

Lunar Dust Mitigation Technology Development

Mark J. Hyatt¹ and John Feighery²

¹*NASA John H. Glenn Research Center at Lewis Field, Cleveland, OH, 44135, USA*

²*NASA Lyndon B. Johnson Space Center, Houston, TX, 77058, USA*

Abstract

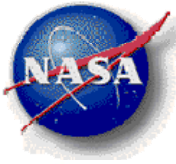
NASA's plans for implementing the Vision for Space Exploration include returning to the moon as a stepping stone for further exploration of Mars, and beyond. Dust on the lunar surface has a ubiquitous presence which must be explicitly addressed during upcoming human lunar exploration missions. While the operational challenges attributable to dust during the Apollo missions did not prove critical, the comparatively long duration of impending missions presents a different challenge. Near term plans to revisit the moon places a primary emphasis on characterization and mitigation of lunar dust. Comprised of regolith particles ranging in size from tens of nanometers to microns, lunar dust is a manifestation of the complex interaction of the lunar soil with multiple mechanical, electrical, and gravitational effects. The environmental and anthropogenic factors effecting the perturbation, transport, and deposition of lunar dust must be studied in order to mitigate it's potentially harmful effects on exploration systems. This paper presents the current perspective and implementation of dust knowledge management and integration, and mitigation technology development activities within NASA's Exploration Technology Development Program. This work is presented within the context of the Constellation Program's Integrated Lunar Dust Management Strategy. The Lunar Dust Mitigation Technology Development project has been implemented within the ETDP. Project scope and plans will be presented, along with a perspective on lessons learned from Apollo and forensics engineering studies of Apollo hardware. This paper further outlines the scientific basis for lunar dust behavior, it's characteristics and potential effects, and surveys several potential strategies for its control and mitigation both for lunar surface operations and within the working volumes of a lunar outpost.

Lunar Dust Mitigation - Technology Development

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Space Technology and Applications International Forum**

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*Mark Hyatt, Project Manager, NASA GRC
Paul Deluane, Deputy Project Manager, NASA JSC*



Outline

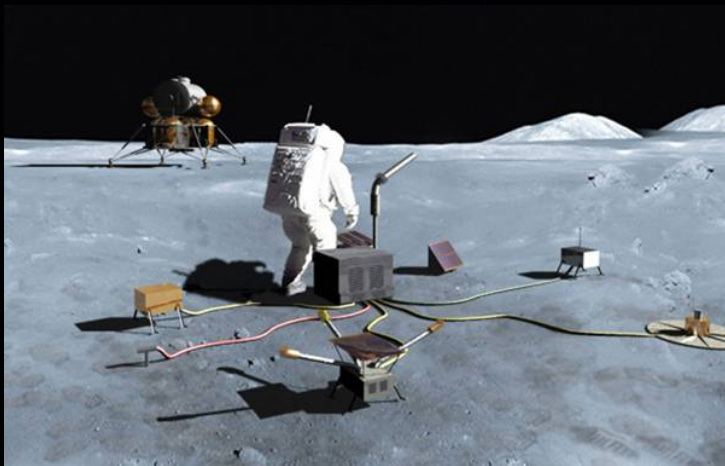
- Framework for Lunar Exploration
- Definitions
- Regolith Management Strategy
 - Technology impact - Performance benefit
 - Project Objectives
- Dust Management Project
 - Engineering Design Environments
 - Regolith/Environment Characterization
 - Simulant Definition, Requirements, and Characterization
 - Apollo Engineering Forensics
 - Technology Development
 - Mechanical Components
 - Materials and Coatings
 - Habitat/Airlock
 - Surface Systems
- Summary
- Acknowledgments

Space Exploration Direction, Authorized by Congress

- Complete the International Space Station
- Safely fly the Space Shuttle until 2010
- Develop and fly the Crew Exploration Vehicle no later than 2014
- Return to the Moon no later than 2020
- Extend human presence across the solar system and beyond
- Implement a sustained and affordable human and robotic program
- Develop supporting innovative technologies, knowledge, and infrastructures
- Promote international and commercial participation in exploration

NASA Authorization Act of 2005

The Administrator shall establish a program to develop a sustained human presence on the Moon, including a robust precursor program to promote exploration, science, commerce and U.S. preeminence in space, and as a stepping stone to future exploration of Mars and other destinations.



Framework for Lunar Exploration

To Achieve

Successful & Safe

Extended Missions & Outpost

Requires

Knowledge of Lunar Environment

Involves

- ✓ Understanding Properties & Processes
 - **Regolith Soil and Dust**, plasma, radiation, meteorites, vacuum, gravity, thermal, etc.
- ✓ Measurements on & near the Moon
- ✓ Evaluation of Returned Samples

Enables

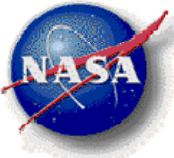
Risk Mitigation

Through

- ✓ Earth-based Testing, Verification & Validation
 - Simulation of environment (**Regolith Soil and Dust**, plasma, radiation, vacuum, thermal, etc.)
- ✓ Lunar-based testing

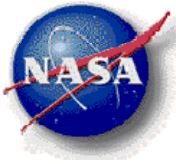
For

- ✓ **Humans**
- ✓ **Hardware**
- ✓ **Instruments**



Useful Definitions

- **Regolith**: General term for the mantle of loose, incoherent, or unconsolidated rock material, of whatever origin, size or character, that nearly everywhere forms the surface of rocky planetary bodies
 - Definition adapted from the Glossary of Geology, 1972
 - Most lunar regolith is formed by hypervelocity impacts
 - Lunar regolith is spatially very heterogeneous in composition and particle size distribution compared to terrestrial regolith
- **Dust**: An informal term - regulatory definitions for “dust” related health concerns set for particle sizes smaller than 10 μ m & 2.5 μ m
- **Lunar Dust**: Particles of Lunar Regolith \leq 20 μ m in size
 - Convention informally adopted at a NESC Lunar Dust Workshop at Ames Research Center, Jan 2007
 - The departure from American regulatory definitions in part reflects the lower surface gravity of the Moon.
 - Pending revision per NEDD (Natural Environments Definition Document)
- **Lunar Regolith Simulant**: Synthetic analogue that approximates, to a known extent, one or more regolith properties at a particular lunar location or region
- **Lunar Dust Simulant**: A regolith simulant where virtually all particles are less than 20 μ m in size



Dust Mitigation Technology Impact - Performance Benefit

Prior experiences from Apollo and other lunar explorations provide a significant list of dust-related problems

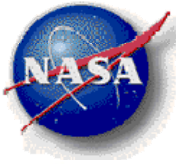
Lunar Regolith Posed Many Operational Challenges *

- Surface obscuration during lunar module descent
- Dust Coating and Contamination
 - Anthropogenic sources
 - Surface Systems Effects
 - Lunar Rover
 - » Thermal control
 - EVA Suits and Mechanisms
 - » Abrasion and wear
 - » Seals
- Crew efficiency
 - Maintenance and cleaning
- Human Exposure
 - Inhalation and irritation



*Sources -

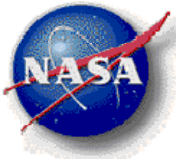
Gaier, J.R., NASA/TM-2005-213610-REV1,
Wagner, S.A., NASA/TP-2006-231053



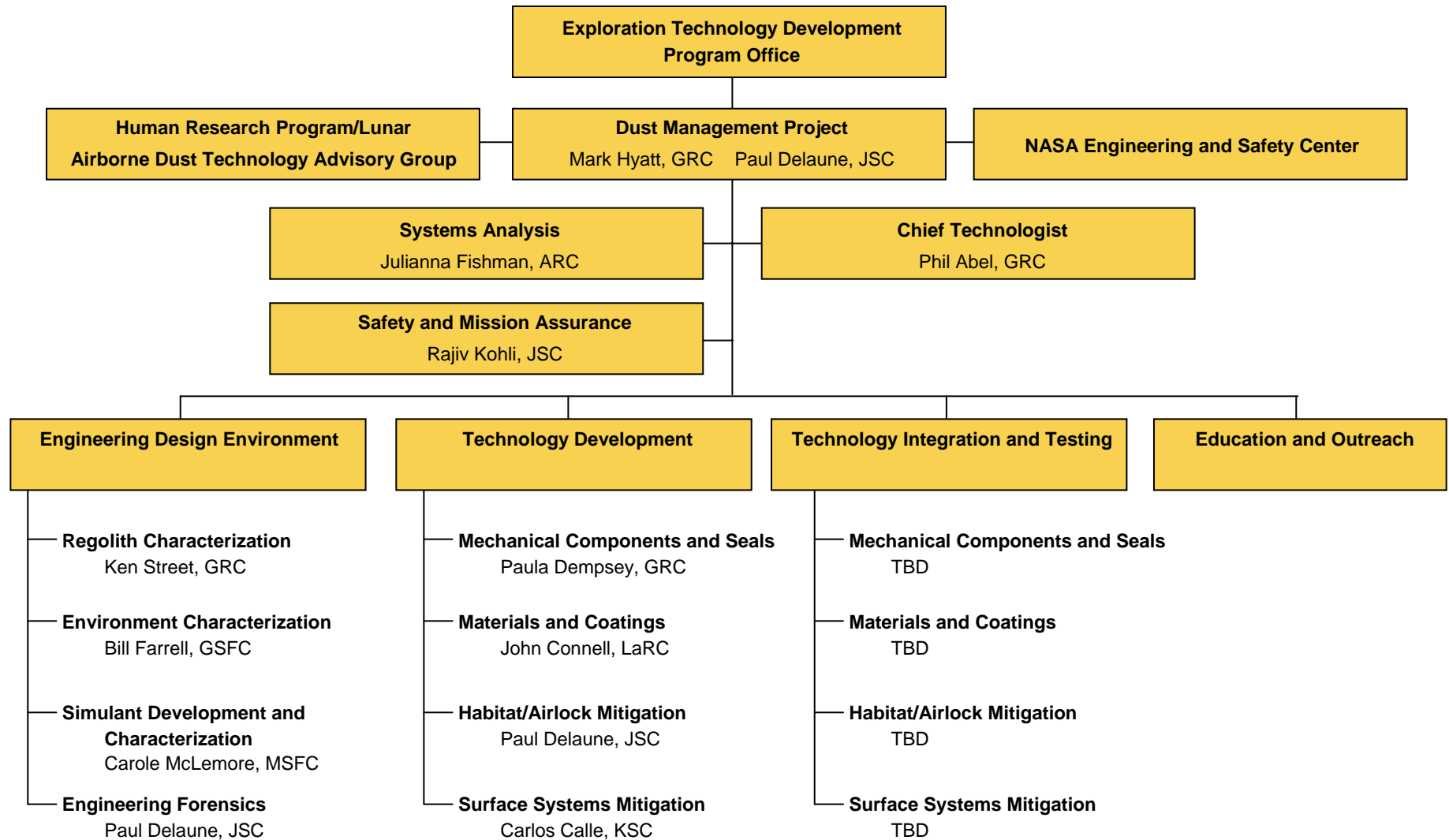
Dust Mitigation Technology Development **Objectives**

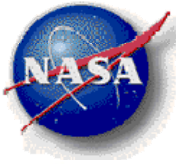
Hence, specific project objectives for the DMP include:

- **Provide knowledge and technologies (to TRL-6 development level) required to address adverse dust effects to humans and to exploration systems and equipment, which will reduce life cycle cost and risk, and will increase the probability of sustainable and successful lunar missions.**
- **Provide coordination across ESMD of lunar dust related activities and information to maximize benefit from Agency investments.**
- **Develop a balance of near- and long-term knowledge and technology development, driven by ESMD needs and schedule requirements, aligned with available technology investments where possible.**
- **Leverage existing Agency capabilities, resources, and invest prudently in to support develop capabilities, as appropriate, where there are gaps.**

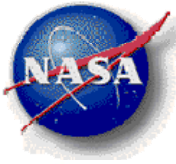


Dust Management Project Team Structure





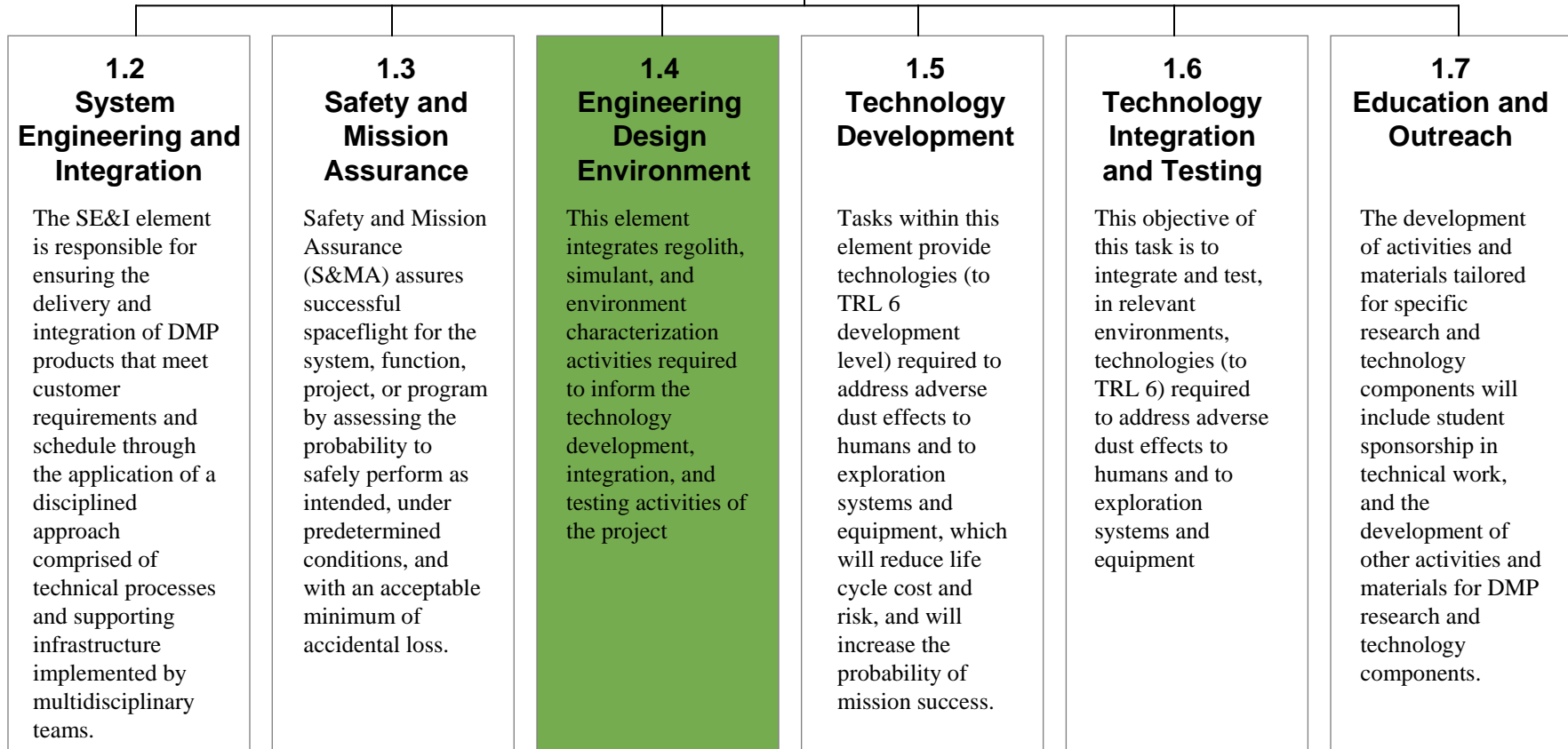
Dust Mitigation Project Technical Content

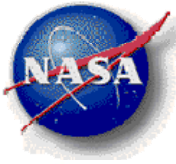


DMP WBS and Objectives

1.1
Dust Management Project

Dust project management will direct, control, maintain, coordinate, and evaluate NASA lunar dust mitigation activities.





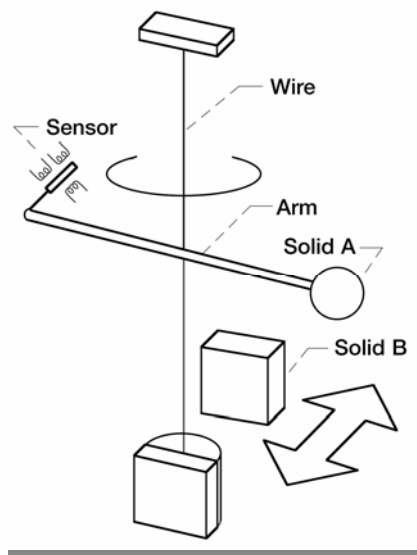
WBS 1.4.1—Lunar Regolith Characterization

WBS 1.4.1 Lunar Regolith Characterization (GRC/ARC)

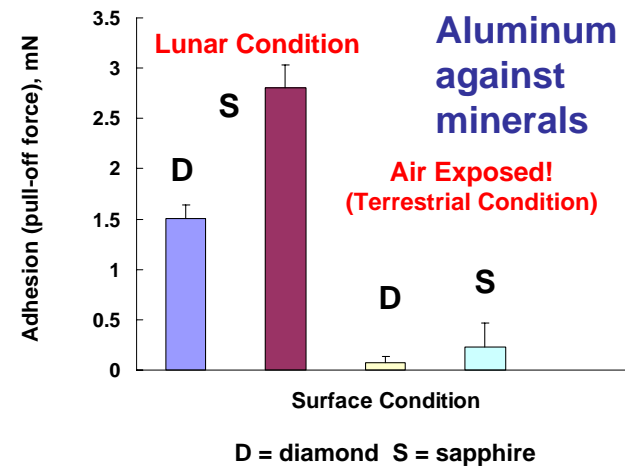
Characterization of physical properties of regolith relevant to dust mitigation and to compare to proposed simulants.

Assist in developing suitable simulant standards or correction factors for use of simulants

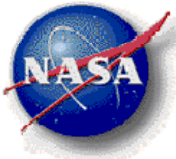
WBS 1.4.1 Adhesion Rig



WBS 1.4.1 Adhesion Results*



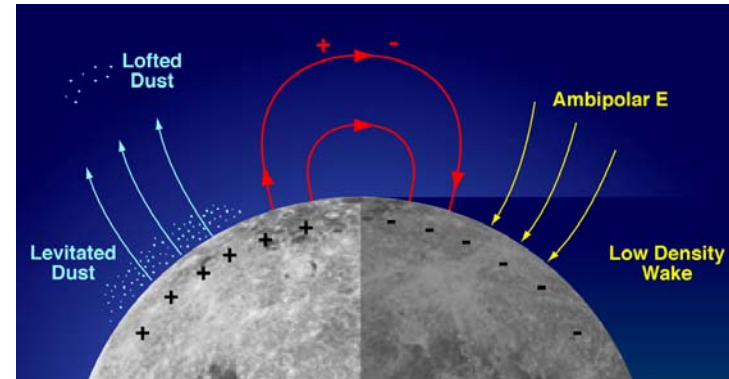
*K. Miyoshi, GRC, submitted for publication



WBS 1.4.2 Environmental Characterization

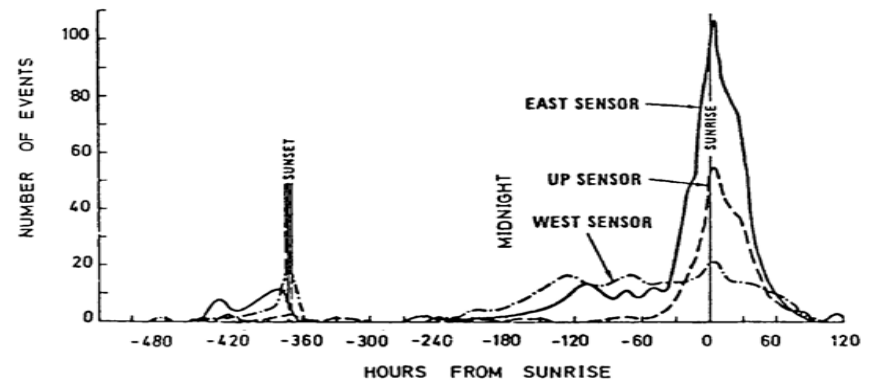
WBS 1.4.2.1 Environmental Characterization (W. Farrell/GSFC)

- **Model development, validation, and dissemination**
 - Surface model/Shackleton region
 - Triboelectrification/charge dissipation
 - Solar storm affects at poles
 - Detail tribocharging/dust current

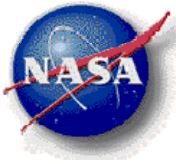


WBS 1.4.2.2 Development of Best Practices (A. Chait/GRC)

- **Model development, application, and practices**
 - Grain model
 - Reduced models for CxP Client analysis
 - Best practices for System Design



Accelerated dust impacts detected by Apollo 17 surface package (from Berg *et al.*, 1976).



WBS 1.4.3—Simulant Development and Characterization

WBS 1.4.3.1 Collect and Assimilate Users' Needs and Provide Consultation (MSFC)

- Establish/define Lunar Dust properties essential to simulant users

WBS 1.4.3.2 Collect and Assimilate Apollo Samples Properties Data (JSC/MSFC)

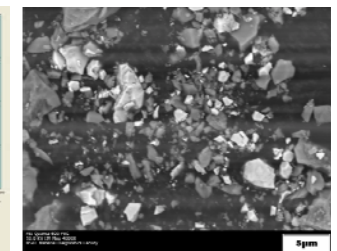
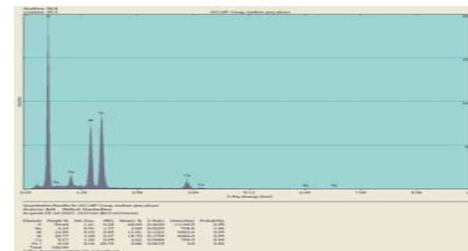
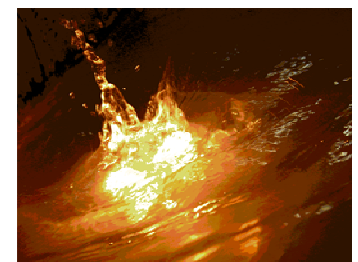
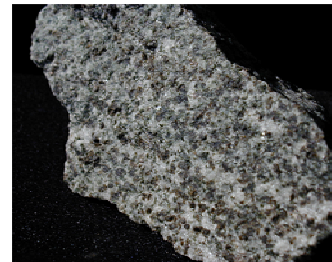
- Establish/define Apollo Lunar Dust properties essential for developing high fidelity dust simulants

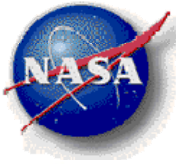
WBS 1.4.3.3 Characterize/Evaluate Simulants (MSFC/GRC/KSC)

- Test simulants and document relevant properties resulting in grades/ratings for “fit and purpose” of simulant use

WBS 1.4.3.4 Develop High Fidelity Dust Simulants (MSFC)

- Develop and produce new dust simulants to meet users' needs (funding dependent)





WBS 1.4.4—Engineering Forensics

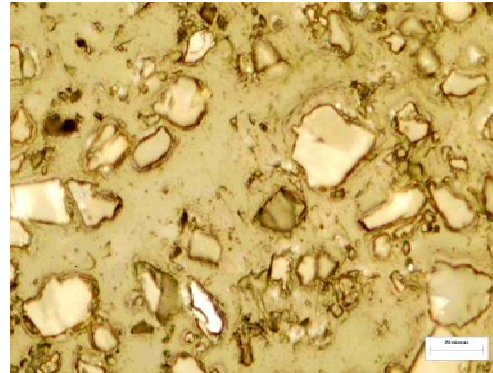
Objective

To obtain useful data on the effects of lunar dust exposure on Apollo equipment and space suits

- Results will be used to guide dust mitigation technology development and to help develop models for the effects of dust exposure on materials and systems

Approach

- Examination of spacesuits at the Smithsonian Institution by XRF and tape peels to reveal trapped dust
- Inspection of LiOH cartridge filters
- Disassembly and Inspection of IVA/EVA glove seal bearings and races
- Chemical analysis of polymer degradation in suit materials
- Direct SEM imaging of exposed surfaces of an EVA glove



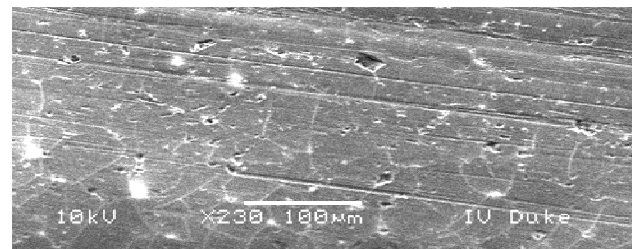
Optical Micrograph of lunar dust vacuumed from Apollo suit.



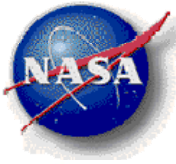
Initial visit to Smithsonian to evaluate condition of artifacts, such as the Apollo 17 suit shown above.



Electron micrographs showing damage to the outer layer of Alan Bean's Apollo 12 suit.



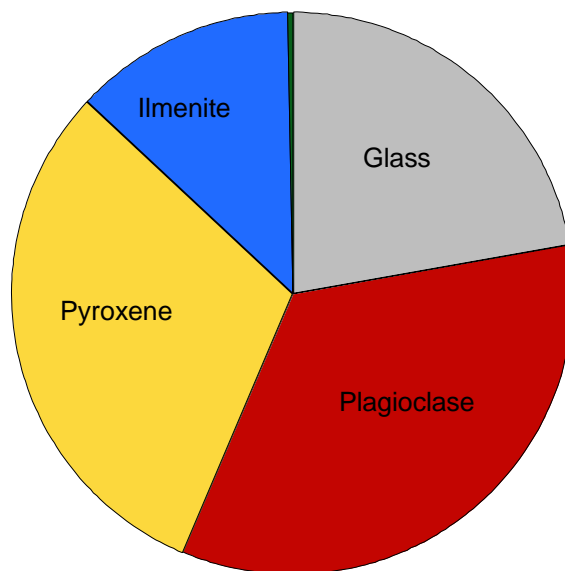
SEM image of inner bearing race from Apollo 12 IVA glove (not lunar exposed control case).



WBS 1.4.4—Engineering Forensics

Mineralogy of Suit Tape Peel Samples

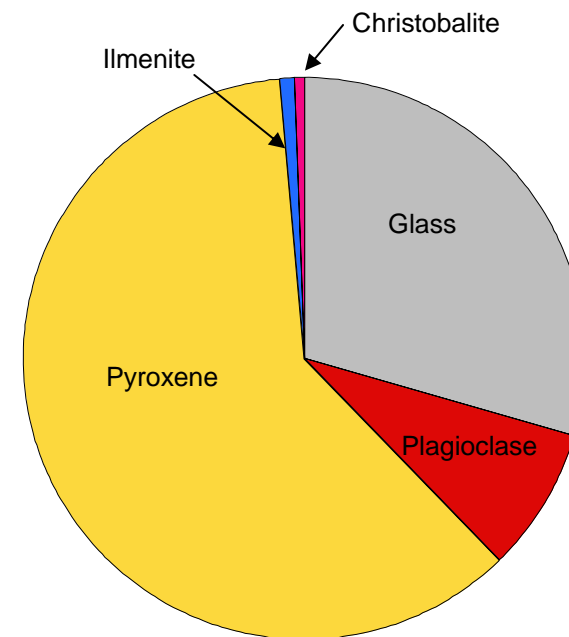
Typical Apollo 17 Soil %Volume



Breakdown by percent volume of lunar grain types for grain sizes between 20 to 90 microns from Apollo 17 (Mare soils 72501, 76501, and 78221).*

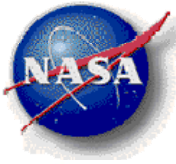
*Papike et. al. 1982

Tape Peel Calculated %Volume



Breakdown by percent volume for each lunar grain type calculated from the tape peels for sizes greater than 2 microns.**

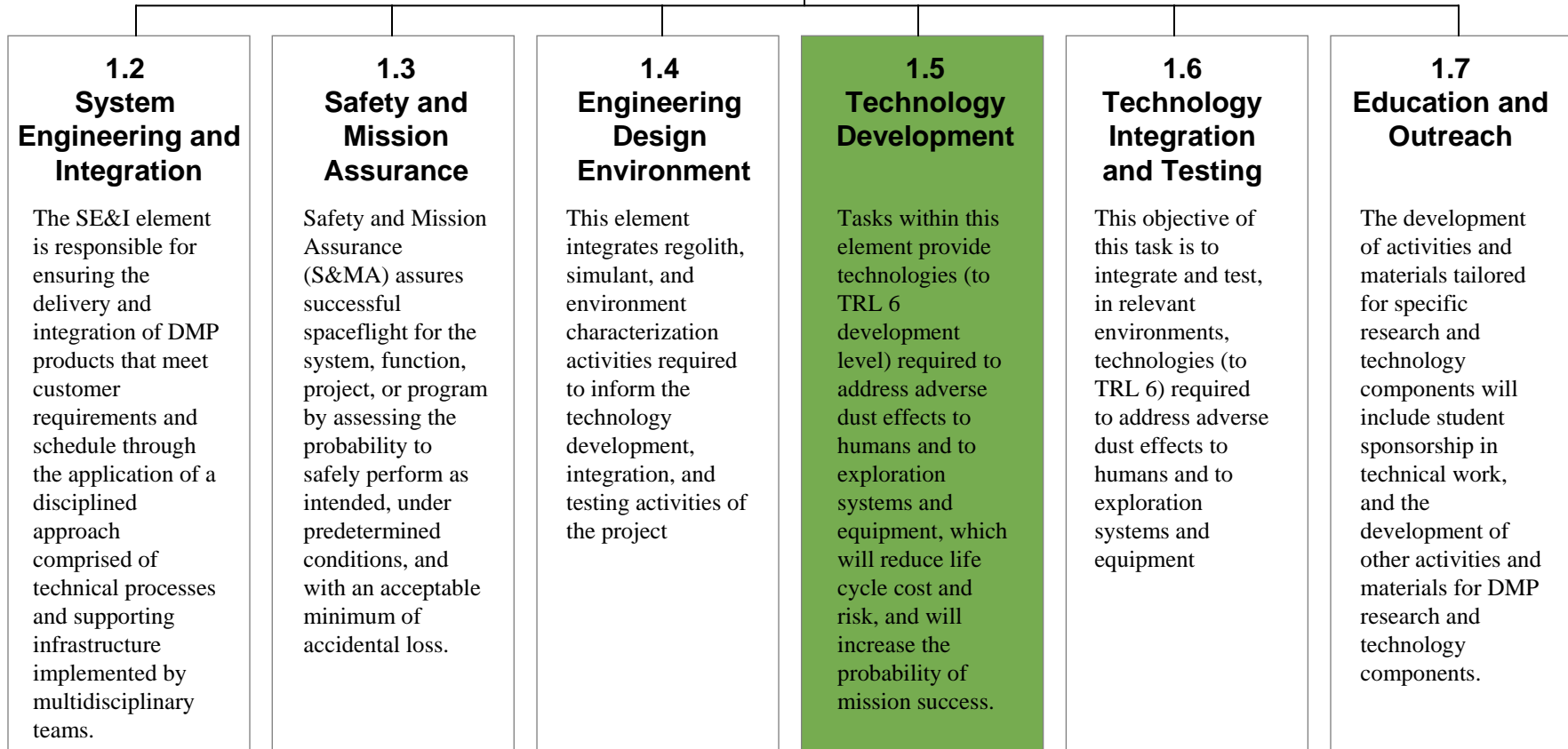
**J. Anneliese Lawrence, Marshall University
John F. Lindsay, Lunar and Planetary Institute
Sarah K. Noble, NASA-JSC

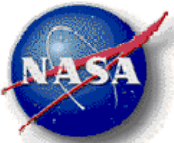


DMP WBS and Objectives

1.1
Dust Management Project

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WBS 1.5.1—Mechanical Components and Mechanisms

WBS 1.5.1.1 Dust Contamination Investigations (GRC/JPL/MSFC)

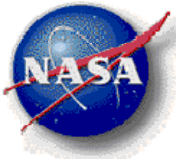
- **Conduct endurance tests on mechanism and drive system components with various levels of dust contamination**



WBS 1.5.1.2 Dust Mitigation Technologies (JPL/GRC/MSFC)

- **Develop and test technologies to stop dust contamination, or mitigate its effects**

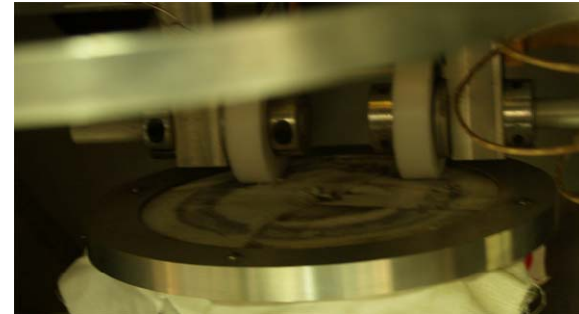




WBS 1.5.2—Materials and Coatings

1.5.2.1 EVA Suit Materials (GRC/GSFC/LARC)

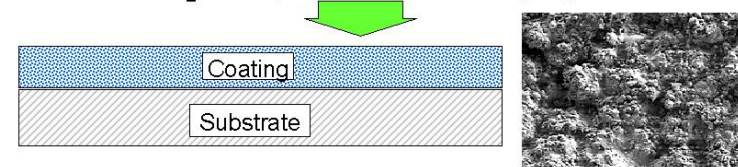
- **Develop testing protocol for dust and abrasion resistance of EVA suit materials**
- **Recommend further technology development needs for suit materials**



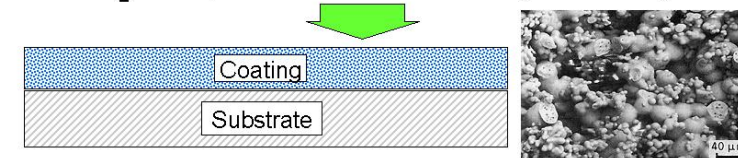
1.5.2.2 Lotus Coatings (GSFC/LARC)

- **Development, Testing and Evaluation of Advanced Nano-structured Material Coatings**

Anatase TiO₂ Nanoparticles in Fluoropolymer Paint

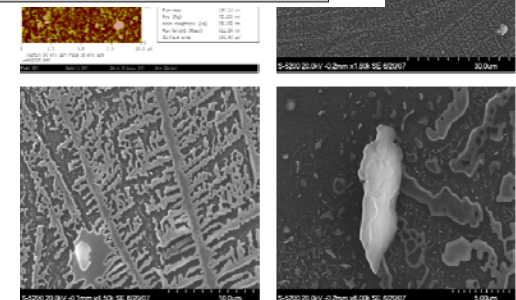


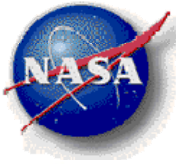
Anatase TiO₂ Nanoparticles in Ormosil Organic Composite



Decontaminating and self-cleaning in one coating

Material surface modification to minimize dust adhesion





WBS 1.5.3—Airlock and Habitat Dust Mitigation Systems

WBS 1.5.3.1 – CO₂ Shower (JPL)

- CO₂ Shower – Demonstrate Proof of Concept (08)
- Analyze concept and identify controlling parameters (08)
- Transfer concept to vendor for fabrication (09)
- Fabricate CO₂ shower prototype system (10)

WBS 1.5.3.2 – Ionic Sweeper Project (GSFC)

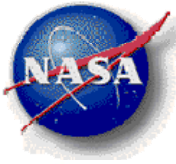
- Ionic Sweeper lab scale proof of concept (TRL 3) (09)
- Ionic Sweeper components demonstration (TRL 5) (11)
- Ionic Sweeper Prototype (TRL 6) (13)

WBS 1.5.3.3 – *Dust Mitigation Industry Solicitation (JSC)*

- *Prepare Industry Solicitation for Dust Removal Technology (09)*
- *Award Industry Solicitation for Dust Removal Technology (13)*

WBS 1.5.3.4 – *Electrostatic/magnetic Cleaning Wand (JSC)*

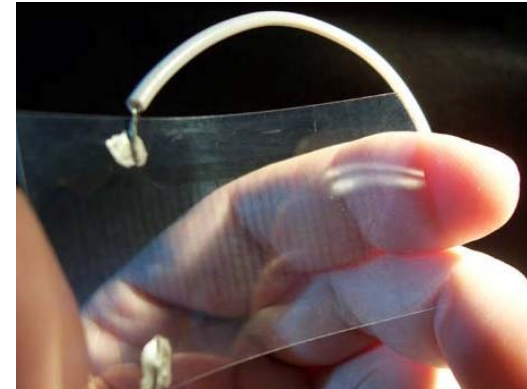
- *Electrostatic/magnetic cleaning wand trade study (10)*
- *Cleaning wand proof of concept in lab (TRL 3) (12)*
- *Cleaning wand system test in relevant environment (TRL 6) (13)*



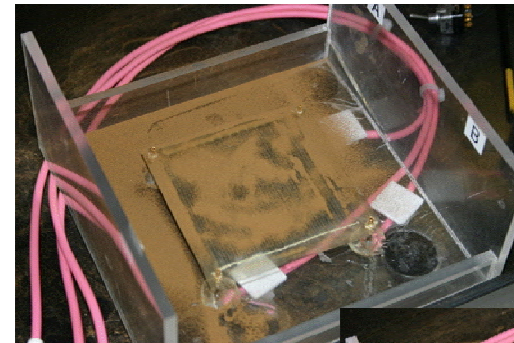
WBS 1.5.4—Surface Systems Dust Mitigation

WBS 1.5.4.1 Electrostatic Curtain (KSC/LaRC)

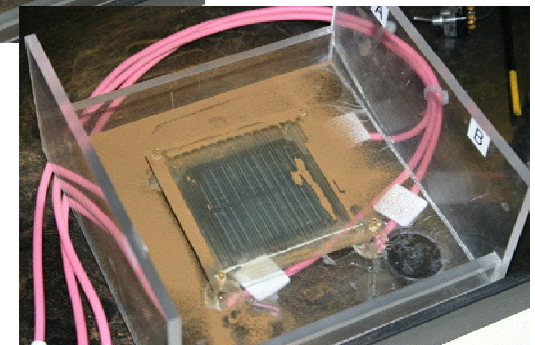
- Develop electrodynamic dust shield to minimize dust accumulation on external surfaces exposed to the lunar environment.
- Investigate the feasibility of application of the electrodynamic dust shield technology to
 - rigid, opaque, electrically conducting surfaces
 - flexible, opaque, electrically insulating surfaces.
- Advanced materials for the electrodynamic dust shield will be identified, designed, synthesized, and tested with the specific combination of physical, mechanical, and electrical properties, and lunar environmental durability.

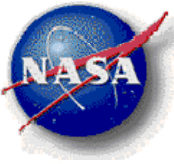


Transparent electrodes on flexible PET (Electrode pattern does not obscure views through the material)



Transparent electrodes on flexible PET over solar panel (before and after activation)

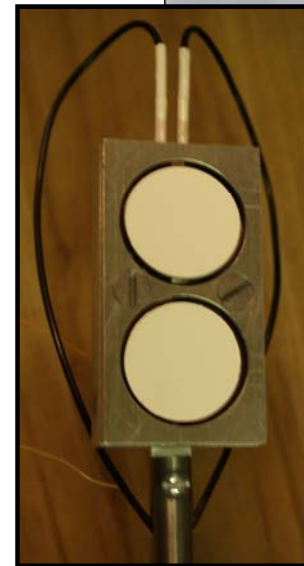
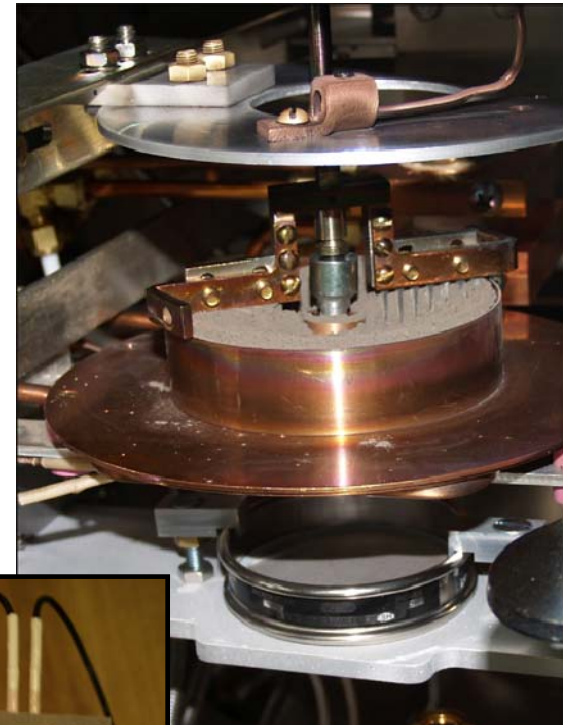




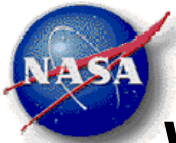
WBS 1.5.4—Surface Systems Dust Mitigation

WBS 1.5.4.2 Mitigation for Radiators (GRC)

- **Determine the extent of degradation of thermal control surfaces for LSAM and Outpost components by lunar dust, and to determine ways to effectively mitigate that degradation.**
 - **Determine the effect of simulated lunar dust on the thermal properties of thermal control surfaces** on aluminum and composite substrates—FY08
 - **Determine the effect of textured thermal control surfaces on the adhesion of simulated lunar dust** in a simulated lunar environment
 - **Determine the effect of workfunction of thermal control surfaces on the adhesion of simulated lunar dust** in a simulated lunar environment
 - **Determine the effect of simulant properties on their adhesion to thermal control surfaces** in a simulated lunar environment
 - **Determine the effect of lunar regolith dust on its adhesion to optimized thermal control surfaces** in a simulated lunar environment



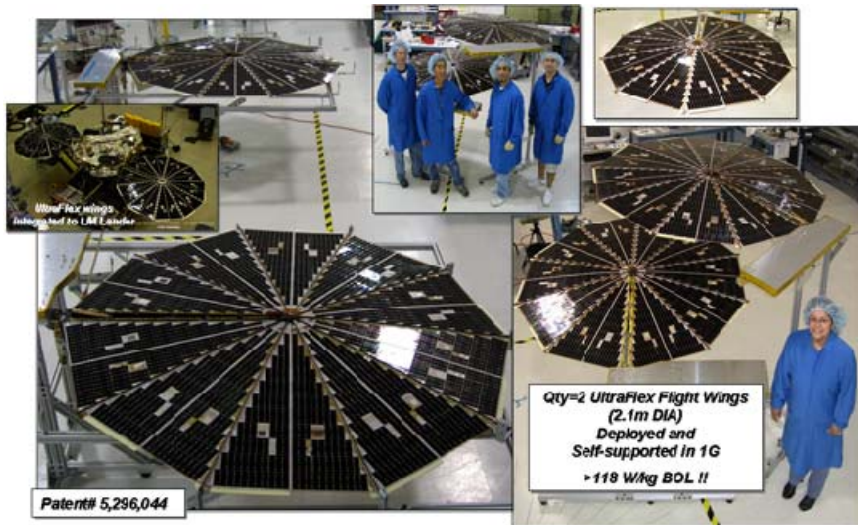
Lunar Dust Adhesion BellJar



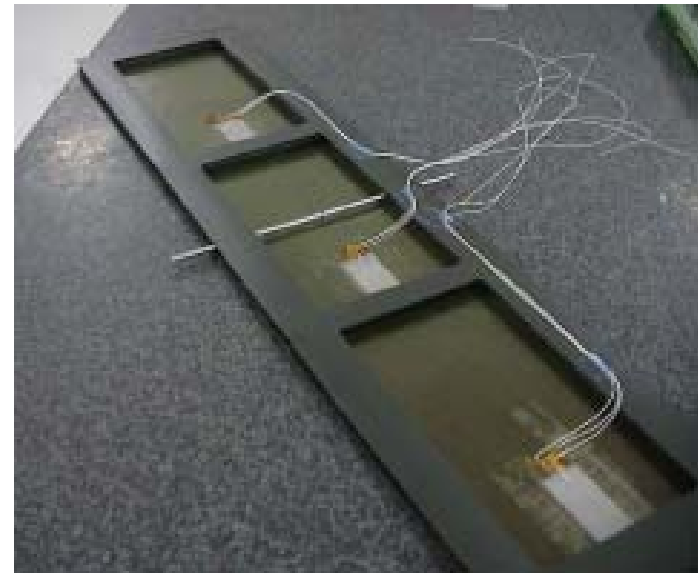
WBS 1.5.4—Surface Systems Dust Mitigation

WBS 1.5.4.3 Self Cleaning PV Array (JPL)

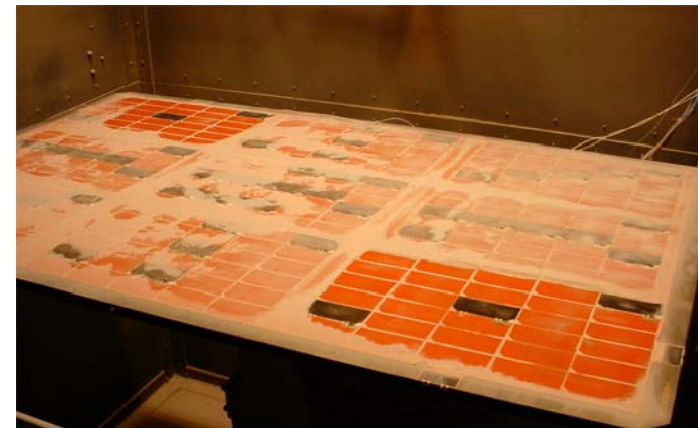
- Development of a cleaning system that removes deposited dust from the surface of the solar array.
 - Perform **UltraFlex dynamic FEA modeling**
 - Retrofit a prototype UltraFlex wing with new **SADRS system** and test



ATK UltraFlex Flight Arrays



1X3 Ridge Panel with Piezoelectric devices

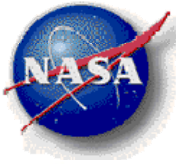


3X3 Ridge Panel with 9 Piezoelectric devices on back and solar cell on front. Two areas on the panel have been clean to 90% recovery



Summary

- US Space Exploration Policy, and plans to resume human missions, of extended duration, to the moon require a strategic approach to management of lunar regolith
- Layered engineering solutions, based on improved understanding of the integrated lunar environment, can allow safe and sustainable mission operations
- The ETDP Dust Project will provide improved understanding of relevant lunar environment characteristics, and develop mitigation technologies required to address gaps in current capabilities



Acknowledgments

- The presenter wishes to recognize the many contributors to this work and the Dust Mitigation Technology Development Project -
- At JSC
 - Paul Delaune, Sarah Noble, Roy Christofferson, John Lindsay, and John Feighery (now at Columbia U.)
- At MSFC
 - Carole Mclemore, John Fikes, and Doug Rickman
- At GRC
 - Phil Abel, Mary Ann Meador, Ken Street, Jim Gaier, Arnon Chait, and Paul Greenberg
- At GSFC
 - Wanda Peters, Sharon Straka, Steve Curtis, and Bill Farrell
- At KSC
 - Carlos Calle, Nancy Zeitlin
- At ARC
 - Julianna Fishman, Tim Snyder, Farid Salama
- At JPL
 - Nick Mardesich, Greg Peters, and Bob Easter
- At LaRC
 - John Connell