An Approach for Achieving a Prioritized Research and Technology Development Portfolio for the Dust Management Project

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Abstract. The Dust Management Project (DMP) supports the overall goal of the Exploration Technology Development Program (ETDP) to address the relevant high priority technology needs of multiple elements within the Constellation Program (CxP) and sister ETDP projects. The project also allocates a portion of its resources toward filling knowledge gaps associated with the characterization of lunar regolith, providing such information to the engineering design process of these technologies, and defining requirements and characterization of lunar dust simulants. The approach to ensure alignment of the DMP research and technology (R&T) portfolio with customer needs is comprised of both technical and programmatic elements. To this end, the overall process goals are to ensure that DMP only invests in R&T that is NASA unique either in technology innovation and/or need timeframe, takes advantage of leveraging opportunities with relevant internal and external entities, and avoids any duplication of effort. Specific objectives have been developed for each process element and product to make certain that these goals are met. The objectives include:

1. Validation of existing DMP R&T portfolio as potential solutions to CxP Technology Prioritization Process (TPP) defined needs.
2. Review of overall agency R&T investments to determine gaps against CxP TPP results.
3. Survey and assessment of potentially NASA-relevant external R&T investments in particle management solutions as potential gap fillers.
4. Identification of CxP TPP need areas without internal or external solutions.
5. Determine options for filling gaps by concentrating DMP efforts only on the gaps that need to be filled by NASA-unique R&T.
6. Review and reassessment of the complete portfolio of agency R&T investments to determine commonalities and overlaps in meeting a given CxP TPP need to determine a path forward for an integrated systems approach to technology development.

To facilitate the process, comparison/decision criteria were developed to assess internal and external solution alternatives. Experts ranked each alternative according to a quantitative rating scale for each criterion using a DMP task as a baseline for the comparison of alternatives. Particular criteria focused on the range of customer needs and missions a particular technology could address; the technology readiness level (TRL) and anticipated degree of difficulty required to achieve TRL 6; the degree of integration and leveraging with other internal or external entities for the purposes of sharing

knowledge and/or resources; the technical and project management experience of the team; and anticipated resource requirements. Results of the technical component of the process include the individual products of the objectives listed above; recommendations for continued or new R&T investment and/or collaboration with other entities, and recommended deferment, cancellation, or renewed teaming arrangements for certain DMP tasks due to low assessment scores. The programmatic element of the review process takes into consideration the results of the technical assessment, as well as budget, and longer-term goals and strategies to achieve a balance of near- and long-term knowledge and technology development investments.

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Abstract— The NASA Lunar Dust Management Project (DMP) has been established to address relevant high priority needs for lunar dust mitigation technologies. 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. [1 2]

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1. INTRODUCTION

The NASA Dust Management Project (DMP) supports the overall goal of the Exploration Technology Development Program (ETDP) to address the relevant high priority lunar dust mitigation technology needs of multiple elements within the Constellation Program (CxP) and sister ETDP projects. The approach to ensure alignment of the DMP research and technology portfolio with customer needs is comprised of both technical and programmatic elements. To this end, the overall process goals are to ensure that DMP only invests in R&T that is NASA unique either in technology innovation and/or need timeframe, takes advantage of leveraging opportunities with relevant internal and external entities, and avoids any duplication of effort.

Assessment Objectives

The technologies included presently in the DMP portfolio should be assessed quantitatively to assist in prioritization

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for subsequent strategic investment planning. To facilitate this, the present assessment was designed around several technical elements that each contribute toward the overall goal of providing a basis for decisions regarding selection of new DMP tasks and the continuation, cancellation, or deferment of existing tasks. The process developed to enable these decisions allows for continued iteration as customer requirements are better defined and may be implemented as a regular activity to ensure timely knowledge of relevant capabilities both internal and external to NASA. For the purposes of this assessment, customer needs are taken from a subset of dust-related technology needs developed during the 2008 CxP Technology Prioritization Process (TPP).

The primary goal of this effort is the assessment of current DMP technology development tasks and alternate external development efforts. The overall assessment process is divided into two parts. First, the analysis component consists of the mapping of relevant TPP results, determination of potential gaps, technical assessments against criteria, discussion of possible leveraging or integrated activities, and recommended next steps. The second part is the programmatic review that takes into consideration the technical assessment results, budget, and longer-term goals and strategies to achieve a balance of near- and long-term knowledge and technology development investments driven by the NASA Exploration Systems Mission Directorate needs. Table 1 provides a short description of the DMP R&T efforts reviewed in this assessment.

2. Implementation Approach

Technology Prioritization Process – Dust Relevant Results

The CxP TPP provided an opportunity for CxP managers to capture and prioritize their technology needs across all projects (Environments and Controls Special Investigation Group [E&C SIG], Lunar Surface Systems [LSS], Lunar Lander [LL]) and mission architectures. CxP TPP results were ordered and ranked by mission architecture (Initial Capability [IC], Lunar Transport [LT], Lunar Surface [LS], and Mars) and priority (Critical [C], Highly Desirable [HD], Desirable [D]). Due to the large number of potentially relevant needs related to dust management across the mission architectures, a subset of needs were selected for this assessment that represent both the highest ranked by the TPP and that are closest to the focus of the current DMP portfolio and intended project scope. The subset of needs used during the course of this assessment is presented in Table 2.

Utilizing the mapping of DMP tasks to dust-relevant TPP needs shown in Table 3, subject matter experts assessed each task against defined criteria.

3. Assessment Criteria

A quantitative assessment of the technologies listed in Table 3, and possible alternatives, was performed based on criteria that reflect the maturity, feasibility, and risks associated with the ability of the particular technology to meet the dust mitigation objectives. Three levels of fulfillment were assigned from high to low for each criterion and a scoring range was assigned to each fulfillment level. Each technology was reviewed in detail and scored according to the criteria. The results were summarized in individual scoring sheets for each technology, which were ranked according to the scores.

As primarily a technology information and awareness exercise at this stage, the assessment criteria were ranked and weighted more heavily to reflect the applicability of the technology, and its potential impact, as well as the level of research and development effort required to mature the technology to Technology Readiness Level (TRL) 6 [1]. Lower weights were attached to the level of its maturity or readiness (TRL), as well as criteria reflecting the ability to develop hardware and delivery systems and the associated safety issues for actual application of the technology during a Lunar mission, since most of the technologies and technology concepts are at very low readiness levels (TRL 1-3) for Lunar missions. Cost-related criteria were also ranked and weighted low since the focus of this assessment was primarily technical.

Technology Scoring and Ranking

Information for each DMP task associated with this assessment was reviewed in detail by subject matter experts for information related to the prioritization criteria. In addition, engineering and scientific judgment were applied to the criteria for each technology, as well as personal knowledge of the current state-of-the-art for technologies that are commercially used presently for relevant or similar terrestrial applications.

Based on this review, the level of fulfillment was determined for each criterion and a score was assigned. Once a score was assigned to a criterion, it was multiplied by the weighting factor to obtain the weighted score for that criterion. The weighted scores were summed and then averaged to obtain the final score for the technology.

Technology Grouping and Summaries

The following sections provide short summaries for the dust mitigation technologies included in this assessment. The technologies are grouped into 3 functional or descriptive categories, and then by the DMP numbers relevant to each category. Alternative technologies that have the potential to meet TPP needs were also identified and assessed along with each DMP baseline technology. Many of these external technologies had been assessed previously for their applicability to dust mitigation [2].

Table 1. Dust Management Project R&T Portfolio elements

Title	Description
Mechanical Components and Seals	Identify dust contamination issues for mechanical components and risk mitigation technologies to develop mechanical components that can perform during long duration lunar missions.
Abrasion Resistant EVA Suit Materials	Develop a testing protocol for determination of abrasion resistance of extravehicular activity (EVA) suit materials.
Lotus Coatings	Provide a coating that has anti-contamination and self-cleaning properties for use as a dust mitigation method on EVA suit material and external spacecraft thermal control surfaces. The unique morphology of the coating will help prevent lunar regolith from adhering to such surfaces and will facilitate dust removal/decontamination from such treated surfaces.
CO_2 Shower	Develop a CO2 snow shower that can be utilized with the electrostatic curtain technology to remove fine dust (less than 1 μm) particles from EVA suits. This task is a component of a larger effort that focuses on technologies that can remove dust prior to entry into the airlock or habitat, thus avoiding high dust loading in the internal environment.
Space Plasma Alleviation of Regolith Concentrations in Lunar Environments (SPARCLE)	Employ charged plasma beams to create a potential difference which removes dust from a surface, or if attraction is desired, attracts dust for collection. It may be used for airlock dust control either as an electrostatic brush or as an electrostatic shower. It works at vacuum so it could operate either outside the vehicle, in a dust removal area outside of the vehicle, or in the airlock itself before pressurization.
Electrostatic Curtain	Develop an electrodynamic dust shield technology for visors, optical systems, radiators, batteries, In Situ Resource Utilization (ISRU), sample recovery containers used in the external lunar environment to minimize dust accumulation on surfaces that are: 1) rigid, opaque, and electrically insulating surfaces (boots), and 2). rigid, transparent, and electrically insulating (solar panels, thermal radiators, visors).
Dust Effects on Thermal Control Materials	Determine the extent of degradation of thermal control surfaces for Altair and Outpost components by lunar dust, and determine ways to effectively mitigate that degradation. Provide protection for thermal control surfaces for Lander and Outpost components from dust in the lunar environment.
Self Cleaning Solar Array	Develop a cleaning system that removes deposited dust from the surface of the solar array in the lunar environment.
Dust Tolerant EVA-Compatible Connectors	Develop connectors (quick disconnects [QD] and umbilical systems) that can be repetitively and reliably mated and de-mated during lunar surface extra-vehicular activities.

Table 2. Summary of DMP Assessment Relevant TPP Dust Capability Needs

TPP #	**Capability Title**	**CxP Project**	**Mission Architecture**	**Priority**
344	Automated lunar regolith cleaning systems	E&C SIG	LS	HD
609	Dust mitigation of mechanical components	LSS	LS	C
611	Dust-tolerant EVA-compatible connectors	LSS	LS	C
622	Environmentally robust electrical docking for rover com	LSS	LS	C
623	Dust/Regolith mitigation techniques within habitable cabin	LSS	LS	C
625	Dust control/remove airborne dust	LSS	LS	C
627	Lander dust mitigation	LL	LT	HD
632	Long-life high-performance drive train and suspension system	LSS	LS	C
633	Dust degradation effects and mitigation for thermal control system	LSS	LS	C
733	Self-cleaning solar array	LSS	LS	HD

Table 3. DMP Task Mapping to Assessment Relevant TPP Dust Capability Needs

Title	TPP #
Mechanical Components and Seals	609, 632
Abrasion Resistant EVA Suit Materials	623, 625, 627
Lotus Coatings	623, 625, 627
CO_2 Shower	623, 625, 627
SPARCLE	623, 625, 627
Electrostatic Curtain	623, 625, 627
Dust Effects on Thermal Control Materials	633, 627
Self Cleaning Solar Array	344, 733
Dust-Tolerant EVA-Compatible Connectors	611

Group 1. Cleaning Technologies—The DMP technologies assessed against alternate technologies in Group 1 include: CO_2 Shower, SPARCLE, and the Electrostatic Curtain. These DMP technologies serve as the baseline technology for each subgroup. Summaries of the technologies in this group are given below.

a) Subgroup 1a

(1) Baseline Technology: CO_2 Shower—Develop a CO_2 snow shower that can be utilized with the electrostatic curtain technology to remove fine dust (< 1 μm size) particles from EVA suits.

(2) Alternative Technology: Air Flow Cleaning—The application of this technology is to use airflow in an airlock to blow dust off EVA suits and other EVA related surfaces. For lunar applications, the airflow cleaning system would need to be implemented in the airlock.

(3) Alternative Technology: Electrostatic Cleaning System—Conducting wires will be embedded in the EVA suit and other hardware (visors, optics) and piezoelectrically driven with electric pulses to remove charged or unchanged dust that is deposited on the surfaces.

(4) Alternative Technology: Automated Magnetic Brush Cleaning System—The magnetic brush concept is based on the idea that the high fraction of magnetic particles in lunar dust will allow a magnet placed on the surface to attract a large percentage of the particles. To clean surfaces, this magnet could be used in combination with a brush to loosen the particles collected on critical hardware or EVA suits. Applications on the moon are suggested and include magnetic brushing, filters and EVA suit cleaning.

b) Subgroup 1b

(1) Baseline Technology: SPARCLE—SPARCLE is an approach to controlling the accumulation of planetary dust on exposed surfaces. This control can be used either to clean surfaces or collect samples. The methodology involved in SPARCLE employs charged plasma beams to create a potential difference which removes dust from a surface, or if attraction is desired, attracts dust for collection.

(2) Alternative Technology: Plasma Cleaning of Surfaces—This cleaning technology utilizes ionized gas or plasma to electrostatically clean surfaces in an airlock on the moon. For lunar applications, plasma cleaning equipment would be installed in the airlock.

c) Subgroup 1c

(1) Baseline Technology: Electrostatic Curtain—Develop active electrostatic curtain technology to minimize dust accumulation on external surfaces exposed to the external lunar environment and on the outer door used when entering or leaving the habitat airlock.

(2) Alternative Technology: Strippable Coatings—Strippable coatings can be applied to surfaces to remove collected dust or to repel dust. The coatings would be applied to a surface by spraying or brushing, either prior to EVA (repel dust or prevent dust collection on component surface), or post-EVA to remove any collected dust. The coating is removed by simply peeling it off the surface together with the adhered dust.

(3) Alternative Technology: Dynamically Switchable Surfaces—An engineered surface, which can change properties in response to an electrical switch, allowing dynamic, time-resolved control of surface hydrophobicity/hydrophilicity at the nanoscale is a potential mechanism for cleaning dust or mitigating dust accumulation on surfaces. This technology is compatible with integration into miniaturized systems.

Group 2. Materials—The DMP technologies assessed against alternate technologies included in Group 2 include: EVA Suit Materials, Lotus Coatings, and the Self-Cleaning Solar Array. These DMP technologies serve as the baseline technology for each subgroup. Summaries of the technologies in this group are given below.

a) Subgroup 2a

(1) Baseline Technology: EVA Suit Materials—Development of testing protocols for dust and abrasion resistance of EVA suit materials and for accelerated dust exposure to include evaluation of abrasion of fabrics using an adapted ASTM Standard D3884 [3]. Also, investigate methods to modify the surface chemistry/topography of existing materials to improve dust resistance or repellant properties.

This topic discusses a class of materials that will support the investigation of existing materials to improve dust resistant or repellant properties. There are a number of commercial fabrics on the market that apply nanocoatings to fabrics for enhanced performance – anti-static, anti-wrinkle, improved moisture wicking, to name a few. The examples provided under this topic are for anti-pollen and anti-static fabrics [4-6].

b) Subgroup 2b

(1) Baseline Technology: Lotus Coatings—Formulate and modify the "Lotus" nano-textured coating to enhance its anti-contamination/self-cleaning properties for repulsion of charged dust. Evaluate the Lotus coating as an overcoat for various substrates, such as radiator surfaces, solar arrays, EVA suit material, and mechanism shields.

(2) Alternative Technology: Polyaniline Nano Coatings—Polyaniline nanofibers can be prepared by a number of methods based on chemical oxidative polymerization and in situ adsorption polymerization. Lack of alignment in these nanostructures has made polyaniline coatings unsuitable for many applications. A chemical oxidative polymerization process has been reported that can control the growth and simultaneous alignment of polyaniline nanofibers on conducting and non-conducting substrates [7]. The nanofiber diameters were controlled within the range 10–40 nm, and the average length was controlled within the range 70–360 nm. The coatings were tailored to show several properties including superhydrophilicity and superhydrophobicity. Useful applications on the lunar surface may include anti-fog coatings, self-cleaning surfaces and transparent electrodes for low-voltage electronics.

(3) Alternative Technology: Switchable Surfaces and Gecko-inspired Coatings—This topic looks at alternative coatings to the passive dust repellant coatings. Rather than repel dust, these coatings are designed to attract dust and/or to be activated to dynamically dislodge dust particulates. Two technology areas could be considered. The first types of coatings are 'gecko' inspired coatings that mimic the nanoscale fibers found on the feet of geckos in nature [8]. It is this nanostructure that enables geckos to scale vertical structures. These structures have been reproduced through polymers and nanotube coatings to provide an adhesive surface that is significantly better than conventional adhesive tapes. It has been found that these carbon nanotube coatings are four times more adhesive than the original gecko-inspired coatings by improving the ability to trap fine particulate matter. These carbon nanotube coatings were fabricated into a patch that demonstrated the ability to stick and release (by twisting), repeatedly [8].

The second type of nano material is a 'switchable' coating that can be electronically biased or optically irradiated to change from a hydrophobic to a hydrophilic surface [9-11]. The former coating requires an electrical charge or field to change the molecular behavior on the surface. For the latter, UV irradiation has shown the ability to switch the molecular surface configuration.

c) Subgroup 2c

(1) Baseline Technology: Self-Cleaning Solar Array—Develop a self-cleaning solar array using piezoelectric vibrators. The induced vibration of the whole array is expected to shake detrimental dust deposits off the surface.

Group 3. Mechanical Components—The DMP technologies assessed against alternate technologies included in Group 3 include: Dust Tolerant Connectors, Dust Mitigation for Bearings and Drives (Seals), Dust Tolerant Bearings for Mechanisms Operating in Dusty Space Environments (Bearings), and Protection of Thermal Control Surfaces. These DMP technologies serve as the baseline technology for each subgroup. Summaries of the technologies in this group are given below.

a) Subgroup 3a

(1) Baseline Technology: Dust Tolerant Connectors—This study aims to assess the effect of lunar dust on mechanical connections by testing various connector designs in the presence of lunar dust simulant and subsequently design and develop concepts of dust tolerant connectors.

b) Subgroup 3b

(1) Baseline Technology: Dust Mitigation for Bearings and Drives Seals)—Investigate specific mitigation technologies for dust contamination of mechanisms applicable to nearer term lunar missions: wear acceleration by dust contaminated grease as a function of gear material; abrasiveness of lunar dust simulant on ceramics for robust mechanical components such as gears or coatings; seal performance versus dust contamination level; and advanced bellows for joints.

(2) Alternative Technology: Ceramic Components—Ceramic-polymer blends offer the advantage of lighter weight as well as greater wear resistance than that of stainless steels. A titanium carbide (TiC) additive allows the manufacture of components which retain the advantages of plastics while exceeding the durability of steel parts. One

polymer-TiC blend exhibited 58 times the sliding wear resistance of steel. Use of ceramic contact surfaces, which are harder than the abrasive components of lunar regolith, will allow seals to be maintained in the presence of dust with minimal abrasive degradation of sealing surfaces over time [12].

(3) Alternative Technology: Dust-Repellant Coatings—Contamination-resistant surface coatings have been produced that have very low surface energy, are transparent in the visible and near-infrared wavelengths, and have been shown to tolerate temperatures between 77 and 673 K without performance degradation.

c) Subgroup 3c

(1) Baseline Technology: Dust Tolerant Bearings for Mechanisms Operating in Dusty Space Environments (Bearings)—Investigate and optimally design zero-liquid-lube all-ceramic (silicon nitride or zirconia races and balls) bearings for use in spacecraft mechanisms subjected to dusty space environment.

(2) Alternative Technology: Ceramic Bearings and Races—Ceramic-polymer blends offer the advantage of lighter weight as well as greater wear resistance than that of stainless steels for bearings and races. As mentioned earlier, one polymer-TiC blend exhibited 58 times the sliding wear resistance of steel. Ceramic parts, which are harder than the abrasive components of lunar dust, will tend to grind contaminant dust rather than be abraded by it [12]. Thus, bearings and races made of such a material will exhibit greater durability on the lunar surface and resist the mechanical failure of traditional bearings in the presence of dust.

(3) Alternative Technology: Dust Repellant Coatings—Contamination-resistant surface coatings have been produced that have very low surface energy, are transparent in the visible and near-infrared wavelengths, and have been shown to tolerate temperatures between 77 and 673 K without performance degradation. In addition, the "Lotus" nano-textured coatings have similar surface, dust mitigation applications.

(4) Alternative Technology: Self-Lubricating Bearings—Polymer or metallic bearings can be designed to have self-lubricating properties. This is accomplished by the addition of a specific solid lubricant to the polymer/metal during the manufacture process. Once completed, the bearing surface exhibits the properties of the stand-alone lubricant. This lubricating surface lasts for the lifetime of the component and allows extended service without the need for maintenance in terrestrial applications. In addition, self-lubricating bearings resist galling, scoring and seizing. Such self-lubricating components will be important since it seems likely that in a lunar environment, dust would wear away a lubricant that is only applied to bearing surfaces.

d) Subgroup 3d

(1) Baseline Technology: Protection of Thermal Control Surfaces—Determine the extent of degradation of thermal control surfaces for Altair and Outpost components by lunar dust, and determine ways to effectively mitigate that degradation. Provide protection for thermal control surfaces for Lander and Outpost components from dust in the lunar environment.

(2) Alternative Technology: Dust Repellant Coatings—Contamination-resistant surface coatings have been produced that have very low surface energy, are transparent in the visible and near-infrared wavelengths, and have been shown to tolerate temperatures between 77 and 673 K without performance degradation.

(3) Alternative Technology: Electrostatic Cleaning System— Conducting wires can be embedded in the radiating surface and piezoelectrically driven with electric pulses to remove dust particles, charged or unchanged, that are deposited on the control surface.

(4) Alternative Technology: Dust-Repellant Coatings in Conjunction with Piezoelectric Vibration Technology—Vibratory systems can only partially get dust off surfaces. Electrostatic adhesion of charged dust, as well as van der Waals interactions of sub-micron particles, is unlikely to be broken through this technique. Vibrations may lead to additional tribocharging and adhesion to surfaces. However, combining this approach with electrostatic screen technology/coating technology may render it effective.

4. Assessment Results

Assessment of DMP Technologies and Alternatives

Individual scoring sheets were developed for each technology in Groups 1 - 3 with individual scores and their rationale for each technology. The key findings along with a short discussion for each DMP technology included in the assessment are provided below.

Group 1. Cleaning Technologies

(1) *CO_2 Shower*—The baseline technology had the lowest score. For the initial missions, the lack of an in-situ source of CO_2 makes this technology logistically nearly impossible to implement on the lunar surface. Three alternative technology options scored higher and may be candidates for further evaluation.

(2) *SPARCLE*—One alternative technology was assessed which is also plasma based. It scored lower than the baseline technology. However, both these technologies are limited in their application and better technology options already exist in the current TPP portfolio.

(3) *Electrostatic Curtain*—Both alternative technology options assessed scored slightly higher than the baseline technology. The primary issue with the electrostatic curtain is the significant development effort required to achieve TRL 6. The material development effort is also nontrivial. If this technology development effort is continued, it is very important that the direction and strategy for its application be critically evaluated, as well as the alternative technology options.

In general, the technologies that have a high level of impact, with the potential to become enabling technologies, had high scores whether they are concepts at low TRL levels or commercially mature technologies at higher TRL levels. None of the identified technologies has been demonstrated at TRL 3 for typical lunar applications. This is a critical milestone and a decision gate for continued support for a given technology. Many of the commercial technologies for dust removal have high scores, but they require much smaller levels of NASA investment to achieve TRL 6 and higher for lunar applications. This support will generally be in the form of facilities for testing in space-unique environments.

Group 2. Materials

(1) *EVA Suit Materials*—Development of a testing protocol that is effective at simulating the lunar environment is a critical aspect to mitigating the effects of dust on the EVA suit. Any significant research findings through the lunar dust characterization, particle size distribution, tribocharging/electrostatic, dust characterization and lunar regolith characterization projects may have impact on the protocol testing.

Although they have been developed for terrestrial applications, these materials may offer potential uses or technical approaches that may be applied to lunar fabrics and support TPP 623 and TPP 625. A benefit of these textiles is that they are readily available and may be tested relatively quickly. Conversely, the fabrics may not be suitable for EVA applications and may need to be modified for the space environment or deemed as non-applicable. Also, the EVA Project Office has ongoing efforts to research and evaluate new materials. The introduction of advanced fabrics should ideally be crosschecked with that office to synergize efforts.

(2) *Lotus Coatings*—Each of the TPPs supported by the technologies assessed here seeks to mitigate dust adhesion and accumulation on surfaces inside and outside the habitat and hence, facilitate dust mitigation strategies (i.e. cleaning, filtration, extended life of components, etc.). The Lotus Coatings approach is an effective method for providing a passive technology for deterring the accumulation of lunar dust on surfaces. Critical to the process will be determining the proper analog testing environment and/or surface properties that will exhibit the anticipated results in the lunar environment. Information was not available to determine the range of coatings to be tested and whether the nano-coatings mentioned only included 'Lotus-type' coatings. Also, the chemical and physical properties attempted to be achieved by the coatings are needed for effective evaluation and would have made for a more compelling description that discussed the charge and size (or roughness) of the nano-structured surface coatings and speculated on how those properties may help to prevent dust adhesion.

(3) *Polyaniline Nano Coatings*—This emerging material for nano coatings is suggested as an alternative material to the conventional Lotus coatings. The attractive aspect of the polyaniline coatings is that nano-polymer synthesis conditions may be controlled to yield coatings with a wide range of tailored properties. Since these coatings are an emerging technology, their maturity may be considered TRL 1. Should the technology continue to mature and demonstrate favorable applications, additional due diligence on these materials and possibly other polymer coatings is suggested.

(4) *Switchable Surfaces and Gecko-inspired Coatings*—These surfaces may provide favorable properties for dust mitigation in certain applications. Since these surface materials are emerging technologies, they may be considered TRL 1 or TRL 2 for the Gecko-inspired surfaces. In contrast to the previously described coatings that repel dust, these coatings are aimed at collecting dust and having it adhere to the surface upon which the adhesive is placed. Such applications may be appropriate where dust containment and/or removal may be needed for advanced 'sticky' mats to clean boots or advanced tape rollers (similar to lint rollers) to extract dust from textiles or other contaminated surfaces. If this strategy is viable, these technologies may be considered in future evaluations.

(5) *Self Cleaning Solar Array*—The approach of using mechanical vibration for the cleaning of a solar array surface is unlikely to succeed for micron particles, which pose the greatest concern (due to van der Waals adhesion). This technology is therefore not deemed sufficient to efficiently process the fine part of the regolith that presents the most risk to lunar operations. No other technology development has been identified that explicitly addresses self-cleaning solar array (TPP 733), but general surface cleaning technologies could be explored for this application.

Group 3. Mechanical Components

(1) *Lunar Environmental Effects*—The extraterrestrial environment for lunar applications is a very low

pressure (<10 torr to 10^{-12} torr), dry environment. As a result, the behavior of volatiles, particle charging, heat and mass transport, and perhaps most important, interactions between hardware and the environment are based on physical behaviors that are not routinely encountered on earth, although particle transport in low pressure (~10^{-3} torr) dry environments is well understood [13,14]. However, experimental design and hardware developed and tested under terrestrial conditions produces interpretations and results that are often inaccurate. As an example, the Mars Science Laboratory had to be redesigned when it was discovered that the particles "clumped" together under apparent triboelectric charging between particles. The ability to foresee and even realistically analyze this issue a priori does not exist.

(2) *Dust Tolerant Connectors*—This technology project has a sound approach to testing and development of connectors. Tests have been done with lunar dust simulant under atmospheric conditions. Future testing needs to take into account electrostatic charging, tribocharging, using actual lunar dust when possible and ideally under high vacuum. No other similar technology assessment/development has been identified.

(3) *Dust Mitigation for Bearings and Drives (Seals)*—Both alternative technologies, ceramic components and dust-repellant coatings, scored similarly in the assessment and have the potential of complementing and improving the performance of seals and sealing techniques. Testing will be required to determine particular applicability and to determine long-term improvements.

(4) *Dust Tolerant Bearings for Mechanisms Operating in Dusty Space Environments (Bearings)*—The three technologies assessed as alternatives to the baseline are either currently included as part of the baseline development effort (use of ceramics, solid lubricants), or are suggested for consideration as part of further trade studies or assessments. In particular, the application of coatings has the potential to improve the long-term performance of rotating components.

(5) *Protection of Thermal Control Surfaces*—The baseline technology development effort includes two alternative technologies, dust-repellant coatings and electrostatic cleaning, which were reviewed during this assessment, although other available commercial products offering similar capabilities could also be assessed for this application. The combination of active and passive dust removal has direct application with the design of thermal radiators, although further testing is required to determine long term performance of combined piezoelectric actuators and dust repellant coatings to remove dust from a surface.

5. CONCLUSIONS

Mission architectures for human exploration of the lunar surface continue to advance as well as the definitions of capability needs, best practices and engineering design to mitigate the impact of lunar dust on exposed systems. The NASA DMP has been established as the agency focal point for dust characterization, technology, and simulant development. As described in this paper, the DMP has defined a process for selecting and justifying its R&T portfolio. The technology prioritization process, which is based on a ranking system according to weighted criteria, has been successfully applied to the current DMP dust mitigation technology portfolio.

Several key findings emerged from this assessment.

- Within the dust removal and cleaning technologies group, there are critical technical challenges that must be overcome for these technologies to be implemented for lunar applications. For example, an in-situ source of CO_2 on the moon is essential to the CO_2 shower technology. Also, significant development effort is required to achieve technology readiness level TRL 6 for the electrostatic cleaning system for removal of particles smaller than 50 μm.
- The baseline materials related technologies require considerable development just to achieve TRL 6. It is also a nontrivial effort to integrate the materials in hardware for lunar application.
- At present, there are no terrestrial applications that are readily adaptable to lunar surface applications nor are there any obvious leading candidates. The unique requirements of dust sealing systems for lunar applications suggest an extensive development effort will be necessary to mature dust sealing systems to TRL 6 and beyond.
- As discussed here, several alternate materials and technologies have achieved high levels of maturity for terrestrial applications and warrant due diligence in ongoing assessment of the technology portfolio.

The present assessment is the initial step in an ongoing effort to continually evaluate the DMP technology portfolio and external non-NASA relevant technology developments efforts to maintain an optimal investment profile. At the same time, there is an ongoing review of agency-wide dust-related R&T activities. The results of these ongoing assessments will be reported in future publications.

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