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The 2023 Annual Meeting of the Lunar Exploration Analysis Group is scheduled for September 20–22, 2023, in Laurel, Maryland, with virtual participation available.The Lunar Exploration Analysis Group (LEAG) supports NASA in providing analysis of scientific, technical, commercial, and operational issues in support of lunar exploration objectives and their implications for lunar architecture planning and activity prioritization. The annual meeting brings together community members from their respective sub-fields (science, exploration, academia, commercial, etc.) to support the exploration of the Moon.

On the Governance of Early Lunar Operations: Solving "The Dust Problem"

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Introduction: Observations by the Apollo astronauts of dust sticking to their space suits even after short extravehicular activities indicated the importance of control of dust contamination [1]. Apollo astronauts uncovered a plethora of issues related to the "dust problem" including clogging of joints and mechanisms, human health toxicology, false instrument readings, vision obscuration, abrasion of surfaces, failures of seals, and thermal control. Apollo samples revealed the presence of a variety of the same grain morphologies but with irregular, sharp edges to smoother glass droplets of volcanic origins [2] that risk abrasive wear. The dust abrasiveness wore down seals, clogged valves or moving parts [3]. Particles smaller than 2 μm would enter hardware gaps, clearances and backlashes between hardware elements, causing the increase of friction and decrease of performance [4]. Aluminum, the most common hardware material of spacecraft and equipment, required methodologies to reduce the surface energy that enabled dust particle adhesion. Active mitigation strategies require external energy to remove or prevent particle accumulation [5]. Passive mitigation strategies did not require external energy since particle adhesion was intrinsic to the material.it adhered to. Controlled alteration of surface topography of the exposed hardware would [6] require composite etching methods to produce multi-scale structures on the surface with micro- and nanoroughness hence, reducing the contact area between the Al substrate by 60 percent [7], Although robot swarms indicates a safer option, there are advantages for employing crewed EVAs: Task flexibility;

Dexterous manipulation; High-resolution visual interpretation of the task; Human cognitive and interpretive capability; Decision-making; Capabity to implement real-time alternative approaches in problem solving.
A qualitative content analysis of several NASA standards documents (NASA's 2020 Technology Taxonomy Roadmap (2020TTR), NASA-STD-3001, Space Flight Human-System Standard (two volume, revised in 2022), and NASA OTPS Lunar Landing and Operations Policy Analysis Report) resulted in a comparative analysis between uncrewed EVAs (robotics) and crewed EVAs. References to robotics and EVAs showed almost even referential frequency per 2020TTR, followed by EVA doubled frequency over robotics per OTPS, and robotics was barely mentioned outside its devoted Section 5 per STD-3001 (version B).NASA Office of Technology, Policy, and Strategy (OTPS) was created in November 2021 to provide leadership with a trade space of data- and evidence-driven options to develop policy, strategy, and technology. It noted majority of human and robotic missions will target the lunar surface areas preidentified for resources (e.g., frozen volatiles), likely found in permanently shadowed regions [8], yet its conservative stance reflects the sensibility of two major decadal surveys by National Academy of Science, Engineering and Medicine. In NASEM's Decadal Survey on Astronomy and Astrophysics 2020 (Astro2020) [9], workshop participants concurred with NASEM's Planetary Science and Astrobiology Decadal Survey 2023-2032 observations regarding NASA's Organizational Structure for Incorporating Science into Human Exploration.
This paper aims to correlate how the dynamics of lunar dust behavior to adhere to surfaces may actually provide the basis either surface repulsion (passive strategy of surface etching) or dust migration away from surface (active strategy of electrodynamics dust shielding). Although both spacecraft/ robotic systems and EVA spacesuits benefit from both strategies, the focus will combine both technologies into a novel technology particularly suited for the former. A brief summary will be provided for the innovative technology of Spacesuit Integrated Carbon Nanotube Dust Ejection/Removal (SPIcDER) system that incorporates carbon nanotube fibers, energized using high voltage, low power, Alternating Current (AC) signals (~350-1000V) to form a travelling wave of electric field around the spacesuit/flexible surface [10].

References:

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[2] McKay, D.S., Heiken, G., Basu, A., Blanford, G., Simon, S., Reedy, R., French, B.M., Papike, J., 1991. In: Heiken, G., Vaniman, D.T., French, B.M. (Eds.), The Lunar Regolith, in the Lunar Sourcebook. Cambridge Univ. Press, New York, pp. 285–356).
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[4] Levine, J.(2021).The impact of lunar dust on human exploration, Cambridge Scholars Publishing.
[5] Immer, C., Starnes, J., Michalenko, M., Calle, C., Mazumder, M. (2006). Electrostatic screen for transport of Martian and lunar regolith, 37th Lunar and Planetary Science Conference, League City, TX.
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lunar dust adhesion mitigating materials. In 3rd AIAA Atmospheric Space Environments Conference (p. 3676).
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[8] J. Flahaut et al., “Regions of interest (ROI) for future exploration missions to the lunar South Pole“. Planetary and Space Science 180 (Jan. 2020).
[9] Valinia, A., Grunsfeld, J. M., Hess, M. G., Green, J., Schier, J., Haas, J. P., ... & Stalcup, E. J. (2022). Unique Science from the Moon in the Artemis Era (No. NESCRP-22-01729).
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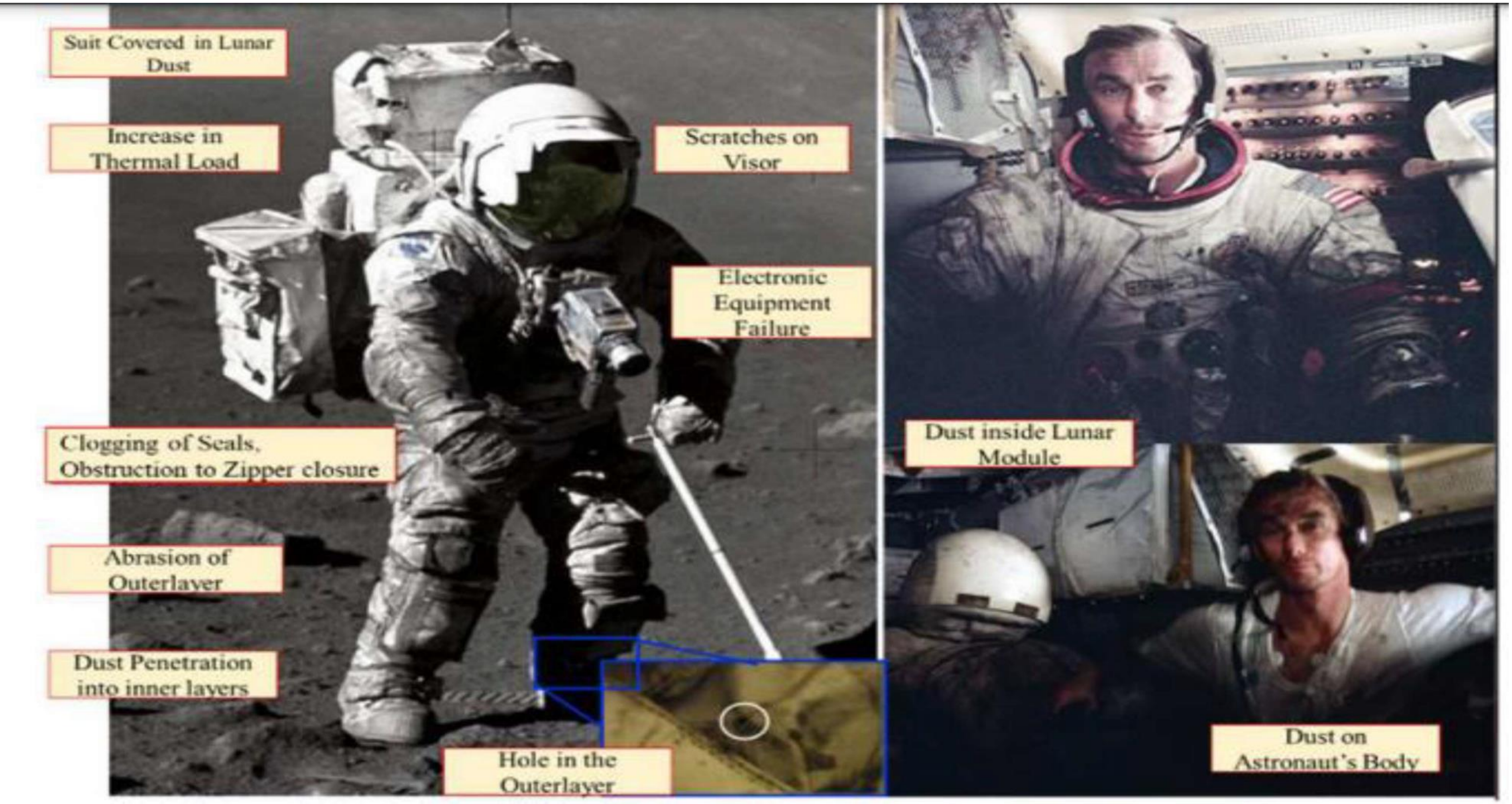
Agenda

1. Introduction
   - --- Apollo Astronauts Observations
   - --- Lunar Dust Scenario
   - --- Dust Flux Measurement: Near Earth vs Moon
2. Technology Acceptance of Lunar Dust Strategies: EVAs vs Robotics
3. Experimental Dust Mitigating Technologies
4. Conclusion

1. Introduction

Apollo 17 Complaints of EVAs in Space Environment

Fatigue apparent from the intensive use of hand and wrist muscles in this assembly process. Clogging of joints and mechanisms, human health toxicology, false instrument readings, vision obscuration, abrasion of surfaces, failures of seals, and thermal control.
Walking or rover movements of stir up dust that travels ballistically and sticks to anything and everything due to lack of atmosphere.
Tiny shards of rock permeating Lunar Module interiors, coating helmet visors, jamming zippers, and penetrating layers of protective spacesuits material.
Unable to put their gloves back on after three days because lunar dust had degraded the seals.


Suit Covered in Lunar Dust
Increase in Thermal Load
Scratches on Visor
Electronic Equipment Failure
Clogging of Seals, Obstruction to Zipper closure
Abrasion of Outerlayer
Dust Penetration into inner layers
Hole in the Outerlayer
Dust inside Lunar Module
Dust on Astronaut's Body

Apollo astronauts complained of dust sticking to their spacesuits even after EVAs

Apollo Complaints of EVAs in Space Environment

Buzz Aldrin (Apollo 11)	Soiled suits and equipment smelled like burnt charcoal or similar to fireplace ashes
Apollo 17 Crew	Fatigue apparent from the intensive use of hand and wrist muscles in this assembly process. Clogging of joints and mechanisms, human health toxicology, false instrument readings, vision obscuration, abrasion of surfaces, failures of seals, and thermal control.
	Walking or rover movements of stir up dust that travels ballistically and sticks to anything and everything due to lack of atmosphere.
	Tiny shards of rock permeating Lunar Module interiors, coating helmet visors, jamming zippers, and penetrating layers of protective spacesuits material.
	Compromised EVA performance and health per dust contamination of suit bearings and joints.
	Abrasive nature of dust experienced after doffing helmets and gloves
Harrison Schmitt (Apollo17)	Smelled like gunpowder. Experienced first case extraterrestrial hay fever (swollen cartilage plates in walls of nasal chambers)

EVA Observations

- Lunar dust (LD), the component of lunar regolith with particle sizes less than 20 µm, covers the surface of the Moon. Due to its fineness, jagged edges, and electrostatic charge, LD adheres to and coats almost any surface it contacts.
- Long-duration crew stays on the Moon may require astronauts wearing increased EVA hardware with potential decreased suit mobility
- Since risk of human ingestion or contact with lunar dust is mitigated with heavy spacesuits of low flexibility/ mobility, astronaut attitude towards use (ATT) may compromise their full acceptance.

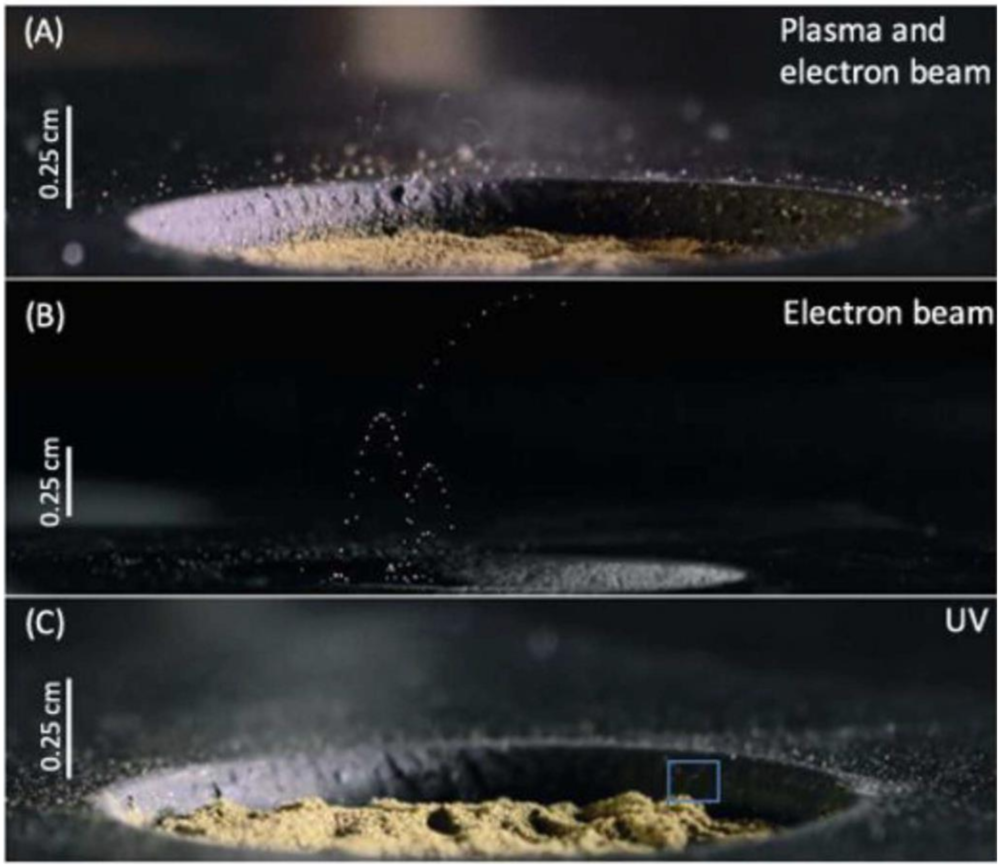
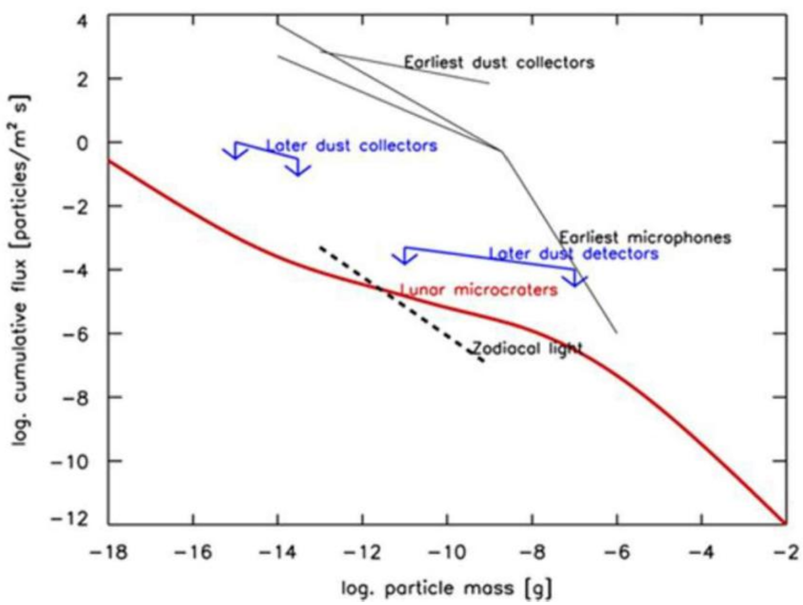


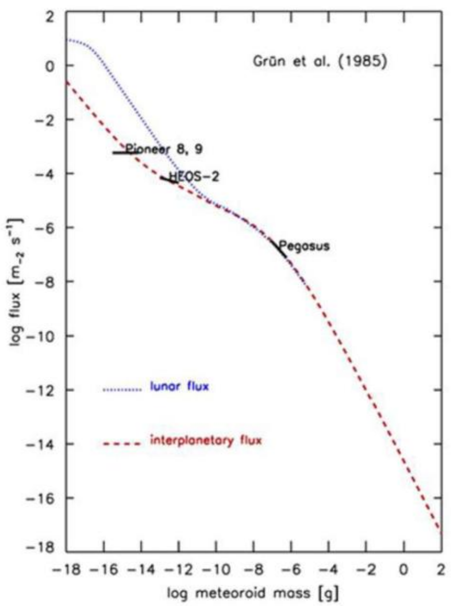
Figure Images of dust transport and hopping trajectories in (a) plasma and electron beam, (b) electron beam, and (c) UV experiments. A blue square in Figure c indicates a hopping trajectory captured under UV illwnination. Deposits of dust. particles on the surface outside the crater also indicate t heir hopping motions in all three images. Large aggregates up to 140µm in diameter are lofted in addition to individual particles (38-4Sµm in diameter).

Dust Flux Measurement: Near Earth vs Moon

Near-Earth Dust Flux Measurements
(from 1960 to 1985)



Interplanetary Dust Flux (dashed line) and
Lunar Surface Dust Flux (dotted line).



1. Governance of ''Lunar Dust Problem''

- International partner-led operations may include the European Large Logistics Lander (EL3), pressurized and unpressurized rovers.
- The first constraint imposed by the landscape is the need to identify relatively flat and uncluttered areas that can function as landing sites.
- The second constraint imposed by the landscape involves moving from one location to another.
- The final general constraint has to do with communications. Early mission plans require near-continuous radio communications with crewed activities ["NASA's Lunar Exploration Program Overview," Artemis Plan, **NASA].**
- In 2020, the **Artemis Accords, Section 9,** expresses a shared goal to preserve outer space heritage, including significant human or robotic landing sites, artifacts, spacecraft, in **accordance with mutually developed standards and practices.**
- Landings on the Moon eject "plume-surface interactions" (PSIs): dust, rocks, by the force of landers' engines, posing a hazard to other objects in the vicinity of the landing zone.
- Artemis Accords provide technical justifications for the design of each safety zone for the landing site boundary.

Planetary External Lunar Sources of Dust and Associated Dust Parameters

PE Lunar Sources of Dust	Particle Size (µm)	Surface Accumulated Loading (g/m^2)	Volumetric Loading (g/m^3)	Dust Velocity (m/s)	Charge to Mass Ratio (nC/g)
Human-Generated Surface Transported Dust	<500 µm [1]	<40 g/m^2 [TBR][11]	N/A	<10 m/s (22.4 mph) [2]	0.1 nC/g - 10 nC/g [15]
Rocket Engine Plume Dust [9, 13]	<10,000 µm [3][12][20]	TBR [21]	10^6 - 10^{13} particles/m^3 [4][15][20]	<4500 m/s (10,066 mph) [13]	>1000 nC/g
Natural Charged Dust Transport [5]	<1000 µm [16]	Combined Loading Case [17, 19]	TBR [6]	Variable [18]	~ 10,000 nC/g [7]
Natural Impact Ejecta [12]	<10,000 µm	Combined Loading Case [17, 19] or 0.01 g/m^2/day [14]	TBR [10]	<2380 m/s (5324 mph) [8]	~ 10,000 nC/g [7]

Notes:
1. Estimated maximum particle size displaced by Apollo lunar rover.
2. Reference NASA-CR-4404, Lunar dust transport and potential interactions with power system components. The Apollo lunar rovers were designed to travel at a maximum of 3.56 m/s (8 mph) (reference Backer, 1971; Hsu and Horanyi, 2012) with particle speeds of up to 7.12 m/s (16 mph) in the forward direction. A 45° trajectory would yield the maximum horizontal distance of 31 m (103 ft) from the wheel's initial location. Consider the maximum speed at which an Artemis Lunar Terrain Vehicle could travel.

Planetary External Pressurized Lunar Sources of Dust and Associated Dust Parameters—EVAs and Hardware

PP Lunar Sources of Dust	Particle Size (µm)	Surface Accumulated Loading (g/m^2)	Volumetric Loading (g/m^3)	Dust Velocity (m/s)	Charge to Mass Ratio (nC/g)
Extravehicular Activity (EVA) Suit Cross-Hatch Transported Dust	<500 µm [TBR] [1]	50 g per suit per EVA [2][3][5]	10 g/m^3 per suit per EVA [2][3][4]	Variable [6]	N/A
Hardware Cross-Hatch Transported Dust	<500 µm [TBR] [1]	Variable g/m^2 [2]	Variable g/m^3 [2]	Variable [6]	N/A

Notes:

1. Apollo 17 suit maximum particle size (NASA/TP-2009-214786). This value may change with new suit materials and/or designs.
2. These values may vary depending on program requirements. In some cases, the requirement for EVA suit cross-hatch transported dust and hardware cross-hatch transported dust may be combined.
3. Assuming 50 g of dust per crewmember per EVA based on EVA to Human Landing System (HLS) requirements.

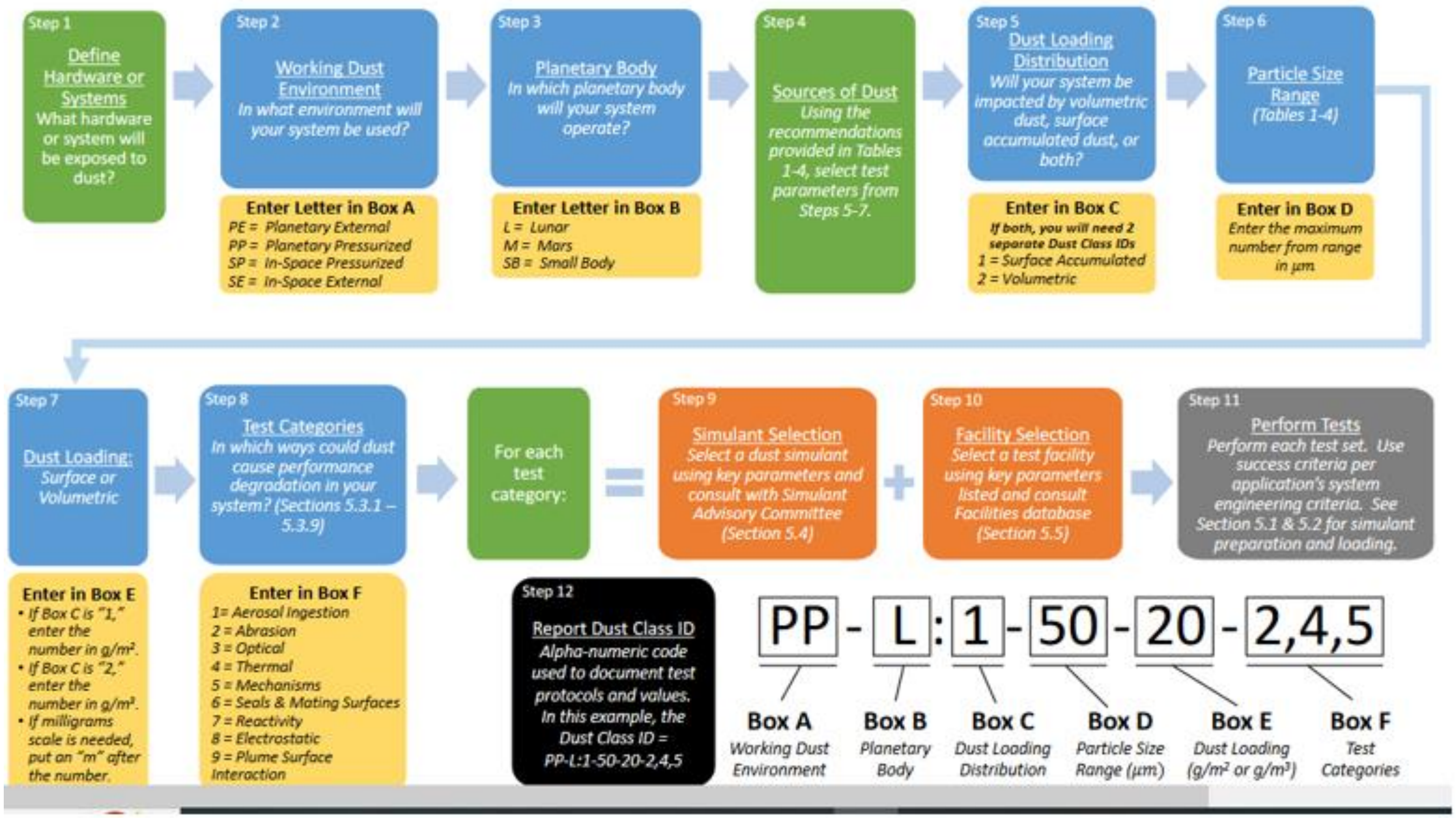


Figure —Dust Impact Assessment Process

Since hardware/system(s) have unique use cases and because of the large array of variables interacting within the dust environment, standardization of this type of testing is not straightforward. It is important to track and annotate the selection and decision-making process to the maximum extent possible. The Dust Impact Assessment Process is designed to guide the decision-making process, providing a standardized means of determining the appropriate test protocols, simulant characteristics, and facility capabilities for the testing of systems and hardware that interact within dusty planetary environments. The Dust Impact Assessment Process indicates how to fill in the alpha-numeric code (i.e., Dust Class ID) that will be used to define the appropriate test conditions. This code can then be used to report the protocol(s) followed in testing the hardware/system(s). Documentation of the simulant and facility selections is expected to consist of a description of the simulant and facility chosen and the rationale for the use of that simulant and facility in the NASA-STD-1008 compliance assessment.

John, K. K., & Rogers, C. E. (2021). *Classifications and Requirements forTesting Systems and Hardware to be Exposed to Dust in Planetary Environments* (No. NASA-STD-1008).

The International Space Exploration Coordination Group (ASI, CSA, ESA, JAXA, and NASA) to evaluate topic discipline areas based on Global Exploration Roadmap (GER) Critical Technology Needs reflected within the GER Technology Development Map (GTDM): Dust Mitigation.

Layered Engineering Defense Plan Example

1st Layer – Mission Architecture Design

- Avoiding special regions (defined as being within a specified radius of the lander/habitat)

2nd Layer – Hardware Design

- Acknowledging that EVA suits will leak/vent—engineering limits must be understood and intentionally accounted for
- Collection/containment of sampling tools

3rd Layer – Operational Design

- Reducing the amount of dust that reaches habitable volumes by having astronauts stomp off dust and brush down their suits on a porch before entering the habitat through an ingress/egress method designed to mitigate the transfer of dust (e.g., the astronauts could use rear-entry suits that they don/doff through a bulkhead)
- Using sampling protocols that limit inadvertent contamination
- Leaving EVA suits on surface prior to ascent to "break the chain" of contamination

4th Layer – Contamination Control

- Conducting verifiable decontamination of EVA hardware at regular intervals
- Conducting exterior and interior cleaning
- Using air quality contamination zones

NASA Governance per Technology Acceptance of EVAs vs Robotics

1. Lunar Landing and Operations Policy Analysis Report:

NASA's Office of Technology, Policy, and Strategy (founded 2021) addresses two questions related to Artemis campaign: what technical and policy considerations factor in the selection of (1) lunar landing and operations sites and (2) safety zones that protect these operations and U.S. interests?

---"A Year in Review 2022" Document word frequency= 11"EVA" vs O " robotic"

2. NASA's 2020 Technology Taxonomy Roadmap

---TTR 2020 Document word frequency= 25 "EVA" vs 41 "robotic"

3 NASA TECHNICAL STANDARD NASA-STD-3001,, REVISION B (2022-01-05)

---"Volume 1 Crew Health" Document word frequency= 50 "EVA" vs 10 "robotic"

---"Volume 2 Human Factors , Habitability, and Environmental Health" Document word frequency= 100 "EVA" vs 50 "robotic"

Suggested Protocol

Layered Engineering Defense Plan Example

1st Layer – Mission Architecture Design

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NASA STANDARD 3001, vol.2 HUMAN FACTORS, HABITABILITY, AND ENVIRONMENTAL HEALTH

4. PHYSICAL CHARACTERISTICS AND CAPABILITIES

From Johnson Procedural Requirements (JPR) 1880.4, Requirements and Limitations for Exposure to Reduced Atmospheric Pressure. The limit for pre-breathe in a spacesuit is 9 hours when that is the only exposure to enriched 02 in a 48-hour _period. The limit is 6 hours when it is the onlY. ex_P.osure to enriched 02 in a 24-hour perioa and also states that consecutive daily exposures shall not exceed 5 consecutive clays.

6.4.4.2 Lunar Dust Contamination

[V2 6053] The system shall limit the levels of lunar dust particles less than 10 µmin size in the habitable atmosphere below a time-weighted average of 0.3 mg/m3 during intermittent daily exposure periods that may persist up to 6 months in duration.

9.3.1.11 Low-Temperature Exposure

[V2 9015] Any surface to which the bare skin of the crew is exposed shall not cause skin temperature to drop below the pain threshold limit of 10 °C (50 F).

11.1.1 Suited Donning and Doffing

[V2 11001] The system shall accommodate efficient and effective donning and doffing of spacesuits for both nominal and contingency operations.

11.1.2.3 Continuous Noise in Spacesuits

[V2 11009] Suits shall limit suit-induced continuous noise exposure at the ear to NC-50 or below without the use of auxillary hearing protection.

11.3 LEA Suited Decompression Sickness Prevention Capability

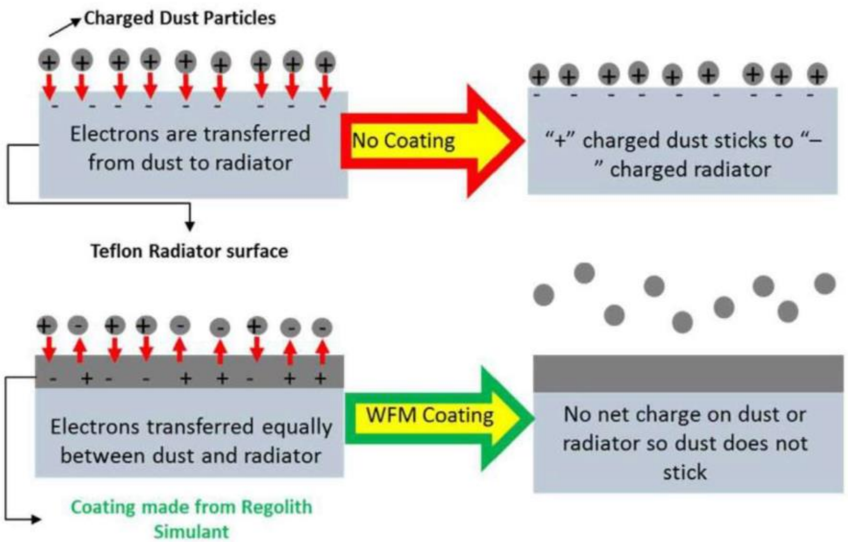
[V2 11032] LEA spacesuits shall be capable of a minimum of 40 kPa (5.8 psia) operating pressure to protect against Type II decompression sickness in the event of a cabin depressurization.

11.10 Nominal EVA Spacesuit Carbon Dioxide Levels

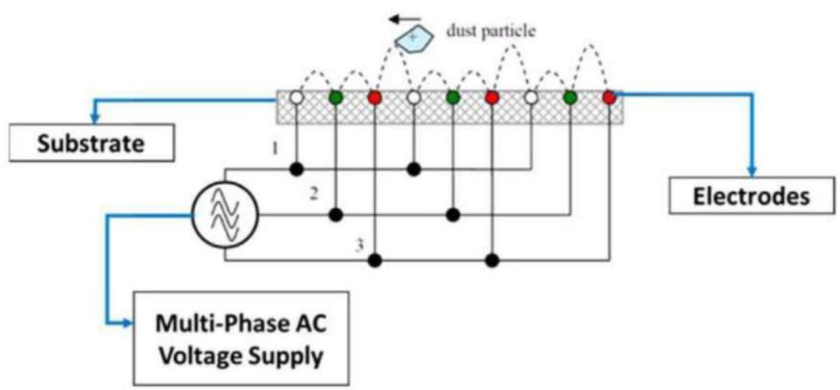
[V2 11039] The EVA spacesuit shall limit the inspired CO2 partial pressure (PICO2) in accordance with Table 23, EVA Spacesuit Inspired Partial Pressure of CO2 (PICO2) Limits.

3. Lunar Dust Mitigating Technologies

Work Function Matching Coating (WFM) passive technology with lunar simulant to lower **adhesion.**



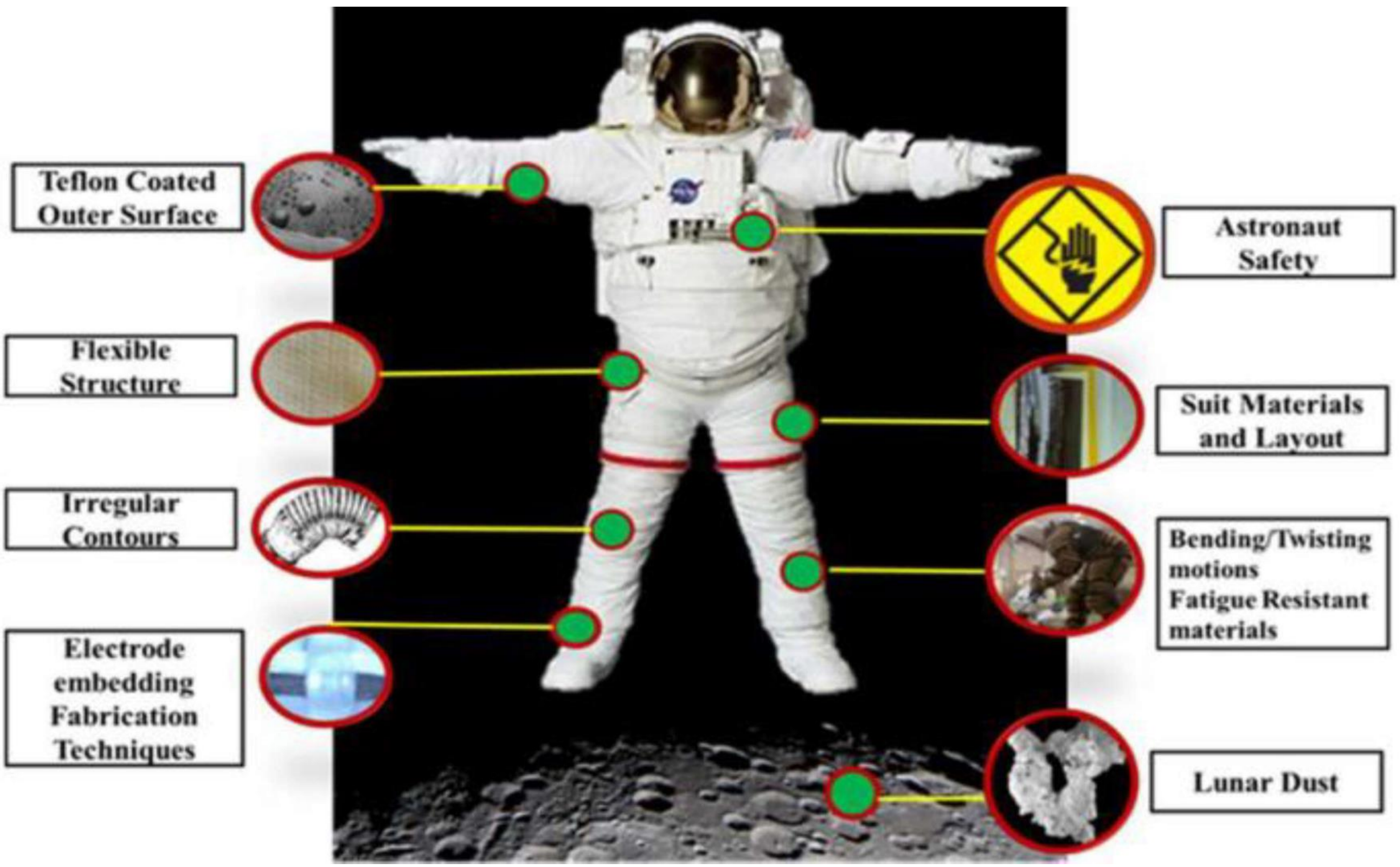
Electrodynamics Dust Shield (EDS) active technology incorporating Carbon-nanotube **fibers as electrode wires.**



Spacesuit Integrated Carbon Nanotube Dust Ejection/Removal (SPIcDER): A Self-cleaning Spacesuit System

SPIcDER has dual action:

1. To prevent accumulation of dust particles
2. To repel dust particles that may have already accumulated on the spacesuit surface. The continuous repulsion and removal of dust protects spacesuits from impacts of dust contamination.
3. 1000V AC cleaning signal through the CNT electrodes confirmed that the electric field intensity at the inner layers of the spacesuit are an order of magnitude below the permissible threshold exposure limits.


Teflon Coated Outer Surface
Flexible Structure
Irregular Contours
Electrode embedding Fabrication Techniques
Astronaut Safety
Suit Materials and Layout
Bending/Twisting motions Fatigue Resistant materials
Lunar Dust

4. Conclusion

1. Lunar dust sticks to everything. Brushing it off proves ineffective. The jagged, sharp properties causes its abrasive behavior.
2. Most NASA standards reports focus more on EVAs than robotics, indicating a legacy of technology acceptance for lunar operations.
3. Both passive and active dust removal technologies have prompted research into "proof-of concept" Spacesuit Integrated Carbon Nanotube Dust Ejection/Removal (SPicDER): A Self-cleaning Spacesuit technology.

Thank You.