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The Dust Management Project: Final Report

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December 2011

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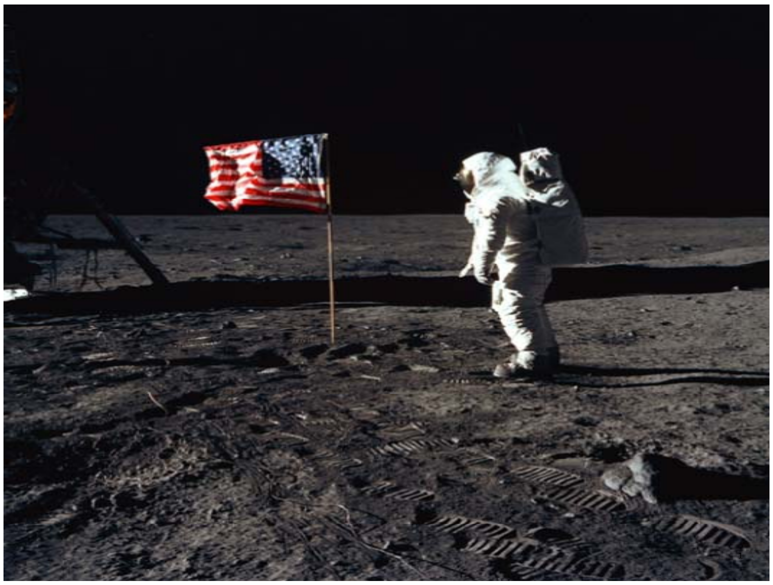
Abstract

A return to the Moon to extend human presence, pursue scientific activities, use the Moon to prepare for future human missions to Mars, and expand Earth's economic sphere, will require investment in developing new technologies and capabilities to achieve affordable and sustainable human exploration. From the operational experience gained and lessons learned during the Apollo missions, conducting long-term operations in the lunar environment will be a particular challenge, given the difficulties presented by the unique physical properties and other characteristics of lunar regolith, including dust. The Apollo missions and other lunar explorations have identified significant lunar dust-related problems that will challenge future mission success. 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 and human explorers. The Dust Management Project (DMP) was tasked with the evaluation of lunar dust effects, assessment of the resulting risks, and development of mitigation and management strategies and technologies related to Exploration Systems architectures. To this end, the DMP supported the overall goal of the Exploration Technology Development Program (ETDP) of addressing the relevant high priority technology needs of multiple elements within the Constellation Program (CxP) and sister ETDP projects. Project scope, approach, accomplishments, summary of deliverables, and lessons learned are presented.



DMP - Background

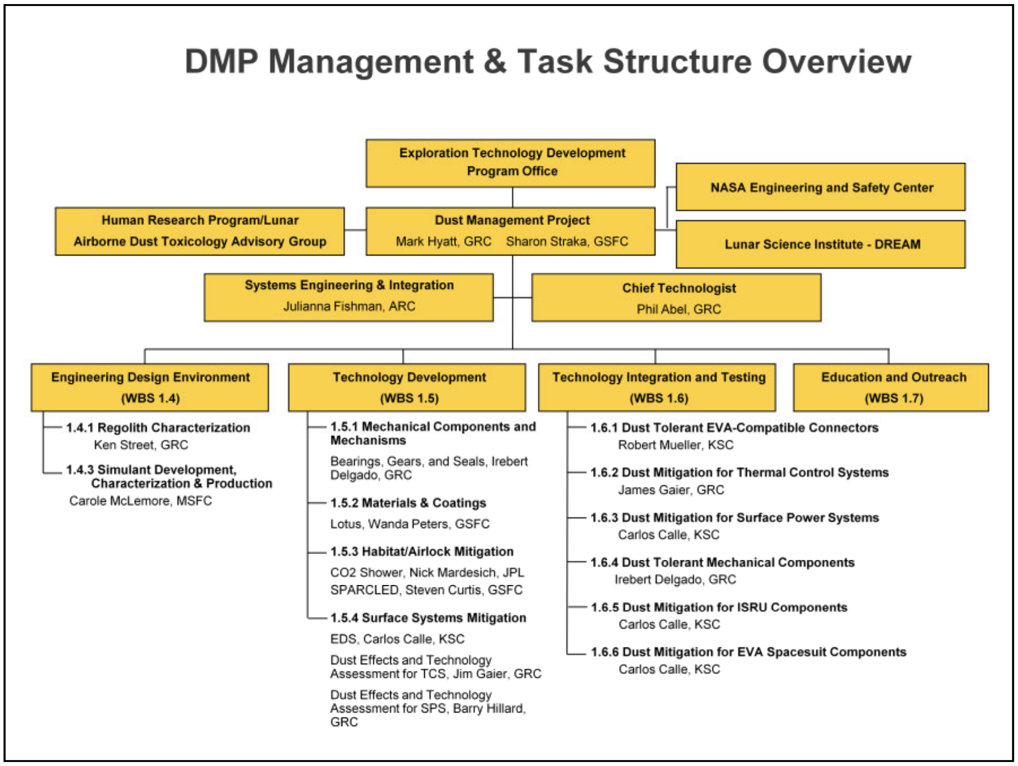
Lunar Regolith Management Technology and Capability Needs

- **Apollo experience and lessons earned applied to development of a Regolith Management Strategy**
- **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

* From Gaier, J.R., NASA T/M-2005-213610-REV1, and Wagner, S.A., NASA/TP-2006-231053

DMP - Specific Project Objectives

- Address high priority technology needs, customer and derived requirements.
- Provide knowledge and technologies (to Technology Readiness Level-6 (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 to support the development of capabilities, as appropriate, where there are gaps.
- Based on the user's needs, develop appropriate, affordable, and timely soil simulants for NASA's Exploration Program to use in risk reduction.



The Dust Management Project (DMP) was structured to address cross-cutting agency needs, and to pursue multiple mitigation strategies in parallel and at different levels. The Work Breakdown Structure (WBS) of the project reflects this multiprong approach.

In this document following are descriptions of the various WBS elements, grouped by type in accord with the WBS structure. At the highest level, WBS element 1.2, the Systems Engineering & Integration activity was used to help manage the overall project portfolio. The technical approaches pursued within the DMP then were broadly grouped within the following three WBS elements.

Basic technology assessment of feasibility activities, typically working at an earlier Technology Readiness Level (TRL), fall under the 1.5 WBS element ("Technology Development Areas"). These efforts range from surface modification to dirt removal techniques, and include generic mechanical component evaluation to understand how mechanisms are affected in the presence of particulates.

Technology integration into example systems, typically at a mid-TRL, was grouped under the 1.6 WBS element ("Technology Focus Areas"). With specific applications targeted, both dust mitigation and dust tolerance technologies fall within this WBS element.

In order to assess technologies' tolerance for or effect upon dust and larger particulates, reasonable simulants of (lunar) regolith are needed. Under the 1.4 WBS element were grouped both the characterization of regolith and the study of simulants for comparison ("Simulants"). Indeed, even the very basis for comparison of simulant to regolith had to be developed, dependent on the type of testing pursued.

This document then concludes with some words on lessons learned and project transition comments.

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POC: Julianna Fishman **WBS: 1.2**

Element Description:

The DMP approach to technology portfolio management includes a broad and inclusive assessment to:

1)Baseline traceability mapping of the DMP portfolio to approved level 1 & 2 requirements and capability needs,
2)Ensure that specific DMP technology development tasks and application areas map to relevant TPP needs,
3)Establish a mechanism to assess the performance of DMP technologies and mitigation strategies at certain stages in their development,
4)Review the technology development efforts of other entities to identify synergies and to avoid duplication of effort,
5)Prepare for insertion of DMP technologies into customer programs / systems 6 months prior to the customer Preliminary Design Review (PDR).

Future Applicability:

All processes developed and/or utilized by the DMP SE&I are applicable to many programs and projects regardless of technical scope. These processes and mechanisms include:

Traceability Mapping
- Level 1 & 2 Requirements/Needs
- CxP Technology Prioritization Process – DMP Task Alignment

Assessments and Mechanisms
- Technology Assessment / Gap Analysis
- Request for Information
- Technical Exchange Meeting
- Implementation

Decision Gate Process
Technology Insertion / Infusion Process (in development)
CxP Lunar Regolith Community of Practice

Element Overview

The Systems Engineering and Integration (SE&I) element of the DMP is responsible for performing portfolio assessments, developing and implementing processes to ensure the delivery and integration of DMP products that meet customer requirements and schedule. The development and application of this disciplined approach comprised of technical processes and supporting infrastructure, is implemented by multidisciplinary teams consisting of DMP developers, customers, and external subject matter experts. This overall approach to technology portfolio management includes the following primary objectives: 1) Baseline traceability mapping of the DMP portfolio to approved level 1 & 2 requirements and capability needs; 2) Ensure that specific DMP technology development tasks and application areas map to relevant TPP needs; 3) Establish a mechanism to assess the performance of DMP technologies and mitigation strategies at certain stages in their development; 4) Review the technology development efforts of other entities to identify synergies and to avoid duplication of effort; and 5) Prepare DMP technology developers and CxP customers for insertion of DMP technologies into customer programs / systems 6 months prior to the customer Preliminary Design Review (PDR).

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Summary of Accomplishments FY08 – FY10:

- **Traceability Mapping**
  - Ensured traceability of DMP tasks to Level 1 & 2 requirements and to CxP Technology Prioritization Process results
- **Assessments and Mechanisms**
  - Performed Technology Assessments / Gap Analyses - Assessed investments in relevant technology development efforts occurring in other NASA programs, other government agencies, academic and commercial sectors
  - Request for Information – Issued to solicit technologies and systems from commercial and other non-NASA organizations to address key technology focus areas for lunar dust mitigation
  - Performed a two-part facility assessment to 1) identify preliminary user needs and 2) facility availability and operational capabilities.
- **Decision Gate Process** – Developed and implemented a process that serves as an objective mechanism for evaluation of DMP Technology Development and Application Areas; offers frequent opportunity for timely go/no go decision; demonstrates maturity at identified points; and identifies the best performing, highest priority technologies.
- **CxP Lunar Regolith Community of Practice** – continued to support the LunRCoP as a virtual forum, providing opportunities for colleagues to learn from one another through the sharing of issues, lessons learned, problems/solutions, and other relevant aspects of dust management; well-organized infrastructure for active and passive knowledge exchange

Process Development and Implementation

The following processes were developed and/or implemented by the DMP SE&I to achieve the objectives of the project element as described above.

Traceability Mapping

Level 1 & 2 Requirements/Needs - Demonstrates traceability of the DMP portfolio to the Exploration Architecture Requirements Document (EARD) and Constellation Architecture Requirements Document (CARD).

Constellation Program (CxP) Technology Prioritization Process - Rationale statements indicate the specific capability/product offered by the DMP task to support the requirement and to indicate DMP task alignment.

Assessments and Mechanisms

Technology Assessment /Gap Analysis - Assess related technology development activities in other NASA programs, other Government agencies, and the commercial sector to eliminate unnecessary duplication of effort.

Request for Information - Leverage the expertise of non-NASA sectors to complement and/or supplement the current Exploration Technology Development Program (ETDP) technology development portfolio to ensure the most optimal solutions are deployed for dust mitigation within available funding profile.

Technical Exchange Meeting Implementation - Bridge CxP projects working to develop their dust mitigation capability needs and requirements with DMP SE&I and investigators to promote direct customer-developer interaction.

Decision Gate Process (DGP) – The DGP provides an objective mechanism for the evaluation of DMP Technology Development and Application Areas at Technology Readiness Levels (TRL) 3 through 6. The process offers frequent opportunities with multiple decision gates to weed-out non-performing technologies before too much is invested in them and while there is time to identify an alternate technology or deviation from an earlier development plan. The DGP also provides an opportunity for DMP investments to demonstrate maturity at identified points and on schedule to instill customer confidence that each DMP deliverable has met qualifying metrics each step of the way. The process also affords a mechanism to identify the best performing, highest customer priority technologies, so that in times of budget reduction, investments may be allocated appropriately to ensure the most chance of success for those technologies.

Technology Insertion / Infusion Process (TIP) – The TIP provides a step-wise process flow and accompanying documentation to support actual technology insertion of DMP technologies into customer systems. The process identifies insertion requirements from both developer and customer perspectives in preparation for insertion.

CxP Lunar Regolith Community of Practice (LunRCoP) – The LunRCoP promotes interaction of the CxP and DMP staff with other internal as well as external technology developers and researchers to share issues, solutions, and best practices from the perspective of a multi-disciplinary community focused on particle management.

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Remaining FY10 Content:

- Continue development of the Technology Insertion Process. Identify insertion requirements from both developer and customer perspectives.

- Report complete and located in windchill at:

  https://ice.exploration.nasa.gov/Windchill/netmarkets/jsp/folder/view.jsp?oid=folder~wt.folder.SubFolder%3A2061516197&u8=1

Report complete, loaded to windchill at:
https://ice.exploration.nasa.gov/Windchill/netmarkets/jsp/folder/view.jsp?oid=folder~wt.folder.SubFolder%3A2061516197&u8=1

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References and Major Deliverables

2008

- Catalog of Agency Investments in Research and Technology Development for Dust Mitigation
- Assessment of portfolio Alignment with Dust-Relevant Results of the Constellation Program Technology Prioritization Process
- Dust Management Project Task Traceability Map
- Cradle Schema and Initial Project Data
- Lunar Regolith Community of Practice Website: http://tia.arc.nasa.gov/lunrcop

2009

- Assessment of Testing Needs and Test Facilities for the Lunar Dust Management Project.
  - Part 1. Preliminary Needs and Facility Availability Overview
- Assessment of Testing Needs and Test Facilities for the Lunar Dust Management Project.
  - Part 2. Operational Capabilities of Enclosed Vacuum Facilities
- Plan for Assessment of the Test Facilities for the Lunar Dust Management Project.
  - Part 3. Operational Capabilities of External Analog Facilities (plan only)
- REQUEST FOR INFORMATION - NASA Lunar Dust Management Project Commercial Technologies for Mitigation of Lunar Dust

2010

- Decision Gate Process and Related Materials
- Decision Gate Process – CO_2 Shower TRL3 Review
- Technology Insertion Process (in development)

Summary of Major Deliverables

The SE&I contributed several major deliverables to the DMP over the course of the project in addition to the development and/or implementation of the processes described above. These contributions range in scope from internal reviews to surveys of both agency-wide dust efforts and similar activities being performed by those in related fields that may have applicability to NASA needs. A summary of major accomplishments is provided below.

Catalog of Agency Investments in Research and Technology Development for Dust Mitigation - This assessment reviewed internal Agency-wide dust-related activities. These agency efforts were captured under several categories to include: Programs, Working Groups, Workshops, and Studies; Research Projects; Technology Development Projects; and Facilities and Simulants. Past projects were captured in an Archive section.

Assessment of Portfolio Alignment with Dust-Relevant Results of the Constellation Program Technology Prioritization Process (TPP) - Each task within the DMP portfolio maps to one or more CxP TPP capability need items in the 2008-2009 time period. The DMP focused on dust-related needs that were ranked highest and that represent those closest to the focus of the current DMP portfolio and intended project scope. Several DMP WBS elements map to more than one TPP. As with the higher-level requirements, rationale statements describing how each DMP task maps to a particular TPP were captured.

Dust Management Project Task Traceability Map - The primary objectives of this effort were to (1) establish a baselined mapping of individual DMP tasks to requirements and capabilities as provided by the Exploration Systems Mission Directorate (ESMD) and the CxP, as well as the TPP, and (2) facilitate continuing capture of refined customer capability needs and requirements and maintain active mapping of DMP efforts. The following requirements document was released from this effort - DUST-REQ-0001.

Cradle Schema and Initial Project Data – Utilizing customer-defined CxP capability needs through review of the TPP results and CxP operational scenarios, developed CRADLE schema for the DMP to establish formal mapping of DMP research and technology portfolio to known CxP customer requirements. Schema for operational, interface, testing facility, and verification criteria were developed. DMP technology development portfolio data was entered to implement requirements traceability and tracking.

Lunar Regolith Community of Practice Website **http://tia.arc.nasa.gov/lunrcop** The LunRCoP is a virtual forum managed by the CxP and implemented by the DMP that provides a facilitated infrastructure to the community of engineers, scientists, and project managers focused on different aspects of fugitive particle management with the purpose of mitigating hardware degradation created by exposure to lunar regolith. The LunRCoP melds the knowledge of the research and scientific inquiry focused community with the community designing systems that tolerate dust in an effort to leverage the collective know-how.

The Lunar Dust Smart Buyer Clinic, June 26, 27, and 28, 2007. This workshop applied a hands-on approach to working through possible mitigation and cleaning options for affected components and systems to gain perspective on needs in terms of technology capability gaps, best practices, and design standards that will allow NASA to develop systems capable of continued operation in the lunar environment. A final report and supporting materials are available.

Lunar Regolith Industry Focus Group, August 13 and 14, 2007. In preparation for human exploration of the lunar surface, NASA is interested in obtaining information from industries that design equipment to operate in dusty environments. As successful surface exploration is dependent upon components and systems that reliably operate in the presence of lunar “soil,” NASA has particular interest in learning how other entities develop components and systems designed to work within a particle-fouled environment or that are involved in the clean-up and maintenance of internal environments or components and systems. A final report and supporting materials are available.

Lunar Regolith Behavior Workshop, August 12-14, 2008. To better understand the lunar regolith as a system of multiple particle sizes, NASA needs to determine what operations may elicit transport, redistribution, and the nature of redistribution so that it may gain an advanced perspective on the technology capability gaps, operational approaches and design standards that will enable us to develop systems that are capable of sustained operation in the lunar environment. The objective of the Lunar Regolith Behavior Workshop was to identify surface activities that will affect regolith transport and redistribution, identify current unknowns related to the behavioral characteristics of regolith, and to design possible investigations to understand regolith behavior. A final report and supporting materials are available.

Assessment of Testing Needs and Test Facilities for the Lunar Dust Management Project. Part 1. Preliminary Needs and Facility Availability Overview. The primary objectives of this assessment were to: 1) Establish the preliminary testing needs and testing philosophy of the DMP, 2) Identify the current available NASA and non-NASA testing facilities that are applicable for dust testing, and 3) Identify gaps between testing needs and current testing capabilities. A final report and supporting materials are available.

Assessment of Testing Needs and Test Facilities for the Lunar Dust Management Project. Part 2. Operational Capabilities of Enclosed Vacuum Facilities. The primary objectives of the overall facility assessment were to: 1) Identify the currently available NASA and non-NASA enclosed and analog testing facilities that are potentially applicable for testing with dust in the environment, 2) Determine the relevant current operational capabilities (“readiness”) of the facilities, and 3) Identify gaps between testing needs and current testing capabilities. A final report and supporting materials are available.

Request for Information (RFI) - NASA Lunar Dust Management Project Commercial Technologies for Mitigation of Lunar Dust. An RFI was developed by the DMP to solicit technologies and systems from commercial and other non-NASA organizations to address key technology focus areas for lunar dust mitigation. The intend was to leverage the expertise of non-NASA sectors to complement and/or supplement NASA's current technology development portfolio to ensure the most optimal solutions are deployed for dust mitigation within available funding profiles.

Decision Gate Process CO_2 Shower TRL3 Review - This report serves as the record of the results of the DGP as applied to the DMP's CO_2 Shower task that was evaluated for TRL 3 in December 2009. The task is lead by Nick Mardesich of the Jet Propulsion Laboratory. The CO_2 Shower was assessed according to established technical and programmatic criteria that were scored and discussed by a Review Team comprised of DMP management, DMP SE&I, a subject matter expert (SME) in precision cleaning, and CxP customer representatives from the Lunar Surface Systems (LSS) Environmental Control and Life Support Systems (ECLSS) and ExtraVehicular Activity (EVA) projects. Specific criteria were developed for the CO_2 Shower technology within the general definition of TRL 3 to provide reviewers with a refined meaning of the TRL to allow more objectivity in the assessment. Other criteria included availability of resources, technical hurdles to be overcome for successive TRLs, expertise of the task team, and the priority of the technology. A final report and supporting materials are available.

Systems Engineering and Integration

Conference Proceedings

R. Kohli, J. Fishman, M.J. Hyatt, P. Abel, and P. Delaune, “Achieving a prioritized research & technology development portfolio for the Dust Management Project,” *IEEE Aerospace Conferenc*e, Big Sky, Montana, March 7-14, 2009.

R. Kohli, M. Boulavsky , H. Yee, J. Fishman, P. Craven, R. Easter, and M. Hyatt, “Assessment of Testing Needs and Facilities for the Lunar Dust Management Project,” *IEEE Aerospace Conference*, Big Sky, Montana, March 6-13, 2010.

A. Chait, “Charging Processes of Lunar Dust in Anisotropic Solar Wind Plasma Lunar Dust, Plasma & Atmosphere: The Next Steps”, presented at the Laboratory for Atmospheric and Space Physics, University of Colorado, Boulder, January 27-29, 2010.

V. Pines, M. Zlatkowski, and A. Chait, “Charging of Dust Grains by Anisotropic Solar Wind Multi-Component Plasma” Advances in Space Research, Volume 45, Issue 6, March 15, 2010, pp. 812-822.

Conference Proceedings

The SE&I released several reports over the course of the project to include a few that are listed as conference proceedings.

R. Kohli, J. Fishman, M.J. Hyatt, P. Abel, and P. Delaune, “Achieving a prioritized research & technology development portfolio for the Dust Management Project,” *IEEE Aerospace Conferenc*e, Big Sky, Montana, March 7-14, 2009. *Abstract*—The NASA Lunar Dust Management Project (DMP) has been established to address relevant high priority needs for lunar dust mitigation technologies to be used during lunar surface operations. To this end, an important goal of the project is to ensure that DMP only invests in research and technologies (R&T) that have been assessed and prioritized to meet NASA needs for lunar exploration. To facilitate the process, comparison/decision criteria were developed to assess and prioritize internal and external technology solution alternatives. This paper describes the technologies and presents the assessment methodology.

R. Kohli, M. Boulavsky , H. Yee, J. Fishman, P. Craven, R. Easter, and M. Hyatt, “Assessment of Testing Needs and Facilities for the Lunar Dust Management Project,” *IEEE Aerospace Conference*, Big Sky, Montana, March 6-13, 2010. *Abstract*—The NASA Dust Management Project has been established to address relevant high priority needs for lunar dust mitigation technologies to be used during lunar surface operations. A key task of the project is to support the assessment of test planning and test facility requirements for dust mitigation technology evaluation and demonstration. The overall objectives of the assessment include a) delineation of testing philosophy and needs and b) the identification and evaluation of the capabilities of available and suitable NASA and non-NASA test facilities to identify potential gaps between testing needs and current operational testing capabilities. The approach, methodology and initial results of this ongoing assessment are described in this paper.

A. Chait, "Charging Processes of Lunar Dust in Anisotropic Solar Wind Plasma Lunar Dust, Plasma & Atmosphere: The Next Steps", presented at the Laboratory for Atmospheric and Space Physics, University of Colorado, Boulder, January 27-29, 2010. *Abstract*—We analyze the fundamental mechanisms of charging of a dust particle in the moon environment by tenuous anisotropic solar wind plasma. The majority of work on dusty (complex) plasmas is largely concerns with laboratory plasmas, whose parameters are considerably different from those corresponding to the solar wind plasma at the moon orbit. We derive a charging equation for dust grain, and calculate basic properties such as characteristic charging time and floating potential as functions of grain size and plasma parameters, including the plasma streaming velocity. We show that charging of small grains is time-dependent and could last, e.g., 30 min or longer for sub-micron particles. We then extend the applicability of these findings from two component (electron/proton) plasma to the general case of multi-component plasma, with properties specific to solar wind composition. The presence of helium and other heavy ions accelerates the charging process and slightly decreases the floating value of grain potential in comparison to two-component solar wind plasma Finally, we distinguish between the lunar surface dust distribution and that which is expected to be found and adhered to surfaces placed off the lunar soil.

V. Pines, M. Zlatkowski, and A. Chait, "Charging of Dust Grains by Anisotropic Solar Wind Multi-Component Plasma" Advances in Space Research, Volume 45, Issue 6, March 15, 2010, pp. 812-822. *Abstract*— In this paper we study the charging process of small grain particles by anisotropic multicomponent solar wind plasmas (electrons, protons and heavy ions), versus two-component (electron/proton) plasmas. We are focusing attention on the important characteristics of the charging process, namely the charging time, floating potential and current content as functions of plasma parameters such as He++/H+ (α/p) number density and Tα/Tp temperature ratios of alpha particles to protons, as well as plasma streaming velocity v0. Measured statistical properties of solar wind plasma parameters at *AU* show considerable variations in α/p -temperature ratios from 1 to 10, in α/p-number density ratio from 0.01 to 0.35, as well as in values of streaming velocity v0 from 200 to 1000 km/s and more.

DMP - Technical Approach

- ❑ **Technology Development Areas**
- ❑ **Technology Focus Areas**
- ❑ **Simulants**

The DMP has developed a comprehensive research, technology, and systems development approach to meet the specific needs and requirements identified for Exploration Systems for Lunar Surface Systems (LLS), Lunar Lander Project Office (LLPO), Orion Crew Vehicle, and Extravehicular Activity (EVA). It also includes required characterization of lunar regolith to inform the engineering design process for these systems, the definition of requirements and characterization of existing and future lunar regolith simulants, and the development and production of Highland and Mare simulant types. Each element has been selected for its potential benefits in lunar dust environment knowledge generation, dust management/ mitigation, or environmental testing. The DMP technology portfolio is organized with respect to multi-application technology development areas (Electrodynamic Dust Shield, Lotus Coating, SPARCLED, and CO_2 Shower), specific technology focus areas (Mechanical Components, Thermal Control Surfaces, Connectors, and Surface Power), and Simulants. Detailed descriptions for each of the technology elements, technology application focus areas, and simulant development are summarized .

DMP - Technical Approach

- **Technology Development Areas**
  - Electrodynamic Dust Shield (EDS)
  - Lotus Coating
  - SPARCLED*
  - CO_2 Shower

*Space Plasma Alleviation of Regolith Concentrations in Lunar Environments by Discharge

Electrodynamic Dust Shield

POC: Dr. Carlos I. Calle

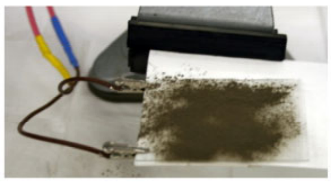
WBS: 1.5.4

Technology Description:

Development of the Electrodynamic Dust Shield (EDS), an active dust mitigation technology to prevent dust accumulation on surfaces exposed to the external environment and affected by surface operations.

The EDS is a non-mechanical, non-contact method of removing dust, significantly more efficient that other proposed dust removal techniques, and can be automated to minimize human intervention.

The electrodynamic cleaning method removes dust from surfaces, prevents dust from falling onto surfaces, and controls dust motion. Particles are removed by applying a multi-phase traveling electric field to electrodes that are embedded in the surface to lift and transport charged and uncharged particles off and away from the surface.



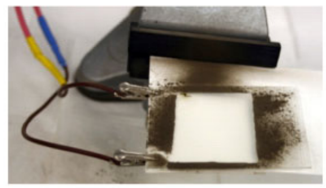


Figure 1: Dust removal demonstration: Before and after activation of the EDS for optical systems, windows, and visors.

This task is focused on the development of EDS technology to minimize dust accumulation on surfaces exposed to the external lunar environment and affected by lunar surface operations. The non-mechanical, electrodynamic cleaning method removes dust particles and prevents dust accumulation on surfaces by applying a multi-phase traveling electric field to electrodes that are embedded in the surface to lift and transport charged and uncharged particles off and away from the surface.[1] The technology is currently at a TRL-3.

The EDS technology has applicability to surfaces exposed to the external lunar environment that need protection, including surface power systems (solar panels, energy storage battery modules, interface cold plates), optical systems (windows, view ports, cameras, spectrometers, light sources), thermal radiators, connectors (quick disconnects and umbilical systems), ISRU sample recovery chambers and steel plates for ISRU production plant design, and sealing surfaces of the airlock hatch and suit port.

Electrodynamic Dust Shield

POC: Dr. Carlos I. Calle **WBS: 1.5.4**

Future Applicability:

Dust control and removal from surfaces is of crucial importance for robotic missions to Mars and the moon. Dust must be removed in order for solar panels, thermal radiators, optical instruments, seals, joints, habitat hatches, and other equipment to operate efficiently and remain active for long durations. Dust motion must be controlled to bring regolith for sampling and to deliver regolith to science instruments.

The EDS also has terrestrial applications for large installations of solar panels and equipment operating in desert conditions.

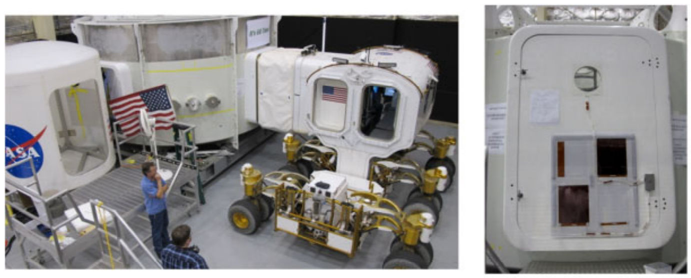


Figure 2: A 21-cm diameter transparent EDS and three 20 cm x 25 cm Copper/Kapton/Thermal Paint EDS installed on Habitat Demonstration Unit

Electrodynamic Dust Shield

Summary of Accomplishments FY08 – FY10:
- •SS-1: Survey of Commercial Materials for use with EDS
- •SS-2: Material Selection for EDS for Solar Panels
- •SS-3: Develop EDS for Solar Panels
- •SS-4: Material Selection for EDS for ISRU Optical Systems
- •SS-5: Develop EDS for ISRU Optical Systems
- •SS-10: Candidate Materials for EDS for Thermal Radiators
- •SS-11: Specifications for Coatings for EDS for Thermal Radiators
- •SS-12: Develop EDS with Thermal Radiator Coating
- •SS-13: Demonstrate Dust Removal at vacuum with EDS for Thermal Radiators
- •SS-14: Test EDS for Thermal Radiators at High Vacuum
- •Reduced Gravity Flight Demonstration of Transparent EDS for Optical Systems for LSS

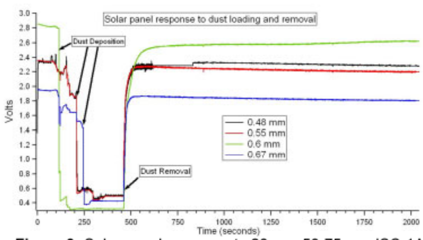


Figure 3: Solar panel response to 20 mg, 50-75 μm JSC-1A dust deposition and removal under high vacuum conditions.

Remaining FY10 Content:
- •SS-23: Final Demonstration of EDS for Thermal Radiators
- •SS-24: EDS Options for Energy Storage Systems

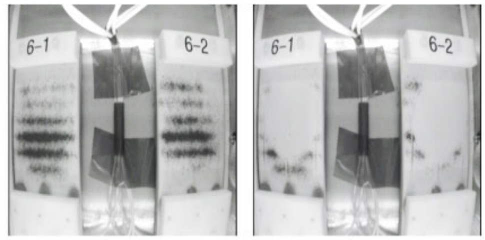


Figure 4: Apollo 16 dust removal at high vacuum and lunar gravity during Reduced Gravity Flight demonstration with transparent EDS for ISRU Optical Systems

Electrodynamic Dust Shield

Technical Readiness Level Progression:

TRL at Project Start: 2-3
Current TRL: 3-5 depending on application

See summary included in Technology Insertion Process, referenced on chart 6 of this presentation.

Electrodynamic Dust Shield

References FY08 – FY10:

- References:

1. Calle, C.I., C.D. Immer, J. Ferreira, M.D. Hogue, A. Chen, M.W. Csonka, N. Van Suetendael, and S.J. Snyder, "Integration of the electrodynamic dust shield on a lunar habitat demonstration unit," *Proceedings of the Annual Meeting of the Electrostatics Society of America*, Charlotte, NC, June 2010.
2. Calle, C.I., C.R. Buhler, M.D. Hogue, M.R. Johansen, N.J. Van Suetendael, A. Chen, S.O. Case, S.J. Snyder, J.S. Clements, J.A. Moebus, J.B. Miller, N.D. Cox, and S.A. Irwin, "Development of a dust mitigation technology for thermal radiators for lunar exploration," *Proceedings of the IEEE Aerospace Conference*, Big Sky, Montana (2010)
3. Calle, C.I., C.R. Buhler, M.D. Hogue, M.R. Johansen, V.B. Cruz, J.W. Hopkins, N.M.H. Holloway, J.W. Connell, A. Chen, S.A Irwin, S.O. Case, N.J. Van Suetendael, S.J. Snyder, and J.S. Clements, "Active dust mitigation technology for thermal radiators for lunar exploration," *Proceedings of the Earth and Space Conference*, Honolulu (2010)
4. Calle, C.I. and J.G. Mantovani, "Transparent conveyor of dielectric liquids or particles," *NASA Tech Briefs*, p. 50, October 2009
5. Calle, C.I., C.R. Buhler, J.L. McFall, and S.J. Snyder, "Particle removal by electrostatic and dielectrophoretic forces for dust control during lunar exploration missions," *Journal of Electrostatics* (2009)
6. Sharma, R., C.A. Wyatt, J.Zhang, C.I. Calle, N. Mardesick., and M.K. Mazumder, "Experimental evaluation and analysis of electrodynamic screen as dust mitigation technology for future Mars missions," *IEEE Transactions on Industry Applications*, 45, 591-596 (2009)
7. Calle, C.I., E.E. Arens, J.M. McFall, C.R. Buhler, S.J. Snyder, J.K. Geiger, R.A. Hafley, and K.M. Taminger, Reduced gravity flight demonstration of the dust shield technology for optical systems, *IEEE Aerospace Conference*, #1510 (2009)
8. Calle, C.I., M.K. Mazumder, C.D. Immer, C.R. Buhler, J.S. Clements, P. Lundeen, A. Chen, and J.G. Mantovani, "Controlled particle removal from surfaces by electrodynamic methods for terrestrial, lunar, and Martian environmental conditions," *Journal of Physics*, 142, 012073 (2008)
9. Calle, C.I., J.M. McFall, C.R. Buhler, S.J. Snyder, E.E. Arens, M.L. Ritz, J.S. Clements, C.R. Fortier, and S. Trigwell, "Dust particle removal by electrostatic and dielectrophoretic forces with applications to NASA exploration missions," *Proceedings of the Electrostatics Society of America Annual Meeting*, Minneapolis, June 17-19, 2008

- # of students sponsored/supported:
  - One NASA Postdoctoral Fellow, 2009-2010
  - Two Summer Faculty Fellows, Summer 2008, 2009, 2010
  - One GSRP Fellow, Summer 2009, January 2010, Summer 2010
  - Two graduate students
  - Five undergraduate students

Lotus Dust Mitigation Coating

POC: Wanda C. Peters **WBS: 1.5.2**

Technology Description:

The **"Lotus"** dust mitigation coating is being developed by NASA Goddard Space Flight Center (GSFC). The **Lotus Coating** task focused primarily on the formulation, characterization and space environmental testing of the "Lotus" dust mitigation coating for space flight application. Secondary objectives of the task was to develop dust removal/cleaning methods that do not require the use of water and obtain a more comprehensive understanding of the particles' (dust) electrostatic properties to tailor the coating's properties or capabilities for enhanced survivability in that environment. This technology was being developed as a countermeasure for dust accumulation during long-duration human space exploration.

The Lotus Coating technology has cross cutting applications. The Lotus coating is designed to preserve optimal long-term performance of spacecraft and habitation components and systems. The coating sheds dust particles utilizing anti-contamination and self-cleaning properties that minimize dust accumulation on spacecraft surfaces. The Lotus coating presently can be applied to metal, glass, polymers and graphite epoxy composite substrates.

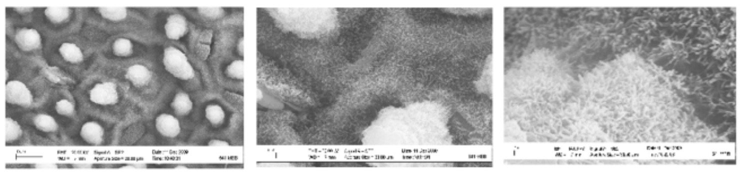


Figure 1: SEM Images of Lotus Leaf

Lotus Dust Mitigation Coating

Future Applicability:

•External lunar environment applications include: critical spacecraft thermal control surfaces [such as thermal radiators and outer layer of Multi-Layer Insulation (MLI) blankets], solar array panels, optics, windows, lenses, mechanism shields, EVA materials, EVA tools, astronaut visors, and rover components

•Internal lunar habitation applications could consist of: airlock, interior crew module walls, and optics/mirrors

•Future research will expand application to various substrates. For added capabilities, this technology can be use in combination with other ETDP Dust Management technologies (such as the Electrostatic Dynamic Shield, thermal control systems, surface power systems, and ISRU optical components).

•The coating can also be modified to incorporate biocide properties for the neutralization of bacteria.

Lotus Dust Mitigation Coating

Summary of Accomplishments FY08 – FY10:

•Lotus coating has been applied to AZ93 white paint, aluminum, stainless steel, fused silica, Kapton, graphite solar cell cover glass and borosilicate substrates

•The Lotus coating has undergone preliminary testing: Thermal Optical/Radiative Property measurements, Scanning Electron Microscopy (SEM) analysis, X-ray Photoelectron Spectroscopy (XPS) analysis, Image Analysis, Thermal Cycling, Ultraviolet Radiation Exposure testing, Solar Wind (low energy radiation) testing, Electrostatic Discharge testing and particulate contamination testing

•Developed a formulation process for an in-house wet chemistry method of the Lotus coating. -Designed and built an in-house coatings development lab (CDL) where the Lotus coating wet chemistry method will be developed and applied

- Wanda Peters, Lotus Coating Principle Investigator, was interviewed by the British Broadcasting Company (BBC) at Goddard concerning the Lotus Coating technology development. The interview included a demonstration of the Lotus technology and scanning electron microscope (SEM) images of a Lotus leaf. Dr. Edgar Mitchell (Apollo 14 Astronaut) also participated in the interview and shared his experience on the moon. Dr. Mitchell stated that the Lotus coating would be beneficial to NASA. This interview will be part of a program entitled "Invisible Worlds" that was aired on BBC and Discovery Channel in March 2010.

•Successfully combined the GSFC Lotus coating technology with the KSC Electrostatic Dynamic Shields (EDS) technology for inclusion on the Habitation Demonstration Unit (HDU). Combining the Lotus coating and EDS technologies enhanced the elimination of dust from the contaminated surface.

•As an outreach activity, our team applied the Lotus coating to 20 solar cells for a study to test dust in a microgravity environment on the Zero-Gravity flight by students from the Washington University in St. Louis

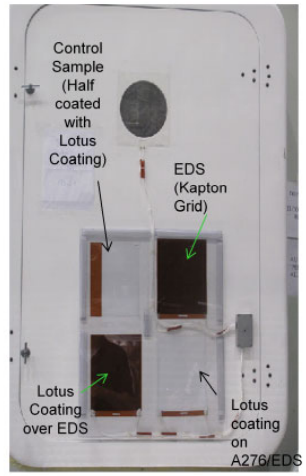


Figure 2: HDU Portal Door

Lotus Dust Mitigation Coating

Remaining FY10 Content:

Deliverable	Due Date
Complete Wet Chemistry Process Development	FY10
Complete Lotus Coating Formulation Development	FY10
Delivery of Test Sample for LDAB	FY11
Complete of Lotus Coating Characterization Testing	FY12
Complete of Lotus Coating Environmental Testing	FY13
Final Component-Level Validation Testing	FY13

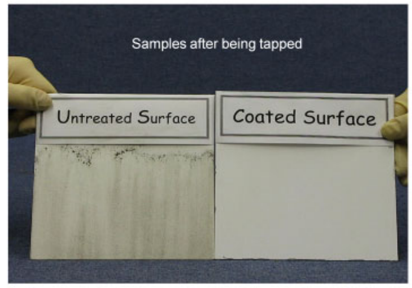


Figure 3: Uncoated radiator sample and Lotus coated radiator sample after being contaminated with JSC-1 Lunar simulant

Lotus Dust Mitigating Coating

Technical Readiness Level Progression:

TRL at Project Start: Lotus Dust Mitigation Coating was at TRL 2 at the beginning of this project in FY06.

•FY08- FY09 research and development activities validated the concept of the Lotus coating, as a dust mitigation tool, is viable and achievable. The Lotus coating is microscopically thin and optically transparent. At the end of FY09, the technology was at a TRL-3.

•1.5 years of development was adversely impacted due to facility issues

•A viable formulation was applied to subsystem level components in FY10 – HDU Project. The coating is scheduled to be tested in an environmental representative of the intended lunar environment to demonstrate this technology's maturity

Current TRL: 3 – 4.

•Some environmental laboratory tests have been performed

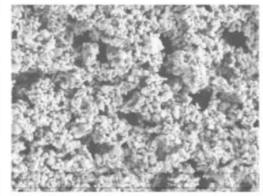
•The Lotus coating has been applied to solar cells and tested in a microgravity environment on the Zero-Gravity aircraft

•The HDU Project will test the coating in a terestrial environment

What is needed to progress to TRL 6 (Technical):

•Technical: Wet Chemistry Development, Characterization Tests, Environmental Tests

AZ-93 White Paint



Lotus Coating over AZ-93 White Paint

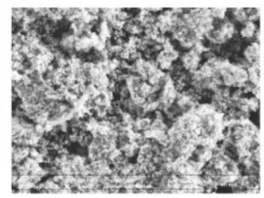


Figure 4: **SEM Analysis 5000X Images**

See DMP Technology Insertion Process, referenced on chart 6

Lotus Dust Mitigating Coating

References FY08 – FY10:

• References: publications, Test Reports, NASA STI Reports, deliverables

- Design and Optimization of the Lotus Coating
- SEM Analysis Test Report
- Lotus coated samples for HDU Project with associated documents
- Effects of Lunar Simulant on Solar Panels, The Effects of Vibration and Lotus Coating on Solar Cell Dust Retention (Washington University in St. Louis)
- The Lotus Coating for Space Exploration – A Dust Mitigation Tool (presented at the SPIE Conference, August 2010)

• # of students sponsored/supported (if applicable)

- Kathy Li, Summer Intern (sponsored for FY08 summer)
- Katie Handler, Summer Intern (sponsored for FY09 summer)
- 5 Students from Washington University in St. Louis (coated solar cells with Lotus Coating)

SPARCLED

POC: Dr. Steven A. Curtis, Fred Minetto **WBS:** 1.5.3.2

Technology Description:

Using a low power electron gun to negatively charge regolith, then applying a point source discharge to move regolith on a collection chamber wall. Figure 1 is a setup using JSC1A sieved down to 20 µm or less. Figure 2 represents dust collected on a chamber wall after collection experiment. Figure 3 & 4 represent release of regolith after initial collection.

Future Applicability:

Technology may be used to collect/remove any dust in vacuum. Such as from mirrors, lenses, solar cells.

Figure 1: JSC 1A simulant applied in glass chamber.

Figure 2: JSC1A simulant is transferred to chamber wall after collection experiment

SPARCLED

Summary of Accomplishments FY08 – FY10:

•Successful movement, collection, and removal of 20 µm JSC1A & NU lunar simulants in a controlled environment on electrically conductive and non-conductive surfaces in vacuum. Where temperatures ranged from 20 to 23 °C and vacuum pressures of between 10**-5 to 10**-6 torr.

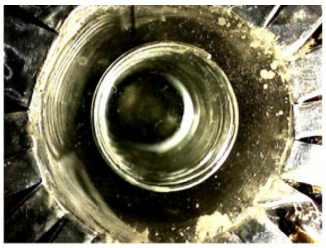


Figure 3: JSC1A is released from chamber wall for disposal.

Remaining FY10 Content:

• Extensive testing remains for Ortho-fabric surfaces.

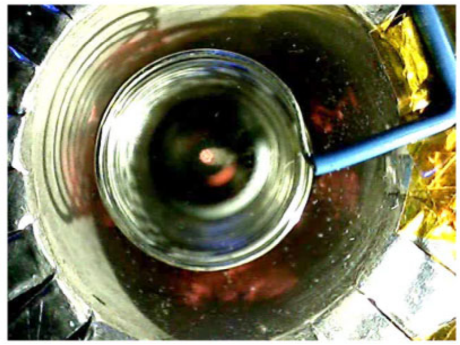


Figure 4: (Video)

SPARCLED

Technical Readiness Level Progression:

TRL at Project Start: 1

Current TRL: 4

See DMP Technology Insertion Process, referenced on chart 6

SPARCLED

References FY08 – FY10:

• References: publications, Test Reports, NASA STI Reports, deliverables

•SPARCLE: SPACE PLASMA ALLEVIATION OF REGOLITH CONCENTRATIONS IN THE LUNAR ENVIRONMENT Mr. Slawomir Zdybski (USRP intern) International Space University (ISU), Strasbourg, France, Dr. Steven Curtis, Dr. Pamela Clark, Mr. Fred Minetto

•CLARK, P.E., CURTIS, S.A., MINETTO, F.A., MOORE, M., NUTH, J., 2008 Characterizing Physical and Electrical Properties of Lunar Dust as a Basis for Developing Dust Removal Tools. NLSI Lunar Science Conference, NASA Ames, Moffet Field, CA - July 20-23 2008.

•CURTIS, S.A., CLARK, P.E., MINETTO, F.A., MOORE, M., 2008. Plasma-Based Tool for Dust Removal on the Moon. 39th Lunar and Planetary Science Conference, League City, TX March 10-14, 2008.

•14 student interns were sponsored during that time period. Budgetary constraints were not an issue, as students were paid using other NASA funding.

CO_2 Shower Cleaning

POC: Nick Mardiesich **WBS: 1.5.3**

Technology Description:

Method to increased the size of sub-micron dust particles by growing crystalline CO_2 coating in vacuum and low temperature (Moon and Mars environment. Include Electrostatic Discharge Screens (EDS) into the astronaut's space suits to expel dust with EDS assistance.

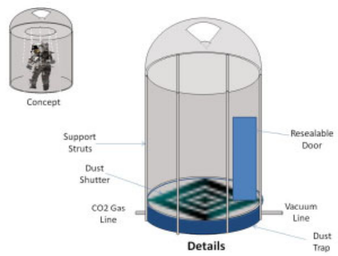


Figure 1: CO_2 shower cleaning concept, where the astronauts enter a external chamber prior to entering the habitat.

Future Applicability:

Provide a protected entry to airlock, the development of deployable, possibly inflatable, dust isolation and removal zones will be conducted using CO_2 snow shower technology. To be used on the Moon or Mars.

Figure 2: Eight percent dust loading (left) with 0.2 atmospheres of CO_2 at -160 °C and after (right) 3.5% dust remaining after EDS dust removal in CO_2 chamber. Surface looks dirty similar to windshield after it rains.

This dust removal process is dependent on the astronauts EVA suits having EDS grids as part of the suit design. Dust will accumulate on the suits from the Moon's surface. The activation of the EDS screen will remove most of the dust, approximately 10% dust loading of micron size particles will remain. VanderWaal adhesion force will keep these small particles adhere to the suits. The astronauts will then be sealed in the CO_2 shower, located in the shadow of the vehicle to maintain temperature, and sprayed with CO_2 to 0.1 to 0.2 atmospheres obtained from the habitat O_2 scrubbers. The CO_2 gas will crystallize on the dust particles reducing the VanderWaal force and allowing the micron size particles to be removed, and allowing the astronaut to enter the habitat. Initial test have shown that a dust loading of 8% can be reduced to 3.5%.

CO_2 Shower Cleaning

Summary of Accomplishments FY08 – FY10:

- Designed built EDS test samples with detectors mounted on back to monitor effectiveness of cleaning.
- Procured EDS power supply.
- Designed and built low temperature CO_2 vacuum chamber. This chamber required a pressure chamber within a vacuum chamber.
- Modified vacuum chamber for high voltage activation of EDS test samples.
- Successfully demonstrated CO_2 crystal growth within chamber.
- Demonstrated effective dust removal aided by CO_2
- Identified inflatable CO_2 shower vendor and obtained quote for prototype.

Remaining FY10 Content:

- Analyze concept and identify controlling parameters of CO_2 shower

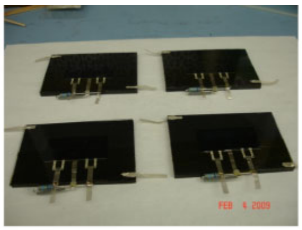


Figure 3: EDS dust monitoring plates with detectors placed under transparent EDS grids.

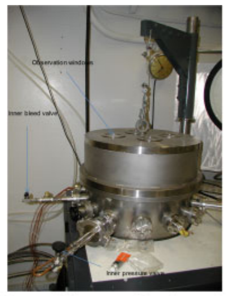


Figure 4: Vacuum chamber with interior CO_2 pressure chamber.

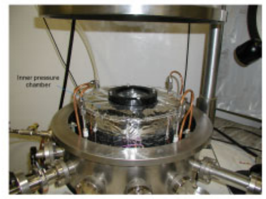


Figure 5: Interior CO_2 pressure chamber.

Figure 6: Interior cold plate mounting surface.

Figure 3 are the test samples prepared with EDS grids on glass slides mounted to solar cells on top of carbon substrates. Light transmission through the glass slide can be monitored before and after dust application and EDS removal. Figure 4 is the test systems with gas and electrical ports with an inner CO_2 pressure chamber, Figure 5. The pressure chamber has a plate that can be cooled to -160 °C to crystallize CO_2 gas Figure 6.

CO_2 Shower Cleaning

Technical Readiness Level Progression:

TRL at Project Start: 1

Current TRL: 3

See DMP Technology Insertion Process, referenced on chart 7

CO_2 Shower Cleaning

References FY08 – FY10:

WebEX PRESENTATION, **Dust Management Task Airlock and Habitat Dust Mitigation Systems (WBS 1.5.3) CO_2 Shower, September 16, 2009**

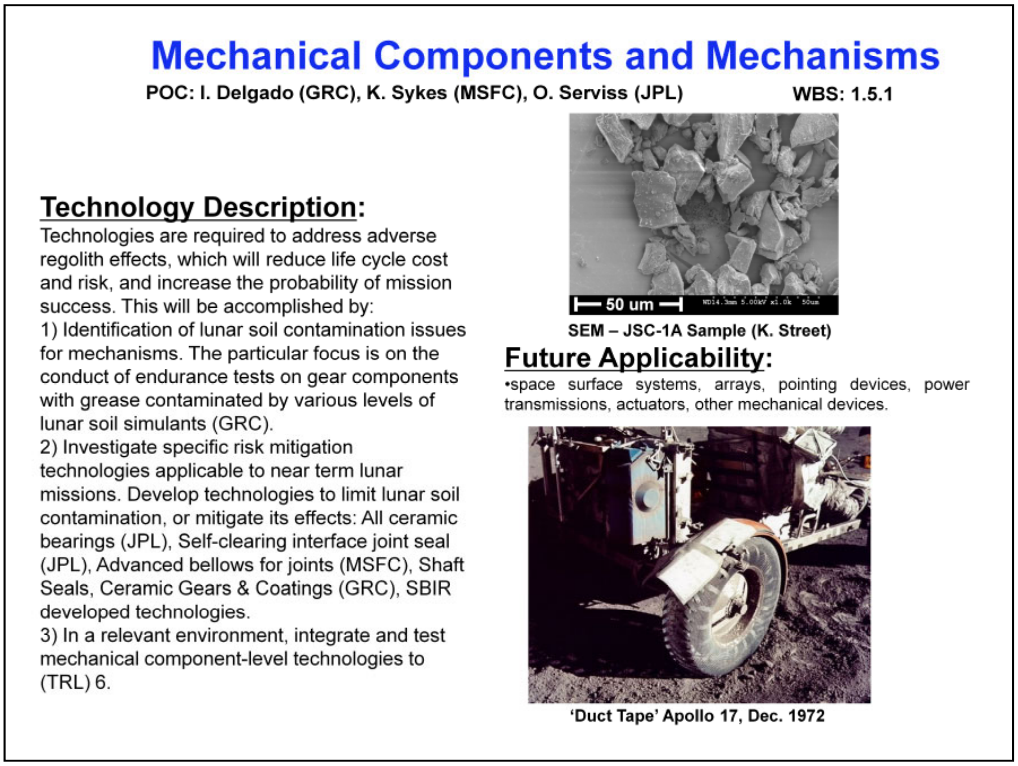
\# of students sponsored/supported:
•2 of students sponsored
•Chris Wyatt (U of A)
•Jason Robison

Webex presentation from 2009 delta TCR package, resides on Windchill in Dust project closeout documentation folder.

DMP - Technical Approach

- **Technology Focus Areas**
  - Dust Tolerant Mechanical Components
  - Dust Tolerant & EVA Compatible Connectors
  - Surface Power
  - Thermal Control Surfaces

The DMP has developed a comprehensive research, technology, and systems development approach to meet the specific needs and requirements identified for Exploration Systems for Lunar Surface Systems (LLS), Lunar Lander Project Office (LLPO), Orion Crew Vehicle, and Extravehicular Activity (EVA). It also includes required characterization of lunar regolith to inform the engineering design process for these systems, the definition of requirements and characterization of existing and future lunar regolith simulants, and the development and production of Highland and Mare simulant types. Each element has been selected for its potential benefits in lunar dust environment knowledge generation, dust management/ mitigation, or environmental testing. The DMP technology portfolio is organized with respect to multi-application technology development areas (Electrodynamic Dust Shield, Lotus Coating, SPARCLED, and CO_2 Shower), specific technology focus areas (Mechanical Components, Thermal Control Surfaces, Connectors, and Surface Power), and Simulants. Detailed descriptions for each of the technology elements, technology application focus areas, and simulant development are summarized.



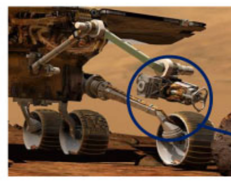
A general description is provided on the scope of the dust mitigation research in relation to the Mechanical Components and Mechanisms area. Technologies investigated include bearings, gears, and seals. Points-of-contact are listed as well as respective NASA Centers GRC, MSFC, and JPL. The primary thrust of the research effort is to identify contamination issues on various mechanical components through testing in a relevant environment including lunar simulant.

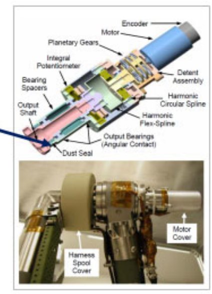
Mechanical Components and Mechanisms

Summary of Accomplishments FY08 – FY10:

- Perform fundamental dust contaminated grease tests. (9/2008, GRC)
- Completed the design and fabrication of the Dust Tolerant Bearing Testbed (10/2008, JPL)
- Completed bearing analysis tool (6/2009, JPL)
- Completed rotary seal dust contamination tests at ambient conditions. (2/2009, GRC)
- Completed baseline rotary wear tests of PTFE Bal Seal seals using anodized Aluminum shafts in vacuum up to 2 x10^{-7} torr. (07/2009, GRC)
- Completed additional dust seal tests with steel shafts. Negligible wear was observed for both seal and shaft. (8/2009, GRC)
- Completed JSC-1A contaminated baseline rotary/linear tests of Barden bearings at ambient conditions. (2/2010, MSFC)
- Complete JSC-1A contaminated baseline rotary/linear tests of Barden bearings in vacuum. (4/2010, MSFC)
- Complete modifications on rotary seal rig for Low-Temperature Mechanisms dust seal tests. (7/2010, GRC)

Bal-Seal Cross-Section



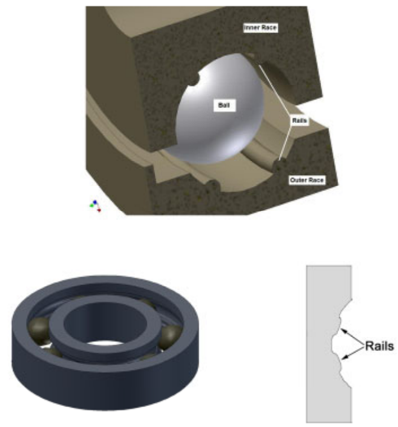


A number of mechanical components were tested with lunar simulant. A baseline study of contaminated grease tests for gearheads was done. The Bal-Seal was tested with either JSC-1A or LHT-2M and its performance was observed in keeping simulant out of the seal/shaft interface. A prototype low-temperature mechanism dust seal was also tested. Contaminated bearing tests were conducted at JPL and MSFC. Simple rotary and linear test mechanisms were fabricated to test Mars heritage bearings in vacuum. JPL used a Dust Tolerant Bearing Testbed as well as a bearing analysis tool to test bearings having different geometries and materials.

Mechanical Components and Mechanisms

Remaining FY10 Content:

- Run contaminated endurance tests on LTM dust seals in vacuum. (9/2010, GRC)
- Design ceramic roller race bearings and identify manufacture. (JPL)
- Complete report on linear and rotary dust contaminated tests of Barden bearings. (6/2010, MSFC)
- Testing Results of Rotary and Linear Bearings Sensitivity to Lunar Dust Simulant



Preliminary design of rail-race bearing. Section of inner race showing rails on which balls ride, with relief for dust accumulation

Endurance testing continues for the low-temperature mechanism dust seal in vacuum and with NU LHT-2M simulant. Over 200,000 cycles at ~40 rpm have been completed thus far with minimal drag torque and temperature rise on the shaft/seal interface. The goal is to reach 1,000,000 cycles. A final report was completed on the Barden Bearing linear and rotary seal tests. The report is being published through NASA channels. Finally work continues on identifying a bearing manufacturer for the ceramic roller race bearing design at JPL.

Mechanical Components and Mechanisms

Technical Readiness Level *Progression*:

JPL : Rail Race Bearing Concept

TRL at Project Start: 0, New Concept

Current TRL: 2, Rail-race bearing concept formulated, implementation and testing needed

What is needed to progress to TRL 6 (Technical):

-Construction of a rail-race bearing

-Testing and validation of design and demonstration of improvement in dust tolerance versus conventional ball bearing design

-Testing in the constructed testbed will enable TRL 6 as it is a relevant, simulated environment.

GRC : Bal-Seal

TRL at Project Start: 1, Design heritage in Mars Exploration Rover IDD

Current TRL: 3 to 4, The design has been cyclically tested at vacuum with Lunar simulant

What is needed to progress to TRL 6 (Technical):

- A platform/system/subsystem is necessary to optimize the design
- Long-term testing at cryogenic temperatures is necessary to validate the design
- Facilities for cyrogenic testing need to be identified

MSFC : Barden Bearings

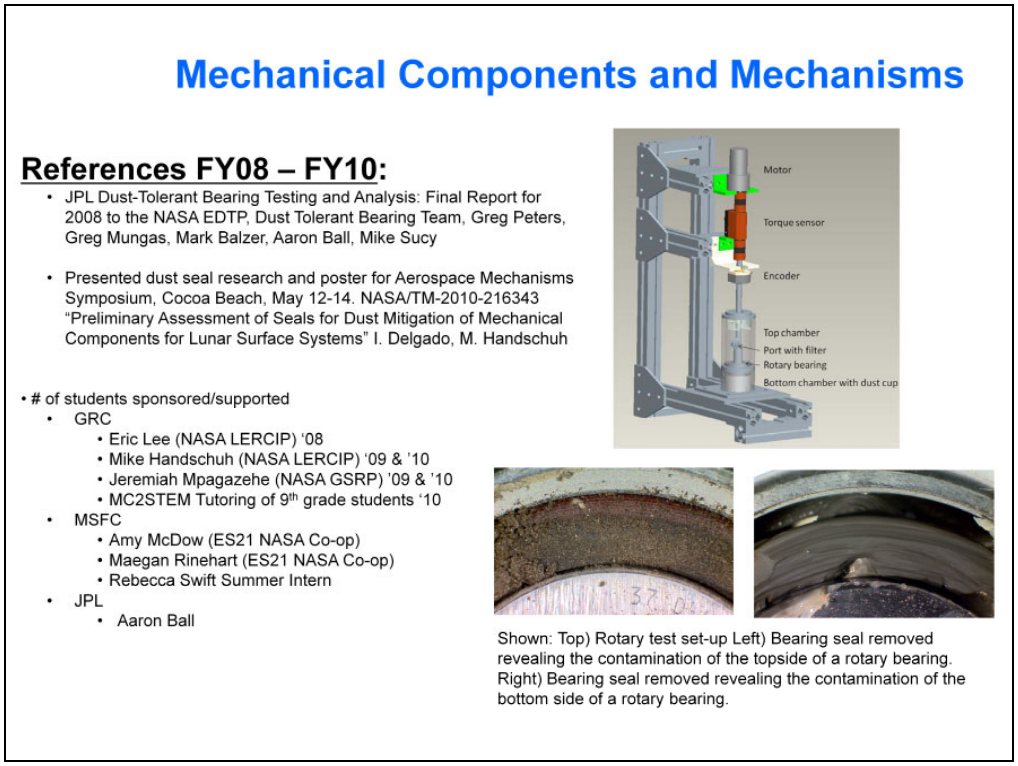
TRL at Project Start: 1, Barden bearings have design heritage in Mars rovers

Current TRL: 3 to 4, Bearings have been cyclically tested in vacuum with lunar simulant

What is needed to progress to TRL 6 (Technical):

- A platform/system/subsystem is necessary to optimize the design
- Long-term testing at cryogenic temperatures is necessary to validate the design
- Facilities for cyrogenic testing need to be identified

The rail-race bearing concept requires test evaluation to validate the current design. As such, its TRL level is at 2. The Bal-Seal and Barden bearing technology have some Martian design heritage. In addition testing has been completed for both in vacuum with lunar simulant (JSC-1a for the Barden Bearing and NU-LHT-2M for the Bal-Seal). As such their TRL levels are approximately 3-4. A more integrated test of the technology in a proposed system (i.e., wheel bearing housing) would be necessary to raise the current TRL level.



A number of co-op, internship support was necessary for successful implementation of the test/analysis mechanical component program.

The reports and references for this task are available on Windchill, in the Dust Project Closeout Documentation folder.

Mechanical Components and Mechanisms

DMP Risks Update

Trend	Risk ID and Open Date	Risk Title	Risk Statement (MUST USE - "Given that (state the fact)..there is a possibility (state the concern resulting in (state the consequence..)"	L	C	Affinity Group (Budget, Performance, Cost, Schedule)	Owner Initiator	Approach (M,W,A,R) Mitigate, Watch, Accept, Research	Status/Context	Mitigation 1	Estimated Start Date Mitigation 1	Estimated End Date Mitigation 1
Constellation Customer Risks Addressed by DMP												
⇨	1.5.1-1	Performance Degradation of Critical Dynamic Mechanical Systems	Based on experience with mechanisms during Apollo lunar surface missions, there is a high probability of performance degradation of critical dynamic mechanical systems during long duration lunar missions.	4	4	Performance	Irebert Delgado	M, W, R	Baseline wear results were obtained of dust contamination on gearhead, rotary seal, Barden bearings, rail-race bearings. Further tests suspended due to resource limitations.	Component tests to determine effects of dust contamination on gear material and lubricants (FY08) Endurance tests on gears and mechanisms (FY09) Develop dust tolerant lubricants, ceramic bearings and mechanisms (FY10-12)	10/01/07	09/30/11
⇨	1.5.1-2	Unavailability of Representative Simulants and Dust Exposure Data	Wear mechanisms of critical components is dependent on the lunar simulant properties representative of the lunar surface. Simulants that are not representative of the lunar surface and limited data on exposure of mechanisms to lunar dust are an internal risk to this task.	4	4	Performance, Schedule	Irebert Delgado	M, W, R	Completed baseline wear results of dust contamination of rotary seal with JSC-1A and NU-LHT-2M. Tests are suspended due to resource limitations.	Development of high fidelity simulants via task 1.4 - Engineering Design Environment Identification of systems with mechanisms exposed to dust. Component tests to determine effects of dust contamination on gear material and lubricants (FY08) Endurance tests on gears and mechanisms (FY09) Develop dust tolerant lubricants, ceramic bearings and mechanisms (FY10-12)	10/01/07	09/30/11

Dust Tolerant EVA-Compatible Connectors

POC: I.I. Townsend/ R. P Mueller **WBS: 1.6.1**

Technology Description:

Development of the Dust Tolerant EVA-Compatible Connectors. The objectives of this task were component level integration and testing of connectors (quick disconnects and umbilical systems) that can be repetitively and reliably mated and de-mated during Lunar surface extra-vehicular activities.

The Dust Tolerant Quick Disconnect consists of a quick disconnect coupled with a dust tolerant housing that uses an end cap for dust protection, a self cleaning quick disconnect where any remaining dust would be blown clear of the quick disconnect and user. The mate/de-mate process is autonomous to the user by twisting one handle that performs the cap removal, cleaning and mating process in one step.

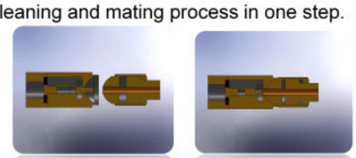


Figure 1: Dust Tolerant Quick Disconnect: Before and after mating of the male/female connectors.

Future Applicability:

Preventing dust intrusion on quick disconnect connectors is crucial for robotic missions to asteroids, Mars and the Moon where the risk of dust intrusion is possible. There exists an urgent need to prevent dust and debris from clogging and degrading the interface seals and causing leakage and spills of hazardous commodities, contaminating the flowstream, and degrading the mechanisms needed for umbilical connection in terrestrial operations as well. Military aircraft, and ground support equipment where clean umbilicals and connectors are required will benefit from this technology.

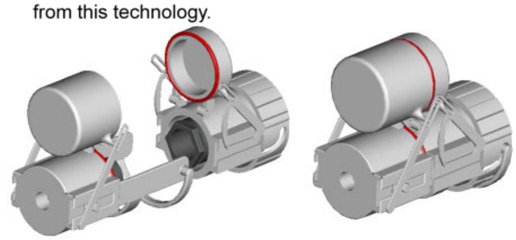


Figure 2: Dust Tolerant Flip Cap QD Housing: Before and after mating of the male/female housing

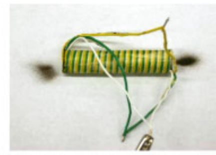
Dust Tolerant EVA-Compatible Connectors

Summary of Accomplishments FY09 – FY10:

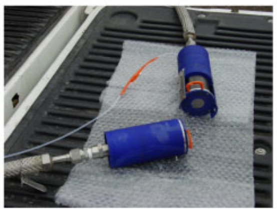
•SS-19: Lessons Learned From Prototype Connector and Dust Cover Concept Development
•SS-21: Prototype Connector and Dust Cover Concept Development
•DTC-1: Subcomponent Development, 09/30/2009
•DTC-2 formerly SS-22: Testing of Breadboard Prototype Connector in a Relevant Environment 11/30/09
•DTC-3: Small Scale Prototype Concept of a Single QD Connector for EVA and LSS Infrastructure, 04/30/2010

Remaining FY10 Content:

• **DTC-4: Small Scale Prototype Connector Fabricated for a Single QD Connector for EVA and LSS Infrastructure, 09/30/2010.**



EDS Dust Impeller prototypes operated at ambient conditions with lunar simulant.



DRATS 2007 demonstration of a quick disconnect concept, and a dust mitigation configuration concept based on EDS

before EDS activation

after EDS activation

Figure 3: SS-19 Desert Rats 2007 Connector Testing

Dust Tolerant EVA-Compatible Connectors

Technical Readiness Level Progression:

TRL at Project Start: 2
Current TRL: 3
What is needed to progress to TRL 6 (Technical):

- Dust Tolerant Connector Enhancements
- Dust Tolerant Connector Housing Enhancements
- Dust Tolerant Connector Integrated with Connector Housing
- Dust Tolerant Connector/Housing ISS Flight Qualification Testing
- Dust Tolerant Connector/Housing for Moon/Mars Surface Fluid Systems
- Dust Tolerant Connector/Housing for Moon/Mars Surface Electrical Systems
- Dust Tolerant Connector/Housing for EVA Spacesuit Components Systems

Dust Tolerant EVA-Compatible Connectors

References FY08 – FY10:

- References:

1. Townsend, I. I., Mueller R. P. "Dust Tolerant EVA Compatible Connectors", *ASTE Earth and Space Conference*, Waikiki, HI, March 2010.

- # of students sponsored/supported:
  - One PHD Summer Faculty from UNC Charlotte
  - Senior Capstone PhD Design Project each year at UNC starting Fall 2010 (10 to 15 students)

Dust Mitigation for Surface Power Systems

Summary of Accomplishments FY08 – FY10:

•Triboelectric charging of a moving rover wheel in JSC-1a lunar mare simulant was compared under hard vacuum to simulate lunar surface conditions and 7 torr of CO_2, characteristic of Mars surface conditions.

•Magnitude of charging under hard vacuum averaged 200 to 400 V, or about twice as much as with CO_2 present.

•Results imply that Triboelectric charging will be twice as severe on the Moon as on Mars.

•Mitigation techniques currently deployed on all Mars rovers are based on attached micro discharge points. Since these use the tenuous Martian atmosphere to bleed charge, they will be ineffective on the Moon.

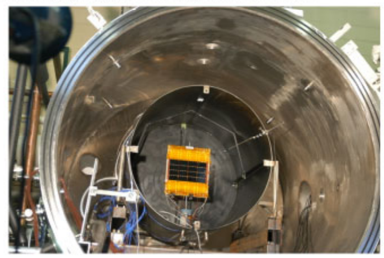
Remaining FY10 Content:

•GRC facility VF-21 is undergoing retrofit to accommodate an LN_2 cold wall to better simulate lunar conditions.

•Shown below - a solar array coupon developed for the ORION spacecraft ready for a thermal balance test in VF-20.

- Several facilities exist at NASA for such tests, all are ultraclean environments.

•No facility exists in the U.S. to perform similar testing under “dusty” conditions typical of either the Moon or Mars. By end of FY10 this capability will be operational at GRC.



This task showed that vehicles moving on the lunar surface will be subject to triboelectric charging at levels approximately twice that experienced on Mars. Because of the hard vacuum environment, mitigation techniques employed on Mars rovers will be ineffective.

Should this effort be resumed, possible mitigation techniques will be explored. The best approaches will involve preventing charging in the first place. We have proposed that matching the electron work function of surfaces in contact with regolith with the work function of regolith itself will, in principle, prevent charge transfer. Whether this principle can be translated into practical materials is unknown.

Dust Mitigation for Surface Power Systems

POC: G. Barry Hillard **WBS: 1.5.4.5**

Technology Description:

This task was reformulated in 2009

Original Task: Convert existing high vacuum chamber VF-21 to dedicated dust facility capable of testing small scale engineering prototypes. Assess degree of triboelectric charging and associated risk to moving vehicles on the surface of the Moon.

Reformulated Task: Upgrade VF-21 with LN2 cold wall to assess thermal behavior of generic solar array technologies as a function of array dust loading under realistic lunar surface conditions.

Future Applicability:

Original Task: Various general approaches to mitigating the occurrence, severity, or effects of triboelectric charging have been suggested for rovers and similar vehicles. Systematic testing and development of practical techniques can be pursued in support of any proposed architecture.

Reformulated Task: Surface power systems for the Moon or Mars which are based on solar arrays will have performance requirements that will be impacted by dust loading. Testing of generic array technologies - e.g. traditional honeycomb designs, lightweight solar cells mounted to single sheet Kapton, or open weave mesh designs – as a function of dust loading would drive future design requirements. This would also enable the development of operational guidelines for deployment of solar arrays and limitations on mobility operations in the vicinity of deployed arrays.

Delivery of the cold wall for VF-21 is delayed until early October 2010. Once in-house, it will be installed and tested as resources are made available. This will provide a facility capable of testing component and subsystems in a dusty, high vacuum environment. With hard vacuum and cold wall, it will simulate lunar surface conditions. The addition of 7 torr of CO_2 and a change of simulants will allow similar testing under Mars surface conditions.

Specific tests on solar arrays that were planned for next year are on hold pending guidance from CxP Lunar Surface Systems.

Dust Mitigation for Surface Power Systems

Technical Readiness Level Progression:

TRL at Project Start: 1-2
Effects of lunar dust on surface power systems not quantified

Current TRL: 1-2
High fidelity lunar simulation chamber will be available upon retrofit to chamber V21

VF-21 will be fully operational by the end of October. TRL for specific testing remains unchanged.

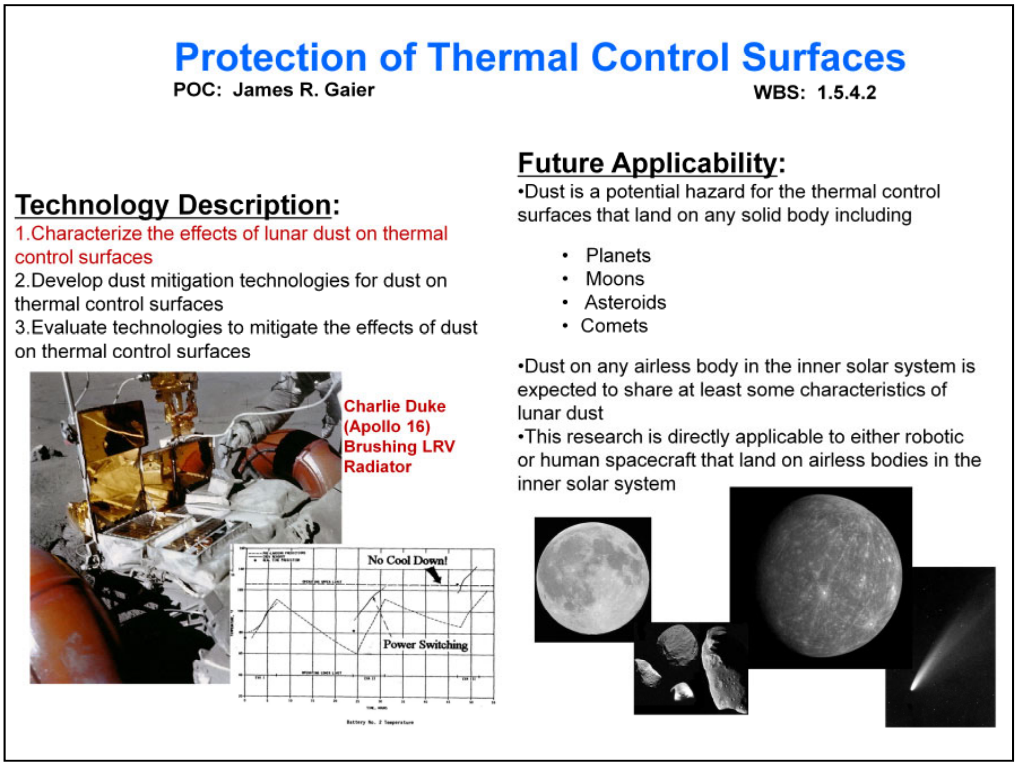
Dust Mitigation for Surface Power Systems

References FY08 – FY10:

"Triboelectric Charging Effects of Lunar Dust: Phase I Studies"; Joel T. Galofaro, Boris V. Vayner and Barry G. Hillard; to be presented at the 11th AIAA Spacecraft Charging Conference, Albuquerque, NM, Sept. 20-24, 2010

# of students sponsored/supported (if applicable)

•Summer 2009, one student and one visiting professor worked on this program, but were not supported by the task. Summer 2010 one student and one visiting professor will each devote half time to facility development but are also not supported by the task.

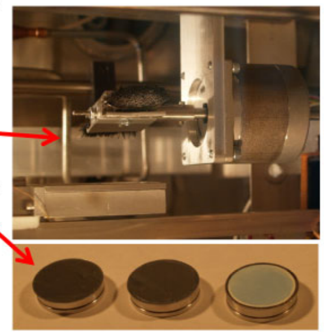


A testing infrastructure and protocol was developed to evaluate the effect of dust on thermal control surfaces. This included the completion of the Lunar Dust Adhesion Bell jar (LDAB), a high fidelity lunar simulation facility. Within the LDAB, lunar simulant is dried by heating to 200 °C in vacuum for 24 hr. It is also subjected to an air plasma for 60 min to oxidize organic contaminants from the surface, and a hydrogen/helium plasma for 60 min to simulate the effects of the solar wind. The plasmas also emit a large amount of energetic vacuum ultraviolet light which can generate free radicals on the particulate surface. The samples of the white thermal control paint AZ-93 and the second surface mirrors silver teflon (AgFEP) and aluminized teflon (AlFEP) can be heated using a 20 sun solar simulator and cooled in a 30 K cold box. The activated dust can be sifted onto the samples through an electron beam, which charges the particles. The emphasis was on determining the effects of sub-monolayers of dust, since the minimum effect was desired. It was also reasoned that thick layers of dust can probably be removed by conventional means, such as brushing, but that there is likely to by some residual layer of dust afterwards. Using the heating and cooling curves, a finite element thermal model of the samples within the LDAB was used to determine the solar absorptance (α) and the thermal emittance (ε) of the samples, both pristine and dusted. The fractional dust coverage was determined by sampling 50 random, non-overlapping frames (of 604) under an optical microscope at 100×. The effects of fractional dust coverage, substrate, solar angle of incidence, dust particle size, and dust type (color) were determined. The steady state temperature of the radiator was not appreciably affected by a sub-monolayer of dust.

Protection of Thermal Control Surfaces

Summary of Accomplishments FY08 – FY10:

•Developed a facility to measure the performance of thermal control surfaces in a high fidelity simulated lunar environment (Lunar Dust Adhesion Bell Jar, or LDAB).
•Developed a thermal model to calculate integrated solar absorptance (α) and thermal emittance (ε) from LDAB data.
•Developed facilities and procedures to calculate the fractional dust coverage on LDAB samples.
•Determined the effect of fractional dust coverage on the α and ε for 4 lunar simulants, 2 substrates, and 3 thermal control surfaces.
•Determined the effect on dust particles size and solar incidence angle on the α of 2 thermal control surfaces.
•Determined the effect of dust coverage on the steady state temperature of 2 thermal control surfaces.
•Found that optically determined α twice that determined thermally.
•Determined the effectiveness of brushing dust off of thermal control surfaces using 3 different brush configurations on 3 types of thermal control surfaces.
•Fabricated and evaluated 7 different textured thermal control surfaces for dust adhesion in LDAB.
•Fabricated 6 different work function matching coatings for dust adhesion in LDAB.



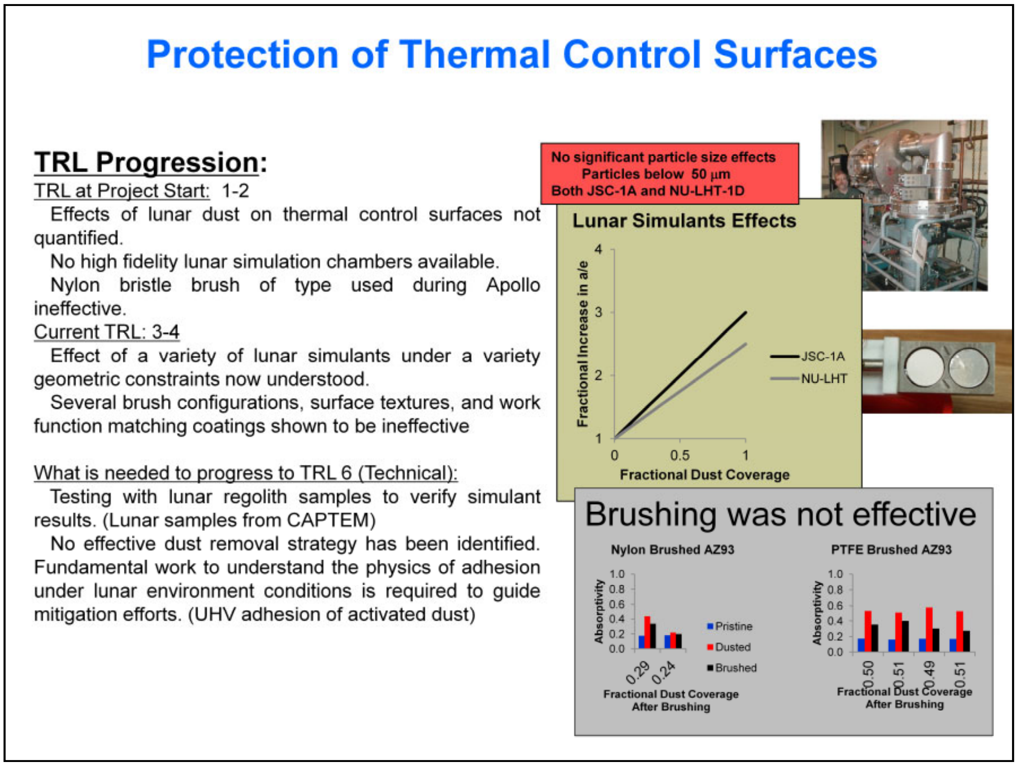
The α and ε of dusted thermal control surfaces was calculated using the optical properties of the surfaces and of the dust using a simple rule of mixtures model. This analysis was found to overestimate the effect of dust coverage by about a factor of 2, probably due to the optical depth of the distributed dust grains being less than the individual grain size.

Although the electrodynamic dust shield technology appears promising to remove dust from thermal control surfaces, the initial tests were plagued by unforeseen materials issues. As of the end of FY10 those issues had not yet been resolved, though resolution appears near.

Protection of Thermal Control Surfaces

Remaining FY10 Content:

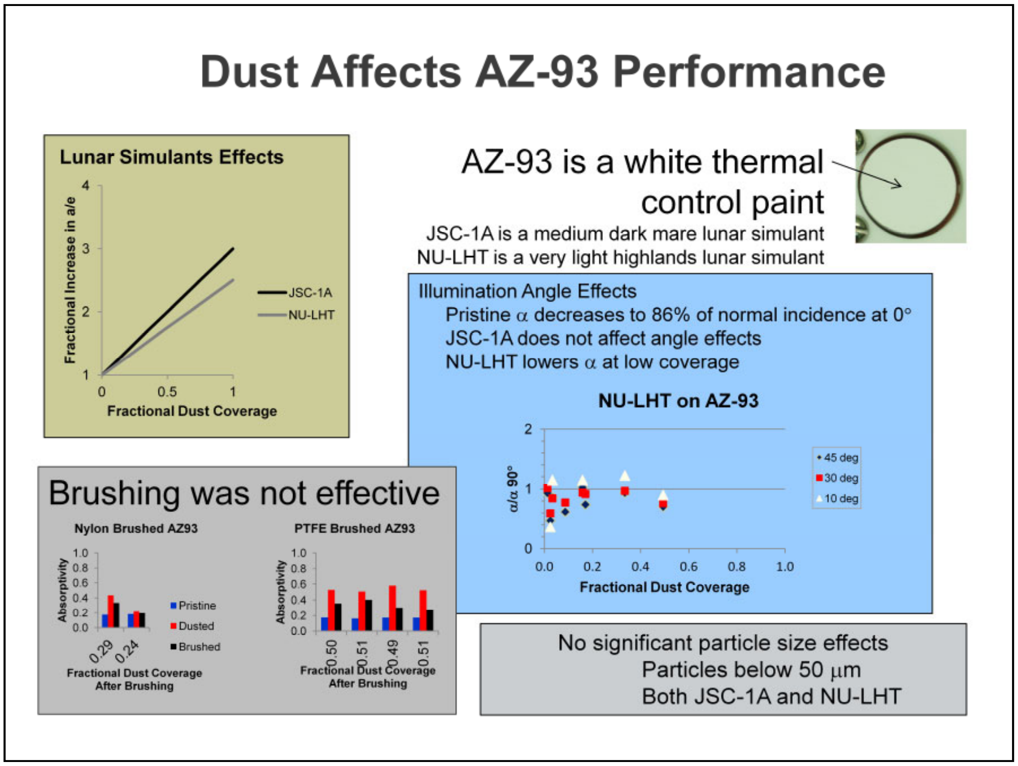
•Evaluate 6 different work function matching coatings for dust adhesion in LDAB.
•Determine the effectiveness of brushing dust off of thermal control surfaces using 7 different brush configurations on 2 types of thermal control surfaces.
•Evaluate the Electrodynamic Dust Shield technology in the LDAB.



At the start of the project, the technology readiness level was described as TRL 1. The Apollo program demonstrated that lunar dust would be a difficult problem for thermal control surfaces. It was discovered that dust had a strong effect on the α of thermal control surfaces, and that it would not be removed by simple brushing with a nylon bristle brush. The relationship between the amount of dust on a thermal control surface and the effect on thermal performance was unknown. Neither were effects such as dust particle size, dust color, or angle of incidence. Further, there were no lunar environment simulation facilities where experiments on the effects of dust on thermal control surfaces could be studied.

After three years of work, the broad outlines of the effects of dust on both AZ-93 white paint and AgFEP or AlFEP thermal control surfaces are understood. It is known that if the dust particles are smaller than 50 μm, that their size distribution is not important. It is known that there is no solar incidence angle dependence on the α beyond simple geometry. It is known that the color of the particles is important with the lightest dust degrading the α/ε of AZ-93 by a factor of 2.5 and the darkest by a factor of 5. The effect is even more striking with AgFEP with the lightest degrading α/ε by a factor of about 1.5 and the darkest by a factor of about 6.5. It is known that these thermal control surfaces on composite radiator substrates have higher α/ε than those on aluminum substrates. It is also known that a monolayer of dust particles will not appreciably change the radiator operating temperature for a given heat load.

Cont'd next chart



Progress has also been made in the area of dust mitigation, moving three technologies into TRL 4. It has been shown that texturing an AZ-93 thermal control paint does not affect the adhesion of dust particles to it in a simulated lunar environment, but that texturing an FEP surface lowers the adhesion. Similarly, although work function matching coatings over an AZ-93 thermal control paint does not affect the adhesion of dust particles to it in a simulated lunar environment, the same coating on an FEP surface lowers the adhesion dramatically. And study of bristle brushes has yielded two configurations that show promise of being able to remove more than 90% of the dust from either an AZ-93 or an FEP surface.

In addition, there are three more mitigation technologies that are at TRL 3 and if supported could be tested to push them to the TRL 4 within a year. These include the electrodynamic dust shield under development at NASA KSC, the lotus coating under development at NASA GSFC, and a coating developed under the LASER program by Ball Aerospace.

The goal of this technology development program was to raise the TRL to 6. All that is required to bring the dust effects on thermal control surfaces characterization efforts up to this level is the testing of lunar regolith samples to verify the simulant results. The largest obstacle to this is obtaining lunar regolith samples from the CAPTEM, which to date has been unwilling to release the 10 to 30 g of material it would require. The resources for verification would be modest, 1.0 FTE/WYE and $25K.

The requirements to raise the dust mitigation program to TRL 6 are less certain. Although there are promising mitigation strategies, none is considered to be without considerable technical risk. Fundamental work to better understand the physics of adhesion under lunar environment conditions is required to guide mitigation efforts. If at least one of the technologies under development proves to be effective, the resources to carry out the evaluation of the technology would require a three year effort funded at about 2.5 FTE/WYE plus $100K per year. This is in addition to resources to further develop the dust mitigation technology and provide samples for test, which varies with the technology.

Protection of Thermal Control Surfaces

References FY08 – FY10:

1. James R. Gaier, "The Need for High Fidelity Lunar Regolith Simulants", NASA – 2008-215261.
2. James R. Gaier, John Siamidis, and Elizabeth M.G. Larkin, "Extraction of Thermal Performance Values from Samples in the Lunar Dust Adhesion Bell Jar", NASA CP (2008).
3. James R. Gaier, John Siamidis, Scott R. Panko, Kerry J. Rogers, and Elizabeth M.G. Larkin, "The Effect of Simulated Lunar Dust on the Absorptivity, Emissivity, and Operating temperature of AZ-93 and Ag/FEP Thermal Control Surfaces", NASA TM (2008).
4. Paul S. Greenberg, Kenneth W. Street, and James R. Gaier, "Physical, Structural, and Compositional Analysis of Lunar Simulants and Regolith" Poster at LEAG-SRR (2008).
5. James R. Gaier, John Siamidis, and Elizabeth M.G. Larkin, "Effect of Simulated Lunar Dust on the Properties of Thermal Control Surfaces" Journal of Spacecraft and Rockets 47(1) (2009) pp. 147-152. doi:10.2514/1.4785.
6. James R. Gaier, Terry R. McCue, Gregory W. Clark, Kerry J. Rogers, and Tsegao Megesu, "Pre-Flight Characterization of EVA Fabric Samples for MISSE-7" NASA/TM-2009-215810.
7. James R Gaier, "Regolith Activation on the Lunar Surface and Its Ground Test Simulation" ICES 2009 paper 2009-01-2337. Also NASA/TM-2009-215648.
8. James R. Gaier, "Effect of Illumination Angle and Particle Size on the Performance of Dusted Thermal Control Surfaces in a Simulated Lunar Environment" ICES 2009 Paper 2009-01-2420. Also NASA/TM-2009-215647.
9. James R. Gaier, Mary Ann Meador, Kerry J. Rogers, and Brennan H. Sheehy, "Abrasion of Candidate Spacesuit Fabrics by Simulated Lunar Dust", ICES 2009 Paper 2009-01-2473. Also NASA/TM-2009-215800.
10. James R. Gaier and Brian J. O'Brien, "Collateral Dust and Soil and Its Roles on Apollo Science Missions", Poster at the Second Lunar Science Forum, July 2009.
11. Brian J. O'Brian and James R. Gaier, "Indicative Basic Issues About Lunar Dust in the Lunar Environment", Poster at the Annual Meeting of the Lunar Exploration Analysis Group, November 2009.
12. James R. Gaier, Kenneth W. Street, and Robert J. Gustafson, "Measurement of the Solar Absorptance and Thermal Emittance of Lunar Simulants", ICES 2010 paper accepted.
13. James R. Gaier, "Effect of Lunar Simulant Type on the Absorptance and Emittance of Dusted Thermal Control Surfaces in a Simulated Lunar Environment", ICES 2010 paper accepted.
14. James R. Gaier, Pablo G. De Leon, Pascal Lee, Terry R. McCue, Edward W. Hodgson, and Jeff Thrasher, "Preliminary Testing of a Pressurized Space Suit and Candidate Fabrics under Simulated Mars Dust Storm and Dust Devil Conditions", ICES 2010 paper accepted.
15. Joseph J. Bango, Michael Dzekian, Edward Hodgson, Bryan Murach, and James Gaier, "Development of Electrospray Technology for the Removal of Lunar Dust from Habitable Space Atmospheres", ICES 2010 paper accepted.

- Students sponsored/supported
  - 2008 – Eric Lee and Kerry Rogers
  - 2009 – Shanon Davis and Khrissaundra Journey
  - 2010 – Stephen Christopher, Shaneise Ellis, and Robert Misconin

DMP - Technical Approach

- ❑ Regolith (and Simulant) Characterization
- ❑ Simulant Characterization, Definition, Requirements, and Prototypes

Regolith & Simulant Characterization

POC: Kenneth Street **WBS: 1.4.1**

Technology Description:
Characterization of lunar regolith and simulants physical and chemical properties in order to ensure simulants will behave as regolith for TRL 6 testing procedures.

Future Applicability:
Procedures and methods developed under this task can be employed for the characterization of regolith form other extra terrestrial bodies (e.g. asteroids, Mars, comets…)

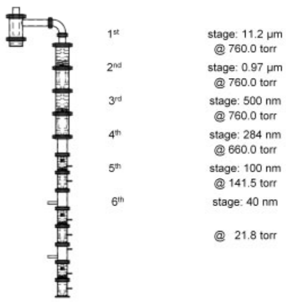


Figure 1: Multi-stage cyclone separator and target specifications.

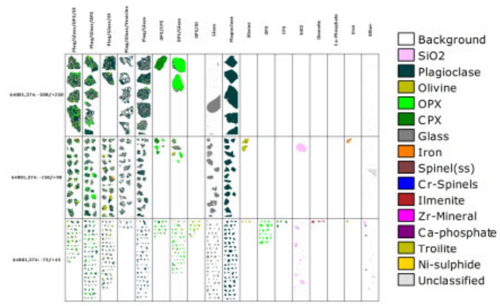


Figure 2: QemScan - particle size and shape as a function of mineral composition.

Technology Description: Self explanatory, all references to regolith infer lunar regolith

Future Application: Application of simulants is rather dubious since we were never granted any regolith to compare simulant properties to. Further, various physical properties are in different stages of development, due in part to budgetary constraints and current technology to assess those properties being undeveloped. See below for specific properties.

Particle Size distribution: Simulant and regolith in the >dust size range have been evaluated by Qem Scan (see Fig. 2 above) to TRL=6. However the dust size range is largely unmeasured to high TRL satisfaction. Some work done by JSC on Lunar Regolith has left simulants undone such that there is no adequate comparison and work done at GRC on simulants falters from lack of Lunar regolith samples to compare. Little if any substantive work has been done with Lunar Regolith because of the questionable integrity of regolith samples. The TRL for the Dust fraction is at approximately 2-3.

Sample composition: The elemental analysis we have for simulants and Lunar regolith are irrelevant as it is mineralogical composition that is required in order to successfully demonstrate comparability. Simulant and Lunar regolith in the >dust size range have been evaluated by Qem Scan (see Fig. 2) to TRL=6. However the dust size range is largely unmeasured to high TRL satisfaction. It was anticipated that the cyclone (see Fig. 1) would answer many questions in the dust size range; however, that technology is, at best, only at TRL 3 with respect to the challenging simulant samples. Little if any substantive work has been done with Lunar Regolith for several reasons, including but not limited to: no effort expended; questionable integrity of regolith samples; little automated equipment exists for characterization at this particle size range. The TRL for composition in the dust range is 1.

Particle Shape: The equipment required to get the appropriate information has just become available. Simulant data has been gathered and is under reduction. No Lunar regolith has been granted for comparison at this time. Current TRL=2-3.

Surface Energy: Surface energy has been determined for simulants to the TRL=6 level; however, no Lunar regolith was granted so the TRL=1 Lunar for regolith. Since there is no comparison between Lunar regolith and simulant, the overall TRL=2-3 for simulant until such comparison is made.

Magnetic Susceptibility: Magnetic susceptibility on a per particle basis has been determined for simulants to the TRL=6 level; however, no regolith was granted so the TRL=1 for regolith. Since there is no comparison between regolith and simulant, the overall TRL=2-3 for simulant until such comparison is made.

Surface Activation: The equipment required to get the appropriate information has just become available. Attempts to adapt it to providing information for simulants has started. No regolith has been granted for comparison at this time. Current TRL=1.

Adhesion: The equipment required to get the appropriate information has just become available. Attempts to adapt it to providing information for simulants has started. No regolith has been granted for comparison at this time. Current TRL=1.

Abrasion: It is difficult to assess this global topic since it covers the span of skin, fabric, metals, ceramics, plastics, etc. None-the-less, some progress has been made in certain areas. Fabric has been evaluated in simulant by two independent methods. For metals and plastics, technology has been developed (see Fig. 4) to a useful stage and quantitative data taken. These methods are not suitable for use with regolith due to the quantity of abrasive required. The current TRL for Fabrics is 2-3.

Tribocharging: This topic has moved to elsewhere in the DMP and is no longer covered under this WBS.

Miscellaneous topics:

Spectral Properties – This topic is covered elsewhere but will also be touched upon here. Literature values appearing on integrated emissivity are questionable due to the fact that many were taken by telemetry which is inherently less accurate. Ground based measurements on simulants are well founded and equipment is available for such measurements. Unfortunately one of the two required instruments does not appear to be working properly. No Regolith has been obtained for comparison. The overall TRL for this effort is 2-3.

Thermal properties – There are two specific items wrapped up under this heading. Melting and phase transitions have been determined of several simulants and their major and some minor components (see Fig. 3). Water determination has been hampered by coevolution of carbon dioxide complicating stand-alone thermogravimetric assay and loss on ignition. No Regolith has been obtained to compare these results to (although none is necessary for the gravimetry since no water of carbon dioxide exists in non shadowed regolith). The TRL for this effort is in the 2-3 range.

Regolith & Simulant Characterization

Summary of Accomplishments FY08 – FY10:

•Procedures, Methods and Equipment have been developed under this task to measure the following properties deemed important to the development of space exploration equipment: Magnetic Susceptibility, Particle Size and Shape; Particle Composition; Size Fractionation (multi-stage cyclone separation in the 0.05-10 um range); Surface Energy; Surface Activation and Chemistry; Adhesion; Abrasion; Spectral Properties (emissivity); Thermal Properties (melting and phase transitions); Water Content

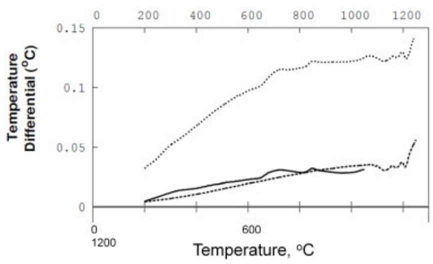


Figure 3: Differential Thermal Analysis (DTA) of JSC-1AF. Lower: (solid) first scan (dashed) repeat scan indicating irreversible phase changes during drying.

Remaining FY10 Content:

•This task is basic research on the "level of effort" basis. We will continue to evaluate and document methods and properties until funding is exhausted.

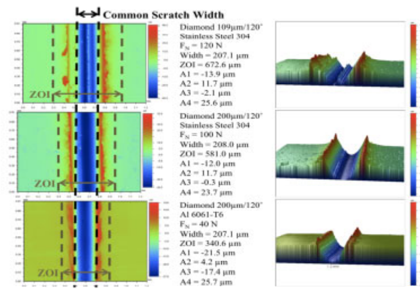


Figure 4: Proposed new ASTM Abrasion Standard: 3 scratches having identical ASTM scratch width but significantly different levels of damage.

Summary of Accomplishments: Rolled up in slide 1 commentary

Remaining Content (not limited to FY10): Considerable work in characterization is required before any simulant will be suitable for TRL=6 testing of equipment. Literally no work has been done on regolith (especially the dust fraction). Simple mineral matching is no guarantee that the simulant will perform as regolith. Many studies have indicated that the agglutinate content of regolith completely changes its properties. Further, the water (and carbonate) content of simulants is an additional complicating issue.

Regolith & Simulant Characterization

Technical Readiness Level Progression:
TRL at Project Start: 1
Current TRL: 1-3 (depending on property)
What is needed to progress to TRL 6 (Technical): In some properties TRL 6 may never be achieved due to the State-of-the-Art in making these measurements. In such cases TRL = 3-4 may be completely adequate for the properties of interest.

TRL at project Start: 1

Current TRL: 1-3 depending on property (as justified by dialog under frame
1) What is needed to get to TRL 6: Providing there are no other properties to be added as comparisons between simulant and regolith.
This estimate assumes that access to regolith will be granted when necessary.
As such TRL 6 may never be achievable for some properties.

Regolith & Simulant Characterization

Selected References FY08 – FY10:

• **References: publications, Test Reports, NASA STI Reports, deliverables**

"Expected Mechanical Characteristics of Lunar Dust: A Geological View." D. Rickman and K.W. Street,. **Am. Inst. Phys Conf Proc, 969**, 949-955 (2008)

"Adsorption of Water on JSC-1A (Simulated Moon Dust Samples) - A Surface Science Study." J. Goering, S. Sah, U. Burghaus, and K.W. Street, Jr. Surface and Interface Analysis, 40(11) 1423-29 (2008).

"Development of a Multi-stage Axial Flow Cyclone." T-C Hsiao, D-R. Chen, L. Li, P. Greenberg, and K. Street, Aerosol Science & Technology, 44(4) 253-261(2010).

"Developing Abrasion Test Standards for Evaluating Lunar Construction Materials." R.L. Kobrick, D.M. Klaus and K.W. Street, SAE Technical Paper 2009-01-2377

"Thermal Properties of Lunar Regolith Simulants." K.W. Street, Jr., C.S. Ray, D. Rickman, and D.A. Scheiman, Earth & Space 2010, Conference proceeding. 2010. NASA/TM-2010-216348

"Developing Abrasion Test Standards for Evaluating Lunar Construction Materials." R.L. Kobrick, D.M. Klaus, and K.W. Street, SAE Technical Paper 2009-01-2377,

"Standardization of a Volumetric Displacement Measurement for Two-body Abrasion Scratch Test Data Analysis." R. L. Kobrick, D. M. Klaus, and K. W. Street, Jr., NASA/TM-2010-216347

" Validation of proposed metrics for two-body abrasion scratch test analysis standards." R.L. Kobrick, D.M. Klaus, and K.W. Street, Jr Submitted to Wear. 2010

"Abrasion Testing for the Lunar Environment." R.L. Kobrick, D.M. Klaus, K.W. Street, Jr., and J.R. Gaier, Submitted for NASA TM 3/4/10.

"Measurement of the Solar Absorptivity and Thermal Emissivity of Lunar Simulants." J.R. Gaier, K.W. Street and R.J. Gustafson, Conference Proceeding 40th International Conference on Environmental Systems (ICES), Barcelona, Spain. 7/11-15/10.

"Three-Body Abrasion Testing Using Lunar Dust Simulants to Evaluate Surface System Materials." R.L. Kobrick, K. Budinski, K.W. Street, Jr. and D.M. Klaus, Conference Proceeding 40th International Conference on Environmental Systems (ICES), Barcelona, Spain. 7/11-15/10.

"Defining an Abrasion Index for Lunar Surface Systems as a Function of Dust Interaction Modes and Variable Concentration Zones." R.L. Kobrick, D.M. Klaus, and K.W. Street, Jr., Journal - PSS paper Conf Proc.

"Magnetic Susceptibility Characterization of Lunar Dust Simulants" L. Li , P. Greenberg, K. and D-R. Chen, Journal of Geophysical Research - Planets, submitted June 2010.

• **# of students sponsored/supported (if applicable)**

• 2 GSRP
• 5 Undergraduates supported by NASA sponsored UNCF Consortium Grant
• 1 Faculty Fellow supported by NASA sponsored UNCF Consortium Grant

Selected References, complete bibliography is on Windchill, in the Dust Project Closeout Documentation folder.

Simulant Characterization, Definition, Requirements & Prototypes

Technology Description: Develop simulants that meet the users' needs (i.e., the required properties/behavior) and provide characterization data, MSDS sheets, handling, and other necessary documentation. The DMP was tasked with the development, characterization, and production of various types of lunar regolith simulants (more than just dust) covering a range of grain sizes and properties depending upon the simulant user's test objectives and applications.

Simulant Production Process:

- Acquire Apollo lunar sample data or other lunar-acquired data to better understand the regolith properties and load into the Figures of Merit (FoM) (Size Distribution, Shape, Composition, and Density) Database
- Investigate feedstock sources to make the simulant types
- Develop simulant processes (crush, grind, mill and blend) for both small and large quantities
- Once the recipe is developed, then start production

Simulant Users' Needs Data Collection:

- Collection and summary of users' requirements for simulants via a web survey
- Develop and supply simulants based on web requests and available budgets
- Provide consultation and guidance to the users on the proper selection, use, handling and storage of the various types of simulants

Future Applicability: Providing different types and fidelities of simulants for technology development and verification/certification of hardware is an essential two-pronged risk reduction "tool". While MSFC was primarily tasked to worked on lunar simulants, other simulants will be needed for other future destinations (i.e., Mars, asteroids, etc.). The Simulant Team including other NASA centers and contractors are prepared to develop those as well.

Technology Description and Future Applicability:

The Simulant Task was assigned to Marshall Space Flight Center (MSFC) in 2003 (pre-ESAS/pre-ETDPO) with the following objectives: 1) reproduce the characteristics of lunar regolith (representing the multiple lunar regions such as mare, highlands, and polar) in simulants, 2) develop processes to controllably reproduce regolith characteristics, 3) produce simulants as inexpensive as practical, 4) produce simulants in the amount needed, and 5) produce simulants to meet users' schedules. In order to successfully realize these goals/objectives, the following must be accomplished: 1) understand the characteristics of the lunar regolith and how it is produced (i.e., study lunar samples), 2) develop techniques/methodologies to reproduce the characteristics of lunar regolith, 3) understand which aspects of the lunar regolith, such as composition, particle size, particle shape, and density, are applicable to each individual technology being developed for use on the lunar surface, 4) advise simulant users on the most appropriate simulant to use for their individual project (i.e., notify users of the risks involved with simulant use and their limitations for accurately reproducing the lunar regolith and be knowledgeable of all available simulants), 5) collect users' data to evaluate the effectiveness of the prescribed simulant and apply the results to the next generation of simulants, and 6) create a method to compare simulants to the lunar regolith and to other simulants quantitatively (hence the creation of the Figures of Merit software) for purposes of judging which simulant(s) has the best fit for the application.

Before the lunar architecture was formulated, MSFC oversaw the SBIR Phase III contract with Orbitec in Madison, WI who was responsible for developing and delivering 16 tons of JSC-1A (a mare simulant) since the previously made JSC-1 which was made by JSC many years ago was all but exhausted. In order to meet the renewed interest and demand for lunar simulants, fourteen tons of the Medium grain size (JSC-1A); 1 ton of the Fines grain size (JSC-1AF); and 1 ton of the Coarse grain size (JSC-1AC) were made. Much of this simulant has been distributed to the user community.

After the first lunar architecture was released in late 2005 with a proposed landing site near the lunar poles, a different type of simulant was required – one that represented the lunar polar region. Since no Apollo missions had visited the poles, there were no samples brought back to Earth from that locale. Thus, other means of predicting the moon's polar regolith properties were required and, fortunately, some alternatives existed. Based upon lunar fly-bys and other "remote" research, lunar scientists were of the opinion that the polar regions were similar to the lunar highlands regions of the Moon. And, NASA was in possession of actual lunar samples from the highlands region which were brought back from the Apollo 16 mission.

In the mean-time, the Simulant Team at MSFC contracted with the US Geological Survey (USGS) in Denver to assist in developing, characterizing, and producing simulants. Using this Apollo 16 lunar sample and research data, the first simulant created under the MSFC/USGS partnership was a highlands prototype simulant named "NU-LHT-1M" (NASA/USGS, Lunar Highlands Type, series 1, grain size Medium). Since its creation, a second generation (NU-LHT-2) has been produced reflecting multiple grain sizes, and a third is in development. Each new generation typically increases in fidelity as needed in order to meet the users' test requirements. That is, each generation becomes more like the lunar regolith. However, it is important to note that no lunar simulant (however good) will ever replicate the actual lunar regolith 100%. Due to the differences in the weathering conditions due to Earth's atmosphere as well as other factors, terrestrial Earth materials are more altered than the lunar regolith.

In order to produce the NU-LHT simulant, Apollo 16 core samples were used to investigate and target mineralogy and composition were defined. Different feedstocks (mined terrestrial rocks) from around the world were investigated for suitability. Different methods of processing (crushing, grinding, milling, blending, and melting) were also investigated to assess how different process techniques could make the terrestrial rock "look and act" like lunar regolith. Once the appropriate feedstocks and processing techniques were defined, "recipes" were developed and production of the simulant(s) commenced. Research and development continues on the Simulant Task for new types of feedstock (both natural and synthetic) to make new types of simulants, including a high-titanium mare basalt.

The Simulant Team created an online Simulant Survey/Request Form to help identify the users' needs more effectively. The Team used that information to get a general idea of the user's task and their objectives in using the simulant(s). The Team then contacted the user to establishment interfaces and clarify and verify the simulant application. In addition, this communication assisted the user in obtaining the best simulant for their task and to provide consultation and guidance in the proper use of the simulant including any downsides involved with the simulant selection. This method provides the most confidence that the risk associated with that lunar technology is reduced as much as possible, thereby, assuring greater mission success.

Simulant Characterization, Definition, Requirements & Prototypes

Summary of Accomplishments FY08 – FY10:

Programmatics

- Supported ETDPO TCRs and IBRs
- Developed and managed budgets (PPBEs)
- Updated Simulant Task deliverables and provided inputs to Dust Project Plan
- Provided multiple presentations to CxP and ETDPO including TIM with CxP/LSS
- Attended multiple conferences (19) including writing abstracts and papers (12) and making presentations
- Provided interviews or exhibits for 13 media events (Wall Street Journal and other newspapers, internet/web, and tradeshows)
- Supported numerous Education and Public Outreach (STEM) activities
- Performed as Sub-Topic Manager, Reviewers, and CoTRs for specific SBIR activities related to Simulants
- Maintained public Simulant website (isru.msfc.nasa.gov)
- Participated in several Workshops including Lunar Regolith Behavior Workshop and Dust Workshop
- Conducted the 2009 Lunar Regolith/Simulant Users Workshop in Huntsville, AL **[SC-19]** (~ 120 attendees including internationals)
- Developed Lunar Regolith/Simulant Users' Needs Survey, data collection and consultation services and polled ETDPO and CxP Projects (35 survey submissions received, analyzed, and reported upon)
- Conducted meetings, webexes, and telecoms with Simulant Users
- Collected (some) Users Test Results that utilized simulants
- Generated 21 documents **(listed on slide under references)**
- Drafted Lunar Regolith Simulant Book as a result of the Lunar Regolith/Simulant 101 Course developed and provided during the 2009 Workshop (still in work; to be published early next year)

Summary of Accomplishments (FY08 – FY10):

Programmatically, the last two years have been extremely productive. The Team supported the normal programmatic/project activities including the Technical Content Reviews, Integrated Baseline Reviews, PPBE exercises, and Project Plan updates. Additionally, the Team supported several TIMs and Workshops as requested by the customer and made presentations on the Simulant Task status. Other activities of the Simulant Team included 12 conferences attended, 19 conference papers written, 13 media appearances or events (newspaper, Internet, and tradeshow booths), and numerous Education and Public Outreach events (e.g., talks to students, simulants used in educational settings, etc.).

The Simulant Team also kept track of specific Small Business Innovative Research (SBIR) projects as Contracting Officer's Technical Representatives. These SBIR projects involved creating lunar regolith simulant components (such as agglutinates or nanophase iron) or technologies for in situ resource utilization and the study of the lunar regolith. Aside from outreach and SBIR work, the Simulant Team focused on the simulant user's needs. The Simulant Team initiated teleconferences with the simulant users to ascertain their needs and to provide guidance on the simulant selection(s). The Simulant Team notified the users of limitations of the simulant regarding how well it replicated the lunar regolith, as well as the safe and proper handling of simulants. Several of the documents related to simulants, simulant use, and other Simulant Team activities are posted on the In Situ Resource Utilization (ISRU) public website (http://isru.msfc.nasa.gov).

The Simulant Team organized a 2009 Lunar Regolith/Simulant Users Workshop that was held in Huntsville, Alabama. This Workshop was attended by over 120 individuals representing various NASA centers including ETDPO and CxP projects; industry; academia; and internationals. As a prelude to the Workshop, a Lunar Regolith/Simulant 101 “course” was conceived and held to educate users less familiar with regolith and simulants. A Survey was developed that is the tool for collecting regolith and simulant requirements based on users’ projections. Thirty-five (35) simulant requests/surveys were collected from ETDPO and CxP, and teleconferences/webexes were set up between the simulant user and the Simulant Team. This data was assimilated and analyzed to assist with forecasting simulant types, fidelities, and quantity requirements in addition to budget requests. A Simulant Users’ Needs Document was written summarizing the results. The Team also provided simulants to the users as supply and budgets allowed. Results from these simulant user tests have been collected, but others have yet to be received.

A total of twenty-one (21) documents were written by the Simulant Team members (see reference list). A book is also being written, tentatively entitled “Lunar Regolith Simulant”, for publication by CRC Press. This book was borne out of the Simulant Project Lead’s idea to have a short course titled, Lunar Regolith/Simulant 101, offered as part of the 2009 Lunar Regolith/Simulant User’s Workshop to assist the novice user in understanding lunar regolith and simulants.

Simulant Characterization, Definition, Requirements & Prototypes

Testing/ Characterization/ Production

- Performed literature search on all existing known Apollo data
- Established what data was unknown and needed in order to develop simulants
- Acquired Apollo 16 core 64001/64002 Samples to complete the data set
  - Performed testing on samples and collected/analyzed data (SEM/EDS instruments)
  - Defined Apollo References for Site-Specific Lunar Regions
  - Determined Apollo properties to be measured
- Developed Figures of Merit (FoM) Software – algorithms were developed to quantitatively compare simulant properties to lunar regolith properties in addition to comparing simulants to each other **[SC-25, 40]**
  - Populated with latest Apollo lunar samples data
  - Collected property data on existing simulants; added to FoM database
- Designed and implemented efficient, effective, and economical simulant development processes (i.e., feedstock, milling, mixing, packaging, shipping, etc.) for both the simulant prototype (small-scale) and production (large-scale) phases. (Documented in the Simulant Development Recipes and Process) – further work is needed to decrease costs
- Characterized 6 simulants and developed/updated documentation
- Developed Feedstocks (natural and synthetic) – glasses and agglutinate production/Zybek, mineral separates production, mineral synthesis, nanophase iron/Orbitec)
- Simulant Development/Production: **(~ 2000 kg LHT Series)**
  - NU-LHT -2M, -2C, -1D Simulants (NASA/USGS Lunar Highlands Type)
  - NU-LHT-2E, and -2EG Simulants (Low Fidelity Excavation Grade, without and with Glass, respectively)
  - DTM-1(Dark Test Material)

Summary of Accomplishments (FY08 – FY10) (Cont.):

Technologically, the Simulant Task has progressed very well. Literature searches with respect to lunar regolith samples were performed to define references for site-specific lunar regions that needed to be simulated. Once the best Apollo mission location(s) were identified to represent the simulant locale desired, various Apollo samples were requested from the CAPTEM Board for further examination if warranted. The Team was approved to receive Apollo 16 core samples 64001/64002 to study. Scanning electron microscopy (SEM) and energy dispersive spectroscopy (EDS) were employed to define the lunar highlands region composition (bulk chemistry and mineralogy). Particle size distributions were obtained from the literature as well as re-measured. Particle shape data is lacking for actual lunar regolith samples and is one of the properties that must still be measured using Apollo samples in order to produce higher fidelity simulants. Some shape data, however, using simulants has recently been measured and collected by KSC/Dr. Phil Metzger and is being incorporated into the FoM database.

The Simulant Team developed the Figure of Merit (FoM) software from algorithms designed to quantitatively compare simulant properties to lunar regolith and to other simulants. The FoM software was updated as new data came in and comes in – from both Apollo samples and new simulant characterization data. The Simulant Team also designed and implemented efficient, effective, and economical simulant development processes for both the Simulant NU-LHT series prototypes and production (large scale) phases. While the team has made strides in these areas, more work is needed to bring the costs of high fidelity simulants down and to address the specific challenges such as the incorporation of nano-phase iron in agglutinates. All of this progress has been described in the Simulant Development Recipes and Process Document.

Approximately 2000 kg of the NU-LHT series simulant was produced. In addition to NU-LHT-2M, four other simulants (FJS-1, Chenobi, OB-1, and JSC-1A) have been characterized for composition, size, and shape – documentation has been developed and updated based on these results. Two low fidelity excavation grade simulants were recently produced from the NU-LHT series feedstock (one with glass and agglutinates and one without). Feedstock development continues, including agglutinate production (with nanophase iron), mineral separation techniques, and mineral synthesis to produce higher fidelity simulants. Work also continues on characterizing simulants not developed by the NASA/USGS partnership but by others for purposes of assessing their potential use for individual tasks (e.g., Black Point 1). In addition to simulants, material that could later be used to make simulants was developed for specific experiments. Case in point, a Dark Test Material (DTM-1) was developed by the team for GRC/J. Gaier to be used in "worst case scenario" thermal/spectral testing.

Simulant Characterization, Definition, Requirements & Prototypes

Summary of Accomplishments FY08 – FY10: (Extras)

- 19 Conference papers written; 12 conferences attended
- 13 media appearances (newspaper, web, and tradeshow booths)
- Maintained cognizance of specific SBIR activities as CoTRs that contribute to Simulant Task
- Communicated/interfaced with the users to understand their needs based on hardware designs, test objectives, and simulant use and applications.
- Provided guidance to the users on simulant(s) selection (including any limitations) and on the safe and proper handling of simulants.
- Posted several simulant documents and conference proceedings on public website (isru.msfc.nasa.gov)

Remaining FY10 Content:

•Finalize the Simulant Development Recipes and Processes Document (USGS, SC 49-50)
•Update the Simulant User's Guide to include user test data collected thus far
•Finalize the "Lunar Regolith Simulant" book which communicates key concepts and highlights "lessons learned".
•Captures everything we've learned (~450 pages, chapters from experts in all fields)

Remaining Tasks to be Performed:

There are still a few documents to be finalized by the Simulant Team for fiscal year 2010. The first is the Simulant Development Recipes and Process Document (SC-49-50). This document, which is being written by the USGS, will contain all the recipes and process controls developed and used to produce the NU-LHT series simulant prototypes. The second is an update to the Simulant User's Guide, which includes the Fit-for-Purpose Matrix. Recent contributions of simulant user data will aid in the document update. The Fit-for-Purpose Matrix advises simulant users on the simulant that will most likely meet their needs, and what specific limitations exist for the individual simulants with regard to specific tasks. However, a word of caution – the Simulant User's Guide and "Fit-for-Purpose" Matrix are not meant to be used in place of conferring with simulant experts who can provide consultation and guidance as necessary. It is critical that engineers consult with simulant experts to ensure that appropriate simulants are being used properly. Finally, the Lunar Regolith Simulant Book will proceed towards publication. The publisher, CRC Press, continues to receive updates on the progress of the book. No definitive deadline has been set for its publication, but it is expected to be complete early spring of 2011.

Simulant Characterization, Definition, Requirements & Prototypes

POC: Carole McLemore **WBS: 1.4.3**

Technical Readiness Level Progression:

TRL at Project Start: TRL-3

Current TRL: TRL-5 for lunar regolith simulant (other regolith simulants such as Mars or asteroids are TBD)

What is needed to progress to TRL 6 (Technical, Schedule, Budget):

Technical:

•Better identification and understanding of Users' needs

•Development of multiple types of simulants reflecting properties as needed for users' test objectives based on lunar regions

•Identification of various feedstocks (affordability, fidelities, purities, locations, accessibility, etc.)

•Improved and more economical processes for development of simulant prototypes and production of large-scale quantities

•More testing of simulant properties as well as Apollo property characterization and other lunar data available

•Increased accuracy and precision in the Simulant "Fit-for-Purpose" Application Matrix (guide for simulant uses)

Schedule:

•2 – 3 years

Budget:

•TBD

TRL Status and Steps to TRL 6 Progression:

Since the Simulant Task does not involve developing flight hardware, it is somewhat difficult to label it in the traditional NASA-defined TRL levels. At the request of the program, though, the Simulant Task was estimated to be at a TRL 3 at the start of the effort. Advances in technologies and processes have occurred over the last few years during the making of the prototype simulants and, eventually, the simulants resulting in a TRL 5 rating. Examples of this include progress made in the separation of minerals, manufacture of synthetic minerals, and new milling techniques.

In order to achieve TRL 6, there are several things that need to occur that will directly and indirectly influence the advancement of the technologies. First, the user requirements for simulants must be better defined which will drive simulant properties and fidelities. Next, more sources of different types of feedstocks (both terrestrial and synthetic) must be located and/or developed/manufactured. This will raise the simulant fidelity and mitigate risk to the hardware. One of the most important items for advancing the technology readiness is to develop new ways for processing/manufacturing the simulants whether it be making the process more efficient, less energy intensive, quicker, or more tight in quality control; any and all of these areas should be tackled to improve the simulant product. After the simulants are made (whether by NASA or others), more testing is required to verify their closeness to lunar regolith. In some cases as more technologies are advanced to improve measurements in accuracy or precision or to higher resolutions, even the Apollo lunar samples will probably need to be re-examined and re-studied. Proceeding from small-scale production quantities to large-scale quantities will require technologies that can assure quality control and product assurance between batches of simulants. As these areas are addressed and technologies matured, they should be documented in the appropriate files. It is expected that these advances could raise the Simulant Task from TRL from 5 to 6 in the next two to three years assuming the budget was provided.

Simulant Characterization, Definition, Requirements & Prototypes

References FY08 – FY10:

• References: publications, Test Reports, NASA STI Reports, deliverables

★ *Documents pertinent to Simulant Users*

1.Plan for Data Acquisition from Apollo Lunar Samples
2.Compilation of Apollo 16 Data Sources Relevant to Simulant Development
3.Analysis of Apollo 16 Samples for the Advancement of Simulant Development
4.Current Standard Analytical Processes for Simulant *aka Test Protocols Document*
5.Lunar Regolith Data Needs
★ 6.Lunar Regolith/Simulant Users' Needs Survey Report
★ 7.Lunar Regolith Simulant User's Guide
8.Lunar Regolith Simulant Requirements (also, Generation of Requirements for Simulant Measurements, NASA/TM-2010-216445)
★ 9.Regolith Simulant Naming Protocol Document
★ 10.Material Safety Data Sheet Lunar Regolith Simulant NASA/U.S. Geological Survey Lunar Highlands Type Series
★ 11.Recommended Sample Preparation Procedures Before Sub-Sampling for NU-LHT-2M Containers
★ 12.Figures-of-Merit Software User's Guide
★ 13.Figure of Merit Characteristics Compared to Engineering Parameters (NASA/TM-2010-216443)
14.Figures-of-Merit Algorithm Description
15.Simulant Recipes and Process Control
16.Stillwater Dump evaluation plan
17.Apollo References for Site-Specific Lunar Regions
18.Feedstock Status Report
★ 19.Simulant Splitting Instructions
★ 20.BP-1 Report (Black Point Basalt Prelim Findings) (NASA/TM-2010-216444)
21.Design and Specifications for the Highland Regolith Prototype Simulants NU-LHT-1M & -2M (NASA/TM-2010- 216438)

Simulant Task Documentation:

Currently, a total of twenty one (21) documents have been written by the Simulant Team that specify any number of tasks undertaken over the last several years based on the achievements to date. These documents include: plans for acquiring lunar samples; user requirements reports; simulant applications and best uses; material safety data sheets; instructions for splitting samples and handling simulants; figure of merit user's guide; and other publications, test reports, NASA Science and Technology Information reports, and deliverables. Some of these detail the plan of study for Apollo samples, the results of studies on the Apollo samples, and the recommendations for simulant development based on those samples. Other documents detail how simulants are compared to regolith via Figures of Merit, and the rationale behind the four properties chosen as Figures of Merit. Many publications document the work of the Simulant Team in defining the appropriate feedstocks, the process controls for simulants, and the evaluation techniques for those simulants. Of the twenty one publications listed here, nine are most pertinent to simulant users. These are specific to user's needs, such as descriptions of simulant types, comparisons of simulants and regolith, recommendations for the appropriate simulants for given tasks, handling instructions, and material safety data sheets.

Simulant Characterization, Definition, Requirements & Prototypes

POC: Carole McLemore **WBS: 1.4.3**

Students sponsored/supported:

- 2007-2009 – Sponsored students for 3 summer (Kyle Chavez for 2 summers; Ariel Baines for 1 summer)
- 2009 - Mentored two interns through the ESMD Intern Program and Minority University Research and Education Program to assist with the Simulant task.
- 2009 – Sponsored Dr. Bill Cross from South Dakota through the ESMD Summer Program
- 2010 – Sponsored 2 students (not paid by Simulant task)

Deliverable – Simulants to Users:

u **NU-LHT-1D (Dust):**
- – Total NU-LHT-1D produced March 2008: 1 kg
- – Total NU-LHT-1D distributed to Dust users: 1 kg
- – Total NU-LHT-1D still in inventory: 0 kg

u **NU-LHT-2M:**
- – Total NU-LHT-2M produced March 2008: 570 kg
- – Total NU-LHT-2M distributed to ISRU users: 367.75 kg
- – Total NU-LHT-2M still in inventory: 202.25 kg
- – Majority distributed to ISRU personnel
- – Small amounts to: Honeybee Robotics, Orbitec (5 kg), Plasma Processes (5 kg)

u **NU-LHT-2C:**
- – Total NU-LHT-2C produced August 2008: 420.75 kg
- – Total NU-LHT-2C distributed to ISRU users: 0 kg
- – Total NU-LHT-2C still in inventory: 420.75 kg

u **NU-LHT-2EG:**
- – Total NU-LHT-2EG produced September 2010: 500 kg (with glass and agglutinates)
- – None yet distributed

u **NU-LHT-2E:**
- – Total NU-LHT-2E produced September 2010: 500 kg (no glass or agglutinates)
- – None yet distributed

Outreach and Status of Deliverables:

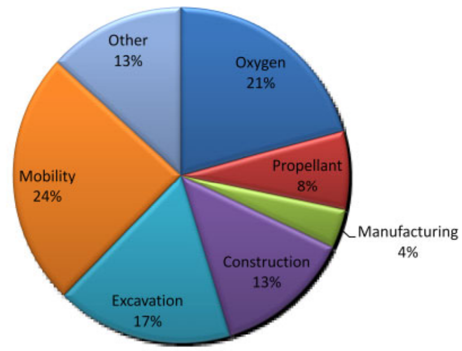
Numerous students and college faculty were sponsored, supported, or participated in work for the Simulant Task so education (STEM) and outreach endeavors were emphasized. Kyle Chavez's first summer (2007) as a NASA intern was spent supporting several fabrication activities. Kyle returned for a second summer (2008) internship and set up an extensive Microsoft Excel (Microsoft Corporation) spreadsheet to gather and sort inputs from the simulant users survey questionnaire that was linked from the ISRU website. Ariel Baines spent one summer internship (2009) supporting the simulant activity by developing requirements and designing a simulant database. Rashidi Hunter (summer 2009), a mathematics and engineering intern from Morehouse College, worked on statistical models of >1 cm particles in the lunar regolith. Dr. William Cross, Department of Materials and Metallurgical Engineering from the South Dakota School of Mines and Technology, spent the summer of 2009 at MSFC and designed beneficiation techniques (specifically, mineral separation techniques) that can be used for simulant development or for lunar regolith examination. This topic continues to be researched by Dr. Cross's senior students. Robert West and Alfredo Wetzel studied X-ray radiographs of Apollo 16 cores to estimate variation in porosity and density, as well as estimating larger particle size abundance. Intern William Betts (Fall 2009) worked on defining shape parameters, analyzing data for volatile loss in simulants, and compiling data on “extinct” simulants. Interns Emily Dixon and Matthew Pendleton (summer 2010) completed analysis of shape for five different simulants, although they were not funded specifically by the Simulant Task.

The Simulant Task also produced five (5) different simulants with two levels of fidelity. NU-LHT-1D was a first-generation, dust-sized simulant with a target particle size of less than 20 μm. None of the dust fraction remains available as it was all distributed to the users. NU-LHT-2M is a second-generation simulant with a target particle size of less than 1 mm. Approximately 200 kg of 2 M remains available for use. The coarsest simulant, NU-LHT-2C, has a particle size less than 10 cm. Just recently, two additional simulants, NU-LHT-2E (excavation grade with no glass or agglutinates) and NU-LHT2EG (excavation grade with glass and agglutinates) have been produced in amounts of 500 kg each. The excavation grade simulants have good physical properties but have low fidelity chemistry properties and are, thus, not appropriate for reactor processing such as carbothermal methods. The NU-LHT-1D, -2M, and -2C series simulants are fairly high fidelity in both the physical and chemical (mineralogical) properties so are appropriate for reactor processing and mechanical type testing, for instance. The Simulant User's Guide and "Fit-for-Purpose" Matrix are a good source of information for simulants; experts should also be consulted. All of these simulants were completely designed, produced, and characterized by the Simulant Team.

Lunar Regolith Simulant Survey Results Summary

Simulant Users Survey - Short Summary

Name	CxP LSS Total (kg)	ETDP Total (kg)	GRAND TOTAL (kg)
Year	Amount	Amount	Amount
2011 *(Including roll-up yrs 2008 - 2010)*	119,444	7,455	126,899
2012	0	9,993	9,993
2013	0	396	396
TBD	18	397	415
TOTAL	119,462	18,241	137,703



Largest Requests from:
CxP/ Excavation: 93,000 kg
CxP/ LSS: 26,000 kg
ETDP/ ISRU: 8,000 kg
ETDP / Hydrogen Reduction of Regolith for Oxygen: 5,000 kg

Lunar Regolith/Simulant Survey Results (Total Requests by Program/Project and Year):

There is a great need for simulant, as revealed by the Lunar Regolith Simulant Survey results. In fact, presently the quantity requested far exceeds the supply. Constellation and Lunar Surface Systems projects constitute the majority of the simulant requests (87%), primarily from the Human Robotic Systems. Exploration Technology Development constitutes approximately 13% of the demand. The task requiring the greatest amount of simulant is mobility (gears, seals, wheels, connectors), followed closely by oxygen extraction, excavation, and construction. Other uses that do not require much simulant are tasks such as dust mitigation, human health, heat transfer, fire protection, life support systems, and radiation shielding. Within six years, approximately 137,703 kg of simulants were estimated for use by all users that filled out the survey/request form. It is the great need for simulants by numerous tasks that makes the availability of high fidelity simulants and *all* types of simulants critical to planetary surface technology development and other areas.

While the Simulant Team focused on lunar simulants, they are also prepared to expand the suite of simulants to Mars, asteroids, and other bodies that robots, hardware, and/or humans will explore. The Survey is a living, breathing document that will evolve and change as users' requirements change and will be updated annually as a minimum.

KPP and Risk Assessment

- **KPP and Risk assessment are as referenced in the DMP Project Plan, dated,**
  - Current status is unchanged due to budget reductions and resulting milestone deliverable changes.
  - KPP updates are included in DMP Technology Insertion Process, referenced on chart 7
  - Project Risks located on windchill at:
    - https://ice.exploration.nasa.gov/Windchill/netmarkets/jsp/folder/view.jsp?oid=folder~wt.folder.SubFolder%3A2178499576&u8=1

Lessons Learned

- **It is better to try to develop technologies with aggressive goals, aggressive schedules, and no budget margin than not to try, even if the risks are very high.**
  - Although we have not met all our technical goals for dust mitigation, we made substantial progress
  - Further development is required for any planetary mission, and will continue to be high risk.

- **Down-selecting technologies before TRL-4 is extremely risky**
  - A serious technology development program supporting serious program schedules should not take this risk.
  - Careful study of dust effects on critical systems is required for informed evaluation of candidate technologies and down select decisions

Transition to ETDD

- **Cross cutting Dust Mitigation Technology (and related) content included in transition formulation:**

  HRS – dust tolerant components work is partially covered in GRC content

  ISRU – includes:
  simulants work (user needs and requirements assessment, characterization, feedstock assessment, etc. as required)
  process stream filtration technology (not current dust content, but includes some of the people who worked in the former Dust and ELS projects)

  Life Support – includes:
  atmospheric particulate management (from ELS project)
  some dust effects content (from Dust and Thermal Control projects)

  EVA – no dust related content included in transition formulation

At Risk Technologies

- **The following DMP technologies are not being funded through ETDD:**
  - Mechanical Components and Mechanisms (minimally funded)
  - Lotus Dust Mitigation Technology
  - CO_2 Shower
  - SPARCLED
  - Electrodynamic Dust Shield
  - Thermal Radiators (minimally funded)
  - Dust Tolerant Connectors
  - Dust Mitigation for Surface Power Systems

- **Means loss of technology and loss of expertise as personnel is re-assigned**

DMP Technologies have other Applications

DMP Technologies should be funded for flexible path applications because they are cross-cutting

- ❑ **DMP Technologies are not Lunar specific and can be applied to a variety of missions (Mars, Asteroids, Planetary bodies, Robotics, life support systems, etc.)**
- ❑ **DMP technologies can be applied to earth, space, and solar observing missions**
  - Contamination sensitive missions requiring self-cleaning surfaces
  - Mechanisms and seals designs applicable for all missions
- ❑ **DMP technologies can be used in Space Station settings to control contamination build-up and bacteria.**

DMP Technologies have other Applications

DMP Technologies are cross cutting and have applications and spin-offs beyond NASA:

- ❑ **DOE**
  - Improved solar array performance
- ❑ **DOD**
  - Dust management in desert conditions
  - Dust mitigation on sensitive instrumentation
  - Protection of electronics
- ❑ **Industry**
  - Automotive industry (Lotus, seals, mechanical components)
  - Medical Industry (Lotus with Biocide)
  - Electronics (EDS, Lotus, connectors)
  - Power Industry (EDS, Lotus, Connectors, Power systems)
  - Mining (Simulant Development and Characterization, Mechanical components, Connectors)
  - Commercial Window and Exterior surface Manufacturers (EDS, Lotus)
  - Optics (EDS, Lotus, SPARCLED, CO_2 Shower)
  - Marine coatings (Lotus)
  - Aeronautics (Mechanisms, seals, Lotus, EDS)

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13. SUPPLEMENTARY NOTES

14. ABSTRACT
A return to the Moon to extend human presence, pursue scientific activities, use the Moon to prepare for future human missions to Mars, and expand Earth’s economic sphere, will require investment in developing new technologies and capabilities to achieve affordable and sustainable human exploration. From the operational experience gained and lessons learned during the Apollo missions, conducting long-term operations in the lunar environment will be a particular challenge, given the difficulties presented by the unique physical properties and other characteristics of lunar regolith, including dust. The Apollo missions and other lunar explorations have identified significant lunar dust-related problems that will challenge future mission success. 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 and human explorers. The Dust Management Project (DMP) is tasked with the evaluation of lunar dust effects, assessment of the resulting risks, and development of mitigation and management strategies and technologies related to Exploration Systems architectures. To this end, the DMP supports the overall goal of the Exploration Technology Development Program (ETDP) of addressing the relevant high priority technology needs of multiple elements within the Constellation Program (CxP) and sister ETDP projects. Project scope, approach, accomplishments, summary of deliverables, and lessons learned are presented.

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