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
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: $\leq 90^\circ$
  - 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%

<table>
<thead>
<tr>
<th>Time (s)</th>
<th>Mean Removal %</th>
<th>Standard Deviation</th>
<th>Confidence Interval (95%)</th>
<th>Estimated Removal % of $&lt;10 \mu m$ particles</th>
<th>Number of Trials</th>
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</thead>
<tbody>
<tr>
<td>10</td>
<td>95.39</td>
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<td>89.10</td>
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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.

<table>
<thead>
<tr>
<th>Nozzle</th>
<th>Variable / Treatment</th>
<th>Mean Removal (%)</th>
<th>Standard Deviation</th>
<th>Confidence Interval (95%)</th>
<th>Estimated Removal of &lt; 10 μm particles</th>
<th>Number of Trials</th>
</tr>
</thead>
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<td>Flat</td>
<td>Black Aramid Kevlar</td>
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<td>Flat</td>
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<td>1.696</td>
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<tr>
<td>Flat</td>
<td>NASA Spacesuit</td>
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<td>Black Aramid Kevlar</td>
<td>96.91</td>
<td>1.603</td>
<td>3.983</td>
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<tr>
<td>Cone</td>
<td>Kevlar - Snap</td>
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</table>
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
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 \( \mu \text{m} \)
  • Vacuum Testing: 98.4% removal | 95.9% of particles < 10 \( \mu \text{m} \)
  • 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
Acknowledgements

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Our Team:

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Thank you!

Questions?