The Impact of Lunar Dust on Human Exploration

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Edited by

Joel S. Levine

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TABLE OF CONTENTS

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
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Jim Burch
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Rice University, Houston, Texas

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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.

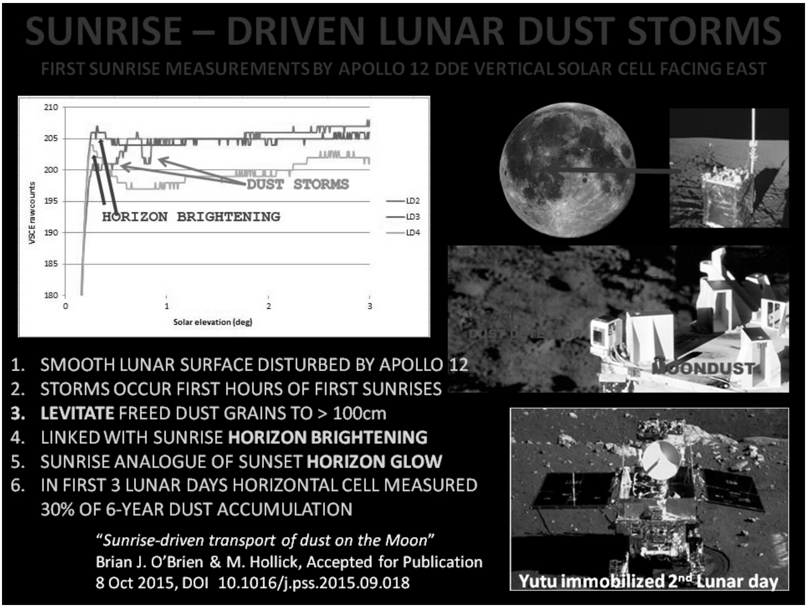

Figure 1-1. A "Nugget" showing Apollo 12 DDE discoveries important to mining on the Moon in one slide.

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.

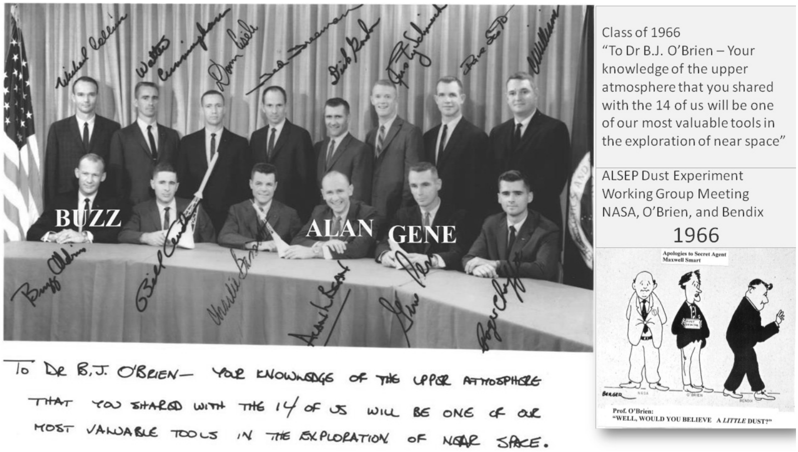

Figure 1-2. Paradox of Apollo astronauts. In 1964 they expressed thanks for my few hours of teaching about radiation hazards, the ionosphere, etc. which had been explored by satellites, including some of mine. But in 1966, as shown in the Get Smart cartoon, I had no champion to support my proposal for 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.

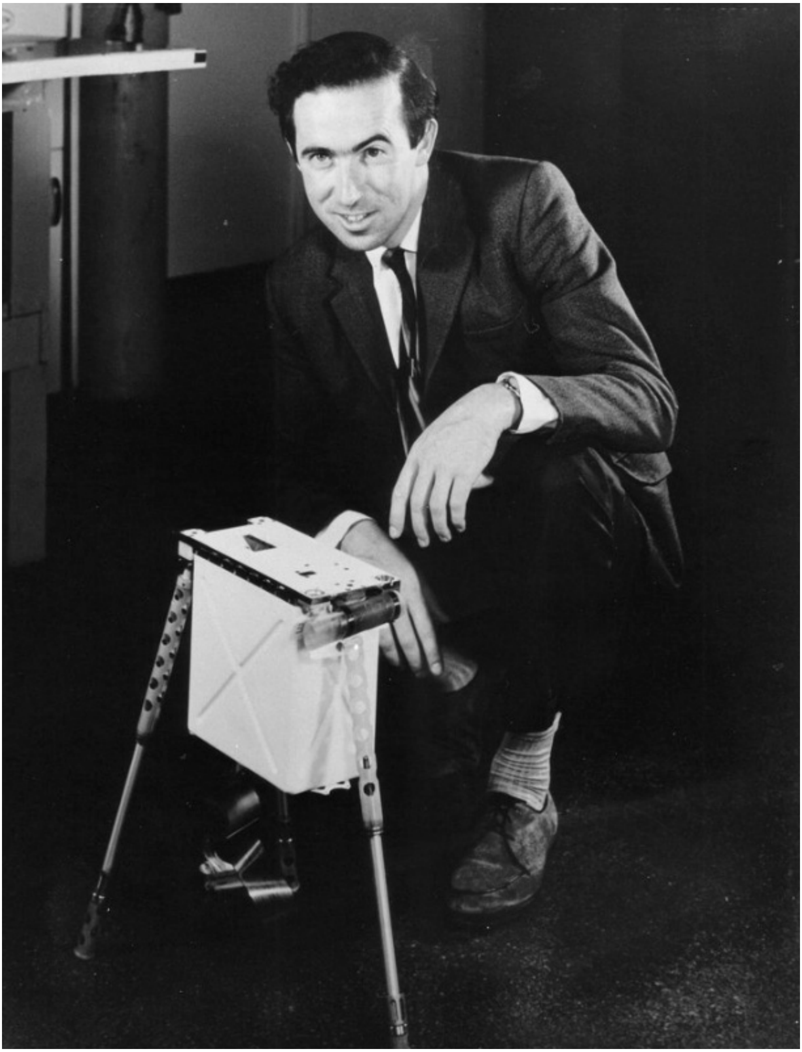

Figure 1-3. Brian O'Brien and the Apollo 13 CPLEE.

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.

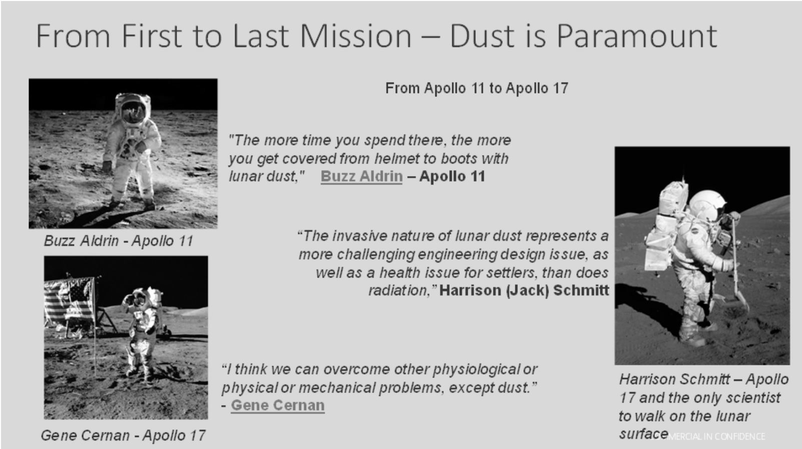

Figure 1-5. Comments about lunar dust from astronauts Buzz Aldrin (Apollo 11), Gene Cernan (Apollo 17), and Harrison Schmitt (Apollo 17).

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.

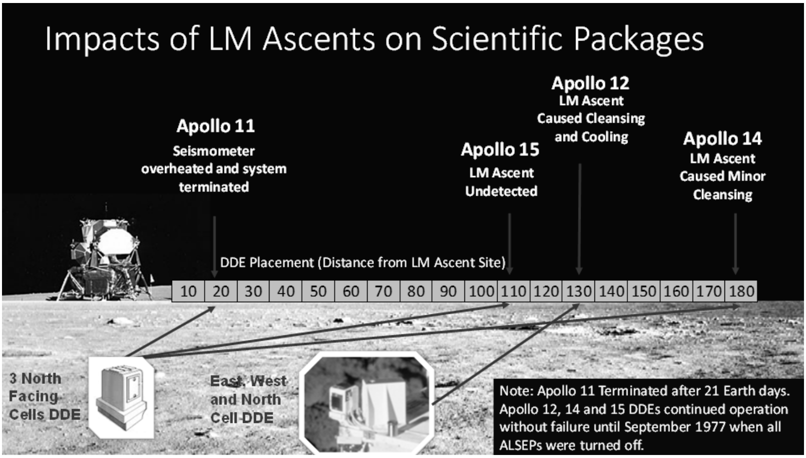

Figure 1-6. Impacts of LM ascents on scientific packages: Apollo 11, 12, 14 and 15.

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