Dust Mitigation Technology Roadmap
LSIC Spring 2026

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STI/DAA #: 20260001844

Dust Mitigation Roadmap Purpose & Scope

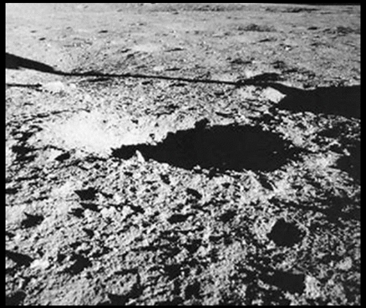
Purpose

- Identify Lunar and Mars regolith dust gaps, gap closure strategies, and candidate investments to address Apollo lessons learned, define the Lunar and Martian dust environment, and mature dust mitigation technologies to support M2M Program/Project risk reduction activities.

Scope

- **Dust Measurement, Modeling, and Testing**
  - Natural Environments Design Spec (DSNE): *M2M-30159*
  - Dust Testing Standard: *NASA-STD-1008*
  - Lunar Regolith Simulants: *Simulant Advisory Committee*
  - Lunar Dust Mitigation: A Guide & Reference (2021) (1st Edition): *https://ntrs.nasa.gov/citations/20220018746*
  - NASA Dust Testing Facilities
- **Passive Dust Mitigation**
  - Mitigation measures that do not require human intervention (or power) to operate properly
  - Includes lunar regolith dust filtration and monitoring, which can require power to be pre-integrated into the system
- **Active Dust Mitigation**
  - Mitigation measures that require human intervention (or power) to operate properly
- **Dust Tolerant Components**
  - Includes mechanisms such as connectors, bearings, seals, umbilicals, etc.

Note: Where applicable, a link to TechPort is provided.



Priorities for Dust Mitigation

- **Acquire actual dust measurements on the Lunar and Martian surface, as well as sample return, for Lander, Mobility and EVA use cases to anchor ground test data, support development of an integrated Lunar Dust Models, Martian Dust Models, and inform risk mitigation plans**

  Benefit: *Reduce uncertainty, characterize dust properties, anchor requirements levied on future assets, and inform Dust Risk mitigation plans. For example, current requirements levied on HLS, xEVAS, LTV, PR are based on Apollo estimates that did not collect quantitative/measured data. Having lunar dust measurements may help inform Martian dust models and requirements.*

- **Provide industry with compatibility guidelines to assist with development and validation of dust resistant coatings**

  Benefit: *Provide a standard methodology for validation and testing of dust coatings to ensure that a coating will not adversely impact the function of the item being coated and standardize assessment of efficacy. Look to Industry to develop coatings to meet NASA and commercial procurement requirements and needs.*

- **Develop capabilities to filter, monitor, and remove dust inside pressurized volumes and assess commonality across M2M**

  Benefit: *Common capability will streamline Operational procedures and provide a consistent way to measure performance and ensure Crew Health. These capabilities may cross over to Martian missions.*

  Dust Monitoring

  Key in assessment and tracking of crew exposure levels for lunar dust, and to inform any medical responses or anomaly resolution activities during a mission. Data is also used post-mission to provide an occupational exposure record. Additionally, lunar dust monitoring provides verification and optimization of controls, and in providing objective measurement data for maturation of mitigation concepts. Available commercial particulate monitoring technologies can likely be employed (with minimal spaceflight adaptations) to provide inflight measurement data. Necessary data will include particle sizes of dust and mass concentration used to demonstrate attainment of health-based standard. (HMTA-0047)

- **Develop alternative methods for active dust mitigation with low integration complexity to increase infusion potential, including methods to remove dust from surfaces**

  Benefit: *Reduce complexity of integrating with a lunar surface asset, ensure Crew safety, adaptable for different uses cases. (e.g., suits, mobility, small science stations)*

- **Define approach and guidelines for testing Dust tolerant components to characterize performance and enable infusion path**

  Benefit: *Provide a methodology and guidelines to share with Industry to avoid prescribing a solution and to let Industry define how to meet the need. Evolution of Artemis architecture and definition of capability gaps (e.g., Logistics) may identify specific applications for critical interfaces where direct investment would mitigate risks.*

Lunar Dust Mitigation Key Observations

- **Limited knowledge of lunar dust and its interaction with the natural electrostatic environment creates a challenge for early surface element development, and requires a phased mitigation approach**
- **Launch and deployment of lunar dust level sensors to gather data is critical to crew health and mission success.**
  - There is significant lack of data of the lunar dust environment. Lunar simulants are not perfect analogs.
- **Data collection from ground tests and lunar surface is the priority to develop and validate dust models.**
- **Significant variability of regolith "simulants" exists due to varied geological composition of Lunar soil in different locations.**
  - Need to test with more than 1 simulant! The Simulant Advisory Committee is available to consult on testing dependent on specific use case and function
- **There is limited availability of passive dust mitigation solutions. These are largely being developed by Industry, potentially limiting availability for future assets.**
  - Some NASA-funded activity is in work, but a majority of development is performed by the xEVAS/LTVS/HLS vendors, International Partners, or Industry
  - Contributions to risk reduction are only to the extent that technologies are shared and available for use by other companies and Agencies
- **Dust is readily removed by HEPA filtration (with pre-filtration for bulk material) with likely adequate removal within a few hours.**
  - HEPA: Removes 99.97% of 0.3-micron particles which is the most limiting performance point, though particles smaller than 0.3 microns are captured at higher efficiencies.
- **Active dust solutions other than Electrodynamic Dust Shield (EDS) have low TRL and are relatively few in number.**
  - Not all solutions scale to TRL 6 and are suitable (i.e., relevant to the use case) for injection into flight Programs or Projects.
  - EDS is a developing technology and may not be an all-encompassing solution; it should not be the only tool in our toolbox.
- **Dust tolerant components are primarily being developed by Industry. NASA's role is to characterize the technical challenges and provide guidance on FOMs and KPPs.**
  - Need more dust tolerance testing, guidance on how to test, and a method for sharing data with Industry and International Partners.

Martian Dust Mitigation Key Observations

- **Martian Regolith Observations**
  - Martian dust, composed of fine particles rich in silicates, iron oxides, toxic metals, and perchlorates, poses serious health risks (e.g. silicosis, thyroid disruption) due to its small size and toxic composition.
  - The dust is highly cohesive and easily suspended by Mars's frequent storms and low gravity, causing hardware issues such as reduced solar panel efficiency and contamination of exposed components like radiators.
- **Solar Power Loss From Dust Accumulation**
  - Majority of Mars Missions see 0.2% daily loss in solar array output due to dust.
  - Observed rates of decrease in "dust factor" vary between 0.05% - 2% per Sol.
  - Observations are from Pathfinder, Phoenix, Spirit, Opportunity, and InSight.
- **Cleaning Events from Natural Surroundings**
  - Dust devils and wind gusts restored solar panel performance for the Spirit and Opportunity rovers.
  - InSight did not experience any natural cleaning, which resulted in steady degradation.
  - Solar array output and cleaning efficiency is highly dependent on location and local atmospheric circulation.
  - Solar array output is highly dependent on location.
- Limited knowledge of Martian dust and its interaction with the natural electrostatic environment creates a challenge for early surface element development, and requires a phased mitigation approach
- Development and deployment of Martian dust level sensors to gather data is critical to crew health and mission success.
  - Limited datasets on Martian dust results in incomplete characterization of the dust environment and simulants that are not fully representative.
  - Cabin & Crew health: Apollo showed dust can infiltrate habitats and affect health prompting insight to Mars mission plans.
  - Suit & Equipment: Lunar dust taught us that fine, abrasive particles can damage suits, rovers, and tools which in turn guides the development of future technology for Mars missions.
- Data collection from ground tests and lunar surface is the priority to develop and validate dust models to characterize the dust environment early on.
  - Utilize both sample return and in-situ characterization of the regolith in regions of planned missions
  - Need to define model purpose and scope and determine how to capture and incorporate ground/Martian surface data relevant to the modeling effort.
- As information is gathered about the regolith, its characteristics will be utilized to develop more analogous Martian simulant to test with hardware and other spaceflight systems so that vulnerabilities may be defined and Martian element design may be influenced. (Lander and rover histories of dust accumulation on and removal from solar arrays on Mars)

	Lunar Dust	Martian Dust
Shape	Irregular, sharp, angular	Irregular, more rounded and smoother
Dust Size	Very Fine	Very Fine
General Properties	Abrasive, causes mechanical wear	Abrasive, causes mechanical wear, dust storms pose challenges
	Clingy and electrostatically charged	Electrostatic concerns also exist, further assessment needed
Material Composition	Silicates, agglutinates, nanophase iron	Basaltic silicates, clays, sulfates, Fe-oxides, perchlorates
Inhalation Toxicity	Manageable , not as toxic as Quartz dust	Lunar Dust Permissible Exposure Limit may serve as an upper bound, further assessment needed
Regional Patterns	Highland and Mare regions have considerable differences	Surface level regolith is more globally homogenous, local enrichments are present
Regolith Enrichments	Unknown amounts of volatiles in Permanently Shadowed Regions may pose health concerns	Perchlorates pose a real, but manageable challenge. Chromium risk is low based on its forms likely to be found on Mars.

Martian Needs and Proposed Investments

- **Martian Dust Characterization & Modeling**
  - There is a need to characterize the dust contamination challenges posed by Martian Regolith and develop a more comprehensive understanding of regolith properties and the environment. Current knowledge gaps that are crucial for developing robust dust mitigation strategies include:
    - Electrostatic & tribocharging of Martian regolith
    - Abrasion and adhesion characteristics of Martian dust
    - Environmental influences and Martian weather activity
    - Particle morphology and particle size distribution of Martian dust and regolith
    - Martian simulant development
- **Expansion of Environmental Chamber Capabilities**
  - There will be an increasing need for NASA to possess the ability to test hardware, systems, and crew under Martian surface conditions. Key gaps for developing robust dust mitigation strategies and needed testing chamber upgrades include:
    - Martian atmosphere replication
    - Test compatibility with Martian simulant
- **External and Internal Dust Removal Tools**
  - Tools will need to be designed for external and internal removal of Martian dust on surfaces such as suits, tools, and vehicles; umbilicals; connectors and other mating surfaces and other dust quantification technology. Key gaps include:
    - Dust-tolerant QD’s, umbilicals, and electrical connectors
    - Seal and hatch development
    - Dust-tolerant actuators, bearings, and mobility components
    - Spectroscopic and surface dust monitoring
  - Dust mitigation technologies for the moon might not be directly applicable to Martian dust
- **Passive and Active Dust Mitigation Technologies**
  - Passive and active dust mitigation technologies will be needed to perform dust mitigation on the Martian surface. Large-scale solutions will be designed for external and internal removal of Martian Dust form surface, such as radiators, solar panels, and FSP elements. Some technologies that might require Martian-specific developments include:
    - EDS
    - Thermal and dust-repellant coatings
    - Filters

Note: These Mars needs and investments will be illustrated in applicable swim lanes in future Dust Mitigation Road Map update.

Dust Mitigation Roadmap – STMD Shortfalls, ESDMD Architecture-driven Technology Gaps, and Architecture-driven Data Gaps

Dust Mitigation Capability Shortfalls/Architecture-driven Technology and Data Gaps

1) Dust Measurement, Modeling, and Testing Capabilities

- Shortfall 1561: Advanced Modeling & Test Capabilities to Characterize Dust Effects on H/W
- DN-008 L: Geotechnical properties of highland regolith at the lunar south pole
- DN-017 L: In situ measurement of particle velocity during lunar plume surface interaction
- DN-019 L: Natural and induced lunar dust particle flux electrical charging, and accumulation on spacecraft structures

2) Passive Dust Mitigation Capabilities (Including Filtration and Monitoring)

"Mitigation measures that do not require human intervention (or power) to operate properly"

- Shortfall 844: Passive Dust Mitigation Technologies for Diverse Applications
- ESDMD Architecture-driven Gap 0801: Lunar Dust Tolerant Systems and Dust Mitigation
- ESDMD Architecture-driven Gap 0802: Mars Dust Tolerant Systems and Dust Mitigation

3) Active Dust Mitigation Capabilities

"Mitigation measures that require human intervention (or power) to operate properly"

- Shortfall 1047: Active Dust Mitigation Technologies for Diverse Applications
- ESDMD Architecture-driven Gap 0801: Lunar Dust Tolerant Systems and Dust Mitigation
- ESDMD Architecture-driven Gap 0802: Mars Dust Tolerant Systems and Dust Mitigation

4) Dust Tolerant Components (Including connectors, bearings, seals, etc.)

- Shortfall 1552: Extreme Environments Avionics
- Shortfall 1592:High Power, Long Distance Energy Transmission across Distributed Surface Assets (Related Gap: PWR-1158)
- Shortfall 1390: Power and Data Transfer in Dusty Environments (Related Gaps: PWR-1158 , AMSC-995, and SURFACE-1389)
- ESDMD Architecture-driven Technology Gap 0801: Lunar Dust Tolerant Systems and Dust Mitigation
- ESDMD Architecture-driven Technology Gap 0802: Mars Dust Tolerant Systems and Dust Mitigation
- ESDMD Architecture-driven Technology Gap 0807: Docking and Berthing between Surface Elements on the Moon and Mars

References:
Civil Space Shortfall Rankings – July 2024
Architecture Definition Document (ADD) - Rev C

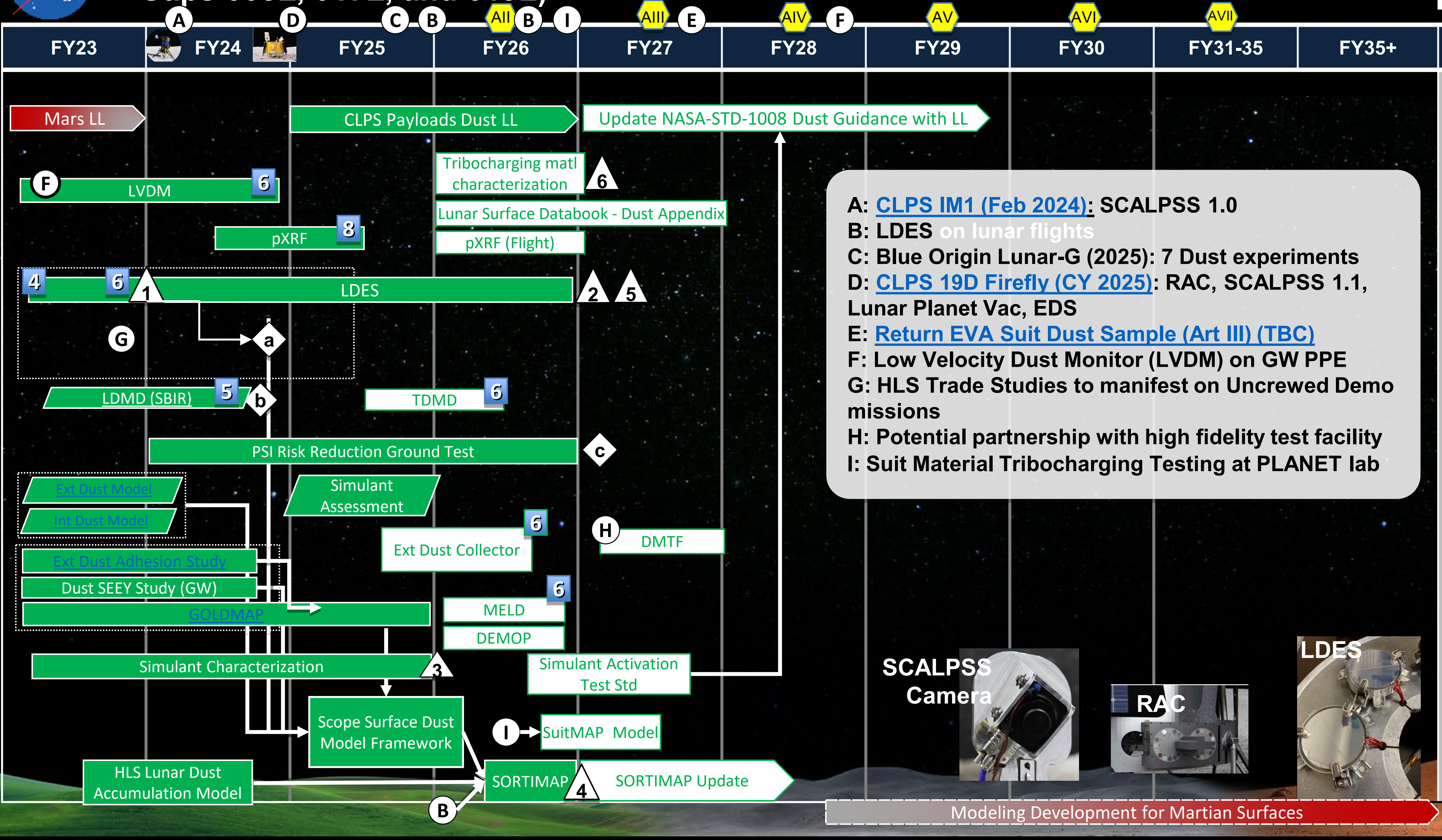
Mid to High TRL NASA Dust Mitigation Investments

1. MEASUREMENT, MODELING, and TESTING	**TRL**	**FY**
Lunar Dust level sensor and Effects on Surfaces (LDES)	7	2023-24
- 2023: Ground testing assessed impact to radiators due to dust (w/ 2 simulants)		
- 2026: Data from CLPS CP-11		
- 2026: Data from CLPS TO 20A		
Low Velocity Dust Monitor (LVDM)	7	2023
Gateway On-orbit Lunar Dust Modeling and Analysis Program (GOLDMAP)	N/A	2023-24
PSI Risk Reduction Ground Test	N/A	2024-25
Lunar Dust Accumulation Modeling (Transport & Adhesion); Collaboration	N/A	2025
2. PASSIVE DUST MITIGATION		
Lunar Glove Thermal and Durability Analysis, Test, and Failure Mitigation	N/A	2022-23
Artemis Suit Material Development	6	2023-26
HEPA Filter Testing (HALO, IHAB)	6	2022-23
Cabin Dust Monitor COTS assessment	4	2023
Metallic Environmentally Resistant Coatings (MERCRII)	5	2021-24
Dust Resisting Thermal Control Material System (TCMS) Coating (*STMD/SBIR*)	7	2024-25
Clear Dust Repellant Coating (CDRC)	4	In work
3. ACTIVE DUST MITIGATION		
Lunar Electrostatic and Dust Mitigation (LEDM) Tool	6	2023-25
Handheld static ionizer tool to remove dust and neutralize electrostatic charge from materials.		
Electrodynamic Dust Shield (EDS)	7	2024
Lunar Dust Capture	5	2024
- Alternate filter media to advance SoA and demonstrate use case of a small portable dust vacuum.		
Development and Test of Lunar Dust Removal using a Gecko Roller	5	2024-25
4. DUST TOLERANT COMPONENTS		
Seal Dust Tolerance Testing	4	2022-23
Extreme Env Tribological Charact. of Advanced Bearing Materials	7	2024-25

DM - Dust Measurement, Modeling, & Testing (Shortfall 1561; (Shortfall 1561; Data Gaps 008L, 017L, and 019L)

POC: Josh Litofsky

Revised: Winter 2025



A: CLPS IM1 (Feb 2024): SCALPSS 1.0
B: LDES on lunar flights
C: Blue Origin Lunar-G (2025): 7 Dust experiments
D: CLPS 19D Firefly (CY 2025): RAC, SCALPSS 1.1, Lunar Planet Vac, EDS
E: Return EVA Suit Dust Sample (Art III) (TBC)
F: Low Velocity Dust Monitor (LVDM) on GW PPE
G: HLS Trade Studies to manifest on Uncrewed Demo missions
H: Potential partnership with high fidelity test facility
I: Suit Material Tribocharging Testing at PLANET lab

Additional Information

Deliverables and Milestones #

1. 1st LDES Flt H/W (TRL 6) ready for CLPS
2. Additional LDES Flt H/W sets
3. Simulants Users Guide, Rev B
4. Initial Lunar Dust Model
5. Finalize LDES thermal models w/ Test Data
6. Incorporate suit material test data into Initial Suitmap model.

Decision Points a

a. Manifest LDES on lunar flights
b. Assess infusion potential to pursue maturation to TRL 6
c. Infuse into HLS

Candidates Under Evaluation

- ERIE (Electrostatic Regolith Interaction Experiment)

Descriptions

- **Regolith Adherence Characterization (RAC)**: Determine how lunar regolith sticks to a range of materials exposed to Lunar environment at different phases of flight. Components derived from Materials International Space Station Experiment (MISSE) facility currently on ISS
- **Crosscutting Capabilities LSIC Focus Group https://lsic.jhuapl.edu/**

🟩 Ground
🟦 ISS / LEO
⬛ Lunar orbit
⬜ Lunar Surface
🟧 Mars Transit
🟥 Mars Surface
● Notes
◆ Decision point
▲ Deliverable/Milestone
Act Funded
Act Unfunded
⬢ Artemis missions
ESDMD
STMD
Industry
▶ Touchpoint
TRL

Objectives (FOM/KPPs): See metrics in STMD Shortfalls list and latest version of the ADD.

NASA and Industry Funded Dust Measurement Investments

Task Bar Name	Description and Status	Start	Finish
LDES	Lunar Dust level sensor and Effects on Surfaces (LDES). Quantify effects of lunar dust on external surfaces, materials, and system performance and develop a sensor to measure in situ local dust accumulation.	2023	2026
GOLDMAP	Gateway On-orbit Lunar Dust Modeling and Analysis Program (GOLDMAP). 3-dimensional model which predicts contamination of exterior Gateway sensitive surfaces and hardware due to transport of charged lunar dust particles within Gateway env. Initial model complete for electrostatic transport of dust. Working to include increased geometry detail for identified susceptible H/W, to include physics for plume impingement and docking forces, HLS Starship geometry, and results of experimental data (adhesion and SEEY)	2023	2026
LVDM	Low Velocity Dust Monitor (LVDM). Lunar dust impact detector (unpowered) to measure exposure to dust contamination during HLS docking and attached operations. Results will be used for early on-orbit validation of GOLDMAP and to inform ongoing dust mitigation strategy. Launched in place on Gateway PPE.	2023	2023
Ext Dust Adhesion Study	Experiment to quantify adhesion forces for lunar dust particles to selected Gateway materials using lunar simulants. Results will be used for GOLDMAP development/validation.	2022	2026
Dust SEEY Study	Dust Secondary Electron Emission Yield (SEEY) Study. Experiment to determine quantitative SEEY data over a range of particle sizes using regolith from Apollo 16 samples. SEEY data is critical in material charging calculations; a phenomena which can produce positive grain potential and a gap in dust dynamic transport modeling. Results will be used for GOLDMAP development/validation.	2023	2026
PSI Risk Reduction Ground Test	Scaled PSI ground testing using NASA LaRC 60-ft vacuum sphere. Ethane (inert) and Hybrid rocket motor ground test to update PSI model	2023	2025
Ext Dust Model	External Dust Model – Investigate lunar dust structure, charging, and mobilization by developing numerical models that couple with the microphysics of grain-scaled processes with near-surface plasma environment.	2023	2024
Int Dust Model	Internal Dust Model – Develops a multi-scale, multi-physics framework to model lunar dust characteristics ranging from microscale physics to macroscale transport in a vacuum environment and conditions inside spacecraft.	2023	2024
LDMD	xEVA Lunar Dust Mitigation Devices (LDMD): Includes testing/modeling dust behavior.	2022	2024
Simulant Characterization	Simulant Characterization Testing. Thermal conductivity measurements (TBD). Electrical conductivity measurements (TBD). Hydraulic conductivity/permeability measurements (TBD).	2023	
Lunar Dust Cam	Very low C-SWAP imaging system for in situ monitoring of sunlight scattered by mobilized dust	2025	2026
HLS Lunar Dust Accumulation Modeling	Collaboration activity to develop Lunar Dust Transport and adhesion with electrostatic properties and spacecraft charging. Early collaboration with Plume/Surface Interaction (PSI) for initial development.	2024	2025

NASA and Industry Funded Dust Measurement Investments (Cont'd)

Task Bar Name	Description and Status	Start	Finish
RAC	RAC will determine how lunar regolith sticks to a range of materials exposed to Moon's environment. RAC will measure accumulation rates of lunar regolith on the surfaces of several materials (e.g., solar cells, optical systems, coatings, and sensors) through imaging to determine ability to repel or shed lunar dust. Results Fall 2025	Jan 2025 Manifest	
Lunar Planet Vac	Lunar Planet Vac will demonstrate pneumatic sample collection of lunar regolith by collecting and sorting regolith within its sample collection chamber (flight Jan 2025, results late 2025)		
SCALPPS	Stereo Camera for Lunar Plume-Surface Studies (SCALPSS) will use stereo imaging photogrammetry to capture impact of rocket plume on lunar regolith as our lander descends on the Moon's surface. SCALPSS 1.1 has 2 additional cameras (flight Jan 2025, results late 2025)		
pXRF for Dust Qualification	Dust Quantification with portable X-ray Fluorescence Spectroscopy (pXRF). Uses a COTS tool to enable measurement of how much dust is collected on a surface to support element requirement verification and provides a capability to assess efficacy of dust cleaning methods	2024	2025
Scope Surface Dust Model Framework	Plan for scoping and developing an integrated Dust model addressing verification needs of surface elements.	2025	2026
SORTIMAP Lunar Dust Model	Surface Operations to Regolith Terrain Interactions Modeling and Analysis Program: Proposed tool to model lunar dust particle interactions with a spacecraft vehicle on the lunar surface. The intent of the tool is to define dust loading induced by vehicle activity to inform design driving requirements and mitigate decreased performance of surface assets. Early iterations of the model will focus on dust load accumulation and will later incorporate charging characteristics.	2026	2026
Thermal Model development	Thermal Desktop tool that incorporates thermal dust model methodology using LDES test data. COMPLETED	2023	2025
Thermal Effects In Plume Surface Interaction During a Powered Decent Landing	As NASA advances its plans for sustained lunar exploration, challenges identified during the Apollo missions must be addressed—one of the most critical being Plume-Surface Interaction (PSI). During a lunar lander's descent, retro-propulsion exhaust may create craters during large lunar lander's decent that destabilize landing sites. Ejecta generated by this process can form dense dust clouds that obscure visibility, interfere with optical navigation, and damage sensitive equipment. Although PSI remains an active research area, many prior experiments have not replicated the extreme thermal gradient between rocket exhaust (~1800 K) and the lunar surface (~250 K or lower). This gradient is significant, as it can induce thermophoresis—driving particles toward cooler regions—and increase particle cohesion, both of which influence ejecta formation and crater behavior. The proposed work aims to close this gap by designing an experimental setup capable of controlling gas properties, thermal gradients, and flow conditions. The effort will include developing diagnostics for high-speed 3D particle tracking, ultra-high-speed capture of incipient motion, and precise measurement of thermal gradients. Systematic testing will evaluate a range of flow and particle characteristics to better predict PSI dynamics and develop mitigation strategies.	2022	2026
Simulant Assessment	Provides an independent evaluation of lunar regolith simulants to help inform decisions of the community in selecting lunar simulants for experiments and/or testing. https://lsic.jhuapl.edu/Our-Work/Working-Groups/Lunar-Simulants.php	2025	2026

Proposed Dust Measurement Investments

Task Bar Name	**Description and Status**
DMTF	Dust Mitigation Testing Facility (DMTF). Capability to perform “end-to-end” simulated dust testing of fluid, electrical, and mechanical systems & support development of operational methods & procedures for removing dust from an EVA Suit.
Lunar Surface Databook - Dust Appendix	Goal is to collect and distribute lunar dust data across M2M and Industry (ground tests and on-orbit)
pXRF for Flight	Upgrades COTS tool for surface dust quantification for use in-flight and during surface mission activities; includes testing and qualification for flight.
MELD	Microgravity Experiment for Lunar Dust (MELD). Phase I: Determine the amount of dust transferred during a simulated docking event in a vacuum chamber using lunar simulants. Phase II: Develop a compact dust transfer apparatus to be mounted aboard a Blue Origin New Shepard rocket. New Shepard flight opportunities funded by NASA but require proven test concept and instruments from Phase I to compete for a ride. Results would be used to validate GOLDMAP.
DEMOP	Dust Effects on Material Optical Properties (DEMOP). Experiment to investigate how optical properties are changed by exposure to lunar simulants. Conducted by Purdue University, funded by GW thermal team. Completed Phase I which measured optical properties of several simulants. Have funding for Phase II which will measure optical properties of several materials that are candidates for thermal radiators before and after exposure to simulants to characterize impact.
Simulant Activation Test Standard	Test Standard will improve fidelity of adhesion testing and inform on criteria to be used to assess minimizing dust adhesion. Dust adhesion testing is complicated due to many factors that depend not only on the environmental factors of the test coupons, but also on the state of the simulants and/or lunar samples. One of the biggest challenges is whether low-fidelity tests of dust adhesion (spinning samples, vibrating samples, inclined-plane tests, pouring, brushing, etc.) can be used as guidance toward material selection for Artemis. Although many adhesion forces can be duplicated in the lab, some are quite challenging and require special instrumentation. Reactivity is related to pristine behavior of regolith, and it is potentially greater reactivity in comparison with simulants formed in a terrestrial environment. This activity would investigate if reactivity creates an additional adhesive force currently not included in testing or modeling and would assist in quantifying this force and how to include this force in testing/modeling.

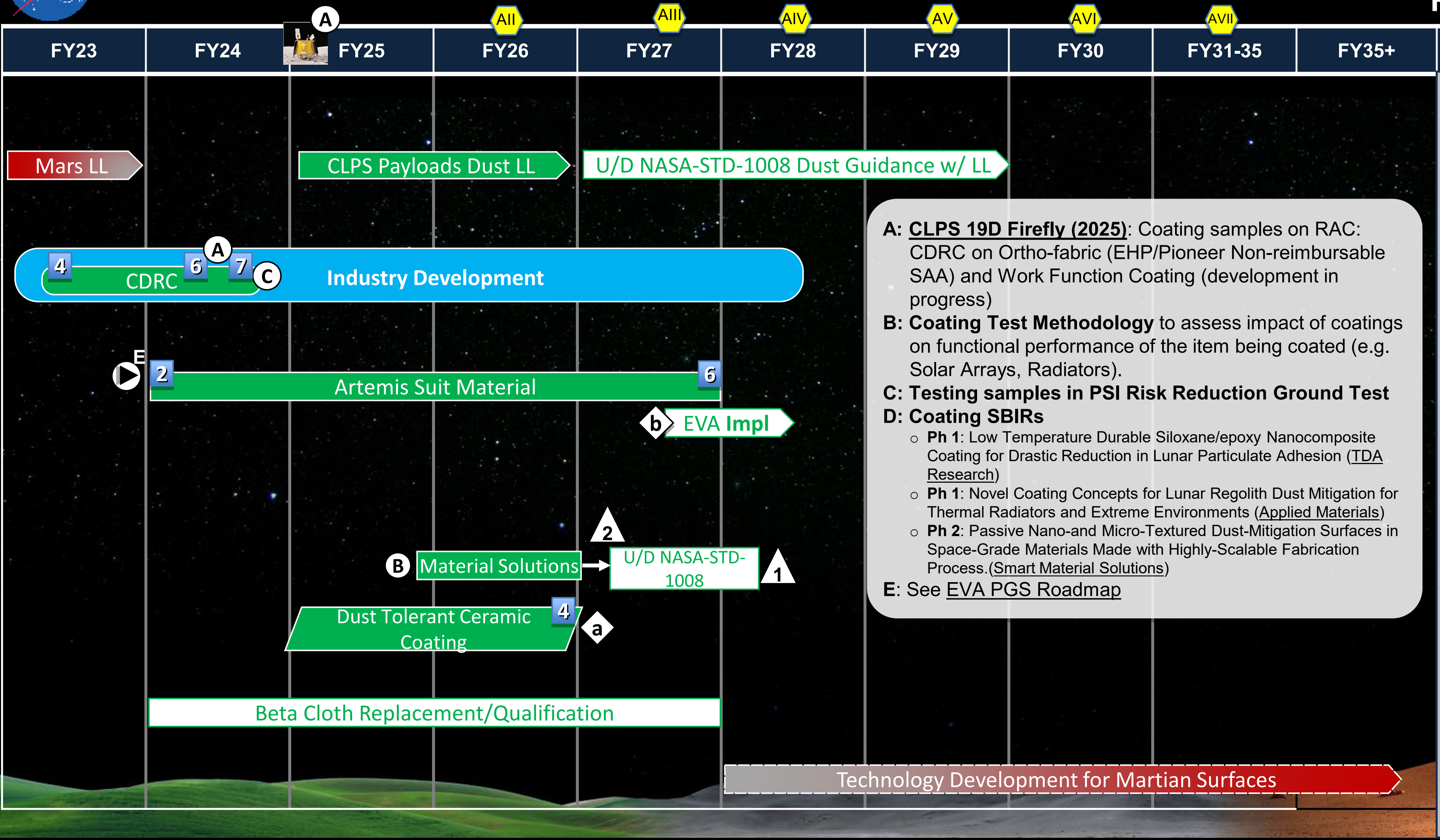
Proposed Dust Measurement Investments (Continued)

Task Bar Name	**Description and Status**
TDMD	PLSS Terrestrial Dust Mitigation Devices (TDMD). Advance SBIR Phase II Lunar Dust Mitigation Devices (LDMD) to prohibit electrostatically charged Martian/Lunar dust from disrupting space suit valves operation. Coupling Computational Fluid Dynamics (CFD) and Discrete Element Method (DEM) shall determine if space suit vent gas is able to clean by coupling discrete Boundary-Layer functionality with advanced dust particle models. Test validation supports LDMD adaption to the Martian space suit and potential upgrade to Lunar EVA suit.
Ext Dust Collector	External passive dust collector (Carbon Nano Tube). Carbon Nano Tube collector based on ISS heritage experiment. To be mounted unto docking target or target MMOD shield to be installed/removed IVA. Collector must be returned to Earth for analysis and results. Results will be used to validate GOLDMAP and to inform ongoing dust mitigation strategy.
SORTIMAP Update	Model update incorporating lessons learned, new regolith data/knowledge, etc.
Tribocharging material characterization	Design and perform test(s) for characterization of tribocharging of spacesuit materials to be used in the EMA Ansys Charge Model. Testing will occur at MSFC/PLANET lab that can simulate vacuum, dust & plasma environment characteristics.
SuitMAP Model	Architect and develop a set of modules for EVA suit-tailored SORTIMAP for the study of lunar dust dynamics and contamination of an EVA suit. SuitMAP outputs include particle flux and charge state, contamination concentration (mass/area) maps across suit surfaces, 3D surface and environment data, particle size distribution, suit surface potentials, and particle liberation behavior

DM - Passive Dust Mitigation Solutions (Shortfall 844/Gaps 0801/0802)

POC: Chris Wohl

Revised: Winter 2025



A: **CLPS 19D Firefly (2025)**: Coating samples on RAC: CDRC on Ortho-fabric (EHP/Pioneer Non-reimbursable SAA) and Work Function Coating (development in progress)

B: **Coating Test Methodology** to assess impact of coatings on functional performance of the item being coated (e.g. Solar Arrays, Radiators).

C: Testing samples in PSI Risk Reduction Ground Test

D: Coating SBIRs

- **Ph 1**: Low Temperature Durable Siloxane/epoxy Nanocomposite Coating for Drastic Reduction in Lunar Particulate Adhesion (TDA Research)
- **Ph 1**: Novel Coating Concepts for Lunar Regolith Dust Mitigation for Thermal Radiators and Extreme Environments (Applied Materials)
- **Ph 2**: Passive Nano-and Micro-Textured Dust-Mitigation Surfaces in Space-Grade Materials Made with Highly-Scalable Fabrication Process.(Smart Material Solutions)

E: See EVA PGS Roadmap

Additional Information

Deliverables and Milestones

1. NASA-STD-1008 Update
2. NASA Technical Memo on Coatings
3. Project Infusion Readiness Assessment (PIRA)

Decision Points a

a. Assess infusion potential to pursue maturation to TRL 6
b. Infuse into EVA – partner with Vendor
c. Infuse into Unpressurized Rover, - partner with Vendor
d. Infuse into Pressurized Rover
e. Infuse into GW

Candidates Under Evaluation

🟩 Ground
■ ISS / LEO
■ Lunar orbit
■ Lunar Surface
■ Mars Transit
🟥 Mars Surface
● Notes
◆ Decision point
▲ Deliverable/Milestone
Act Funded
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Objectives (FOM/KPPs): See metrics in STMD Shortfalls list and latest version of the ADD

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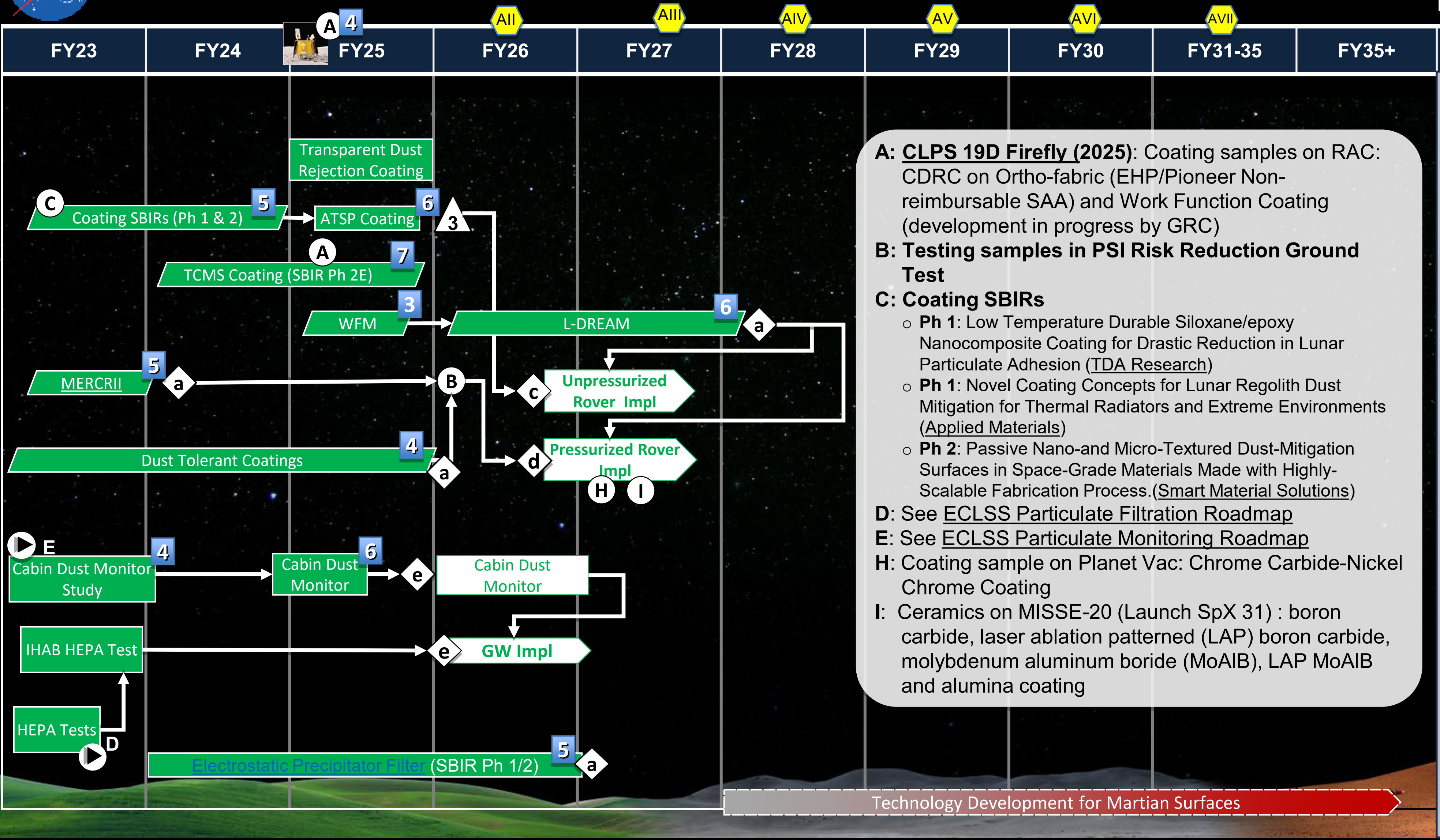

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D: See ECLSS Particulate Filtration Roadmap

E: See ECLSS Particulate Monitoring Roadmap

H: Coating sample on Planet Vac: Chrome Carbide-Nickel Chrome Coating

I: Ceramics on MISSE-20 (Launch SpX 31) : boron carbide, laser ablation patterned (LAP) boron carbide, molybdenum aluminum boride (MoAlB), LAP MoAlB and alumina coating

Additional Information

Deliverables and Milestones △#

1. NASA-STD-1008 Update
2. NASA Technical Memo on Coatings
3. Project Infusion Readiness Assessment (PIRA)

Decision Points ◆a

a. Assess infusion potential to pursue maturation to TRL 6
b. Infuse into EVA – partner with Vendor
c. Infuse into Unpressurized Rover - partner with vendor
d. Infuse into Pressurized Rover
e. Infuse into GW/HLS

Candidates Under Evaluation

🟩 Ground
■ ISS / LEO
■ Lunar orbit
■ Lunar Surface
■ Mars Transit
🟥 Mars Surface
● Notes
◆ Decision point
▲ Deliverable/Milestone
Act Funded
Act Unfunded
⬢ Artemis missions
ESDMD
STMD
Industry
▶ Touchpoint
TRL

Objectives (FOM/KPPs): See metrics in STMD Shortfalls list and latest version of the ADD

NASA and Industry Funded Passive Dust Mitigation Investments

Task Bar Name	Description	Start	Finish
MERCRII	Development of coated conventionally and additively manufactured materials for tribological and radiation resistance improvement at Lunar and Martian surfaces. Testing SoA composite coatings applied to lightweight metal substrates using tribological evaluation techniques (three-body abrasion and direct particle erosion).	2021	2023
Work Function Coating	Work Function Matching Passive Lunar Dust Mitigation Coating. Samples on RAC on Firefly. Significantly lowered adhesion of simulants on smooth surfaces. Current development (CIF) is focused on making coating conductive for solar cell charge dissipation applications and testing with other than mare simulants. Achieved TRL-3 per CIF-25 closeout review. 20110014224.pdf	2019 2025	2021 2025
TCMS Coating	Integration of Dust Resisting Secondary Emission Engineered Passive Thermal Control Material Systems (TCMS) Coating (Applied Material System Engineering). demonstrate, through simulated space environments, insertion of its dust shedding coating technology	2024	2026
CDRC	Clear Dust Repellent Coating (CDRC). Voyager/Pioneer developing and testing a commercial coating targeted for lunar dust mitigation on various surfaces. Samples flew on RAC on Firefly	2022	Cont.
Lunar Glove Durability	Lunar Glove Thermal and Durability Analysis, Test, and Failure Mitigation. Develop consistent/standardized testing defined to evaluate durability of existing glove for Lunar surface to baseline Lunar performance data on the Phase VI gloves from which to compare new design.	2023	2024
Artemis Suit Material	Develop several Environmental Protection Garment (EPG) material solutions that can be used to mitigate the near-term robustness risks of the xEVAS vendor suit and gloves not being designed for sustained lunar EVAs. This development includes unique evaluation of several concepts to increase material robustness including, but not limited to new materials (fiber, yarn) and fabrication, (weave, finger seems, heater switch)	2023	2026
HEPA Tests Stage 3 Filter Test results	Demonstrate that HEPA filter can filter out lunar dust by showing that efficiency of HEPA filter does not decrease after testing with lunar dust. Measured pressure drop, loading capacity, HEPA filter efficiency, and a damage assessment to HEPA filter media caused by lunar dust simulant. Stage 1 and 2: Provided lunar dust test data on HLS ECLSS HEPA filter media. Stage 3: Providing lunar dust test data on the Gateway HALO ECLSS HEPA filter media test. Note: STMD funded initial test facility development and HEPA media test.	2021	2022
IHAB HEPA Test	JAXA/KHI conducting HEPA filter testing with lunar simulant in Japan in accordance with NASA-STD-1008	2023	2023
Cabin Dust Monitor Study	DM Detect. Validate performance of seven COTS dust monitors with a range of varying particle sizes and concentrations through analysis of diverse lunar simulants. Completed down select on best performer.	2023	2023
Electrostatic Precipitator Filter	Autonomous Habitat Filtration System (AHFS) using an electrostatic precipitator and autonomous regeneration system to effectively remove ultrafine (<100nm) dust from habitable environments in long-duration missions	2023	2026

NASA and Industry Funded Passive Dust Mitigation Investments

Task Bar Name	Description	Start	Finish
Dust-Tolerant Coatings	Development of protective coatings and materials (i.e., scalable COTS) and novel materials and architectures (i.e., laser ablation patterning, bio-inspired surface design) to mitigate abrasive wear and adhesion by dust on lunar components. Testing performed using standard tribological methods, Taber abrasion (with standard and regolith-simulant-based abrasive wheels), dust adhesion and surface energy characterization, microstructural characterization (profilometry, optical and electron microscopy), thermal shock screening and environmental testing (abrasive wear by dust in vacuum environment, cryogenic solid particle erosion); MISSE-16 and MISSE-20 flight experiments for space environment exposure; one sample on PlanetVac on Firefly. COTS Dust Tolerant Coatings TM ; Laser ablative patterning of B4C and MoAlB ceramics	2019	2025
Dust Tolerant Ceramic Coating	Development and assessment of Yttria Stabilized Zirconia (YSZ) ceramic coatings for impact and wear resistance against lunar dust by Embry-Riddle Aeronautical University graduate student (2 years project with goal to achieve TRL-4 – assumes testing complete at LaRC test facilities)	2025	2026
Transparent Dust Rejection Coating	Develop a conductive, low surface energy, low surface roughness, transparent, wear- and scratch-resistant diamond-like carbon coating to mitigate buildup of dust on (transparent) surfaces in a lunar environment.	2025	2025
L-DREAM	(1) A passive lunar dust mitigation coating that minimizes electrostatic adhesion forces and is designed for: (a) solar cells such that optical clarity is unaffected, (b) thermal control surfaces (TCS) to maintain emissivity, and (c) nonwoven fabric for EVA suits. (2) Coating compatibility with large-scale manufacturing methods. (3) Solutions for synergistic use of the coating with active dust mitigation strategies and insulation of dust-tolerant coatings.	2026	2028
High Performance Polymer for Dust Tolerant Extreme Environment Bearings	Development and demonstration of ATSP-based coating used for dust abrasive conditions in combination with wide temperature changes. Designed for dust tolerant bearings for lunar and Mars applications, compositive seals to increase wear life expectancy for any dynamic or slow-moving seals, and composite seals used as high-pressure static seals in a wide range of temperature variations.	2023	2025
Cabin Dust Monitor Environmental Study	Testing of COTs cabin dust monitor devices under lunar surface environmental conditions, including radiation vibration and vacuum cycling. Project demonstrated ability of COTs devices to survive cabin and airlock conditions.	2024	2025

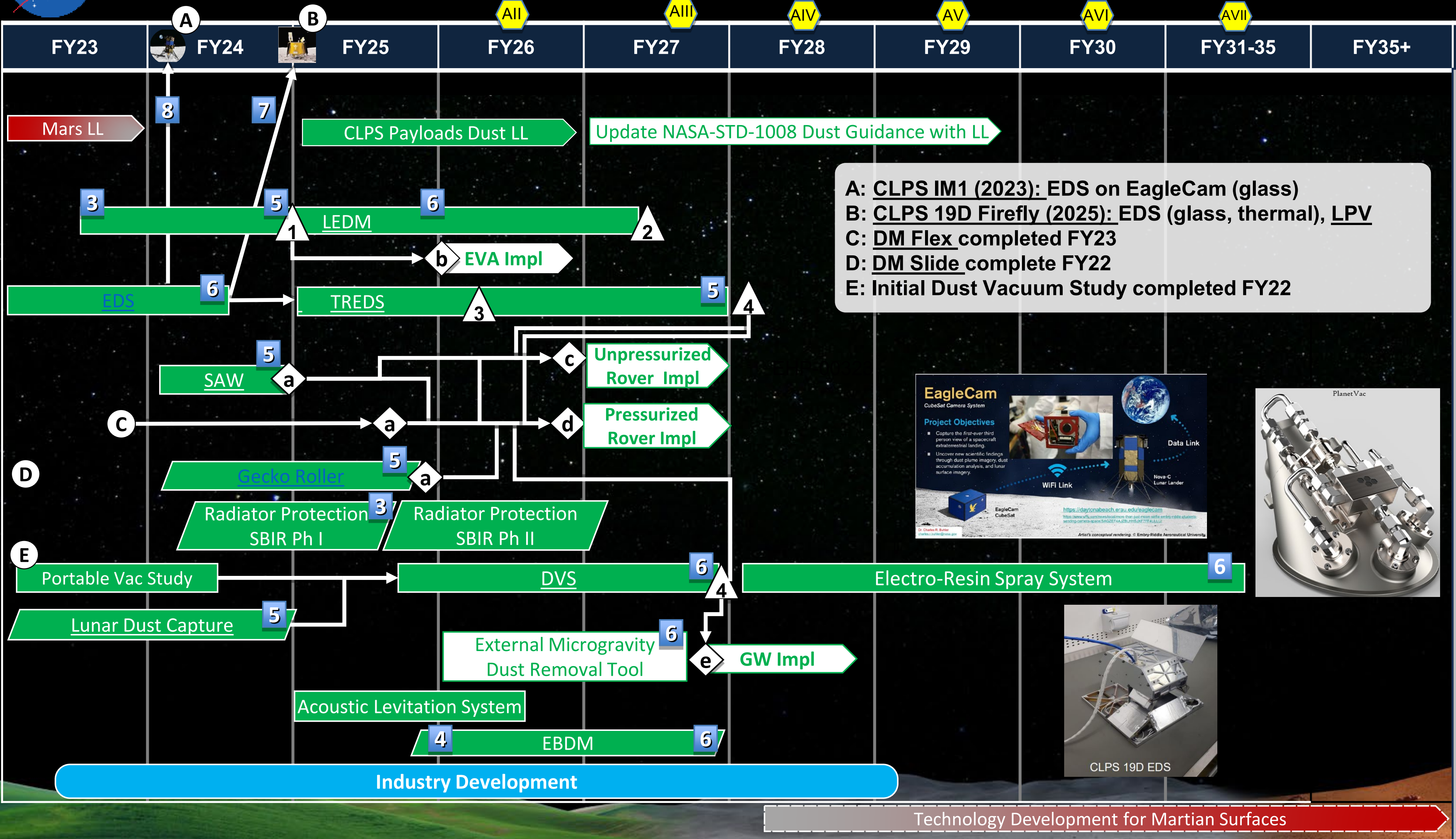
Proposed Passive Dust Mitigation Investments

Task Bar Name	**Description**
Cabin Dust Monitor	Develop a portable lunar dust monitor leveraging previously assessed COTS solutions to provide a capability for In-flight monitoring in habitable environments to characterize concentrations of dust to enable any necessary crew action to maintain health and safety, tracking of average exposure, while also informing necessary treatment options after the mission, and providing a record of crew exposures. Lunar dust monitoring is informed by specific particle size ranges and mass-based concentration limits (relevant from a human health perspective and monitoring is dependent on mission characteristics and other factors. (Ref. NASA STD 3001, Vol 2). ROM in work for flight certification of COTS monitor.
Material Solutions	Coating Compatibility Guidelines. NASA Technical Publication on expected coating behavior based on NASA test methodologies performed to assess functional performance of specific material surfaces being coated for various applications to qualify the use of dust mitigation coatings on lunar surface assets.
Beta Cloth Replacement / Qualification	Solution to beta cloth no longer being made by the company that had manufactured it for the last 70 years. Beta cloth was planned to be used for the outer layer of habitats and suits due to its resistivity of abrasion by dust, among other properties that make is desirable its replacement will need the same or better properties.

DM - Active Dust Mitigation Solutions (Shortfall 1047, Gaps 0801/0802)

POC: Amy Fritz

Revised: Winter 2025



A: CLPS IM1 (2023): EDS on EagleCam (glass)
B: CLPS 19D Firefly (2025): EDS (glass, thermal), LPV
C: DM Flex completed FY23
D: DM Slide complete FY22
E: Initial Dust Vacuum Study completed FY22

EagleCam

CubeSat Camera System

Project Objectives

- Capture the *first-ever* third person view of a spacecraft extraterrestrial landing.
- Uncover new scientific findings through dust plume imagery, dust accumulation analysis, and lunar surface imagery.

WiFi Link

Data Link

Nova-C Lunar Lander

EagleCam CubeSat

https://daytonabeach.erau.edu/eaglecam

https://www.wfty.com/news/local/more-than-just-moon-selfie-embry-riddle-students-sending-camera-space/SAGZEF4AJZBLHHSJXF7FF4ULLU/

Dr. Charles R. Buhler
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Artist's conceptual rendering. © Embry-Riddle Aeronautical University

Additional Information

Deliverables and Milestones

1. LEDM Breadboard
2. LEDM Ground Prototype ready for flight demonstration
3. Dust Adhesion & TVAC test on LDES
4. PIRA

Decision Points a

a. Assess infusion potential to pursue maturation to TRL 6
b. Infuse into EVA - partner with vendor
c. Infuse into Unpressurized Rover - partner with vendor
d. Infuse into Pressurized Rover
e. Infuse into GW

Candidates Under Evaluation

- Lunar Dust Removal Tool (LDRT)

Notes

- Artemis III Crew Training starts at ~ L- 2 years.

🟩 Ground
🟦 ISS / LEO
⬛ Lunar orbit
⬜ Lunar Surface
🟧 Mars Transit
🟥 Mars Surface
● Notes
◆ Decision point
▲ Deliverable/Milestone
Act Funded
Act Unfunded
⬢ Artemis missions
ESDMD
STMD
Industry
▶ Touchpoint
TRL

Objectives (FOM/KPPs): See metrics in STMD Shortfalls list and latest version of the ADD

NASA and Industry Funded Active Dust Mitigation Investments

Task Bar Name	Description and Status	Start	Finish
Electrodynamic Dust Shield (EDS)	Clears dust off surfaces and prevents accumulation by using a pattern of electrodes to generate a non-uniform “wavelike” electric field over the surface being protected. It will repel dust off materials such as coated Kapton and glass to demonstrate applications for thermal radiators, camera lenses, solar panels, and other hardware and equipment. (TRL-~~9~~ 8)	Various	Various
Lunar Electrostatic and Dust Mitigation (LEDM) Tool	Develops a ground prototype of a handheld static ionizer tool for astronauts to remove dust and neutralize electrostatic charge from materials in a lunar environment. This tool will be similar to a commercially available static ionizer gun with miniaturization and portability. The tool will measure electrostatic charge on a target surface to be cleaned and tailor an output high voltage waveform to produce a plasma from a compressed consumable gas pulse to remove dust and charge. (TRL-6)	2023	2026
Lunar Dust Capture	Lunar Dust Capture Using a Novel, Multiplexed Inertial Filter - Objective is to contain lunar dust with less pressure drop and minimal to no filter clogging. Year 2 concluded with extremely small (<1000 cc) system prototype in a vacuum application. Year 3 will add electrostatics to improve collection of <3 micron fines in a small vacuum application.	2024	2024
SAW	Self-Sensing Surface Acoustic Wave (SAW) Active Dust Mitigator. The proposed Transparent SAW (TP-SAW) system will provide active dust mitigation for all charged and uncharged particles to be moved off the surface of sensitive equipment such as solar panels, radiators, reflectors, optical sensors, cameras, etc. A pair of Inter Digitated Electrodes (IDEs) on a transparent piezoelectric film enables to propagate an effective surface wave to perceive and remove dust particles.	2024	2024
Gecko Roller	Development and Test of Lunar Dust Removal using a Gecko Roller. Remove lunar dust from spacesuits and hard surfaces (e.g., solar panels). Works same way as a common terrestrial lint roller, but with an elastomeric gecko-skin-inspired membrane replacing the adhesive sheet. Also, will develop an appliance to clean gecko roller after use. Can be used by an astronaut by hand or integrated into a cleaning robot.	2024	2026
DMFlex	Utilizes simple mechanical, vibrating solution for dust removal from flexible, roll-out solar arrays.	2021	2024
Portable Vac Study	Portable Vacuum Study to evaluate 4 COTS vacuums.	2023	2023
DM Slide	Ability of cleaning methods to remove lunar simulant dust was evaluated on different substrate materials. Each cleaning method-substrate pair was evaluated in four categories: cleaning efficiency, cleaning material longevity, ease of use, and surface damage. Testing was done on 5 cm X 5 cm substrate coupons in a dry environment. Test substrates and cleaning media selected to represent wide range of materials. <Report>	2021	2022

NASA and Industry Funded Active Dust Mitigation Investments (Cont'd)

Task Bar Name	Description and Status	Start	Finish
Dust Vac Tests	Evaluated removal efficiency of particles embedded on ortho fabric to support development or selection of a vacuum cleaner for use on lunar missions. A resuspension curve (trend of removal efficiency as a function of time) was determined for multiple initial loading states, with increasing severity of penetration/ grinding into fabric sample. Testing also demonstrated how variations to preparation method affected repeatability.	2020	2021
Radiation, dust and coolant freeze-out mitigation	Development and demonstration of an innovative multilayered system that attenuates UV radiation, eliminates dust adhesion and prevents coolant freeze-out. Technology is compact, lightweight, fast actuation, low power and maintenance-free.	2024	2025
Thermal Radiator with EDS (TREDS)	Assess efficacy of EDS for Thermal Radiators. Mature a solution to remove dust contamination of thermal radiators that may be used on critical systems needed for mission success on the Lunar and Martian surfaces by developing an Electrodynamic Dust Shield (EDS) that can be integrated into a thermal radiator without significantly impacting thermal performance.	2025	2027
Acoustic levitation system	Solution to provide de-adhesion of dust and regolith particles from surfaces utilizing sound waves and provide a medium for creation of hybrid levitation systems for dust sorting.	2025	2027
Dust Vacuum System (DVS)	Develop an integrated system of one blower and two filters to effectively control lunar dust and clean cabin atmosphere after a discharge of a fire extinguisher.	2025	2027
Electron Beam Dust mitigation (EBDM)	An Electron Beam to charge particles to mitigate dust hazards for exploration on dust rich airless bodies like the Moon. Demonstration of technology via parabolic flight.	2026	2026
Electro-Resin Spray System	Develop a system that sprays conductive resin on lunar simulants in a vacuum environment creating an electrically conductive dust free zone of up to 1000 square meters with less than 30 kg of resin.	2028	2031

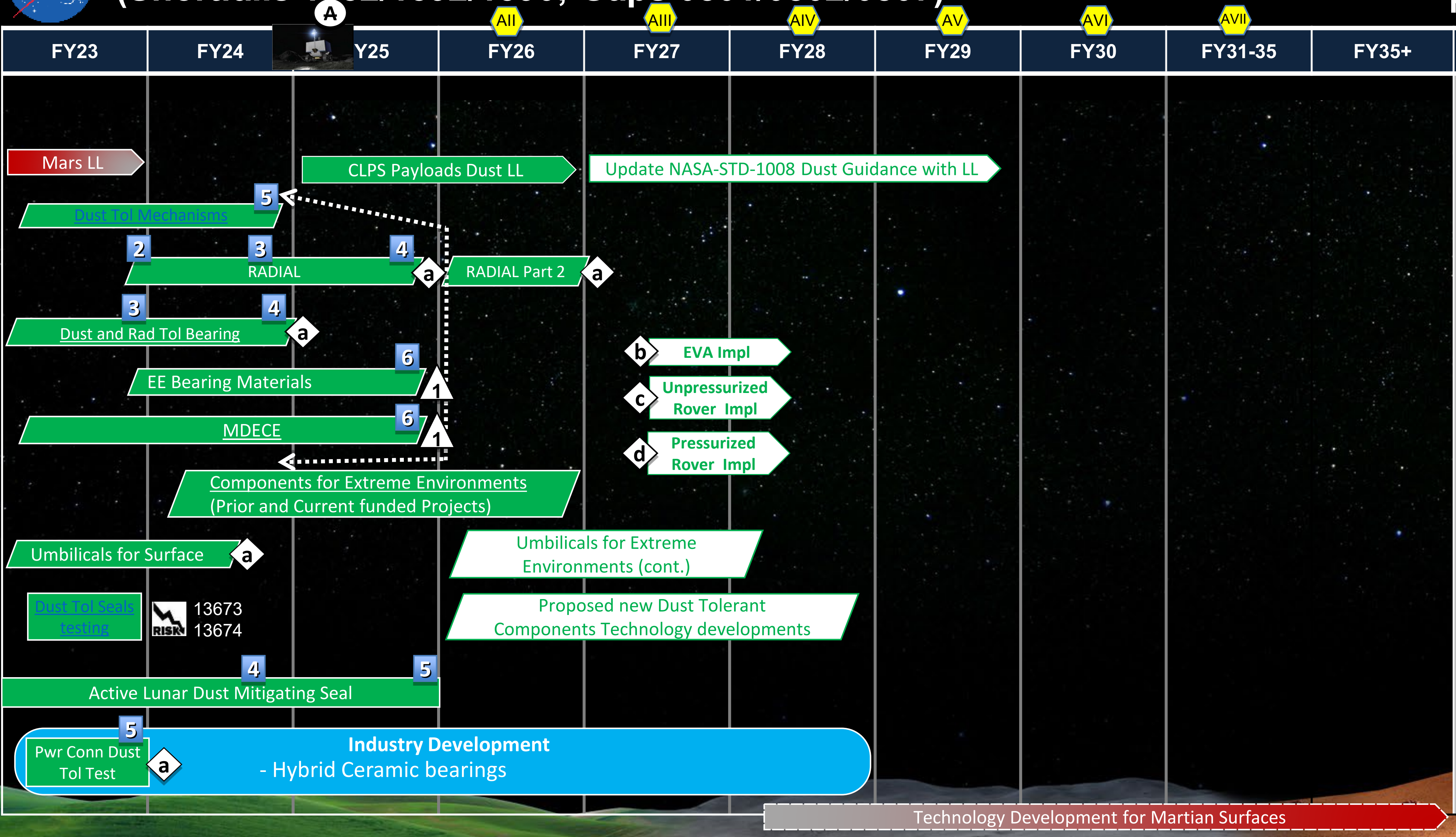
Proposed Active Dust Mitigation Investments

Task Bar Name	**Description and Status**
External Microgravity Dust Removal Tool	Tool to remove dust from External Gateway surfaces, GERS compatible.
Update NASA-STD-1008 Dust Guidance with LL	This NASA Technical Standard establishes minimum requirements and provides effective guidance regarding methodologies and best practices for testing systems and hardware to be exposed to dust in dust laden and generating environments. As technologies and methodologies mature, this NASA Standard will be updated.

DM - Dust Tolerant Components (Shortfalls 1552/1592/1390; Gaps 0801/0802/0807)

POC: Drew Smith

Revised: Winter 2025



A AII AIII AIV AV AVI AVII

FY23 FY24 FY25 FY26 FY27 FY28 FY29 FY30 FY31-35 FY35+

Mars LL

CLPS Payloads Dust LL

Update NASA-STD-1008 Dust Guidance with LL

5 Dust Tol Mechanisms

2 3 4 RADIAL a

RADIAL Part 2 a

3 4 Dust and Rad Tol Bearing a

6 EE Bearing Materials 1

6 MDECE 1

Components for Extreme Environments (Prior and Current funded Projects)

b EVA Impl

c Unpressurized Rover Impl

d Pressurized Rover Impl

Umbilicals for Surface a

Umbilicals for Extreme Environments (cont.)

Dust Tol Seals testing

RISK 13673 13674

Proposed new Dust Tolerant Components Technology developments

4 5 Active Lunar Dust Mitigating Seal

5 Pwr Conn Dust Tol Test a

Industry Development

- Hybrid Ceramic bearings

Technology Development for Martian Surfaces

Additional Information

Deliverables and Milestones

1. PIRA

Decision Points a

a. Assess infusion potential to pursue maturation to TRL 6

b. Infuse into EVA - partner with Vendor

c. Infuse into Unpressurized Rover - partner with Vendor

d. Infuse into Pressurized Rover ~~PR~~

Candidates Under Evaluation

○ Dust Tolerant CryoMag Coupler

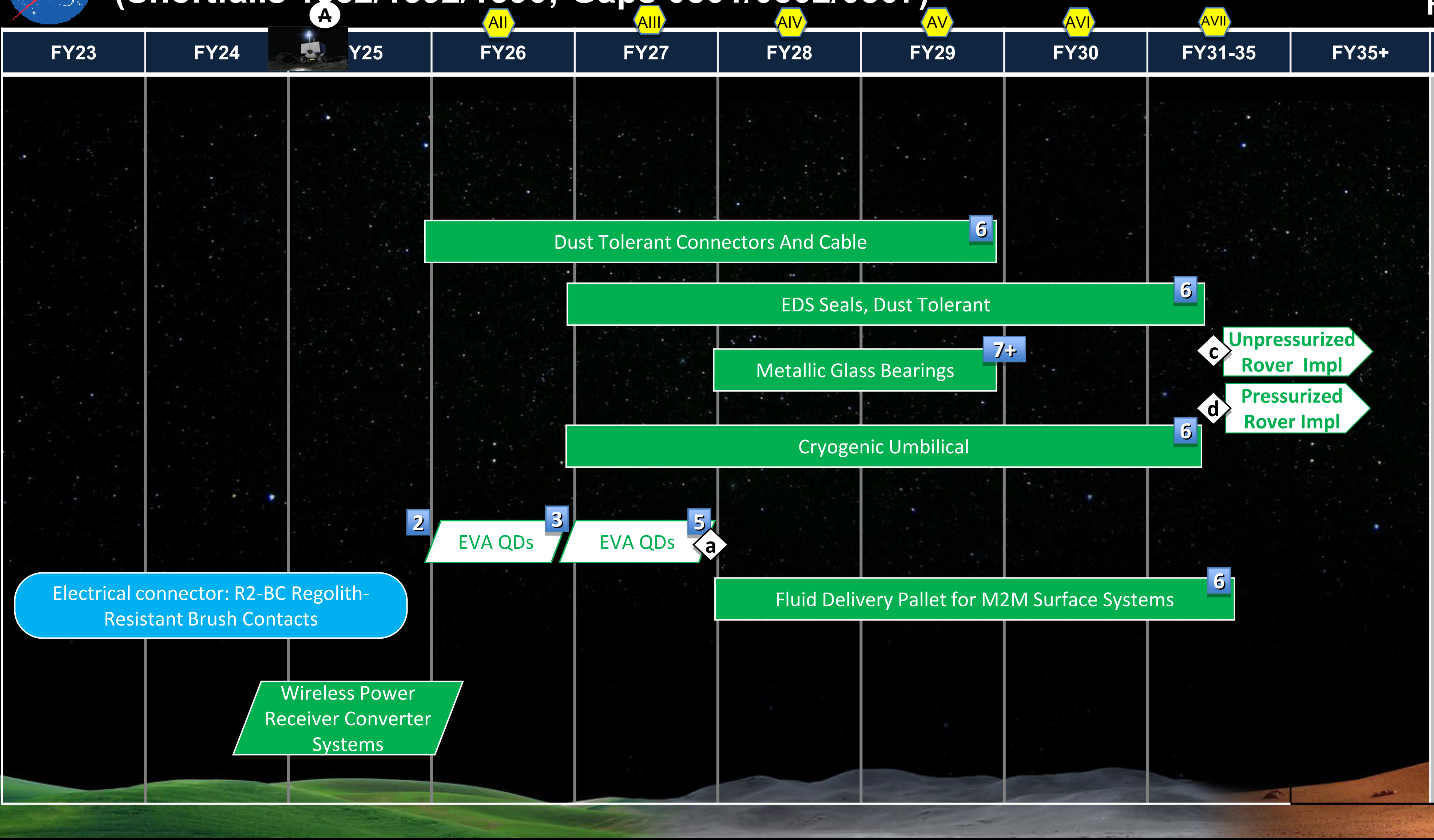
🟩 Ground
■ ISS / LEO
■ Lunar orbit
■ Lunar Surface
🟧 Mars Transit
🟥 Mars Surface
● Notes
◆ Decision point
▲ Deliverable/Milestone
Act Funded
Act Unfunded
⬢ Artemis missions
ESDMD
STMD
Industry
▶ Touchpoint
TRL

Objectives (FOM/KPPs): See metrics in STMD Shortfalls list and latest version of the ADD

DM - Dust Tolerant Components (Continued)
(Shortfalls 1552/1592/1390; Gaps 0801/0802/0807)

POC: Drew Smith

Revised: Winter 2025



Dust Tolerant Connectors And Cable

EDS Seals, Dust Tolerant

Metallic Glass Bearings

Unpressurized Rover Impl

Pressurized Rover Impl

Cryogenic Umbilical

EVA QDs

EVA QDs

Electrical connector: R2-BC Regolith-Resistant Brush Contacts

Fluid Delivery Pallet for M2M Surface Systems

Wireless Power Receiver Converter Systems

Additional Information

Deliverables and Milestones

1. PIRA

Decision Points a

a. Assess infusion potential to pursue maturation to TRL 6

b. Infuse into EVA - partner with Vendor

c. Infuse into Unpressurized Rover - partner with Vendor

d. Infuse into Pressurized Rover

Candidates Under Evaluation

○ Dust Tolerant CryoMag Coupler

~~*Notes:*~~

~~A: Prior and current funded Dust Tolerant Components Investments (Details shown on slides 31-33)~~

~~B: Proposed New Dust Tolerant Components Investments (Details shown on slide 34)~~

🟩 Ground
■ ISS / LEO
■ Lunar orbit
■ Lunar Surface
■ Mars Transit
🟥 Mars Surface
● Notes
◆ Decision point
▲ Deliverable/Milestone
Act Funded
Act Unfunded
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Objectives (FOM/KPPs): See metrics in STMD Shortfalls list and latest version of the ADD

NASA and Industry Funded Dust Tolerant Components Investments

Task Bar Name	Description	Start	Finish
Dust Tolerant Mechanisms	Provides groundwork for a long-term dust mitigation strategy collecting information on SoA solutions that currently exist (via market analysis and development of a Best Practices Guide Book), developing NASA standards for classifying the definition, testing and mitigation of dust, developing low Technology Readiness Level (TRL) technologies (such as piezoelectric-driven dust, plasma/e-beam dust lofting, and electrodynamic dust repellers/collectors, coatings and soft polymeric materials) and integrating mature technologies into systems that require dust mitigation solutions. (such as Electrostatic Dust Shield and Patch Plate Materials)	2023	2024
MDECE	Motors for Dusty and Extreme Cold Env (MDECE). Unheated magnetically-geared motor and an unheated piezoelectric motor that can operate continuously for a long duration at an ambient temperature of -243 ºC (33K). Utilizes an inherently lubricant free gearbox at lower temperature for longer times. Improve lunar dust tolerance relative to conventional actuators.	2023	2024
RADIAL	Reversible Auto-aligning Dusty Interface for Autonomous Latching (RADIAL) Connector. Project seeks to eliminate redundant cost of developing several similar connectors in parallel for various lunar surface operations by integrating key functional requirements of each into a single, universal design capable of meeting requirements of nth percentile use case driven by a cost-benefit analysis of all interfacing components expected to deploy on the lunar surface. Achieved TRL-4 per CIF-25 closeout review.	2024	2024
Dust and Rad Tol Bearing	A radiation-resistant and super hard material for dust-resistant mechanical bearing applications on the lunar surface that is more than 30% lighter than the chrome steel commonly used for bearings, and about 15% lighter than Nitinol. This highly incompressible ceramic material is able to be formed into intricate bearing geometries directly from powder to create dense, hard, geometrically precise, and wear-resistant bearing surfaces. Phase I demonstrated the technical feasibility of producing bearing geometry components from the material formulation. Phase II: Design, build and test roller bearings and further develop the microstructure to optimize the density, strength, and surface finish of the material. (*MILLENITEK*)	2023	2024
EE Bearing Materials	Extreme Environment Tribological Characterization of Advanced Bearing Materials. Fabricate a prototype of bearing material solutions to meet extreme temperatures, pressures, dust environments. (*ATSP Innovations*)	2024	2026
Dust Tol Seal Testing	Matured testing methods/process for seals, characterized performance of representative seals when exposed to lunar dust simulants via testing, evaluated alternate seal surface treatments. Testing done on Orion docking hatch and docking system (NDS). *Phase I - III completed. Phase* 1-Develop performance database for seals - TM-20230015308. Phase II - Seal Cleaning Tests. Phase 3: Evaluate Alternate Seal Surface Treatments.	2020	2023
Power Con Dust Tol Test	Testing an Industry solution to characterize performance in dust environment	2024	2024

NASA and Industry Funded Dust Tolerant Components Investments (Continued)

Task Bar Name	**Description**	**Start**	**Finish**
Regolith Immune Linear Actuator Family	Linear Actuators for surface systems, lubrication free, stroke range 0.1”-60”, force range 100 – 3000 lbf. Phase II SBIR project will deliver 4 full size Engineering Test Unit (ETU) prototypes to TRL5. In addition, a small-scale qual unit will be delivered at TRL6 to be flown on a potential future surface pallet flight demonstration raising the technology to TRL7.	2024	2026
Lunar Truss Design and Construction	Produce an automated assembly technique that can build a 50m tower on the lunar surface. Additionally, advancements to RFSSW machine design for survivability in the lunar environment will be shown, and design improvements will be made that benefit both extraterrestrial and earth-based products. (TRL3 to TRL5 or greater)	2024	2026
Low Mass, High Voltage Cables for Long Distance Lunar Power Distribution	At the conclusion of these efforts, the high-fidelity prototype cable assembly will have been tested in a relevant environment. This will address critical gaps in technology as identified by NASA, assessing temperature swings and space radiation level analysis. This will ensure the cable technology supports up to 10kW power transfer with low mass materials. (TRL4 to TRL 6)	2024	2026
Flexible Lunar Robotics/Rover Dust Mitigation Covers	Develop scalable and adaptable flexible hermetically sealed dust cover technologies that are broadly applicable to a range of uses on the lunar or Mars surface. This includes rotary, linear, and ball joints, as well as entire assemblies of rovers and robotics. Dust cover technology will be a part of a layered strategy where dust mitigation technologies compliment one another for maximum protection. (TRL3 to TRL5)	2024	2025
Resonant Transformer Connectors for High Voltage Transmission Lines	A novel resonant transformer connector system to electrically interface with high voltage transmission lines, while being completely sealed with no exposed conductive terminals to operate effectively for harsh environmental conditions. The purpose of this R&D effort is to develop a resonant transformer connector system for high voltage AC transmission lines that can reliably interface with power sources on the Moon and Mars. (TRL1 to TRL4)	2024	2025
Magnetic Gearing Applications for Space	Magnetic gears transfer power through the interaction of magnetic fields, instead of mechanical contact. This non-contact operation allows magnetic gears to potentially mitigate the reliability, maintenance, and lubrication challenges associated with mechanical gears. (TRL2 to TRL4)	2024	2026
Six-Axis Force-Torque Transducer for Use in Cryogenic and High-Radiation Environments	A six-axis force and torque sensor that can survive and function in harsh environments expected during a lander mission to Europa, or a similarly high-radiation, low-temperature environment. ATI has successfully developed a six-axis force/torque sensor suitable for use on Mars (SHA FTS on 2020 Perseverance Rover), additional validation is required to ensure the same fundamental technology would be successful in more extreme environments. (TRL3 to TRL5)	2021	2022

NASA and Industry Funded Dust Tolerant Components Investments (Continued)

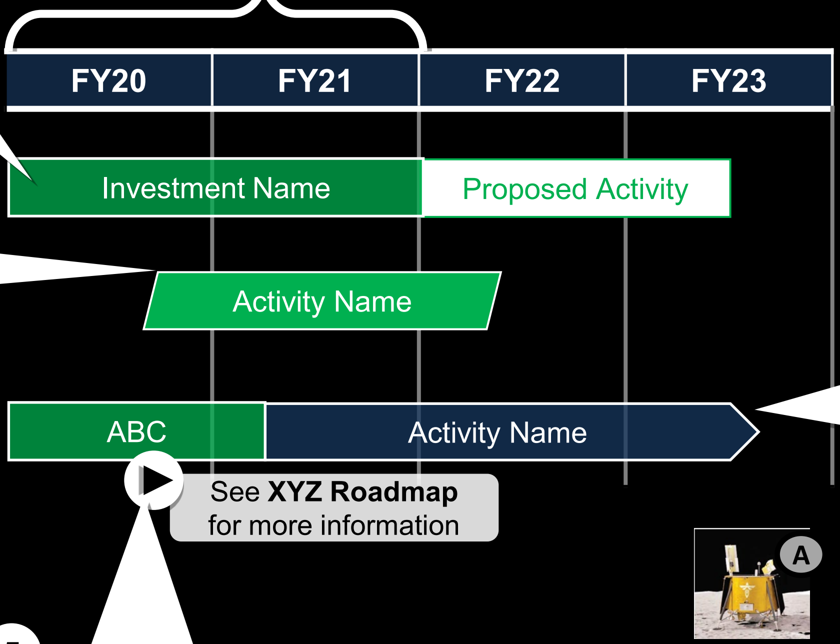
Task Bar Name	Description and *Status*	Start	Finish
Payload Universal Multi-purpose Adapter (PUMA)	Interface for in-space and surface science instrument servicing, assembly, upgrading & swapping. Incorporates EVA compatibility and lunar dust mitigation features (TRL2 to TRL4)	2024	2025
Electrical connector: R2-BC Regolith-Resistant Brush Contacts	Dust-tolerant brush contacts with low mating force and redundant mating surfaces that have been qualified in sand and dust and meet MIL-DTL-55302	2023	2025
Active Lunar Dust Mitigating Seal	Using additives to make silicone conductive to be able to repel dust with a like charge. These seals can be used in a multitude of ways and locations and are currently at TRL4.	2023	2025
Dust Tolerant Cryogenic Umbilical (CU) for M2M Surface systems	Dust Tolerant Umbilical for M2M Surface Systems	2027	2031
EDS Seals	A lunar and Martian rated EDS (Electrodynamic Dust Shield) seal prototype will be designed, fabricated, and tested in representative lunar and Martian environments.	2027	2031
Metallic Glass Bearings	Development and testing of bulk metallic glass, BMG (aka amorphous metal), cryogenic-tolerant bearing materials as well as dust-tolerant connectors/sealing surfaces. BMG gears are at TRL-7	2028	2029
Dust Tolerant Connectors and Cable	Dust tolerant connector and cable system with a high mate / de-mate capability that can meet the M2M-30002 Artemis Requirement M2M-R-0083 Bi-Directional Power Exchange capability of a 6kW 120 VDC bi-directional physical connector.	2026	2029
Fluid Delivery Pallet for M2M Surface Systems	Propellant and gasses Delivery and Loading Pallet for M2M Surface Systems	2028	2031
Wireless Power Receiver Converter Systems	Very short-range wireless connector to avoid dust issues with metal-to-metal contacts, contract 80NSSC24PB486	2025	2025

Proposed Dust Tolerant Components Investments

Task Bar Name	Description and Status
Umbilicals for Extreme Environments	Subtopic: 1) Surface System Umbilicals and Innovative mechanisms for connecting and protecting umbilical interfaces in the presence of dust.
Seals for Extreme Environments	Sealing materials, fabrics, and flexible metallic seals and techniques that can seal/protect mechanisms by preventing regolith intrusion and remain compliant and functional in the extreme Moon/Mars environments.
Electrical Connectors for Extreme Environments	Dust-tolerant electrical connectors that can function with (or mitigate) light dust coating in the relevant Moon/Mars environments.
Ambient Fluid Connectors for Extreme Environments	Dust-tolerant ambient fluid (gas and liquid) connectors that can function with (or mitigate) light dust coating in the relevant Moon/Mars environments. Tech advancements from these connectors may also aid in advancing EVA QDs.
Fluid Connectors for Extreme Environments	Surface systems cryogenic disconnects that are light weight and compatible with the extreme environments. Tech advancements from these connectors may also aid in advancing EVA QDs.
Dust Tolerant Mechanisms	Moving components for dust protection (iris, hatch, covers, louvers, airlocks, closures, hinges, joints, trusses, etc.).
EVA QDs	User-friendly dust-tolerant QDs for Artemis and beyond, increasing stakeholder confidence in critical hardware.

Back-up

Tips for Reading Roadmaps



1 Each box represents an activity or set of activities and the length of the box denotes the duration of the activity.

2 The color of each box represents the activity is planned/funded and the platform where the activity takes place (not the platform where the technology will be enabled). In this example the activity takes place on the ground although it may be the development of hardware for flight.

3 The shape of each box represents the source of funding. NASA ESDMD, NASA STMD, or Industry. See legend below for shapes.

4 Color codes and icon keys are located in the bottom left corner of each slide.

5 Play button icons show "touchpoints" between roadmaps.

6 CLPS lander icon indicates manifested H/W related to activity.

7 Capability objectives, FOMs, or KPPs are located in the bottom right corner.

8 Boxes that end in an arrow indicate activities without a defined end date or where the hardware will go into regular operation after a demo.

9 White background indicate activities that are under evaluation but are not yet confirmed or fully funded.

🟩 Ground
🟦 ISS / LEO
⬛ Lunar orbit

▨ Lunar surface

● Notes
◆ Decision point
▲ Deliverable/Milestone

Act Funded
Act Unfunded
⬢ Artemis missions

ESDMD
STMD
Industry

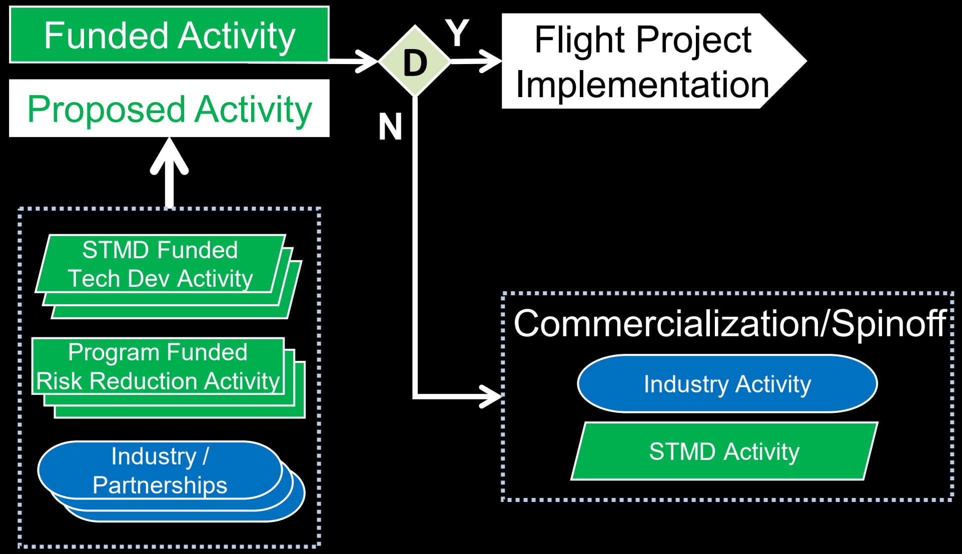
Risk
▶ Touchpoint
TRL

Objectives (FOMs/KPPs):
Performance measures that define the required capability

Life Cycle of Technology Integration

(Iterative, but not necessarily a serial process)

Shortfall /Gap Title/#



1. **Review capability/technology challenges**
2. **Identify activities to mitigate risks and close shortfalls**
3. **Periodically assess project/activity status**
4. **Decide on Infusion**
5. **Implement in Flight Program and/or Flight Project**
6. **Initiate Technology transfer to sponsor commercialization or spinoff**

Technology maturation and demonstration to enable Mars occurs in parallel and follows similar life cycle