Leidenfrost Dusting as a Novel Tool for Dust Mitigation

An effective and synergistic tool with high potential for Artemis implementation

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Summary and Background

- **Concept**
- **Background**
  - No literature on cryogenic cleaning
  - Leidenfrost Effect and Liquid Cryogen Sprays
- **Verification**: TRL 2-5
  - What's the next, simple, effective step?
  - How do we verify the solution for lunar use?
  - What demonstration shows system efficacy?
- **Impact/Lunar Architecture**

Testing our Hypothesis

Experimental Test Plan and Procedure
TRL 3: Handheld Liquid Cryogen Sprayer
TRL 4: Environmental Testing in a Vacuum
TRL 5: 1/6 Scale Prototype Testing in a Vacuum
Modelling
Simulating a Relevant Environment

Experimental Test Plan

Goal: Prove that the boiling effect of cryogenic liquids can be harnessed for lunar dust mitigation, achieving a removal of over 90% of particles less than 10 µm

Objectives

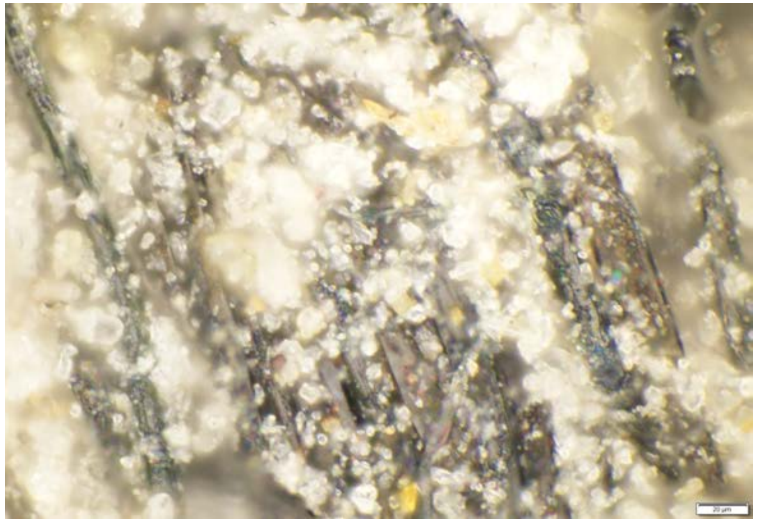
- Determine optimum parameters for cleaning
- Determine parameters for prototype system
- Demonstrate dust removal on 1/6 scale astronaut

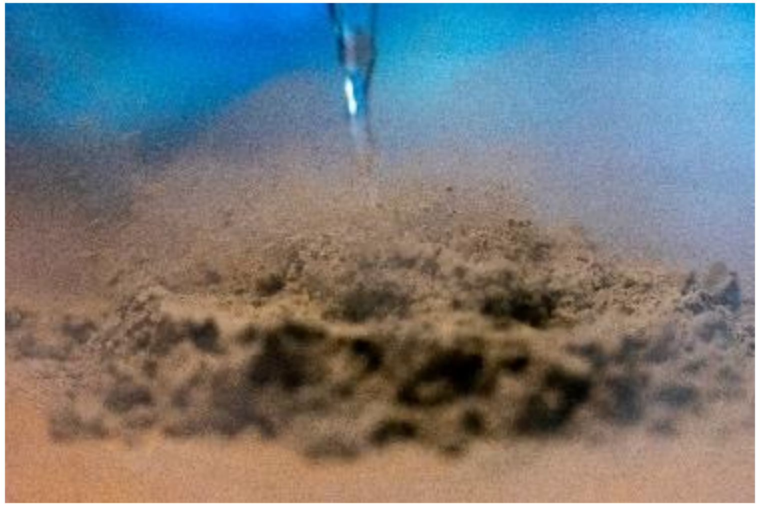
Design Considerations

- Minimize system size and requirements
- Prevent toxicity and flammability
- Must work with the life support systems
- Dust disposal system should be designed

Final Design

- Vertical Spray bar
- Overhead nozzles and handheld sprayer





Preliminary Tests

- **Compressed Air Treatment:** 69.2%
- **Liquid Nitrogen Pour:** 73.8%

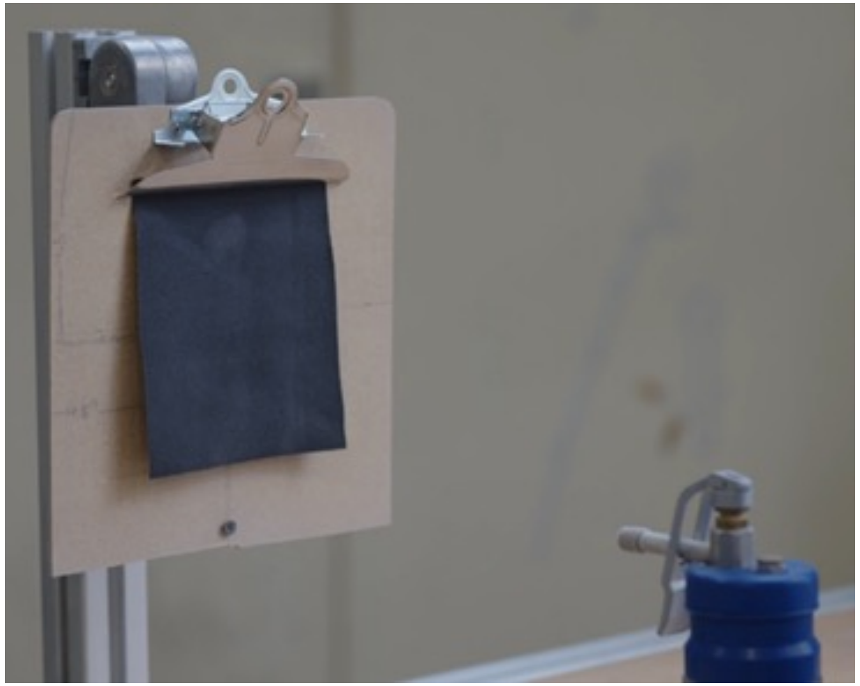
TRL 3: Liquid Cryogen Sprayer

- **Initial Average Removal of 92.0%**

- **Ideal Parameters**
  - Angle of Inclination: ≤ 90°
  - Spray Distance: 40 cm
  - Application Time: 20-40 seconds

- Under all three of the ideal parameters our final TRL 3 system achieved an average removal of 97.0%

Time (s)	Mean Removal %	Standard Deviation	Confidence Interval (95%)	Estimated Removal % of < 10 µm particles	Number of Trials
10	95.39	1.02	0.73	88.21	10
20	96.46	2.61	1.22	90.95	20
30	97.01	0.54	0.25	92.35	20
40	96.74	0.88	0.63	91.66	10
50	95.74	0.82	0.59	89.10	10



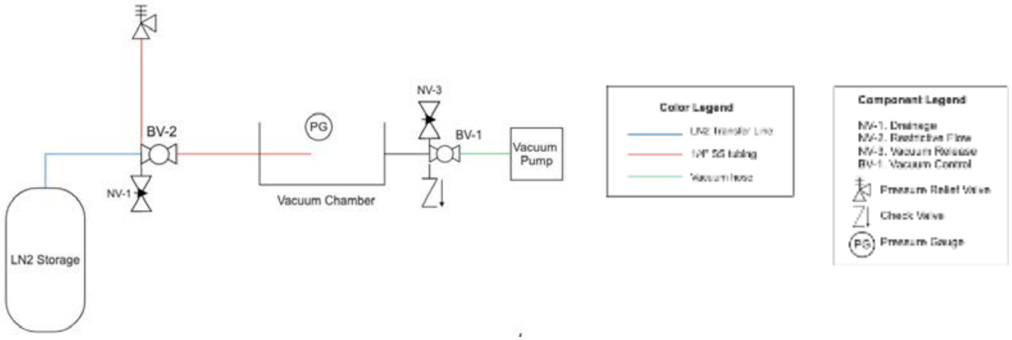
TRL 4: Vacuum System

Goal: Verify results in a relevant environment.

Leidenfrost dusting cleans with greater removal in a low-pressure environment. Cleans below triple point of nitrogen.

Flat nozzle: average of **98.4%** mass removal.

2-13kg of LN2 per suit wash. This equates to less than half of the cryogen necessary to pressurize an airlock.



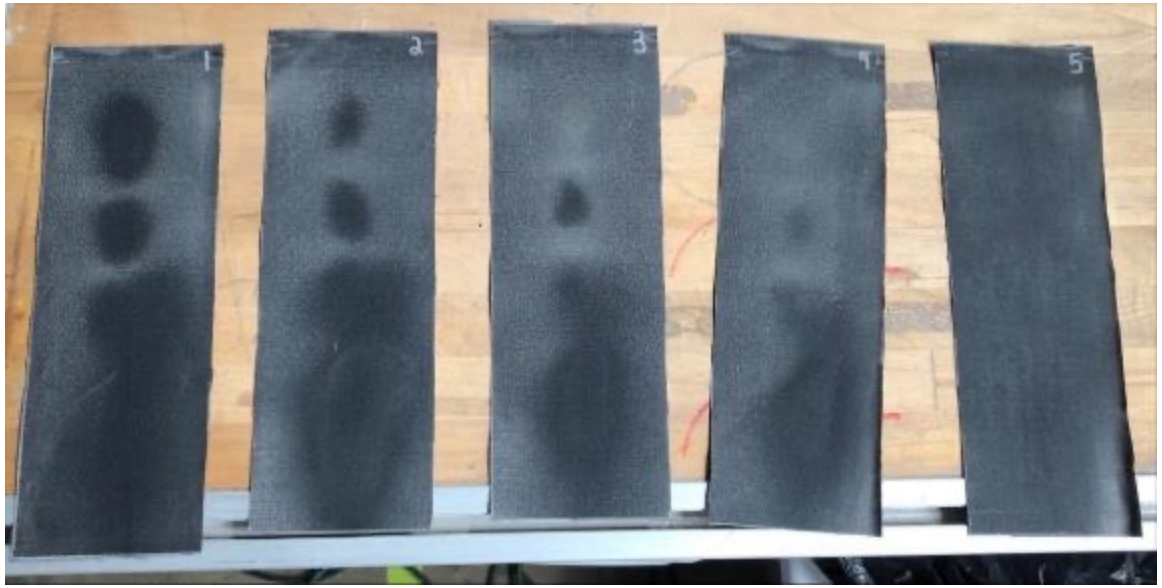
Nozzle	Variable / Treatment	Mean Removal %	Standard Deviation	Confidence Interval (95%)	Estimated Removal of < 10 µm particles	Number of Trials
Flat	**Black Aramid Kevlar**	98.38	0.991	0.829	95.85	8
Flat	PBI Max LP Ortho-fabric	97.52	1.367	1.696	93.65	5
Flat	NASA Spacesuit	95.26	N/A	Very high	87.88	1
Cone	Black Aramid Kevlar	96.91	1.603	3.983	92.10	3
Cone	Kevlar - Snap	93.69	3.374	2.821	83.86	8
Cone	Kevlar - No Cooling	60.44	5.499	13.66	Estimation invalid	3

TRL 5: 1/6 Scale System

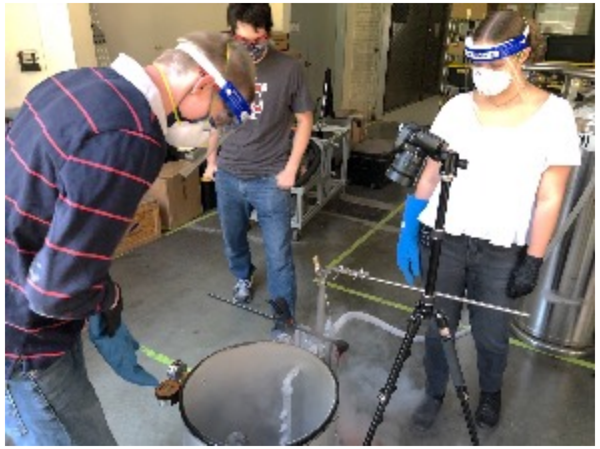
Removal of 85.3%-90.6% of applied ash.

LN2 boiloff resulted in a gradient of spray, with vapor from the top nozzles and liquid spray from the bottom nozzles. This is one of the biggest challenges faced while testing.

Two-step dust mitigation:
1. The scale astronaut was cleaned in 10 different positions with the spray bar.
2. Spot treatment with the liquid cryogen sprayer.



TRL Progression



Preliminary Tests: Proved our system was viable for further testing..

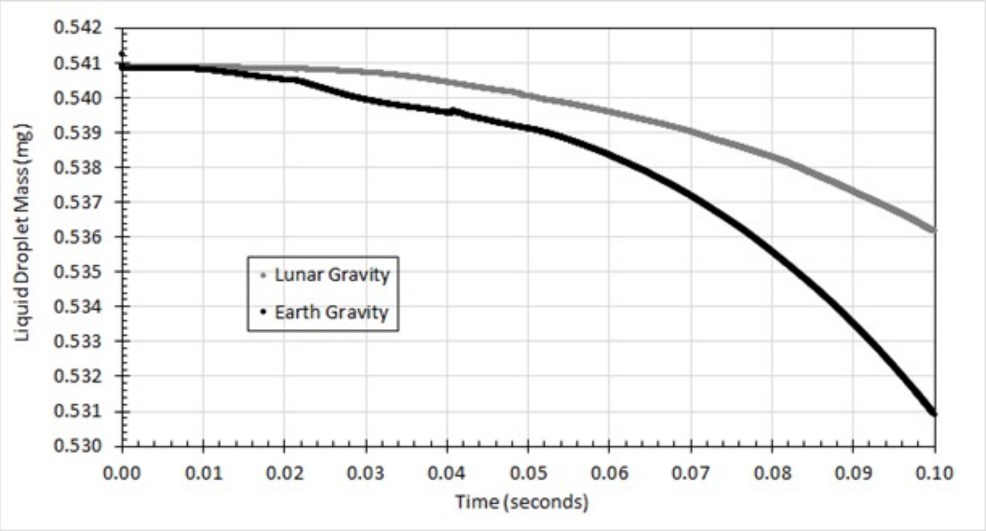
Liquid Cryogen Sprayer: Average of 97.0% removal by mass with ideal parameters

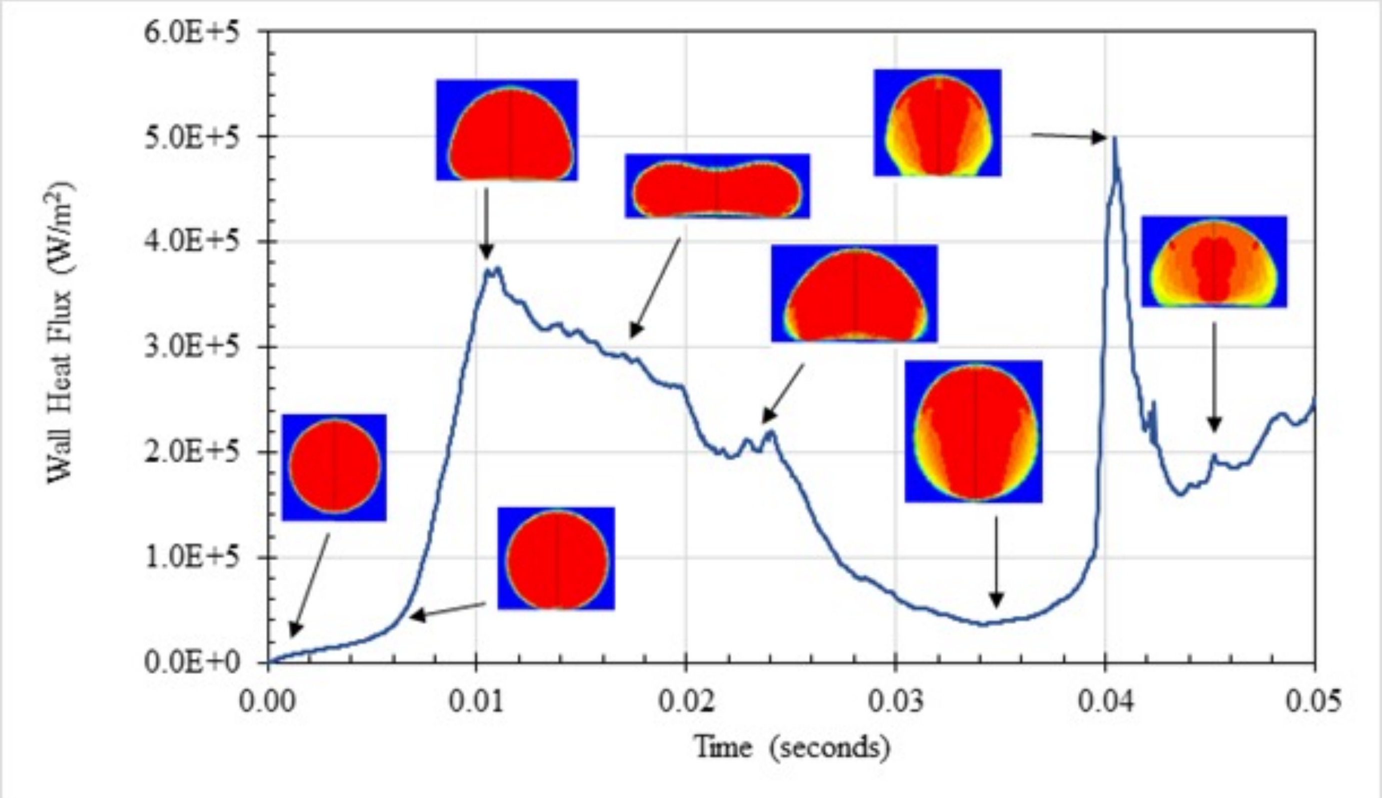
Vacuum chamber with flat nozzle: 98.4% mean removal by mass.

1/6 Scale Spray Bar: Qualitative Assessment

Lunar Gravity Modelling

- Modeled LN2 droplet falling onto room-temperature surface
- Software: StarCCM+, Realizable k-ε turbulence
- Diameter: 2mm
- Duration: 0.1 seconds
- Lunar gravity: showed similar motion, but slower (compared to earth gravity)
- Conclusion: Leidenfrost effect expected in Lunar gravity.





Simulating Relevant Environment

Dust material (DSNE 3.4.2.2)

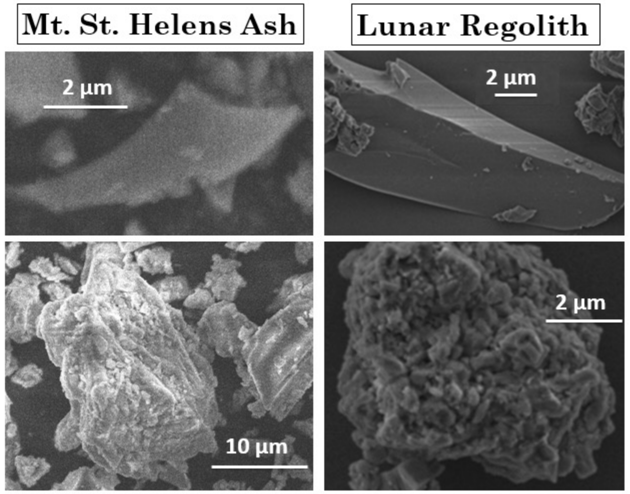
- Mt. St. Helens ash used
  - Extensive characterization indicated highly similar particle morphology, size distribution, and minerology
- Verified with NASA approved Off Planet Research Highland Regolith Simulant and Exolith Lunar Dust Simulant

Suit material

- Primarily tested Black Aramid Kevlar
- PBI Max LP Ortho-fabric
- Nasa-provided spacesuit material

Gravity

- Expect lunar gravity (1.62 m/s/s)
- Experiment used earth gravity (9.81 m/s/s)
- CFD showed similar droplet motion in earth and lunar gravity



- Pressure
  - Expect between high-vacuum and 1 atm
  - Primary concern is effectiveness below nitrogen triple point (0.124 atm)
  - Experiment showed similar performance at 0.03 and 0.95 atm
- Atmosphere Composition:
  - Expect to use liquid air mixture
  - Experiment used nitrogen, which has similar properties

Space Launch System (SLS) Program, and National Aeronautics and Space Administration . *Cross-Program Design Specification for Natural Environments (DSNE)*, Rev. H ed., NASA, 2021, pp. 211–283.

Looking Ahead

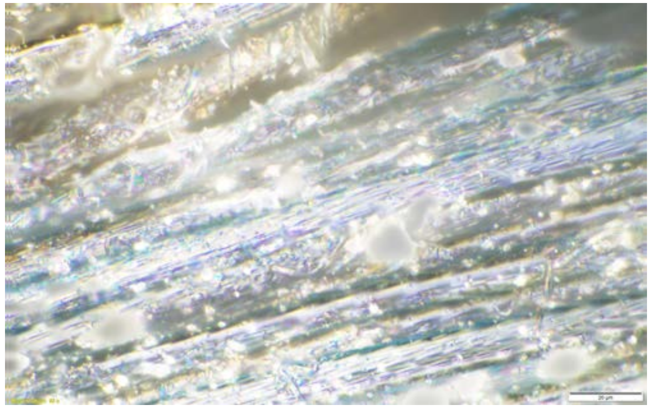
Path to Flight
Future Work

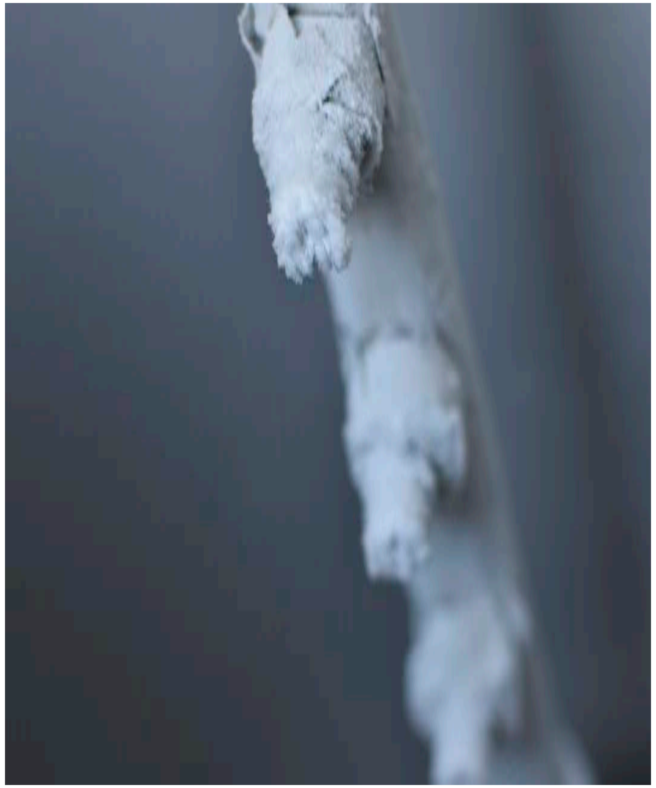
Path to Flight

- Investigation of impact of lunar dust on spacesuit materials needed.
- CFD or low gravity testing is required for advancement.
- Investigation should be done of spray bar shapes.
- Technology has other potential applications.
- A nitrogen liquefaction method is recommended.
- All components need qualification in a full-scale system.
  - After full-scale verification, it will be ready for terrestrial testing on an EVA suit.
- Technology can be ready for use on the Moon in the NASA Artemis Missions by 2026.
- Potential application to future Martian missions.

Future Work

- Effect of multiple washes on dust removal and on spacesuit material
- Further investigation of cleaning mechanisms
- Test removal of electrically charged dust particles
- Exploration of nozzle size, shape, and distance
- Development of a full-sized array in a large vacuum chamber
- HVAC system for moisture control when testing
- Low-gravity testing using hyperbolic aircraft flight or a suborbital rocket





What We Learned

Conclusions
Acknowledgements

Conclusions

- This system can be used on future lunar missions with high efficacy
- Testing indicates that the technology will remove dust at high levels
    - Cryogen spray exceeds conventional treatments
    - Cryogen Sprayer Testing: 92.4% of particles < 10 μm
    - Vacuum Testing: 98.4% removal | 95.9% of particles < 10 μm
    - Qualitative efficacy on a 1/6 scale astronaut
        - Achieving TRL 5/6
    - Recommended parameters established
- Benefits include:
    - Synergy with airlock pressurization
    - Low material and power requirements
    - Simple path-to-flight
    - Very high dust removal
- Refinement and improvement will increase efficacy
- Viable use by 2026 for the NASA Artemis missions back to the moon

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BIG IDEA CHALLENGE

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Thank you!

Questions?