the Moon will be achieved by *in situ* resource utilization (ISRU) strategies (European Space Agency, 2018), presenting possible scenarios of inevitable exposure to lunar dust. A logical extrapolation from the Apollo lunar experiences is that critical issues related to dust exposure will occur during a sustained human presence on the Moon. To be prepared for the inevitable exposure and to design appropriate safety measures, lunar dust and its unique properties must be thoroughly investigated from a toxicological perspective.

The Unique Origin and Composition of Lunar Dust

Since the first Apollo astronauts' debriefings, lunar dust toxicity has been one of the major concerns for future lunar exploration, and it became clear during the Apollo experience that lunar dust has an almost uncanny ability to get absolutely everywhere.

Lunar dust is formed by the continuous micrometeorite bombardment of the lunar surface and is subjected to high energy radiation in the absence of humidity and atmosphere. Due to these unique environmental conditions, lunar dust exhibits physico-chemical features uncommon on Earth. Amorphous material dominates the compositional range of lunar dust: 80% of the fraction below 1 μm is composed of glass (Thompson et al., 2010). The fraction smaller than 5 μm is rich in impact glass and nanophase zero-valent iron (np-Fe^0) (Taylor et al., 2010), which is formed during vapor deposition caused by the flash heating of mineral or glass phases due to (micro)meteoroid impacts. The abundance of np-Fe^0 increases as the particle size decreases. The presence of np-Fe^0 is relatable to the high reactivity of lunar dust (Wallace et al., 2010) and may play an important role in lunar dust toxicity.

Another feature that must be considered is the toxicity of ilmenite – an iron titanium oxide – which might have adverse effects if inhaled because of the presence of iron as well as titanium. Moreover, in the reduced 1/6 g of the Moon, dust easily becomes airborne inside habitats, increasing the risk of inhalation and increasing the fraction of particles that can reach the peripheral lung by escaping the lung clearance mechanism (Darquenne et al., 2013).

Possible Dust Exposure Scenarios

The Apollo experience showed that exposure to dust was an inevitable consequence of lunar surface activity. A future lunar habitat will almost certainly include an airlock with the benefit of reducing the entry of dust that has accumulated on suits and equipment surfaces during EVAs. However, it seems plausible that any EVA activity will likely bring with it dust exposure that will require mitigation. These activities include:

- Routine EVAs, including EVAs for scientific activities and construction, maintenance, and ISRU purposes;
- Transfer from the lunar surface into the lunar habitat; from the lunar surface into a lunar access vehicle; and from the lunar access vehicle into the crew exploration vehicle (CEV);
- Activities during a contingency situation;
- Engineering failure of the dust control systems (e.g. Heat, Ventilation and Air Conditioning (HVAC) filters, electrostatic removal, magnetic capture, etc.). This includes contamination of the inside of the space suit and/or module and habitat after extravehicular activities.

Routes of Human Exposure to Celestial Dusts

The most likely, and very possibly the most consequential, dust exposure is that associated with the inhalation of airborne dust. This route will directly impact the lung epithelium as well as the oropharyngeal and nasopharyngeal regions. It is well-known that terrestrial environmental exposures to inhaled particulate matter pose a significant health risk to humans, and there is every reason to suspect that the same will be true for celestial dusts.

There are also routes for non-pulmonary exposure:

- Entry of dust into the body through skin penetration. This exposure can occur via a traumatic injury or a penetrating injury resulting in a wound that becomes contaminated with dust. Alternatively, dust can gain entry through minor wounds or abrasions when spacesuits abrade the skin, as current EVA suits have been observed to do. Moreover, if celestial dusts enter the suit interior, as was the case during the Apollo missions, this could serve as an additional source of abrasion or enhance suit-induced injuries (Scully et al., 2015).
- Ocular exposure both during routine exposures, such as the removal of suits following an EVA, and during contingency exposures. Such exposure has the potential to irritate the cornea, the eyelids and lid margins, and the conjunctiva.
- Gastrointestinal exposure. Such exposure can occur acutely as dust is tracked into habitats and potentially contaminates food and food preparation surfaces, in much the same way as pulmonary and ocular exposures might occur. Furthermore, gastrointestinal exposure will very likely be secondary to pulmonary exposure. Most of the dust entering the airways is captured and removed by the mucociliary clearance system, a mucous-covered conveyor belt. This clearance system moves any captured components, in this case dust, to the throat, where those components are swallowed and subsequently disposed of in the gastrointestinal tract. Therefore, as long as there is respiratory or pulmonary exposure, there will also be gastrointestinal tract exposure, even if dust is kept out of food and water.

In the context of prolonged residence on the Moon or other celestial locations there is a likelihood that crews will start growing edible plants *in situ*. This may involve the use of lunar or other planetary soils. In this case, the direct or indirect contamination of plants must be taken into account. Eating vegetables grown in extraterrestrial soils may be a way of directly ingesting celestial dust or toxic ions leached by irrigation water and absorbed by plants. Another concern is represented by the systemic absorption of toxic ions, leached from the soil, absorbed, and concentrated by plants. For example, soluble perchlorate salts, which are believed to have widespread distribution on the Martian surface, ranging from 0.5 to

1% w/w, are easily leached due to their high solubility in water, making it a potential hazard to humans on the red planet (Davila et al., 2013).

Toxicity of Lunar Dust

Lunar Dusts and Lunar Dust Simulants

There are several peculiar physico-chemical features of lunar dust that are likely relevant to toxicity. The lunar regolith was formed in relatively reduced conditions in the absence of atmospheric water and oxygen and continuous micro-meteorite impact events. Furthermore, the continuous bombardment of solar wind implants protons, which radically modify the physico-chemical properties of the dust particle surface. Studies of returned samples have shown that the bulk of this lunar regolith – generally defined as the size fraction below 1 cm of the regolith covering the lunar surface contains a significant amount of reactive dust, including a respirable fraction below 10 μm. Grain size distribution analyses of Apollo lunar soil samples have revealed that between 5 and 20% by weight of lunar soils is in the respirable range (James, 2007).

From a mineralogical point of view, lunar dust is mainly made of impact glass (mostly agglutinitic glass), plagioclase, and pyroxene, which together constitute 70–98% of the dust. Pyroxene and plagioclase are virtually equally distributed in mare dusts, whereas highland dust contains about equal proportions of plagioclase and agglutinitic glass (Taylor et al., 2001a, 2001b, 2010). Minor components include pyroclastic volcanic glass beads and ilmenite and olivine as trace minerals. The abundance of agglutinitic glasses increases with decreasing grain size. The fine fraction of most soils generally contain more than 50% of agglutinitic glass, and the inhalable fraction may contain up to 70% (Taylor et al., 2001a, 2001b, 2010).

Since lunar rocks crystallize in systems with a paucity of free oxygen (negligible partial pressure of O_2), iron at zero-valance state – Fe^0 – represents a stable species and occurs in all lunar rocks as myriads of nanometric iron grains (nanophase zero-valent iron, np-Fe^0) deposited on the rims of agglutinitic glass. Moreover, meteoritic FeNi metal from metal-rich impactors, such as iron meteorites, is also present. Besides this highly reduced form, all remaining Fe is present as Fe^{2+} while virtually no highly oxidized form (Fe^{3+}) occurs. The oxidation state of iron is one of the most relevant geochemical differences between Moon and Earth minerals, where Fe^{3+} dominates mineral chemistry. As a result of this, apparently similar minerals (e.g. ilmenite) on the Earth and the Moon show quite different chemical properties and may present different reactivity towards biomolecules and tissues when inhaled. Several studies on the interaction between toxic minerals and human lungs demonstrated the peculiar role of reduced iron ions exposed at the mineral surface (Weitzman et al., 1984; Kamp et al., 1995; Gazzano et al., 2007; Turci et al., 2011). A second key difference is the presence of minerals containing structurally bound hydroxide or water molecules in many terrestrial minerals, which are rare or absent in lunar rocks. Conversely, volcanic glasses on the Moon are generally orders of magnitude more water-rich than their terrestrial equivalents. The different hydration states of the material may have an important impact on inhalation toxicology and warrant further consideration.

The Big Simulant Rush

The ideal material for toxicity studies would be real lunar dust, but with a total mass of Apollo samples being lower than 500 kg, and the dust constituting just a fraction of that, this material is priceless, and only limited quantities are made available for well-planned non-destructive research. This necessitates the use of lunar dust simulants that can be accessed by the wider scientific community. The ideal simulant exhibits high fidelity, and chemical and mineralogical homogeneity. Moreover, it must be easily available and inexpensive to produce and purchase. The features required in a simulant are strictly dependent on the research purposes for which the simulant will be used.

The production of lunar dust simulants started in 1994 with JSC-1, the first lunar soil simulant standardized by NASA. JSC-1 was produced from volcanic tuff/ash mined just north of Flagstaff, AZ (McKay et al., 1994), and it contained abundant volcanic glass (49 wt.%, Hill et al., 2007). Its bulk chemistry resembled some Apollo 14 soils (McKay et al., 1994; Hill et al., 2007). Because of its high glass content, mimicking the high levels of agglutinate glass in lunar soils, this simulant possessed the appropriate lunar geotechnical properties and was originally meant to be used mainly for mechanical engineering purposes. However, McKay and co-workers (1994) stated that JSC-1 exhibited a wider range of physico-chemical features (including bulk chemical composition, mineralogy, particle size distribution, specific gravity, angle of internal friction, and cohesion), which fall within the ranges of mare soil samples. This overestimation of JSC-1 fidelity may have led to the mischaracterization of JSC-1 as representative of all mare soils, which it definitely is not.

In 2005 NASA organized the Lunar Regolith Simulant Materials Workshop with the purpose of establishing requirements for the production and distribution of lunar simulants. The simulants were to be exploited in different branches of research (Sibille et al., 2006) and a "root simulant" needed to be produced. A "root simulant" is a large-volume, homogenized, and fully characterized mare or highland soil simulant that can be used as the base for future simulants. Derivative additives could be added to the root simulant for specific purposes, including toxicity studies (Sibille et al., 2006).

With the urgent need for lunar simulants, ORBITEC produced 15 tons of simulant JSC-1A. JSC-1A is the mass-produced replica of JSC-1 and ORBITEC offered JSC-1A free of charge to all NASA-funded researchers working on ISRU projects. The simulant rapidly became a common reference in lunar dust research, including toxicity investigations.

In the specific context of toxicology, a simulant demands special processing to properly simulate the peculiar features of the real dust and achieve the required size fraction (namely, <10 μm for human toxicology studies). The peculiar features of lunar dust are difficult to reproduce. Attempts have been made to produce np-Fe^0 in JSC-1A by Liu and Taylor (2011), but physico-chemical analyses suggest that Fe was principally present as nano-magnetite with only some minor nano-sized Fe and larger grains of metallic Fe, resulting in a material that was far from anything resembling lunar agglutinitic glass (Liu et al., 2007). Lunar-like simulations of np-Fe^0 in silica-rich glass were successfully produced in the size range of vapor-deposited glass coatings and in agglutinitic glass by Liu et al. (2007) and Noble et al. (2007). For vapor-deposited glass rims, the technique proposed by Liu et al. (2007) has the potential of being employed for more realistic compositions and for generating thin coatings similar to vapor-deposited glass coatings on lunar soil particles. These represent promising additives to lunar "root simulants." If surface reactivity is needed for testing purposes, then the Fe^0 simulant produced by Wallace and colleagues (2010) has been shown to have comparable surface reactivity and oxidative activity to lunar soils.

Besides JSC-1 and JSC-1A, other simulants have been developed over the years. Liu and Taylor (2011) provided an overview of the available simulants in comparison to real lunar soil samples. Since then, additional space agencies and nations interested in future robotic and manned lunar missions have developed their own simulants. To date, these newest simulants have not been subjected to the same wide range of studies as JSC-1 and JSC-1A.

Besides simulants from NASA, well-characterized simulants have been produced by the Chinese Academy of Sciences (CAS). These simulants are mainly intended for engineering studies, and the material description for investigating the toxic properties of the dust, such as mineralogy, particle morphology, and the relative abundance of glassy/amorphous phases, is not readily available. Among these simulants, CAS-1 was obtained by crushing the volcanic scoria (20–40 vol.% of glass) from Sihai pyroclastics at the Jinlongdingzi Volcano, China (Zheng et al., 2009) to produce an analog of Apollo 14 soil 14163. CAS-1 is essentially a good duplicate of JSC-1 in terms of bulk chemistry. However, the mineral abundance in CAS-1 has not been reported, and CAS-1 does not contain agglutinates or np-Fe^0. It may however be a good simulant for its geotechnical properties. NAO-1 was produced to mimic Apollo 16 highland soils from a Quni-Zaxiding gabbro from Tibet (Li et al., 2009). Plagioclase was picked from the gabbro and subsequently melted at 1550 °C to form glass, which was mixed with the gabbro and then milled to obtain a particle size smaller than 100 μm. The NAO-1 simulant is similar to JSC-1 in terms of specific gravity but differs from the highland samples. The mean and median particle sizes of NAO-1 are similar to Apollo 17 soils. The morphology and abundance of glass and their relationship with grain size are unknown. The reported chemistry of the plagioclase and bulk-soil chemistry of NAO-1 would seem to make it an approximation for some highland soils. Also, in this case, no np-Fe^0 is contained within the simulant. Other simulants produced by Chinese scientists include CUG-1A (He et al., 2010, 2011), NEU-1a and NEU-1b (Li et al., 2019), and TJ-1 and TJ-2 (Jiang et al., 2010, 2012). Each of these simulants mimic slightly different characteristics of the lunar soils, allowing specific features of the lunar soils to be studied.

The European Astronaut Centre lunar regolith simulant 1 (EAC-1) has recently been developed by the ESA with the aim of providing a large volume of lunar regolith simulant material. This was developed for research activities at the European Lunar Exploration Laboratory (LUNA), a large training and operations facility that the EAC is building at the German Aerospace Centre (DLR) campus in Cologne, Germany. EAC-1 was thoroughly characterized by Engelschiøn et al. (2020) with a comparison with the most widely characterized simulants (including JSC-1A) and Apollo 17 samples. The findings showed that EAC-1A shares similar physical and chemical characteristics to the lunar regolith, but there are some notable deficiencies and variances. In detail, the cohesion, sphericity, grain size distribution, and major element composition of EAC-1 are comparable to the Apollo 17 samples with the main exceptions of the alkali components, feldspathoids, and the hydrated amphibole and chlorite groups.

These simulants have often been initially developed for the study of specific, frequently engineering-related, aspects of lunar exploration missions (e.g. ISRU activities). In the absence of a well-defined set of universally applied analytical protocols, direct comparisons between the properties of different simulants are difficult. Quantitative figures of merit (FoM) have been developed to compare the physico-chemical properties (considering particle composition, particle size distribution, particle shape distribution, and bulk density) of ten available lunar simulants with the properties of an Apollo 16 core sample. This enabled an assessment of the potential suitability of the simulants for a range of technical, ISRU, and toxicity studies. Broader applications of this approach seem to have stalled, but it would be useful to apply or further develop quantitative measures of sample suitability when designing dust toxicity studies.

Despite concerns about the applicability and accuracy of the simulants, simulants are, and will remain well into the future, the most accessible method to begin to understand how lunar samples may impact short- and long-term human health. Working with simulants is particularly crucial for methodology testing and experimental optimization in preparation for handling the rare and precious lunar samples. The methodological approaches used in the efforts to study the biological effects of dust – *in vitro* and *in vivo* studies – each start with simulants and then, in the event of promising data, move to experiments with the lunar dust samples. Often, *in vitro* and *in vivo* studies can be done in parallel, each aiming to address a specific biological question.

Studies on the Health Effects of Lunar Dust

Due to its compressed timeline, no research was done on the toxicity of the lunar dust during the Apollo program. In the decades since the program ended, investigations have begun to expand our understanding of the health effects of the lunar samples. In 2005 the Lunar Airborne Dust Toxicity Assessment Group (LADTAG) was founded by NASA and was tasked with defining a permissible exposure limit for the fine respirable airborne lunar dust (defined as particles under 2.5 μm in diameter) as well as determining the ocular and dermal effects of dust exposure. LADTAG undertook ground-based *in vitro* and *in vivo* experiments to achieve this goal.

Dermal Irritation Experiments

Lunar dust's surface properties suggest that it is highly abrasive and there is potential that it could irritate the dermal/water vapor barrier (dermis), leading to dermatitis and/or sensitization of the skin. A transdermal-impedance technique was used to measure the abrasive effect of lunar dust on the skin. This technique measures damage to the dry, outermost layer of the skin, the stratum corneum, which is important for the barrier function of the skin. Pig skin, a high-fidelity model for human skin, was abraded with the lunar soil simulant JSC-1A to test the methodology. Once this approach was proven, pig skin was abraded with Apollo 11, 16, and 17 lunar soil in the 43-125 μm size fraction. The preliminary results of these studies showed that JSC-1A and lunar dusts are as abrasive as commercial sandpaper (Jones et al., 2008). The authors concluded that classical skin toxicology studies, including chemical irritancy evaluation and sensitization tests, needed to be performed.

Chemical and Mechanical Eye Irritation Experiments

The chemical and mechanical irritability effect of lunar dust on eyes was carried out by Meyers et al. (2012). The chemical irritability test was done by applying 100 mg of fine (mean particle diameter = 2.9 ± 1.0 μm) ground Apollo 14 lunar dust directly to the surface of cultured human keratinocytes, and a commercial kit was used to assess cell viability. This *in vitro* model is globally accepted as a more humane method to do eye irritability testing than testing directly on animal eyes, and it is believed to be a good mimic of the stratified corneal epithelium of the eye. The cell culture results indicated only minimal irritability of the ocular tissue by the dust. To be sure of the results and to assess a larger particle size and a greater number of endpoints, an *in vivo* study was conducted in which three rabbits were exposed to a larger size fraction of unground lunar dust (particles <120 μm; median particle diameter = 50.9 ± 19.8 μm). The *in vivo* study also showed minimal and transient eye irritation. No special precautions were recommended against ocular exposure to the dust, although in cases where the dust is very thick and becomes irritating, fully shielded goggles could be worn (Meyers et al., 2012), as is common practice when working with terrestrial dusts.

Pulmonary Toxicity Experiments

To study the pulmonary toxicity of lunar dust, *in vivo* intratracheal instillation experiments were first performed in rats (James et al., 2013), followed by nose-only inhalation experiments (Lam et al., 2013) in rats using Apollo 14 dust preparations, and compared with the responses to crystalline silica (strong response control) and titanium dioxide (low response control). Apollo 14 dust was used because it is believed to represent a mix of both highland and mare soil types (Meyer, 2011). Based on multiple biological endpoints, including 19 biomarkers measured in the bronchoalveolar lavage fluid, and tissue histopathology assessments, these experiments demonstrated that the pulmonary toxicity of lunar dust in rats is intermediate between that of titanium dioxide and crystalline silica. Detailed modeling and sophisticated efforts to reconcile all the scientific information into a single safe exposure estimate resulted in the recommendation that safe exposure levels have a minimum of 0.2 mg/m^3 and a maximum of 0.7 mg/m^3. At present, NASA has set a somewhat conservative preliminary permissible exposure limit (PEL) of 0.3 mg/m^3 (NASA 2015) to be used in design studies for forthcoming lunar missions in the Artemis program.

Reactivity

Oxidative Reactivity

As observed with a variety of terrestrial particulates, when in contact with biological fluids, many dusts generate free radicals via various mechanisms, including reactive oxygen species (ROS) by the reduction of oxygen, •OH from hydrogen peroxide (Fenton mechanism), and the homolytic rupture of carbon-hydrogen bonds (Fubini et al., 2003). Several surface moieties (i.e. surface sites which may exchange electrons) are associated with these reactions, including unsatisfied valences, poorly coordinated transition metal ions, defects, and electron-donating centers (Andreozzi et al., 2017; Turci et al., 2017). The oxidative activity of mineral dusts is a widely accepted factor contributing to the development of diseases. The formation of particle-driven ROS, including superoxide ($•O_2^-$), hydrogen peroxide (H_2O_2), and hydroxyl radicals (•OH), is the result of the stepwise reduction of dissolved molecular oxygen. When the amount of ROS overcomes the antioxidant cell's defenses, oxidative stress can occur, inducing cell and tissue damage and even death. To our knowledge, the first study on lunar dust and simulants' oxidative reactivity was by Wallace and co-workers

(2009), who studied the reactivity of Apollo dust in comparison with a very fine fraction of JSC-1A lunar simulant (JSC-1A-vf) and employing Min-U-Sil quartz as the positive control measuring the production of •OH. The authors tested Apollo dust samples of varied maturity and source (highland versus mare). Aqueous suspensions of mare and highland soils found that highland soils, characterized by lower total FeO contents and less np-Fe^0, are less reactive than mare soils of the same maturity. Comparisons between ground samples of lunar dust, lunar simulant, and quartz revealed that ground lunar dust is able to produce over three times the amount of hydroxyl radicals as lunar simulant and an order of magnitude more than ground quartz. These results induced the authors to conclude that the production of •OH occurred with the involvement of low redox state iron in its reactivity via the Fenton reaction, shown by equations (1) and (2):

$$Fe^{2+} + H_2O_2 \rightarrow Fe^{3+} + OH^{-} + \bullet OH \quad (1)$$
$$Fe^{3+} + H_2O_2 \rightarrow Fe^{2+} + HOO\bullet + H^{+} \quad (2)$$

Even though Wallace et al. (2009) did not measure the H_2O_2 involved in the Fenton reaction, a previous study by Hurowitz et al. (2007) showed that freshly fractured terrestrial basaltic minerals generated H_2O_2 when contacted with water. Wallace and co-workers (2010) further investigated the role of np-Fe^0 in the reactivity of lunar dust and simulants in inducing ROS production. The authors concluded that the reactivity of ground lunar soil can be attributed to the np-Fe^0. Moreover, initial testing of the decay rate of the ground soils has shown that the half-life of the reactivity is ~3.5 h (a potentially important finding that requires further investigation). Finally, the increased reactivity of lunar soil in comparison to lunar simulant has been ascribed to the presence of the unique np-Fe^0 in the agglutinitic glass.

Turci and co-workers (2015) investigated the oxidative reactivity of lunar dust at the molecular level by employing a complementary set of tests, including terephthalate (TA) hydroxylation, free radical release as measured by means of the spin-trapping/electron paramagnetic resonance (EPR) technique, and cell-free lipoperoxidation. The investigation was carried out on JSC-1A-vf in biologically relevant experimental environments. The findings proved that JSC-1A-vf is able to hydroxylate TA in anaerobic conditions, indicating that molecular oxygen is not involved in such a reaction. Spin-trapping/EPR measurements showed that the •OH radical is not the reactive intermediate involved. The authors proposed that a surface reactivity implying a redox cycle of phosphatecomplexed iron via a Fe(IV) state was involved. The role of this iron species was investigated by assessing the reactivity of JSC-1A-vf toward H_2O_2 (Fenton-like activity), formate ions (homolytic rupture of C-H bonds), and linoleic acid (cell-free lipoperoxidation). JSC-1A-vf was active in all tests, confirming that redox centers of transition metal ions on the surface of the dust may be responsible for dust reactivity.

To further clarify the chemical mechanism of ROS generation and the nature of the moieties involved in such reactivity, Kaur et al. (2016) employed simulants JSC-1A, NU-LHT-2M, OB-1, and CSM-CL-S, as well as two simulants, JSC-1A and NU-LHT-2M previously treated, to create high-quality synthetic-Fe^0-bearing agglutinates. Out of all simulants, CSM-CL-S was found to be the most reactive, followed by OB-1 and then JSC-1A. The authors studied the effect of activation by grinding under an oxidative atmosphere (O_2) and under a vacuum and the effect of the atmosphere on the reactivity operating both under oxygen and nitrogen (inert) atmospheres. The findings showed that freshly ground dusts were all more reactive than unground dusts. Moreover, the absence of oxygen and water had the effect of increasing reactivity. The results indicate that mechanical stress and the absence of molecular oxygen and water, which are important environmental characteristics of the lunar environment, can lead to an enhanced production of ROS in general. Simulants treated to create agglutination, including the formation of Fe^0, showed a lower reactivity than untreated simulants. Moreover, reactivity showed a direct correlation with the amount of agglutinitic glass. ROS are formed rapidly when simulants are dispersed in pure water, but the concentration of ROS either stabilizes or decreases over time. In contrast, ROS generation in simulated lung fluid (SLF) is initially slower than in deionized water, but the ROS formation was more prolonged over time. This suggests that in the human lung the production of H_2O_2 is likely sustained for at least hours after inhalation of the simulant, which could lead to chronic inflammation within the lung.

Dissolution

Due to human exploration, water will inevitably come in contact with lunar dust on future missions, especially during long-term stays. Water will be transported along with other mission assets in critical vehicle and habitat life support systems, and it will likely be extracted in quantity through ISRU processing of lunar minerals (Anand et al., 2012). Lunar dust suspended in water leaches metals and other elements for at least months, which suggests that the dust particles in aqueous media will gradually dissolve (Keller et al., 1971). Moreover, dust will come in contact with the water-rich body compartments, especially airways and the gastrointestinal tract, upon astronaut exposure. Since lunar dust, *in situ*, is exposed to intense radiation on the Moon, and particle radiation can disrupt the structure of mineral particles, it is possible that lunar dust is more susceptible to dissolution than terrestrial dusts that are not exposed to radiation. Contact with an aqueous environment can induce dust particle dissolution with the release of potentially toxic ions. In particular, iron or other redox active metal ions may induce the release of •OH radicals via Fenton reactivity, playing a role in oxidative stress. Furthermore, several transition metal ions that can be released from lunar dust (including Ni, Co, and Cr) can induce allergic responses (Hedberg, 2018; Lidén, 2018), and some of them are classified as carcinogenic (International Agency for Research on Cancer, 1996) or possibly carcinogenic (International Agency for Research on Cancer, 2006). The dissolution behavior of lunar dust was studied by Johnson et al. (1972) by employing Apollo 12, 14, and 15 regoliths. The solubility of all the samples was negligible in pure water, whereas high amounts of Al, Fe, Ca, and Mg and Co, Cr, Ni as minor components were observed after 3 h of incubation in an acidic environment (HCl 0.1 M and 1.0 M).

Further, the solubility of particles has effects on biopersistence, which is one of the key players in mineral dust toxicity (Linnarsson et al., 2012). Studies *in vivo* were carried out. Freshly returned lunar dust was injected into tissues of mice and later examined when the animals died naturally in about two years. It was seen in these animals that some particles persisted, but further examination to document the extent of the dissolution or the physical and chemical nature of the surviving particles was not performed (Holland et al., 1973; Johnston et al., 1975).

Effect of Microgravity

Because the lung presents by far the greatest surface area of the body exposed to the environment (ca. 50-80 m^2), understanding the pulmonary deposition and subsequent clearance of inhaled dust is important in the context of toxicological effects.

The deposition of aerosols in the human lung occurs through a combination of inertial impaction, gravitational sedimentation, and diffusion. For 0.5 to 5 μm diameter particles under resting breathing conditions, the primary mechanism of deposition is sedimentation, and therefore the fate of these particles is markedly affected by gravity (Darquenne, 2014). The first experimental study of aerosol deposition in altered gravity was carried out by Hoffman and Billingham by employing 2 µm diameter particles for gravity (g) levels ranging from 0 to 2 g. There was an almost linear increase in deposition with increasing g level (Hoffman et al., 1975). Subsequent studies by Darquenne et al. (1997) have shown this to be broadly correct for particles in the size range of 0.5 to 3 µm. Thus, in lunar gravity (⅙ g), the deposition of particles is less than in 1 g due to the reduced sedimentation rate. However, the reduction in sedimentation means that particles that would normally be deposited in the medium- and small-sized airways in 1 g remain in suspension, and are then able to be transported to the peripheral lung where they eventually deposit through sedimentation in the smaller peripheral air spaces, or through the effects of diffusion. The effect of reduced gravity on deposition was studied by Darquenne and Prisk (2008) in six subjects on the ground (1 g) and during short periods of lunar gravity (⅙ g). In this study, the deposition of boluses of aerosolized monodisperse polystyrene latex particles (0.5 and 1 µm diameter particles) administered to six healthy subjects was examined. While deposition was reduced in lunar gravity compared to normal gravity, the penetration volume required to achieve a given level of deposition was greater in ⅙ g than in 1 g, indicating that the peripheral deposition of particles was enhanced in lunar gravity (Darquenne et al., 2008).

Another potential influence on dust deposition is that of the density of the cabin or spacesuit gas. This is likely to be quite different to that on Earth, with the proposed lunar habitat atmosphere having a gas density about ½ that of sea-level air and with EVA suit atmospheres even less dense. The deposition of particles in conditions approximating the lunar habitat atmosphere showed a minor effect of gas density, with the key finding that gravity, and not gas properties, is the main factor affecting aerosol deposition in the lung (Darquenne et al., 2013).

Knowing the site of particle deposition in the lung has important implications for toxicological studies. Particles that deposit in the large central and medium-sized airways are rapidly removed from the lung by the mucociliary clearance system with clearance times of hours to days. However, particles that deposit in the peripheral lung do so beyond the reach of the mucociliary clearance system (Darquenne et al., 2013). Thus, the residence time of particles deposited in the lung periphery is much longer (weeks to months). This difference may have important implications as the longer the contact time between the tissue and the particles, the greater the potential of deposited particles to induce lung damage.

Measurements of the rate of clearance of deposited particles in the lung under conditions of altered gravity have never been made. However, direct observation of the site of the deposition of inhaled particles allows inferences to be made regarding clearance times. In humans, the absence of gravity caused a smaller portion of 5 μm particles to deposit in the lung periphery than in the central airways of the lung. For 5 μm diameter particles, deposition is dominated by inertial impaction, a mechanism most efficient in the large- and medium-sized airways. In the absence of gravity, sedimentation (which is more efficient in the smaller airways) was eliminated, allowing the large inhaled particles to stay in suspension and subsequently be exhaled. In contrast, for fine particles (∼1 μm), both aerosol bolus inhalations in humans and direct studies in rats show that particles deposit more peripherally in reduced gravity than in 1 g (Darquenne, 2014). Thus, it is likely that while overall deposition in the lung may be reduced in low gravity, those particles that are deposited will be those in the smaller size fractions (likely < 2 μm) and will be deposited in the more peripheral regions of the lung. This will result in prolonged residence times in the lung, serving to raise their potential for causing toxicological effects.

Future Perspectives

Developing New Simulants for Long-term Toxicity Assessment

The University of Central Florida (UFC) maintains the online Planetary Simulant Database (www.simulantdb.com) of all known regolith simulants (past and present) and their compositional information. Few of these are recorded as dust simulants, and hazardous or toxic properties are typically actively reduced for the purpose of safer human handling. Hence, there is a clear need for developing new dust simulants for long-term toxicity assessment.

Considerations for Future Lunar Simulants

Future lunar dust simulants for toxicity assessment will initially require the production of the sub-20 μm dust size fraction, including accurate recreation of the particle size distribution curve of real lunar dust. The sub-2.5 μm size fraction, which will be essential for *in vivo* and *in vitro* toxicity studies, should also be thoroughly characterized for size and crystallo-chemistry. These two fractions account for around 20 wt.% and 2 wt.% respectively of the lunar soil (Park et al., 2008; Cooper et al., 2010).

It is important to accurately represent the particle size distribution, as this is not only related to surface area and reactivity, but can also have a significant bearing on pulmonary deposition and distribution, as well as affecting clearance and translocation (Nakane, 2012). When developing simulants for specific applications, it is desirable to derive it from a "root simulant" to aid standardized methods for future replication (Carter et al., 2004; Sibille et al., 2006). The continual gardening process through micrometeorite bombardment occurring on the surface of the Moon sees the delicate glassy rinds rich with nanophase metallic iron (np-Fe^0) preferentially concentrated into the finer fraction (e.g. Taylor et al., 2001b). This concentration of np-Fe^0 within the finer fraction is also a function of its vapor deposition process being surface-area dependent (Noble et al., 2001). Hence, developing a dust simulant for toxicity assessment is not merely a case of grinding a "root simulant" down to fine respirable size. Key additive components are also required, including the agglutinitic silicate glasses that constitute around 50-80 wt.% of the dust size fraction, as well as the np-Fe^0 (McKay et al., 1991; Taylor et al., 2001b). The latter will ideally be synthesized utilizing the processes of Yang Liu et al. (2007) and Noble et al. (2007). Other key properties relating to toxicity assessment are particle shape, texture, crystallinity, and reactive surface areas in relation to particle size. One of the most relevant, yet unexplored, discrepancies between all currently available "root simulants" and real lunar dust is the effect on the surface chemistry of high energy space radiation.

The most frequent particle size for the <2.5 μm fraction is the 0.1 to 0.2 μm range, with an overall smooth decrease in particle size observed down to around 20 nm (Park et al., 2008; McKay et al., 2015), which creates a large surface area. The highly vesicular nature of the glassy agglutinates that dominate the comparatively larger regolith fraction (McKay et al., 1991) is all but absent in the <2.5 μm size fraction of an Apollo sample (14003, 96), appearing as mostly smooth amorphous glasses (McKay et al., 2015). This may be a factor as to why lunar dust is less toxic than ground quartz (Lam et al., 2010; McKay et al., 2015) and is an important consideration for the development of the finest fractions of lunar dust simulants. None of the main larger-volume lunar simulants currently and historically available reproduce the highly irregular particle shapes of many real lunar soils. It has been noted that particle shape and shape distribution with size is particularly hard to reproduce in simulants (e.g. Taylor, 2010). Given that this may be a significant parameter affecting surface area and toxicity, it may, however, still be worth addressing. The compositional trend of increasing np-Fe^0 with diminishing particle size in bulk regolith (e.g. McKay et al., 1991) stands true down to 2 µm, as does the decreasing trend of MgO and FeO, and increasing Al_2O_3 (plagioclase feldspar) that has previously been noted for the <20 µm fraction (McKay et al., 2015). This chemical trend is attributed to a combination of diminishing mafic minerals, such as olivine (plus pyroxene), with a comparative increase in plagioclase (e.g. Cintala et al., 1992) with the <20 µm dust fraction. Conversely, the trend for bulk regolith coarser than 20 µm trends toward an increase in both the mafic minerals and plagioclase components with decreasing grain size, and a steady decrease in lithic fragments (Papike et al., 1982). The compositional variation below 20 µm may be better reflected with crystalline mineral additives when deriving simulant dusts for toxicity assessment from root regolith simulants. Accurate representation of surface area and nanophase iron content would benefit assessments involving the activation and monitoring of dust, such as that conducted by Wallace et al. (2009).

Near-term human missions, such as Artemis, and longer-term sustained activities at the lunar surface are largely targeting polar locations for the science and resource potential offered by polar water ice and other cold-trapped volatiles. The polar region is dominantly highland terrain, and it would therefore be prudent at this stage in time to also focus on a high-fidelity highland dust. Currently the best authentic examples of highland that we have are samples in the Apollo collection from the Apollo 16 landing site, with additional compositional information provided by lunar meteorites.

Considerations for Future Martian Simulants

Mars' surface dust has only been studied remotely by robotic missions. There are different geological processes that have acted on the surface regolith on Mars when compared to the geological processes on the Moon, including physical erosion by wind and water and chemical weathering by fluids and oxidants (see e.g. Cannon et al., 2019 and references therein). Among the 100 µm particle size range (i.e. the detection limit of the Spirit rover), grains appear to be rounded and agglutinates are absent. This is in stark contrast to the equivalent size range regolith on the Moon and is attributed to wind alteration on Mars, and supported by an observed difference between this rounded surface dust and underlying coarser regolith (McGlynn et al., 2011). The wind also acts to homogenize the fine-grained dust at the surface on a global scale (Yen et al., 2005; Schuerger et al., 2012; Downs et al., 2015) with the most common silicate minerals being feldspar, pyroxene, and olivine, similar to the composition of basaltic Hawaiian volcanic ash. This dust is highly oxidized, contains nanophase iron oxides, and is rich in salts (Morris et al., 2006).

Of particular significance for toxicity is the high concentration of global perchlorate salts, measured in the regolith at 0.5 to 1 wt.%, which is several orders of magnitude greater than that for soils on Earth (Davila et al., 2013). Perchlorate anion can interfere with normal thyroid function by competitively inhibiting iodide uptake, reducing thyroid hormone production and further affecting normal metabolism, growth, and development of organisms (Wolff, 1998; ATSDR, 2008). If plant species are irrigated naturally or artificially with water containing perchlorate, uptake will occur, including uptake into edible portions of the plant. Cucumber, lettuce, and soybean demonstrated their potential to take up perchlorate from contaminated sand. There was a significant perchlorate concentration burden for cucumber and lettuce (Yu et al., 2004). Perchlorate accumulation was detected in edible portions of several garden plants, although with a lower bioconcentration. Another study indicated that perchlorate was selectively partitioned in chinaberry and mulberry trees, with leaf concentrations of 1.3-5.0 mg/kg of dry weight and fruit concentration of 0-0.5 mg/kg of dry weight (Tan et al., 2004). Nitrates are also present (Stern et al., 2015). The adsorption of H_2O_2 into the regolith may also be occurring as a result of H_2O_2 production induced by electrostatic fields generated by charged particles in dust storms (Atreya et al., 2006; Scully et al., 2015). These are all considerations for additives to a “root simulant” for the toxicity assessment of Martian dust.

Similarly to the Moon environment, the ⅜ g Martian gravity will serve to increase the fraction of particles that can reach the peripheral lung, escaping the lung clearance mechanism (Darquenne et al., 2013). Before developing a more accurate simulant for toxicity purposes, knowledge of particle size distribution, charge state, component solubility, porosity/surface to volume ratio, and textures are other factors of Martian dusts that need to be determined, beyond just Martian soil composition. There are numerous Martian simulants that have been produced, with many of them honed specifically for the testing and development of new analytical instruments for the Mars 2020 rover. These instruments will inform on the aforementioned properties and hazards posed by Martian dust, including XRF and ultraviolet RAMAN for analyzing fine-scale elemental and mineralogical compositional, and an array of atmospheric sensors that will also measure radiation, and dust size and shape (www.mars.nasa.gov/mars 2020). Furthermore, the Mars 2020 mission will cache collected samples on the surface of Mars for future retrieval and return to Earth.

Currently, none of the available Martian simulants have the perchlorates included, precisely because of their toxic nature. The new MGS-1 simulant presents a possible viable “root simulant” for starting to develop a toxicity simulant that can be spiked with perchlorates. The MGS-1 simulant is created by mixing pure minerals together (Cannon et al., 2019) in the proportions based on the Curiosity rover’s measurements of the Rocknest soil in Gale Crater (e.g. Bish et al., 2013; Achilles et al., 2017).

Using this approach aims to avoid the tendency for simulants to gain water through interaction with the terrestrial atmosphere (i.e. via absorption or adsorption), which appears to be the case for JSC Mars-1 and MMS simulants that are derived from hydrothermally altered volcanic material (Allen et al., 1998; Peters et al., 2008). For example, JSC Mars-1 contains approximately 20 wt.% water (Allen et al., 1998), whereas 1.5-2.0 wt.% water has been measured in the upper layer of Martian regolith at the Rocknest location by the Curiosity rover (Jun et al., 2013; Archer Jr et al., 2014). Unknown, poorly crystalline/amorphous material comprises approximately 20 wt.% of the Rocknest soil and cannot be explained by any single component. Separate experimental analyses have led to the inference that this portion may be a mixture of basaltic glass, nanophase oxides such as ferrihydrite, and sulfate species. These are all being included in MGS-1 (see Cannon et al., 2019 and references therein). MGS-1 and all alternative Martian simulants are cataloged in the online Planetary Simulant Database (www.simulantdb.com). JSC Mars-1 and MMS are largely no longer available outside of NASA.

In situ Analyses and Authentic Dust

Toxicity assessment using authentic dust may be possible after the successful demonstration of techniques utilizing simulants and after notable efforts to scale down experiments for smaller sample masses (Taylor et al., 2016). Such analyses will require the necessary preparation to separate a representative dust or respiratory fraction from bulk regolith samples, and where desired, the reactivation of surfaces. With regard to separation, dry sieving is only effective typically to the 45 μm size range, after which wet sieving or gravitational settling techniques using water, Freon, or alcohol tend to be applied (e.g. Basu et al., 2001; Park et al., 2008). For toxicity studies, not only is it less favorable to be exposing the particles to potentially chemically altering liquids, but such separation processes are estimated to require a starting bulk regolith mass on the order of kilograms to attain a few grams of the <2.5 μm-sized fraction

(McKay et al., 2015). This is just not feasible when using such rare material.

Alternative separation processes were applied by the LADTAG consortium to study Apollo 14 sample 14003 (McKay et al., 2015), which was taken to represent a mix of both highland and mare type soils (Meyer, 2011). A combination of jet mill crushing, involving self-collision between particles, and cyclone extraction conducted under an ultra-pure nitrogen environment was deemed an appropriate separation method. The resultant dust compared relatively well to the considerably smaller mass of "native respirable dust" that had been extracted using cyclone extraction alone, albeit slightly less rich in the nano-phase iron component than the native dust (McKay et al., 2015). The subsequent *in vivo* and *in vitro* experiments utilizing the separated respiratory dust are discussed elsewhere in this paper and described in full by James et al. (2013) and Lam et al. (2013).

Given that surface reactivity is such an important factor relating to toxicity studies, it is vital that *in situ* studies are conducted at the lunar surface prior to the sustained presence of humans. Another approach may be to specifically target lunar dust samples as part of future sample return missions. Should this be deemed an important step for human space exploration, the development of sample collection, containment, and curation methods that best preserve surface reactivity in returned lunar dust will need to be investigated in the near future.

High-energy Activation of Lunar Dust

The effects of space radiation on lunar dust is an important gap in our understanding of lunar dust toxicity. Space radiation interacts with lunar dust and can alter its chemical properties. Radiation exposure on the lunar surface is much higher than on Earth because the Moon has no atmosphere and a weak magnetic field. Components of the space radiation spectrum can therefore interact with dust: UV, solar wind, acute solar particle events, and sustained exposure to galactic cosmic rays.

These effects have been known since the Apollo 11 mission. Loftus et al. (2008) reviewed the work by Hapke et al. (1970) in which the effect of UV irradiation of Apollo 11 samples induced changes in the optical properties of lunar dust (reflectance spectra, absorption spectra). The authors attributed the phenomenon to the probable oxidation of Fe^{2+} to Fe^{3+}. Additional studies of energetic photon effects done with X-rays showed that the absorption spectrum was affected in the 4.5 eV energy range, again indicating changes in the oxidation state of iron (Hapke et al., 1970). The re-examination many hours after x-radiation evidenced some reversibility of these changes, although detailed passivation studies were not performed. The irradiation of Apollo 11 lunar dust samples with low energy protons, to mimic the solar wind, resulted in changes in the visible and IR reflectance spectrum, indicating changes in the chemistry of lunar dust, of similar magnitude to the effects of UV exposure (Hapke et al., 1970).

Solar wind is a low-energy stream of charged particles composed mainly of protons along with trace proportions of heavy elements including O^{7+} and ^{3}He (Killen et al., 2012). Solar wind interacts with the lunar surface inducing the implantation of ions. Furthermore, the intense radiation and particle radiation can disrupt the structure of mineral particles. For this reason, it is possible that the dissolution behavior of lunar dust is different from terrestrial dusts that are not exposed to radiation. Disruption of the mineral structure could indeed affect the dissolution of lunar dust in an aqueous environment. One of the first studies on solar wind implantation in lunar dust was carried out by Bibring et al. (1974), who studied the combined effects of collision and ion implantation into micron-sized lunar dust grains (namely lunar minerals extracted from an internal chunk of lunar igneous rock 15065) with a high-voltage electron microscope (HVEM). They exposed the sample to high fluxes of low-energy ions, including H, D, ^{13}C, N, Ne, Ar, Kr, Xe, and Pb nuclei. The observation of micron-sized grains either naturally exposed to space environmental parameters on the lunar surface or artificially subjected to space simulated conditions strongly suggests that such events could drastically modify the mineralogical composition of the grains and considerably ease their aggregation during collisions at low speeds.

The disruption of the mineralogical structure of lunar dust particles by high energy radiation bombardment may influence the dissolution rate of lunar dust. The bioavailability of metal ions (primarily iron) could be increased following high energy radiation bombardment. This could exert a dual yet contradictory effect, as has been observed in some inhaled terrestrial particles. On the one hand, high solubility can determine a low biopersistence of inhaled particles; on the other hand, the release of toxic ions at high local concentrations can induce acute inflammation or other toxic effects.

Coronal mass ejections from the Sun interrupt the solar wind and inject into the interplanetary system high fluxes of protons with energies up to a few hundreds of MeV. These solar particle events can deliver very high doses, even lethal doses, for unprotected crews. Exposure to solar particle events can also alter the chemical properties of the lunar dust, potentially making the dust surface more reactive when in contact with human tissue.

Finally, the issue of sustained exposure to galactic cosmic rays is largely unexplored. Even if galactic cosmic rays induce low radiation doses compared to solar particle events, they are very energetic and include a small but significant component of heavy ions. Galactic cosmic rays can penetrate the soil much deeper than solar wind, and the heavy ions can produce more significant chemical modifications (Durante et al., 2011).

Passivation Kinetics and Chemical Endpoints

An important factor in designing a future lunar habitat and mitigation procedures is determining a method by which to "deactivate" reactive lunar soil. A simple method to determine this deactivation time was proposed by Wallace et al. (2010) by subjecting ground lunar dust samples to conditions of known temperature and humidity (25 °C and 50% relative humidity) and then measuring the production of •OH by the terephthalate assay (TA). The time required to reach one half of the initial reactivity was ca. 220 min. The decay values did not seem to correlate with the maturity or origin of the soils (mare versus highland). Even after one week of deactivation, the tested soil (67461) did not return to its unground value. This finding was observed on all samples tested, as well as the highland soil sampled during Apollo missions. Hendrix et al. (2019) studied the reactivity of JSC-1A and several mineral components occurring in lunar regolith by detecting HO• radicals by Electron Paramagnetic Resonance spectroscopy coupled with spin trapping techniques. Some information on passivation kinetics was found by these authors by measuring HO• from freshly pulverized augite, one of the mineral components of lunar mare regolith, after being exposed to the air for increasing periods of time. The capability of augite to release HO• decreased as a function of the time of exposure to the air similarly to that observed for quartz in the same experimental conditions. This suggests that a deactivation process induced by an oxidative environment occurred. The information provided by this study is limited to only one mineral component, and the humidity and temperature conditions are not reported.

However, it should be noted that it is still unknown if "deactivated" soil will have any detrimental *in vivo* health effects (such as the production of H_2O_2) if it is inhaled by astronauts.

Description of Biological Endpoints

Cellular Endpoints

Cellular studies using epithelial cells present a promising avenue for assessing the acute effects of lunar dust on the lung that will serve to form a bridge between the chemical activity studies and studies in animals. Physiologically relevant *in vivo*-like lung-mucosa models with primary human cells cultured at the air-liquid interface are becoming a realistic alternative for pulmonary toxicity testing (Upadhyay et al., 2018). The use of such micro-physiological systems offers a unique opportunity for the direct deposition of particles of different origins onto a semi-dry apical cell surface consisting of mucus and beating cilia, a situation that mimics the deposition of particles onto the airway surface *in vivo* (Ji et al., 2017). These multi-cellular airway wall models can be co-cultured with innate effector cells (macrophages) which enable studying cell-to-cell interactions and crosstalk between cells that are present in human lungs (Ji et al., 2018).

The features of the micro-physiological systems not only mimic the *in vivo* situation but also avoid the constant concern of species differences when using animal models. Lung anatomy, cellular composition, or molecular responses in animal models significantly differ from humans. For instance, chronic bronchitis and chronic obstructive pulmonary disease are characterized by excessive mucus production. However, bronchial glands in mice and rats are anatomically localized only in the proximal trachea, making it difficult to reproduce these disease entities. Therefore, a debate has arisen in the last decade regarding the predictive value of mouse models in inflammatory diseases.

The use of *in vitro* models has been established, which aim at improving our understanding of pathophysiological processes and to provide novel and more reliant experimental systems for toxicological studies. The use of our established multicellular air-liquid interface models, which are considered as the next level advancement to mimic communications occurring between different cell types, are comparable to the *in vivo* situation. Hence, multicellular air-liquid interface models with human primary cells including various cell types such as various epithelial cell types (ciliated cells, goblet cells, club cells, and basal cells) and macrophages are expected to be the most physiologically relevant airway mucosa models to use for the evaluation of health effects of ultrafine particles of different origins. Further, another important feature in these airway wall models is the formation of a thin liquid lining layer, including mucus together with the presence of ciliary movement mimicking the mucociliary clearance present *in vivo*. Therefore, these multicellular air-liquid interface models provide high-fidelity models of *in vivo* lung mucosa with comparable tissue morphology and function to that seen *in vivo*, including extensive cell-cell interaction.

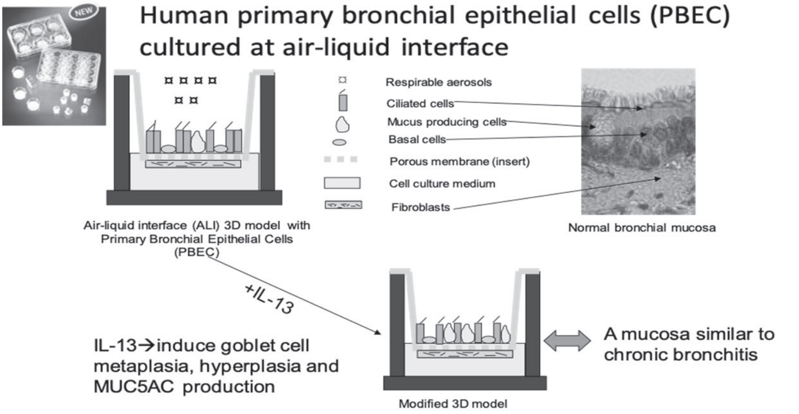


Figure 8-2. Normal and chronic bronchitis-like mucosa. Gerde and Palmberg have successfully established both normal and interleukin-13 (IL-13) induced chronic bronchitis-like multicellular bronchial mucosa models (Ji et al., 2017, 2019), and have exposed those models to different particles like carbon nanoparticles, diesel particles, and gases (aldehydes and diacetyl) (Ji et al., 2017, 2018, 2019; Dwivedi et al., 2018; Thimraj et al., 2019).

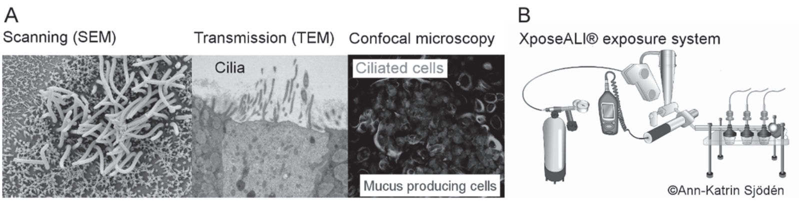


Figure 8-3. Bronchial mucosa model and exposure system. Microscopic details of the bronchial mucosa model (A) and an overview of the XposeALI® exposure module (B), which utilizes the PreciseInhale® aerosol delivery platform.

Figure 8-3A illustrates our established bronchial models with ciliated cells, mucus-producing cells in scanning and transmission electron microscopy (SEM and TEM) and confocal microscopy (Upadhyay et al., 2018). Figure 8-3B is the XposeALI® module that we routinely use to expose bronchial and alveolar mucosa models to aerosolized particles (adapted from Anna Steneholm's thesis).

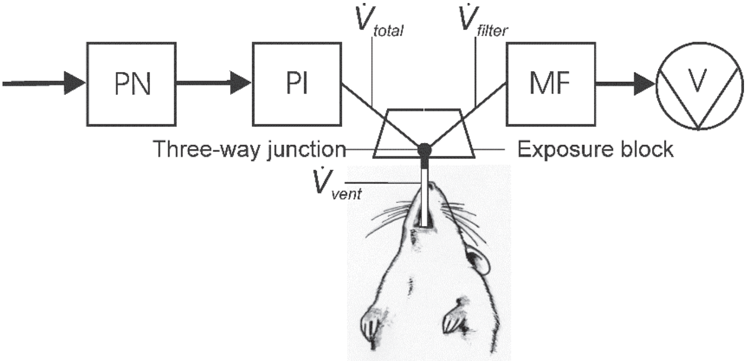
In Vivo Endpoints

Studies in animals have been the mainstay of inhalation toxicology assessment. In the context of lunar dust, the current permissible exposure limit set by NASA came as a direct result of the studies of rats exposed to aerosolized ground lunar material delivered via a nose-only inhalation technique performed by LADTAG (James et al., 2013; Lam et al., 2013). They assessed toxicity via both histopathological changes in the lungs and over a dozen inflammatory markers in the bronchoalveolar lavage fluid. Chinese scientists have also recently investigated the pulmonary and cardiovascular effects of the exposure of Wistar rats to several Chinese simulants (Sun et al., 2018, 2019a, 2019b).

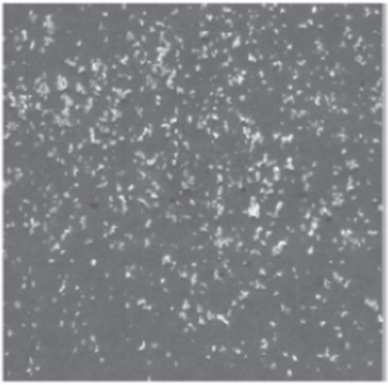
Going forward, similar studies will likely be required to address the issue of whether the dust present on the lunar surface has a higher toxicological potential than samples curated for over 40 years, which may have different surface chemistry. *In vitro* exposure models will need to be complemented with rodent exposures to the same dust aerosols for investigating corresponding *in vivo* endpoints. Unfortunately, the techniques used in the LADTAG studies (rats, aerosolized exposure, exposures of many days) present significant problems in terms of future studies. Any studies performed using actual lunar material will be constrained by the availability of such material, especially if sample return or curated pristine samples are to be used.

An alternative to the method used by LADTAG is the recently developed PreciseInhale® aerosol delivery platform (Figure 8-3B), which is suitable for both *in vitro* (Figure 8-3B) and *in vivo* (Figure 8-4) exposures. This platform can be used for the delivery of the same aerosols to different exposure modules *in vitro* and *in vivo*, enabling the comparison of various toxic endpoints with a minimum level of translational errors in dosage between the modules.

In preliminary studies the lunar dust surrogate sample JSC-1a-vf was aerosolized with the DustGun generator of the PreciseInhale® platform. Aerosol at a concentration of 2.5 mg/L with a mass median aerodynamic diameter of 2.5 µm (GSD=1.9) was consistently generated. Intratracheally intubated rats were exposed to this aerosol during spontaneous breathing and reached a deposited dose of dust in the lungs of 1.2 mg (SD=4%, n=4) within about 20 minutes of exposure time. The substance utilization in terms of lung deposited amounts as a fraction of spent amount was approximately 1%. This is lower than during intratracheal instillation, but considerably higher than during nose-only tower exposures (Fioni et al., 2018). In both the *in vitro* and *in vivo* exposure modules, highly reactive dust samples can be kept under inert conditions until shortly before the exposure of the cells or animal to the aerosol.



A)



B)

Figure 8-4. Configuration of the intratracheal single rodent exposure set up. A schematic of the exposure system for the lung phantom exposures: PN, the pneumotachograph; PI, the PreciseInhale® exposure platform (see Figure 8-3B); MF, the end filter; V, the vacuum pump; Q_{total}, the exposure airflow; Q_{vent}, the ventilation airflow, generated by the lung phantom ventilated with the rodent ventilator; Q_{filter}, the constant component of the exposure airflow. The balance of the airflow streams at the three-way junction is expressed as $Q_{total} + Q_{vent} + Q_{filter} = 0$. Scanning electron microscopy micrograph of aerosolized JSC-1a-vf collected on a membrane filter (frame size 500 µm).

While simulant usage may be a viable alternative to the use of actual lunar material, the aggressive timeline of the Artemis program (first boots on the Moon in 2024) means that studies will need to be performed rapidly. A study design that allowed for a single exposure of an animal to lunar dust with subsequent readout of the response would be ideal. The highly robust immune system of rodents compared to humans presents a challenge here. However, a lung-selective knockout of vascular endothelial growth factor in mice presents a possible solution.

These mice show a much higher sensitivity to cigarette smoke than other mice (Lee et al., 2019). As such, lunar dust (or a high-fidelity lunar simulant) could potentially be delivered in a single exposure using intratracheal inhalation via an aerosol delivered from the PreciseInhale® platform. This would serve to bypass the highly effective dust filtration system of the rodent nose, allowing a single high dose to be delivered to the lung. The high sensitivity mice would permit experimental designs using a single exposure. Minimal amounts of material would be required, allowing studies with actual lunar material to be performed if desired. Following a single dose, animals can be studied at various time points using both bronchial alveolar lavage (multiple time points if required) and a histopathology assessment of the tissues (terminal endpoint). Such an approach would allow for both rapid throughput and minimal material requirements.

Long-term Exposure – A Major Gap in our Knowledge

During the Apollo crewed missions, exposures to lunar dust were uncontrolled and brief but sufficient to cause acute health effects (Cain, 2010). However, future lunar missions will be of much longer duration, ranging from surface stays of about 6.5 days in the early phase of Artemis to more than a month in later phases. Thus, the potential for ongoing episodic exposure to lunar dust will likely increase as crews will be performing repeated surface EVAs, each with the potential for exposure to dust.

Extrapolating human health effects from long-term animal or cellular exposure studies is fraught with difficulty. Therefore, it seems likely that an ongoing medical surveillance program for the crews will be needed. Such a program could readily include the provision of the capability to perform both forced spirometry as a standard (but rather insensitive) means of detecting the pulmonary effects of the dust, but also more sensitive means of detecting pulmonary inflammation such as exhaled nitric oxide levels. Both technologies are compact in nature, meaning they could be deployed to the lunar habitat, and both have been successfully used on the ISS in measuring the effects of long-term exposure to microgravity on the lung and any issues relating to the ISS environment.

Eye Irritation/Toxicity

The current literature on eye irritation and toxicity is limited to one paper on the ocular effects of real lunar dust. The paper by Meyers et al. (2012) is excellent preliminary work, but it reports only studies on Apollo 14 lunar dust (a low-titanium mare lunar dust). Dust from the highlands area of the lunar surface has a substantially different mineral content, and therefore, these results may not be representative of that dust nor of dust from exotic locations such as the areas in the basins of craters near the poles. Future work would likely be done using the well-established *in vivo* human keratinocytes culture system.

Cardiovascular Effects

It is well-accepted that air pollution affects people with cardiovascular disease (Rajagopalan et al., 2018), and there is literature that suggests airborne dusts do the same (Querol et al., 2019). It could be prudent to understand what the cardiovascular effects of lunar dust exposure could be in an effort to understand the full human health effects of lunar dust exposure.

Recommendations

Since 2010, the ESA Topical Team on the Toxicity of Celestial Dust (T3CD) working group has involved researchers from academia and space agencies across a broad spectrum of technical backgrounds. T3CD is currently charged with identifying the most challenging questions related to the toxic effects of celestial dust on humans and suggesting approaches to address these questions. In this contribution, T3CD and supporting topical experts have reviewed the current knowledge on the determinants of dust toxicity, the composition and size of lunar dust, and all aspects related to its toxicity. The group has identified a number of knowledge gaps that need to be addressed in an effort to constrain the required extent of mitigation activities protecting astronauts from the potentially toxic effects of lunar and Martian dust.

Pertaining to the issue of the radiation activation of lunar dust and its toxicological implications, T3CD recommends that a broad multi-agency, multi-national effort be undertaken to perform the needed ground-based studies, using archived lunar dust samples. Adequate experimental techniques and resources are available to effectively close this important knowledge gap and to pave the way for a safe, sustained human presence on the Moon.

Further, T3CD recommends a range of future studies (as detailed above) using ground-based, irradiated lunar simulants to unravel the toxicity of lunar and Martian dusts in their real environment and foster safer crewed exploration of celestial bodies.

Conclusion

Since the first Apollo astronauts' debriefings, the ubiquitous presence of lunar dust and its potential toxicity has been one of the major concerns for lunar exploration. Such concern prompted NASA to form the Lunar Airborne Dust Toxicity Advisory Group (LADTAG) in 2005. After extensive *in vitro* and *in vivo* testing, LADTAG was able to recommend a safe exposure estimate for lunar dust particles, and at present, NASA has set that value as the preliminary permissible exposure limit (0.3 mg/m^3) to be used in design studies for forthcoming lunar missions in the Artemis program. The program plans call for several phases with increasing potential exposure to lunar dust, both in terms of quantity and time, as the residence time of humans on the lunar surface increases. Further, the number of astronauts will grow as the Artemis program proceeds, raising the possibility of toxic effects in some. Particular attention must be devoted to designing those IRSU activities that exploit lunar rocks and soils. The main activities that could expose astronauts to airborne lunar dust have been ranked as follows: i) routine EVAs, including EVAs for scientific activities and construction, maintenance, and ISRU purposes; ii) astronauts' transfers between the lunar surface, lunar habitat, lunar access vehicle, and crew exploration vehicle (CEV); iii) activities during a contingency situation; and iv) engineering failure of the dust control systems.

The main route of exposure to lunar dust is certainly inhalation. However, the new prolonged exposure scenarios require that other non-pulmonary exposure routes are taken into consideration. These include but are not limited to: i) skin penetration; ii) ocular exposure; iii) gastrointestinal exposure; and iv) indirect exposure to toxic soil contaminants through edible plants.

The new planetary exploration phases envisaged by the Artemis program will require the availability of a new generation of celestial dust simulants, specifically designed to consider the new long-term exposure. In particular, a "root simulant" (perhaps more than one), mineralogically similar to celestial soil, will need to be adapted to toxicological studies by considering: i) particle size distribution; ii) the occurrence of crystalline and amorphous phases that are not present in Earth materials; and iii) the effect of space radiation on the chemical reactivity and solubility of the crystalline and amorphous phases.

The analysis of the currently available simulants highlights the need for experiments that will deliver the necessary information to design toxicologically relevant simulants. *In situ* quantification of the surface reactivity of the lunar dust should ideally be carried out on the lunar surface prior to the long-term sustained presence of humans.

Looking forward to lunar and Martian exploration objectives, additional *in vitro* and *in vivo* studies are urgently needed to expand the understanding of the effects of short- and long-term exposure to celestial dust on human health. Ideally this work should have begun before the next humans put their footprints on the Moon, and ultimately on Mars, to keep our crews safe.

Acknowledgments

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CHAPTER NINE

HUMAN EXPOSURE TO LUNAR DUST IN THE ARTEMIS PROGRAM: PRIMARY PREVENTION, TOXICITY, AND POTENTIAL HEALTH EFFECTS

PETER ALAN SIM

Introduction

Astronauts have had physical contact with extraterrestrial dust only during the Apollo missions. Lunar dust is extremely fine and powdery in consistency. Individual grains are sharp, jagged, mechanically abrasive, and cling electrostatically to most everything. Apollo 17 Lunar Module Pilot Harrison Schmitt famously experienced the noxious effect of inhaled lunar dust—symptoms he described as "lunar dust hay fever" (NASA, 2005)—and dust on the Moon will be a significant challenge for the inhabitants of a future lunar base, not only from a health perspective, but also because of known and anticipated adverse effects on mechanical devices and surface operations.

NASA's Artemis program is scheduled to return astronauts to the Moon in the next several years. In the 47 years since the final Apollo mission, multiple samples of lunar regolith and dust (unfortunately altered by exposure to Earth's atmosphere) have been exhaustively analyzed, but there are still important gaps in our knowledge.

This discussion will focus primarily on what we currently know about lunar dust and the deducible potential toxic health effects of exposure. The respiratory system will be most at-risk, but the eyes, skin, and quite possibly the cardiovascular and gastrointestinal systems may also be affected. Prevention of exposure should be the ultimate goal, but plans to monitor, minimize, and mitigate almost inevitable exposures must also be in place.

Primary Prevention of Exposure to Lunar Dust

The avoidance of direct human contact with lunar dust will be of paramount importance. Both old and new technologies and methods of dust control, along with careful monitoring of astronauts and their environment, must be utilized to keep exposure as close to zero as possible. This is both an essential and achievable goal. As we have painfully learned once again during the COVID-19 pandemic, primary prevention of a medical problem is always superior to remediating the problem after it has occurred. It is both much more efficient and less costly, especially when dealing with a sizable population of those at risk. A common example of primary prevention would be vaccinations, particularly against dangerous and sometimes deadly illnesses, like tetanus, diphtheria, measles, polio, or coronaviruses.

Scuba diving provides a good analogy to space exploration, where humans enter an unnatural environment full of hazards, especially (in the case of diving to significant depths) the effects on the body of pressure on gases. One's life depends—literally—on comprehensive training and excellent equipment in good working order. Potentially deadly effects can be almost completely eliminated through knowledge of the risks, proper training, and appropriate equipment. But unanticipated accidents and events may still occur, and in these instances prior education and drills can minimize the consequences. Therefore, when astronauts enter the lunar environment they must be prepared to deal with the sequelae of significant exposure to lunar dust, should it occur.

Time and Location of Maximal Risk

Most potential exposures will occur when astronauts move from one protected environment to another, such as spacesuit to hab, or hab to suit to rover. Changing into and out of spacesuits and thereby possibly exposing the interior of a breathable environment to lunar dust will require great caution and carefully thought out, prescribed maneuvers. Post-EVA (extravehicular activity) periods will be the time of greatest potential dust exposure. The new xEMU suit (Exploration Extravehicular Mobility Unit) has a group of dust-tolerant features to prevent inhalation or contamination of the suit's life support system or spacecraft. Keeping habitats dust-free by minimizing incursions and establishing effective atmospheric filtration systems will be a major challenge.

Monitoring the dust that is present inside lunar habitats will be crucial, since the hab is the place where astronauts are most likely to be exposed.

Because of this, the quantity, size, and potential toxicity of the “hab dust” is of paramount importance. Dust monitoring requirements are essential before the Artemis missions begin (McCoy, 2020).

Determinants of Lunar Dust Toxicity

The key characteristics of the lunar dust particles to consider are: 1) particle size; 2) particle morphology and surface reactivity; 3) chemical composition; and 4) biopersistence (Fubini and Otero-Arean, 1999).

Particle Size

That particle size is important in determining the health effects of dust exposure has long been appreciated. The U.S. Environmental Protection Agency has more stringent regulations for particles smaller than 2.5 µm (termed PM2.5, with a 24-hour exposure limit of 35 µg/m3) compared to particles smaller than 10 µm (termed PM10, with a 24-hour exposure limit of 150 µg/m3) (EPA, 2012).

The median particle size of lunar dust averages 70 µm (Lucey et al., 2006), but 10%-20% of the soil is even finer, less than 20 µm (Heiken, Vaniman, and French, 1991). Particle size is a key factor in toxicity studies because it defines transport pathways into the lung. The total *inhalable* dust fraction is that portion of airborne material which enters the nose and mouth during breathing and is therefore available for deposition in the respiratory tract. Most of this material will be cleared from the lungs by the mucociliary clearance system. The *respirable* dust fraction is that smaller-sized portion (considered to be < 5 µm) which penetrates deepest, to the gas exchange regions of the lung, the alveoli (proz.com, 2004).

Particle size determines, to a large degree, where in the respiratory tree a dust particle will land. The transport of inhaled particles in the airways is generally considered to be governed by three principal mechanisms: 1) inertial impaction, which affects particles primarily of a size range >~5 µm; 2) sedimentation, which dominates the size range from ~0.5 to 8 µm; and 3) diffusion, the primary transport mechanism for particles smaller than ~0.5 µm (West, 2001). Because of these different transport mechanisms, the locations in the airway where particles tend to deposit varies by size. Of the three mechanisms, sedimentation is gravity-driven and is therefore altered in lunar gravity, where acceleration due to gravity is only ~1/6 of that present on Earth (Linnarsson et al., 2012: 382-388). The very finest particles (~1 µm and smaller) deposit more peripherally in lunar gravity than in 1G, and this is beyond the reach of the mucociliary clearance system (Darquenne, 2014).

A comprehensive study of the properties and composition of the very small size fraction of lunar dust (particles < 1 μm) is missing (Linnarsson et al., 2012: 272-273). Such a study will be required to bridge the current knowledge gap between size fractions relevant to toxicity studies and the currently state-of-the-art work by Taylor and co-workers that groups all particles < 10 μm as the smallest fraction (Taylor et al., 2010).

Morphology/Surface Reactivity

The shapes of individual lunar soil particles are highly variable, ranging from spherical to extremely angular. In general, the particles are somewhat elongated and are subangular to angular (Heiken, Vaniman, and French, 1991). Imaging of lunar dust particles by scanning electron microscopy reveals convoluted surfaces, with sharp edges and microcraters. Although surface shape and surface area are key aspects in dust toxicity research, the surface morphology of lunar dust grains is at present still poorly characterized (Liu et al., 2008). Superficial lunar dust (the top-most few inches—most relevant to crew exposure) has the least variability among different landing sites; variation with depth is more significant than between equatorial and polar regions.

Although the current consensus is that surface reactivity is likely a secondary consideration, the breaking of surface bonds on mineral substrates on Earth has been shown to increase the toxicity of well-studied minerals like quartz. "From what we know about lunar dust, it's fairly reactive and it has properties that are quite similar to fresh fractured quartz here on Earth. And fresh fractured quartz is known to be very toxic" (Prisk, 2013). However, NASA studies show a poor correlation of reactivity with the observed toxicity of studied dusts (McCoy et al., 2020).

Environmental conditions that produce reactive sites on lunar dust are diverse, and some examples are solar radiation fluxes, micro-meteoroid impacts, and plasma charging at the terminator (James and Kerschmann, 2008). Size reduction may lead to an increase in surface reactivity (Fubini, Ghiazza, and Fenoglio, 2010).

Because they have not been exposed to radiation and micrometeoroid impacts for the last 46 years, and have not been kept under vacuum, the chemical reactivity of Apollo-era lunar samples is not likely to mirror that of lunar material in situ (Linnarsson et al., 2012: 806-810). In 2015, McKay et al. separated the respirable dust and other size fractions from an Apollo 14 bulk sample in a dry nitrogen environment. At the end of their study they concluded: “Uncertainty remains as to how well we have simulated the physical and chemical state of fresh lunar dust, which cannot be addressed without fresh lunar soil tested immediately after collection. Such studies must await future lunar sample return missions or in-situ measurements on the lunar surface” (McKay et al., 2015).

Chemical Composition

The Apollo samples studied to date are of near-equatorial origin, and their mineralogy and physical properties may not be representative of other areas on the lunar surface, including the South Polar region and the floor of the South Pole-Aitken basin, where future landing sites are proposed (Linnarsson et al., 2012: 277-280).

About 5% of lunar dust is composed of a variety of crystalline silicas (Papike, Taylor, and Simon, 1991). Taylor and colleagues suggest that the respirable size fraction of lunar dust is likely dominated by impact glass (amorphous SIO_2) and is rich in metallic nanophase (np-Fe^0) iron (Taylor et al., 2010; McKay et al., 2015). A study by Thompson and Christoffersen confirmed that approximately 80% of submicron dust particles consists of glass (Thompson and Christoffersen, 2010). The proportion of nanophase iron also appears to increase with decreasing dust grain size (Linnarsson et al., 2012: 264). This dominance of extremely small particles, coupled with their abundant np-Fe^0 spheres, makes lunar dust unique among any dusts breathed by humans during their evolution (McKay et al., 2015). We need to know more about the associated gases and metals in the very fine dust fractions (McCoy, 2020).

Vitreous materials (like glass in appearance or physical properties), which are abundant on the lunar surface, have not been rigorously studied in terms of their toxicity. Their reactivity—hence toxicity—might differ from either their crystalline counterparts or other amorphous forms not obtained by mechanical stress, but by e.g. sedimentation. This could have a substantial effect on toxicity, analogous to the observed toxicity contrast between vitreous and precipitated amorphous silicas (Ghiazza et al., 2010). Continuous exposure to radiation and solar winds will enrich the particles in reactive sites and electron-donating centers (Linnarsson et al., 2012, 337-342). This extremely large concentration of surface charges, unsatisfied valencies, and reactive sites is expected to readily react when particles are immersed in any body fluid (Loftus et al., 2010; Wallace et al., 2010). Lunar dust dissolves in aqueous solutions like those found in the human body, possibly releasing a variety of toxic materials, including metals like np-Fe^0.

It is possible to create crystalline silica from amorphous silica. Processing the amorphous silica in lunar regolith (e.g. by microwaving to make a hard-surface and relatively dust-free landing site, or “bricks” for construction) could possibly create toxic crystalline silica moieties.

Nanophase iron particles are an expected source of toxic risk both because of their size and the complex redox chemistry taking place at their surface when exposed to air. Such nanoparticles have been reported to be embedded into a vitreous matrix in the rims of lunar dust grains (Wallace et al., 2010). It is currently unknown if direct interactions between the np-Fe^0 and the body will occur. Because of the long clearance times expected (possibly allowing enough time for partial dissolution of the amorphous silicate) and the continuous particle disruption taking place at the Moon’s surface, it seems likely that the reduced iron surfaces will come in direct contact with body fluids, cells, and tissues (Linnarsson et al., 2012, 361-369). But we do not yet know if submicron glass particles with $npFe^0$, inhaled beyond the limits of mucociliary clearance, truly represent a source of toxicity.

“Vitreous silica” is a particular form of amorphous silica, much neglected in experimental studies on silica toxicity. In spite of the incorrect term “quartz glass,” often employed as a descriptive, this material is fully amorphous. When reduced in powdered form by grinding, the particulate appears most close to workplace quartz dust but, opposite to quartz, is not crystalline (Ghiazza et al., 2010). Merget et al. (2002) have reported that animal inhalation studies with purposely manufactured synthetic amorphous silica showed partially reversible inflammation, granuloma formation, and emphysema, but not progressive fibrosis of the lungs as seen in silicosis. Epidemiological studies have not supported the hypothesis that amorphous silicas have any relevant potential to induce fibrosis in workers with high occupational exposure to these substances, but one study disclosed four cases with silicosis among workers exposed to apparently non-contaminated amorphous silica (Merget et al., 2002). As silicosis and lung cancer are also found among workers exposed to “quartz glass,” the question arises of whether crystallinity is the prerequisite feature that makes a silica dust toxic. When tested on a macrophage cell line (MH-S), vitreous silica and pure quartz, but not monodispersed silica spheres, showed a remarkable potency in cytotoxicity, nitric oxide synthase activation and release of nitrite, and tumor necrosis factor-alpha production, suggesting a common behavior in inducing an oxidative stress. All of the above features appear to indicate that crystallinity might not be a necessary prerequisite to make a silica particle toxic (Ghiazza et al., 2010). Data are limited, but a risk of COPD (chronic bronchitis or emphysema) cannot be excluded. There is no study that allows the classification of amorphous silica with regard to its carcinogenicity in humans. Further work is necessary in order to define the effects of amorphous silica on the morbidity and mortality of workers with exposure to these substances (Merget et al., 2002).

Biopersistence

Depending upon particle location in the airway, the time it takes to clear the deposited particle from the lung can differ significantly. Both the site of deposition and the time required for removal have the potential to affect the magnitude of the toxic effect of a given particle load delivered to the lungs. Therefore the changes in deposition as a consequence of reduced gravity may alter the toxicological potential of an airborne lunar dust (Linnarsson et al., 2012, 389-394).

Particles that reach the most peripheral (alveolar) regions of the lungs are removed by alveolar macrophages, which engulf the particles (in a process known as phagocytosis) and ultimately transport them to the mucociliary clearance system for removal. However, this process is considerably slower than the direct mucociliary clearance of particles in the more proximal airways. A study in humans using magnetically-labeled particles showed that while approximately half the particles were removed from the lung with a mean residence time of 3.0 ± 1.6 hours, the remaining half of the particle burden had a mean residence time of 109 ± 78 days (Moller et al., 2004). This could greatly increase the toxic potential. Interestingly, Oberdörster and co-workers showed that nano-sized particles can escape macrophage surveillance, producing even longer residence times than have been observed for micron-sized particles (Oberdörster et al., 2005).

Exposure Limits to Lunar Dust

LADTAG (the Lunar Airborne Dust Toxicity Assessment Group) established a PEL (permissible exposure limit) to lunar dust, based on detailed peer-reviewed studies, specific to conditions existing on the lunar surface: Exposure to particles < 10 μm in the habitable atmosphere shall remain below a time-weighted average of 0.3 mg/m3 during intermittent daily exposures, for up to 6 months in duration. The standard presumes episodic (not continuous) exposures and is conservatively targeted to all particles < 10 μm, but is most applicable to dust < 2.5 μm that may be deposited more deeply in the respiratory tree.

Pneumoconiosis Related to Significant Inhalation of Lunar Dust

Pneumoconiosis is an irritation and inflammation of the lungs caused by the inhalation of dust or other particulate matter, generally over an extended period. Lunar dust is about 5% crystalline silica, but quartz is notably rare on the Moon (Papike, Taylor, and Simon, 1991), and the majority (80%) of the very smallest (submicron) particles in the respirable portion (<5 μm) consists of impact glass.

Silicosis is a specific pneumoconiosis due to the deposition in the lungs of fine respirable dust containing crystalline silicon dioxide. Silicosis presents as a nodular pulmonary fibrosis, and the most common form of the disorder only develops after decades of exposure, however accelerated silicosis can develop after several months or years of high-level silica dust exposure. The end result is respiratory impairment characterized by dyspnea, hypoxemia, and pulmonary hypertension.

The long-term inhalation of silica dust on Earth also increases the risk of COPD, lung cancer, autoimmune disease, chronic kidney disease, nocardiosis, systemic sclerosis, rheumatoid arthritis, and tuberculosis (Lara, 2018). The total silica dose one person accumulates over time is expressed as “mg/m3 years,” calculated by multiplying the average exposure each year in mg/m3 by the number of years with that exposure, or by an estimated average for each year. As the total dose increases, so does the likelihood of developing silicosis, lung cancer, or COPD (silica-safe.org, 2019).

The respirable portion (< 5 μm) of lunar dust is primarily composed of amorphous (vitreous) SiO_2, and it will be deposited more peripherally, i.e. more in the alveoli, in lunar gravity (0.166 G) than on Earth. As stated above, about 80% of the very smallest (submicron) particles consist of impact glass with abundant np-Fe^0 spheres, but we currently do not know if submicron glass particles with npFe^0, inhaled beyond the limits of mucociliary clearance, truly represent a source of toxicity.

Potential Cardiovascular Effects of Inhaled Lunar Dust

The cardiovascular and pulmonary systems are directly linked at the blood-air interface in the alveoli of the lungs. Gases are able to cross this interface, and dust particles smaller than 100 nm (0.1 μm) are also believed to cross from the alveolar surface into the pulmonary capillaries (Nemmar et al., 2002). Nanoparticles have been discovered in the lymph nodes (Brain, Godleski, and Kreyling, 1994; Harmsen et al., 1985), spleen (Semmler et al., 2004), heart (Semmler et al., 2004), liver (Oberdörster et al., 2000; Peters et al., 2006), and even the bladder (Nemmar et al., 2002) and brain (Oberdörster et al., 2004). Experimental evidence indicates that in exposed rats some nanoparticles reached the brain, overcoming the blood-brain barrier possibly through the olfactory nerve (Oberdörster et al., 2004). These observations raise the question: What are the potential health effects of inhaled particles on the cardiovascular system and the organs where the particles accumulate? There is very good evidence of a relationship between inhaled terrestrial dust and cardiovascular morbidity and mortality. Careful monitoring will be necessary to determine if generally healthy astronauts will run a similar risk from inhaled lunar dust.

Potential Gastrointestinal Effects

Particles cleared from the respiratory tract move via mucociliary clearance to the oropharynx and are then swallowed. These particles are thereby transferred from the respiratory tract to the gastrointestinal tract (Kreyling and Scheuch, 2000; Lippmann, Yeates, and Albert, 1980). Therefore ingestion, either directly by mouth or indirectly by transfer from the respiratory tract, provides yet another potential route of exposure to lunar dust, and the potential risk of adverse effects of ingested dust upon the gastrointestinal system must be considered. A "borderline" association between exposure to dust and a diffuse form of stomach cancer has been found for miners and quarry workers (Santibañez et al., 2012). García-Pérez et al. (2015) found excess mortality from colorectal cancer in the vicinity of Spanish facilities producing cement. The duration of occupational exposures in the above-referenced studies far exceed the comparatively brief exposures likely to be experienced by Artemis astronauts, but when we reach the point of extended lunar habitation, these findings will become more relevant (nasa.gov).

Ocular Toxicity of Lunar Dust

During Apollo missions, lunar dust adherent to spacesuits became airborne when the lunar module left the Moon's surface and returned to microgravity on the return trip to Earth, and it was reported to be irritating to the eyes (Gaier, 2005). The crew simply put on their helmets while the dust was cleared by filters in the environmental control and life support system. No injuries were reported in the available NASA records (Meyers et al., 2012).

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

Skin Abrasions

Because of its profound abrasiveness, lunar dust in contact with the skin may cause friction-induced injuries, especially at pressure points inside a spacesuit. The abrasive properties of lunar dust have been documented in multiple settings (Gaier et al., 2009; Kobrick, Klaus, and Street Jr, 2010). Hopefully the new xEMU spacesuit will minimize this potential. To keep the dust at bay, the xEMU does not have zippers or cables, and its main components are sealed. Possibly an electrostatic (or other modality) cleansing of the interior of the suit to remove any intrusive dust particles prior to donning, or "underwear" to protect vulnerable friction points, may be of benefit.

Conclusion

Because of its physical and chemical properties, human exposure to lunar dust, in sufficient doses, represents a toxic threat to astronaut health when we return to the Moon during the Artemis missions. The risks will be amplified as we establish a long-term presence. The respiratory system is particularly vulnerable, but the eyes, skin, and possibly the gastrointestinal tract and other organs may also be affected. Primary prevention of exposure should be our number one goal.

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CHAPTER TEN

DUST INHALATION IN REDUCED GRAVITY: TOTAL LUNG DOSE, REGIONAL DEPOSITION PATTERNS, AND POTENTIAL TOXICITY

CHANTAL DARQUENNE, ELLEN C. BREEN, AND G. KIM PRISK

Introduction

The deposition of particulate matter (PM, often referred to as aerosols) in the human lung is known to lead to adverse health consequences. On Earth, PM has been implicated as a risk factor in various diseases, both in the short- and long-term, and the atmospheric level of PM has been subject to stringent regulation (Dockery et al., 1993; Pope III et al., 2002). While the toxicity of celestial dust is largely unknown to date, a significant fraction is expected to be in the inhalable and respirable range with potential potent toxicological properties (Allen et al., 1998; Cain, 2010; Graf, 1993). For example, Martian and lunar dust are thought to be highly reactive in nature and may prove toxic when brought into contact with the lining of the human respiratory system (Cain, 2010; James and Kahn-Mayberry, 2009).

Exposure to celestial dusts in future planetary exploration is an almost inevitable consequence of such activities. The Apollo experience showed clearly that dust exposure was unavoidable and that lunar dust was pervasive and readily transported into the habitats (Gaier, 2005). Once inside the habitat, the dust poses a risk to exposed mucous membranes, the eyes, and especially the lungs.

Effect of Gravity on Aerosol Deposition in the Lung

The deposition of inhaled particles in the airways is generally considered to be governed by three main mechanisms: inertial impaction, which primarily affects particles larger than 5 µm; sedimentation, which dominates the size range 1-8 µm; and diffusion for particles smaller than 0.5 µm (Darquenne, 2012). Of these mechanisms, sedimentation is a gravity-driven process and so is altered by changes in gravity level. Studies of aerosol deposition in altered gravity have shown a significant effect of gravity on the amount and site of aerosol deposition in the human lung (Darquenne, 2014; Darquenne et al., 1997, 2013; Darquenne and Prisk, 2013, 2008; Darquenne, West, and Prisk, 1999, 1998). For continuous aerosol exposure, data of total deposition (i.e. the overall fraction of the inhaled particle load that deposits in the lung) show a non-linear relationship between deposition and gravity (Darquenne et al., 1997; Darquenne and Prisk 2008) with overall deposition being reduced in microgravity (µG) and lunar gravity (~1/6G) and increased in hypergravity (~1.6G) when compared to normal gravity (1G) (Figure 10-1).

Gravity affects not only overall deposition but also the relative distribution of deposited particles between different regions of the lung. The gravitational effect on regional deposition is particle size-dependent. For large particles (~5µm), most deposition in reduced gravity occurs centrally, while for small particles (<2µm), there is a shift in the site of deposition toward the lung periphery. Indeed, studies in humans using coarse particles (~5 µm in diameter) show a significant shift in the distribution of deposited particles away from the lung periphery toward large airways when particles are inhaled in µG (Figure 10-2). This shift in deposition pattern is the direct result of a decrease in peripheral deposition in the absence of gravity as opposed to an increase in central deposition (Darquenne et al., 2013). Conversely, for small particles in the size range of 0.5-2 µm, indirect measures of regional deposition in humans following aerosol bolus inhalations suggest that, for a given deposition fraction, deposition occurs much more peripherally in reduced gravity than in 1G (Darquenne and Prisk, 2013, 2008; Darquenne, West, and Prisk, 1999, 1998) (Figure 10-3). These results are also supported by direct measurements of the spatial distribution of deposited particles in rats exposed to fine particles (~0.9 µm) in reduced gravity (Darquenne et al., 2014). Although breathing patterns were not controlled in these animal experiments, there was a trend for both total deposition and for deposition in the central region of the lung to be reduced in µG compared to 1G, while deposition in the lung periphery was similar between G levels

(Figure 10-4). These animal data again suggest that, in reduced gravity, fine particles deposit predominantly in the lung periphery.

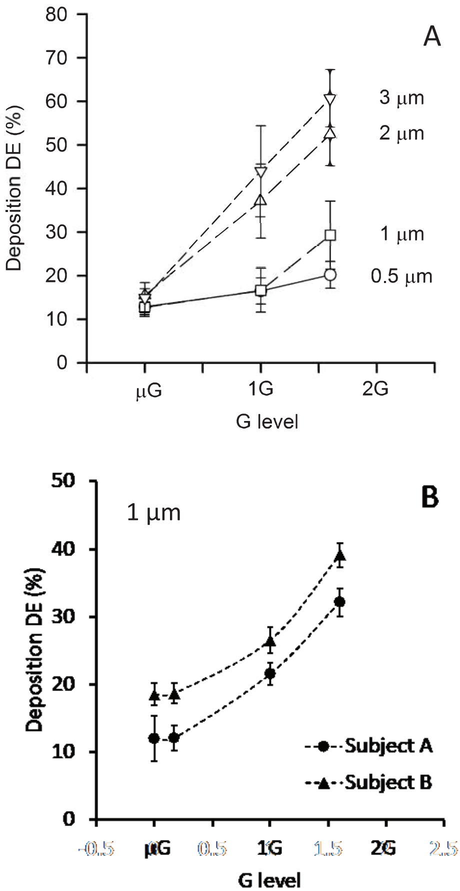

Figure 10-1. Total deposition (DE) of aerosol particles in altered gravity. A: Experimental data (mean ± SD, N=4, healthy subjects) for 0.5-3 µm-diameter particle sizes. Data from Darquenne et al. (1997). B: Total deposition of 1 µm-diameter particles as a function of G level (including lunar gravity) in 2 subjects. Data are averaged over several breaths and are shown as mean ± SD. Data from Darquenne and Prisk (2008).

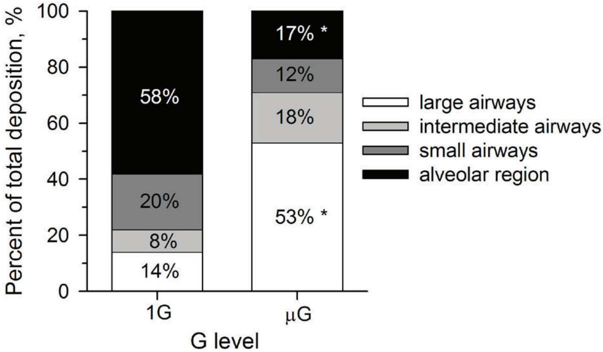

Figure 10-2. Effect of gravity on the distribution of deposited particles between the large, intermediate, and small airways and the alveolar region following controlled exposure to a coarse aerosol (5 μm) in healthy human subjects. There is a shift toward central deposition (large and intermediate airways) in μG. *Significantly different from data in 1G, P < 0.001. Data from Darquenne et al. (2013).

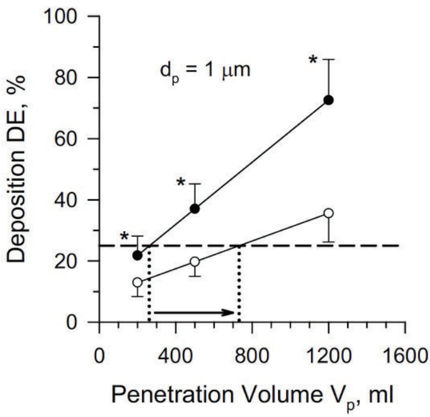

Figure 10-3. Deposition of inhaled aerosol boluses in 1G (closed symbols) and in lunar gravity (1/6G, open symbols) plotted as a function of penetration volume, i.e. volumetric depth in the airways to which the aerosol bolus was inhaled. A penetration volume of 300 ml indicates deposition in the small- to medium-sized airways, while a penetration volume of 1200 ml is within the alveolar region. Although deposition is reduced in lunar gravity compared to that in 1G, a given deposition fraction (say 25%, as indicated by the dashed line) occurs much more peripherally in reduced gravity. Data (mean ± SD, N=6, healthy subjects) from Darquenne and Prisk (2008).

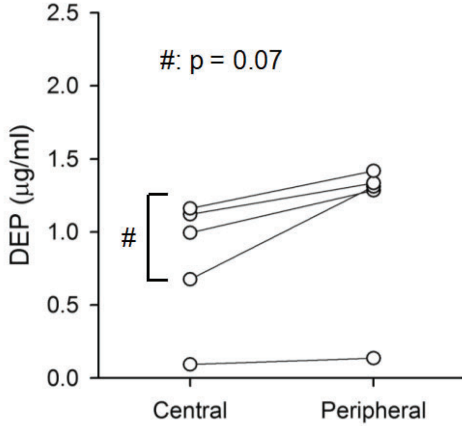

Figure 10-4. Deposition in the central and peripheral region of rats exposed to 0.9 µm-diameter particles in µG (○) and 1G (•) (N=5, mean ± SD). As was the case in humans, there is a shift toward more peripheral deposition in µG for small particles. For purposes of clarity, only one-sided error bars are shown in the figure. Data from Darquenne et al. (2014).

Site of Deposition and Aerosol Retention

Besides the nature of the particles themselves, the toxicity of inhaled particles also depends on aerosol retention, i.e. the difference between the number of deposited particles and the number of particles cleared from the airspaces. Thus, the toxicity of inhaled particles depends not only on how many particles deposit in the lung, but also on how fast deposited particles can be removed or translocated. Put simply, particles that are retained in the lung for a longer period of time have a greater potential to exert any toxic influence.

The lungs are challenged by dusts on a continuous basis and, as such, particle deposition is an ever-present effect. The lung deals with this through clearance mechanisms. Particles that deposit in the conducting airways are primarily removed by mucociliary clearance, whereas most of the particles that deposit in the alveolar region of the lung are phagocytized and cleared by alveolar macrophages. The rate of these clearance mechanisms differs by several orders of magnitude, with mucociliary clearance being very much the faster process (half-life of hours/days versus months/years for alveolar clearance) (Moller et al., 2004; Scheuch, Stahlhofen, and Heyder, 1996). Therefore, the location at which particles are deposited is critical for determining their overall toxic effect as it will determine the time required to clear the particles from the lungs.

Although the effect of reduced gravity on mucociliary clearance and alveolar macrophage phagocytosis remains unknown (Linnarsson et al., 2012), it is likely that, even in reduced gravity, mucociliary clearance will be a faster mechanism than phagocytosis by alveolar macrophages. Therefore, as small particles (i.e. 0.5-2 μm particles) are deposited more peripherally in reduced gravity than in normal gravity (Darquenne et al., 2014; Darquenne and Prisk, 2013, 2008), they will not be readily cleared by the mucociliary clearance system, and thus aerosol retention in the lung will be increased. This increased residence time has the potential to significantly increase the toxicological impact of celestial dust inhaled in reduced gravity.

Toxicity of Celestial Dust

Exposure to celestial dust is a recognized risk for planetary exploration, albeit currently poorly defined. With the exception of lunar dust, celestial dusts are at present uncharacterized as no sample return missions have yet occurred. In the case of lunar dust, where samples are available, studies by the JSC Toxicological Laboratory (Lam et al., 2013) have shown that lunar dust shows a toxicity level between TiO_2 (a nuisance dust) and crystalline silica (Min-U-Sil 5), and these experiments have been used to set the current Permissible Exposure Limits (PELs). However, these studies utilized dust that had been exposed to the atmosphere. At present, it remains unknown whether lunar dust on the lunar surface under a high vacuum has a greater toxicological potential than the studies to date have shown (Linnarsson et al., 2012). However, studies that would utilize “pristine” samples will have to be designed such that the exposures can be performed quickly (before the pristine nature of the samples degrades) and with minimal use of material, given that supplies of curated lunar dust kept under vacuum, or future supplies of celestial dust from sample return missions, will necessarily be extremely limited. Thus, the risk associated with celestial dust exposure may likely not be fully addressable until sample return occurs.

Toxicity is typically assessed by the measure of neutrophil and total protein concentrations in the bronchoalveolar lavage fluid (BALF) of rodents or humans exposed to particulates and/or chemicals. Increase in the number of neutrophils in BALF is a biomarker of lung inflammation, while increase in the total protein concentration relates to lung lining permeability and injury (Wesselkamper, Chen, and Gordon, 2001).

Animal models have long been used as surrogates to predict possible adverse health effects in humans arising from chemical and/or particulate exposures. Studies in rodents have shown that inhalation of both lunar and Mars dust simulants have some of the characteristics of particulate matter that are known to cause adverse health effects in humans (Lam, James, McCluskey, et al., 2002; Lam, James, Latch, et al., 2002). However, the full toxicological effect of inhaled dust may have been underestimated as most animal exposure models of chronic lung disease result in only mild inflammation due to a robust rodent immune system that does not accurately reflect human defense systems (Zschaler, Schlorke, and Arnhold 2014).

The Immune System During Spaceflight

As far back as the Apollo, Skylab, and US Space Shuttle missions, evidence emerged of altered immune function in returning astronauts and of increased vulnerability to infections during spaceflights (Kimzey, 1977; Taylor, Neal, and Dardano, 1986). For example, 15 of 29 Apollo crew members developed bacterial or viral infections during their missions or immediately after their return during the first week after recovery (Hawkins and Ziegelschmid, 1975). While not directly measured, it is possible that the changes in immune responses induced by space flight could have contributed to decreased resistance to infection. Studies in cosmonauts have also shown a severe decrease in the ability of their leukocytes to produce interferon-α/β (an important cytokine that is both antiviral and immunoregulatory) when their blood was sampled and tested immediately after return from flight (Talas et al., 1983). A more recent study by Chen et al. (2017) in Rhesus macaques suggested that long-term microgravity (~6 weeks) might alter the function of the immune system and cause lung damage, altered lymphocyte distribution and function as well as cytokine production.

Alterations in immunity have mostly been documented immediately following spaceflight, and as such, these observations are influenced by the confounding variables of high gravity levels during reentry and readaptation to terrestrial gravity. There is very little in-flight information on the immunocompetence of astronauts. In one study on board the Space Shuttle, Crucian et al. have shown that immune system dysregulation does occur during spaceflight prior to any physiological stress associated with landing and readaptation (Crucian et al., 2013). This observation provides some evidence that human immunity is influenced by flight-associated variables such as microgravity, radiation, and/or the unique stresses that occur during missions. In a subsequent study, the same group studied astronauts during a 6-month spaceflight on board the International Space Station (ISS) and showed that immune system alterations persist during long-duration missions (Crucian et al., 2015).

In future planetary exploration missions, it is very likely that astronauts will be exposed to some level of airborne dust. As missions become longer, the greater dose and/or duration of celestial dust exposure will increase the potential human health risk. A weaker immune system is likely to further enhance any toxicological impact of celestial dust exposure to astronauts during long-duration spaceflight.

A Sensitive Mouse Model for Celestial Dust Toxicity Assessment

The robust immunological response for rodents presents a challenge to performing inhalation studies, should they be performed using actual celestial dust samples or simulants. Because of this robust response, studies must use high dose levels, and the dosing may need to proceed over a long period of time. Both of these effects serve to make these toxicological studies expensive and overly time-consuming. A more sensitive animal model would have the potential to make this type of study more feasible and quicker.

The activation of the vascular endothelial growth factor (VEGF) as a defense mechanism is a first response to sudden contact with pollutants. Our group recently developed a highly-sensitive VEGF-deficient mouse model that better mimics the human immunological response to inhaled irritants (Lee et al., 2019). This model is obtained by targeting the ablation of the VEGF gene to the lung airways through intratracheal delivery of an adeno-associated Cre recombinase virus (AAV/Cre) to VEGF*loxP* mice (Tang et al., 2004).

No studies with lunar or Martian simulants have been carried out in these mice to date. However, the high sensitivity of the model has been demonstrated in a study where mice were exposed to cigarette smoke over a four-month period. Data showed that, compared to control mice on a C57BL/6J background, pulmonary VEGF-deficient mice have a weakened protective lung barrier and display amplified inflammation upon cigarette smoke exposure, as evidenced by a significant increase in neutrophil counts in the BALF (Figure 10-5). These data, along with a pro-inflammatory cytokine response following cigarette smoke exposure, support the use of this innate immune-compromised mouse as a robust model for exposure studies including, in the future, exposure to celestial dusts by either intratracheal instillation or inhalation.

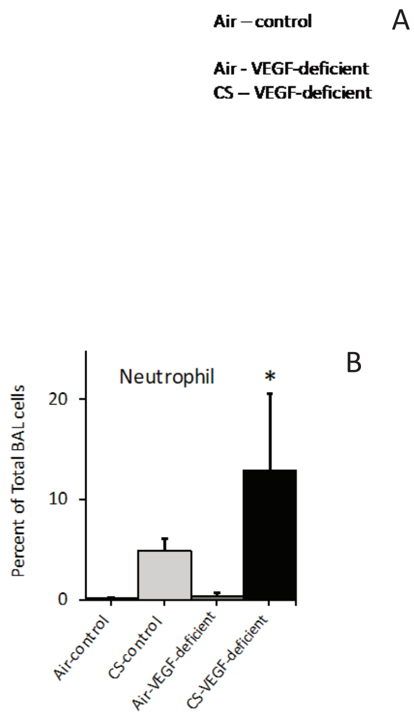

Figure 10-5. A: Differential cell analysis of bronchial alveolar lavage fluid (BALF). B: Zoom of the percent of neutrophils in the BALF for the four experimental conditions. *Significant difference between neutrophil proportions of VEGF-deficient and control mice exposed to cigarette smoke (CS) ($P < 0.05$). Modified from Lee et al. (2019).

Conclusions

There is a significant effect of gravity on the amount and the site of aerosol deposition in the lung, which will likely serve to reduce the clearance of celestial dust particles deposited in the lung during exploration activities. Current data suggest an increase in the retention of small particles deposited in the lung, which is as a result of a more peripheral site of deposition. Combined with any weakening of the immune system during long-duration spaceflight, this increased aerosol retention may significantly enhance the toxicological impact of inhaled celestial dust.

Acknowledgments

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SECTION THREE:

LUNAR DUST REDUCTION AND MITIGATION

CHAPTER ELEVEN

AEROSOL SCIENCE AND ENGINEERING AS AN ENABLER IN THE STUDY OF LUNAR DUST PARTICULATE MATTER: SENSORS, TRANSPORT MODELS, AND MITIGATION

PRATIM BISWAS

Introduction

The lunar surface's soil is characterized by particles with a distribution of sizes and shapes with varying compositions. These particles are entrained as dust in transient environments due to impacts, electrostatic levitation, and human activity (e.g., rocket exhaust, surface movements, and mining). To accurately understand the effects, a detailed description of the particle dynamics that are influenced by the dust particle size distribution (of sizes, shapes, and compositions) is to be developed. However, the only measurements of the dust size distributions have been from samples brought down by the Apollo missions (Park et al., 2008; McKay et al., 2015). There are no real-time size distribution measurements that have been done on lunar surfaces. Accurate and real-time information of the size distribution can be used to develop more relevant models for lunar dust particle dynamics accounting for the distribution of sizes, shapes, and compositions. Simulating the composition-dependent phenomena is also a fundamental aspect of understanding lunar dust charging. As the size distribution of the dust is a fundamental aspect of understanding lunar dust charging, fate, and transport, there is a need to develop an instrument to determine the size distribution of the levitated dust. Aerosol science and engineering can enable such developments working under relevant conditions pertinent for the lunar surface.

Aerosol science and engineering deal with entrained particulate matter systems – starting with formation (clusters from the molecular state), growth (molecule-cluster, particle interactions, particle-particle interactions), transport (interaction with flow fields, and other external fields such as electromagnetic and gravitational), and deposition (Friedlander, 2000; Biswas and Wang, 2019). This fundamental knowledge is relevant for understanding lunar dust (i) characteristics (measurement), (ii) transport accounting for size-dependent phenomena (determining entrainment processes), and (iii) methodologies for the prevention of deposition (protection on future human missions for both equipment and humans). Each of these is described briefly in the following sections.

Lunar Dust Size Distribution Measurements

Advances in aerosol science and engineering have enabled the development of a range of instrumentation capable of measuring particle size distributions in real time, such as the differential mobility analyzer with the condensation particle counter (range of 1 nm to 1000 nm), and other aerodynamic and optical techniques for particles larger than 1 μm up to 100 μm. These instruments are accurate and are widely used in research laboratories and Earth-based atmospheric field studies. Such conventional aerosol instrumentation can accurately measure the particulate matter (PM) concentration at fixed locations and are of a relatively high cost. Due to the larger sizes and higher cost, larger numbers cannot be deployed and thus do not provide high spatiotemporal resolution. Due to these reasons and the bulky sizes, these instruments are not the most practical for use in outer space.

As a potential alternative method for PM concentration measurement, low-cost PM sensors have been studied extensively in Earth-based applications in recent years due to their price advantage, compact size, and moderate accuracy (Li and Biswas, 2017; Li et al., 2018; Patel et al., 2017; Wang et al., 2015). Figure 11-1 is an illustration of the comparison of various instruments with approximate dimensions and price ranges. Compared to bulky laboratory instruments costing up to thousands of dollars, palm-sized and wearable low-cost sensors usually cost in the region of hundreds of dollars. To make low-cost PM sensors functional, circuit board design, programming, and calibration are necessary to establish the relationship between electrical signals (current, voltage, or pulse width) and PM concentrations. After fabrication and laboratory calibration, low-cost PM sensors exhibit good linearity against reference instruments, showing promising potential for personal PM monitors and sensor networks (Wang et al., 2015). These sensor networks can significantly enhance the spatiotemporal resolution with moderate cost, which is very suitable for highly dynamic outer space applications.

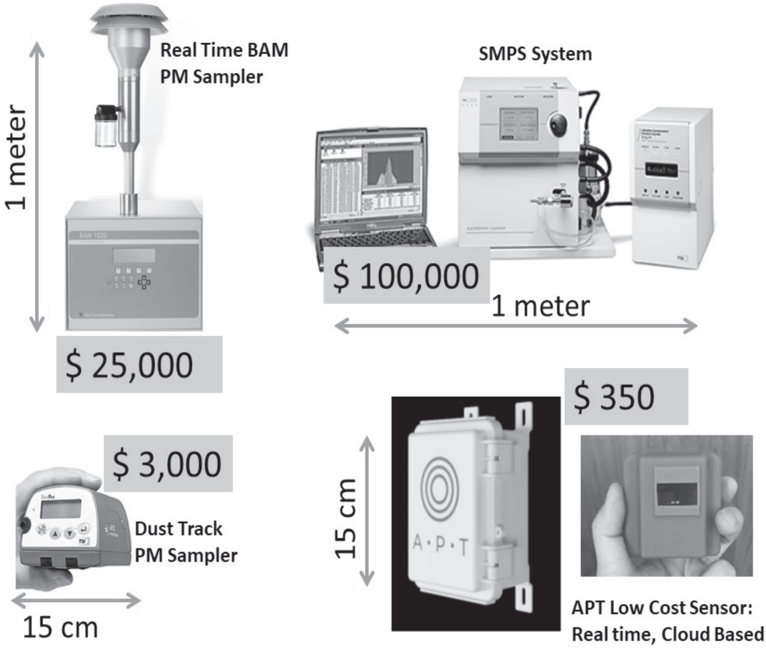

Figure 11-1. Illustration of various types of aerosol instrumentation for the measurement of particle size distributions. Low-cost PM sensors are portable and can be deployed in larger numbers to obtain a high spatiotemporal resolution.

Several researchers have explained the performance characteristics of low-cost sensors on the basis of their working principles (Li and Biswas, 2017; Zhang, Marto, and Schwab, 2018). They have extensively calibrated a variety of low-cost PM sensors for different aerosol sources, and these studies demonstrated the advantages and limitations of these sensors. Networks of these sensors operating on wireless modalities have been deployed in various environments such as households, meeting rooms, factories, and cities to monitor the dynamic process of particle events with high spatiotemporal resolution (Kim, Chu, and Shin, 2014; Leavey et al., 2015; Patel et al., 2017; Jeon et al., 2018). Several of these studies have developed and examined the algorithms used to organize sensor data and extract appropriate information (Li et al., 2018). Li et al. (2020) demonstrated an integration of measurements from multiple methods by synergizing the data from 75 stationary monitoring stations, 2,363 low-cost sensors, and the Terra remote sensing satellite for the island of Taiwan. A machine learning method was used to identify useful data from the large low-cost sensor datasets, following which ordinary Kriging was used to create a daily PM concentration map. Their results successfully demonstrated an improvement in the data quality and creation of heat maps to also enable deciphering sources of particulate matter. Similar modalities demonstrated for Earth-based observations can also be used to obtain lunar spatial surface dust distributions.

Another important application is combining low-cost PM sensors with drones or other unmanned vehicles for sampling environments where the setup of a static sensor network may not be viable. Our group (Cashikar, Li, and Biswas, 2019) developed a mobile robot cart with a low-cost PM sensor (AAQRL-ROBOPM ©) to map spatial PM distributions over time. The robot was moved via Bluetooth inputs from an Android device, autonomously by following preprogrammed instructions, or with basic artificial intelligence (AI) and an algorithm. PM concentration readings were sent to the Android device for monitoring and storage. The mobile sensor module was tested for both indoor and outdoor environments, and effectively found the locations of the highest PM concentrations.

There are many low-cost sensors available commercially, and these include MAXIMA and MINIMA (Applied Particle Technology [APT], illustrated in Figure 11-1), Purple Air, Alphasense, and Dylos (Li, Mattewal, and Biswas, 2019). These use a single particle counter which measures the size distribution by sorting the scattering signal into multiple size bins. The APT and Purple Air sensors are equipped with a Plantower (Plantower Co., Ltd., Beijing, China) single-particle sensing module. The Alphasense and Dylos sensors have custom-designed sensing modules. Due to the differences among these various sensors, the data reporting formats of each are different. The APT and PurpleAir sensors report the size distribution of particles ranging from 0.3 to 10 μm distributed into six bins. The Alphasense has a better resolution and reports the sizes ranging from 0.3 to 38 μm in 24 size bins. The Dylos has only two bins for particles larger than 0.5 μm and 2.5 μm, respectively. The PurpleAir and APT monitors can upload data to a webpage or dashboard through a Wi-Fi module. Alphasense and Dylos do not have a wireless module, hence they need to be connected to a computer to store and display data in a real-time manner. The Alphasense, APT, and PurpleAir technologies also have internal off-line data logging systems that can record the data on a Micro

SD card in the event of a connection malfunction. The sampling interval of the APT is adjustable, and for most of these sensors, a high frequency (every second or faster) of data collection is possible.

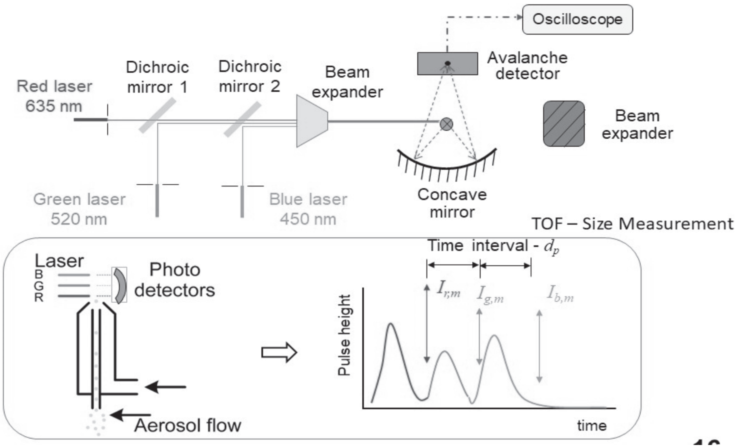

Figure 11-2. Illustration of a multiwavelength and multiangle scattering intensity detection system for PM sensors. Integrated with the system is a time of flight measurement to independently obtain the size of the particles.

This knowledge base can also be used to develop newer designs that would be appropriate not only to provide physical measurements of particle size distributions, but also to obtain information on refractive indices (representation of the chemical composition) of the particles. Figure 11-2 illustrates a concept of a layout where multiple wavelengths and scattering angle measurements can provide a robust data set for inversion to obtain the above information. Machine learning-based algorithms guided by optical scattering theories are used for such configurations to obtain the particle size, shape, and refractive index (composition) of the particles.

While these instruments have been developed for Earth use, the features described above can be readily modified for outer space applications. Based on these design principles, units can be fabricated for deployment as a series of networked PM sensors for the measurement of lunar dust.

Preliminary measurements of lunar dust simulants using these sensors are being obtained (Vidwans et al., 2020). Furthermore, a network of these sensors could be deployed and integrated with satellite measurements for mapping out lunar dust concentrations with greater accuracy.

Transport Models for Lunar Dust

There is a need to develop comprehensive particle transport models for continuous particle distributions accounting not only for size and shape, but also for the size-dependent distribution of charge and composition. Such models cannot only be used to study levitated dust characteristics, but also to examine deposition onto surfaces. Strategies to minimize the deposition of dust on instruments and infrastructure will be proposed based on the results.

The generalized governing equation for particle transport can be written accounting for the various forces and particle-particle interactions as (Bai and Biswas, 1990),

$$\nabla \cdot (n(v)\vec{U}_p) = 0 \tag{1}$$

Expanding the equation, and accounting for various dynamic phenomena, the equation is

$$\nabla \cdot (n(v)\vec{U}_p) = \frac{1}{2}\int_0^v \beta(v', v - v')n(v')n(v - v')dv' - n(v)\int_0^\infty \beta(v, v')n(v')dv'$$

where the velocity of the particles (U_p) is expressed as

$$\vec{U}_p = \vec{U} - \frac{2}{Pe}(\nabla \ln(n)) - \quad St(\vec{U} \cdot \nabla)\vec{U} - \frac{2K_t}{\mathrm{Re}}\frac{\nabla T}{T + T'} - \vec{U}_{ext} \tag{2}$$

and where U is the fluid velocity, Pe the Peclet number, St the Stokes number, Re the Reynolds number, and T the temperature. Two sets of force fields should be considered to examine levitation: 1) lander jet engine exhaust and coupling the flow fields to the aerosol dynamic models, and 2) solar radiation- and solar wind-induced surface plasmas resulting in electrostatic forces. Post levitation, aerosol transport models can be solved in varying pressure flow fields for 1) and under vacuum conditions where drag and diffusional forces are negligible for 2). In the transport model for lander jet engine conditions, additional complexities are to be considered due to particle phenomena in multiple regimes – free molecular, transition, and continuum regimes (as determined by the local Knudsen number). For the solar radiation levitation models, the particle transport processes are governed by free molecular regime expressions. Finally, the transport equations listed can be solved to establish deposition rates onto surfaces of interest (space suits, lander surfaces, instrumentation).

Several numerical approaches are being used to solve the particle transport and dynamics equations (Zhang et al., 2020). These include mathematical integral methods such as moment and modal methods, which are fundamental and simpler for simulating particulate behavior over large spatial and longer temporal scales.

Dust Capture Methodologies

As highlighted in a comprehensive report by the National Research Council of the US National Academies, a critical need for future exploration architecture is an effective dust mitigation system that needs to be engineered to last for longer days under harsh environmental conditions. Electrostatic precipitator units have been proposed for use in outer space applications for both lunar and Martian exploration (Calle et al., 2011). The Aerosol and Air Quality Research Laboratory has significant expertise in dust (aerosol) control technologies (Zhuang et al., 2000; Jiang, Lee, and Biswas, 2007; Kulkarni et al., 2002; Lee et al., 2016).

While electrostatic precipitator designs have been proposed and used by earlier missions, there are certain minima in the selected size ranges for these devices. This is due to a fraction of particles not being charged, especially in the submicrometer size ranges (Zhang et al., 2000). One key methodology that has been developed is the integration of photoionization with the corona-based electrostatic precipitator systems that enhance the charging of particles to ensure high capture efficiency across the entire size spectrum of interest (Kulkarni et al., 2002; Kettleson et al., 2009, 2013). This is especially effective for submicrometer-sized particles that are prevalent in lunar dust, and the capture efficiency as a function of particle size is shown in Figure 11-3.

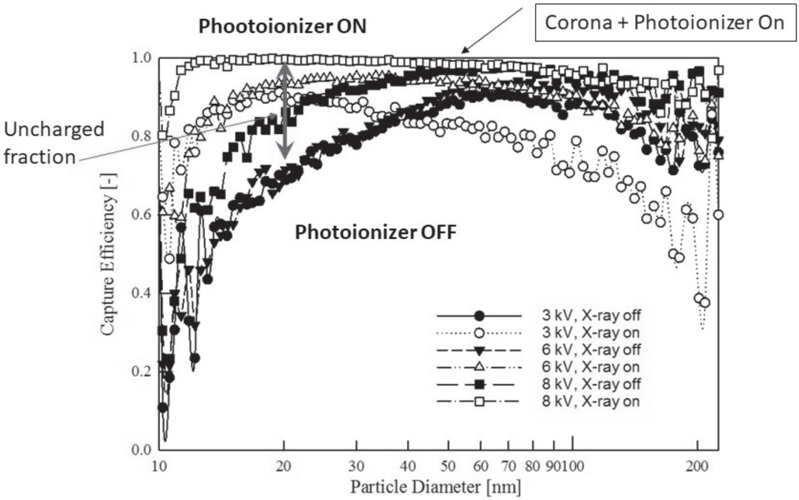

Figure 11-3. Enhancement of the capture of submicrometer-sized particles using a photoionizer-enhanced (soft x-ray in these experiments) corona system. Ozone production is also completely suppressed, making it useful for human compatibility.

The designs discussed in these studies are readily amenable for use in the cabin environments of the lunar modules and habitations to be set up. A key advantage of the use of these systems in the future habitats for longer-term human occupation is the ability to remove not only lunar dust particles with high efficiency at a lower operating cost, but also bioaerosols (such as human-generated viruses and bacteria) with high efficiency. New designs will be necessary for outside applications to prevent deposition onto equipment surfaces. However, the use of electrostatic fields for mitigation is a favorable methodology to use as lunar dust particles carry a nascent charge, as described above. Finally, such systems can be readily integrated with miniaturized PM sensors for the real-time tracking of concentrations to ensure their safe operation and for the added protection of human explorers.

Summary

This paper has outlined how aerosol science and engineering can assist in addressing issues related to lunar dust. From fundamental knowledge of particle transport and deposition under a variety of conditions, including size regimes from free molecular to continuum, size distribution, including shape effects, pressure (vacuum), and flow (jet engine exhausts), one can not only develop accurate models but also design instruments for measurement and design mitigation methodologies. A few examples have been provided, but more needs to be done to demonstrate the feasibility of the proposed approaches by utilizing the expertise of aerosol scientists and engineers.

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CHAPTER TWELVE

TESTING AND INTEGRATED CONCEPT OF OPERATIONS THROUGH SIMULATION AND ANALOGS WITH TECHNOLOGY FOR DUST QUANTIFICATION, CHARACTERIZATION, AND MITIGATION

ESTHER BELTRAN, JULIE BRISSET, AND ASHLEY ROYCE

Introduction

The National Aeronautics and Space Administration (NASA) and its commercial partners are planning for several manned and robotic missions to the Moon in the next few years, as part of the Artemis program. These missions, in part, will use the surface of the Moon as a test-bed to ensure that vital equipment can be protected in harsh environments, in preparation for future explorations to Mars. Of particular interest is protecting instruments from increased surface activity that exacerbate dust-related hardware issues. We are now at a crucial point in space exploration when human missions to the Moon are being planned and there is a strong need to address the impact of dusty environments on hardware and science measurement quality. Understanding the regolith's material properties and its interactions with human space operations is required in dust mitigation approaches. Disparate technologies are currently scattered throughout NASA's Mission Directorates roadmaps. An integrated, crosscutting strategy concept of operations is a powerful tool to evaluate the effects of lunar dust on human missions. In this paper we will discuss some background information on the regolith, and a research strategy will be proposed in order to address knowledge gaps identified in the lunar dust mitigation workshop. Our goal is to show how taking advantage of current technologies can benefit and considerably expedite solve problems for human space exploration on the Moon. Acknowledging these described approaches can also pave the way for and help develop the capabilities needed for human missions to Mars.

Background on the Regolith on the Moon

As we know from Solar System exploration missions, many planetary bodies are covered by regolith of various size distributions (e.g., McKay, Fruland, and Heiken, 1974). In particular, target objects of current interest to NASA missions to the Moon, which is vastly covered by a fine-grained regolith, which interacts with any landed hardware on the planetary surface. The regolith can be generated by various weathering processes. On the Moon, the absence of atmosphere allows for micrometeorite impacts and solar wind irradiation to garden the surface material, creating

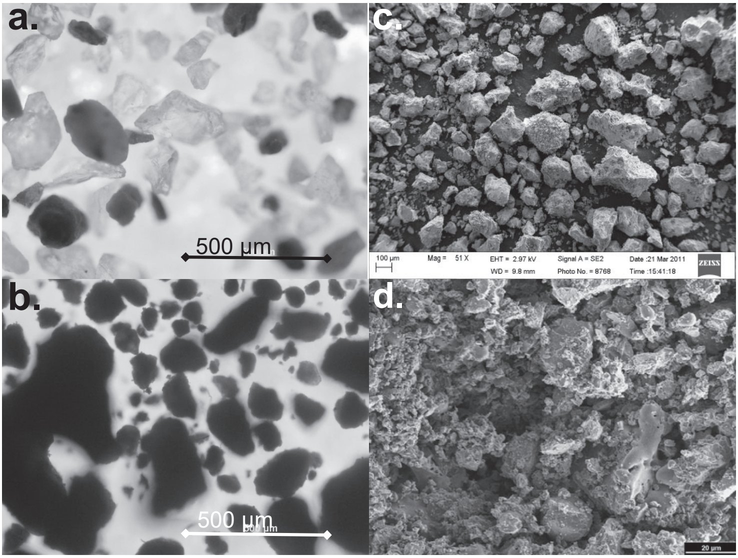

Figure 12-1. Microscope pictures of the regolith and simulants (a) Quartz sand grains, characteristic of Earth-type regolith; (b) JSC Mars-1 simulant grains displaying rounded shapes similar to the sand grains; (c) Scanning Electron Microscope (SEM) pictures of JSC-1 lunar simulant grains, showing similar shapes and surface structure to (d) SEM pictures of actual lunar regolith collected in a mare basalt region during the Apollo 12 mission (Photo credit: Brisset et al. 2018; Robens et al. 2007).

irregular and abrasive grains with sizes <1 mm (e.g., King, Butler, and Carman, 1971). Interaction with solar plasma charges regolith grains and causes them to stick to any surfaces and materials exposed to them (Calle et al., 2011; Vangen et al., 2016). On Mars, the regolith is believed to have been generated by erosion processes more similar to the ones operating on Earth (e.g., Ojha et al., 2018), thus leading to more rounded grains (**Error! Reference source not found.**) in a highly oxidizing environment.

Robotic and Human Interactions with Lunar Dust: "The Moon Space Operations Mud Room"

Moon dust is expected to influence all Moon surface operations, ranging from power systems, habitats, rovers, extravehicular activities (EVAs), re-evaluating parts of the design of spacesuits, retrofitting already operational elements, and tools. How we approach solving the findings on the identified knowledge gaps will help us in our understanding for better-suited space operations for the Moon's dusty environment. These issues can be addressed prior to humans setting foot again on the Moon, and for its planning by using upcoming robotic missions. Landed missions to the Moon and Mars have collected the first data on how planetary regolith behaves when interfacing with robotic equipment and human spacesuits. In particular, mission reports from the Apollo program detail the extreme nuisance associated with the fine surface dust in the absence of an atmosphere when performing exploration and science operations on the surface of the Moon (Gaier, 2005). The authors clearly defined two general dust transport mechanisms: natural and anthropogenic (Gaier, 2005). The report also sorts the problems encountered into various categories, including false instrument readings, dust coating and contamination, and thermal control problems. Gaier (2005) analyzes each of these problems, detailing the issues encountered by the Apollo astronauts and their equipment, and concludes that dust will be a major issue to deal with during future long-duration activities planned for the Moon.

Since it is clear the lunar dust problem consists of these two major transport mechanisms, we present an approach to solve for the one generating its largest effect: the anthropogenic, human-induced processes. In the absence of atmosphere and low gravity, Moon dust is easily levitated. Katzan and Edwards (1991) identify the currently known natural sources of Lunar dust levitation due to meteoritic impacts, terminator electrostatic levitation, and find that their production of suspended dust particles is negligible compared to the amounts generated by human-induced activities, i.e: rover operations, possible mining and construction, or even walking. The anthropogenic generation of Moon dust is the tenacious deposition of levitated dust on all types of surfaces. This leads to not only mechanical issues, but also to loss of performance for several hardware and instrument components; these include radiators, solar panels, and any optical surfaces of instruments, such as cameras or spectrometers. Such problems can aggravate into fatal failures of robotic equipment by overheating of electronic components or loss of power, which is illustrated by several instances of rover loss believed to have occurred due to dust-related issues. For example, Lunokhod 2 accidentally dumped regolith on its solar panels and then on its radiators, eventually causing it to overheat and stop functioning (Stooke, 2007).

The planned increase of scientific, exploration, and exploitation activities on the Moon requires a thorough understanding of how to protect instrumentation from the ever-present dust.

In this article we will explore the idea of implementing an integrated concept of operations (CONOPS) based on simulations and testing in analogs with available technologies to evaluate, determine, and make possible recommendations as to what would be the best strategies for lunar dust mitigation for human operations. These approaches will be departing from work already identified and cited in existing dust mitigation methods by the "2016 Dust Mitigation Gap Assessment Report" by the International Agency Working Group. The working group identified areas of improvement ranging from fluid-based methods (e.g., use of CO2 or incompressible fluid jets or gel or foam) to electrical methods (Clark et al., 2009 Calle et al., 2011; Kawamoto and Inoue, 2012), to filtration and coatings. Mechanical methods, such as brushing, were found to be ineffective in the Apollo missions (Wagner, 2014). The best strategy is what is currently used in other operational settings in other fields of study, a combination of methods, with a specific step-by-step flow to decrease the effects of lunar dust on human surface operations. This concept of not a single method of dust mitigation but a combination of multiple ones is presented by Wagner as a layered engineering defense approach (Wagner, 2014). This approach is based on a holistic method encompassing identified best NASA practices and technologies, including lessons learned from the Apollo missions with their implications on crew maintenance time, and evaluations of the possible enhancement or hindrance of incorporating autonomous systems which will require additional mass and power for the entire space operation system.

Sustaining Human Presence on the Surface of the Moon

Our project uses preliminary laboratory data, incorporates data from wearable devices, and integrates it in combination with virtual simulations. Our goal is to understand the implications on crew operations, maintenance, and preparation time, and to do preliminary testing with lunar regolith simulant to support possible solutions for the lunar dust mitigation and control working group. Our project will provide results and findings for the identified strategic knowledge gaps. The overall goal is to help with the characterization and optimization of lunar dust for space operations, while we can also incorporate steps for scientific lunar operations on pristine regions of the Moon. Additionally, we develop and test possible operational protocols that will help to pave the road for tackling the concerns over human missions to Mars regarding Planetary Protection (PP), as listed in the 2018 Planetary Protection consensus report of the Committee on Space Research (COSPAR) (Kminek and Rummel, 2017).

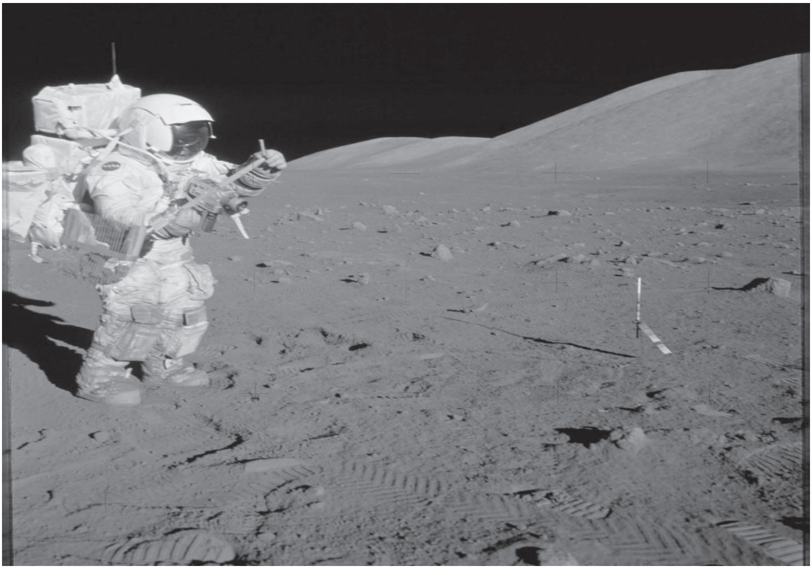

Figure 12-2. Astronaut Harrison H. Schmitt, Apollo 17 (Photo credit: space.com).

Creating Possible Scenarios for Space Operations

By studying the interactions between the regolith and mission equipment and operations, our project is preparing for upcoming operations on the dusty surface of planetary bodies and aims to support future landed missions to the Moon. The goal of our investigation is the development of operational procedures to optimize scientific activities on regolith-covered planetary surfaces. Our innovative approach combines small-scale laboratory experiments with integrated wearable device measurements and computer simulations, working with state-of-the-art regolith simulants composed and identified for the correct specific operational region of the Moon (Exolith Lab).

Our project has been divided into three themes:

Theme I: Characterize the interaction between equipment and dusty surfaces

This theme studies (1) how operations on dusty surfaces generate increased dust pollution; (2) how hardware performance is impacted by these increased dust levels; and (3) mitigation options for hardware protection.

Theme I.A: Quantify the levels of dust production from robotic and human activities in relevant Moon conditions and classify the expected dust pollution for various operational scenarios

In this theme, we quantify the amounts of dust that will be lifted during operations in low-pressure, low-gravity environments. Katzan and Edwards (1991) performed a first analysis of the ranges to which artificially lifted dust would reach, but no quantification has been provided yet of the overall dust pollution to be expected from regular activities on the surface of the Moon. **Science**: We study regolith lifting by the surface interfacing of equipment activity (impacts, grinding, drilling, etc.) in various environmental conditions (low-pressure, low-gravity) and on various scales (local, intermediate, global).

Theme I.B: Quantify the impact of dusty environments on mechanical and electronic (i.e., instrument support) hardware performance

We measure the performance loss of radiators and solar panels during operations in the lunar environment. As some data is available in the literature on the impact of dust coating on radiator and solar panel performance (Hollingsworth et al., 2006; Appels et al., 2012; Sayyah, Horenstein, and Mazumder, 2014), we are working on running a limited number of tests for the purpose of evaluating our measurement setup. **Science**: We perform hardware performance measurements in various environmental conditions and compare the measured performance with models and published experimental data. **Science Operations**: We study hardware performance in dusty environments during a variety of operation scenarios during field tests. **Technology**: We perform laboratory and field measurements on specifically purchased radiators and solar panels mimicking planetary exploration hardware. We will also field-test the Regolith Advanced Surface Systems Operations Robot (RASSOR) developed at Swamp Works (Mueller et al., 2013) and monitor its health and status data for various levels of dust pollution.

Theme II: Optimizing science measurements on surfaces covered in the regolith

This theme characterizes the effect of dusty environments on science measurements with the goal of getting a thorough understanding of how dust affects scientific measurements, such as micro-structures essential to future mission operations. We test dust mitigation solutions and quantify instrument performance after their implementation. In this theme, we implement the same mitigation solutions used in Theme I, namely engineering controls and electrostatic shielding/cleaning, to relevant instrument components and subsystems. We design and implement the installation of these mitigating components and measure the instrument performance after outfitting with these mitigation solutions. **Science**: We perform instrument performance measurements after the implementation of dust-mitigating solutions in various environmental conditions and compare the measured performance with the one before implementation. **Science Operations**: We study the performance of the newly equipped instruments in dusty environments at the subsystem and system levels during a variety of operation scenarios. **Technology**: We design and implement the engineering controls discussed in Theme I and can adapt electrostatic shielding (portable EDS unit) to existing instrument components. We can determine surface material chemistry in a dusty environment involving various combinations of human and robotic systems and identify an optimal combination (automation, teleoperation, human EVA) from the viewpoint of human safety and the precision of the data and measurements collected.

Theme III: Prevention and mitigation of lunar dust for sustained human presence and operations on the surface of the Moon

We are developing and integrating CONOPS testing for NASA operational protocols aimed at mitigating the impact of dust on equipment and measurements and minimizing it. These protocols, together with the data gathered during our project, can then be further expanded and used as needed for the generation of possible PP procedures to work on pristine regions of the Moon. Also, we aim to enhance mission planning for a sustained human presence on the Moon and for future missions to Mars. Operational procedures are designed and tested using virtual simulations with motion capture technology, virtual reality, and artificial reality, conducted at the University of Central Florida's Downtown Campus in the Florida Interactive Entertainment Academy (FIEA) studio. In this studio we can track and understand human movement, test acceptable crew timelines and crew behavior, and obtain measurements that can streamline the process of humans working and living in these dusty environments. The studio has a 500 motion capture system, which is a centerpiece of FIEA. Motion capture (also known as MOCAP) is a process by which the movements of live actors are "captured" by a large number of specialized cameras that continually track a study participant or an actor's position in a three-dimensional space. Once these movement and protocol simulations have been evaluated to approximate the best possible outcomes, the selected protocols can be further developed and implemented in other Moon analogs and evaluated in other possible natural environments for more operational feasibility and practicability. These tests can be escalated with a set of guidelines and recommendations supporting mission designs in the future.

We are considering one type of mission that will be composed of two major components: (a) resource prospecting and exploitation; and (b) pristine lunar surface investigation. In the near future, missions to the Moon will be more focused on resource prospecting and exploitation, while also developing possible operational capabilities for missions to Mars.

Parameter/Mission Type	**Resource Prospecting**	**Pristine Surface Investigation**
Planetary body	Moon (near-future), Mars (future)	Specific designated areas of the Moon, Mars
Expected dust pollution	High	Low
Instrument sensitivity	Low	High
Planetary protection requirements	Low	High

Table 12-1. Two types of missions considered in the present study.

Laboratory Simulations

Small-scale laboratory simulations of interactions with regolith analogs allow for the thorough preparation and optimization of the operational protocols. In addition, the collected experimental data provides input for scaling field and virtual simulation results to actual planetary environments and full-scale surface operations.

We use three laboratory facilities: the Florida Space Institute (FSI) laboratory, which is equipped with a vacuum chamber and drop tower and has access to various regolith analogs; the NASA Kennedy Space Center (KSC) Swamp Works regolith bin, which contains over 120 tons of lunar dust analog; and the UCF-FIEA laboratory, which is equipped with motion detection and capture hardware geared for the entertainment and videogame industry. To analyze these dust simulation activities fully, our team is using software available to capture the individual movements. This technology allows us to better prepare for space operational procedures and feasible protocols suitable for the complexity and crew time management optimization of lunar missions.

The regolith analog material used in our planned laboratory activities is provided by the FSI's Exolith Lab. This lab produces high-fidelity lunar simulants adapted for use in laboratory environments (e.g., Britt et al., 2018, 2020). These simulants are currently readily used by a variety of research groups for the study of asteroid, lunar and Martian environments.

Development of an Integrated CONOPS for Space Operations with Scenarios for Lunar Dust-related Testing

We include activities characteristic of the robotic and human activities expected to be performed on planetary surfaces in the near and mid-term future (see Table 12-1 for the types of missions considered). Operations protocols can be conducted consistent with NASA's best practices currently used in the leading NASA analogs: the Human Exploration Research Analog (HERA), the NASA Extreme Environment Mission Operations (NEEMO) project, Neoteric eXploration Technologies (NXT), and the Scientific International Research in Unique Terrestrial Station (SIRIUS) project. An integrated and comprehensive CONOPS diagram allows for the traceability of the activities and tasks and for linking them to the available resources.

Operational scenarios include activities such as suited human motion, provided by one of our co-investigators, regolith extraction (shuffling, drilling, hammering, etc.), as well as measurement sequences using the relevant simulation instruments. Measurements performed during the analogs include dust levels produced by various activities, mechanical and electronic hardware performance, and instrument/scientific measurement performance, and, if possible, also assess the level of contamination introduced by the tested activities.

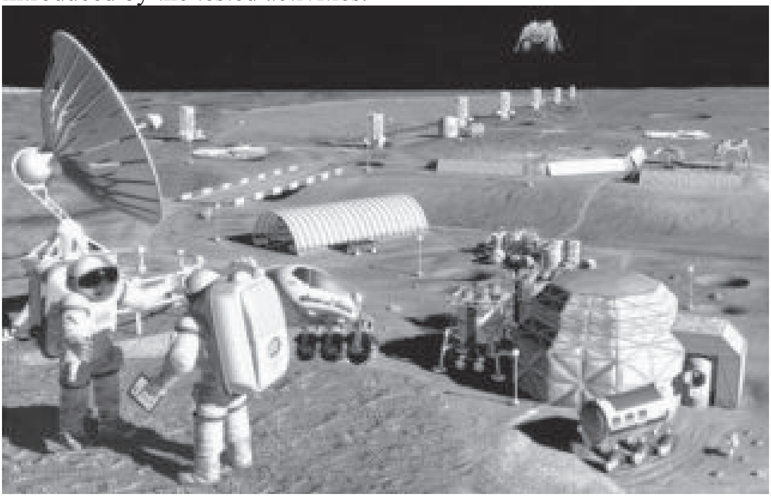

Figure 12-4. Artist's concept of a possible colony on the Moon (Photo credit: NASA).

Virtual Simulations

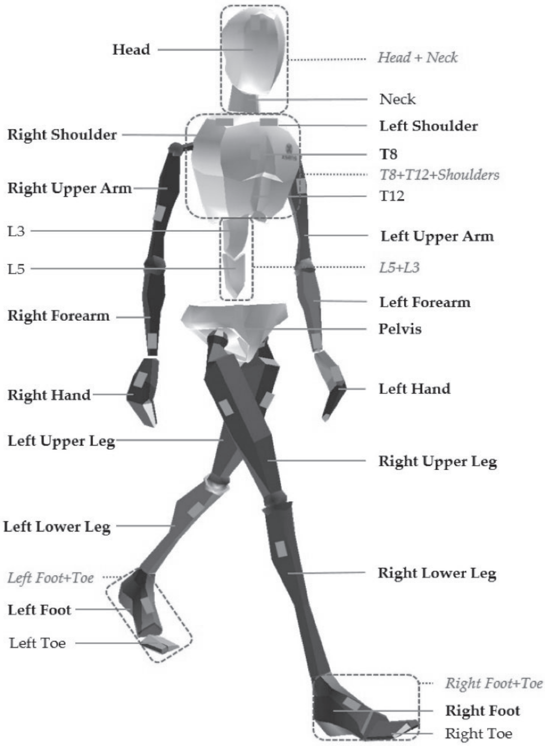

Figure 12.5. Motion capture technology (Photo credit: Xsens).

We are working on two types of virtual simulations (VSs). The first is VS-1 – FIEA laboratory measurements, small-scale simulations at FIEA using motion-capture studios, with computer software for augmented reality and virtual reality, to study the specific motions, steps, and best design of the staging areas for dust control and mitigation, as well as establishing best practices for protocols and guidelines. We are poised to continue evaluating the recorded motion capture and video data to simulate entire procedures and thus prepare for possible field simulations (VS-2). It is also important to mention the value of using computerized virtual simulations to extrapolate our collected laboratory and field data to the possible magnified and compounding effects of repetitive missions, adding robotic and human presence on planetary surfaces. We scale up simulations for dust pollution of large operations on dusty planetary surfaces. We will gather data and then use computerized virtual simulations to extrapolate these data and information gathered during the study to evaluate the possible effects of dust control and mitigation to large scales that cannot be achieved in a regular study setting. In these tasks, the target scales could even possibly be at the industrial plant level, mimicking future activities on the Moon. These computerized virtual simulations will provide estimates of the overall dust pollution, impact on equipment and science, and contamination of full-scale missions and surface activities on the surface of the Moon. These findings will provide a better understanding of the impact of increased human activity on the planetary environment, which will be essential for optimized operations (dealing with the dust) and science return when sampling.

Conclusion

Our investigation is allowing the scientific and regulatory communities to gain knowledge of dust/regolith interactions with human activities and is helping to significantly advance our practical experience in operations procedures on Earth in order to prepare for space missions to the Moon and to gain experience for missions to Mars. We will gain further understanding of the needed capabilities for operations in extreme environments and learn how to create effective scenarios with realistic conditions for human and robotic interfaces. We will accelerate scientific knowledge and experience in operations testing relevant to current NASA goals and provide insight into a possible organizational structure for optimum human-robotic surface exploration. Accomplishing these goals will provide a substantive framework of space operational procedures understanding that can be used for implementing future dust mitigation layered approaches, which can be later combined with PP protocols, procedures, and policies guiding our future habitation of lunar and Martian surfaces.

Acknowledgment

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CHAPTER THIRTEEN

LUNAR DUST SIMULANT PARTICLE ADHESION ON COPOLYIMIDE ALKYL ETHERS

CHRISTOPHER J. WOHL, LEANNA L. FOSTER, DAWSON E. CONNELL, WILLIAM T. KIM, DENIZHAN YAVAS, ASHRAF BASTAWROS, AND JOHN W. CONNELL

Abstract

Mitigation of lunar dust contamination is one of the greatest challenges to be overcome to realize a sustained lunar presence. Likely solutions will integrate active mitigation strategies, requiring the input of external energy, and passive materials, exhibiting an intrinsic resistance to lunar dust adhesion. In this work, a series of copolyimide alkyl ethers containing perfluorinated side-chains were generated to evaluate the influence surface modification agents have on surface chemical, topographical, and mechanical properties. An expanded testing protocol to characterize the adhesion interaction between a lunar dust simulant and the copolyimide substrate was carried out. The interfacial adhesion strength was in-situ measured by a custom-built particulate adhesion instrument, utilizing a sonic wand. Surface mechanical properties were characterized by nanoindentation, utilizing the continuous stiffness measurement approach. A nominal presence of surface modifying agents, 1 wt%, resulted in a six-fold reduction in the adhesion strength of the interface. A strong inverse correlation between the adhesion strength and the substrate's Young's modulus was identified. The reduction was attributed to a synergistic interaction between the surface energy, surface roughness, and modulus of the copolyimide alkyl ethers film.

Introduction

Extra-terrestrial exploration has been an active area of scientific research ever since it was discovered by Babylonian astronomers that planets other than Earth existed. Thus, it is no surprise that a significant number of NASA's missions have, historically, been focused on understanding more about other planets in our solar system and, with recent advances in their detection, planets that orbit other stars. However, one of the major challenges regarding mission success in these endeavors has long been the identification and application of materials capable of surviving in these extreme environments. Satellites in low Earth orbit (LEO) are constantly bombarded by atomic oxygen (Banks et al., 2004) and those traveling through interplanetary space face challenging levels of radiation (Chancellor et al., 2018; Goswami et al., 2012; Simonsen et al., 2000). Although significant research efforts have identified atomic-oxygen resistant materials (Connell, 2000) and radiation protecting systems (Thibeault et al., 2015), these extreme environment hazards still present a formidable challenge.

For extra-terrestrial surface missions, there are a gamut of extreme environments that impede research activities. One of the most difficult hazards to mitigate, as identified in the 2013 Global Exploration Roadmap, is particulates or dust (ISECG, 2013). This was certainly demonstrated during the Apollo missions as the lunar dust infiltrated all exposed surfaces clogging gears, compromising seals, abrading visors and gloves, and potentially presenting health hazards to the crew (Gaier, 2005; Gaier et al., 2010). Difficulties with particulate contamination were also experienced on the Martian surface as dust accumulation reduced the efficiency of solar energy harvesting, which was partially restored by a serendipitous dust devil (Lorenz et al., 2015). A decline in performance of lunar retroreflectors left by the Apollo XIV astronauts has also been attributed to the continual accumulation of lunar dust on the reflective surfaces arising from peculiar dust levitation and migration processes (Murphy Jr. et al., 2010).

Numerous methodologies have been developed to mitigate extra-terrestrial dust contamination, which can be readily separated into two categories: active and passive (Afshar-Mohajer et al., 2015). Active mitigation strategies are those that require input from an external energy source such as electrostatic dust screens (Calle et al., 2008; Horenstein et al., 2013) and regolith microwave sintering devices (Lim et al., 2017; Lim et al., 2019). Passive mitigation strategies require no external energy as the dust mitigation properties are intrinsic to the material. Most materials developed as passive dust adhesion mitigation surfaces have been biomimetic, imitating solutions found in natural systems, such as the self-cleaning properties of many leaf surfaces (Barthlott et al., 1997; Wong et al., 2011). Although most natural systems require water for self-cleaning, which is not present in the liquid form in either lunar or Martian environments, the principles taken from these terrestrial examples are still considered to be relevant in dry, extra-terrestrial locations. The success of self-cleaning plants arises from two main surface properties: hierarchical surface topographies and low surface energy chemical functionalities (Nosonovsky et al., 2007; Celia et al., 2013; Quere, 2008). Using these observations, researchers have fabricated a multitude of biomimetic, self-cleaning, superhydrophobic surfaces (Kesong et al., 2012; Nishimoto et al., 2013; Geim et al., 2003; Jung et al., 2011).

Lunar dust will present a unique challenge regarding the need to mitigate or minimize its influence on long-duration missions' success (Walton, 2007; Calle, 2017; Eberhard et al., 2011; Heiken et al., 1991). Extra-terrestrial habitation has received renewed interest, especially with the identification of water deposits on both the lunar and Martian surfaces (Liu et al., 2012; Shuai et al., 2018; Carr et al., 2015). The specific lunar dust particle size range of interest for this work consists of particulates with diameters $\leq$ 50 μm. These particles have largely been generated through meteorite and micrometeorite impacts (Popel et al., 2018, 2020). As a result, many of the particles consist of agglutinated smaller particles, often forming complex, jagged conformations. The energy from impacts can result in the formation of glassy deposits and elemental iron patinas (McKay et al., 2015). Lunar dust particle surfaces can also be chemically reactive due to the lack of an atmosphere. Finally, dust particles have been observed to levitate and translate across the lunar surface due to unique and complex electron transport phenomena between the day and night sides of the Moon (Horanyi et al., 2015; Stubbs et al., 2006; Abbas et al., 2007). This dust levitation was observed as a horizon glow at the lunar terminator (the day-night line) when viewed from the dark side of the Moon. Collectively, these particulate properties and environmental conditions make the identification of materials that would exhibit intrinsic lunar dust adhesion mitigation properties challenging.

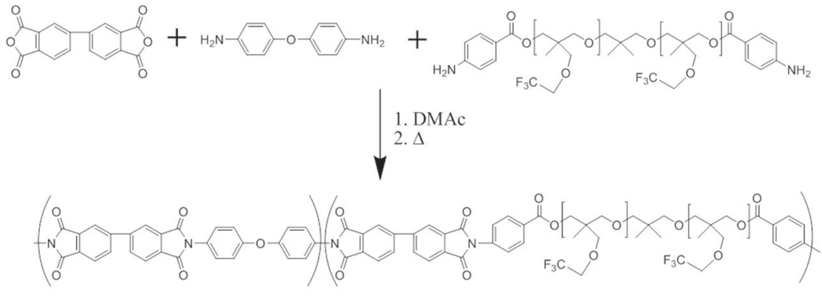
Figure 13-1. Lunar dust will interact with exposed surfaces through a myriad of mechanisms. *Image credit: Susanne Waltz, Media Fusion.*

Surface modification has become a broadly utilized technique to impart changes in the response of a surface to an environmental stimulus with the benefit of largely retaining bulk properties (Pinson et al., 2019). There are a number of techniques for the modification of existing polymeric surfaces: plasma, laser ablation, corona discharge, etc. Surface modifying agents, though, are an approach to controllably alter a polymeric material's surface properties as it is being prepared (Zhang et al., 2019; Harney et al., 2009; Sangermano et al., 2003). These moieties will typically possess either Si or F functionalities. Thermodynamically, the surface modifying agent experiences less favorable interactions with the surrounding polymer matrix than at the polymer-air interface. These moieties will migrate to the surface to populate a more enthalpically favorable environment overcoming the entropic cost of surface concentration. The resultant polymeric material will exhibit surface chemical and mechanical properties that can deviate significantly from bulk properties. Teflon-like surfaces have been demonstrated in partially fluorinated matrices using this approach (Tan et al., 2004; Glaris et al., 2015).

In this work, a series of copolyimide materials are evaluated for use as lunar dust adhesion mitigating materials via a custom-built particulate adhesion instrument. Differences in alkyl ether structure resulted in changes to surface mechanical properties manifesting as strong differences in adhesion force, amounting to six-fold differences. These differences are reconciled through measurements of the surface roughness, adhesion energy, and mechanical properties of the surface-modified copolyimide material system. Details of the experimental protocol, experimental results, and analysis are elaborated.

Experimental

Materials and Methods. The copolyimide alkyl ethers utilized in this work were synthesized as described previously (Scheme 1; Wohl et al., 2015). In short, a series of amine-terminated alkyl ethers were synthesized through a two-step reaction starting with hydroxyl-terminated partially fluorinated oxetane-derived alkyl ethers (PolyFox materials, Omnova Solutions, Beachwood, OH). These surface modifying oligomers were combined with an aromatic dianhydride (3,3',4,4'-biphenyl tetracarboxylic dianhydride, s-BPDA, ChrisKev Company) and an aromatic diamine (4,4'-oxydianiline, 4,4-ODA, Wakayama Seika Kogyo), forming a polyamide acid intermediate. The total surface modifying oligomer content was 1 wt% for each oligomer utilized in this work. Film-casting this solution followed by thermal imidization, liberating the water byproduct and generating the permanent imide heterocycle, yielded free-standing copolyimide alkyl ether films. The compositions utilized in this work are described in Table 13-1.



Scheme 13-1. Copolyimide alkyl ether synthesis.

	Polyfox	Oligomer Molecular Weight	Number of F Atoms per Oligomer	Tensile Modulus, MPa	θ_A
PI Control	--	--	--	3590±110	80±2
$PIAEF_{18}$	PF636	1310	18	3230±50	108±4
$PIAEF_{30}$	PF656	1530	30	3190±110	94±4
$PIAEF_{30B}$	PF154N	3200	30	3010±60	95±2
$PIAEF_{40}$	PF7002	1640	40	3510±70	98±2
$PIAEF_{60}$	PF6320	4740	60	3440±70	91±2

Table 13-1. Copolyimide alkyl ether compositions. All compositions included s-BPDA, 4,4'-ODA, and 1 wt% of the alkyl ether.

Lunar Dust Simulant Adhesion Determination. Adhesion experiments were conducted utilizing the NASA/USGS Lunar Highlands Simulant with particle diameters ≤ 25 μm. Figure 13-2 shows an SEM micrograph of the simulant demonstrating the rough surfaces and angularity described in actual lunar dust. The adhesion-testing apparatus (Figure 13-3) was previously described in detail (Wohl, 2011). It consisted of an aluminum environmental chamber (Abbess Instruments and Systems Inc., Holliston, MA 0.227 m^3), a 20 kHz sonication device (Vibracell VCX-750, Sonics and Materials Inc., Newtown, CT), and an optical particle counter (Solair 3100, Lighthouse Worldwide Solutions, San Jose, CA). All measurements were conducted at ambient pressure within the environmental chamber. Samples were prepared by affixing a 6 mm circle of the substrate, cut from a hole punch, onto the tip of the sonication device (12.7 mm diameter) using a cyanoacrylate adhesive (Hot Stuff, Satellite City Inc., Simi, CA). It should be noted that the dynamics of the developed adhesion-testing apparatus are unique in directly applying the forces normal to the adhesion surface, and thereby it can be accurately correlated to the adhesion forces and adhesion energy. This is different from the commonly utilized centrifugal system, wherein the centripetal decohesion forces are applied to shear off the particle from the surface, in a sliding or a rolling motion (Wang, 1990). In such a system, the cohesion forces might be very different when measured in shear mode vs. tensile mode due to asperity interaction at the interface (Evans and Hutchinson, 1989).

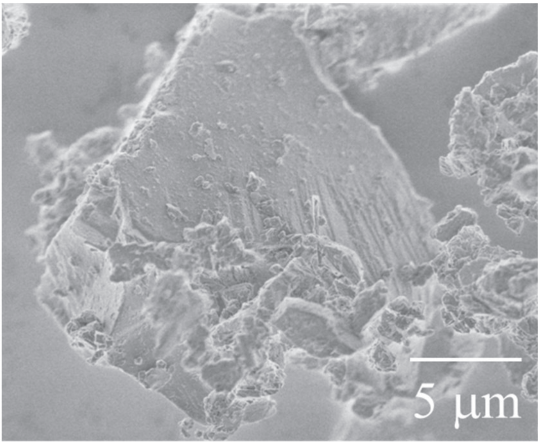


Figure 13-2. SEM micrograph of rough surface topology present in lunar dust simulant.

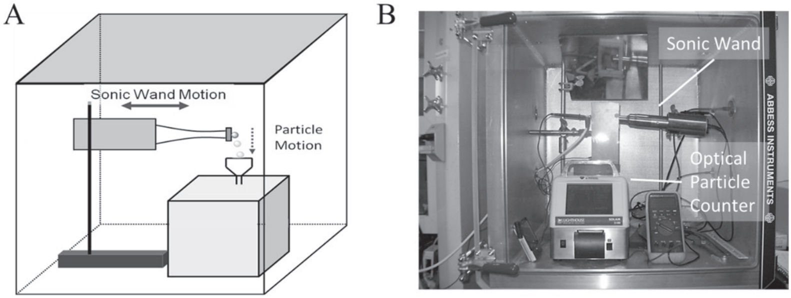


Figure 13-3. An illustration (A) and an image (B) of the particulate adhesion-testing device.

In order to yield accurate and reproducible adhesion data, an approximate monolayer coating of particulate material was necessary. To achieve an approximate monolayer coating, a simple aerosolization technique was developed where particulates were lofted into the free space of an enclosed container, kept at ambient conditions, using approximately one burst per milligram of particles from a compressed air canister (Figure 13-4). Optical microscopy was used to verify the extent of particulate coating. Particulate coating was restricted to the area comparable to the hole punch size, and particulates deposited outside this region were carefully removed using dust-free laboratory wipes (Kimwipe®, Kimtech Sciences). Pre-sonication micrographs were taken documenting particulates deposited on the substrate and particulates remaining at the completion of the simulant detachment experiment, respectively, as depicted in Figure 13-6.

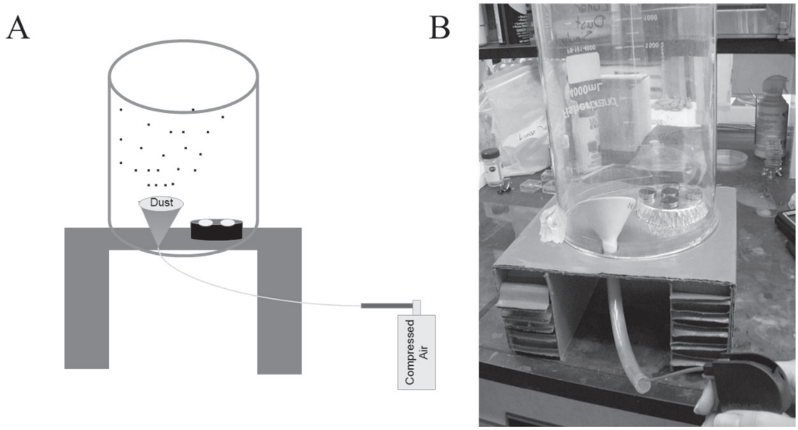


Figure 13-4. An illustration (A) and an image (B) of the particulate contamination chamber.

Particle detachment experiments were conducted by applying a programmed series of sonic wand pulses synchronized with the optical particle counter via a LabVIEW virtual instrument program. To enable the collection, fitting, and removal of background contributions to the detected particles, a period of 15 s prior to and at the completion of the sonic wand activity was utilized to collect ambient particle counts. Ambient aerosolized particles in the range of interest, 10-25 μm, were observed to decay at an exponential rate. This suggested some level of turbulence was created in the closed environment by the exhaust from the optical particle counter (Bosse et al., 2006), though this was not anticipated to alter the results from the particle detachment studies. Starting at the minimum displacement amplitude of 25 μm (~20%), the displacement amplitude was increased in 2% increments up to the maximum displacement of 124 μm (100%). The sonic wand was activated four times for 0.5 s at each displacement amplitude with a 7 s break between pulses to enable the optical particle counter values to return to ambient levels. Once completed, the collected particle count data was sorted into sonic wand active and inactive data points. The sonic wand inactive data points were fitted to an exponential decay function, and this was applied as a background subtraction from the sonic wand active data set. This data, along with the surface clearance percentage (*Clear*$_{\%}$), described below, was utilized to calculate the force required to remove 50% of the deposited lunar dust simulant particles, *Clear*$_{50\%}$.

After the completion of the particulate detachment experiment, the sample surface was imaged using optical microscopy to determine percent surface clearance, *Clear* $_{\%}$. For surfaces that exhibited complete clearance, the data from the optical particle counter was used directly. For surfaces that did not completely clear, Image J software was used to approximate percent clearance by determining the area of the image coated with particulate material, $Area_0$ and $Area_F$, from the optical images collected before and after the particulate detachment experiment, respectively. To perform the particle analysis, the optical micrograph samples were converted to an 8-bit grayscale image and then converted to a threshold image where the lower and upper threshold limits were set to separate the particulate material from the substrate. Size and circularity patterns were adjusted to capture particle sizes of significance for the particular study. *Clear*$_{\%}$ was calculated according to:

$$Clear_{\%} = \left(1 - \frac{Area_F}{Area_0}\right) \times 100\% \tag{1}$$

The particulate adhesion force was considered to be equal to the detachment force required to observe the particulate with the optical particle counter. This assumes that the substrate mechanical response remains elastic during the particulate release process. Using the particle's size and the kinematics of the vibration motion of the sonic actuator, the detachment force can be determined according to:

$$F_{Detach} = ma \tag{2}$$

where m is the mass of a particle and a, the surface acceleration, is computed from Zimon (1969):

$$a = 4\pi^2 f^2 A \tag{3}$$

where f and A denote the frequency and amplitude of oscillation, respectively. This relationship assumes that the change in acceleration of the sonic wand follows a sinusoidal pattern. *Clear*$_{50\%}$ was calculated by scaling the displacement amplitude, and therefore the F_{Detach} value, to the value at which 50% of the total deposited particulates were detached from the interrogated surface. All reported measurements in this work are for an optical particle counter bin of 10 μm. Thus, a 10 μm mean particle diameter will be used in all the analyses.

Nanoindentation Characterization. Nanoindentation was utilized to probe the effective mechanical properties, including Young's modulus, *E*, and hardness, H_c, of different surface-modifying PIAEF films to correlate the substrate's mechanical effect on the measured adhesion forces and energies (Doerner et al., 1986; Oliver et al., 1992). Nanoindentation is suitable to probe subtle changes near the film's surface, as well as the progressive changes of properties into the film core (Yang et al., 2009; Yavas et al., 2017a, 2017b). All indentations were performed in force control using the Hysitron TI 950 TriboIndenter (TriboIndentor™ by Hysitron Inc.). A trapezoidal loading profile, which consisted of a 5 s linear loading, 2 s hold at the peak load, and 5 s linear unload, was utilized to impose regular patterns of nanoindentation using a cube corner tip with a tip radius of about 100-150 nm. Several indentations were performed on each sample with a peak load of 750 μN. A continuous stiffness measurement mode was utilized to measure the variation of the contact modulus and hardness with the depth from the free surface of the modified film. Figure 13-5 shows a representative set of force and indentation depth curves obtained from indentations preformed on the reference (polyimide with no surface modifying agent), and specimens with a different number of F atoms per oligomer, showing a more compliant response.

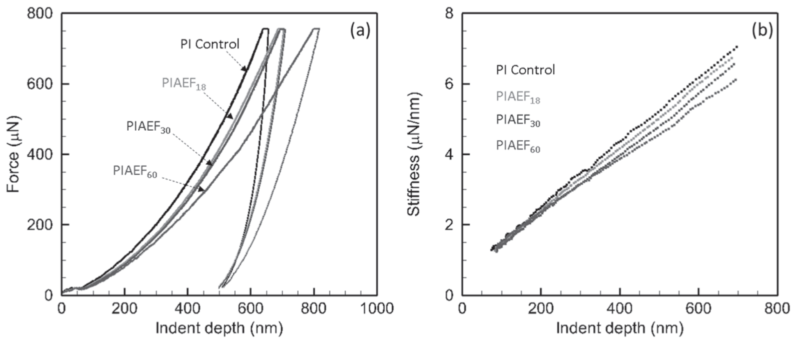


Figure 13-5. (a) A representative set of force-indent depth curves for the 'Control' and treated samples with a different number of F-atoms per oligomer. (b) The corresponding variation of the measured contact stiffness as a function of indent depth.

The data analysis method proposed by Oliver and Pharr (1992) was utilized to determine hardness, H_c, and reduced modulus, E_r. H_c was calculated as follows:

$$H_c = \frac{F_{\max}}{A} \tag{4}$$

where F_{max} is the maximum load and A_c is the corresponding contact area, which is obtained from the indentation depth using the tip-area correlation function, evaluated at every step of the loading increment. In addition, E_r was determined by the following expression:

$$E_r = \frac{\sqrt{\pi} S}{2\sqrt{A_c}} \tag{5}$$

where S is the slope of the unloading curve obtained by curve fitting. The indentation-derived Young's modulus, E, after accounting for the indenter tip modulus, E_{tip}, was given by

$$\frac{1}{E_r} = \frac{1-\nu^2}{E} + \frac{1-\nu_{tip}^2}{E_{tip}} \tag{6}$$

Results and Discussion

Lunar dust simulant adhesion testing was performed on a series of copolyimide alkyl ether materials containing different partially fluorinated moieties. This characterization was performed by lightly depositing lunar dust simulant onto surfaces of interest through aerosolization. Once generated, the contaminated specimens were mounted to an ultrasonic device that was subsequently activated at increasing displacements above an optical particle counter. Optical microscopy was used to determine the initial and final surface contamination levels (Figure 13-6). Using image analysis, these images were utilized to calculate initial, final, and $Clear_{50\%}$ contaminant surface coverage percentages.

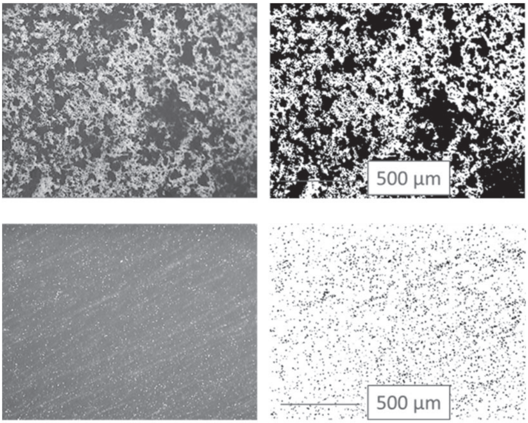


Figure 13-6. Pre-sonication (top) and post-sonication (bottom) images of a copolyimide alkyl ether surface with lunar simulant deposits. The images on the left are the optical micrographs and the images on the right are the same images after ImageJ analysis.

Precise particle deposition control for sample preparation was not possible in this study. However, the generated data was utilized to ascertain consistency throughout the particle detachment experiments. Cumulative particle counts were compared to the calculated number of particles in an ideal monolayer. The number of particles required to form an ideal monolayer on the sample surface, a 6 mm diameter circle, was determined by approximating the lunar simulant as spheres arranged in a face-centered cubic closest packing configuration. A monolayer consisting of only 5 µm or 10 µm particles would contain 283,000 or 71,000 particles, respectively. Calculated cumulative particle counts were typically less than 50% of these values, and often significantly lower. This indicated that, although there may have been aggregated species of few particles at the beginning of each experiment, these aggregates never resulted in particle concentrations greater than what would be present in a monolayer of particles on the surface. With the particle-particle cohesion force (230 nN for 12.5 µm particles) (Oudayer et al., 2018) being comparable or lower than the adhesion force determined on the surfaces evaluated in this work, initially aggregated particles may separate and become adhered to the surface being interrogated immediately after the cohesion force was overcome.

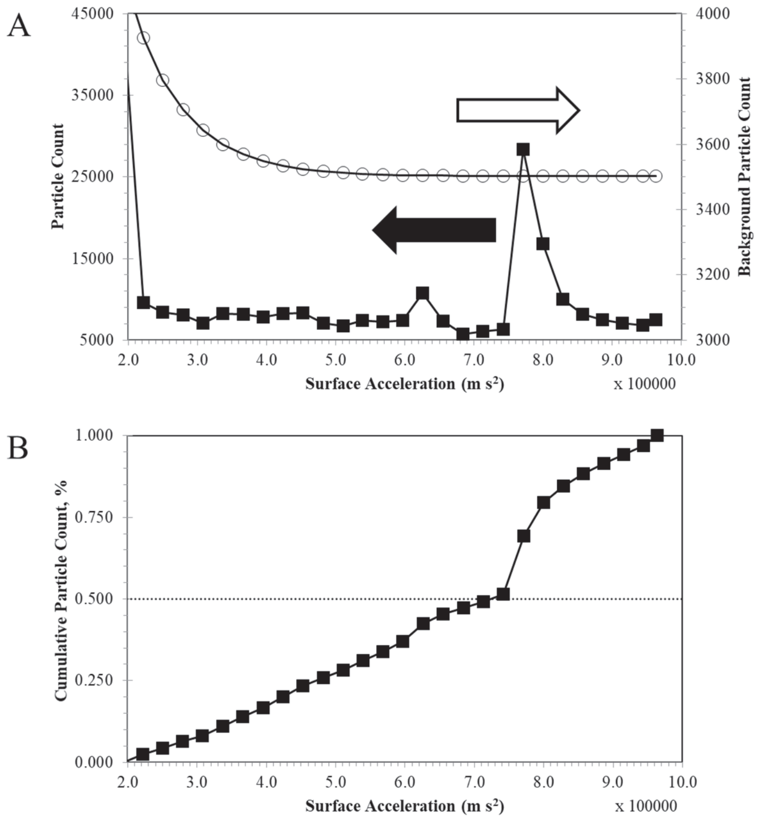


Figure 13-7. (A) Example of raw data and background data collected during a particle detachment experiment. (B) Cumulative particle count data after background subtraction. The surface acceleration value where the cumulative particle count crosses the dashed line represents the $Clear_{50\%}$ value.

As can be seen below (Table 13-2 and Figure 13-8), as the degree of surface modifying oligomer fluorination increased, the overall clearance of lunar dust simulant increased and the $Clear_{50\%}$ force decreased, exhibiting more than a five-fold modulation of the interfacial particle-substrate adhesive force. Interestingly, the mechanical properties as highlighted in Table 13-1 do not provide a simple relationship between adhesion testing parameters and advancing water contact angle or tensile modulus (collected from a macroscopic tensile test of film segments). This is indicative that the confluence of the surface energy, surface morphology, and surface mechanical properties may synergistically play a significant role in surface-particle interactions, as will be discussed below.

	$Clear_{\%}$	**$Clear_{50\%}$, µN**
PI Control	77%	1.59
$PIAEF_{18}$	73%	1.26
$PIAEF_{30}$	68%	0.69
$PIAEF_{30B}$	93%	0.75
$PIAEF_{40}$	93%	0.80
$PIAEF_{60}$	100%	0.30

Table 13-2. Lunar dust simulant adhesion testing results.

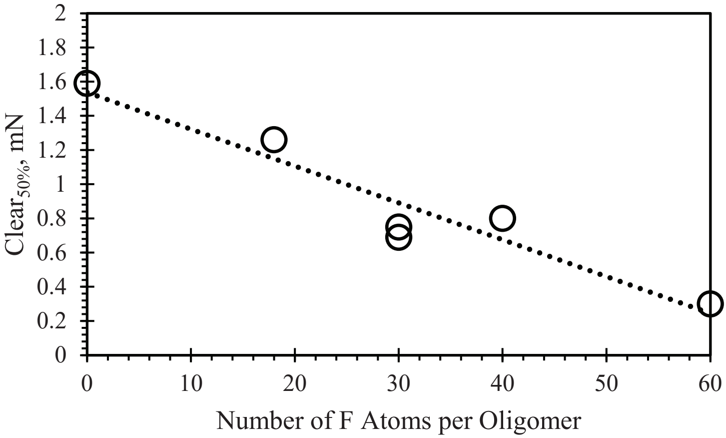


Figure 13-8. $Clear_{50\%}$ values determined for 10 µm lunar simulant particles on copolyimide alkyl ether surfaces.

The continuous stiffness measurements shed some light on the role of the number of F atoms per oligomer. A summary of the nanoindentation measurements along with the average RMS surface roughness and average dominant roughness wavelength, λ, is provided in Table 13-3. Surface properties are the initial surface values at a depth of about 100 nm, the depth where a reliable contact stiffness can be measured. The reported bulk properties are the average values recorded at a depth of 550 nm, where near plateau values were reached. Figure 13-9 shows the depth variations of both E and H for different copolyimide surfaces. The details were quite subtle, though there was a clear difference in moduli (either the near surface or the bulk moduli) between different copolyimide compositions. The hardness *H* did not show a statistically significant strong correlation, implying that the presence of different surface modifying oligomers did not significantly change the surface hardness, except for $PIAEF_{18}$.

	Storage Modulus, GPa (Surface/Bulk)	**Hardness, GPa (Surface/Bulk)**	**RMS roughnes s (nm)**	**λ (nm)**
PI Control	5.53±0.13/5.56±0.02	~0.73±0.06/0.63±0.01	0.20	900
$PIAEF_{18}$	5.24±0.07/5.39±0.05	~0.95±0.07/0.67±0.01	0.42	875
$PIAEF_{30}$	4.79±0.07/5.08±0.10	~0.64±0.04/0.63±0.01	0.29	285
$PIAEF_{30}$ B	4.83±0.22/5.05±0.04	~0.53±0.22/0.62±0.01	0.49	400
$PIAEF_{40}$	5.22±0.20/4.98±0.09	~0.70±0.08/0.64±0.02	0.60	650
$PIAEF_{60}$	5.15±0.12/4.83±0.02	~0.69±0.05/0.64±0.01	1.75	570

Table 13-3. Summary of the measured nanoindentation modulus and hardness sampled at the surface (~100 nm) and bulk (~650 nm) of the samples, along with the asperity RMS roughness and the smallest asperity mean spacing, λ determined by AFM.

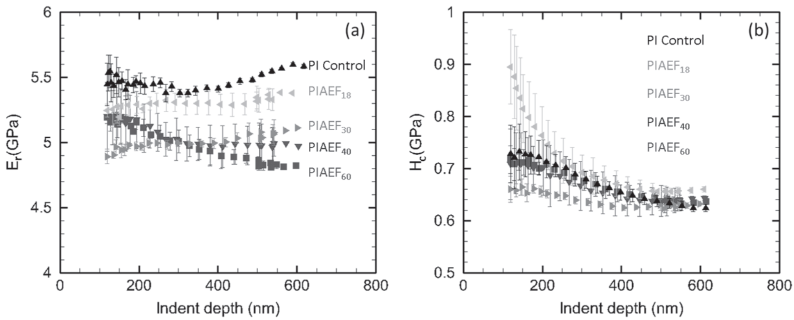


Figure 13-9. Variation of surface mechanical properties, a function of indent depth for the examined samples; (a) indentation modulus, E_r and (b) hardness H_c. The data points are the average of at least three independent measurements and are presented with error bars denoting standard deviation.

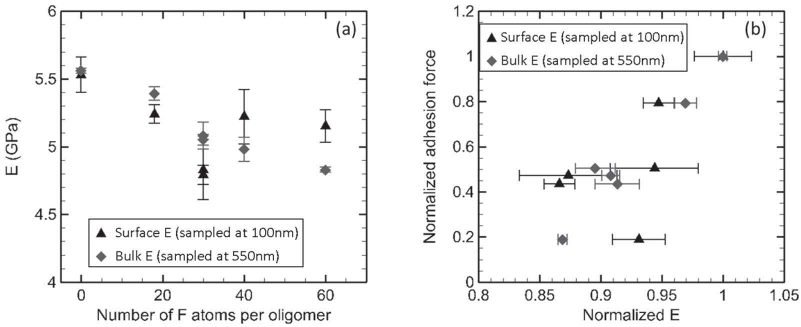


Figure 13-10. (a) The variation of the surface modulus (sampled at 100 nm) and bulk modulus (sampled at 550 nm) with the number of F atoms per oligomer. (b) The variation of the normalized adhesion with the normalized surface modulus (sampled at 100 nm) and bulk modulus (sampled at 550 nm). Control specimen properties were used for normalization.

To highlight the role of the surface-modifying oligomer on the indentation modulus, Figure 13-10a summarizes the measured indentation modulus with the number of F atoms per oligomer. A strong decay in the indentation modulus was observed, both at the surface and in the bulk of the film. To rationalize the effect of reduction in the modulus on the measured adhesion force, Figure 13-10b summarizes such correlation in a normalized form with the reference sample properties. The experimental measurements show a clear proportionality between F_{detach} and E. Though E dropped by 15%, F_{detach} was modulated by 80%. Another way to understand this disparity is that a change in E by 1.17 corresponds to a five-fold reduction in the adhesion force. The observed trend in Figure 13-10 is unique as (i) the trend is not supported by contact mechanics theories for elasto-plastic bodies with adhesion (e.g., DMT: Derjaguin, Muller, & Toporov, 1975; and JKR: Johnson, Kendall, & Roberts, 1971), wherein the detachment force does not depend on the surface modulus, and (ii) the trend is reversed compared to the previously reported experimental trend of a four-fold increase in the adhesion force of 7 μm silica-coated particles on a ceramer substrate with a seven-fold reduction in its modulus (Dejesus et al., 2006). In their work, the strong modulation of the adhesion forces was attributed to asperity roughness, without a clear mechanistic view of the role of the surface modulus. For their experiments, the reported surface energy was similar for all grades of substrates and within the error of the experimental measurements.

Interfacial Surface Adhesion Reduction. In the current study, we report changes of the substrate pull-off forces and thereby its surface energy by more than five-fold, with a strong correlation with the number of F atoms per oligomer (Table 13-2). We also observed a modest reduction (~15%) of the surface modulus and modest changes of the contact angle and the corresponding surface energy (Table 13-1), though we observed strong changes (nearly an order of magnitude) in the mean asperity RMS roughness of the examined surfaces (Table 13-3). Apparently, the synergistic effect of these three factors has resulted in more than a five-fold reduction of the interfacial adhesion force. To understand such a synergistic effect, the major interaction forces between the lunar dust simulant and the substrate must be considered. The two major interacting forces are those arising from the electrostatic and van der Waals (VDW) interactions. The electrostatic forces were estimated to be on the order of 1 nN for smooth or irregularly shaped particles (Hays 1995, 1996). The simplified models of electrostatic attraction between the particle and the substrate account for a very small fraction of the adhesion forces. Thus, it can be safely argued that the VDW interactions have the strongest influence on the adhesion forces in the current framework, while the electrostatic forces have a very weak influence.

The VDW force can be estimated from Hamaker's theory for an idealized spherical particle on a planar substrate (Hamaker, 1937) or according to contact mechanics theories (e.g., DMT and JKR). The interaction of the VDW force is given by,

$$F_A = \frac{H\ R_p}{6 s_o^2} \qquad (7)$$

where H is the Hamaker constant (~10^{-19} J in air), s_o is the distance of the closest approach between surfaces (~0.3 nm), and R_p is the particle radius. Noting that the adhesion force is the derivative of the potential energy with respect to the approach distance (Popov, 2010), the DMT and JKR theories can similarly provide the VDW forces as a function of the work of adhesion, w_s (in J/m^2),

$$F_A = 2\xi\pi R_p w_s \quad ; \quad \begin{cases} \xi = 1 & \text{for DMT} \\ \xi = \dfrac{3}{4} & \text{for JKR} \end{cases} \qquad (8)$$

The work of adhesion, w_s, is related to the surface energy of the particle γ_p and the substrate γ_s and their interfacial energy γ_{sp} ($\sim \sqrt{\gamma_s \cdot \gamma_p}$),

$$w_s = \gamma_s + \gamma_p - \sqrt{\gamma_s \cdot \gamma_p} \quad (9)$$

From Eqs. (7) and (9), the Hamaker constant can be estimated for each of the treated surfaces:

$$H = 12\pi\xi s_o^2 w_s \quad (10)$$

Utilizing Table 13-1 for the measured contact angle, γ_s can be evaluated for each surface. Using $\gamma_p = 50.54mJ$ as that for silicon dioxide (Kinloch, 1987), w_s can be estimated for each of the examined substrates. Table 13-4 summarizes the estimated surface adhesion, work of adhesion, and Hamaker constant (using $\xi = 1$) for each of the examined surfaces. It is evident that while the surface energy showed strong modulation with the F atoms per oligomer, both w_s and H are almost constant for the entire set of surfaces. Utilizing either Eq. 7 or Eq. 9 to estimate VDW force, the result will be almost independent of the F atoms per oligomer. Thus, it can be concluded that the substrate surface energy has a negligible role in affecting the substrate work of adhesion and the corresponding adhesion pull-off forces.

	Surface Energy (mJ/m^2)	**Work of Adhesion (mJ/m^2)**	**Hamaker Constant ($J \times 10^{-19}$)**
PI Control	25	39.99	1.357
$PIAEF_{18}$	8.7	38.27	1.298
$PIAEF_{30}$	15.7	38.07	1.291
$PIAEF_{30B}$	15.1	38.01	1.290
$PIAEF_{40}$	13.4	37.92	1.286
$PIAEF_{60}$	17.5	38.30	1.299

Table 13-4. Summary of the calculated surface energy, work of adhesion, and Hamaker constant.

To understand the role of surface roughness on the adhesion pull-off force, it is well documented that asperities several orders of magnitude smaller than the particle diameter can greatly reduce the adhesion force from its idealized perfectly smooth interaction (Fuller et al., 1975; Rabinovich et al. 2000a, 2000b). Approximating the surface roughness with hemispheres, Rumpf (1990) included the effect of a single hemispherical surface asperity on the adhesion of larger particles. Rabinovich et al. (2000a, 2000b) modified Rumpf's approach to include a non-centered hemispherical asperity at the contact, yielding a model for the generalized adhesion force that depends on the surface RMS roughness of the dominant asperity and their wavelength, λ. The roughness modulated VDW adhesion force becomes

$$F_A = \frac{H\,R_p}{6s_o^2}\left(\frac{1}{1+\dfrac{58\,R_p RMS}{\lambda^2}} + \frac{1}{\left(1+\dfrac{1.82\,RMS}{s_o}\right)^2}\right) \qquad (11)$$

In Eq. 11, the first term represents the asperity-particle interaction, and the second term is the attraction forces from the rest of the surface and the particle, and tends to greatly diminish with increasing roughness. We utilized Eq. 10 to rationalize the role of the surface roughness, reported in Table 13-3 on the adhesion forces. Figure 13-11 summarizes the prediction of Eq. 11 for the adhesion forces and compares it with the experimentally determined values. While the predicted force is lower than the measured values for the reference and low roughness surfaces, it over predicts the adhesion forces for the rougher surfaces. Qualitatively, this trend is similar to the trend reported by Rabinovich et al. (2000b), where increasing the roughness by an order of magnitude from 0.17 to 1.64 nm decreased the adhesion forces by 3.7 times for a 10 μm glass sphere on a titanium surface. However, it is quite remarkable to reach an estimate of the adhesion forces that relies on two independent experimental measurements (contact angle and surface topology) and for it to be of the same order of magnitude as the experimentally measured pull-off force from a third independent measurement. The error of the predicted value of the adhesion force is within -10% of the experimentally measured value for the control sample, and within 35% for the highest F atoms per oligomer.

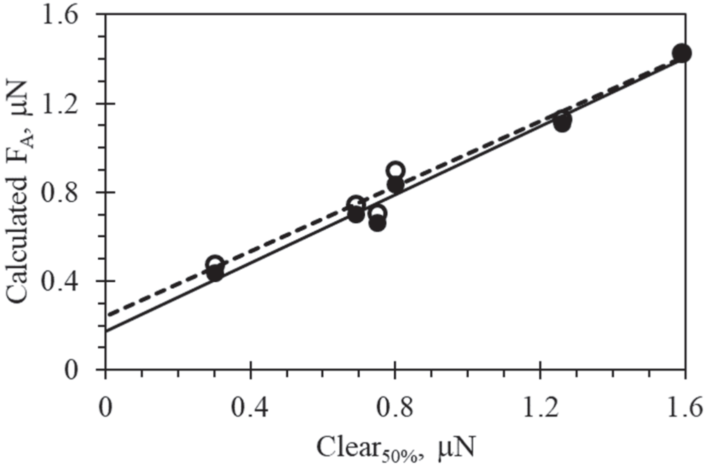


Figure 13-11. Comparison of experimentally determined adhesion force values, $Clear_{50\%}$, and adhesion force values calculated according to Eq. 11 (open symbols) and Eq. 13 (filled symbols). The dashed line and solid line are linear fits to values obtained from Eq. 11 and Eq. 13, respectively.

The remaining additional effect may stem from the mechanical properties of the substrate and their effects on modulating the pull-off adhesion force. To understand this effect, the dynamics of the experimental configuration should be considered, wherein the actuator forces are applied along the particle pull-off direction. One might expect a larger effect of the kinematics of the substrate, similar to the trampoline effect. During the forward stroke of the ultrasonic wand, the surface is pushing on the particle, with a force that reaches its maximum at the end of the stroke. During this push-forward cycle, the substrate is being deformed underneath the contacting particle storing elastic strain energy. At the start of the reverse cycle, the substrate is almost elastically unloaded and releases this stored energy into the contact area. Then, the process dynamics are switched to pull-on forces on the particle. The kinematics of this process highlight the strong effect of the stored elastic strain energy within the substrate, and thereby the role of its elastic modulus. Realizing that the process dynamics of the sonic wand is a force control process, an order of magnitude estimate from Hertzian contact can be utilized for a scaling purpose. The stored elastic strain energy within the substrate under a controlled applied load can be estimated from

$$U_s \sim \frac{F_A^{5/3}}{E_r^{2/3}\ R_p^{1/3}} \qquad (12)$$

It is evident that under the same applied particle indentation force on the substrate, the stored elastic strain energy within the substrate is increased for a more compliant substrate. This scaling can be utilized in a phenomenological way to either scale-up the measured adhesion force or scale-down the predicted VDW forces from Eq. 11. For an order of magnitude analysis, we propose the scaling of VDW forces of Eq. 11:

$$F_A^* = \left(\frac{E_r\big|_{specimen}}{E_r\big|_{control}} \right)^{2/3} F_A \qquad (13)$$

Eq. 13 provides an approximate 10% reduction of F_A for a 15% reduction in the modulus, as highlighted in Figure 13-11. It is remarkable that the substrate modulus-modulation, while small, appeared to be working in tandem with the surface roughness evolution to reduce the effective pull-off force and the work of adhesion of the copolyimide surfaces. Although not shown in Figure 13-11, the linear fit generated from the values calculated from Eq. 13 had a slope closer to 1, a smaller y-axis intercept value, and a larger correlation coefficient, relative to the values calculated from Eq. 11, indicating better correlation with the experimental data.

Conclusion

Surface modifying agents have often been considered to play a limited role in changing surface properties, where only changes to surface chemical properties are considered. In the work described here, it has been demonstrated that their presence resulted in changes to surface chemical, topographical, and mechanical properties. These changes provided a synergistic effect toward reducing the adhesion interaction with lunar simulant particles. The utilization of these interaction-modifying surface properties in other material systems could lead to further development in lunar dust adhesion resistant materials. Decoupling the measurement technique influence, i.e., sonic wand motion imparting stored elastic strain energy in the substrate, on the results was critical to elucidate these interactions.

Acknowledgments

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CHAPTER FOURTEEN

AN UPDATE ON NASA'S DUST MITIGATION STRATEGY

MICHAEL R. JOHANSEN

Introduction

It is well known that the Apollo lunar surface missions experienced a number of issues related to dust, which are sometimes referred to as "The Dust Problem." The jagged, electrostatically charged lunar dust particles can foul mechanisms and alter thermal properties. They tend to abrade textiles and scratch surfaces. NASA and other interested parties require an integrated, end-to-end dust mitigation strategy to enable sustainable lunar architectures.

Dust is realized to be one of the principal issues in returning to the lunar surface. It has been shown that lunar dust is very abrasive and highly adhesive, impairing optical instrumentation, altering thermal properties, and fouling mechanical systems. A number of NASA technologies have been developed to mitigate the effects of lunar dust for future exploration missions. However, it is possible that dust mitigation solutions exist outside of the solution space that is currently known by the agency. A number of terrestrial industries must also manage fine particulates – such as industrial plants processing cosmetics, powdered sugar, and pharmaceuticals. The focus of this broad search should find novel dust mitigation solutions within government, industry, and academia.

Below are some comments on the lunar dust problem from Apollo astronauts:

> "The dust went as far as I could see in any direction and completely obliterated craters and anything else… I couldn't tell what was underneath me. I knew I was in a generally good area and I was just going to have to bite the bullet and land, because I couldn't tell whether there was a crater down there or not." – Pete Conrad, Apollo 12 Commander

> "At about 50 to 60 feet, the total view outside was obscured by dust. It was completely IFR [Instrument Flight Rules]. I came into the cockpit [that is, switched his attention from the view out the window to the instrument readings that Jim Irwin was giving him] and flew with the instruments from there on down." – David Scott, Apollo 15 Commander

> "Probably the most difficult job of all the closeouts was trying to dust the suits… The real-time transcripts will show just how much time and effort was spent in dusting." – Gene Cernan, Apollo 17 Commander

Dust has a specific definition from geologic and other scientific and technical areas. Dust, soil, and other terms used to define the particulate on the lunar surface can have different meanings for different scientific groups. Furthermore, the word "dust" has been used loosely to mean anything from a very specific particle size distribution to nearly all of the particulate. This loose definition of dust has been used in NASA's official documents, including past and future solicitations. Even furthermore, when developing technologies and strategies for dealing with the lunar particulate, it may not be (and likely is not) necessary to have two classes of technologies: one for dust and one for larger or smaller sized particles. Even *more* furthermore, the "finest fraction" of lunar material will be the most troublesome for most systems. However, particle sizes outside of the finest fraction will likely still pose a threat to systems. Excluding all but the finest fraction of particulate from the definition of dust (based on NASA's history of using the word) may mislead commercial entities and technology developers that any particle outside of the geologic definition will not present a problem to NASA architecture.

A definition is proposed here: the term "dust mitigation" will include all lunar particulate that will need to be mitigated. The term "finest fraction" of lunar regolith should be used to define the fine particulate that will likely cause the most concern – potentially aligning with the geologic definition of dust.

The capability needs for the reduction/mitigation of lunar dust are as follows:

- *Optical Systems* – Viewports, camera lenses, solar panels, space suit visors, mass spectrometers, other sensitive optical instruments
- *Thermal Surfaces* – Thermal radiators, thermal painted surfaces, thermal connections
- *Fabrics* – Space suit fabrics, soft wall habitats, mechanism covers
- *Mechanisms* – Linear actuators, bearings, rotary joints, hinges, quick disconnects, valves, linkages

- *Seals and Soft Goods* – Space suit interfaces, hatches, connectors, hoses
- *Gaseous Filtration* – Atmosphere revitalization, ISRU processes

Dust mitigation strategies are needed for:

1. Surface operations
2. Surface habitats
3. Descent/ascent operations
4. Orbital operations (Command Module, Gateway, etc.)

Some notional architecture and operational considerations for dust mitigation for human surface operations are provided below:

- Slow, methodical movements
- Kickoff boots and lower extremities/removable dust covers
- Adequate time for dust cleaning protocols
- Ground preparation/dust tarp near lander/habitats/other elements
- Quick disconnects
- Dust-tolerant mechanisms
- Brushes

Dust Mitigation Strategies: A Three-Pronged Approach

An effective dust mitigation strategy includes three components: operational and architecture considerations, passive technologies, and active technologies.

The component that can have by far the biggest impact on dust exposure is operational and architecture considerations. With proper planning, this component of the integrated strategy can also be the most cost-effective. An example of an architecture and operational consideration is lessening the risk of astronauts falling on the lunar surface through changing EVA procedures and adjusting tool design to accommodate better balance.

Active and passive technologies can be used to close the gap between expected dust exposures and system dust tolerance limits. Passive technologies include nano-materials and other surface modification techniques and simple tools. Active technologies typically require non-negligible power consumption and/or some form of mechanical actuation.

This three-pronged approach to a dust mitigation strategy can be viewed from an architecture element perspective or a capability need perspective.

Dust mitigation strategies are needed for optical systems (viewports, camera lenses, space suit visors), thermal surfaces (thermal radiators, thermal painted surfaces), fabrics (space suit fabrics, soft wall habitats, mechanism covers), mechanisms (linear actuators, bearings, quick disconnects), seals and soft goods (space suit interfaces, hatches, connectors), and gaseous commodities (spacecraft atmospheres, *In Situ* Resource Utilization (ISRU) processes).

With these considerations in mind, NASA is forming an integrated dust mitigation strategy.

An Integrated Dust Mitigation Strategy

Nearly every system on the lunar surface or in orbit will experience deleterious effects due to lunar dust. Thus, every system should be responsible for a piece of the integrated dust mitigation strategy.

A notional integrated dust mitigation strategy may have the following features:

- Lunar Surface Operations
    - Architecture and operational considerations
        - Slow, methodical movements
        - Removable dust covers for high-exposure regions
        - Adequate time for dust mitigation protocols
        - Ground preparation or a dust tarp
        - Materials compatibility
    - Passive technologies and tools
        - Dust brushes
        - Boot scrapers
        - Dust-tolerant mechanisms and quick disconnects
        - Nano-coatings
    - Active technologies
        - Electrostatic dust removal
        - Magnetic dust removal
        - Compressed gas dust removal
- Lunar Surface Habitats
    - Architecture and operational considerations
        - Dust airlock or "mudroom"
        - Single or staged "softwall"
        - Materials compatibility

    - Passive technologies and tools
        - Dust brushes and wipes
        - Two-stage cabin filtration (inertial separation and media filtration)
        - Nano-coatings
    - Active technologies
        - Electrostatic or magnetic dust removal
        - Compressed gas shower
        - Dust vacuum
- Lunar Ascent/Descent
    - Architecture and operational considerations
        - Descent/ascent trajectories
        - Prepared and unprepared landing surfaces
        - Landing proximity to other surface assets
        - Blast ejecta in lunar orbit
    - Passive technologies and tools
        - Capped connectors and docking mechanisms
        - Dust brushes and wipes
        - Two-stage cabin filtration
        - Nano-coatings
    - Active technologies
        - Dust vacuum
        - Electrostatic or magnetic dust removal
- Lunar Orbital
    - Architecture and operational considerations
        - Proximity to blast ejecta in orbit
    - Passive technologies and tools
        - Capped connectors and docking mechanisms
        - Two-stage cabin filtration
        - Dust wipes
    - Active technologies
        - Dust vacuum
        - Electrostatic or magnetic dust removal

Dust Mitigation Projects

NASA's Space Technology Mission Directorate is funding a variety of dust mitigation projects to enable the integrated dust mitigation strategy. The projects listed below will ensure that existing active and passive technologies are mature and can potentially be infused into the various architecture elements.

Patch Plate Materials Compatibility Assessment. A number of heritage and new spaceflight materials should be extensively tested in the lunar environment to understand both how the materials change with time and how the regolith adheres to surfaces. A microscope and dust sensor addition to this passive experiment will greatly improve the science retrieved from this passive payload.

Lunar Demonstration of Electro-dynamic Dust Shield. This is a mature active dust removal technology that uses electric fields to remove dust from surfaces. This technology can be integrated into optical systems and thermal systems. It is currently undergoing a technological demonstration on the International Space Station.

Dust-tolerant Mechanisms Testing. Rovers and other architecture elements will have rotary joints for steering, suspension, and drive actuators. These joints will be subjected to a dusty lunar environment. This work will enable better rotary joint design for small and large architecture elements.

Lunar Dust Mitigation Best Practices Guide. Many architecture elements are in need of a guide to design dust-mitigating mechanisms, optics, and many other applications. This “Best Practices” guide will call on experience from previous NASA projects, military operations, and industry knowledge.

Other dust mitigation investments and activities are being coordinated through the Small Business Innovative Research program, NASA’s Human Exploration and Operations Mission Directorate, and NASA’s Science Mission Directorate.

Dusty Environments Classifications

One last piece of NASA’s lunar dust mitigation strategy is the development of dusty environments classifications to enable requirements generation and systems engineering and integration functions. The dusty environment classifications will be organized by various dust loading parameters such as surface dust loading, volumetric dust loading, and dust velocity. The classifications will define testing protocols and metrics. Testing to a pre-defined protocol described in the classification will also raise awareness of where additional dust mitigation strategies are needed for a given system.

Conclusion

An integrated dust mitigation strategy requires coordination from architecture to technology development. Many of the concerns associated with lunar dust can be lessened with early consideration. Through architecture and operational considerations and technology maturation, NASA aims to resolve "The Dust Problem."

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