

NASA Dust Mitigation Technology Roadmap

LSIC Fall 2024

JSC/Amy Fritz
MSFC/Shawn Breeding
KSC/Gabor Tamasy

This publication does not contain information which falls under the purview of the U.S. Munitions List (USML), as defined in the International Traffic in Arms Regulations (ITAR), 22 CFR 120-130, nor the Export Administration Regulation (EAR), 15 CFR 730-774, and is not export controlled. Release to the public requires approval through the appropriate NASA Release Process (e.g., FOIA, NASA STI, etc.).

Purpose

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

Scope

• Dust Measurement, Modeling, and Testing

- Natural Environments Design Spec (DSNE): [SLS-SPEC-159](#)
- Dust Testing Standard: [NASA-STD-1008](#)
- Lunar Regolith Simulants: [Simulant Advisory Committee](#) & [Lunar Regolith Simulant User's Guide Revision A](#)
- Lunar Dust Mitigation: A Guide & Reference (2021) (1st Edition): <https://ntrs.nasa.gov/citations/20220018746>

• 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 surface for Lander, Mobility and EVA use cases to anchor ground test data, support development of an integrated Lunar 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.*
- **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.*

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.

- **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.*



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**
- **Development and deployment of lunar dust level sensors to gather data is critical to crew health and mission success.**
 - The lunar dust environment is not well understood and there is a significant lack of data. Lunar simulants are not perfect analogs.
- **Priority is needed to gather data (ground and lunar surface) to develop and validate dust models to characterize dust environment.**
 - Need to define model purpose and scope and determine how to capture and incorporate ground/lunar surface data relevant to the modeling effort.
- **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 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/LTV/HLS vendors, International Partners, or Industry
 - Contribution 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 it is actually better with smaller particles.
- **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 excellent and useful technology but 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 relevant metrics.**
 - Need more dust tolerance testing, guidance on how to test, and a method for sharing data with Industry and International Partners.



Dust Mitigation Roadmap – STMD Shortfalls



Dust Mitigation Capability Shortfalls	Useful Links
1) Dust Measurement, Modeling, and Testing Capabilities	
- Shortfall 1561: Advanced Modeling & Test Capabilities to Characterize Dust Effects on H/W	Civil Space Shortfall Rankings – July 2024
2) Passive Dust Mitigation Capabilities (Including Filtration and Monitoring)	
<i>“Mitigation measures that do not require human intervention (or power) to operate properly”</i>	Architecture Definition Document (ADD)
- Shortfall 844: Passive Dust Mitigation Technologies for Diverse Applications	
3) Active Dust Mitigation Capabilities	
<i>“Mitigation measures that require human intervention (or power) to operate properly”</i>	
- Shortfall 1047: Active Dust Mitigation Technologies for Diverse Applications	
4) Dust Tolerant Components (Including connectors, bearings, seals, etc.)	
- Shortfall 1552: Extreme Environment Avionics	
- Shortfall 1592: High Power, Long Distance Energy Transmission across Distributed Surface Assets	
- Shortfall 1390: Power and Data Transfer in Dusty Environments	



Mid to High TRL NASA Dust Mitigation Investments



1. MEASUREMENT, MODELING, and TESTING

- Lunar Dust level sensor and Effects on Surfaces (LDES)
 - 2023: Ground testing assessed impact to radiators due to dust (w/ 2 simulants).
 - 2025: Potential selection for Lunar Flight.
- Low Velocity Dust Monitor (LVDM)
- Gateway On-orbit Lunar Dust Modeling and Analysis Program (GOLDMAP)
- PSI Risk Reduction Ground Test
- Lunar Dust Accumulation Modeling (Transport & Adhesion); Collaboration

TRL

FY

POTENTIAL INFUSION TARGET

7	2023-24	CLPS, HLS
	Completed	
9	In work	Multiple
7	2023	On PPE (JAXA contribution)
N/A	2023-24	GW
N/A	2024-25	HLS
N/A	2025	HLS, EVA, LTV, PR, Habitats

2. PASSIVE DUST MITIGATION

- Lunar Glove Thermal and Durability Analysis, Test, and Failure Mitigation
- Artemis Suit Material Development
- HEPA Filter Testing (HALO, IHAB)
- Cabin Dust Monitor COTS assessment
- Metallic Environmentally Resistant Coatings (MERCRII)
- Dust Resisting Thermal Control Material System (TCMS) Coating
- Clear Dust Repellant Coating (CDRC)

N/A	2022-23	EVA
6	2023-26	EVA
6	2022-23	GW
4	2023	HLS, GW, PR, Habitats
5	2021-24	HLS, LTV, PR, Habitats
7	2024-25	HLS, LTV, PR, Habitats
4	2023 ->	HLS, LTV, PR, Habitats

3. ACTIVE DUST MITIGATION

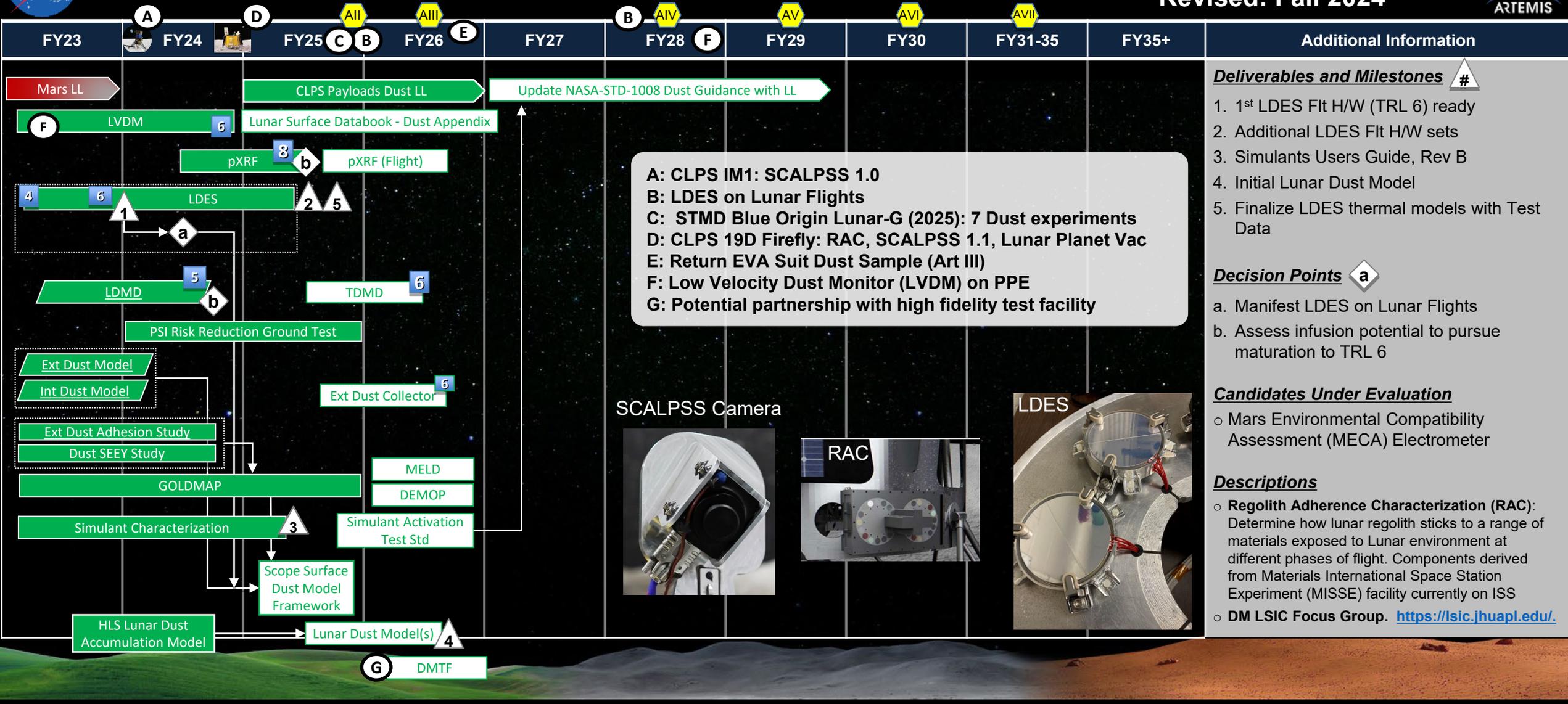
- Lunar Electrostatic and Dust Mitigation (LEDM) Tool
 - Handheld static ionizer tool to remove dust and neutralize electrostatic charge from materials.
- Electrodynamic Dust Shield (EDS)
- Lunar Dust Capture
 - Alternate filter media to advance SoA and demonstrate use case of a small portable dust vacuum.
- Development and Test of Lunar Dust Removal using a Gecko Roller

6	2023-25	EVA, M2M
7-9	2024	CLPS, M2M
5	2024	GW, HLS, PR, Habitats
5	2024-25	EVA, LTV, PR, Habitats

4. DUST TOLERANT COMPONENTS

- Seal Dust Tolerance Testing
- Extreme Env Tribological Charact. of Advanced Bearing Materials

4	2022-23	HLS, PR, Habitats
7	2024-25	EVA, LTV, PR, Habitats



- Deliverables and Milestones** #
1. 1st LDES Fit H/W (TRL 6) ready
 2. Additional LDES Fit H/W sets
 3. Simulants Users Guide, Rev B
 4. Initial Lunar Dust Model
 5. Finalize LDES thermal models with Test Data

- Decision Points** a
- a. Manifest LDES on Lunar Flights
 - b. Assess infusion potential to pursue maturation to TRL 6

- Candidates Under Evaluation**
- o Mars Environmental Compatibility Assessment (MECA) Electrometer

- Descriptions**
- o **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
 - o **DM LSIC Focus Group.** <https://lsic.jhuapl.edu/>

A: CLPS IM1: SCALPSS 1.0
B: LDES on Lunar Flights
C: STMD Blue Origin Lunar-G (2025): 7 Dust experiments
D: CLPS 19D Firefly: RAC, SCALPSS 1.1, Lunar Planet Vac
E: Return EVA Suit Dust Sample (Art III)
F: Low Velocity Dust Monitor (LVDM) on PPE
G: Potential partnership with high fidelity test facility

SCALPSS Camera



■ Ground ■ Lunar surface ● Notes ■ Act Funded ESDMD STMD Industry
■ ISS / LEO ◆ Decision point ■ Act Unfunded ● Artemis missions ⚠ Risk ⏸ Touchpoint # TRL
■ Lunar orbit ▲ Deliverable/Milestone

Objectives (FOM/KPPs): See metrics in STMD Shortfalls list

See acronyms list. All mission information is notional and for planning purposes only



NASA and Industry Funded Dust Measurement Investments



<u>Task Bar Name</u>	<u>Description and Status</u>	<u>Start</u>	<u>Finish</u>
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	2025
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	2025
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.	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	2024
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	2024
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 – Horanyi. 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 – Ni. 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	EVA Lunar Dust Mitigation Devices (LDMD): Includes testing/modeling dust behavior.	2022	2023
Simulant Characterization	Simulant Characterization Testing. PSD and Particle Geometry via LD and DIA (2023). Magnetic Susceptibility measurements (2023). Thermal conductivity measurements (2024). Electrical conductivity measurements (2024). Hydraulic conductivity/permeability measurements (2024).	2023	2024



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



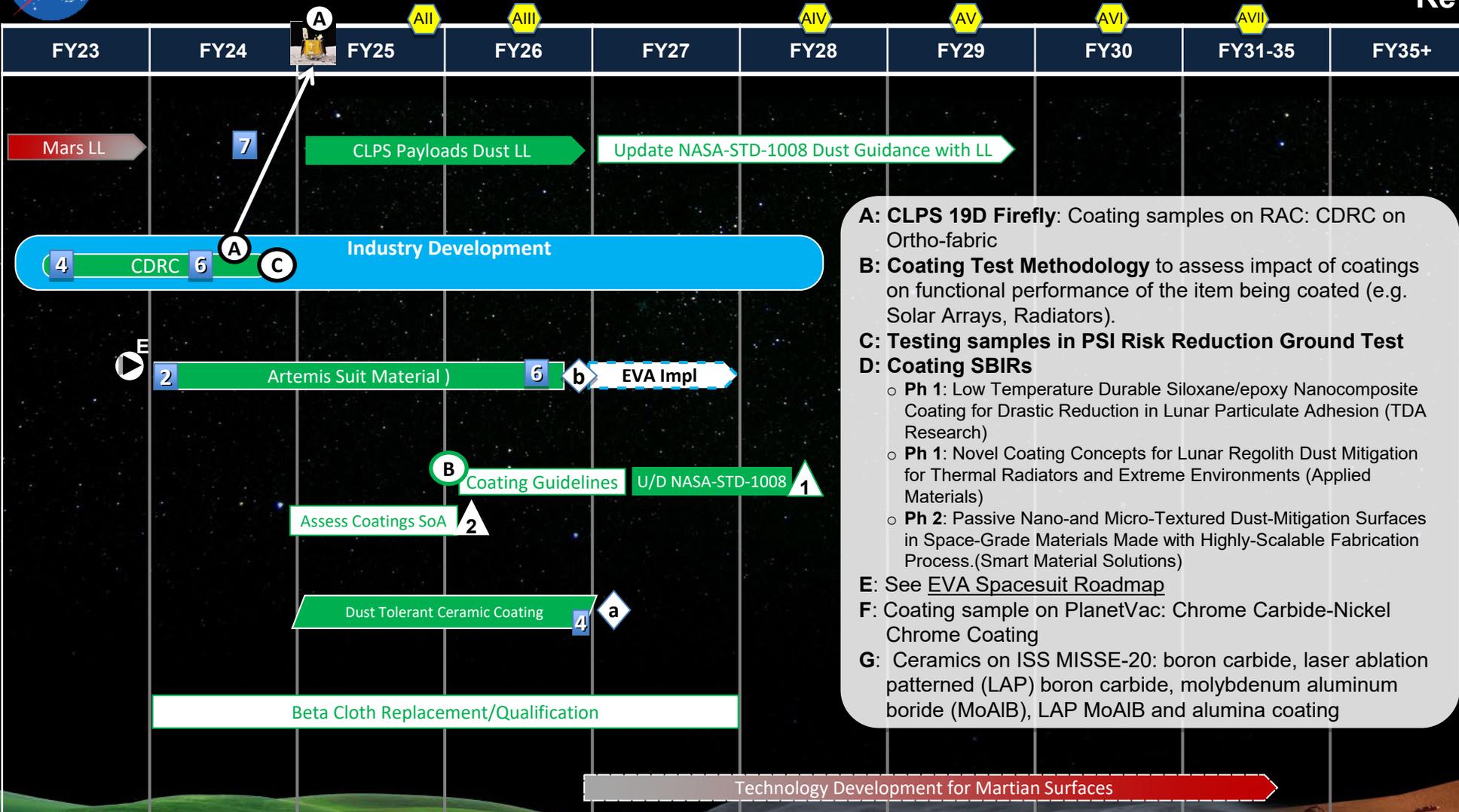
<u>Task Bar Name</u>	<u>Description and Status</u>	<u>Start</u>	<u>Finish</u>
<u>RAC</u>	RAC will determine how lunar regolith sticks to a range of materials exposed to Moon's environment. RAC will measure accumulation rates of lunar regolith on the surfaces of several materials (e.g., solar cells, optical systems, coatings, and sensors) through imaging to determine ability to repel or shed lunar dust.	Late 2024 Manifest	
<u>Lunar Planet Vac</u>	Lunar Planet Vac will demonstrate pneumatic sample collection of lunar regolith by collecting and sorting regolith within its sample collection chamber		
<u>SCALPSS</u>	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		
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
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



Proposed Dust Measurement Investments



<u>Task Bar Name</u>	<u>Description and Status</u>
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 Apx	Goal is to collect and distribute lunar dust data across M2M and Industry (ground tests and on-orbit)
pXRF for Flight	TBD
Lunar Dust Model(s)	Lunar Dust Model(s) continued development.
MELD	Microgravity Experiment for Lunar Dust (MELD). Phase 1: Determine the amount of dust transferred during a simulated docking event in a vacuum chamber using lunar simulants. Phase 2: Develop a compact dust transfer apparatus to be mounted aboard a rocket. 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 1 which measured optical properties of several simulants. Have funding for Phase 2 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.
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.
Scope Surface Dust Model Framework	Plan for scoping and developing an integrated Dust model addressing verification needs of surface elements.
Thermal Model development	Thermal Desktop tool that incorporates thermal dust model methodology using LDES test data.



A: CLPS 19D Firefly: Coating samples on RAC: CDRC on Ortho-fabric

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

- o **Ph 1:** Low Temperature Durable Siloxane/epoxy Nanocomposite Coating for Drastic Reduction in Lunar Particulate Adhesion (TDA Research)
- o **Ph 1:** Novel Coating Concepts for Lunar Regolith Dust Mitigation for Thermal Radiators and Extreme Environments (Applied Materials)
- o **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 Spacesuit Roadmap

F: Coating sample on PlanetVac: Chrome Carbide-Nickel Chrome Coating

G: Ceramics on ISS MISSE-20: boron carbide, laser ablation patterned (LAP) boron carbide, molybdenum aluminum boride (MoAlB), LAP MoAlB and alumina coating

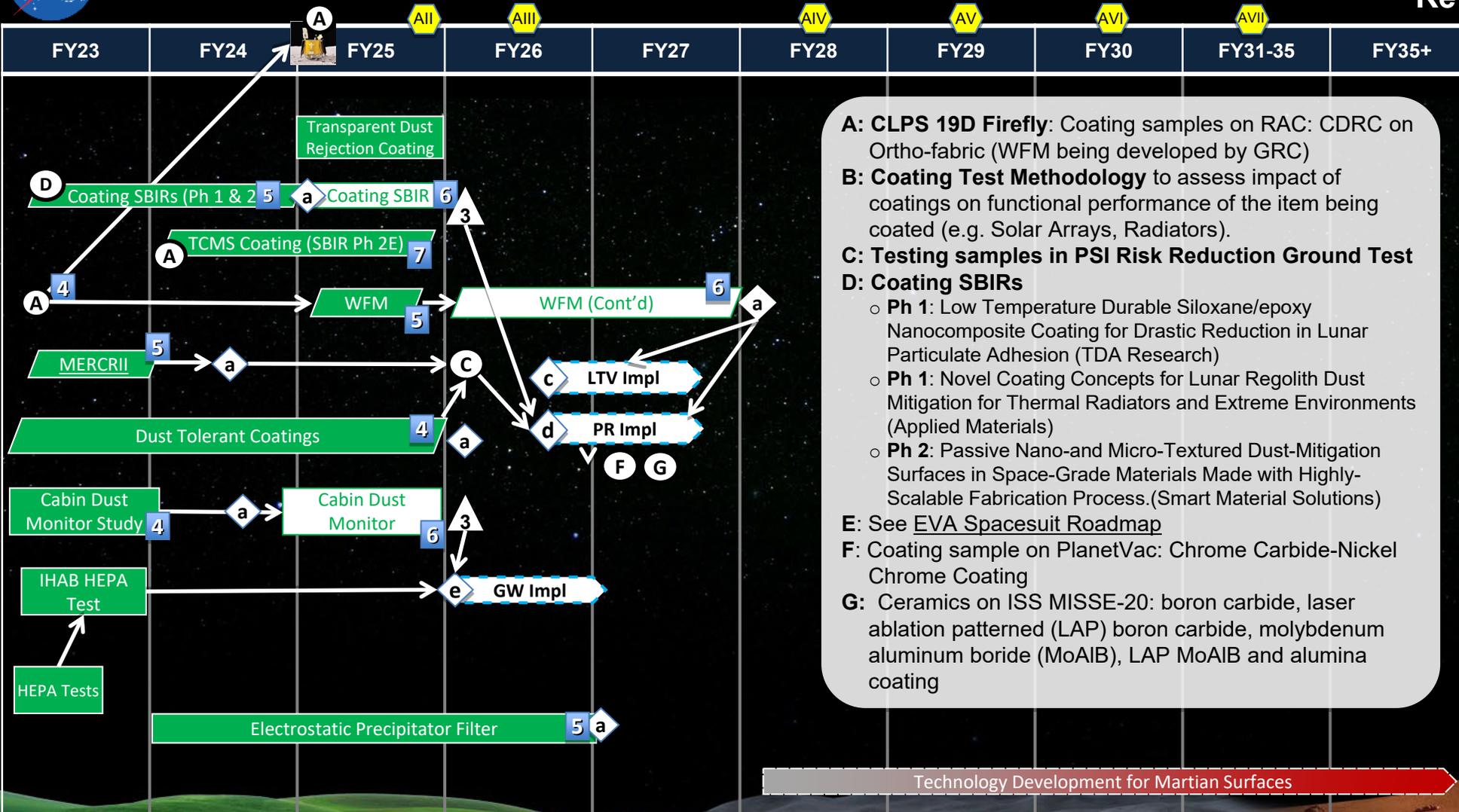
- Deliverables and Milestones #**
1. NASA-STD-1008 Update
 2. NASA Technical Memo on Coatings
 3. Project Infusion Readiness Assessment (PIRA)
- Decision Points a**
- a. Assess infusion potential to pursue maturation to TRL 6
 - b. Infuse into EVA – partner with Vendor
 - c. Infuse into LTV - partner with Vendor
 - d. Infuse into PR
 - e. Infuse into GW

Candidates Under Evaluation

■ Ground ■ Lunar surface ● Notes ■ Act Funded ESDMD STMD Industry
■ ISS / LEO ■ Lunar orbit ◆ Decision point ■ Act Unfunded Risk ▶ Touchpoint # TRL
▲ Deliverable/Milestone ● Artemis missions

Objectives (FOM/KPPs): See metrics in STMD Shortfalls list

See acronyms list at front of document. All mission information is notional and for planning purposes only



A: CLPS 19D Firefly: Coating samples on RAC: CDRC on Ortho-fabric (WFM being developed by GRC)

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 Spacesuit Roadmap

F: Coating sample on PlanetVac: Chrome Carbide-Nickel Chrome Coating

G: Ceramics on ISS MISSE-20: boron carbide, laser ablation patterned (LAP) boron carbide, molybdenum aluminum boride (MoAIB), LAP MoAIB and alumina coating

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 LTV - partner with Vendor
- d. Infuse into PR
- e. Infuse into GW

Candidates Under Evaluation

■ Ground ■ Lunar surface ● Notes ■ Act Funded ESDMD STMD Industry
■ ISS / LEO ◆ Decision point ■ Act Unfunded Risk Touchpoint # TRL
■ Lunar orbit ▲ Deliverable/Milestone ● Artemis missions

Objectives (FOM/KPPs): See metrics in STMD Shortfalls list



NASA and Industry Funded Passive Dust Mitigation Investments



<u>Task Bar Name</u>	<u>Description and Status</u>	<u>Start</u>	<u>Finish</u>
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
<u>Work Function Coating</u>	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 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 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	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



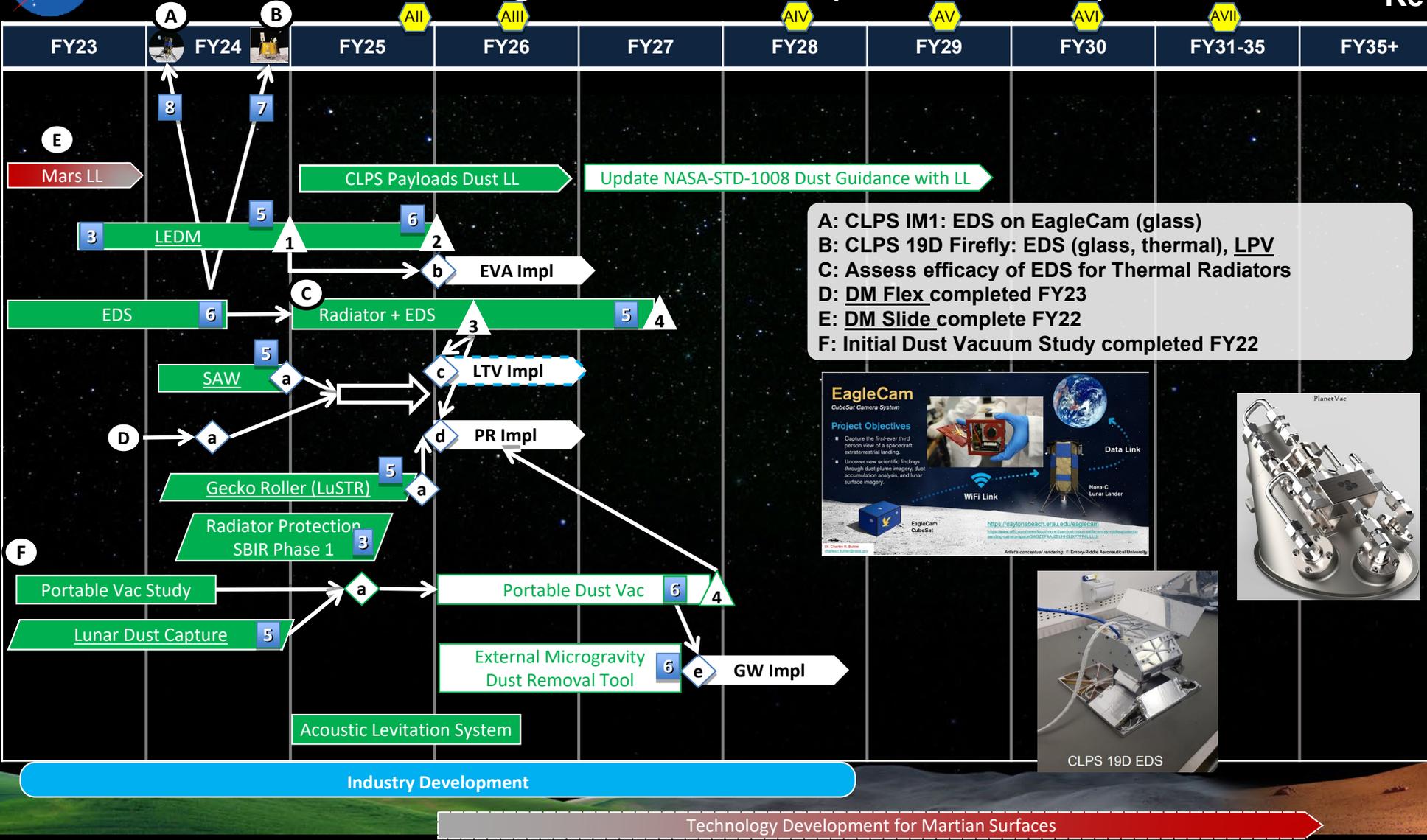
<u>Task Bar Name</u>	<u>Description and Status</u>	<u>Start</u>	<u>Finish</u>
Dust-Tolerant Coatings	Development of protective coatings and materials (i.e., scalable COTS) and novel materials and architectures (i.e., laser ablation patterning, bio-inspired surface design) to mitigate abrasive wear and 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 Ytria 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



Proposed Passive Dust Mitigation Investments



<u>Task Bar Name</u>	<u>Description and Status</u>
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.
Assess Coatings	Evaluate current State Of The Art coatings and develop a summary listing each coating benefits and pros/cons for different applications
Coating Guidelines	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.
Work Function Matching Coating	Increase technology readiness to TRL6 by testing coated solar cells in ground lunar simulation VF-13 chamber.
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.



A: CLPS IM1: EDS on EagleCam (glass)
B: CLPS 19D Firefly: EDS (glass, thermal), LPV
C: Assess efficacy of EDS for Thermal Radiators
D: DM Flex completed FY23
E: DM Slide complete FY22
F: Initial Dust Vacuum Study completed FY22



Additional Information

Deliverables and Milestones #

- LEDM Breadboard
- LEDM Ground Prototype & Infusion Readiness Assessment
- Dust Adhesion & TVAC test on LDES
- PIRA

Decision Points a

- Assess infusion potential to pursue maturation to TRL 6
- Infuse into EVA - partner with vendor
- Infuse into LTV - partner with vendor
- Infuse into PR
- Infuse into GW

Candidates Under Evaluation

- Lunar Dust Removal Tool (LDRT)
- Electron beam Lunar Dust mitigation (ELDM)

Notes

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

■ Ground ■ Lunar surface ● Notes ■ Act Funded ESDMD STMD Industry
■ ISS / LEO ◆ Decision point ■ Act Unfunded ■ Artemis missions ⚠ Risk 🎯 Touchpoint # TRL
■ Lunar orbit ▲ Deliverable/Milestone

Objectives (FOM/KPPs): See metrics in STMD Shortfalls list



NASA and Industry Funded Active Dust Mitigation Investments



<u>Task Bar Name</u>	<u>Description and Status</u>	<u>Start</u>	<u>Finish</u>
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-6)	Various	Various
Lunar Electrostatic and Dust Mitigation (LEDM) Tool	This project will develop 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	2025
<u>Lunar Dust Capture</u>	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
<u>SAW</u>	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
<u>Gecko Roller</u>	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	2023
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.	2021	2022
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



NASA and Industry Funded Active Dust Mitigation Investments



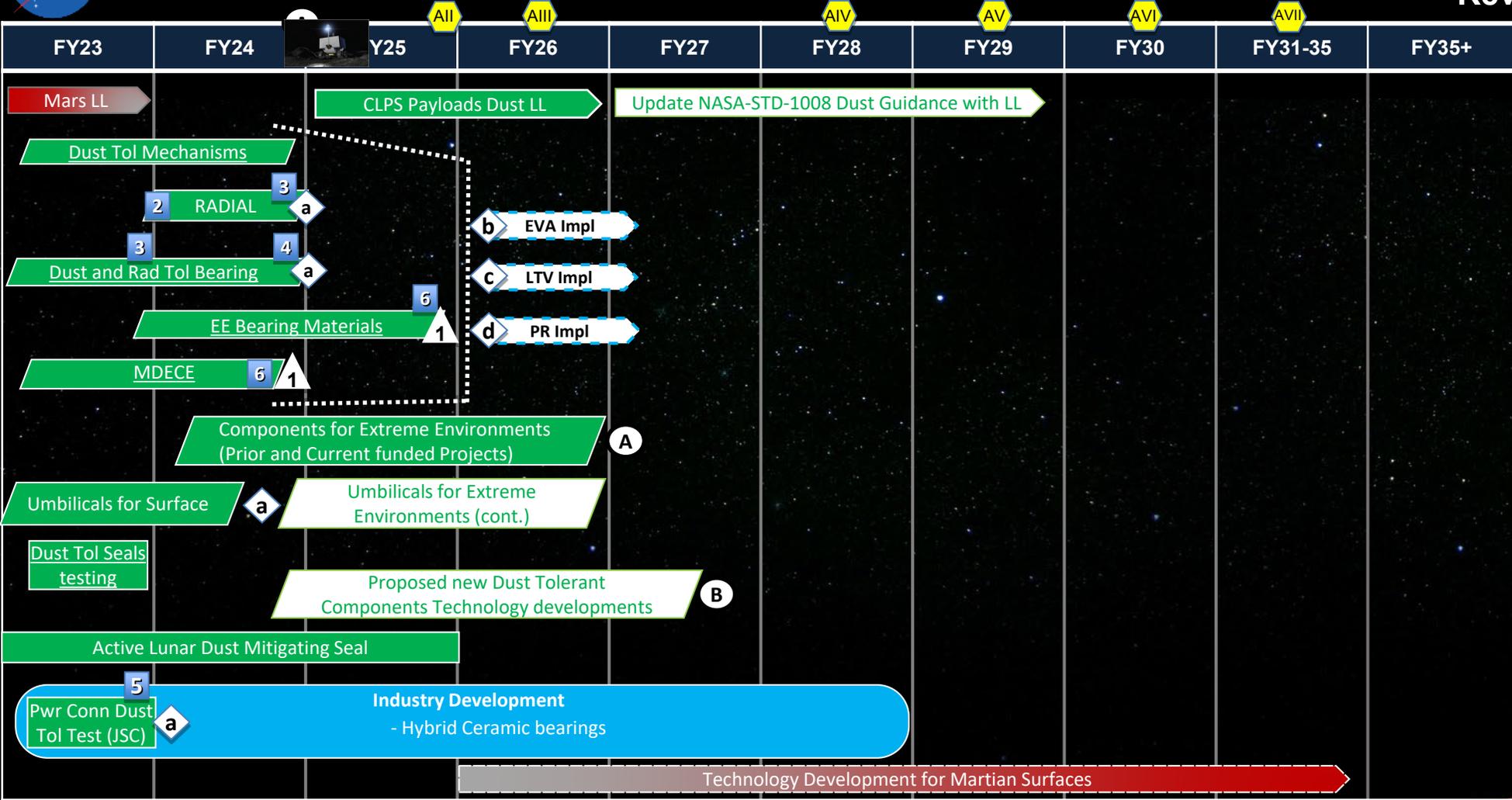
<u>Task Bar Name</u>	<u>Description and Status</u>	<u>Start</u>	<u>Finish</u>
Radiation, dust and coolant freeze-out mitigation	Development and demonstration of an innovative multilayered system that attenuates UV radiation, eliminates dust adhesion and prevents coolant freeze-out. Technology is compact, lightweight, fast actuation, low power and maintenance-free.	2024	2025
Radiator + EDS	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



Proposed Active Dust Mitigation Investments



<u>Task Bar Name</u>	<u>Description and Status</u>
Portable Dust Vac	Portable Dust Vacuum to collect residual dust in a pressurized habitat. Low SWAP leveraging Multiplexed Inertial Filter.
External Microgravity Dust Removal Tool	Tool to remove dust from External Gateway surfaces, GERS compatible.



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 LTV - partner with Vendor
- d. Infuse into PR
- e. Infuse into GW

Candidates Under Evaluation

- o Dust Tolerant CryoMag Coupler

Notes:

A: Prior and current funded Dust Tolerant Components Investments (Details shown on slides 23-25)
B: Proposed New Dust Tolerant Components Investments (Details shown on slide 26)

Legend for chart elements:

- Ground (Green)
- Lunar surface (Grey)
- ISS / LEO (Blue)
- Lunar orbit (Dark Grey)
- Notes (White circle)
- Decision point (Blue diamond)
- Deliverable/Milestone (White triangle)
- Funded (Green box with 'Act')
- Unfunded (White box with 'Act')
- Artemis missions (Yellow hexagon)
- Risk (Red square)
- Touchpoint (Blue circle)
- TRL (Blue square with '#')
- ESDMD (White box)
- STMD (White box)
- Industry (Blue box)

Objectives (FOM/KPPs): See metrics in STMD Shortfalls list

See acronyms list. All mission information is notional and for planning purposes only



NASA and Industry Funded Dust Tolerant Components Investments



<u>Task Bar Name</u>	<u>Description and Status</u>	<u>Start</u>	<u>Finish</u>
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-g geared motor and an unheated piezoelectric motor that can operate continuously for a long duration at an ambient temperature of -243 °C (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.	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.	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.	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). <i>Phase 1-3 completed. Phase 1-Develop performance database for seals - Phase 2- Seal Cleaning Tests. Phase 3: Evaluate Alternate Seal Surface Treatments.</i>	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)



<u>Task Bar Name</u>	<u>Description and Status</u>	<u>Start</u>	<u>Finish</u>
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
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



NASA and Industry Funded Dust Tolerant Components Investments (Continued)



<u>Task Bar Name</u>	<u>Description and Status</u>	<u>Start</u>	<u>Finish</u>
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



Proposed Dust Tolerant Components Investments



<u>Task Bar Name</u>	<u>Description and Status</u>
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.
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.
Fluid Connectors for Extreme Environments	Surface systems cryogenic disconnects that are light weight and compatible with the extreme environments.
Dust Tolerant Mechanisms	Moving components for dust protection (iris, hatch, covers, louvers, airlocks, closures, hinges, joints, trusses, etc.).



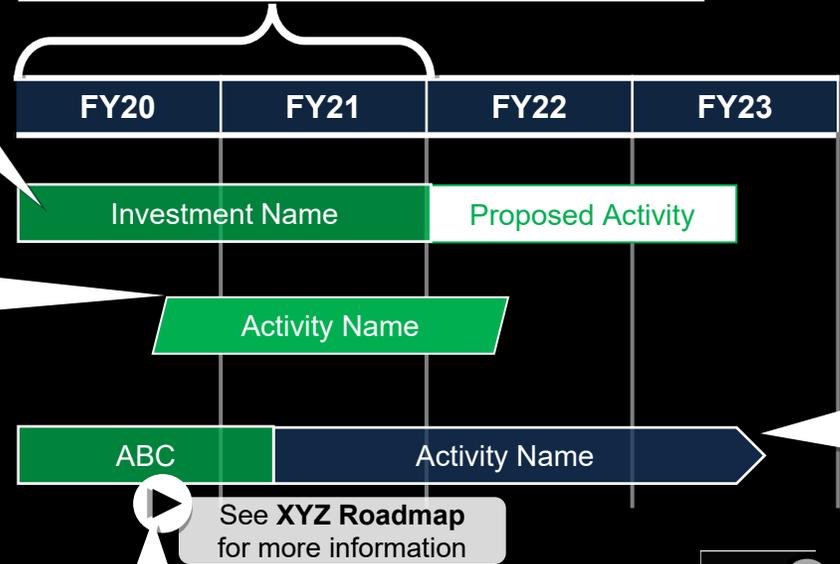
Backup

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.

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



5 Play button icons show "touchpoints" between roadmaps.

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



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

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.

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

Ground	Lunar surface	Notes	Funded	ESDMD	STMD	Industry
ISS / LEO		Decision point	Unfunded			
Lunar orbit		Deliverable/Milestone	Artemis missions	Risk	Touchpoint	TRL

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

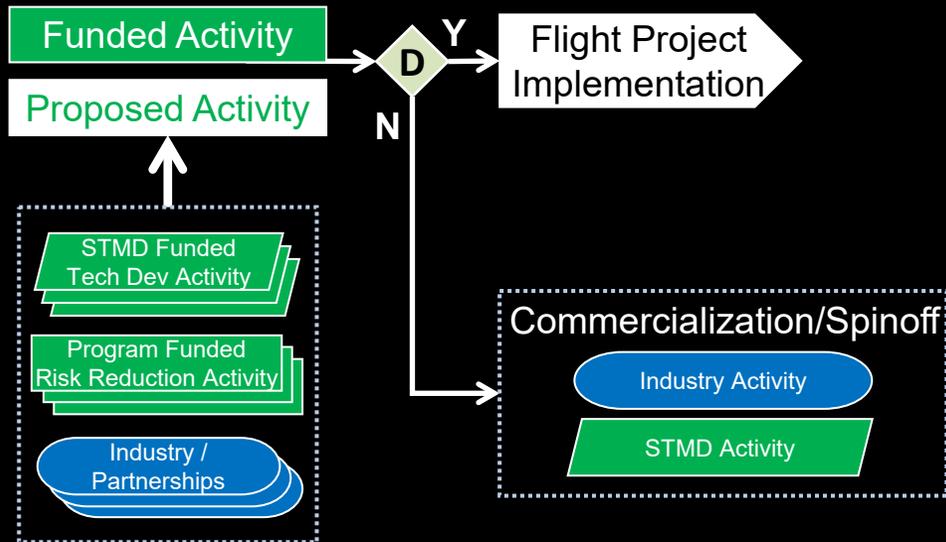


Life Cycle of Technology Integration

(Iterative, but not necessarily a serial process)



Shortfall 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

