https://ntrs.nasa.gov/search.jsp?R=20060050035 2018-02-25T14:01:18+00:00Z

NASA/TP-2006-213726

The Apollo Experience Lessons Learned for Constellation Lunar Dust Management

Sandra A. Wagner
Johnson Space Center

September 2006

The NASA Scientific and Technical Information Program Office ... in Profile

Since its founding, NASA has been dedicated to the advancement of aeronautics and space science. The NASA Scientific and Technical Information (STI) Program Office plays a key part in helping NASA maintain this important role.

The NASA STI Program Office is operated by Langley Research Center, the lead center for NASA's scientific and technical information. The NASA STI Program Office provides access to the NASA STI Database, the largest collection of aeronautical and space science STI in the world. The STI Program Office is also NASA's institutional mechanism for disseminating the results of its research and development activities. These results are published by NASA in the NASA STI report Series, which includes the following report types:

- TECHNICAL PUBLICATION. Reports of completed research or a major significant phase of research that present the results of NASA programs and include extensive data or theoretical analysis. Includes compilations of significant scientific and technical data and information deemed to be of continuing reference value. NASA counterpart of peer-reviewed formal professional papers, but having less stringent limitations on manuscript length and extent of graphic presentations.
- TECHNICAL MEMORANDUM. Scientific and technical findings that are preliminary or of specialized interest, e.g., quick release reports, working papers, and bibliographies that contain minimal annotation. Does not contain extensive analysis.
- CONTRACTOR REPORT. Scientific and technical findings by NASA-sponsored contractors and grantees.
- CONFERENCE PUBLICATION. Collected papers from scientific and technical conferences, symposia, seminars, or other meetings sponsored or co-sponsored by NASA.
- SPECIAL PUBLICATION. Scientific, technical, or historical information from NASA programs, projects, and missions, often concerned with subjects having substantial public interest.
- TECHNICAL TRANSLATION. English-language translations of foreign scientific and technical material pertinent to NASA's mission.

Specialized services that complement the STI Program Office's diverse offerings include creating custom thesauri, building customized databases, organizing and publishing research results ... even providing videos.

For more information about the NASA STI Program Office, see the following:

- Access the NASA STI Program Home Page at **http://www.sti.nasa.gov**
- E-mail your question via the Internet: help@sti.nasa.gov
- Fax your question to the NASA STI Help Desk at (301) 621-0134
- Telephone the NASA STI Help Desk at (301) 621-0390
- Write to:

NASA STI Help Desk
NASA Center for AeroSpace Information
7121 Standard Drive
Hanover, MD 21076-1320

NASA/TP-213726

The Apollo Experience Lessons Learned for Constellation Lunar Dust Management

Sandra A. Wagner
Johnson Space Center

National Aeronautics
and Space Administration

Johnson Space Center
Houston, Texas 77058-3696

Spetember 2006

Available from:

NASA Center for AeroSpace Information
7121 Standard Drive
Hanover, MD 21076-1320

National Technical Information Service
5285 Port Royal Road
Springfield, VA 22161

This report is also available in electronic form at http://ston.jsc.nasa.gov/collections/TRS

CONTENTS **PAGE**

ACRONYMS

ALSEP	Apollo Lunar Surface Experiments Package
CSM	Command Service Package
CDR	Commander
CM	Command Module
CWG	Constant Wear Garment
DCON	Decontamination
ECS	Environmental Control System
EMU	Extravehicular Mobility Unit
ETB	Equipment Transfer Bag
IFR	Instrument Flight Rules
LCG	Liquid Cooling Garment
LCRU	Lunar Communication Relay Unit
LEC	Lunar Equipment Conveyor
LEVA	Lunar Extravehicular Visor Assembly
LiOH	Lithium Hydroxide
LREP	Lunar Robotic Exploration Program
LM	Lunar Module
LMP	Lunar Module Pilot
LRV	Lunar Roving Vehicle
LTG	Lunar Traverse Gravimeter
LSAM	Lunar Surface Access Module
MESA	Modular Equipment Stowage Assembly
MET	Mobile Equipment Transporter
OPS	Oxygen Purge System
PGA	Pressure Garment Assembly
PLSS	Portable Life Support System
PSE	Passive Active Experiment
RCU	Remote Control Unit
ROD	Rate of Descent
RTG	Radioisotopic Thermoelectric Generator
SEP	Surface Electric Properties
SRC	Sample Return Container
SWC	Solar Wind Composition

EXECUTIVE SUMMARY

> *"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."*
>
> *Gene Cernan*
> *Apollo 17 Technical Debrief*

> *"A common sense, layered, engineering design defense can solve any apparent problem with dust during long-term human activity and habitation in the lunar environment."*
>
> *Jack Schmitt*
> *Ames Research Center*
> *Lunar Dust Symposium*
> *February 2, 2004*

As NASA embarks on its Exploration Vision, it will encounter many technical challenges. For lunar exploration missions, perhaps its greatest challenge will be to learn to live with lunar dust. NASA will have to be prepared to meet that challenge. Lunar dust can be managed by using good engineering design for reliability and ease of maintenance and by incorporating innovative technologies and operations into Lunar mission design.

Problems associated with lunar dust during the Apollo Program were reviewed and are detailed in this report. The Apollo Mission Reports and Technical Debriefs were used to identify problems, solutions, and lessons learned. These documents were chosen because they were prepared immediately after the missions, while crewmembers memories of their lunar experience were still fresh. This report intentionally did not include later documentation and statements by crews, because memories fade and change, this methodology should produce a historically factual report. This report should be considered a starting point.

However, recollection at a distance from an event doesn't necessarily degrade the quality of the information, but, tends to cull less memorable events and reinforce the very memorable ones. This can be useful as well. Review and analysis of additional documents should also be performed to supplement the information contained in this report to ensure all available information is considered. Supplementary reports should be published periodically as additional information is evaluated.

The report evaluates information presented in the Apollo documents and proposes forward work to manage lunar dust in Constellation's lunar missions. Recommendations center on solutions to address root causes and strive to ensure fiscal responsibility.

INTRODUCTION

This report is divided into eleven sections.

1. Surface Obscuration During Descent
2. LM Descent Engine Regolith Transport
3. Lunar Module Contamination
4. Contamination during Transfer between the LM and CSM
5. Command Module Contamination
6. Mechanisms for Lunar Module Contamination
    a. General Effects
    b. Traction
    c. Cables and Cords
    d. Translation Aids
    e. Lunar Rover Vehicle
    f. Pockets
7. External Environmental Lunar Dust Effects:
    a. Experiments
    b. Cameras
    c. Translation Aids
    d. Radio isotopic Thermal Generator
    e. Lunar Rover Vehicle
    f. Lunar Materials Sampling and Samples
8. Space Suits and Seals
9. Dust Characterization
10. Human Effects
11. Hygiene

Each section is divided into the following subsections:

- Summary provides a compilation of lunar dust problems encountered.
- Observations contain relevant quotations, describing dust problems, from Apollo documents.
- Recommendations and Lessons Learned contain quotations from Apollo documents.
- Analysis is a combination of analysis presented in Apollo documents and analyses by the author.
- Future work contains recommendations for on-going future work to manage lunar dust during Constellation's lunar exploration missions.

SURFACE OBSCURATION DURING DESCENT

During Apollo landings, crews experienced regolith entrainment during the final maneuvers for landing. This obscured fine scale topography during the final touchdown and required landing the LM into a cloud of regolith.

Summary

Surface obscuration during descent varied for each LM landing. For Apollo 11, visibility was degraded; During Apollo 12 and 15 the surface was completely obscured; For Apollo 14 and 17 LM descents, the surface was readily visible; and Apollo 16 descent visibility was moderate.

Contributing factors that may be considered in mission and engineering design include:

- Landing site selection may be a factor in mission design, however, mission reports indicated that landing sites were similar, both in terms of characteristics and behavior of lunar dust.
- Improved hovering procedures may have contributed to improved visibility due to reduced blowing dust.
- Solar elevation angle may affect visibility.
- Landing radar output was affected by blowing dust and debris.

Observations

The Apollo 11 Mission report states, *"Surface obscuration caused by blowing dust was apparent to 100 feet and became increasingly severely as the altitude decreased. Although visual determination of horizontal velocity, attitude, and altitude rate were degraded, cues for these variables were adequate for landing."* [1]

The blowing dust caused by the Apollo 12 LM landing appears to have been worse than that of Apollo 11. In fact, a standup extravehicular activity (EVA) was performed by the crew to assess the site prior to performing lunar surface EVAs because blowing dust completely obscured the view during landing.

The Apollo 12 Mission report described dust effects on landing visibility. *"During the final phase of the lunar module descent, the interaction of the descent engine exhaust plume with the lunar surface resulted in the top layer of the lunar soil being eroded away. The particles were picked up by the gas stream and transported as a dust cloud for long distances at high speeds. Crew visibility of the surface and surface features was obscured by the dust cloud."* [2]

The report continues, *"The first time that dust is detected from the photographic observations occurs 52 seconds before touchdown. This time corresponds to an altitude of about 100 feet. There is no commentary in the voice transcription relative to dust at this point, but postflight debriefings indicate the crew noticed the movement of dust particles on the surface from a relatively higher altitude. At 180 feet altitude the Lunar Module Pilot made the comments that they could expect to get some dust before long. However, the initial effect of the dust, as first observed in the film or by the crew, indicates that there was no degradation in the visibility prior to about 100 feet in altitude. However, the crew stated that dust was first observed at an altitude of about 175 feet. Dust continued to appear in the sequence camera photographs for the next 10 or 12 seconds as the lunar module descended to about 60 to 70 feet in altitude. Visibility is seen to have degraded, but not markedly. Beyond this point, the film shows the dust becoming more* *dense. Although surface features are still visible through the dust, impairment of visibility is beginning. Degradation of visibility continues until the surface is completely obscured and conditions are blind. The point at which this total obscuration occurs is somewhat subjective. At 25 seconds before touchdown, the dust cloud is quite dense, although observations of the film show some visibility of the surface. From the pilot's point of view, however, visibility is seen to be essentially zero at this time, which corresponds to an altitude of about 40 feet…obscuration occurred at an altitude of about 50 feet is confirmed. The Commander considered visibility to be so completely obscured at this point that he depended entirely on his instruments for landing cues."*[2]

Pete Conrad described the blowing dust in the Apollo 12 Technical Debrief: *"I've already commented on the blowing dust. I felt it was very bad. It looked a lot worse to me than it did in the movies I saw of Neil's landing. I'm going to have to wait and see our movies to determine if it doesn't show up as badly in the movies as it does to the eye. Maybe we landed in an area that had more surface dust and we actually got more dust at landing. It seemed to me that we got the dust much higher than Neil indicated. It could be because we were in a hover, higher up coming down; I don't know. But we had dust from – I think I called it around 300 feet."* [3]

The Apollo 14 LM landing site apparently was less dusty than the previous two sites. However, Mitchell refers to landing procedures that may have reduced the blowing dust.

Alan Shepard described lunar landing in the Apollo 14 Technical Debrief. *"I believe that we had less problem with dust than they've had before. I think it's because as we comment later on, the surface of the general area in which we landed was less dusty, that is, exclusive of the dust around the rim of craters. The general area appeared to have less dust and we certainly had no problem with dust at touchdown. I referred to the cross pointers during the final stages of the descent at less than 100 feet, but only to assure myself that I had done the best I could as far as cross velocity was concerned. The dust was obvious, but you could also see the rocks through the dust. We had no problems here."* [4]

Mitchell continued, *"Yes. That's what we had practiced because of the dust problems. When we went into* [rate- of-descent] *ROD mode, we leveled out on ROD and kept it flying on over until I was sure we were to Triplet and into that area where we wanted to land, then we started on down. I might add that looking at the film of the descent last night the dust problem appears a lot worse on the film than it appeared to me on the window. I thought I could see a lot better…just looking out the window you can see the dust is no great problem at all."* [4]

The Apollo 14 Mission report observed, "Blowing dust was first noted at an altitude of 110 feet, but this was not a detrimental factor. The dust appeared to be less than 6 inches in depth and rocks were readily visible through it…Touchdown occurred at shutdown with some small dust-blowing action continuing during engine thrust tail-off or decay. As might be expected, these areas are generally coincident with those in which blowing surface dust was noted at low altitudes." [5]

Scott, in the Apollo 15 Technical Debrief said, *"I went on down to 200 feet and started rounding out at 150 feet. I could see dust – just a slight bit of dust. At about 50 to 60 feet, the total view outside was obscured by dust. At about 50 to 60 feet, the total view outside was obscured by dust. I was completely* [Instrument Flight Rules] *IFR. I came into the cockpit and flew with the instruments from there on down."* [6]

He continued, *"But at the altitudes looking down as we approached the landing, it was very difficult to pick out the depressions. I did know that I was landing past the crater which I thought was the one north of Salyut, which I believe now was probably Last Crater. I could see that I was going to land to the west of that, but as far as the other shallow depressions there and the one in which the rear pad finally rested, I couldn't see that they were really there. It looked like a relatively smooth surface."* [6]

The Apollo 15 Mission report states, *"A trace of blowing surface dust was observed at a height of 130 feet with only a slight increase down to 60 feet. Beginning at this altitude, out-of-the window visibility was completely obscured by dust until after touchdown."* [7]

In addition to obscured visibility, radar was affected by blowing dust. The Mission report states, *"Landing radar outputs were affected at an altitude of about 30 feet by moving dust and debris."* [7]

During Apollo 16 LM descent, surface obscuration was moderate. John Young, the in the Apollo 16 Technical Debrief said, *"We did a hover for a short period of time there at about 40 feet off the ground, and the rates were practically zero and there was blowing dust."* [8]

Duke suggested, *"It started at about 80 feet, John."* [8]

Young responded, *"Yes, 80 feet. Certainly, it started there and it got a lot worse, but you could still see the rocks all the way to the ground. The surface features, even the craters and with something like that – which really surprised me. I was expecting two things: either the dust would be so bad we couldn't see anything, or there probably wouldn't be as much dust as there was. Possibly, it's the 15-degree Sun angle that did all that. Because there's certainly plenty of dust down there to blow, and there's nothing thin about that regolith around the LM."* [8]

The Apollo 16 Mission report stated, *"Small traces of dust were evident at approximately 80 feet and the dust increased all the way to touchdown; however, the vehicle had lunar contact before the visibility obstruction due to dust prevented the Commander from seeing craters or small boulders on the surface."* [9]

The Apollo 17 lunar landing generated a thin dust layer at a lower altitude than other landings. The Mission report states, *"Dust was first observed at 60 to 70 feet altitude, as indicated on the tape meter."* [10]

Cernan, in the Apollo 17 Technical Debrief says, *"The dust layer was so very thin that I could definitely see through it all the way down. It didn't hamper our operations at all."* [11]

Analysis

The Apollo 12 Mission report compared blowing dust.

"*Compared to the Apollo 11 landing, the degradation in visibility as a result of dust erosion was much more severe during Apollo 12. During Apollo 11, the crew likened the dust to a ground fog; that is, it reduced the visibility, but never completely obscured surface features. On Apollo 12 the landing was essentially blind for approximately the last 40 feet. In order to better understand the reasons for these differences, a detailed analysis was initiated of the factors which affect erosion and visibility. The results of that analysis, although not completed, are summarized here.*

"First it was important to establish whether the surface material characteristics were different at the Apollo 11 and Apollo 12 landing sites. The various data sources provide no firm basis for a belief that a significant difference exists between the lunar material characteristics at the two sites. On the other hand, the following evidence indicates that the surface material behavior was essentially the same at the two sites.

a. The height at which erosion first occurred was essentially the same on the two missions. The Apollo 11 sequence camera photographs indicate the first signs of dust at about 120 feet altitude about 65 seconds before landing.
b. Photographs taken during the extravehicular activity in the general area of the lunar module revealed that the soil disturbances cause by the descent engine exhaust produced about the same effects on the two missions.
c. Photographs of the crewmen's boot prints indicate that the soil behaved about the same at the two sites. Although there were local variations in bootprint penetrations, such variations were observed at both sites.
d. Analysis of the returned core tube samples indicates that the lunar soil had about the same density and the same particle size distribution at both sites.

Since the soil characteristics were apparently the same at the two sites, the analysis was concentrated on the aspects of the two flights that were different, that is, the descent profile over the last 200 feet of altitude and the sun elevation level at landing.
Results of these analyses indicate that both of the effects contributed to the poor visibility conditions on Apollo 12. The thrust level on Apollo 12 was somewhat higher over most of the final descent and was significantly higher (about 20 percent) at about 30 feet altitude at 15 to 20 seconds before landing. This greater thrust caused a higher surface loading and therefore produced greater erosion rates. More significant, however was the effect of the lower sun angle. For given dust cloud density and combined effects of light attenuation, veiling luminance, and a diffuse illumination on the surface are much more serious at the lower sun level and can be shown analytically to produce the effects observed on Apollo 12. Analysis is continuing on a parametric variation of the factors which affect erosion and visibility. However, all these analyses are based upon certain assumptions about the optical scattering properties of the lunar dust and upon an idealized lunar model. Thus, these limitations make it impossible to conclusively prove that the effects noted can indeed be attributed to the sun elevation angle. Undeterminable differences in critical soil properties, such as cohesion, could have produced the same effects."[2]

The report continues, *"Preliminary studies show the impracticality of various means for reducing the dust effects on visibility, largely because of the weight and performance limitations of the spacecraft. The lunar module was designed with the capability to be flown entirely on instruments during the landing phase. The two accomplished lunar landings have provided the confidence that an instrument landing is within the capability of the spacecraft systems. Therefore, on Apollo 13, onboard software will be modified to permit reentry into an automatic descent program after manual modes have been exercised. This change will allow selection or redesignation of a suitable landing site, followed by automatic nulling of horizontal rates and automatic vertical descent from the resulting hover condition, which would occur at an altitude above appreciable dust effects."* [2]

Note that, after Apollo 12, the LM was modified to permit automatic descent. This change was the result of confidence in landing instruments. However, during the Apollo 15 landing, landing radar outputs were affected by dust and debris.

Recommendations and Lessons Learned

Scott, in the Apollo 15 Technical Debrief recommended, *"I would recommend maintaining an altitude of at least 150 feet so you don't get into dust problems. I think dust is going to be variable with landing sites."* [6]

Future Work

Additional documentation describing Apollo landing sites should be reviewed to definitively define dust variation, the effect of sun elevation on visibility, efficacy of hovering procedures, and radar operation. Based on review findings generate applicable Concept of Operations and requirements for Lunar Surface Mission Design, LSAM descent stage design, landing procedures and landing sites to mitigate dust risk during descent.

LM DESCENT ENGINE REGOLITH TRANSPORT

Blast ejecta from lunar descent and ascent may present problems for lunar missions when precursor missions include staging equipment and supplies prior to human landing. Damage to pre-positioned assets may threaten mission success. Blowing soil and debris may also damage the lunar lander and may present a risk to mission success. Some have suggested that descent engines may erode a crater underneath the lander, which could lead to slope failure and lander tip over. However, there was no indication that any significant erosion of a crater occurred beneath the DPS engine bell during final landing maneuvers.

Observations

Conrad, describing effects of the Apollo 12 LM landing, observed, *"Now the one comment I made in flight was that there was a rock about 3 by 4 by 2 inches lying right under the engine ball. It hadn't been blown away. I can't figure out how it was lying right out at the skirt edge. We took a photograph of it. I don't know whether it will show or not, but it didn't get blown away. I was quite surprised after seeing all that dust and stuff flying on landing that it did not blow a rock that size away."*[3]

This would seem to suggest that cratering was not a problem. Understandably, Conrad was interested in this phenomenon because both crew members were cognizant of potential ejecta problems associated with their LM landing. A mission objective was to obtain a camera from the Surveyor III spacecraft in the vicinity of the landing site. Damage to the equipment would degrade mission success.

The Apollo 12 Mission report describes mission planning to protect the Surveyor. *"In addition, if the descent path were exactly nominal, the crew could apply manual site redesignation in ample time to land outside the Surveyor crater. Actually, as discussed in the previous section, the unperturbed (automatic) descent trajectory was very close to nominal (170 feet south and 380 feet west of Surveyor), and the crew elected to over-fly the crater to the right side, eventually touching down very near its far rim. The final landing location, which was 535 feet from the Surveyor, was influenced by the preflight consideration that the landing occur outside a 500-foot radius of the target to minimize contamination of the Surveyor vehicle by descent engine exhaust and any attendant dust excitation."*[2]

Bean described the condition of the Surveyor, *"We noticed the Surveyor had turned to sort of a tan appearance, including the white parts, the chrome, and the shiny parts. We looked at it closely and rubbed it. You could rub off this brown color if you rubbed hard enough. It gave you the feeling that it wasn't blown on when we flew down in the LM, or rather that it had adhered to it over the years it had been in the crater. We took enough pictures to document this."*[3]

The Mission report detailed Surveyor camera collection and related activities. *"The Surveyor was sitting on a slope of approximately 12 degrees. All components were covered with a very tenacious dust, not unlike that found on an automobile that has been driven through several mud puddles and allowed to dry. While the dust was on all sides of the Surveyor, it was not uniform around each specific item. Generally, the dust was thickest on the areas that were most easily viewed when walking around the spacecraft. For example, the side of a tube or strut that faced the interior of the Surveyor was relatively clean when compared to a side facing outward.*

"Retrieving the television camera was not difficult using the cutting tool. The tubes appeared to sever in a more brittle manner that the new tubes of the same material used in preflight exercises. The electrical insulation had aged and appeared to have the texture of old asbestos. The mirrors on the surface of the electronic packages were generally in good condition. A few cracks were seen but no large pittings. The only mirrors that had become unbonded and separated were those on the flight control electronics package. As a bonus, the Surveyor scoop was removed. Although the steel tape was thin enough to bend in the shears and could not be cut, the end attached to the scoop became debonded when the tape was twisted with the cutter."[2]

The report also provided a description of the Surveyor site. *"Examination of the photographs taken at the Surveyor III site suggest that the lunar surface has undergone little change in the past 2 ½ years. The trenches excavated by the lunar material sampling device on Surveyor, as well as the waffle pattern of the Surveyor footpad imprint, appear much the same as when formed on Surveyor landing. Many of the Surveyor components were observed to be coated with a thin layer of dust, but some other process could also have discolored them. The results of a detailed postflight examination of the Surveyor components returned to earth will be published in a separate science report. The Surveyor components returned were a cable, a painted tube, an unpainted tube, the television camera, and the scoop."*[2]

The report described cratering at the landing site. *"The area in the vicinity of the descent engine after touchdown appeared to have been cratered only to a depth of about 6 inches and, as photographs show, only in a small, well-defined area."*[2]

Bean describing lift-off said, *"We got some good movies, I think. He fired some of the thrusters, and I took some 16-millimeter movies out the window. Hopefully, the geologist can get some feel for movement of dust with that engine and maybe compare or extrapolate down to the descent engine."*[3]

The Apollo 14 Mission report described no observable dust effects during LM ascent. *"The lunar dust detector of the central station is showing normal outputs from all three photoelectric cells. No changes in the outputs of there cells were observed during or after lunar module ascent, indicating that dust from the ascent engine exhaust did not settle on the central station."*[5]

The Apollo 15 Mission report described similar effects for the ALSEP. *"There was no indication of significant dust collection on the instrument's solar cells as a result of the lunar module ascent."*[7]

"The instrument measured a lunar surface temperature change of 330 F° during the eclipse. There was no indication of significant dust collection on the instrument's solar cells as a result of the lunar module ascent."[7]

The LM ascent stage had as a launch pad the descent stage, which inhibited the impingement of the ascent stage exhaust on the lunar surface.

Analysis

The Apollo 12 Mission report described the mechanism causing erosion. *"The type of erosion observed in the Apollo 11 and 12 landings is usually referred to as viscous erosion, which has been likened to the action of the wind blowing over sand dunes. The shearing force of the gas stream at the interface of the gas and lunar soil picks up weakly cohesive particles, injects them* *into the stream, and accelerates the particles to high velocities. The altitude at which this erosion is first apparent and the transport rate are dependent upon the surface loading caused by the engine exhaust plume and upon the mechanical properties of the local lunar soil. This dependence is expressed in terms of several characteristic parameters, such as engine chamber pressure, exit Mach number, material density, particulate size, and cohesion."*[2]

The Apollo 12 Preliminary Science report concludes, *"The optical properties indicate that the lunar surface in the area of the Surveyor spacecraft has not received a new covering of dust nor been mechanically altered by the lunar environment during the 30 month. A significant change occurred in the reflectance of the Surveyor footpad over the 30-month span, the change may have been caused by microscopic mechanical alteration of the compressed surface."*[12]

The Apollo 12 Preliminary Science report, postulates ejecta as a cause for pitting observed on returned Surveyor components. *"In addition to the possible meteoroid impacts, numerous surface effects of probable low-velocity origin were noted on the TV camera surface. In general, these low-velocity effects were shallow craters, and most were of recent origin, as indicated by their whiteness against the sandy-brown color of the painted surface of the TV camera housing. There was a definite concentration (10 to 100 times more) of these white craters on the side of the TV camera facing the LM, as compared with the other side of the camera. The number and density of these craters peaked at a region approximately directly in line with the LM. In addition, protuberances on the camera (such as screwheads, support struts, etc.) left dark shadows on the camera paint, which again pointed toward the LM. After a detailed examination of the geometry involved and by taking into account the relative angles of the shadowing, the TV camera, the Surveyor spacecraft, and the LM position, it was readily shown that the LM was the most probable origin for these craters. It is, therefore, postulated that in the final moments of landing, the LM generated a dust shower that affected the Surveyor 3 spacecraft and sandblasted that camera surface that faced toward the LM. This is the most significant examination of the Surveyor 3 TV camera to date.*

"The preliminary examination of the polished tube at low magnification revealed four craters that exhibited the characteristics of hypervelocity impacts. Subsequent detailed examination at higher optical magnifications has ruled out the possibility that one of these craters was caused by a hypervelocity impact. The examination revealed the crater to be a surface pit caused by polishing, and the other three craters have not yet been identified positively as impact pits. Further analysis of these craters is proceeding. The detailed scan has established that the surface of the tube is covered with polishing scratches and gouges being easily mistaken for lipped hypervelocity craters. There appears to be a marked concentration of surface effects on the same side of the tube as the deposit, and the significance of this correlation is currently being analyzed.

"Both sections of the polished aluminum tube have been examined with a scanning electron microscope at up to 12,000- power magnification. At this power, it has been possible to observe suspected micrometeoritic craters in sufficient detail and examine the residue in some of them. Analysis of all the data obtained to date is in progress, and a comprehensive report will be made available at a later date."[12]

The conclusions of this report appear to conflict. The observation that "*the Surveyor spacecraft has not received a new covering of dust nor been mechanically altered by the lunar environment during the 30 month*" period does not seem to agree with the postulation that "*in the final moments of landing, the LM generated a dust shower that affected the Surveyor 3 spacecraft and sandblasted that camera surface that faced toward the LM.*" One would assume that if the spacecraft was "sandblasted" the dust around the spacecraft would have been disturbed. Further, the crew felt that "*it wasn't blown on when we flew down in the LM, or rather that it had adhered to it over the years it had been in the crater.*"

Instruments in the vicinity of Apollo 14 and 15 LM ascent did not indicate any performance degradation due to blowing dust and/or debris.

Future Work

Scientific investigators performed numerous analyses on the camera since the preliminary report cited in the above. Findings of these results should be reviewed and, if discrepancies still exist, further investigations should be performed. The results should be used in LSAM descent module analysis and trade studies, particularly if erosion of spent LSAM descent stages is considered an issue. If evidence and analysis suggest probable undesirable damage to assets by lunar ejecta; then, dust management for lunar surface architecture and mission and hardware designs should be included in requirements.

LUNAR MODULE CONTAMINATION

Summary

Lunar Module dust, dirt and debris contamination presented numerous challenges for several of the Apollo missions. The Apollo 12 crew observed that at 1/6-g the cabin atmosphere was excellent, however, after orbital insertion lunar dust filled the atmosphere and caused eye and nose irritation. The Apollo 14 crew observed little dust in the LM and cited no dust related problems. The floor of the Apollo 15 LM was dirty. The Apollo 16 crew appears to have had the most difficulty with dust, citing the following: Velcro on the floor was caked with dust; crew feet, hands and arms were covered with dust that was transferred into the suit upon donning; the midstep was covered with dust; eye and mouth irritation; and, the cabin fan in zero-g did not appear to clean the atmosphere. The crew of Apollo 17 cited sinus and nostril irritation after EVAs, however, observed good cabin cleaning and atmosphere in 1/6-g.

Observations

The Apollo 12 Mission report says, *"Cabin repressurization after each extravehicular period was positive and rapid. Once inside the spacecraft, the dust on the suits became a significant problem."*[2]

Bean described effective cabin cleaning during Lunar Module depressurization. *"The first cabin depressurization was pretty interesting because as soon as Al opened the depressurization valve after our 3.5-psi check, everything in the spacecraft disappeared out the valve. There was much outgassing, which is not unusual…I had seen it in Gemini. All loose particles that happened to be floating around disappeared from the spacecraft; it gives the spacecraft a real flush."*[3]

Bean spoke of LM ventilation, *"Cabin atmosphere from activation planning was excellent. When we got back inside the first time, in one-sixth g, the atmosphere remained that way although we brought in quite a lot of dust. The same with the second time and the cabin jettison depressurization. Once we got into orbit in zero-g, there was a lot of dust and dirt floating around the cabin and we chose to remain in our suit loops as much as possible because of all this dirt, dust, and debris that was floating around. When we finally got back to the command module and docked with the CSM we wanted to figure a way to keep this dust and dirt from filling the command module, but we weren't really sure how to do that."*[3]

The Apollo 12 Mission report describes LM cabin atmosphere and associated health hazards to the crew, *"After ascent orbit insertion, when the spacecraft was again subject to a zero-g environment, a great quantity of dust and small particles floated free within the cabin. This dust made breathing without the helmet difficult and hazardous, and enough dust and particles were present in the cabin atmosphere to affect vision."*[2]

In the Apollo 14 debrief, Alan Shepard spoke of dust contamination. *"We did find that we had to take the boots off because there's so much dust in your overshoes that we did take those off before we went to bed."*[4]

Mitchell continued, *"In training, we thought that maybe was an unnecessary time-consuming step and we'd probably sleep with the boots on, but they were so covered with crud that I didn't want it sifting down in my face during sleep. We took them off."* [4]

Shepard described dust contamination in the LM, *"We had no problem with recharge, changing out batteries,* [Portable Life Support System] *PLSS feedwater collection, or dust control inside the cabin. We seemed to have a little extra dust on the floor. Other than that, it was not too bad."* [4]

Shepard described cleaning techniques, *"We found that the brush that we had planned to use to dust off the suits was effective. It did take off the first layer of loose dust. I would suggest that jumping up and down on the footpad or stomping one's boots on the ladder is just as effective with respect to the boots themselves. Just banging the boots against the ladder is enough to shake off that dust. From the boots on up the lower legs, backs of the legs, insides of the thigh, and so forth, the brush did appear to be fairly effective in getting the first layer of dust off."* [4]

Scott, in the Apollo 15 Technical Debrief, described dust management techniques after EVA, *"The first order of business after we got repress was to go through the checklist and do the EVA post and try and come up with a plan on how to handle all the dirt in the cabin. We were pretty dusty. We had planned prior to the flight to take the jettison bags and step into them with the suits to keep the lower portion of the suit isolated from the rest of the cabin. Our legs from about thigh down were just completely covered with dirt. I guess the dust brush worked fairly well. It got most of it, but we were still pretty dirty."*[6]

Scott continued, *"We could have combined some things as we did do later. We were going sort of slow, feeling our way around the cabin, trying to get settled down to some sort of system to control the dirt and stay organized. I think the jettison bags over the legs worked fairly well. I think we kept the majority of the dirt out of the cabin and kept it in the bag. We just cinched it up around our legs. It was not problem getting in and out of our suits with the bags on them. We took another jettison bag and stuck it up on the midstep, and I stood on that to keep my* [Constant Wear Garment] *CWG clean. You stood on one of the* [Oxygen Purge System] *OPSs to keep off the floor, which was pretty dirty."* [6]

During the Apollo 16 Technical Debrief, Young noted, *"It was extremely clean until after the first EVA, and then from then on, it was really dirty."* [8]

The Apollo 16 crew brought a lot of dust into the LM after each EVA. Young said, *"EVA 3 Post Activities, "Repress was normal. Again we tracked a lot of dirt with us."* [8]

Young provided insight into LM dust contamination, *"You know all that Velcro on the floor, it just gets caked with dirt. You can't stand on the floor. I guess it didn't hurt anything, but I know when we donned the suit, we had our jettison bag down to stand on like everybody said, but our feet and hands and our arms were all full of dust when we put the suit on. So it was all going into the suit. And it didn't seem to bother anything. You don't know how much it's going to bother. You don't have a feel for whether it's going to give you problems or not. There's just no way to avoid it. The second EVA, we had in places that much dirt and dust on the floor and that's after cleaning each other real good."* [8]

Young continued, *"We put a bag down on the floor to stand on, but that did not keep us from getting dust all over the place. One of the problems was that we had dust on the bottom of the PLSSs even though we wiped it off, and the dust on the side of the OPSs for some reason. They were lying on the floor. As a result, when we got in our LCGs, we were sort of standing around, like I had one foot on OPS and one foot on the midstep and was sort of leaning back against the shelf on my side. Charlie was sort of standing with his foot on the* [Equipment Transfer Bag] *ETB and one foot on the midstep, and we were up out of the dirt. Our hands were black when we* *started taking each other's wrist rings off. We got our hands dirty and I didn't get dirt off my hands until after we'd landed. Washed them up good. I don't think Charlie did either. We managed to get dirt on the bottom of the LCGs, on our sleeves, and on our hands that got into the suits. It was just a little dust. I don't know what problem it entailed, but it sure looked like it might become a problem. The only thing I can say is we stayed out of the dirt as best we could. It was all over the floor. Just hardly any way to get off of it. We even had some on the midstep where we'd laid the ETB up there. It was dust covered too from dropping it in the dirt because the* [Lunar Equipment Conveyor] *LEC was too long to keep it off the ground."*[8]

Wondering about the effects of cabin depressurization, Mattingly asked, *"I was thinking about the subsequence depress. Did you have a lot of rocks and crud fly through there?"*[8]

Young answered, *"No, actually it cleaned the floor off pretty good. When I opened the door, the dirt would go 'zip' right out."* [8]

The crew discussed LM atmospheric contamination and failure of the cabin ventilation system to remove dust. Duke comments, *"We did one thing procedurally at insertion. We had a lot of dust and pebbles floating around in the cockpit with us. We did turn on the cabin fan and left helmets and gloves on until docking, because we had so much dust in there."* [8]

Young responded, *"That didn't clear any dust out because you have to open the inflow valve to get any of that stuff in the suit loop to clean it out."* [8]

Unidentified Speaker, *"It just circulates around. It has a filter behind it."* [8]

Unidentified Speaker, *"Does it have a filter behind it? Well, it didn't clean much of the dust out."* [8]

The Apollo 16 Mission report described LM contamination, *"A major concern with housekeeping, on the post-extravehicular doffing of the pressure garment assemblies, was dust in the cabin. A jettison bag was placed over both legs of the suit and the suits were laid on the engine cover as prescribed. There was a considerable about of dust on the suits around the neck, around the helmet, on top of the oxygen purge system, and on the back of the portable life support system. Most of this dust ended up on the floor of the lunar module. The dust floor was cleaned by wetting a rag, caking the dust into mud and picking it up in the rag; however, there was no way to remove the dust from the Velcro on the floor. Since the Velcro does not restrain the crew to the floor in zero gravity, it is not needed."* [8]

Schmitt, in the Apollo 17 Mission Debrief articulated nasal and sinus irritation and the effectiveness of LM cabin atmospheric management, *"Cabin atmosphere was good, good ventilation, good odor cleaning…The dust clearing was good, considering the amount of dust we had. It was within a couple of hours after ingress. Although there was a lot of irritation, at least to my sinuses and nostrils, soon after taking the helmet off, about 2 hours later, that had decreased considerably."* [11]

Describing LM cabin atmospheric conditions at zero-g, Cernan says, *"The commander kept his helmet on throughout the rendezvous and docking. I took my gloves off after insertion and left them off. As soon as were hard docked, the commander took off his helmet. As I look back at that, because of dust debris in the LM spacecraft, I'm sorry I did. I could have left the helmet on, and would have had a lot less eye and mouth type of irritation. You knew you were in a very heavily infiltrated atmosphere in the LM because of the lunar dust. I don't know how much lunar dust* *previous flights had, but I think we saved a great deal of grief by sweeping all the dust we could find in the floor into the holes and putting our tape covers over those holes. I think that had to help a great deal. There was an awful lot of dust on the floor that we didn't see."* [11]

Recommendations and Lessons Learned

Bean described cleaning suits in the Apollo 12 Technical Debrief, *"One other thing, we tried to dust each other off. Usually, it was Pete trying to dust me off. I would get up on the ladder and he would try to dust me off with his hands, but we didn't have a lot of luck. We should have some sort of whisk broom on the MESA. Before we get back in, we'll dust each other up high. Then the LMP will get on the ladder and the CDR will give him a dust or vice versa and then we will get on in. We are bringing too much dust into the LM. Another possibility is that just as soon as you get in you slip on some sort of second coveralls that fit over the feet on up to the waist, because that's the dirty area. Then you keep that on all the time you're in the LM and take it off just before you get out. The other alternative to this is that you put on a similar something when you're getting out onto the lunar surface. The reason I suggested the former was that I think you want to be as free as you can possibly be when on the lunar surface. Adding another garment over the top of the already existing equipment is going to be restrictive and might give you a few more problems."*[3]

The Apollo 14 Mission report says, *"On previous missions, dust carried into the cabin during ingress was a problem. However, it did not seem to be a problem on Apollo 14, perhaps because there was less dust on the lunar surface, or perhaps, being aware of the problem made the crew more meticulous in contamination control that they would have been otherwise. Care was taken to remove the dust from the pressure garment assembly and other equipment before entry into the cabin. The brush that was used for pressure garment assembly was adequate. The technique of stomping the boots against the lunar module ladder seemed to help to some extent."* [11]

After their Apollo 16 experience, the crew recommended removing Velcro from the floor, *"I would like to see the Velcro taken off the flight floor, because it sure got dusty."*[8]

Young replied, *"Sure did."* [8]

Duke said, *"Make it terrible to clean. If you took that Velcro off you could take a damp cloth and swab the floor."* [8]

Young added, *"All that dust and mud and throw it in a jettison bag."* [8]

Duke replied, *"But with the Velcro there, you couldn't do that."* [8]

Young said, *"For the short time you'll be in zero-g, you could use the tie downs."* [8]

Duke agreed, *"That's right."* [8]

Young noted, "*You're going to be in there suited anyway."* [8]

Duke added, *"In fact you want to float free in zero gravity at least I did. I felt more comfortable floating. And the hoses really did restrain you to some degree. The Velcro didn't work. I tried that and I just came right up off the floor."* [8]

Young agreed, *"I guess I agree, Charlie. I don't think you lose anything by getting rid of the Velcro, but you would sure get rid of a lot of dirt."* [8]

Apollo 17 Mission report explained taping the LM floor prior to ascent, *"Prior to ascent from the lunar surface, the cabin activities included covering all holes in the lunar module floor into which dust had collected could be swept. Although considerable dust appeared in the cabin upon insertion, taping the holes definitely prevented a major dust problem in zero-g."*[10]

Analysis

Dust was brought into the Lunar Module during ingress after EVA. The source of contamination was dust, soil, and debris covered extravehicular activity units, samples, and equipment. The mechanism of contamination and recommendations for removing dust from these sources is discussed in Section 6 of this report.

Numerous operational and engineering solutions were implemented to manage dust inside the LM cabin. They include:

- Jettison bags were used to contain dust on space suits
- Dust brushes worked well in some cases
- Wet wiping surfaces
- Jumping and stomping boots against the LM ladder
- Crews were meticulous in contamination control
- Covering all the holes in the LM floor prior to ascent

Some problems were not corrected during the Apollo Program. The root cause of the LM cabin contamination, dust brought into the cabin, was not resolved.

Future Work

Although dust cleaning procedures and technologies will be developed to lessen the amount of dust brought into the Lunar Surface Access Module (LSAM), total removal of dust is not feasible. Therefore, atmospheric revitalization and cleaning technologies and operations will probably be required to manage risks presented by lunar dust contamination. The crews noted that the combination of zero-g and depressurization was effective cleaning the CM cabin. This technique may be considered as well.

Engineers and Operators should review this report and other historical documents to gain insight into techniques and equipment that were effective and ineffective during the Apollo Program.

Operational Scenarios and Concept of Operations should be developed to identify and evaluate air revitalization and airlock concepts for LSAM and Habitats. Dust management requirements should be created for incorporation into requirements for LSAM and Habitat projects. Trade studies should be performed to identify existing technologies and perform technology gap analyses for each concept. These activities should be phased to accommodate scheduled missions defined by NASA's Constellation Program.

CONTAMINATION DURING TRANSFER BETWEEN LM AND CSM

Summary

After docking, equipment and space suits were transferred from the LM to the Command Module (CM). During the transfer, dust, soil and debris contaminated the CM to varying degrees.

The Apollo 11 crew vacuumed suits, samples and equipment in the LM before transferring these items to the CM. Because the suction was low, this was a tedious job. The vacuum used in Apollo 12 did not remove dust from the space suits, but was used to brush dust off sample boxes. Dust and debris in the LM impeded transfer operations and although the gear that was transferred was filthy, very little dust was transferred to the CM. In Apollo 14, the vacuum performed satisfactorily and very little dust was transferred to the CM. The cabin fan filter cleaned the atmosphere well. The vacuum and the cabin fan used in Apollo 15 worked well. During Apollo 16, the vacuum cleaner and cabin fans failed resulting in severe CM contamination. This was exacerbated by a decision to postpone LM jettison. The CM filled up with dust and rocks immediately and dust coated all the surfaces within an hour. The Apollo 17 tunnel transfer went smoothly. A small amount of dust was transferred to the CM; however, the cleaning control system, combined with running the vacuum cleaner in the LM kept the CM air clean.

Observations

The Apollo 11 Mission report describes preparing items for transfer from the LM to the CM, *"Following docking, the tunnel was cleared and the probe and drogue were stowed in the lunar module. The items to be transferred to the command module were cleaned using a vacuum brush attached to the lunar module suit return hose. The suction was low and made the process rather tedious. The sample return containers and film magazines were placed in appropriate bags to complete the transfer and the lunar module was configured for jettison according to the checklist procedure."*[1]

Conrad spoke of tunnel transfer operations in the Apollo 12 Technical Debrief, *"Tunnel operations were smooth as glass. The LM was filthy dirty and it had so much dust and debris floating around in it that I took my helmet off and almost blinded myself. I immediately got my eyes full of junk, and had to put my helmet back on. I told Al to leave his on. We left the helmets on and took off our gloves. Once we got stabilized and had the hatches open and everything, the flow system of having the command module more positive than the LM seemed to work. We did not pick up much debris in the command module; very little, if any, that was floating in the LM. But, it stayed very good in the LM all the way through our checklist.*[3]

"We tried to vacuum clean each other down, which was a complete farce. In the first place, the vacuum didn't knock anything off that was already on the suits. It didn't suck anything, but we went through the exercise. It did clean the rock boxes, that much I'll say for it. I don't think it sucked up any of the dust but it brushed the dirt off the boxes. We put them in their proper containers, and transferred them. [3]

"Dick brought over the LiOH B-5 and 6. We stowed those and it took a long tome to get all the gear transferred. Then Al and I, because we and the spacecraft were so dirty, stripped naked and transferred the suits up to Dick. He stowed them under the couch and let us come in dirty and pack our own suits to keep himself and the spacecraft as clean as possible. We packed the two suits in the lower part of the L-shaped bag, and to my knowledge we had very little debris come across from the LM." [3]

Conrad continued, *"During that time Dick was busy and Al and I were naked. We didn't have any clothes on; we wanted to get cleaned up after we had stashed everything because all of gear we were stashing was dirty."* [3]

The Apollo 12 Mission report adds, *"The transfer of equipment between both vehicles was impeded by the large amounts of dust and debris in the lunar module. Therefore, the timeline became very tight in meeting the schedule for lunar module jettison."* [2]

The Apollo 14 crew described tunnel transfer operations in the Technical Debrief. Mitchell explains, *"I think we probably got our suits off a little earlier than the checklist called for. It certainly improved our mobility. One of the first things you do after you get the tunnel open is get those suits off and get them brushed down and stowed. It makes it a lot roomier in the cockpit and gives you easier access to everything in the cabin. We were a little bit hesitant when we planned, in the time line, to remove our suits that early in the game because of the dust problem. But we went ahead, took a chance on it, and wrote it that way. Since we didn't have any dust, it worked out real well."* [4]

Shepard added, *"The vacuuming procedures seemed to be satisfactory. I think with each pass with the vacuum brush, you could see the dust coming off. In other words, you make a pass or two on the side for example, or on the back, and you'd see the loose dust, off the top, that was still there, come off into the vacuum cleaning bag. So, that is an effective procedure. At least, you remove just one more layer of dust. Of course, the smudges were still there. I think that, as a general comment, using the procedures that we used, as written, we got very little dust back in the command module. The things that were dirty, the suits, were put away in bags right away. Stu was ready for them and they went into the bags, the L-shaped bag. The rock boxes and so on were in the extra decontamination bags. I thought the command module was remarkably clean. It was a lot cleaner than I had expected it to be."* [4]

Roosa added, *"I thought it was exceptionally clean. When you passed the suits over to me, they were dirty, but they weren't dusty. In other words, there was no loose dust coming off the suits. The only dust that came off was when as I was shoving them into the bag; but that was a contact thing. There was nothing floating free at all from the suits."* [4]

Apollo 14 Mission report said, *"On previous lunar missions, lunar surface dust adhering to equipment being returned to earth has created a problem in both spacecraft. The special dust control procedures and equipment used on this mission were effective in lowering the overall level of dust."* [5]

Apollo 14 Mission report reiterated the effectiveness of cleaning operations. *"A vacuum cleaner assembly and cabin fan filter, used for the first time, along with the normal decontamination procedures eliminated practically all of the objectionable dust such as that present after the Apollo 12 lunar docking. The fans were operated for approximately 4 hours after lunar docking."* [5]

In the Apollo 15 Technical Debrief, Scott described the effectiveness of the vacuum cleaner in containing dust in the LM, *"The vacuum cleaner worked pretty good I thought. We brought the vacuum cleaner over to the LM and just turned it on and let it run. It did a pretty good job of clearing the dust out. We were pretty dirty."* [6]

Worden added, *"The vacuum cleaner is a big bulky piece of gear, we were all surprised at how effective it was in flight. It really worked out well."* [6]

Scott agreed, *"I thought it did, too. We stowed the* [Commander] *CDR and* [Lunar Module Pilot] *LMP suits in the L-shape bag, to get the dirt out of the cabin. We left Al's suit out because of the bulk. Al's suit was still clean. We put the filter on the cabin fans and turned the cabin fans on. We already talked about the foreign object in the cabin fan which we heard periodically. When the cabin fan was running with that filter, I thought it did an excellent job of cleaning the cabin. You could sure see the particulate matter floating around there after we finished with the transfer."* [6]

In the Apollo 16 Technical Debrief, Mattingly described preparation for tunnel transfer, *"After docking, we went through our transfer items even though we knew we were going to be retaining the LM and going to bed. From my side, the time line entering the LM was a little bit slower than I had anticipated even though I pressurized the cabin prior to rendezvous. Taking things out and finding a place for them just seems to take a little bit longer. Perhaps that was because I'm methodical about it. The first thing we did was pass in the vacuum cleaner. I had checked the vacuum cleaner operation to the extent that I turned it on and it worked and I turned it off. I didn't try to vacuum clean anything. I didn't try to verify that it really was sucking anything up. There's some question in my mind whether the vacuum cleaner really ever worked properly."* [8]

Duke answered, *"It did. The screen was covered with dust. It probably was so covered that it stalled out, and that's what failed it."* [8]

Mattingly explains the vacuum cleaner failure. *"In any event, some time later, I went into the tunnel to get something, and the vacuum cleaner was laying there making some funny little noise. I noticed the switch was on, but it didn't sound like it was running, so I turned it off. It didn't interest me enough to see if it was still working. I think it had probably failed then. We tried it later and it wouldn't start after that; it would just make this little hum. I suspect it failed at the time I found it the first time. That was within an hour of the time we started with it."* [8]

Apollo 16 Mission report explains tunnel transfer problems associated with vacuum cleaner failure. *"The vacuum cleaner failed after less than 1 hour of use while attempting to clean items in the lunar module that were to be transferred to the command module…During the equipment transfer, a large amount of dust had begun floating around and much of it was transferred to the command module cabin. The vacuum cleaner failed after it had been used for about 20 minutes. Therefore, all the dust could not be collected. Most of the sample collection bags were free of dust and debris and the only things that really needed cleaning were the deep core sample and the big rock bags. Dust particles in the lunar module cabin atmosphere did provide some hindrance to the crew during the unsuiting and the dry-out period."*[9]

Apollo 16 Mission report described the vacuum cleaner failure, *"The vacuum cleaner failed after becoming clogged with dust. The vacuum cleaner was cleaned postflight and it operated properly. The design of the vacuum cleaner is such that lunar dust can clog the impeller."* [9]

Mattingly described CM conditions and cabin fan failure. *"The command module filled up with LM dust and rocks and things almost immediately. Within an hour, it was very noticeable that there was a coating of dust on all the instrument panels and all the surfaces. You'd see little rocks float by in front of your nose. I was surprised how rapidly that stuff all had diffused in. It came over as soon as we brought the first bag or the first suit, or whatever it was. That stuff was just coming off of everything and it never stopped. The command module cabin fans were on at the time of docking. I turned them on right after docking and before removing any tunnel hatch* *equipment. They were working properly at that point with the cabin fan filter on. They failed some time EVA morning. The material we brought in we just stashed away."* [8]

The report then described CM contamination, *"Once the transfer of equipment from the lunar module began, the command module cockpit became noticeably dusty with quite a few rock chops floating around. The dust could be found on almost all surfaces although there was never any problem with the floating dust."* [8]

Duke described tunnel transfer operations. *"We tried to vacuum the suits and some of the bags that were dirty like the big rock bags and found it almost totally worthless. You could do a little bit, but the best method was to take a damp towel to wipe things down. We were able to get some of the dust off this way. Fortunately, most of the things that were dusty went over in DCON bags. That was a lifesaver. Once we opened one of the DCON bags just a little bit to see what bag was in there. The dust just floated out and we closed that in a hurry. That was a real mistake. I think Apollo 14 did the same thing. The transfer of the equipment was expeditiously done just according to the Time Line Book from my side. Ken was doing a great job taking care of everything as I passed it over. Had we been on a nominal two-rev-to-jett time line, we'd have been adequately prepared to jettison the LM at the time. I think it's a very loose time line. I think Ken does have time to stow things, at least temporarily, and we don't just throw them in there."* [8]

He continued, *"The samples did not need to be vacuumed except one bag before I put it in the DCON bag. That was the big rock bag. Everything else was in good shape. Since we are going to retain* [the LM] …[we] *could have jettisoned the LM by keeping our suits on. But that was not the decision. The decision was to keep it. So, we had to take the suits off. John and I both doffed the suits in the LM. I thought it was quite a hazard over there floating through the LM with all that dust and debris. A number of times I got my eyes full of dust and particles. I felt my right eye was scratched slightly once."* [8]

The Apollo 17 Mission report described post-docking activities. *"The post-docking activities in the lunar module and the command and service module were accomplished as planned with the checklist as an inventory list and as a backup to common sense. The vacuum cleaner was operated continuously in the lunar module to remove dust floating in the cabin. As a result of this operation and the special attention paid to the bagging and sealing of the samples prior to transfer, the command module remained remarkably dust free. During vacuum cleaner checkout, a main bus B undervoltage light was illuminated; however, there were no caution and warning lights when the vacuum cleaner was used for the lunar module post-docking activities. Preparation for lunar module jettisoning was normal through hatch closure."*[10]

Cernan, in the Apollo 17 Technical Debrief spoke of Tunnel Transfer operations, *"The commander had his helmet and gloves off all throughout the entire transfer. We handled the transfer the way we'd planned. The LM pilot did most of the preparation of the gear in the LM, and the commander stayed in the tunnel and passed things on. The inventory was going on in the command module side and on the LM side, both. We vacuumed each other other's suits the best we could and everything else that got supposedly transferred, unbagged, or uncovered."*[11]

The crew discussed cleanliness of the CM. Schmitt remarked, *"In spite of the CMP's comments to the contrary, I think we got things remarkably clean. There wasn't an awful lot of dirt in the command module coming back."* [11]

Evans said, *"That's true."* [11]

Schmitt continued, *"In contrast, he may have thought it was dirty, but I was surprised we were able to keep the level of contamination in the command module down."* [11]

Cernan observed, *"After I took my helmet off, I could go halfway through the tunnel and stick my head up in the command module, and it was a totally refreshed, unpolluted atmosphere up there. It never did get polluted."* [11]

Schmitt reflected, *"I think having that vacuum cleaner running in the LM had a lot to do with keeping the flow in the other direction, filtering out the air."* [11]

Evans added, *"We never did vacuum in the command module because it just wasn't necessary."* [11]

Schmitt said, *"The suits were noticeably cleaned by the vacuum cleaner. You could tell you were pulling stuff off them, although they were still dirty. I think most of the dust was taken care of."* [11]

Cernan commented, *"Cleaning control in the command module was excellent, considering all the dust and dirt that just seemed to adhere to everything in the LM. When we got back in the command module, with the exception of the suits, and LMP and CDR, everything was clean. Everything was clean because everything was bagged before we brought it over – bagged and zipped. We never did open anything once we got it zipped up. So the command module stayed exceptionally clean throughout the remainder of the flight."* [11]

Schmitt added, *"In the bagging of the decontamination bags, I made a special effort, after requests prelaunch, to pull those zippers as tight as I could. They should be pretty tight."* [11]

Recommendations and Lessons Learned

In the Apollo 12 Technical Debrief, Bean recommended, *"I think the procedures should be developed so that a positive flow of air is maintained from the command module to the LM, not necessarily to keep lunar bugs out of the command module, but to keep all this dust and dirt out of the command module."* [3]

Bean also recommended, *"I think this is completely unsatisfactory, and there must be some way to clean up that cabin atmosphere so that you can work in a good, acceptable environment when you do get back to the command module. It's possible that you could get up and dock with the command module before you open the upper hatch, dump the cabin down to 3-1/2 psi, and hope it doesn't blow a lot of the dirt and debris out of there, then slowly fill the cabin up in the command module and that will keep it filled. There ought to be some way to do this job."*[3]

In the Apollo 14 Technical Debrief, the crew discussed lessons learned and recommendations. Mitchell said, *"I'd recommend that to future crews: get the suits off as soon as you can."* [4]

Shepard adds, *"We felt the procedures that were suggested, perhaps by Apollo 12, and carried out in our time line, certainly reduced the dust to a minimum."* [4]

Apollo 14 Mission report said, *"A vacuum cleaner with detachable bags was added to assist in removing lunar dust from suits and equipment prior to intravehicular transfer from the lunar module to the command module after lunar surface operations, and for cleanup in the command module."* [4]

Analysis

During the Apollo Program lessons learned in each mission were incorporated in subsequent missions that improved tunnel transfer operations. These improvements included:

- Maintaining the CM at a positive pressure differential to the LM
- Improved vacuum cleaning equipment and procedures
- Removing suits before beginning tunnel transfer operations
- Securing decontamination bags

The root cause of the contamination problems associated with tunnel transfer operations, LM contamination was not resolved. This problem is addressed in Section 6.

Future Work

Interface requirements for CEV to LSAM and associated engineering design solutions developed. Possible requirements may be to maintain a positive differential pressure to the LSAM and limitations on dust transferred to the CM.

COMMAND MODULE CONTAMINATION

Summary

Command Module lunar dust contamination varied with each Apollo mission. During Apollo 12 transearth coast dust permeated the whole command module. The Lithium Hydroxide (LiOH) filters were not collecting dust and the Environmental Control System (ECS) system pumped it back out the hoses where it collected onto circuit breakers; the vacuum cleaner system did not work well; and the dust caused eye and nose irritation. The Apollo 14 CM was relatively clean. The crew of Apollo 15 cleaned the screens everyday as the inlet to the cabin fans and return line collected a lot of dust. During Apollo 16, pebbles and rocks floated around the CM cabin and the crew was concerned about the risk of those going through their dump valves. The cabin fan inlet screen was covered with trash and the cabin fan was turned off after it made a load moaning sound.

Observations

Bean, in the Apollo 12 Technical Debrief described CM contamination.
"We were plagued by it when we finally did get back into the command module. Pete and I had to remove our hoses so that we could use them for vacuum cleaners. Incidentally, they didn't perform too well. There wasn't enough vacuum there. We had to remove our helmets from our suits, to keep our eyes from burning and our noses from inhaling these small particles floating around; we just left our helmets sitting on the tops of our heads. This isn't a very good configuration to be in, but we had not other alternatives at the time." [3]

Conrad explained CM contamination.
"However, something we found out later and not until we got back to the ship, was that the fine dust was on the suits and on almost all of the equipment that was contained inside the bags. The dust is so fine and in zero g it tended to float off the equipment and it must have permeated the whole command module. It floated out of those bags; it floated out of the contingency sample bag. This we could see any time we opened up (which we stopped doing right away) the LiOH container that had the contingency sample in it. The whole thing was just a cloud of fine dust floating around in there. You could actually see it just float out of the bag through the zipper; and you can forget those zippers. They don't hold anything in. When we got all the gear back here and opened it up, back on the carrier, we found out that it had all cleaned itself. That was where all this dirt was coming from in the command module. The dirt is so fine I don't think the LiOH filters were taking it all out. It would pump it in the ECS system and pump it back out the hoses. This was indicated by Dick's blue suit hose, which we had tied over the left-hand side and was blowing on panel 8 circuit breaker panel. That whole thing was just one big pile of dust that was collected on the circuit breakers. The only reason it's there is the ECS hose was blowing on it. It's got to have taken the dust in through the LiOH canisters and filters and everything and blown it back out the blue hose. So the system is not doing the cleaning, the dust is too fine."[3]

Apollo 12 Mission report described the cleaning effect of zero-g.
"During the transearth coast phase, it was noticed that much of the dust which had adhered to equipment while on the lunar surface had floated free in the zero-g condition, leaving the equipment relatively clean. This fact was also true of the suits, since they were not as dusty after flight as they were on the surface after final ingress." [2]

On the subject of cabin atmospheric cleaning, Shepard, in the Apollo 14 Technical Debrief said,
"Yes, that's got to be a pretty effective system (not only the return hoses, but also the cabin

screen) of clearing that cabin atmosphere. We were obviously picking up lint and the system kept the cabin very clean and very few things came floating around, except for a little while after Stu opened the rock bag right in front of everybody on television." [4]

Mitchell commented on the effectiveness of repress in cleaning the cabin.
"A lot of that dust, I believe, kind of got whipped outside when we did our dump repress. The cabin dust kind of swirled around. A lot of that went out through the relief valve at that point, which might have reduced it somewhat." [4]

The Apollo 14 Mission report says, *"The procedures for contamination control in the command module were quite satisfactory, and particles were not observed in the command module subsequent to hatch opening."* [5]

In the Apollo 15 Technical Debrief, Scott commented on the ECS.
"I was surprised how clean the spacecraft was. I think most of the dust had been removed. That's right. It surely had." [6]

Irwin added, *"That night, it was fairly clean, you know, when we went to sleep. I don't know how all that dust got out of there."* [6]

Scott agreed, *"Yes, the ECS does a pretty good job of cleaning the place out. The smell was gone. But that had all cleaned out. By the time we got up the next morning things were in pretty good shape."* [6]

The Apollo 15 crew discussed CM dust contamination, Worden said, *"When we got up the next morning, the cabin was as clean as it was before the initial separation. Cleaning the screens was another thing we were doing quite often. Especially post-lunar-orbit activities, when we had all the dirt. We had to get around and clean those screens at least daily. We'd lost, somehow, two of them. One or two? … The cabin fan filter is on the output side of the cabin fans. We noticed on the way home, that inlet to the cabin fans seemed to be the thing that was collecting all the dust and dirt. That's like a register in a home; it's just a metal grill. There seemed to be a lot of dust and particles collecting around that, and we could see it some of the hardware inside that metal grill."* [6]

Irwin added, *"It was an inner grill. There was an inner grill there that seemed to be collecting a lot of dust and debris, and we couldn't get to that. I don't recall seeing anything in the cabin fan filter. It didn't seem to be collecting anything, because everything seemed to be collecting on the return line."* [6]

Scott continues, *"Yes. We looked in the cabin fan filter, and we took it off on the inside."*[6]

Worden agreed, *"That's right, and it looked pretty clean to me. It just surprised me that we had a cabin fan filter there."* [6]

Apollo 16 Mission report described problems with the cabin fan.
"The cabin fan filter was installed on the first day of the flight. After rendezvous, the cabin fan was turned on prior to opening the lunar module hatch and ran continuously until after transearth injection when it made a very load moaning noise and was turned off. The cabin fan inlet screen was generally covered with a great deal of trash. After the fan was turned off, a piece of paper was taped over the cabin fan inlet screen in an attempt to retain the dust within the

ducting. There was no problem with dirt coming out of the duct, even when the fan filter was removed for entry. [9]

"When the spacecraft was received for postflight testing, the cabin heat exchanger inlet duct screens were blocked with lint and debris with paper taped over the screens. However, this had no effect on the operation of the fans. Operation and sound level were normal and the fan current was within specification. Visual inspection of the fans did not show any nicks or indications of interference. Two small pieces of gray tape, approximately ¼ inch in diameter and dust were found on the cabin exhaust filter. [9]

"The most probable cause for the fan noise was some object which got into the fan and was later freed." [9]

Duke, in the Apollo 16 Technical Debrief, observed, *"We saw a few dust particles fly our way but that was all. To do the actual depress we used the overhead valve and just left it open. I never noticed much floating away. The LM was extremely clean. You know how many screws and washers and things we found floating in the command module. I guess maybe on the whole flight we found five in the LM the whole time."* [8]

The crew discussed their concern with pebbles and rocks floating around the CM cabin. Young said, *"…we had a lot of pebbles and rocks that were on the suit that we didn't get cleaned off and on the* [Lunar Extravehicular Visor Assembly] *LEVAs and on everything else that we brought back. We were sitting there and there were at least four or five pebbles and rocks that came floating by. That stuff can go through your dump valve and it gets lodged in there so you couldn't close it. That would be a bad thing. I know that's a big valve and a big hole, but I assume that there's something that size that could get through there. Sure would be good to have a screen over it, I think."* [8]

Recommendations and Lessons Learned

Mattingly recommended in the Apollo 16 Technical Debrief, *"Seems like you ought to have a screen, or you ought to have a thorough understanding that the inlet is the minimum cross section. Anything that gets started in there is going to keep going. Even then I think a screen is the proper answer, because there's just no way you could get in there and operate on that thing and clean it out. The only thing I could think of to do was if it didn't seal, I figured a rock would crush in the thing, a lot of mechanical advantage. But for something like those little screws that we saw go by, I never would have gotten those things crushed."*[8]

Analysis

Two mechanisms for contamination were observed; 1) transfer of dust covered equipment, samples and space suits into the CM and 2) dust inside sample containers released into the atmosphere.

The command modules had good air cleaning systems to manage lunar dust contamination. The exception was on Apollo 16, which had failures in fans and the vacuum cleaner.

Redesigned sample return containers to maintain vacuum during trans-lunar and transearth flight are addressed in Section 7.

Future Work

Constellation will develop a strategy to manage dust; however, dust contamination will most likely not be completely eliminated. Requirements for the CEV Command Module should be developed for air revitalization, air filtration and secure sample storage based on Human Research Standards and Scientific Investigation needs.

MECHANISMS FOR LUNAR MODULE CONTAMINATION

Summary

During each Apollo Surface EVA dust collected on surfaces and was transferred to the Lunar Module causing the contamination described in that section of this report. Although not specifically mentioned in the Mission Reports or Technical Debriefs, historical video footage recorded the crews experiencing dust contamination due to falling on the lunar surface and being covered by dust.

During Apollo 12, the Equipment Transfer Bag strap was covered with dust and was transferred to Pete Conrad's space suit. The LiOH box fell off the conveyor and was covered with dust. The end of the strap of the Lunar Surface Conveyor rested on the surface and collected dust that was subsequently deposited on the crew and transferred to the LM. The Apollo 12 crew appeared to encountered greater dust contamination than the Apollo 11 crew, which caused greater LM contamination. This is most likely a function of the amount of time spent on the lunar surface. The Apollo 12 crew spent more time on the surface.

The Apollo 15 crew encountered dust contamination while transferring the Sample Return Container using the Lunar Equipment Conveyor. The seat bags, under the seat pan of the Lunar Roving Vehicle (LRV) were full of dust. One crew member fell down after tripping while backing up in soft soil.

During Apollo 16 EVAs, strap-on pockets filled with dust that upon ingress to the LM fell opened, allowing the dust to fall on the LM floor. The LRV lost a fender causing dust to rain down on the crew, LRV, and equipment. The extravehicular mobility units were covered with small dust clots.

Apollo 17 also experienced a fender failure on the LRV. The effects were similar to those on Apollo 16.

Observations

General

The Apollo 12 Mission report described dust contamination, *"The amount of lunar dust encountered by the Apollo 12 crew appeared to be appreciably greater than in Apollo 11. This condition manifested itself by contaminating the atmospheres in both spacecraft and depositing dust over much of the lunar surface equipment and onboard systems. The cohesive properties of lunar dust in a vacuum, augmented by electrostatic properties, tend to make it adhere to anything it contacts. These properties diminish in the presence of the gas of an atmosphere. Upon attaining zero gravity, some of the lunar dust floats up in the cabin atmosphere and becomes widely dispersed. This process tends to be continuous, and renders present atmosphere filtration techniques inadequate. The presence of the lunar dust in the cabin of either spacecraft does not detrimentally affect the operation of onboard systems, but the dust could present a hazard to crew health, and at least it constitutes a nuisance. The potential health hazards are eye and lung contamination when the dust floats in zero g. In an effort to minimize this nuisance on future flights various dust removal techniques were evaluated for cleaning the spacesuits and equipment on the lunar surface prior to ingressing the lunar module."*[2]

The Apollo 16 Mission report explained problems with dust contamination. *"Because of the dust problem, the lower limbs of the liquid-cooled ferments were dirty. Each crewman had to help the other crewman remove his suit. Consequently, there was appreciable dust on each crewman's hands and up to the elbows of the liquid-cooled garments. There is not way to avoid this problem; the crewmen's hands could not be cleaned while on the lunar surface after the first extravehicular activity."* [9]

Traction

Slippery conditions on the Lunar Surface did not appear to present a problem for Apollo astronauts. According to the Apollo 11 Mission report slippery conditions on the ladder were not dangerous, *"Movements in the 1/6-g environment were slow enough to allow deliberate foot placement after the jump. The ladder was a bit slippery from the powdery surface material, but not dangerously so."*[1]

Alan Bean in the Apollo 12 Technical Debrief states that he did not experience slippery conditions. *"I never noticed any slippery surfaces as Neil and Buzz pointed out. The ground never felt slippery at all to me." Pete Conrad followed up with, "I didn't notice any slipperiness."*[3]

In the Apollo 15 Technical Debrief, Irwin described falling while performing surface operations, *"I was pulling on the lanyard with one hand and trying to take pictures with the other. And of course I fell down there once because I tripped backing up in that soft soil."* [8]

Cables and Cords

Cables and cords presented a tripping hazard to all the crews during the Apollo Program. Although crews mentioned that this problem was a result of dust, the record appears to point to other root causes. The Apollo 11 Mission report described trip hazards to the crew resulting from equipment cords in the work area. *"The television system presented no difficulties except that the cord was continuously getting in the way. At first, the white cord showed up well, but it soon became covered with dust and was therefore more difficult to see. The cable had a 'set' from being coiled around the reel and would not lie completely flat on the surface. Even when it was flat, however, a foot could still slide under, and the Commander became entangled several times."*

In the anomaly resolution section, the report continues discussion. *"The cable for the lunar surface television camera retained it coiled shape after being deployed on the lunar surface. Loops resulting from the coils represented a potential tripping hazard to the crew. All the changes that have been investigated relative to changes in cable material and in stowage and deployment hardware have indicated only minimal improvement in deployed cable form, together with a weight penalty for the change. No hardware changes are planned. This anomaly is closed."*[1]

During Apollo 12, Alan Bean states during the Technical Debrief, *"One thing that continually disturbed us the whole time, particularly Pete, was the fact that the TV cable was right in front of the MESA. Our TV cable laid flat on the ground. It didn't tend to curl up or anything like that; but, because it rests on top of the dust and your feet go beneath the dust, you end up pushing the cable around quite a bit. I think this is a completely unsatisfactory situation and I would recommend that that connect for the TV be moved either over to quadrant 3 or quadrant 1 so that the TV cable would never have to be in the vicinity of the MESA or the area near the front of the* *ladder. It's just too highly traveled an area to have something like that TV cable underfoot. We never fell over it but it was just a constant problem trying to avoid it."*[3]

Scott, in the Apollo 15 Technical Debrief mentioned tripping over a wire. *"Oh yes. That reminds me of aligning the electrical box on the heat flow. After the initial alignment and all the shuffling around there with the probes and all, at one point I tripped over one of the wires to the probe and I moved the electrical box from its alignment position. I think the ground called up and we didn't have all the photos, I started digging the trench."* [6]

Young, in the Apollo 16 Technical Debrief said, *"The second problem, which was a continual one was the battery cable. Even though I didn't deploy the battery too far out in the sunshine the battery cable had a mind of its own and insisted on staying 4 inches off the ground around the camera where I was walking, even though I pulled the whole thing back in there. So, every time I walked around the camera I had to pick my feet up to avoid the battery cable and 2 to 3 times I tripped over it, but fortunately it was the battery that moved and not the camera."* [8]

Translation Aids

The Apollo 11 Mission report discussed problems with the Lunar Equipment Conveyor. *"The initial operation of the lunar equipment conveyor in lowering the camera was satisfactory, but after the straps had become covered with lunar surface material, a problem arose in transporting the equipment back into the lunar module. Dust from this equipment fell back onto the lower crewmember and into the cabin and seemed to bind the conveyor so as to require considerable force to operate it. Alternatives in transporting equipment into the lunar module had been suggested before the flight, and although there was no opportunity to evaluate these techniques, it is believed they might be an improvement over the conveyor."*[1]

Pete Conrad described suit contamination while using the Equipment Transfer Bag during the Apollo 12 Technical Debrief. *"The problem is that the lower end of the strap got completely covered with dust and I got dust all over my hands and over my suit arms from handling that strap."*[3]

Conrad described LiOH box contamination. *"When I removed the first LiOH box on the first EVA to send it up, that one fell off and I had to pick it up out of the dirt. Once it gets in the dirt, forget it."*[3]

Bean observed, *"There's no way to dust anything off there, which brings up a good point that we'll be covering in a few minutes concerning when we got back in."* [3]

The Apollo 12 Mission Technical report stated, *"The single-strap lunar surface conveyor was easy to deploy and generally performed satisfactorily. The end of the strap resting on the surface collects dust, which is subsequently deposited on the crewmen and in the lunar module cabin."*[2]

Shepard in the Apollo 14 Mission Debrief described dust effects of the Modularized Equipment Transporter. *"I really expected more dust to be collected by the tires and thrown up on the MET. That didn't turn out to be the case at all. We dragged it through some fine-grained stuff near the edges of the smaller craters; and, although the tires sunk in more, in that fluffy, less dense regolith, it still didn't throw up an awful lot of dust."*[4]

Mitchell notes, *"Dust didn't adhere in any appreciable amount to the rolling surface of the tires. The MET seemed to mash it down, but it didn't adhere. It didn't throw out a rooster tail as we might have suspected."*[4]

Shepard adds, *"Even at fairly good speeds."* [4]

Mitchell agreed, *"Yes, that was very surprising."* [4]

The Apollo 14 Mission report says of the modular equipment transporter, *"The smooth rubber tires threw no noticeable dust. No dust was noted on the wheel fenders or on top of the metal frame of the transporter."* Later it adds, *"The wheels did not kick up or stir up as much dust as expected before the flight. Very little dust accumulated on the modular equipment transporter."* [5]

Irwin described being covered with dust in the Apollo 15 Technical Debrief, *"I think this is the point at which I transferred the* [Sample Return Container] *SRC with the* [Lunar Equipment Conveyor] *LEC and got all dirty."* [6]

Scott adds, *"It seemed like they were still working pretty well. The connectors got covered with dust – one of mine. One of the primary problems was that LEC. On EVA-1, when I passed you the rock box on the LEC, I just got covered with dirt all down the front. The result was pretty dirty connectors."* [6]

Scott re-iterated dust contamination problems caused by the LEC. *"Well, I didn't have any problem getting up and I could get to the first rung with a leap with any bag, with a good spring. And another problem I found with the LEC was when we transferred the ETB at the end of EVA-1, the LEC line had been in the dirt and that's the dirtiest I got, I think, in the whole trip. It just spread dust all up and down the front of me as the thing went up and I guess I could have grabbed that one handle and held it, but that would have been putting an awful lot of force on you and I think that the effort expended by the guy in the cabin to hold that stiff up is not worth it. I'd recommend just taking up the bags one by one manually, putting them on the porch."* [6]

In the Apollo 16 Technical Debrief, Young notes, *"We didn't want any dust on the [Equipment Transfer Bag] ETB so we could keep the dust out of the cockpit. We had to adjust it on the later EVA."* [8]

Lunar Roving Vehicle

The Apollo 15 crew discussed dust contamination caused by the Lunar Roving Vehicle, (LRV). Scott says, *"It went right up there without any trouble at all. When we got off the vehicle, we noted our boots sank in the soft soil a half an inch or so, maybe more. The Rover tracks just made a very slight surface disturbance.*[6]

Irwin noted, *"I'd estimate we sank (boots) in maybe 3 inches."* [6]

Scott added, *"It was really deep there, wasn't it? The wire wheels are excellent. They picked up very little dust. We did have an accumulation coming up under the fenders. I think the fenders are well designed and quite adequate. It seems to keep the dust off pretty well. You had a chance to see if there was a rooster tail behind the Rover when I drove. Did you see much?"* [6]

Irwin answered, *"One time I did comment on the rooster tail. I guess it was on the Grand Prix."* [6]

Scott asked, *"How much was it?"* [6]

Irwin replied, *"It kicked up, I'd estimate, 15 feet in the air. We had one over your head and it impacted in front of you."* [6]

Scott queried, *"Did it really?"* [6]

Irwin answered, *"Yes."* [6]

Scott observed, *"I didn't notice it looking forward."* [6]

Irwin added, *"It was really impressive. It's too bad that sequence camera did not operate."* [6]

Scott said, *"I didn't notice, when we were driving at the higher rates, any dust or dirt coming forward into our view."* [6]

Irwin noted, *"I think at that particular time, you were just doing a max acceleration, and that's when it kicked up the rooster tail."* [6]

Scott added, *"Auto max acceleration. I don't remember at any time feeling a particular wheel slippage.* [6]

"Dust generated by the wheels – we'd have to say was minimum. We did have to dust off the mirrors quite a bit, but it was far less than I expected to see. [6]

"Yes. I don't know whether all that dust was created by the wheels. It could have been the dust generated by us just getting on and off because we kicked a lot of dust, you know.[6]

"I really didn't see much dust going forward from the wheels. I could see it hitting the fenders, and it seemed like the fenders did very well. I really didn't see anything going forward. [6]

"No. That's why I had a difficult time accounting for the dust that was on the mirrors. [6]

"Yes. Except it could have been very fine over a long period of time that we couldn't see. The dust accumulation was minimum. It was a fine dust." [6]

Scott observed, *"…just forward of the hand controller, was almost completely covered most of the time. If I used it, I had to brush it off."* [6]

Apollo 15 Mission report stated, *"Dust accumulation on the vehicle was considered minimal and only very small particulate matter accumulated over a long period of time. Larger particles appeared to be controlled very well by the fenders. The majority of the dust accumulation occurred on the lower horizontal surfaces such as floorboards, seatpans, and the rear wheel area. Soil accumulation within the wheels was not observed. Those particles which did pass through the wire seemed to come out cleanly. Dust posed no problem to visibility."* [7]

The Apollo 16 crew discussed dust contamination after losing a fender on the LRV. Young said, *"I think it was station 8 where we lost the rear fender and that was because I fell over it. I was coming out to help you and I tripped over the thing and it fell off. Avoid those fenders if you can. Every time that wheel came off the ground and went back in and dug in, it was like we were watching rain. Dirt came over it, covered up the battery cover, and the instrument panel so bad* *that you couldn't read the POWER DOWN or POWER UP decals. When we got back to the lunar module, I brushed off not only the camera, but the batteries and the instrument panel as well. As that made the problem of dusting me and Charlie off even worse too. We had a lot of dust on top of our OPSs, had dust all over the place, dust on the helmet, dust around the neck ring, what a mess."*[8]

Duke added, *"Raining dust. Yeah, the message is don't trip over the fender. It didn't bother us any apparently, but it sure was dusty."* [8]

Young says, *"Dust Generated by wheels: We've got plenty of photography of what happens when you lose a fender. And the Grand Prix says what's going on the rest of the time."* [8]

Apollo 16 Mission report described the effects due to the loss of the fender, *"The right fender was lost at station 8. Subsequently, the right rear wheel produced a shower of dust over the vehicle which appears in the 16-mm motion photography as falling snow. However, a great deal more dust was actually produced by the wheel than shows up in the film. The crew and the front of the vehicle, particularly the instrument panels, were covered with dust. The instrument panel and the start, stop, and closeout decals had ¼ inch of dust over them at the completion of the third extravehicular activity."* [9]

The Apollo 17 crew also lost a fender on the rover during their mission. Schmitt said, *"You've covered pretty well how the Rover performed on various kinds of terrain. Gene, why don't you describe the fender. That was the major dust problem."*[11]

Cernan responded, *"With the loss of one of the fender extensions, any one of them, the dust generated by the wheels without fenders or without fender extensions is intolerable. Not just the crew gets dusty, but everything mechanical on the Rover is subject to dust. Close to the end of the third EVA, all the mechanical devices on the gate and on the pallet in terms of bag holders and pallet locks and what have you were to the point that they would refuse to function mechanically even though the tolerances on these particular locks were very gross. They didn't work because they were inhabited and infiltrated with this dust. Some could be forced over center. Others just refunded to operate even after dusting, cleaning, and a slight amount of pounding trying to break the dust loose."* [11]

Apollo 17 Mission report commented on the lost fender, *"The right fender was accidentally knocked off by catching it with a hammer handle. This resulted in breaking about 2-inches off of the inside rail on the permanent fender. The fender extension was replaced and taped into position; however, tape does not hold well when placed over dusty surfaces. The fender extension was lost after about an hour's driving. Prior to the second extravehicular activity, a temporary fender was made from maps and taped and clamped into position, where it worked satisfactorily. Loss of the fender created concern that the dust problem would severely limit the crew's operation and the capabilities of the rover systems, not only thermally, but mechanically."* [10]

The report added, *"During the first extravehicular activity at the lunar module site, the Commander inadvertently knocked off the right rear fender extension. While still at the lunar module site, the Commander taped the extension to the fender. Because of the dust surfaces, the tape did not adhere and the extension was lost. Lunar surface maps were clamped to the fender. This fix was adequate."* [10]

Pockets

Duke said, *"The place where most of that dirt came from in the place you can't clean was the strap-on pockets we had."*[8]

Young responded, *"We got smart after EVA-1, and before we got in, we closed the flap. But the first time, I got in with that flap open, and my pocket caught on a hatch sill and when I came in with that right leg, the dust just flopped out."* [8]

Duke added, *"You had a pocketful – you had a contingency sample right in your pocket."*[8]

Recommendations and Lessons Learned

As recorded in the Apollo 12 Mission Technical Debrief, the inability to bend at the waist while performing scientific objectives lead Bean to recommend modifications to reduce suit contamination. *"You want to reach down, get down, and look at rocks, and you want to pick up things. You don't always want to stop and use those tongs. I had the feeling that if we just had a strap mounted on our back, or to one side of our back or something, we could work as a team. One fellow could hold the other while he leans over and picks up or inspects a rock, or looks in a hole, or whatever he wants to do, and then lift him back up and he wouldn't get dirty. We had talked earlier about just falling over on our faces and catching ourselves on our hands, or getting down on our knees, and inspecting whatever rocks we wanted to look at. When we got there, we could have done this physically, but the problem was, it was just so dirty that you didn't want to do it. I went down on my hands a couple of times, but each time I did, I went down where I would land with my hands on a rock. I would stand there until I saw what I wanted to see, and then to a kind of push-up from the rock. But there isn't always a rock around to do this sort of thing. If we just had some simple strap, worked as a team and got the big rocks fast, and looked at what you wanted real fast, I don't think it would interfere with anything else you did."*[3]

The Apollo 12 Mission report described needed engineering considerations for wheels to mitigate dust contamination, *"…certain constraints, such as the dust which would be set in motion by any wheels, must be considered in the design of such a vehicle. Also, under the light gravity, objects carried on such a conveyance would have to be positively restrained."*[2]

Alan Shepard, in the Apollo 14 Technical Debrief commented. *"There is not much you can do with those cables except just try to stay clear of them. You might dig a trench and bury them if you thought it was worth the time, and it's about the only thing I can think of. Bury them at least in the area of high activity right around the MESA."* [4]

Mitchell continues, *"Or mover them closer to the LM or out to the side so that they're not right in your walking area. I think we can make a comment right here that cable-set on all the cables was a problem. Just about every cable we pulled out has some set in it that made it curl or kink, and it would not lie flat."* [4]

Scott noted dust contamination problems with payload storage on the LRV, *"Because of dust accumulation, I'd recommend those seat bags have a cover on them. Beta bags underneath the seat pan, some firmer cover, because my seat bag got full of dust. I'm glad we had the flaps stowed over the film mags and the 500-mm, otherwise we would have run into the same trouble as you did with your camera, with all that dust in there. Because almost every time I got under the seat pan, there was almost a solid layer of dust over it."* [6]

Young recommended in the Apollo 16 Technical Debrief, *"Maybe an overflap that you Velcro on the other side of it to keep the dust out of there because I just don't think you should have a problem donning and doffing. We really got a lot of dust and I don't see really any way out of it when you're picking up a bag on the Moon and you're holding a bag and Charlie's dumping dirt in there, the dust goes all over the place and it's just as easy for it to go down your shirtsleeve as not. The fact is we had both dirt and rocks underneath the flap that you raise to get the glove open."* [8]

Duke said in the Apollo 16 Technical Debrief, *"Everyone of those cables had a memory. Everyone of them were off the ground.* [8]

"If I had to do it over again, I'd put all those cables up in the air so they would not get in the way of the crewmen. I sure didn't think of it. I know that everybody said you had to step over the cables very carefully and I thought I was doing it, but I sure wasn't." [8]

The Apollo 16 Mission report discussed concerns with dust contamination, *"The dust was always a major cause of concern in that the crew never knew when dust might get into some equipment and compromise the lunar module or the extravehicular mobility unit environmental control systems. A program to improve housekeeping procedures must be actively pursued to reduce the amount of dust in the spacecraft as rapidly and as simply as possible.* [9]

"Because of the loss of the rear fender, both of the extravehicular mobility units, were covered with small dust clots. The only method discovered to satisfactorily remove the dust from the pressure suits was to beat the appendages of the suit against a surface area such as the lunar roving vehicle tool pallet, the lunar module landing gear struts, or the lunar module ladder. Dusting with the brush caused a coated layer of dust. Therefore, dusting with the dust brush should be the last resort in cleaning the suits." [9]

Apollo 17 Mission report commented, *"The dust brush was probably one of the most often used pieces of equipment. It was employed on the rover thermal surfaces and reflectors, for cleaning the television camera lens, and by both crewmen in an attempt to minimize the dust carried into the cabin."*

Analysis

Lunar dust transferred from equipment and spacesuits into the Lunar Module habitable volume caused cabin contamination. Due to the nature of the lunar environment, dust contamination will not be completely eliminated; however, thoughtful design can reduce the amount of dust accumulation on exposed equipment and spacesuits.

Cleaning materials and suits reduced some dust contamination; however, the root cause of this problem was not resolved during the Apollo Program. Cleaning was accomplished by brushing and banging against hard surfaces prior to ingress and material transfers into the LM. These techniques removed dust to varying degrees particularly when crew hand fatigue after a long EVA greatly limited manual dexterity and the fine scale motor skills necessary to do a good cleaning job.

Inadequate mission and hardware design increased the amount of dust accumulation on equipment and suits. Improvements to consider for future lunar missions include:

- Rover fender design and other mechanisms to reduce amount of raised dust
- Equipment transfer and mobility aid design to eliminate parts that lie on the lunar surface
- Space suit design that eliminates accumulated dust in pockets, crevices, etc.
- Eliminate tripping hazards in high traffic areas
- Spacesuit design that increases flexibility and visibility to reduce slips and falls
- Contamination control strategy for transfer of crew and materials from the lunar environment into the habitable volume within the LSAM
- Innovative cleaning and/or contamination control technologies and techniques for cleaning crew and materials prior to egress

Future Work

The Constellation Program should charter a Lunar Dust Working Group to integrate dust management activities. Membership should include customers, system and subsystem engineers, the astronaut office, operators, human factors specialists, flight surgeons, planetary geologists, and other subject matter experts and stakeholders as needed. This group should:

- Research, document, and communicate Apollo lessons learned
- Develop and recommend Lunar Dust Management Concept of Operations and Requirements
- Provide recommendations for strategies and tools to design, test and optimize systems and operations to minimize dust accumulation
- Prioritize and establish the Dust Management Technology Portfolio and associated schedule to ensure NASA funds are spent wisely
- Maintain the Lunar Dust Website to encourage integration and communication

An annual Lunar Dust Focus Group should identify and catalog promising dust management technologies to manage dust. Information collected should include technology descriptions, technology readiness levels, investment required to mature to TRL 6, time frame for maturation, and identify technology gaps.

EXTERNAL ENVIRONMENT LUNAR DUST EFFECTS

Summary

During the Apollo Program experiments, cameras, watches, rovers, translation aids and sampling equipment were affected by dust.

Experiments

Apollo 12 experiments were affected by dust exposure. Electrostatic repulsion between the skirt on the Passive Seismic Experiment (PSE) and the ground led to dust contamination. However, the presence of dust did not significantly degrade any data returned). Dust entering the experiment caused a thermal short. A contrast chart dropped in the dust was rendered useless. Dust accumulation on thermal control surfaces resulted in high equipment temperatures. A sample container lost vacuum due to binding threads, possibly the result of lunar dust.

During Apollo 14 Geophones were difficult to emplace. Because the upper 10-20 cm had very poor sheer strength a geophone tended to fall over. The signal strength was not affected. The geophone was re-emplaced and performed as expected.

The Apollo 16 crew experienced thermal problems with the PSE due to dust contamination on thermal surfaces. The Heat Flow Experiment was ruined after a tripping incident. This failure may have been partially due to the Commander's concern that lifting his feet too high around the central station results in kicking dust onto the PSE. However, the root cause was that he could not see the cable because of the limitations associated with working the A7LB. Before the flight he recommended reinforcing the cable connections in the experiment; however these recommendations were not accepted. This was later corrected and was not a problem on Apollo 17. The Cosmic Ray Detector experienced high temperatures when a film, in addition to dust, accumulated on thermal control surfaces. A locking device on the Radioisotope Thermoelectric Generator failed.

During Apollo 17, Velcro failure led to dust contamination on a mirrored surface of the Surface Electrical Properties experiment. Dust permeation on various equipment bound moving parts. The Lunar Ejecta and Meteorites Experiment experienced high temperatures due to dust accumulation on thermal control surfaces.

Observations

General

Pete Conrad stated in the Apollo 12 Technical Debrief, *"We got back to the ALSEP and started a normal deployment. The first thing we noticed was that, as soon as we put the packages down on the surface, they began to accumulate dust."* [3]

Alan Bean added, *"The first experiment I put out was the passive seismic. It had two anomalies that I know. One was the skirt. The aluminum foil, the skirt, didn't want to lie down. It wasn't that it had a memory. When I placed it near the ground, the many layers seemed to separate. The skirt seemed to have some kind of static charge on it that would not allow it to touch the ground. It took quite a little pushing to get it to lie down on the ground. The only way I could make it lie flat was to put a little dirt on it, which I tried. But that wasn't a good idea because it's difficult to put little clods of dirt on it. I later got some Boyd bolts and made little alignment tubes to sit on it. That worked really well; it held down the skirt pretty well. The second anomaly was that the little* *dish that passive seismic sits in needs to have a solid bottom so when it is placed on the ground, there is not danger of dirt easing up through the center of it, as there was in the case of our dish, and touching the bottom of the passive seismic itself and causing a thermal short that would ruin it. We spent quite a bit of time tapping out a nice neat hole so this wouldn't occur. Really, I think the fix should be to put a solid bottom to that dish…We left the area so that the exposed mirrored surface would be nice and clean and the two detectors would not get dust in them. I'm pretty sure that we did get some dust on the top of it. I hope it's not enough to bother the operation…I think we are kidding ourselves if we think there is any way to deploy the experiment without getting a lot of dust and dirt on it. The pictures are going to show this. They just have to be designed to accept dirt and dust. If they can't accept the dirt and dust, then they are going to have to be packaged in some way so that they can be deployed completely and then, the last act would be to pull some sort of pin and flip off the covering that would have all the dirt and dust on it, exposing the nice clean experiment."* [3]

Conrad described solar wind spectrometer deployment.
"The only one I deployed was the solar wind spectrometer and it went exactly as advertised. I checked the four legs down, took it out the proper distance, aligned it, and turned her loose. The Boyd bolts, as Al pointed out, were no problem; it would probably be easier if the cups were lower. The bolts should be kept covered with the tape though, because of the dust problem." [3]

Conrad explained dust problems with colored contrast charts.
"One other item in the first EVA, the colored chart, I took out because I could not bend over, and there was not reasonable way to stick in the ground. I tried to work it into the ground so that it was perpendicular to the Sun. It didn't work because of the soft dirt. It fell over and became covered with dust. I got back up and tried to brush it off, but it was impossible. I just made a complete shambles of it. The dust clung to it so badly that we didn't get a color shot of that." [3]

Bean adds, *"I want to discuss number 41 which is the contrast charts. We had three of them. One of them got dropped in the dirt and was completely covered with dust; so it was useless. There was no way to dust it off."* [3]

The Apollo 12 Mission report added, *"All shades on the contrast charts could be seen under the conditions tested. One of the charts was accidentally dropped to the surface and the dust coating rendered it unusable. The other two charts were used to look at the two extreme lighting conditions, up sun and down sun on the walls of a crater."* [2]

Bean described Solar Wind Composition (SWC) Experiment Retrieval.
"Finally it did tear about a 6-inch longitudinal rip; and I realized then that it just wasn't flexible enough and didn't want to roll up. So I let it go and let it sort of window-shade all the way around and then tried to roll it up by hand and not get my fingers on any of the foil. I'm sure I wasn't able to do this entirely. I expect there is some dust from my gloves on the foil but I did the best I could." [3]

The Apollo 12 Mission report noted, "*It was impossible to work with the various pieces of experiment equipment without getting them dusty. Dust got on all experiments during off-loading, transporting, and deployment, both as a result of the equipment physically touching the lunar surface and from dust particles scattered by the crewmen's boots during the deployment operation."* [2]

It also described high temperature problems.

"Temperatures measured at five different locations in the instrument were approximately 68° F higher than expected because of lunar dust on the thermal control surfaces." [2]
The report described a sample container.
"The environmental sample and the gas sample were easy to collect in the container provided, but there was a noticeable binding of the threads when replacing the screw-on cap. The binding could have been caused by a thermal problem, operation in a vacuum, or the threads being coated with lunar dust. Although the lid was screwed on as tightly as possible, the gas sample did not retain a good vacuum during the trip back to earth." [2]

Mitchell spoke of deploying seismometers in the Apollo 14 Technical Debrief.
"Deploying the seismometers into the surface was a bit of a trick because of the softness of the soil. I had a little bit of difficulty getting them under my boot to push them in. Eventually, in all three cases, I ended up using the thumper plate itself. I would dangle them above the surface, pick up the thumper plate, and very carefully get the little stake started into the ground. Then I would step on it and push it in. However, the soil was sufficiently light and non-cohesive for the first few inches so that the seismometer had nothing that would hold it in place. This is the reason the second one pulled out. All you had to do was just touch it, and it either would tip over or pull out completely. When we finally got them in place, they were all within the 7-degree constraint. I'm sure they were. The second one was until it got pulled out; but, when it was eventually reset, it was all right also." [4]

The Apollo 14 Mission report says of the Superthermal Ion Detection experiment, "*Despite a large amount of lunar dust which adhered to one end of the package when it fell over several times during the deployment the temperatures throughout the lunar day and night remained within the range allowed for the instrument."* [5]

The report said of the Active Seismic Experiment Thumper anomaly, *"Corrective action for Apollo 16 consists of adding a positive detent mechanism, properly aligned with the selector switch contact and dust protection for the firing switch actuator assembly."* [5]

Irwin, in the Apollo 16 Technical Debrief stated, *"One small comment as far as aligning the central station after it has been erected. It's quite easy to do. I don't know whether it was just the soft soil where we had the central station, or whether it was typical one-sixth g. Even though its erected, it's easy to shift to line up the shadow device."* [8]

In the Apollo 16 Technical Debrief, Young described tripping and breaking the Heat Flow Experiment.
"A guy really can't lift his feet too high around a central station, because when he does, he kicks dirt all over the PSE. It was a bad thing, but I still think it was incompatible with the kind of limitations that we are working with in the pressure suit. I tripped over the whole thing, but I didn't even know I had done it. I was completely out as far as the active seismic experiment when I looked around and saw this cable following me…with that rock between the PSE and the central station walking on one side or the other of that rock would tend to get a little dirt on the skirt." [8]

Young continued, *"Yes. And, because they keep falling over the rocks as I walked by it…It sure was a tragedy. If it had just moved the central station before it broke. I would have stopped right there and fixed it."* [8]

Duke described dropping the RTG package into a crater.
"I thought I'd blown it then because of those very fragile fins on the RTG. But, I looked at it and it hadn't been damaged at all. In fact, it was hardly dusty." [8]

The crew discussed thermal problems with the PSE. Young said, *"They said they were having thermal problems with the PSE."* [8]

Duke replied, *"Already! That's because there's dust on them."* [8]

The Apollo 16 Mission report described overheating.
"The passive seismic experiment was deployed as planned. All elements of the experiment have functioned normally with the exception of the thermal control system. Two days after activation, the temperature increased markedly beyond the controller set point and eventually exceeded the range of the sensor, 61.4° C. The temperature stabilized at night to 52.2° C. Photographs of the instrument show the shroud skirt to be raised at several places (fig, 4-5); further, dust was inadvertently kicked onto the skirt after the photographs were taken. These factors are believed to be responsible for the abnormal temperatures. The temperatures are not expected to affect instrument life or seismic data, but will degrade the tidal data." [9]

The report explains degradation of the Cosmic Ray Detector, *"The plastic in all panels of the experiment was degraded by heating above the design limit of 54° C, which temperature degradation begins. The high temperature was most likely caused by a film accumulating on the thermal control surface, in addition to lunar dust."* [9]

The report stated, *"The solar wind composition experiment for this mission differed from those of previous missions in that pieces of platinum foil were attached to the specially prepared aluminum foil used to entrap noble gas particles. This was done to determine whether or not the platinum foil pieces could be cleaned with flouridic acid to remove lunar-dust contamination without destroying rare gas isotopes of solar wind origin up to the mass of krypton."* [9]

The Apollo 17 Mission report discussed the gravimeter.
"The gimbal was observed to be free swinging after the initial release and after all subsequent jarrings and shakings. A small amount of dust fell off the universal handling tool into the gimbal housing during the final jarring of the gimbal, but all final alignments and leveling by the crew were normal." [10]

The report commented on the Lunar Mass Spectrometer.
"The deployment of the lunar mass spectrometer was as planned. A small amount of dust (approximately 0.1-mm thick) covered about 30 percent of the north-facing surface of the experiment." [10]

The report discussed the Surface Electrical Properties Experiment.
"Velcro pile pad was bonded to the Kapton bag and the Velcro hook strap was bonded to the Kapton flaps. The bond of the Velcro pads for moth flaps had already failed before the Lunar Module Pilot configured the receiver at the end of the first extravehicular activity, thus resulting in dust accumulation on the mirror surface under both flaps. The bond of the Velcro pads to the Kapton failed, leaving no trace of the adhesive on the Kapton, and the pads remained attached to the straps. The polyurethane PR-127 A and B bonding material used was acceptable and recommended for bonding Velcro to Kapton. The failure most likely resulted from a weak bond caused by improper bonding preparation or procedure. The mixing and timing of the bonding application and mating are critical, as well as maintaining the surface free of contamination." [10]

The report described condition of the cosmic ray detector.

"Microscopic examination of the detector surfaces showed very little dust. The maximum temperature of approximately 400° K was well below the critical limit." [10]

The report noted difficulty moving mechanical parts.
"At the end of the second extravehicular activity, the Lunar Module Pilot returned to the lunar surface experiment deployment site for additional verification on the deployment of the lunar surface gravimeter. The second extravehicular activity duration was 7 hours and 37 minutes during which time the lunar roving vehicle traveled approximately 20.4 kilometers. A total of 60 samples were collected with an accumulated weight of approximately 75 pounds. At the end of the extravehicular activity, all hardware systems were operating as expected, except for a noticeable difficulty in the movement of some mechanical parts because of dust permeation." [10]

The report continued, *"The geopallet was used as planned for the first two extravehicular activities. By the start of the third extravehicular activity, most of the moving parts of that pallet had begun to bind because of dust permeation along interfacing surfaces."* [10]

The report discussed successful gravimeter deployment.
"The gimbal was observed to be free swinging after the initial release and after all subsequent jarrings and shakings. A small amount of dust fell off the universal handling tool into the gimbal housing during the final jarring of the gimbal, but all final alignments and leveling by the crew were normal." [10]

The report mentioned dust on the Lunar Mass Spectrometer.
"The deployment of the lunar mass spectrometer was as planned. A small amount of dust (approximately 0.1-mm thick) covered about 30 percent of the north-facing surface of the experiment." [10]

The report explained effects of dust on the mirror surface of the Surface Electrical Properties experiment receiver.
"A dust film of about 10 percent on the mirror surface could result in the indicated degradation of thermal control and a film of this amount may not be apparent to the crew." [10]

The report described overheating in the Lunar Ejecta and Meteorites Experiment.
"It is postulated that when the experiment is on, the charge differential observed at these times may result in an accretion of lunar dust on the east and west sensors. Based on this, the experiment was turned off each sunset and sunrise after the second lunar day. The presence of dust on the sensor film and grid would degrade the thermal control system and result in higher experiment temperatures during the lunar day." [10]

Schmitt said, *"You've heard all about the ALSEPs and the LTG problem in real time. It's on the transcript. It was something in the dome removal strip. We pried it off with a hammer. The ALSEP traverse surprised me in that the package seemed heavier than I expected."* [11]

Cernan added, *"You lost a block."* [11]

Schmitt responded, *"I lost a block. It just came off the Velcro. I may have hit it with my leg. Really the dust was so deep and soft that the blocks were relatively ineffective, and I ended up putting a rock underneath one corner."* [11]

Recommendations and Lessons Learned

The Apollo 12 Mission report recommended, "*Because there does not appear to be a simple means of alleviating this dust condition, it should become a design condition. Although both experiment and package tools worked well, the deployment could have been more efficient if the tools had been from 2 to 5 inches longer. The difficulty in fitting and locking both tools in most of the experiment receptacles was frustrating and time consuming. Looser tolerances would probably eliminate the problem."* [2]

Irwin observed in the Apollo 15 Technical Debrief, *"Might make a comment here that the dust covers that were put on the various experiments, really paid off because we were in probably the worst situation that I've seen as far as dust and soil, but they kept all the Boyd bolts clear of any dust."* [6]

Schmitt, in the Apollo 17 Technical Debrief observed, *"I'm sure we'll get into this in the system experiments, but as a general comment for any radiator surfaces that need to be protected, you need to have more than just a cursory design on the protection of those radiators. The SEP is the case in point, and that was a completely inadequate design to protect those radiators. If we ever do it again in a dust environment, you must have clear and very tight protection of your mirrors and radiators for driving."* [11]

Cameras

Apollo 12 documents described dust-covered lenses. The crew of Apollo 15 experienced failure due to dust in drive mechanisms and difficult to release film magazines from cameras. They reported lenses covered with dust and were unable to install the polarizing filter due to dust in the bayonet fitting. Dust on television cameras caused a halo effect and created glints due to sun light interacting with dust covered lenses.

Observations

The Apollo 12 Mission report spoke of problems with cameras.
"The exterior of both cameras became extremely dusty on the lunar surface. It is believed that some dirt was on the lens, although this condition was difficult to detect because the lenses were recessed. Cleaning the lens was not possible but would have been desirable. Toward the end of the second extravehicular period, the fluted thumbwheel on the screw that attaches the camera to the camera mounting, which then attaches to the front of the suit, worked free from the screw. The camera could no longer be mounted to the bracket or the suit and was therefore not used for the remainder of the extravehicular phase." [2]

Bean described problems with cameras.
"I would like to say something about the camera. We got a lot of dust on ourselves and also on the outside of the camera. We kept looking at the lens to see if there was any dust on it and to see if it was going to degrade the pictures. Neither Pete nor I could see it on each other's camera, although the other parts of our camera were covered with dust. We'll have to take a look at the pictures that we returned. If it does turn out to be a problem, we're going to have to come up with some sort of brush we can use to dust off the lens, because I don't see any other way. We were trying our best to keep the equipment clean; but just moving around, trenching, leaning over, and all the other things tend to get dust on the equipment." [3]

In the Apollo 15 Technical Debrief, Scott spoke of dust in the drive mechanism, *"—and I guess the problem with the camera, we brought it back for the people to look at – I think the problem is* *definitely dirt in the drive mechanism. I fiddled with it that night and got it going. The next day, it hung up again. After we got into orbit, we worked on it some more, and you could see that the wheel exposed by the Reseau place was hanging up. If you put your fingernail in there and triggered it, it would get going. I think with the amount of dirt that you have, and the fact that the camera is level with the area in which work when you roll up the bags, you get dirt, in the camera."* [6]

Irwin continued, *"Dust accumulation also gave a problem as far as removing the film mags from the camera. There were several times where it was very difficult to release it."* [6]

Scott said, *"I think the camera would be better off if we'd protect it a little better. We used the lens brushes on the cameras, and they were very good."* [6]

Irwin added, *"On the TV also."* [6]

Scott agreed, *"On the TV also. That lens brush is really a good brush. It cleaned it off very well. The dust brush, to clean off the suits seemed to work pretty good. It got the gross dirt off. It didn't get everything, I guess it also worked quite well on the LRV and the LCRU mirrors – cleaned them off pretty well."* [6]

The Apollo 15 Mission report said, *"Lunar dust on the television camera lens caused a halo effect and sun reflected glints. Improvement in picture quality was restored periodically after the crew brushed the lens."* [7]

The report stated that the polarizing filter could not be installed. *"The polarizing filter for the Hasselblad electric data camera could not be installed because of excessive dust in the bayonet fitting."* [7]

On the subject of Azimuth adjustment, the report suggested the problems were caused by grease rather than dust, *"To adjust the azimuth to the proper dial reading, the camera is rotated on a 12.5 inch-diameter ball-bearing ring. The bearing is not sealed; however, the crew did not observe any lunar dust on the bearing.* [7]

"The azimuth ring bearing was packed with a waxy, low-outgassing grease which stiffens appreciably at temperatures below 50° F. This grease is normally used as a sealant rather than a lubricant. The camera was intentionally kept in the shade to protect the film from high temperatures. As a result, the grease stiffened. The manual azimuth adjustment operation was not included in cold chamber tests with other operations of the camera." [7]

Recommendations and Lesson Learned

Bean recommended brushes for cleaning dust off cameras. *"The thing that worried me most about the cameras was that we were getting a lot of dust on them. I was afraid we were getting dust on the lens, and we had no means whatsoever to clean it off. I think it would be definitely desirable to have a whiskbroom on the MESA. We could use the whiskbroom to dust off the suits, and perhaps the back of the broom could have something so that you could use to dust off the lens of the camera. I suspect that as missions get longer, we're going to get some pretty good dust covering on the lens of the cameras. Such a dust covering is going to degrade the photographs unless we have some means of cleaning the camera lens off, which we did not have in this case".* [3]

Scott recommended, *"I think we ought to put some little Beta booties over the top of the camera to keep it clean, at least over the joint there where the film mag goes on. They were getting so dirty that every time we reset our f-stop and lens, I had to brush mine off, because I couldn't see the settings on the camera, it got so dirty. I'd recommend maybe Velcro tabs and a little piece of Beta right up on top of the camera to keep that mechanism clean."* [6]

Translation Aids

Observations

The Apollo 12 Mission report described lock buttons on the LEC, "The metal pin that retains the lunar module end of the conveyor was not large enough to prevent it from slipping out of the yoke. By the end of the second extravehicular period, the lock buttons on the two hooks were extremely difficult to operate because of accumulated dust. This locking feature is not necessary." [2]

Recommendations and Lessons Learned

The Apollo 12 Mission report stated, *"The lunar equipment conveyor was redesigned to a single strap arrangement to preclude any possible binding caused by lunar dust."* [2]

Watches

Watches failed on both Apollo 14 and 16 missions. Although the root causes were not dust related, they may have provided a mechanism for dust contamination that resulted in failure.

Observations
Mitchell described his watch malfunction. *"I think that my Omega might have gotten some dirt or something in it because it would not run when it wound down very much, I had to keep it wound up at all times, and so I was winding it three or four times a day. It stopped on one occasion when I don't think it should have."* [4]

Duke continues, *"Another comment on the EVA. We mentioned out failures, except I failed to mention that my watch blew a crystal on EVA-3 and it stopped running at that point. So the flight watch went belly up and I got it brought back to let them examine it. But the crystal either blew out or broke, and I don't ever remember hitting it. The face of the watch doesn't look like it's scratched. So I think what happened is the crystal just blew out and we got dust in it, and the thing was just not running and that happened on EVA-3."* [8]

The Apollo 16 Mission report stated, *"At depressurization, just prior to the third lunar extravehicular activity, the Lunar Module Pilot noted that his chronograph crystal was gone. The chronograph hands and face were not hit. However, about 12 minutes later the movement stopped. Most likely, warpage caused by thermal cycling allowed the differential pressure across the acrylic crystal to pop it out of the case. The exposure to and penetration of lunar dust contamination about the Lunar Module Pilot's sleeves probably caused the failure of the chronograph movement."* [9]

RadioIsotopic Thermal Generator

The Apollo 16 Mission report explained the failure of a locking collar on the RTG, *"Subpackage 2 was laid flat on the surface so that the radioisotope thermoelectric generator could be serviced. The subpackage was then reoriented in order to provide the Lunar Module Pilot a clear access path to the radioisotope thermoelectric generator housing. The reorientation may have forced dust into the locking collar which, later could have prevented the Lunar Module Pilot from making a positive lock-on to the carrying bar."* [9] Note: Duke earlier reported dropping the RTG into a crater.

Lunar Rover Vehicle (LRV)

LRVs and associated equipment experienced anomalies during the Apollo Program. During Apollo 15 and 16 mission batteries overheated. Apollo 16 and 17 LRV fenders broke off (as discussed in Section 6). The Apollo 17 crew found displays and checklists unreadable; they increased the amount of time cleaning dust from the rover; and commented on deteriorating Velcro due to dust contamination.

Observations

Scott, in the Apollo 15 Technical Debrief, thought that connectors and controls worked well. *"Connectors and controls, I thought, all worked very well. I think it was a good idea that they put that plastic plate over the flags in the*[Remote Control Unit] *RCU, because that sure got dirty."* [6]

Irwin said, *"I guess we commented about the general dust condition on the Rover after the EVA."* (See the Section 6 for more detail). [6]

Apollo 15 Mission report discussed battery overheating. *"At the beginning of the second extravehicular activity, the battery 1 cover had closed automatically, as expected. Battery 2 apparently had not cooled down enough and the cover was still open. It was closed manually powering up the vehicle. When the vehicle was activated, battery-1 temperature was 68 degrees F and battery-2 temperature was 78 degrees F. The difference was probably caused by the difference in dust accumulation on the thermal mirrors. These temperatures are consistent with predicted cool-down rates with the covers open and warm-up rates with the covers closed. During the second traverse, the battery-1 and battery-2 temperatures increased to 92 F and 98 F, respectively. The battery covers were opened at the conclusion of the second extravehicular activity period."* [7]

The report continued, *"At the beginning of the third extravehicular activity, both covers were open. Little battery cool-down had occurred, probably because of further dust accumulation on both battery mirrors, although the battery covers had been closed for the traverses. The covers must not have been closed tight enough against the Velcro edges to keep dust off the mirror surfaces. Only a small amount of dust on the surface will preclude the desired cool-down. At the conclusion of the traverse, battery-1 and battery- 2 temperatures had increased to 108 F and 113 F, respectively, which is an acceptable level."* [7]

Young, in the Apollo 16 Technical Debrief expressed concerns about design of the battery covers. *"There's plenty of dust on the radiators just coming from opening the battery covers. It's very difficult for me to reach across there to close the battery covers. I would think that the next time anybody designs a vehicle, they'd put the opening and closing mechanism on the outboard side, instead of on the inboard side of the radiator. I was always afraid that I was going to end up falling right in the middle of the batteries."* [8]

Young, in the Apollo 16 Mission Debrief expressed concerns with the LRV battery covers, *"When we were opening the battery covers, of course, we had to dust the [Lunar Communications Relay Unit] LCRU (they got dusty all the time), the LCRU did badly when they opened the battery covers. We had to park the LRV such that it was rolled into the Sun a little. That may have given them a thermal problem they didn't know about. We parked it at the right heading, but when we opened that battery covers the dirt just flew up in the air and came right back down on the batteries. We had to dust the batteries. I could see why they got dusty. There's hardly any way to avoid it. That was on the dust EVA before we lost any fenders. We were relatively free of dust in the front of the vehicle other than what we accumulated on the front of it as we drove."* [8]

Duke remembered problems resulting from the broken fender, *"The RCU got dusty due to our dust fender problem. I had a tough time reading mine even though it had the plastic over it. They really did a good job putting that plastic over the top of that thing or we never would have been able to read it."* [8]

The Apollo 16 Mission report described the effect of open battery covers, *"At the conclusion of the first extravehicular activity, the vehicle was parked with the front of the vehicle pointing towards the north. The battery temperatures were 104° F and 105° F with 108 and 105 ampere-hours remaining. The battery covers were brushed and opened, the radiator surfaces were dusted, and the power-down was completed. The battery covers did not close between the first and second extravehicular activities and temperatures at power-up for the second extravehicular activity were 70° F and 82° F."* [9]

The report continued, *"The crew noted that the forward wheels tended to dig in when attempting to climb slopes without rear-wheel power. The right rear fender extension was knocked off and, thereafter, dust was thrown up from the right rear wheel and covered the crew, the console, and the communications equipment. Midway through the second extravehicular traverse, the ampere-hour integrator for battery 1 began indicating about four time the normal battery usage. Because of the higher-than-desired temperatures on battery 1, a series of procedures were initiated to lower the load. These procedures probably caused the inadvertent removal of drive power from a pair of wheels, thereby losing two odometer inputs and the associated static range, bearing, and distance displays. The problem cleared when the normal switch and circuit breaker configuration was restored."* [9]

The report explained a battery temperature caution and warning flag. *"The battery covers were opened at the completion of each extravehicular activity. Opening the battery covers threw dust onto the battery mirror surfaces; therefore the mirrors were completely brushed after each extravehicular activity and were brushed twice at final rover parking after completing the third extravehicular activity. Even though the mirror surfaces were brushed as well as possible, battery 2 temperature caused the actuation of a caution and warning flag while driving to station 11/12."* [9]

Cernan said in the Apollo 17 Technical Debrief, *"Crew restrictions, Limitations, and Capabilities – Displays – I could see and read all displays all the time except when we got dust on the checklist down in front of the hand controller. Then that became effectively unreadable until I could get off the Rover at the next stop and dust it."* [11]

Cernan suggested, *"They should be sealed or protected. We had absolutely no dust problem with the wheels, and those are sealed units. Dust accumulated on the radiator."*[11]

Schmitt added, *"That goes for tools too. The only tools we had locks on were the scoop and the rake, and those were getting stiff and wouldn't lock. They wouldn't relock once you adjusted them."* [11]

Cernan spoke of dust contamination. *"The period of time when we had lost the rear fender just put a solid coat of gray dust over everything. Once we got the fender repaired, the dust problem was at a minimum. After the long traverse rides, the radiators all required a good amount of dusting. That required X amount of time. That's going to be required again any time we have a lunar surface operation."* [11]

Cernan added comments about problems with Velcro, "*Something else that dust penetrates that I don't think has been mentioned before is that it penetrates and deteriorates the capability of Velcro. I could see it on the* [Lunar Communication Relay Unit] *LCRU covers and the SEP covers. The Velcro pulled off to keep the SEP covers closed, but the Velcro that kept them open didn't pull off but it was deteriorating. If you want to use tape on the lunar surface after what you're taping has been exposed to the dust, you first have to clean that surface off with a piece of tape or something and get the mirror dusted off before the tape will even begin to adhere to the surface you are applying it to."* [11]

Recommendations and Lessons Learned

Bean suggested appropriate wheel design for a lunar rover in the Apollo 12 Technical Debrief, *"It wasn't very difficult, I don't think to operate on that slope, Pete. It wasn't particularly slippery…I know that they are trying some sort of wheel vehicle for the next flight. My impression was that you could use a wheel vehicle but you probably should have one with wide tires. Although the dust was only an inch deep or something like that, if you had some skinny tires it might give you a problem. I don't know how big the diameter they ought to be, but they ought to be fat things to help it ride along the surface."* [3]

Schmitt recommended dust protection for mechanical equipment, *"What we're really saying is that in any future operation, mechanical joints or levers and this sort of thing are going to have to be protected."* [11]

The Apollo 17 Mission report spoke of cleaning batteries, *"The batteries were not dusted until well into the second extravehicular activity; however, after that time, the battery covers were brushed clean at every stop. The cleanliness of the batteries is attributed to the fact that the covers were continually dusted and kept clean. Dusting was time-consuming, but it was no greater problem than anticipated preflight, and it was part of the overhead in system management that leads to successful vehicle operation."* [10]

Lunar Materials Sampling and Samples

This section contains information on mechanical problems caused by lunar dust and information that provides insight into regolith and the associated effectiveness of regolith sampling methods. The emphasis is on mechanical problems. However, the additional information is included to provide future hardware and mission designers information to help in evaluating various designs.

The Apollo 12 crew experienced slight binding of the locking collar for the shovel or core tube due to dust collection in the mechanism. The sample return container lid did not maintain vacuum because the lid was coated with dust. During Apollo 16 a bag of rocks fell off the tool harness because the Velcro was clogged with dust and failed. The Apollo 17 crew was unable to use the scoop extensively during the third EVA due to dust in the scoop locking mechanism.

Observations

Bean described sampling, *"The entire lunar surface was covered with this mantle of broken-up material, fine dust of varying depth. As a result, everything looked pretty much the same – sides of the craters, tops of the craters, flat lands, and ejecta blanket. If you're going to any geology, you're going to have to dig through this mantle of brown or black and to look beneath the surface a little bit. We had a shovel that we used for trenching, but because of the length of the extension handle and the inability to lean over and what have you, we never could trench more that about 8 inches. That was about the best we could do, and that was a pretty big effort."* [3]

The Apollo 12 report said, *"The extension handle was also from 3 to 5 inches too short for optimum use with the shovel. The upper collar that mates with the aseptic sampler is no longer required and could be removed. The locking collar for the shovel or core tube was binding slightly by the end of the second excursion, probably because of dust collection in the mechanism. The shovel was used to dig trenches, as well as to collect soil samples. With the present extension handle for the shovel, it was only possible to dig trenches about 8 inches in depth. Trenching operations were very time consuming."* [2]

The report said, *"Closing of the sample return containers was not difficult and was similar to that experienced during 1/6g simulations in an airplane. The seal for the sample return container lid became coated with considerable dist when the documented samples were being loaded into the container. Although the surface was then cleaned with a brush, the container did not maintain a good vacuum during the return to earth."* [2]

Mitchell asked Shepard to remark on core sampling, *"Would you remark about your experience with the core tube where you drilled at point A, so we can contrast it with my experience later at Triplet?"* [4]

Shepard responded, *"Point A is where I took the double core. It went down all the way. It went down relatively easy for the first section. The next half of the second core wasn't bad, requiring just general tapping; then I had to bang it very hard to get the last half of the top core, but I did get it."* [4]

Mitchell asks, *"Did you get it in all right?"* [4]

Shepard answers, *"1-3/4 to 1-7/8. I guess it was two cores. That's about the deepest penetration we had…You were making an attempt to do a triple core. It looked as if Ed and I should have changed positions because it was not soft enough for him and it was too soft for me. We practiced digging the trench in the edge of the crater, because it was mechanically and physically easier to dig the trench on the side of the crater. By the side of the crater, the dust just wasn't cohesive enough to get a good sample of soil mechanics. We probably did get a pretty good idea of what the composition of the soil was, because it wouldn't hold more that a 60-degree angle on the side of the trench before it all started falling back down in…We felt that we had less dust throughout our area perhaps than the previous landing sites."* [4]

Scott in the Apollo 15 Technical Debrief stated, *"I thought the lock box worked just fine. I guess we can't think of any improvements on that."* [6]

Scott says, *"The next order of business was drilling the stems for the deep core. As I started out the soil was very soft, and the drill went very easily and too fast down to the bed rock. The ground gave a call for the rates, which I had forgotten in my haste to finish up the drill. We were* *supposed to go an inch per second. I got about a stem and a half in before the ground reminded me of the rate, and I slowed down to an inch per second. I hit bed rock, or the very hard soil, which was a step-jump in hardness as I drilled."* [6]

The Apollo 16 Mission report says, *"The sample collection bag attachment to the tool harness was unsatisfactory. On one occasion, one half-full bag of rocks fell off the tool harness and, fortunately, lodged between the rear fender and the frame of the lunar roving vehicle. Because the Velcro is subject to clogging with dust, the manner in which it is used to attach the bags to the portable life support system tool harness will not assure positive retention of the sample collection bags on the portable life support system tool harness.* [9]

"The Velcro strap, when tightened down, keeps the bag from floating or bouncing off the hooks. During the lunar roving vehicle operations, the Velcro strap sometimes loosened because of the entrapped lunar dust so that the bag could come off. [9]

Apollo 17 Mission report, *"The lunar surface scoop was the primary sampling tool used by the Lunar Module Pilot and it worked well. However, by the beginning of the third extravehicular activity, dust in the scoop-locking mechanism prevented extensive use in any of the multiple detents. Only the 45-degree position was used during most of the third traverse."* [10]

Recommendations and Lessons Learned

Bean recommended, *"If we're going to do any good geology, it's going to take a lot of trenching to get down below the surface. I'd like to recommend that we get a better trenching tool. Maybe all we need to do is lengthen the extension handle about 6 inches; but if we're going to look and see what's beneath the surface, we're going to have to dig it out of there somehow. I also recommend that we get a lot more core tubes aboard the next flight. I felt that, on the surface everything was pretty much the same and the real secrets were hiding about 2 to 8 inches under the surface. We really need to scrape away the upper surface or core down through it."* [3]

The Apollo 12 Mission report recommended, *"Because of the continuous mantle of dust that coats most of the lunar surface, trenching should be deeper and more frequent on future mission. A specific trenching tool should be used."* [2]

The Apollo 16 Mission report noted, *"For Apollo 17, the sample container bag hooks that are attached to the portable life support system tool carrier have been redesigned to prevent the bag from floating or bouncing off the portable life support system. The new hook design consists of a flat spring and a stop so that the same force is required to install and remove the bag."* [9]

Apollo 17 Mission report described modifications to lunar sample return containers, *"A triple seal arrangement maintained a vacuum during trans-lunar and transearth flight. Seal protectors were also provided to prevent lunar dust from getting on the seals. The strap-latch system consisted of four straps and two cam latches. When closing the container, the crewman engaged the cam latches, thus tightening the straps over the lid."* [10]

Analysis

Dust raised by crews and equipment covered everything that was used on the lunar surface. In order to manage the risks to mission success created by lunar dust, everything that comes into contact with the lunar surface must be designed for reliability in the dusty environment.

Cleaning techniques were used with varying effectiveness. These techniques, promising new technologies and operational procedures should be evaluated and developed to manage risk.

During Apollo cleaning operations were very time consuming and labor intensive. Future lunar exploration missions should reduce the amount of time required for these activities. In addition, operational timelines should accommodate the need for cleaning as defined by dust management systems design and operational concepts.

Future Work

Future work recommended for Surface Equipment is the same as Section 6. Each topic in this section should also consider reliability of surface equipment and work efficiency index.

SPACE SUITS AND SEALS

Summary

Space suit anomalies caused by lunar dust created problems for the Apollo program. During Apollo 12 wrist and suit hose locks became difficult to operate, suit fabric was abraded and leak rates increased. The Apollo 14 crew reported helmet visor scratches that decreased visibility. The Apollo 15 crew was hampered by difficulty in connecting and disconnecting PLSS PGA connection and disconnection. During Apollo 16 lunar operations, dust in zippers led to difficult operation; wrist ring pull connectors were covered with dust, degrading mobility; PLSS RCU displays were abraded and could not be read; and dust in helmet visor mechanisms resulted in over visors that would not retract. The Apollo 17 crew reported stiff glove connectors, stickiness in helmet visor retraction, and reduced visibility due to scratches and dust accumulation on visors.

Observations

Conrad described concerns with the effects of dust on space suits in the Apollo 12 Technical Debrief. *"I got quite concerned with not only the wear and tear on the suits but the effect of the dust on the suits. On our final hookup back on the LM ECS system for ascent it was all we could do to get our wrist locks and suit hose locks to work. They obviously were beginning to bog down with dust in them. When you go over these suits later, you'll be able to analyze this. I have no idea what the effects were on the O-rings. Suit integrities did stay good, but there's no doubt in my mind that with a couple more EVA's something would have ground to a halt. In the area where the lunar boots fitted on the suits, we wore through the outer garment and were beginning to wear through the Mylar. I'm sure they will be very carefully inspected to see what these effects were. Al and I had extreme confidence in the suits; therefore, we didn't give a second thought to working our heads off in the suits and banging them around – not in an unsafe manner but to do the job in the way we had practiced it on Earth. These suits were more worn than our training suits. We must have had more than a hundred hours suited work with the same equipment, and the wear was not as bad on the training suits as it is on these flight suits in just the 8 hours that we were out. I think it has to be the abrasiveness of the dust."*[3]

Bean adds, *"If we had had the suits opened up, I'm afraid that we would have had a lot more trouble with dust in the zippers, inside the suit, and inside the helmets. It was tough enough just on the wrist rings and neck rings. We tried to wipe them off before we put our equipment back on the next morning but we did notice it harder to put on. I didn't have any other leak rate for all the pressure checks prior to launch and at other times, but during the last pressure check that we pulled I had a leak rate of something like two tenths over the minute. So, the thing was leaking somewhere and it must have been around the neck and wrist rings because those were the only openings that had changed."* [3]

Conrad agreed, *"My suit was the same way. I had about 0.15 over a minute although I had very little on our first check prior to getting out."* [3]

Apollo 12 Mission report says, *"During the last hookup of the suits to the electronic control assembly prior to ascent, the lunar dust on the wrist locks and suit hose locks caused difficulty in completing these connections. In addition, much dust was carried into the lunar module after the extravehicular periods. Dust may have contaminated certain suit fittings, since during the last suit pressure decay check, both crewmen reported a higher-than-normal suit-pressure decay. However, no significant difference in oxygen consumption between the two extravehicular periods was apparent.* [2]

"Considerable dirt had adhered to the boots and gloves and to the lower portion of the suits. There were fillets of dirt around the interior angles of the oxygen hose connectors on the suit. The suit material just beneath the top of the lunar boots chafed sufficiently to wear through the outer suit layer in several spots. The dust and dirt resulted in a very pronounced increase in the operating force necessary to open and close the wrist rings and the oxygen hose connectors. The Commander's suit had no leakage, either prior to launch or prior to the first extravehicular activity. Just before his second egress, the leak rate was 0,15 psi/min and, prior to cabin depressurization for equipment jettison, was 0.25 psi/min. If the suit zippers had been operated for any reason, the suit leakage might have exceeded the 0.30 psi/min limit of the integrity check. [2]

"The pressure suits operated well throughout the extended use period. The outer protective layer was worn through in the areas where the boots interface with the suit. The Kapton insulation material just below the outer layer also showed wear in these areas. In addition, a minute hole was worn in one of the boot bladders of the Commander's suit. Suit performance was not compromised by this wear, as shown in the following table:" [2]

	Leakage, scc/min	
	Preflight	Postflight
Commander's suit	105	400
Lunar Module Pilot's suit	51	45
Specification value	180	740

Note: The leak through the hole in the Commander's boot is estimated to have been about 325 scc/min.

Mitchell in the Apollo 14 Technical Debrief stated, *"I have the comment that although my suit did exceptionally well, far better than the training suit ever did, it was still stiffer and took more effort to just hustle around than the training suit did, which was well broken in. I encountered a little bit of a problem with bending over, which I had not encountered in one-g, and I think this is in proportion to the forces between the one-sixth g and the stiffness of the suit as compared with the well-worked-in suit in one-g. I found that I could not bend down to the MET level. I could not just bring my body forward like I could in the training suit and get down to the MET. I had to bend my knees or get down on a knee to reach things low on the MET such as the weigh bags down on the side, or the camera retaining clips on the MET. It was more difficult for me to bend down for them."* [4]

Shepard responded, *"I don't know whether it was unique to Ed's suit or not, because I didn't have that problem."* [4]

Shepard said, *"We did clean and lubricate the PGA seals at the neckrings and the wristrings. I think it was a good way to go. We didn't get an awful lot of dirt, but we did get just enough of a smudge on the wiping cloth to indicate there was a trace of dust there, so I think that's a good way to go. It doesn't take too much time and I recommend doing that."* [4]

Mitchell agreed, *"Yes. I think it's interesting – I don't know whether that had anything to do with it or not – but my EMU leak rate was less on the second EVA than on the first. That is completely inexplicable to me. The only thing that was different was that we lubricated the rings. Whether that has anything to do with it or not, I don't know. As I recall, I had only 0.15 leak rate on the second EVA – I mean on the pressure check for the second EVA. My leak rate was much closer to specification during the second EVA than during the first."* [4]

Shepard said, *"I used the EMU maintenance kit only as we had described before, to clean the seals one time between EVAs. It wasn't a problem."* [4]

Mitchell spoke of scratches on helmet visors. *"And the helmet and LEVA operations were all right, except it certainly is easy to scratch up the helmet and the LEVA. The scratches cause shafting light or diffused light problems and that obstructs your vision. All I can say is that you have to darn careful with them when you're using them. Just the slightest touch can cause a scratch. My glove problem has been documented already."* [4]

Scott, in the Apollo 15 Technical Debrief, said, *"Everytime we checked them they were configured right. We did lubricate all the wrist rings, connectors, and helmet rings on this one, which was easy. I think that little dab of lubrication material works just fine."* [6]

Irwin continued, *"It was easy and I think it paid off because it was very easy to make the connections."* [6]

Scott added, *"We never had a problem with the zipper at all. Both zippers worked very good throughout the flight. I don't remember having your zipper hang up."* [6]

Irwin said, *"We used the lubricant out of the bag. We never used the replacement seals or the rings, never had to."* [6]

Scott said of PLSS PGA operations, *"Everything connected and disconnected all right, except when we got the dust and dirt. Then, sometimes it would stick, but in general, I thought it worked great."* [6]

Irwin spoke of the protective over gloves, *"I'd taken my protective covers off my gloves before I even went out on EVA-1 so, of course, they were off for this operation. I was kind of reluctant to grasp that drill very hard, afraid I might rip the gloves."* [6]

Scott agreed, *"That's a good point. I had to leave mine on the whole time because of the drill. The protective covers can restrain your hand movements even more that the gloves. I had sort of degraded mobility because of those protective covers, all the way. I finally took them off after we got through with the drill…When my palms got dirty, I had a difficult time manipulating the handle squeeze and the opening and closing because of all the dirt in the tongs. And so, about half way through EVA-2, I switched to the other set of tongs that were clean. That helped quite a bit. The problem in not having a yo-yo is that I had to stick them in the ground while we were gathering the samples."* [6]

Irwin mentioned visibility problems, *"I had some difficulty seeing my flags with the visor down."* [6]

Scott answered, *"I did too. I found that it was the dust accumulation."* [6]

Young, in the Apollo 16 debrief said, *"Every time we took the suit off – it's real handy that the thing is standing up by itself in one-sixth gravity. It's really handy for you to close the zipper up to lube the pressure zipper and get those connectors before you put the thing away for the night. On the second and third EVA, because everything was really getting dirty, and I don't know whether it's a problem or not or an imaginary problem, we were really getting concerned about whether we were going to be able to do things like fasten the connectors. So we were taking special care to lube everything and, therefore we ran out of lube."* [8]

Duke said, *"We had one left for the zipper on EVA-3."* [8]

Young added, *"We also lubed the zippers during doffing, instead of on donning as we had in our checklist, because it was just more convenient to do. The suit was standing up there right in front of you and all of the connectors were visible. It would sure help to get the zipper lubed and, also, it helped to Charlie to load that bag up."* [8]

Young continued, *"Donning was hard, I'll tell you, pulling that restraint zipper was really rough. After we got the dust in the zipper, closing the zipper and locking it was pretty, pretty bad."* [8]

Duke replied, *"Give me a new restraint zipper."* [8]

Young said, *"Restraint zipper and, also, closing the gloves and locking once we got the dust in there was really bad. It didn't hurt wrist mobility, but it sure was hard to get them closed."* [8]

Mattingly spoke of problems with his EMU, *"I guess this is a good a time as any to talk about the only two EMU comments I have. We had two things before I went out. I found it was very difficult to move my left wrist. My first thought was that maybe all this stuff about how you lose your strength when you lay around like a marshmallow for 10 days was really true and that I had just gotten super weak. And so I wasn't about to complain about it. Now, I look back on it and I'd like to have someone look at that glove because I think there's something wrong with it. At no time was I able to comfortably move it. Occasionally I could move it with my wrist, but generally, in order to make my left wrist move very much, I had to use my right hand to push the glove over to where I wanted it. And then I could keep it there."* [8]

Duke said, *"It sounds like an Ed Mitchell problem to me, like he had on Apollo 14."* [8]

Young noted, *"I ended up on the first EVA leaving a hole in my wrist with a wrist ring. I had some wristlets that I had taken up with me, but unfortunately they were in my lower pocket and they were all full of dust. So, I borrowed one of Charlie's and used that on the other two EVAs, but it just kept getting worse."* [8]

Young said, *"We said we needed some more lube in there for the surface operation and the dust."* [8]

Young said, *"They told us to give a PLSS check, and I couldn't read my RCU numbers because I made a mistake reaching up with my finger and tried to wipe off the dust. Apparently, the dust acts like an abrasive as it just completely clobbered the RCU and I couldn't read what percent oxygen I had from then on. I think they ought to do something about that."* [8]

Duke added, *"I dusted mine all the time. It got dusty."* [8]

Young responded, *"I couldn't read mine."* [8]

Young spoke of doffing the Pressure Garment Assemblies (PGA), *"PGA doffing was the usual problem of getting the PGAs off. As we said before, we lubricated the zipper when we got the PGA off, and then fastened the zipper, and pulled the seals down tight. It was after EVA-1 that we noticed the wrist rings were getting clogged with dust. There should be some way to cover those wrist rings (the things that snap in and out), the sliders that keep them from getting full of dust because it makes them practically impossible to work. After EVA-1, we experienced a little stickiness with the helmet. Not a great deal, so we didn't pay attention to it. When we took the suits off they were all dust covered, up to our knees, even though we kicked our boots off as we came up the ladder. We took the suits off and put them into a jettison bag, pulled the jettison bag up over the legs, and laid them in the couch like everybody else has done."* [8]

Duke said, *"On closeout, the LM was still as dusty and debris covered as ever. We had the same problems with the wrist rings as we had on the lunar surface. We managed to get buttoned up all right and on time for the jett maneuver."* [8]

Apollo 16 Mission report described problems with wrist rings.
"The crew had a continual problem of donning and doffing the gloves because there was dust in the wrist ring pull connectors. Even though the connectors were blown out repeatedly and appeared to be free of dust, it was extremely hard to pull the wrist ring devices in or out and, in fact, rotate the glove on or off. Some type of wrist dirt seal over these connectors is necessary. [9]

"After exposure to a dusty lunar environment, the both crewmen's suit wrist-ring disconnects were hard to rotate to the locked and unlocked position." [9]

Apollo 16 Mission report discussed visibility problems.
"On the third extravehicular activity, the Commander's extravehicular mobility unit overvisor would not retract; this was due to dust that had accumulated on the helmet as a result of the loss of a rear fender from the lunar roving vehicle. [9]

"Because of the extensive dust coverage, the Commander's remote control unit was difficult to read. An attempt was made on the surface to dust it off with a glove and the abrasive dust scratched the remote control unit face. After the remote control unit oxygen gage was scratched, it was impossible to read oxygen quantity on the lunar surface and it could read only marginally inside the lunar module. A scratch resistant material should be used to cover the remote control unit face." [9]

Cernan, in the Apollo 17 Technical Debrief said, *"Suit doff and don – This will cover all the EV prep and post activities. We both found, LMP and CDR that donning and doffing the suit in 1/6g was relatively easy. Once again, we had no problems zipping up the suits. In the course of doffing, and prior to getting the suit fully off, we mutually lubricated each other's open zippers and all the connectors. When we doffed the suit, we went into a drying mode as the checklist suggests prior to the sleep period. I'm really glad we did because our suits stayed relatively fresh and clean on the inside. We doffed out LCGs every day and slept in CWGs rather than the LCG. And I'm glad we did that because it was much more comfortable. We made it a buddy system in the entire donning and prep when it came to the suit operations, except for putting on the gloves. We found it easier to put them on in parallel and get them locked and verified locked. We actually, each individually in almost all cases put our own dust covers and ring covers on. Maybe we had to help each other once in a while. And contrary to some of our initial desires, we decided to go ahead and put those dust covers on for every EVA. After the first EVA, we found out what the dust problem really was."* [11]

Schmitt added, *"One of the tabs on the LMP's dust covers did break off on the first prep."* [11]

Cernan said, *"We obviously took extreme care of our suits – the best we could – because we had to use them several times. I think that care paid off because even at the integrity check of the CM/EVA, the suits were tighter than a drum. I think the wrist connectors, even with the dust covers, were tending to get a little bit stiff."* [11]

Schmitt added, *"Yes, mine were very stiff."* [11]

Cernan said, *"But nothing ever really froze up on us."* [11]

Schmitt remarked, *"LEVA operation – I did have the sticky visor problem and it was dust. We could force it closed, once we got it off. We tried once on the surface, and we couldn't get it closed."* [11]

Cernan said, *"Connectors and controls were good on the PLSS throughout the flight. They are the one thing that did not seem to get affected by the dust. They may have gotten a little stiffer, but I could not tell it."* [11]

Cernan noted, *"Helmet visor reflections – I had not particular problems with the helmet. My gold visor got very dirty and dusty and scratched up very early in the first EVA, and I cleaned it as the ground prescribed before each EVA, but it really didn't do much good. I just learned to live with it, and it really didn't degrade the operations much at all."* [11]

Apollo 17 Mission report discussed degraded sun shade operation, *"The Lunar Module Pilot encountered some difficulty in operating the sun shade of the lunar extravehicular visor assembly because of lunar dust in the slide mechanism. Dust and scratches on the outer gold visor prompted the crew to operate with the outer visor in the partially raised position during part of the third extravehicular activity."* [10]

The report described donning and doffing operations, *"Suit donning and doffing was accomplished essentially as planned. Particular care was exercised in the cleaning and lubrication of zippers and other dust sensitive portions of the extravehicular mobility unit. The dust protectors on the wrist lock-locks were used on each extravehicular activity, but it is difficult to determine how much protection these provided. The conservative approach was to use them; however, the moving parts of the extravehicular mobility unit seemed to be usable for an indefinite number of extravehicular activities providing that proper care was given to them."* [10]

The report described closeout on the second EVA, *"The closeout time for this extravehicular activity was also lengthened to account for additional effort required in dusting the extravehicular mobility units."* [10]

Apollo 17 Mission report, *"One of the two sets of spacers, which were subject to galling from dust, were removed from the lunar extravehicular visor assembly."*[10]

Recommendations

Apollo 12 Mission report observed, *"Some type of throwaway overgarment for use on the lunar surface may be necessary."* [2]

The Apollo 14 Mission report says, *"It should be noted that the wrist-ring and neck-ring seals on both pressure garment assemblies were lubricated between extravehicular activities. At that time, there was very little evidence of grip or dirt on the seals. Lubricating the seals between extravehicular activities is a procedure that should be continued on subsequent missions."* [5]

In the Apollo 15 Technical Debrief, Scott said, *"Yes, that's true. I might comment that lunar dust is very soluble in water. It seems to wash off very easily. I would say if you ever have a connector problem that was really stiff, you could take the water gun and spray it in and loosen it up."* [6]

Scott noted, *"We tried to brush them off and clean them off. We found that the booties which had been placed over the PLSS connectors were good protection from the dirt."* [6]

Irwin added, *"We did not loosen the suit connections for EVA-2 but we did for EVA-3."* [6]

Scott recommended, *"put booties over all the connectors or some sort of protective device. In the old days, they had a bib to keep them clean – or for double protection, I guess. Something like that would sure prevent problems later on and would save time cleaning the connectors. They sure get dirty. If you are going to go out there and do the job, you are going to get dirty. If you try to keep everything clean, you are just not going to be able to do the job on time. I think those little booties are a pretty good idea. They were no problem on the donning and doffing."* [6]

Apollo 15 Mission report said, *"Neck ring dust covers were provided to keep lunar dust out of the pressure garment assemblies when not being worn."* [7]

In the Apollo 16 Mission Technical Debrief, Young said, *"I think you should have some more lube in case you do get to a situation where as you're doing your last donning, something is not working right and you need to go back and lube it again to make sure…Yes. That's been remarked on before. Somebody said they taped their wrist ring but that seems like to be a kluge. I think they should come up with something that keeps the dust our of the wrist ring."* [8]

Apollo 16 Mission report described EMU improvements. *"The extravehicular mobility unit was modified to improve its operational capability, safety, and to provide increased dust protection…Dust protections were added to the oxygen purge system gas connectors and portable life support system water connectors…Velcro was added to the battery covers to provide increased protection against dust. Reflective tape was added to provide more radiative cooling…New underseat stowage bags with dust covers were provided…The thumper selector switch was modified to provide a more positive detent and all openings around the thumper selector knob and arming firing knob were covered with dust protectors."* [9]

The report described improved wrist disconnects. *"Postflight inspection of the wrist disconnects showed that lunar dust in the clearance areas cause the problem. Rubber dust covers for the ring disconnects which will afford better protection from contamination will be added for Apollo 17."* [9]

Duke said, *"We started a little bit early on the helmets and gloves because of a wrist ring problem."* [8]

Young agreed, *"I'm glad we did, because we had a problem. Every time we put the wrist rings on we didn't know if we were going to get them on, and then once we got them on we didn't know if we could get them off again. We knew we were going to get 'em off, but it sure wasn't the normal* *click click, push pull. I think we need some protection against dirt getting into those wrist locks."* [8]

Mattingly suggested, "*If you'd wrap a piece of tape around—*" [8]

Young responded, *"I thought about wrapping tape around it but would the tape stick?"* [8]

Mattingly added, *"That gray tape would do it."* [8]

Young answered, *"I'm not sure it would stick in a vacuum very long. I think you need something more than tokenism on that cover."* [8]

Analysis
Many of the Apollo crews expressed problems with wrist locks and mobility due to dust on surfaces. Dust that was allowed to accumulate on these surfaces may have infiltrated during EVAs or while in the LM. Also, CM pilots on Apollo 14 and 15 experienced wrist mobility problems as well. The training suits allowed more mobility, however, they were used for many more hours. More investigation is needed to determine the mechanism for dust contamination; if mobility problems were caused by engineering design; and if a break-in period, associated with the training suits, allowed for better mobility. Zippers were difficult to operate during Apollo 16. Dust mitigation techniques were implemented with varying degrees. Lubrication and dust covers appeared to improve the situation in some cases, but was not as effective in others. More investigation is needed to determine the cause of these problems and evaluate the effectiveness of dust management techniques.

The Apollo 12 crew reported that after a couple of more EVAs mechanisms would have ground to a halt, while the Apollo 17 Mission report suggested that the EMU would function for an indefinite number of EVAs, however the crew mentioned stiffness in wrist connectors.

Scratches and dust accumulation reduced visibility for some Apollo crews. This problem was not corrected during the Apollo Program.

The Apollo 11 crew reported increased suit pressure losses, while the Apollo 12 crew noted reduced suit pressure losses. The problem appears to have been corrected after Apollo 11.

Future Work
NASA should perform comparative analysis on flight and training suits to determine the root cause of mobility and locking problems.

Members of the team assigned to develop the Lunar Surface Suit should participate in the Lunar Dust Working Group and abrasion, mechanisms, and seals should be included as topics in the Lunar Dust Focus Group.

DUST CHARACTERIZATION

Summary

This section is included to provide information for consideration in technology portfolio and operations design, lunar stimulant selection and LREP missions.

Regolith refers to the material formed by physically weather, by some form of either abrasion or stress, bedrock to produce a bed of finer grained rock fragments that have not been chemically altered. The fine fragmental material we are concerned with is regolith. Dust refers to a particular size fraction, not the material in aggregate. However, many NASA documents refer to the regolith as dust, so this report uses dust and regolith interchangeably.

During Apollo 14, the crew experienced dust that appeared to differ from other sites. Although the report described the dust as clinging to surfaces, the crew mentioned, that the dust did not adhere to equipment. There were also many references, in the Mission report and Technical Debrief, to the non-cohesive nature of the dust.

Some Apollo crewmembers reported odors they described as gun powder smell and attributed these to the lunar dust. This may indicate that the dust may be reactive. There is no evidence of this to date. However, because the containers containing lunar samples lost vacuum, there is no way to determine if the dust reacted with the humidity in the atmosphere of the spacecrafts. Therefore, it is not possible to conclusively answer this question. If data is gathered that indicates that the dust is reactive then reactivity should also be considered in hardware design to ensure system integrity and reliability.

If dust properties vary from site to site, mission, operations, and hardware designers must consider these differences in their designs and lunar simulants used for systems testing must be appropriate. Recommendations for lunar dust characterization should be made to the LREP Project to ensure the knowledge base contains enough information to properly design reliable equipment and operations.

Observations

The Apollo 11 Mission report described the characteristics of the dust Tranquility Base. *“The bulk of the surface layer consists of fine-grained particles which tended to adhere to the crewmen’s boots and suits, as well as equipment, and was molded into smooth forms in the footprints.*[1]

“The regolith is weak and relatively easily trenched to depths of several centimeters. At an altitude of approximately 30 meters prior to landing, the crewmen observed dust moving away from the center of the descent propulsion blast. The lunar module foot pads penetrated to a maximum depth of 7 or 8 centimeters. The crewmen’s boots left prints generally from 3 millimeters to 2 or 3 centimeters deep. Surface material was easily dislodged by being kicked. The flagpole and drive tubes were pressed into the surface to a depth of approximately 12 centimeters. At that depth, the regolith was not sufficiently strong to hold the core tubes upright. A hammer as used to drive them to depths of 15 to 20 centimeters. At places, during scooping operations, rocks were encountered in the subsurface.[1]

"The crewmen's boot treads were sharply preserved and angles as large as 70 degrees were maintained in the print walls. The surface disturbed by walking tended to break into slabs, cracking outward about 12 to 15 centimeters from the edge of footprints." [1]

Bean described the soil in the Apollo 12 Technical Debrief, *"The core tube was pretty easy to drive. I think we must have been in a different sort of soil that Buzz was in; I augered it a bit as I drove it in, but I really never had the feeling that that was necessary. I think all that was necessary was to hit it pretty doggoned hard and drive it in there. We had no trouble going the full length."* [3]

Shepard in the Apollo 14 Technical Debrief said of sampling, *"I did what I was supposed to do and put it in the bag. I was surprised that there was little adherence of the surface dust. I expected a little bit more. It didn't adhere very much."* [4]

The Apollo 14 Mission report said, *"The lunar module footpad penetration on landing appears to have been greater than that observed on previous Apollo landings. Bootprint penetrations for the crew ranged from ½ to ¾ inch on level ground in the vicinity of the lunar module to 4 inches on the rim of small craters. Lunar soil adhered extensively to the crewmen's clothing and equipment as in earlier Apollo missions. Tracks from the modular equipment transporter were ¼ to ¾ inch deep and were smooth."* [5]

The report continued, *"Footprints on the lunar surface were not more than ½ to ¾ inch deep except in the rims of craters, where, at times, they were ¾ inch to 1 ½ inches deep. The modular equipment transporter tracks were seldom more than ½ inch deep."* [5]

The report stated, *"Dust on the lunar surface seemed to be less of a problem than had been anticipated. The dust clings to soft, porous materials and is easily removed from metals. The pressure garments were impregnated with dust; however, most of the surface dust could be removed. The little dust that accumulated on the modular equipment transporter could easily be removed by brushing. The lunar map collected dust and required brushing or rubbing with a glove to make the map usable."* [5]

Apollo 15 Mission report commented on the Rover's performance. *"The surface material varied from a thin powdered dust which the boots would penetrate to a depth of 5 to 8 centimeters (2 to 3 inches) on the slope of the Apennine Front to a firm rille soil which was penetrated about 1 centimeter (one-quarter to one-half inch) by the boot. In all cases, the rover's performance was changed very little."*[7]

Young said in the Apollo 16 Technical Debrief, *"That moon is really looking at a geology field trip through 6 feet of dirt and its kind of tough."* [8]

Apollo 16 Mission report said, *"Lunar dust and soil continues to cause problems with some equipment although procedural measures have been taken and equipment changes and addition have been made to control the condition."* [9]

The Apollo 17 Mission report described lunar dust, *"Surface texture, dust generation, cohesiveness, and average footprint depth indicates soil properties at the surface comparable to those at other Apollo landing sites."* [10]

Scott, in the Apollo 15 Technical Debrief said, *"When you took your helmet off, you could smell the lunar dirt. It smelled like – the nearest analogy I can think of is gunpowder."* [6]

Evans, in the Apollo 17 Technical Debrief, said, *“Odors – Every time I got up in the tunnel after docking or anytime, there was always a musty burned odor or something. It’s hard to describe.”* [11]

Schmitt adds, *“Like a powder burn.”* [11]

Evans said, *“Kind of like a powder burn. I guess. This was there both in lunar orbit docking and transearth docking. This was the second day we were out when we finally went up in the tunnel. Every time we opened up the tunnel, that’s what it smelled like.”* [11]

Analysis

Lunar dust characteristics may be different from site to site. Different lunar landing sites may require different dust management techniques and technologies.

Future Work

Proposed landing sites should be evaluated to determine lunar dust properties and appropriate engineering and operational solutions should be designed to ensure effective dust management. Lunar dust simulants should be evaluated to ensure relevant characteristics of the dust are represented while testing dust mitigation and system reliability.

HUMAN EFFECTS

This section is included for use by toxicologists and physicians who will establish standards for human inhalation. These standards will become mission and hardware design constraints and will be included in system requirements.

Observations

Young said, *"Dust, Density and Effects on Visual and Respiratory Systems."* [8]

Duke responded, *"It was dusty when we got back in orbit, we've already commented on all that stuff."* [8]

Young said, *"I don't think it was any problem."* [8]

Duke responded, *"I got one piece in my eye – a little something when I was over in the LM that gave me problems, but it was okay; it cleared right up, watered it out."* [8]

Cernan said, in the Apollo 17 debrief, *"In sputum – I didn't spit anything up. I didn't feel any aerosol problems at all until after rendezvous and docking when I took off my helmet in zero-g and we had the lunar module cabin running the whole time. I did all the transfer with my helmet and gloves off, and I'm sorry I did because the dust really began to bother me. It bothered my eyes, it bothered by throat, and I was tasting it and eating it and I really could feel it working back and forth between the tunnel and the LM. Ron, did you feel any effects of the dust when we docked and rendezvoused, particularly?"* [11]

Evans answers, *"Only when I stuck my head in the LM. When I climbed up in the tunnel I could definitely tell there was a lot of dust up in the LM and you could smell it. It's a difference, so I think you noticed it from that standpoint, but there never really was dust in the command module. The only time you ever got any dirt in the command module was when you touched something that had dirt on it. But as far as floating around in the command module – I don't think it ever did."* [11]

Schmitt said, *"Eye irritation during photos – I did not notice any. Helmet visor reflections I guess have been very well covered. With the dust and scratches on the helmet, of course, you needed to shade the helmet more and more in order to see with the Sun directly on the helmet."* [11]

Schmitt added, *"Dust – We'll just talk about in-cabin dust. After the first EVA, there was considerable dust in the cabin. It would be stirred up by movements of the suit and the gear that we had. Almost immediately upon removing my helmet, I started to pick up the symptoms that you might associate with hay fever symptoms. I never had runny eyes or runny nose. It was merely a stuffiness in the nose and maybe in the frontal sinuses that affected my speech and my respiration considerably. After about 2 hours within the cabin, those symptoms gradually disappeared. By morning of the next day, they were gone completely. After the second and third EVAs, although I'm sure the dust was comparable, the symptoms were not nearly as strong as after the first EVA. That was as if I either developed a mucous protection of the affected areas or had some way or another very quickly developed an immunity to the effects of the dust."* [11]

Future Work

The Lunar Dust Working Group should include toxicologists and physicians to ensure human exposure standards are included in dust management strategies and engineering and operational design.

HYGIENE

This section is included as information to provide insight into personal cleaning for technology and operations designers and developers.

Observations

Conrad speaks of cleaning, *"The potable water was used for personal hygiene, and I'd also like to have some soap along for personal hygiene and just to get clean after lunar surface operation – just to get the dirt off. That's another reason we wanted more towels. We all stripped down all the way and washed down with the water and our towels several times during the flight."*[2]

Young explained, *"Potable water Used for personal hygiene. We'd get the towels and wipe up. But that sure is not the way to get clean. All that does is smear the dirt around."* [8]

Cernan, during the Apollo 17 Technical Debrief said, *"If Jack and I had one request, it would be to carry one more CWG for cleanliness. Particularly when you come back from the LM as dirty as you are, we could have used one more CWG throughout the entire flight."* [11]

Cernan said, *"After rendezvous and docking – After the CDR and LMP had been living with this dust for 3 days on the lunar surface, there was a compelling urge on both of our parts to get clean. We spent about 2 or 3 hours prior to going to bed doing nothing by effectively taking soap and water and trying to wash as much of our body as we could to get free from what is really sort of a dirty feeling due to the dust. Even with soap and water it was sometimes very difficult to get clean, and the dust would get under your fingernails and other places on your body."* [11]

CONCLUSION

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.

> *"Dust – I think probably the most aggravating, restricting facets of lunar surface explorations 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 effects 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 al 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, camera, 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."*

Gene Cernan
Apollo 17 Technical Debrief

REFERENCES

1. Manned Space Center, “Apollo 11 Mission report.” NASA MSC-00171, Houston, Texas, November 1969.

2. Manned Space Center, “Apollo 12 Mission report.” NASA MSC-01855, Houston, Texas, March 1970.

3. Manned Space Center, “Apollo 12 Technical Debrief.” NASA, December 1969.

4. Manned Space Center, “Apollo 14 Technical Debrief.” NASA, February 1971.

5. Manned Space Center, “Apollo 14 Mission report.” NASA MSC-4112, May 1971.

6. Manned Space Center, “Apollo 15 Technical Debrief.” NASA MSC-4561, May 1971.

7. Manned Space Center, “Apollo 15 Mission report.” NASA MSC-5161, December 1971.

8. Manned Space Center, “Apollo 16 Technical Debrief.” NASA MSC-4561, August 1971.

9. Manned Space Center, “Apollo 16 Mission report.” NASA MSC-7230, August 1972.

10. Manned Space Center, “Apollo 17 Mission report.” NASA MSC-7904, March 1973.

11. Manned Space Center, “Apollo 17 Technical Debrief.” NASA MSC-7631, January 1973.

12. Manned Space Center, “Apollo 12 Preliminary Science report.” NASA SP-235, 1970.