THE IMPACT OF DUST ON LUNAR SURFACE EQUIPMENT DURING APOLLO. J.R. Gaier, NASA Retired, (jrgaier@hotmail.com)

Introduction: When Apollo astronauts began lunar surface operations they were surprised by the many great difficulties the lunar dust[1] caused [1]. 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 [2]. Collateral dust is clearly visible on publically available photographs of the spacesuits and many instruments deployed on the lunar surface, yet it has received little attention.

The dust posed challenges not only to EVA systems but the LRV itself was adversely affected by collateral dust [3]. In addition, collateral dust degraded the science return of many of the Apollo instruments. Although effects on individual instruments have been reported, these have been systematically collected only sparsely [4], and nowhere discussed in detail. This report hopes to remedy that.

The objective of this report is to highlight the ways that collateral dust degraded the performance of Apollo systems. Most of these systems were exposed to the lunar environment for only a few days, and 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 Robust Systems: 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. This includes the descent and ascent spacecraft of the Lunar Excursion Module (LM), all subsystems of the spacesuit and ECLISS systems, the mechanisms of the LRV, and many of the science experiments.

Listed below, and in Table 1, are the eleven instrument that 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 [5].

Table 1: Experiments Not Affected by Collateral Dust

Instrument	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

Experiments Designed to Study Dust and Regolith: Three Apollo experiments, discussed below and listed in Table 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 2: Experiments Designed to Study Dust and Regolith

Instrument	Missions
Lunar Dust Detector	11, 12, 14, 15
Soil Mechanics Penetrometers	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 O'Brien later explained [6] 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: with one bare and two with protective cover glasses, 0.15 or 0.51 mm thick,

[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.

with one cell pre-irradiated with $1x10^{15}$ 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 paper 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.

Soil Mechanics Penetrometers: 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, 14, and 17 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, various objects of known geometry and mass that came in contact with the lunar surface.

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^o 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 the EVA 2. In addition to the penetrometer measurements, soil mechanics properties could be inferred from such activities as coring and trenching.

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 12 candidate thermal coatings. Two duplicate arrays, each containing samples of the 12 coatings, were exposed to the lunar environment. After Astronaut Shepard covered them with dust, one was tapped 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 record 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 1, 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 [7] hypothesized that this was in part due to the short time that the samples were exposed to the full lunar environment. Tests in the Lunar Dust Adhesion Bell jar 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, resulting in substantially greater adhesion.

Figure 1: TDS showing strong cohesion of lunar dust dislodged from the serial number on the mounting plate.

Experiments Affected by Collateral Dust: Perhaps of most interest is to examine the impacts on the seven experiments that were affected by the accumulation of collateral dust.

Table 3: Experiments Affected by Collateral Dust

Experiment	**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 ground 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 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 continually 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. It 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: 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 greater 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 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 [8]. 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. On Apollo 17 a set of smaller detectors was used, one solar facing and the other anti-sun facing.

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 the 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% cover of dust would have produced excessive heating.

Lunar Ejecta and Meteorites: 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. Three classes of particles to be measured included lunar ejecta, interstellar grains, and cometary debris and these were distinguished by particle speed, momentum, and kinetic energy as well as radiant direction. 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.

Unusual data events followed by laboratory investigations with the spare LEAM unit were attributed to the transport of lunar surface fines. Reported dust particle flux increased dramatically 10 hr 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 [9].

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 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 ALSEP deployment so that dust would not accumulate on it. On Apollo 12, it would not lie flat; it was believed that it had been folded for so long that it had “elastic memory.” It could also have been due to electrostatic effects. It was resolved by putting lunar soil and bolts along the skirt edges, though this affected the skirt's function.

The Apollo 16 experiment got hotter than planned. This was likely due to dust that was inadvertently kicked onto the skirt after deployment.

Several of the stations exhibited thermal control problems. For collection of tidal data, limiting the instrument operation temperature to a band of ~1.1 K was desirable. This limitation was not achieved, partly because of problems with deployment of the thermal shroud. Heat loss during lunar night and the solar input incurred during the lunar day was greater than desired.

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 EVA 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 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 was obtained during EVA 2 on the traverses from the SEP transmitter site toward Station 2 and from Station 4 towards the transmitter. Data was 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.

Dust Effects on Lunar Roving Vehicle: Heat rejection from power systems will be necessary for human and robotic activity on the lunar surface. 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 [10]. 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 [11]. 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, that some dust would still find its way onto the radiators. However, a study by Jacobs, Durkee, and Harris, 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 [12]. 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 [13]. Both batteries warmed to about 47 °C, about 4 °C below their maximum rated operating temperature. The experience on Apollo 16 was similar, and at the end of the third EVA the temperature had exceeded the maximum rated survival temperature [14]. The battery temperature profile on Apollo 17 was again similar and after a little more than 4 hr into the third EVA the batteries exceeded their maximum operating temperature. By 6 hr, the batteries had reached their maximum survival temperature [15].

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.

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 Extra-Vehicular Activity (EVA) systems, primarily the Apollo surface space suit. 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 [1]. Although simple dust mitigation measures were sufficient to mitigate some of the problems (i.e., loss of traction) it was found that these measures were ineffective to mitigate many of the more serious problems (i.e., 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.

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 [16] 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 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 verified in the lab [17], yet this has not been taken into account in most dust transport models to date.

The lunar environment is incredible complex, with a vacuum harder that any than is routinely replicated on Earth, a constant barrage of solar wind and micrometeoroids, and complex plasma phenomenon 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.

The second recommendation is that much more coordinated work be funded to develop dust mitigation strategies. Dust mitigation development undertaken to date has been, for the most part, haphazard in the sense that the efforts have not been been coordinated or systematically evaluated against one another. NASA should re-establish an organization within the lunar exploration program to coordinate, prioritize, and evaluate dust mitigation technologies. Funding should be available to all organizations on a competitive basis, but all should submit their technologies to a single evaluative body for apples-to-apples comparison for each 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.

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