LEIDENFROST DUSTING AS A NOVEL TOOL FOR DUST MITIGATION

Ian Wells, Mechanical Engineering Junior
Nathaniel Swets, Mechanical Engineering Junior
Lauren Reising, Mechanical Engineering Junior
Camden Butikofer, Mechanical Engineering Junior
John Bussey, Materials Science and Engineering Sophomore
Stasia Kulsa, Flute Performance Graduate
Gregory Wallace, Mechanical Engineering Graduate

Dr. Jacob Leachman, Dr. John McCloy, and Dr. Konstantin Matveev

Washington State University
Washington NASA Space Grant Consortium

BIG IDEA CHALLENGE

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HYPER
Face Shield
NITROGEN
HYPER

1. QUAD CHART

Washington State University
Leidenfrost Dusting as a Novel Tool for Dust Mitigation

Concept Synopsis

The Leidenfrost Effect harnesses the high-power density of boiling cryogen to levitate a droplet while blowing particulates from a surface. This effect has never been investigated as a tool for lunar dust mitigation. Our suggested cleaning paradigm is two-fold:

- A spray shower and vertical bar for broad cleaning
- A handheld cryogen sprayer for spot treatment.

Concept Visualization

Innovations

TRL 2: Demonstrated Leidenfrost effect to remove dust with LN2 pour.

TRL 3: Adapted an existing handheld cryogen sprayer to verify spray cleaning.

TRL 4: Proved Leidenfrost effect removes dust in a relevant environment with vacuum chamber.

TRL 5: Demonstrated spray bar manifold for 1/6 scale astronaut testing in vacuum.

Verification Testing Results & Conclusions

- Liquid Cryogen Sprayer Test results show minimum of 95.9% total mass dust removal with recommended system.
- Vacuum Test results show minimum of 96.6% total mass dust removal and 95.9% removal of particles less than 10 μm with recommended system.
- 1/6 Scale Spray System results show efficacy of the full spacesuit cleaning concept.
- All results with recommended system show greater than or equal to 90% mass removal of dust for particles less than 10 μm, thus a liquid cryogen spray can be an effective lunar dust mitigation tool.

2. EXECUTIVE SUMMARY

The Apollo 17 debrief team signaled lunar dust as one of the greatest inhibitors to returning to the lunar surface [23]. Lunar regolith is comprised of electrically charged, sharp, and irregular dust particles that pose concern to astronaut health, spacesuits, and systems across the lunar habitat [1]. Among active dust mitigation solutions, fluidal, mechanical, and electrostatic/electrodynamic methods have been investigated but determined not yet ready for lunar use [2].

As part of the NASA Big Idea Challenge, the Washington State University (WSU) Hydrogen Properties for Energy Research (HYPER) Laboratory made a pertinent observation: the Leidenfrost effect can be harnessed for dust mitigation. The high-power density of boiling liquid nitrogen droplets results in a phase change to nitrogen gas nearly 780x less dense. The vapor blowing from droplets can transport dust and remove it from a surface. The HYPER-Borea team has developed a dual-paradigm dust mitigation solution composed of a cryogen shower with vertical spray bar for broad mitigation and a handheld liquid cryogen dispenser for localized mitigation.

The challenges this concept solves are the removal and disposal of lunar dust from spacesuits in the airlock of a lunar habitat. This solution simultaneously partially pressurizes the airlock while cleaning a spacesuit. The benchmarks that this system achieves are:

1. Dust mitigation of >90% of particles less than 10 µm.
2. Removal of dust in a relevant environment.
3. No consumables are required as the nitrogen can be recycled for future use.

Verification was conducted by the team to advance the concept with scaled Technology Readiness Level (TRL) testing from TRL 2 at the benchtop level to TRL 5 vacuum chamber testing of a 1/6 scale model. All tests were performed with a high level of safety, established by the Hazard and Operability Safety plan with associated procedures and testing methods. The goal of this testing was to optimize system parameters to increase the TRL of the solution. Verification results have shown high levels of lunar dust simulant removal, with optimized parameters exceeding 90% removal by mass of particles smaller than 10 µm for TRL 3-5 testing.

Testing results were confirmed with mass comparisons and optical microscopy. Liquid cryogen dusting has a minimum mass removal of 95.92% for a handheld liquid cryogen sprayer on a flat swatch. In relevant environments, a mean removal value of 98.38% by mass of lunar dust simulant with a single nozzle in a vacuum chamber was found with high certainty. This value corresponds to 95.85% removal of particles smaller than 10 µm. TRL 5 testing of a 1/6 scale astronaut in the vacuum chamber included a custom liquid spray-bar as well as a hand-held spray applicator adapted from off-the-shelf medical equipment for total Extra Vehicular Activity (EVA) suit treatment.

This research impacts future Moon and Mars missions in the NASA technology roadmap. In addition to near complete dust mitigation, liquid air treatment not only requires zero energy input during application but has the ancillary benefit of partial pressurization of an airlock. When combined with a lunar habitat air liquefaction and management system, this approach has totally recyclable materials with no consumables.

3. PROBLEM STATEMENT AND BACKGROUND

The previously investigated dust mitigation paradigms of fluidal, mechanical, and electrostatic/electrodynamic removal do not successfully address each of the barriers to the lunar adaptation of these methods. Among these options, fluidal mitigation is the simplest paradigm for space applications because it has minimal parts to operate and consumables to transport. Other research groups have found incompressible fluids to show the most promise for dust mitigation [2]. Cryogenic liquids, however, harness spray boiling which aids in the removal of dust and improves upon previous fluidal mitigation methods. The use of cryogenics for dust mitigation synergizes well with airlock pressurization needs and can be integrated into this system. Additionally, the method is non-toxic and presents no flammability concerns. Leidenfrost dusting, when progressed to TRL 8-9, could potentially solve the problem of extra-terrestrial dust mitigation.

Given the harmful effects of lunar dust, our approach focuses on keeping dust out of the habitat. The HYPER-Borea team harnessed the Leidenfrost effect to develop an active dust mitigation technology for cleaning EVA suits in a lunar airlock. Initial testing was conducted by pouring liquid nitrogen to verify the cleaning abilities of the Leidenfrost effect. The use of spray nozzles showed measured improvement over pouring, allowing an increase in TRL. Testing in a vacuum chamber verified the system's ability to clean in a relevant environment (TRL 5). Test results indicate that this technology can additionally be applied to other key areas of lunar exploration for non-destructive cleaning of surface-exposed substrates, cloth, and other materials.

Our technology fits within NASA's planned Lunar Architecture by providing a key solution for the Artemis Base Camp at the lunar South Pole. This aids NASA's Exploration Level Zero Goals by ensuring the safety of American astronauts on the Moon and aiding sustained lunar surface activities. These activities are made possible by providing a reliable method of lunar dust mitigation which keeps astronauts safe and improves the longevity of equipment. Additionally, successful system use on the lunar surface may highlight cryogen dusting as a viable option for future Mars missions, enabling Mars-forward Testing.

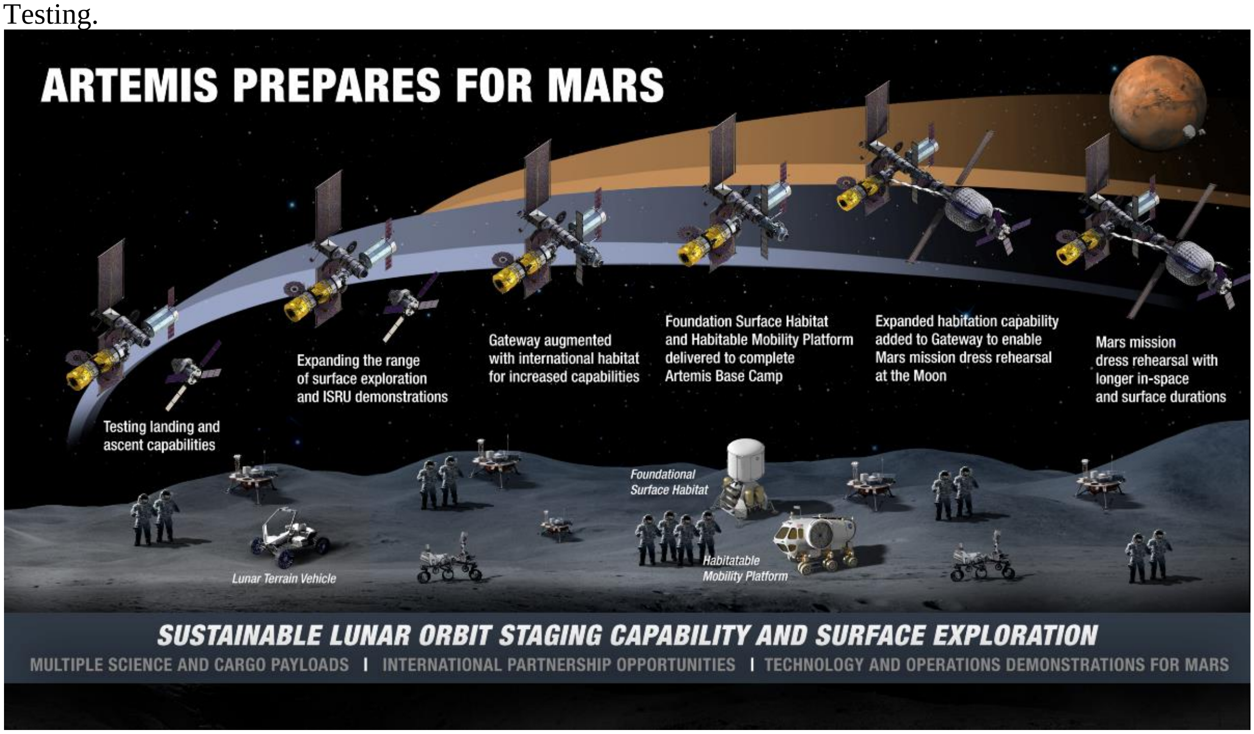

Figure 1: NASA's post-2024 Artemis road map. Credit: NASA

The Lunar Architecture (*Figure 1*) indicates a Foundational Surface Habitat for up to four astronauts to occupy. The HYPER-Borea Dust Mitigation System can be employed at the airlock for this habitat. The Artemis Base Camp will be testing technologies from the Lunar Surface Innovation Initiative providing ample opportunity for field testing of liquid cryogen dusting within the habitat. With successful testing through TRL 8-9 and further development, this system could also be employed in the airlock of the Habitable Mobility Platform, the Lunar Surface Access Module, and future pressurized Lunar Terrain Vehicles.

Assuming the Foundational Surface Habitat airlock is similar to the Joint Airlock on the International Space Station, the HYPER-Borea Dust Mitigation System forms natural synergies with the other systems. The airlock design already includes the necessary systems to handle this change, although some modifications to control algorithms and instruments may be required. With liquid nitrogen and oxygen stored on the outside of the airlock, atmospheric control systems in the airlock will simply need to be reprogrammed to accommodate liquid nitrogen or air as a mechanism to assist re-pressurization [3][4].

4. PROJECT DESCRIPTION

The scope of this project was to prove that the boiling effect of cryogenic liquids can be harnessed for lunar dust mitigation. Our goal was to achieve a cleaning efficacy of over 90% of the particles less than 10 μm in a vacuum chamber. The following objectives were pursued to advance this concept from TRL 3 to TRL 5:

1. Determine optimum parameter cleaning efficacy of handheld cryogen sprayer. Deliverables: A table of experimental measurements showing material, angle of inclination, drop height, and removal percentage. Timeline: January 2021-August 2021.
2. Determine spray nozzle shape for 1/6 scale spray bar prototype design and demonstrate effective cleaning of relevant simulants in a vacuum chamber. Deliverables: Recommended spray nozzles for spray bar prototype. Timeline: August 2021-September 2021.
3. Demonstrate dust removal from a 1/6 scaled astronaut wearing a mock EVA suit with a spray bar manifold in a relevant environment. Deliverables: Two-fold paradigm for lunar dust mitigation and TRL 3-5 advancement via efficacy tests in vacuum chamber. Timeline: September 2021 - October 2021.

To build a prototype concept, a spray bar shape needed to be determined. The system design process used a modified Design Structure Matrix (DSM) which systematically evaluates the viability of a prototype given design factors, importance multipliers, and rankings from 1-4 based on the merits of the design for a given factor.

Design factors considered: ease of testing simplicity; minimized system parts, volume, wash cycle time, LN2 usage, mass, and movement required from an astronaut; maximum suit coverage from a spray; angle optimization; spray distance from suit; and ease of testing.

Given these factors, a vertical spray bar was ranked above the arch, half-arch, and shower head shapes. It can be observed that a vertical spray bar did not have full suit coverage, so the full cleaning paradigm includes spray nozzles from above and a handheld cryogen sprayer (*Figure 2,3)* together with the vertical spray bar. The series of nozzles overhead also limits aerosolized dust in the airlock. In addition, a curtain to contain aerosolized dust may be implemented.

Figure 2: A CAD model of the prototype HYPER-Borea Dust Mitigation system (left) and an image of the Liquid Cryogen Sprayer (right).

Seamless integration is essential for a lunar mission. Specific integration considerations for this system are enumerated below:

- System must work with life support systems pressurizing the airlock. Based on previous tests, the system is predicted to use approximately 2 kg of LN2 per full EVA suit wash which can assist with airlock pressurization. This is enough to fill an airlock with $1.5m^3$ of nitrogen at STP or raise the pressure of a $34m^3$ airlock by 5 kPa, per wash.
- LN2 or liquid air transfer lines must be installed.
- An LN2 liquefaction process must be present at the lunar habitat. Cryogens require energy to be liquified. Using the amount of liquid nitrogen applied per gram of ash removed, a specific energy consumption estimate per system wash can be obtained. For liquid cryogen sprayer tests, 50 cm^3 of LN2 was applied per wash to remove approximately 0.5 grams of lunar dust simulant from a 30 in^2 swatch of fabric. Assuming no energy loss from liquefier cycles and an electrical energy requirement of 759 kJ per kg of LN2 at 98% purity, the system consumes approximately 16.9 W*h/g of ash removed. This can be scaled up to find an approximate energy consumption of 435 W*h per full system wash. This energy required can be significantly decreased by utilizing the extreme temperatures of the lunar environment and improvements in liquefaction efficiency.
- A dust disposal system should be designed. We recommend lunar dust be collected at the lowest point in the airlock so that it can be emptied on to the lunar surface or disposed of via existing waste disposal technologies. Liquid nitrogen evaporation results in accretion deposits of simulant that are convenient for disposal.

The stakeholder directly associated with this project is NASA. The research funded through the Big Idea Challenge seeks to advance the TRL of the proposed technology and investigate the viability of cryogenic dust mitigation solutions for the Artemis missions. Another potential stakeholder for this project is Smart Materials Solutions (SMS). They have utilized our testing procedures and washing method to verify removal of lunar dust simulant from patterned materials compared with un-patterned ones. This shows the feasibility of using our cleaning method for testing of other lunar dust mitigation technologies.

5. VERIFICATION TESTING

The team iterated through the following TRL to advance the technology for use on Artemis missions.

TRL 2: Liquid Cryogen Pour: Optical verification of the removal of lunar dust simulant from a surface.

TRL 3: Liquid Cryogen Sprayer: The team determined relevant variables to control or modify. A low-fidelity test was designed using a handheld liquid cryogen sprayer shown in *Figure 3*. This testing verified the efficacy of cryogenic dust mitigation in a laboratory environment on relevant materials.

TRL 4-5: Environmental Testing in a Vacuum: The efficacy of Leidenfrost cleaning in a relevant environment was verified using a single spray nozzle in a vacuum chamber on relevant materials.

TRL 5-6: 1/6 Scale Prototype Testing in a Vacuum: Performed the vacuum verification testing on a 1/6 scale astronaut Mock-EVA suit with a vertical prototype spray bar manifold in tandem with the cryogen sprayer to demonstrate our two-fold cleaning paradigm.

The team used the facilities available at the Washington State University Pullman campus. Testing was completed in the WSU Thermal Fluids Research Building. An FEI Field Emission Scanning Electron Microscope (SEM) and BX53-P Olympic Microscope were used as characterization equipment to verify dust simulant removal. An Ohaus PX84 Pioneer Analytical Balance with 0.0001 g precision was used in addition to a Toledo AT261 DeltaRange Analytical Balance with .000001 g precision. We performed all tests except for TRL 2-3 proofs of concept in a modified vacuum chamber. Optimum testing parameters in the included data tables are bolded.

5.1 Liquid Cryogen Sprayer Procedure

Masses were measured with a Toledo AT261 DeltaRange © balance with 0.00001 g precision for cleaning method, angle of application, and some distance tests. An Ohaus PX84 Pioneer Analytical Balance with 0.0001 g precision was utilized for the remaining distance tests, time tests, and dust simulant comparison tests. The following procedure was followed for all tests:

1. Cut ortho-fabric to 194 cm^2 swatches (rectangles 12.7 cm by 15.24 cm).
2. Mass suit simulant swatches.
3. Dust ortho-fabric by brushing 1.0 g of dust simulant into ortho-fabric and tap so that between 0.4 and 0.6g of dust simulant remain on the ortho-fabric. This simulates the removal of excess simulant from spacesuit movement.
4. Mass swatch with dust simulant added.
5. Testing setup adjusted for the specific experimental variables. (i.e., Application angle, distance, time, or removal method) and simulant clipped onto the sample stand. For tests applying specific amounts of liquid nitrogen, load the liquid cryogen sprayer with 25 mL excess liquid nitrogen to account for liquid not reached by liquid cryogen sprayer transfer hose.
6. Operate liquid cryogen sprayer by fully pulling down trigger while measuring time elapsed.
7. Spray across ortho-fabric with 10 horizontal passes (starting with left to right) and 3 vertical passes (starting with top to bottom) for every 50 mL expended.
8. Mass washed ortho-fabric swatch.
9. Calculate the mass fraction of removal. Subtract the mass of the swatch after cleaning from the mass of the swatch after dusting. Divide this by the difference between the mass of the swatch initially and the mass of the dusted swatch.

Testing best practices included:

- Performing a minimum of 5 trials for each treatment.
- Minimizing boiloff by precooling glassware in a liquid nitrogen bath.
- Precooling liquid cryogen sprayer before testing by filling and spraying until empty.
- Ensuring all ortho-fabric preparation areas are clean to prevent swatch contamination.
- Prioritizing safety to minimize dust simulant exposure, risk of asphyxiation, and cryogenic burns.

a) 

b) 

Figure 3: Labelled diagrams of the a) testing setup and b) liquid cryogen sprayer modification.

5.2 Liquid Cryogen Sprayer Results

Initial tests investigated whether liquid nitrogen is a significantly more effective cleaning method than other traditional methods. Tests were conducted with a liquid cryogen sprayer, liquid nitrogen pour, and compressed air treatment. The liquid cryogen sprayer had 91.99% removal by mass of lunar dust simulant with approximately 50 cm^3 of applied liquid nitrogen on a 194 cm^2 swatch of fabric. Approximately 50 cm^3 of liquid nitrogen poured over the same size fabric had 73.77% dust simulant removal by mass. The compressed air treatment had 69.24% removal by mass. Thus, liquid nitrogen cleaning via a liquid cryogen sprayer is likely more effective than other tested techniques for the removal of lunar dust simulant.

Mass fractions of removal combined with particle size distributions provide relative estimations for a given particle size removed. These masses are combined with optical microscopy to give an estimation of the sizes of the particles removed and remaining. As shown in the microscopy performed on spacesuit samples, *Figure 4*, there is a significant visual difference between the fabric before and after treatment with the liquid cryogen sprayer.

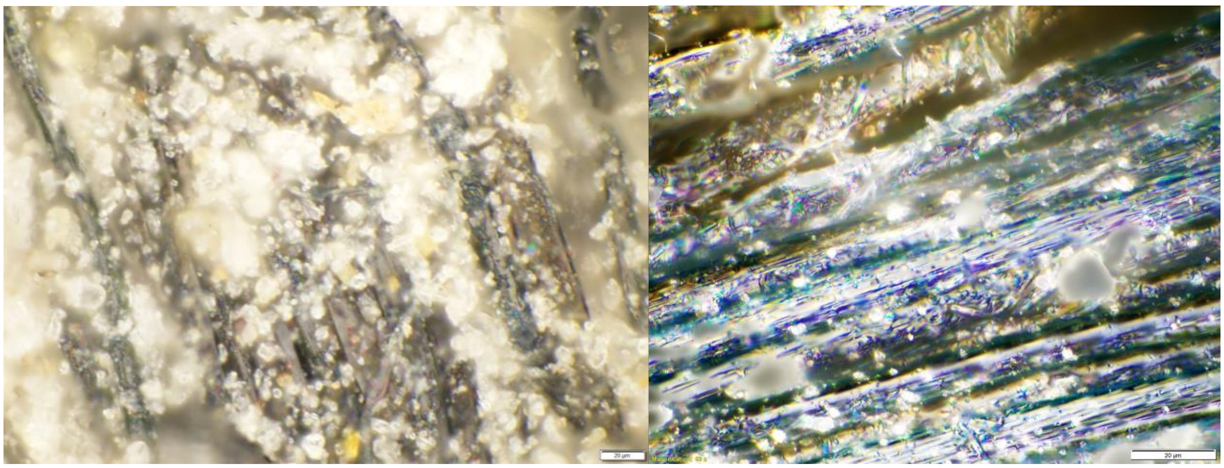

Figure 4: 100x optical light microscopy on a model BX53-P from Olympus of (left) spacesuit simulant dusted with Mt. St. Helens ash (right) spacesuit simulant dusted with Mt. St. Helens ash and cleaned with the liquid nitrogen sprayer with calculated >96% ash removal.

An extensive test to determine normality is the Shapiro-Wilks test [4]. This test was performed for both the data from 195 mm and 400 mm from nozzle of cryogen sprayer to test swatch. The results were p-values of 27% and 90%. Thus, the null hypothesis that the data is normally distributed cannot be rejected. These results were verified by a survey of Kurtosis (peakedness) values. However, due to the slight skew, limited trials, and peakedness difference, Student's T Distribution was used instead of a normal distribution for analysis, adapting results based on the number of trials performed. Confidence intervals with an α value of 5% were then calculated from the Student's T Distribution.

A sample with greater than 96% dust removal was analyzed via Electron Dispersive Spectroscopy (EDS). All remaining particles were below 10 μm and the vast majority were below 3 μm. The EDS data and calculations verify the calculated removal of particles less than 10 μm.

Extrapolating from the 50 cm^3 of liquid nitrogen used per 194 cm^2 swatch of ortho-fabric in liquid cryogen sprayer tests, approximately 2 kg of liquid nitrogen would be needed to clean a spacesuit with a 1 m^2 external surface area. Approximately 25-30 kg of liquid air are needed to pressurize an airlock with the same dimensions as the Joint Quest Airlock on the ISS (34 cubic meters) to room pressure [5].

5.2.1 Angle Testing

The angle of inclination was found to directly correlate with lunar dust simulant removal. Angle is measured horizontal to the ground (0 degrees indicates dusted side of the cloth facing down). Tests were performed with the liquid cryogen sprayer 195 mm from the test sample. Results can be found in *Table 1* and seen graphically in *Figure 5*. Generally, as the angle of inclination decreased removal increased. It appears that smaller angles likely have higher removal with the highest removal at acute angles.

Table 1. Angle of inclination relative to horizontal in degrees versus dust removal by mass percent.

Angle (degrees)	Mean Removal %	Standard Deviation	Confidence Interval (95%)	Estimated Removal % of < 10 µm particles	Number of Trials
165	90.90	3.62	2.59	76.72	10
150	89.88	1.55	1.11	74.13	10
135	90.61	2.38	1.70	75.99	10
120	93.02	2.74	1.58	82.16	14
105	94.77	1.56	1.12	86.62	10
90	92.92	1.63	0.76	81.90	20
75	93.83	0.97	0.69	84.23	10
60	95.86	1.14	0.82	89.42	10

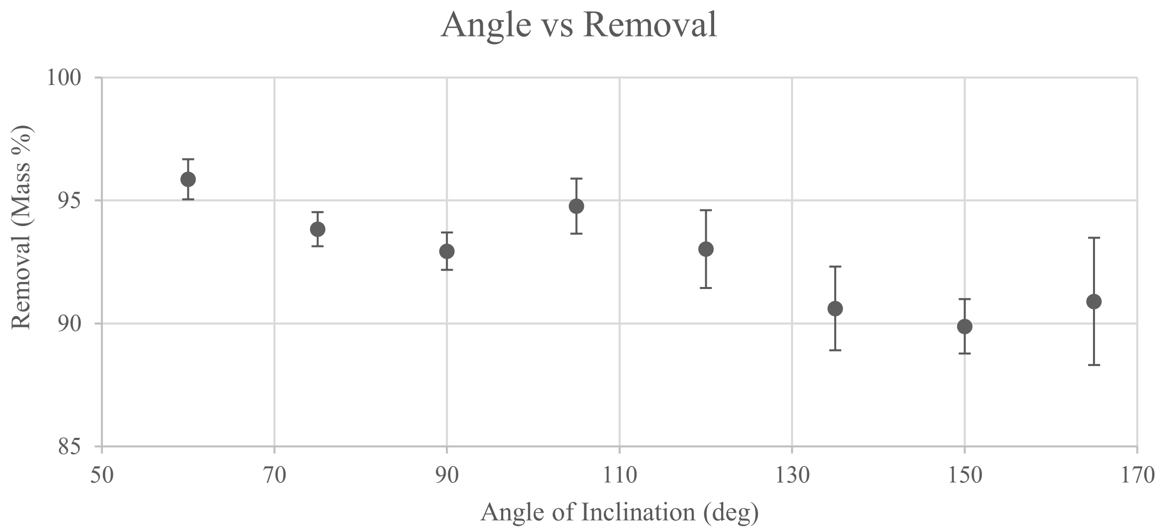

Figure 5: Lunar dust simulant removal mass (%) versus sample angle of inclination (degrees) at a distance of 19.5 cm.

5.2.2 Distance Testing

Increasing distance correlated with increasing lunar dust simulant mass fraction removal. Results can be found in *Table 2* and seen graphically in *Figure 6*. Removal efficacy increased as distance increased. Distance was measured from the nozzle outlet to the center of the sample when in the 90-degree configuration (the fabric orthogonal to the liquid cryogen sprayer nozzle). These measurements were acquired with 50 cm^3 of liquid nitrogen applied. A different nozzle will likely have different removals at these distances. This is likely due to several variables including nozzle geometry and jet diameter.

Table 2. Application distance in millimetres versus percent mass removal.

Distance (mm)	Mean Removal %	Standard Deviation	Confidence Interval (95%)	Estimated Removal % of < 10 µm particles	Number of Trials
100	89.17	1.83	1.31	72.31	10
195	92.94	1.55	0.69	81.95	22
300	94.03	1.08	0.66	84.73	13
400	96.55	1.13	0.35	91.19	42
500	96.71	1.08	0.69	91.59	12

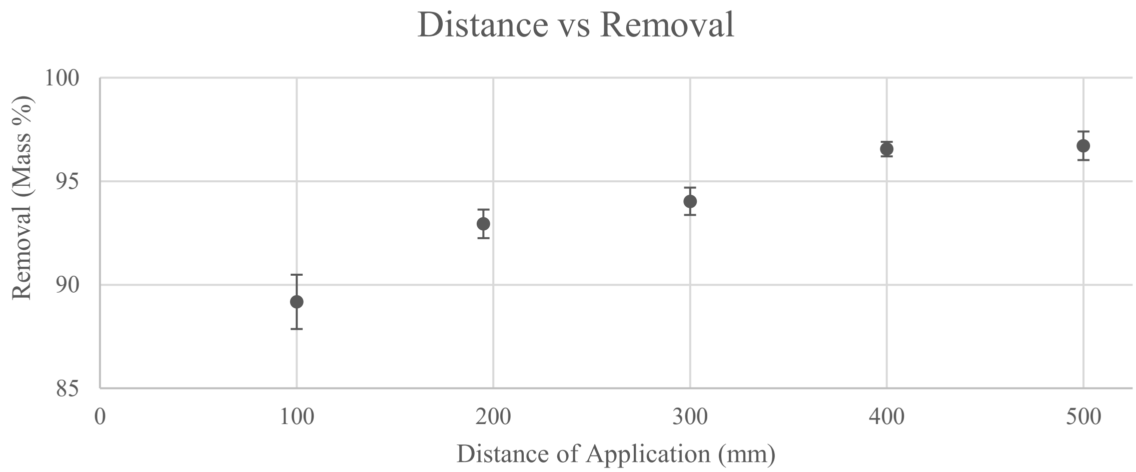

Figure 6: Lunar dust simulant removal mass (%) versus sample distance of application (mm) at an orthogonal angle of inclination.

5.2.3 Application Time

For these tests, the liquid cryogen sprayer was loaded with 150 cm^3 of liquid nitrogen and sprayed for a set amount of time. A distance of 400 mm at a 90-degree angle to the fabric was selected due to superior results in prior tests. Results can be found in *Table 3* and seen graphically in *Figure 7*. Our hypothesis for decreasing removal with longer spray times is that larger volumes of LN2 loaded into the liquid cryogen sprayer resulted in lower mass flow rate from its nozzle.

Table 3. Application time in seconds versus percent mass removal.

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

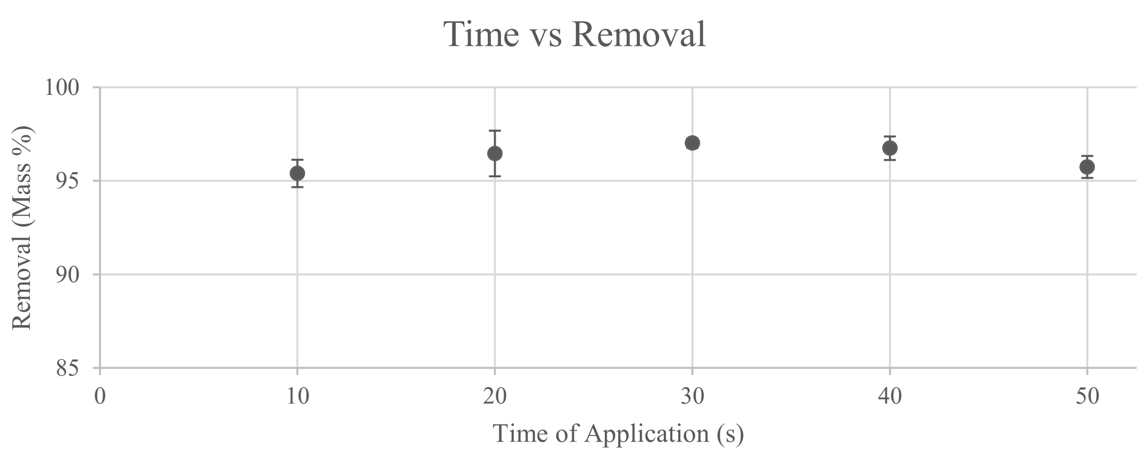

Figure 7: Lunar dust simulant removal mass (%) versus liquid nitrogen application time (s) at an orthogonal angle of inclination and distance of 40 cm.

5.2.4 Further Testing

Further testing investigated key variables including suit simulants, dust simulants, and hysteresis.

Testing was conducted to verify performance across several different suit simulants. The ripstop Nomex-Kevlar suit simulant was compared to proprietary spacesuit PBI ortho-fabrics. Tests were completed with 50 cm^3 of liquid nitrogen applied at 195 mm and an inclination of 135 degrees. Removal on the ripstop Nomex-Kevlar blend fabric was 86.26%, removal on PBI Max LP Ortho-fabric was 90.67%, and removal on a multi-layered PBI ortho-fabric was 85.88%. The multi-layered fabric had visible ash between the layers, and we hypothesize if the fabric edges were sealed, as they would be on a spacesuit, the mass removal percentage would be higher. Thus, it was determined that the ripstop Nomex-Kevlar blend was similar enough to real spacesuit ortho-fabrics for use as a standard testing suit simulant.

Mt. St. Helens Ash was compared to NASA-approved lunar dust simulants. Testing occurred at 90-degree inclination, distance of 400 mm, and with application of 50 cm^3 of liquid nitrogen. Mean mass fraction removal of ash was 95.62 %, removal of OPRH2N Near Highland Simulant from Off Planet Research was 98.10% and removal of LHS-1 Lunar Dust Simulant from Exolith Labs was 90.95%. The particle size distribution is the primary difference between these simulants, shown in *Figure 8*. The liquid cryogen sprayer removed a similar percentage (within 1%) of particles below 10 μm regardless of lunar dust simulant. Statistical testing (t-test) revealed that this difference is not significant (p values > .14%). This indicates our liquid cryogen dusting system varied cleaning based on particle size, removal of particles less than 10 μm does not significantly change based on simulant type, and Mt. St. Helens ash is a viable and reputable simulant to be used for low-mid TRL testing.

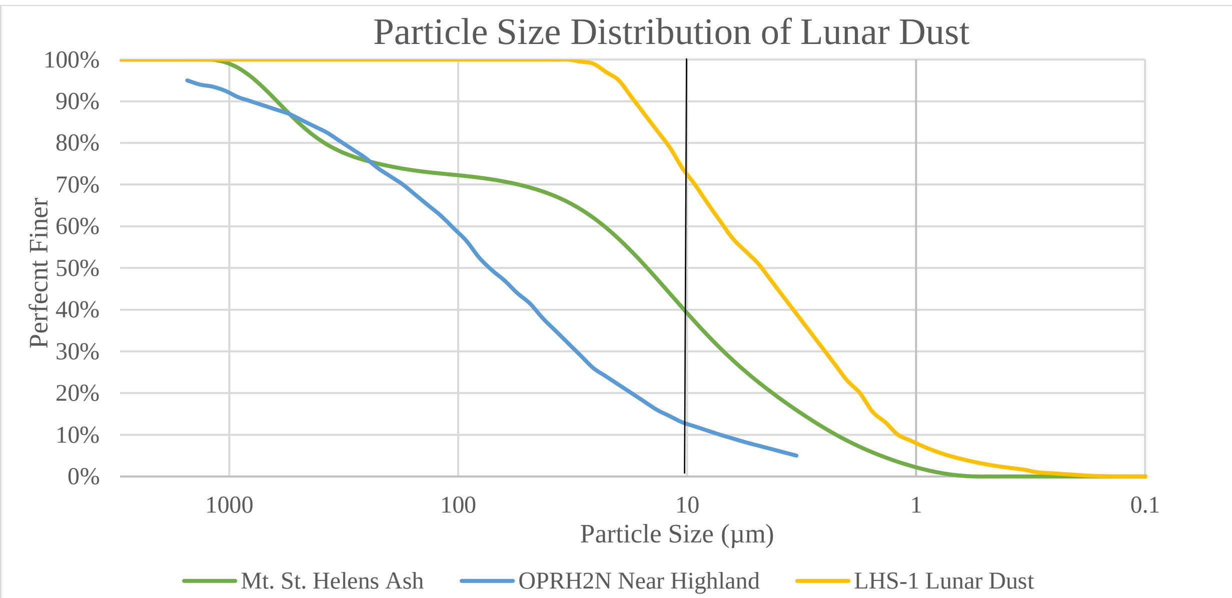

Figure 8: Particle size distribution of Mt. St. Helens ash collected in Pullman, Washington, average of Apollo lunar regolith samples [6] and Exolith Labs LHS-1 lunar dust simulant [7].

Multiple wash-cycle tests followed the Liquid Cryogen Sprayer Procedure (Section 5.1) but repeated the ashing and washing steps for 2 iterations per sample. First wash removal was 96.35%, while second wash removal was 97.97% with an average removal between the two washes being 97.12%. This results in an average difference of 1.62% increase in removal. This result is statistically significant (p value = 0.024) indicating more dust simulant is removed on the second wash. We hypothesize that dust simulant particles fill "sites" within the suit simulant, leading to lower ash adhesion during repeat ashing. This is corroborated by an 18.0% decrease of dust simulant application between washes. These results suggest that after each EVA, there will be an increase in removal of lunar dust from the spacesuit. A potential method to achieve these high levels of cleaning prior to EVA cycling is a coating could be applied to fill fabric sites which would otherwise become occupied by lunar dust.

Additional testing was completed to investigate the possibility of hysteresis with the liquid cryogen sprayer. Using a single blind testing procedure, the data does not show signs of hysteresis. Testing was also completed on patterned substrates supplied by SMS which indicate synergy of the liquid cryogen sprayer dust mitigation solution with other dust mitigation solutions, including for possible application on the lunar surface. Microscopy of these results appears to indicate little or no damage to the substrates from the liquid nitrogen washing method. Finally, testing was conducted by attaching various nozzles to the end of the liquid cryogen sprayer. All nozzles appeared to reduce cleaning distance, spray diameter, and cleaning efficacy. Thus, we suggest a minimum nozzle internal diameter of 2.17 mm for spot treatment handheld liquid cryogen sprayers, dependent on other requirements.

Liquid Nitrogen Spray Results Summary

Original tests with the liquid nitrogen sprayer demonstrated a 91.99% removal by mass of lunar dust simulant with 50 cm^3 of applied liquid nitrogen on a 194 cm^2 swatch of fabric. Further tests found that the angle of inclination and distance of spray were found to directly correlate with removal percent. It was determined that as the angle of inclination decreased, the removal increased, seen in *Figure 5*. Additionally, increasing the distance of the spray correlated with an increase in removal as well, seen in *Figure 6*. Our data showed that an application time of about thirty seconds is ideal. Three different lunar dust simulants, and their mean mass percent removals were compared: Mt. St. Helens Ash with 95.62%, OPRH2N Near Highland Simulant from Off Planet Research with 98.10%, and LHS-1 Lunar Dust Simulant from Exolith Labs with 90.95%. The use of Mt. St. Helens ash as a lunar dust simulant for low-mid TRL testing was determined to be a credible solution. Three suit simulants were also tested: PBI Max LP Ortho-Fabric, a Nomex-Kevlar blend fabric, and a multi-layered PBI ortho-fabric. Using Mt. St. Helens ash, removals were 90.67%, 86.26%, and 85.88% respectively. The results of these tests allowed us to determine that the Nomex-Kevlar blend performed similarly enough to the other suit simulant materials to be used as a standard testing simulant. Lastly, nozzle parameters were tested. Out of the nozzle dimensions tested, all reduced overall cleaning efficiency, it was concluded that a minimum nozzle diameter of 2.17 mm for handheld spot treatment with liquid nitrogen spray is ideal.

5.3 Vacuum Testing Procedure

1. Cut ortho-fabric to 6.45 cm^2 swatches (squares with 2.54 cm sides).
2. Mass suit simulant swatches. Masses were measured with a Toledo AT261 DeltaRange © balance with 0.00001 g precision for cleaning method, angle of application, and some distance tests. An Ohaus PX84 Pioneer Analytical Balance with 0.0001 g precision was utilized for the remaining distance tests, time tests, and dust simulant comparison tests.
3. Dust ortho-fabric by brushing 0.2 g of dust simulant into ortho-fabric and tap. This simulates the removal of excess simulant from spacesuit movement.
4. Measure mass of swatch with dust simulant added.
5. Testing setup adjusted for the specific experimental variables (i.e. Nozzle, spray apparatus) and simulant clipped onto the sample stand.
6. Seal the vacuum chamber and start the vacuum pump until the chamber has reached P_{gauge} = -0.920 bar.
7. Precool LN2 line until liquid is venting out of drainage valve.
8. Spray LN2 into the chamber until desired pressure level or application time is reached.
9. Close main valve on the LN2 dewar and shut off vacuum pump.
10. Release the vacuum and safely remove the test swatch.
11. Measure mass of washed ortho-fabric swatch.
12. Calculate the mass fraction of removal.

Testing best practices included:

- Perform a minimum of 3 trials for each treatment.
- Precool liquid cryogen transfer line by starting cryogen flow once P_{gauge} = -0.850 bar
- Ensure all ortho-fabric preparation areas are clean to prevent swatch contamination.
- Prioritize safety to minimize dust simulant exposure, risk of asphyxiation, and cryogenic burns.

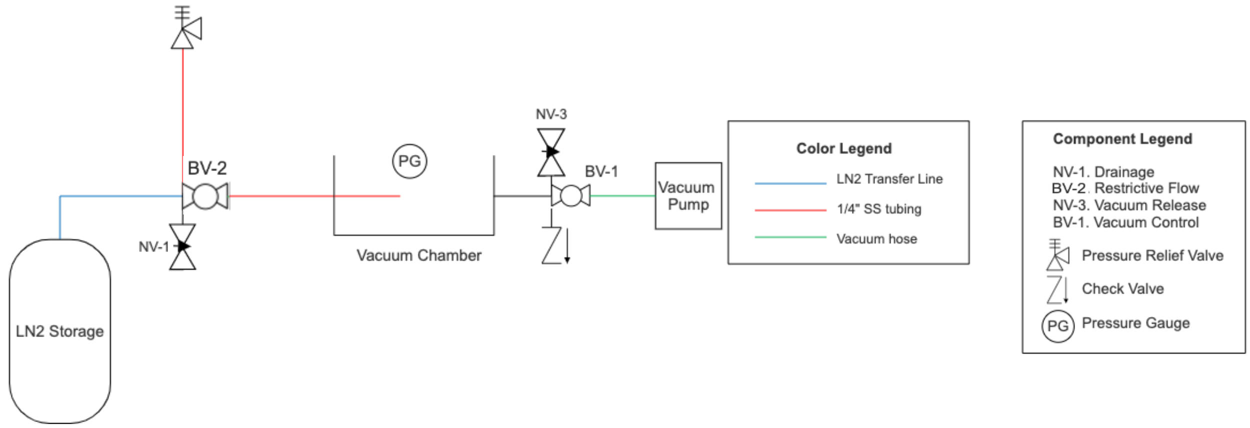

Figure 9: Labelled diagram of the Vacuum testing setup

5.4 Vacuum Results

Vacuum tests investigated whether pressure affected cleaning efficacy and allowed for testing of a similar system as the proposed airlock pressurization system. Tests were conducted in a modified vacuum chamber connected to a LN2 dewar. Variables changed include: amount of LN2 applied, time, nozzle type, and suit simulant viability. The vacuum data suggested that the liquid cryogen sprayer data is still valid in a vacuum and more realistic spray conditions. Further, the removal appears to be even higher inside the vacuum system than from the liquid cryogen sprayer. Removal of 98.38% of particles was found given the recommended parameters, with 95.85% removal of particles less than 10 µm.

Similar statistical analysis was applied to vacuum testing as described in Section 5.2, Student's t-distribution was utilized, and assessment of data viability was applied from liquid cryogen sprayer results. The same estimation process was used to estimate cleaning of particles less than 10 µm in size.

Testing was initially conducted to verify system performance and to attempt to determine cleaning method. One remarkable initial result is that even with cleaning of less than 1 second, 93.69% of dust was removed. Visually, the dusted swatch appeared to be cleaned instantaneously, or in a "snap", hence the name snap cleaning. In order to allow liquid to be sprayed into the vacuum chamber, the LN2 line needs to be cooled to cryogenic temperatures, or else the liquid will boil, and gas will be sprayed. Testing conducted without precooling indicated only 60.44% removal. This value likely corresponds to the cleaning due to gas flow, not liquid, and is similar to the cleaning observed outside the visibly cleaned area. This also indicates that liquid is likely at least part of the phenomena causing cleaning. The cleaning method was unable to be fully determined, although the results appear consistent with what is described by the use of liquid nitrogen for spray cooling [21]. The highest cleaning appears to be closest to the center of the spray with Leidenfrost droplet transport outside that spray area and nitrogen gas coverage beyond the film boiling region.

The results from liquid cryogen sprayer testing on suit simulants were verified. The difference between PBI Max LP Ortho-fabric and Black Aramid Kevlar Fabric was not statistically significant ($p = 0.231$). One swatch of NASA Spacesuit fabric was analyzed and demonstrated slightly lower, though similar results. Variability has been present in all tests, so this difference is not statistically significant. The NASA Spacesuit fabric did appear to lose some "powder" that had accrued on the surface that was present when delivered to the HYPER-Borea team. It is unknown whether this "powder" was characteristic of the spacesuit, or something added later. Relevant vacuum testing results are presented below in Table 5.

Table 5. Vacuum Testing Results

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

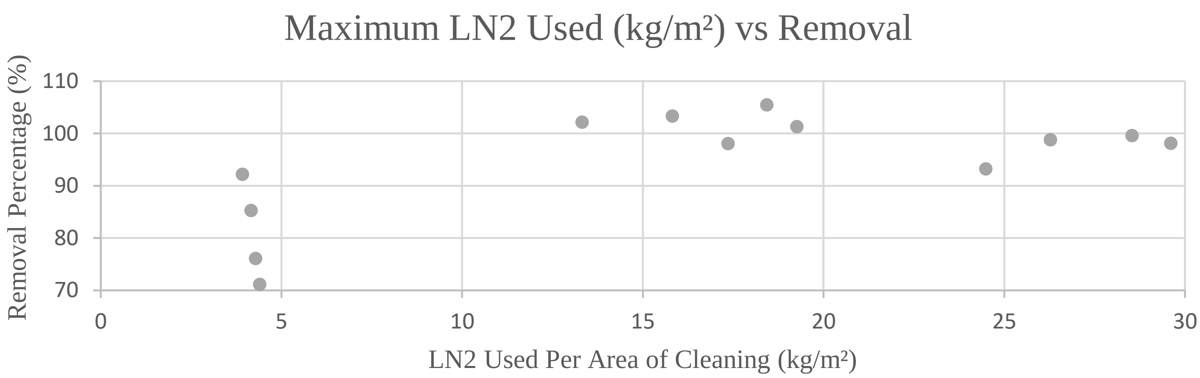

Figure 10: *Lunar dust simulant removal mass (%) versus liquid nitrogen applied (kg/m²) at an orthogonal angle of inclination in a vacuum chamber. Unlike previous figures, individual data points are presented, hence the high uncertainty. Testing issues render the individual removal values inaccurate.*

To examine the possible synergies of this method between space suit cleaning and airlock pressurization, calculations were performed with data gathered during vacuum testing. Using the ideal gas law, the pressure change measured in the system, and the volume of the vacuum, LN2 usage was estimated. Difficulties with installing a thermocouple in the vacuum system prohibited measuring temperature, so a range of temperatures was utilized, from the triple point of nitrogen up to room temperature. Using ImageJ software, the area of the highest cleaning was visually found to be approximately 49.54 cm^2, with a Student's-T distribution 95% confidence interval lower bound at 40.28 cm^2. That was used to normalize the amount of LN2 added. While the amount of LN2 needed to clean varied, it was found that above 13 kg/m^2 of LN2 added, cleaning was a maximum. This indicates around 13 kg of LN2 to fully clean a spacesuit with 1 m^2 surface area as is estimated [8]. This value could be as low as 2kg/m^2, given uncertainty in LN2 usage calculations. Therefore, this method appears synergistic with pressurizing a lunar airlock. Comparing the amount of LN2 added with removal identifies multiple potential trends. The maximum possible amount of LN2 needed was conservatively used in the below estimations. The removal appears to happen in 2 phases, one with limited, but rapidly increasing removal and one with high levels of removal consistent with other vacuum testing results as demonstrated in *Figure 10* above.

Schlieren analysis of the spray was performed to determine the cleaning mechanism for the nitrogen spray in a vacuum chamber. As shown in Figure 11, there is no clear liquid-vapor or vapor-gas boundary present, only very turbulent flow. Based on the position of the schlieren mirror and the nitrogen application nozzle, it is difficult to conclusively determine the state of the nitrogen when dusting occurs. However, if the spray behaves similarly to n-heptane, the cleaning is likely due to either vapor or liquid, not gas [9]. This corroborates data found for compressed air cleaning and no-pre-cool vacuum cleaning where removal percentages ranged from 60%-70%.

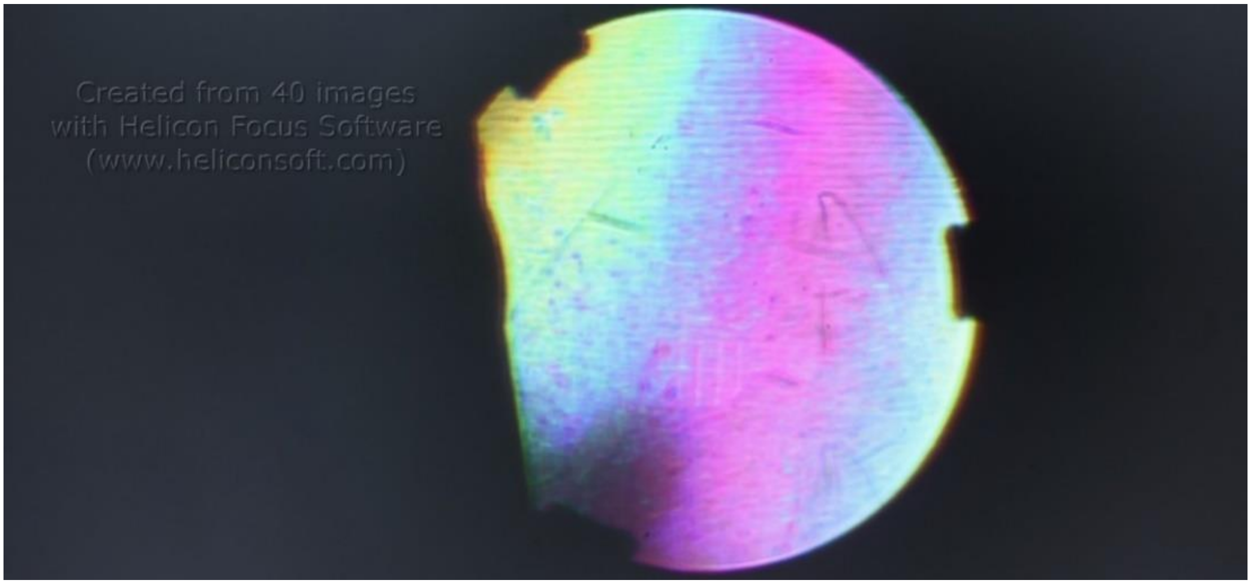

Figure 11: A stack of 40 Schlieren images of the nitrogen spray (on right) applied to an ortho-fabric sample (on left) collected at 60 Hz at 1080p through 1.5" acrylic with a Digital Single-Lens Reflex Camera

As revealed by t-testing, the flat nozzle in the vacuum demonstrates statistically significant additional removal when compared to the liquid cryogen sprayer system (p value = 0.0050). This indicates that not only do results from liquid cryogen sprayer testing remain applicable, but that there is improved cleaning under simulated vacuum and airlock pressurizing conditions. This cleaning corresponds to 95.85% removal of particles less than 10 µm, significantly higher than the benchmark of 90% removal at 10 µm.

Vacuum Results Summary

The variables tested in this section were the amount of LN2, time of application, nozzle type, and suit simulant viability. Our tests proved that the use of a liquid nitrogen sprayer is still viable within a vacuum, with a removal percent increasing to 95.85% for particles under 10 µm, and a 98.38% removal overall. In order to obtain the best results, the LN2 line, from the LN2 Dewar to the vacuum, has to be precooled. The absence of precooling results in a lunar dust removal of about 60.44%. Additionally, verification tests were performed on each of the suit simulants and our data showed that the difference in cleaning between them was not statistically significant. Using the data collected for lunar dust simulant removal, synergies between space suit cleaning and airlock pressurization were found. The highest area of cleaning was found to be approximately 49.54 cm^2, this helped to inform our calculations for amount of LN2 added during cleaning. It was determined that with 13 kg/m^2 of LN2 added cleaning was at a max, however this value could vary and be as low as 2 kg/m^2 due to uncertainties in calculations. It should also be noted that this maximum mass value remains less than ½ the mass of air required to pressurize a typical airlock.

5.5 1/6 Scale Astronaut Procedure

Tests followed Vacuum Procedure (see section 5.3) with the modification of a spray bar replacing the nozzle inside the vacuum chamber. The initial spray bar cleaning verification results used samples 4"x12" and 2"x12" to find the optimum sample size for a burst spray of LN2 from the spray bar. For 1/6 scale astronaut testing, further modifications to the testing setup were made including construction of an acrylic stand to support the scale astronaut. The 1/6 scale astronaut suit was constructed based on multiple spacesuit designs [10]. Layers of these suits were simplified and scaled, detailed in Figure 12. These suits were adapted and scaled down to fit our 1/6 scale astronaut, named Rosie the Coug-monaut.

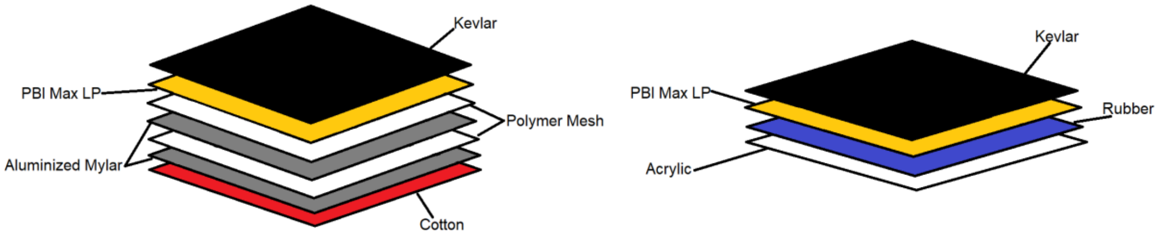

Figure 12: 1/6 scale astronaut suit (left) and helmet(right) layers used in model construction

5.6 Scale System Results

5.6.1 Spray Bar

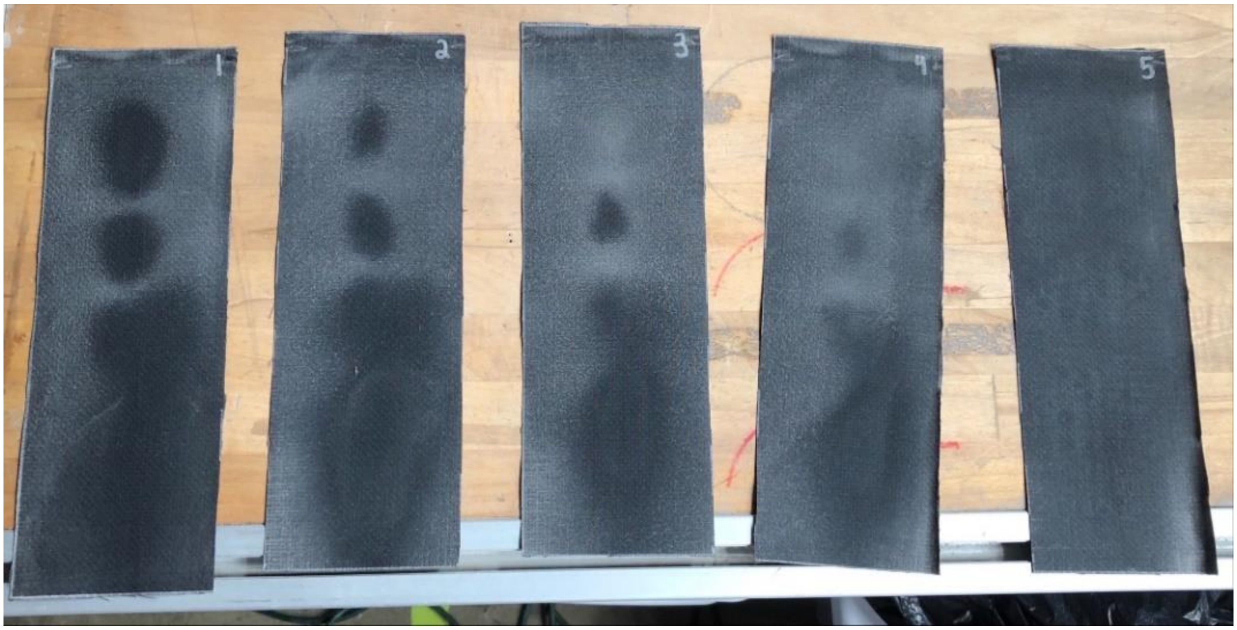

Figure 13: Spray bar cleaning of 4"x12" swatches, #1-4 for 10 seconds, #5 for <1 second

Figure 14: Spray bar manifold with flat nozzles.

The spray bar prototype was designed and built to increase the system to TRL 5 for testing with a scaled astronaut. Removal of lunar dust simulant from the above swatches ranges from 85.32% - 90.62% by mass. This cleaning involved only fully cleaning portions of the simulants, as shown visually in *Figure 13*. The high levels of cleaning are likely from cleaning outside the direct impact area, cleaned by a different, less effective mechanism. Swatches 1-4 were cleaned for 10 seconds and swatch 5 was "snap" cleaned. The spray from the nozzle is irregular due to LN2 boiloff. The top nozzles are spraying nitrogen gas or vapor while the bottom nozzles spray liquid. This can be mitigated when the system is run outside of the vacuum chamber with uniform spray achieved out of all nozzles. These patterns are especially prevalent with this system due to small chamber size, vacuum pump type, the lack of optimization of nozzle diameter, pipe size, and system heating and cooling cycles causing significant spray nonconformity. Further testing is needed to optimize the factors above and account for the difference in spray sizes from the spray bar, which could be achieved with a higher fidelity vacuum test system.

5.6.2 1/6 Scale Astronaut

Additional 1/6 scale prototype results are included in the verification demonstration video. Limited results are presented here in Figure 15 showing the feasibility of using this system in an environment indicative of a lunar airlock.

Figure 15: 1/6 scale astronaut after ashing (left) after ashing and treatment in a vacuum (center) after ashing, treatment in a vacuum, and spot treatment with a handheld liquid cryogen spraye (right).

A similar pattern of visible dust was observed on other treated cloth, including for 1/6 scale model cleaning. Some areas appeared coated in dust despite high mass removal percentage, indicating the need for further investigation of the cleaning mechanism behind cryogen dust mitigation.

While not providing any quantitative results, this testing demonstrated the viability of extrapolating data from Liquid Cryogen Sprayer and Vacuum testing onto 1/6 scale testing. With further development and optimization of the 1/6 scale spray bar, we would anticipate similar results to those described previously in the sections entitled Liquid Cryogen Sprayer and Vacuum Testing data.

Scale System Results Summary

Final steps included the testing of our prototype spray bar system as well as a test on a 1/6 scale astronaut. Although there was still visible ash on the swatches after cleaning, the spray bar system removed between 85.32% - 90.62% of applied ash. The large variation in our results, seen in *Figure* 13, is due to irregularities in LN2 boil off. Further testing is needed to verify percent removals and to quantify the effect of the limitations of our set up such as lack of optimization of nozzle diameter, vacuum pump type, small chamber size, etc. (full list of limitations listed above in 5.6.1). With only one 1/6 scale astronaut to test our data is limited. However, as shown in *Figure 15*, our prototype system is potentially viable for an environment similar to that of an airlock in the lunar habitat. Further modeling and optimization of the spray bar is needed to identify why there are spots of high and low removal on the 1/6 scale astronaut.

5.7 Modelling Results

Computational modelling intending to complement experimental results was conducted of liquid nitrogen on room-temperature surfaces. We cannot easily test the effects of reduced gravity in experiments. Nor can we investigate the mechanisms of cleaning, which are not yet well-understood, to good resolution. By using Computational Fluid Dynamics (CFD), these factors can be investigated. Gravity can be easily changed, particle paths can be followed, and even electrical charge can be included. It would also give future researchers the ability to investigate more complicated systems.

For current CFD software to model a relevant scenario, multiple assumptions must be applied that significantly reduce the fidelity of the results. The simulation also needs to be unsteady, include two-phase flow, have a phase change reaction, model dust particles, and include a complicated and uneven cloth surface with surface tension effects. It might also need to account for capillary effects of individual threads in the cloth and electrostatic effects of the dust. For non-horizontal surfaces, we would also need to test how liquid nitrogen rolls down slopes, such as with a moving reference frame. Ultimately, we were able to model a boiling liquid nitrogen droplet on a solid, horizontal surface. It forms a vapor layer below and the droplet will even bounce if dropped from sufficient height. The work and results are described below, to assist future investigators in troubleshooting and in understanding the problem.

Modelling used Siemens' StarCCM+ (finite volume) software [11] because of the considerable number of built-in features and team familiarity with the software. The model was set as unsteady (with a time step of 1e-5 seconds (10 microseconds) with up to 5 inner iterations per step. Larger time steps caused spikes in mass residual (mass was inexplicably lost or gained). An axisymmetric (2-Dimensional) model was used because we assume rotational symmetry and this allows rapid troubleshooting, but this prohibits modeling non-horizontal surfaces and dust movement. Gas properties change based off both temperature and pressure, so instead of parametric functions lookup tables were generated in Engineering Equation Solver [12] for use in StarCCM+.

The Results are close to what would be expected from literature. The steady droplet forms a depressed sphere and holds itself off of the surface on a cushion of boiloff gas [13]. The droplet bounces when dropped from a height [14]. But gas and liquid mix over a large gradient instead of maintaining separation at a surface. This should not be the case. Either gas is dissolving into the liquid, or the liquid is boiling while inside the droplet and failing to separate from the liquid. See Figure 16, of the density at 0.1 seconds into the simulation. Density should show a sharp gradient from 800kg/m^3 to 5kg/m^3 between saturated liquid and vapor. But instead, there is a wide gradient from high to low density because vapor and liquid phases fail to separate.

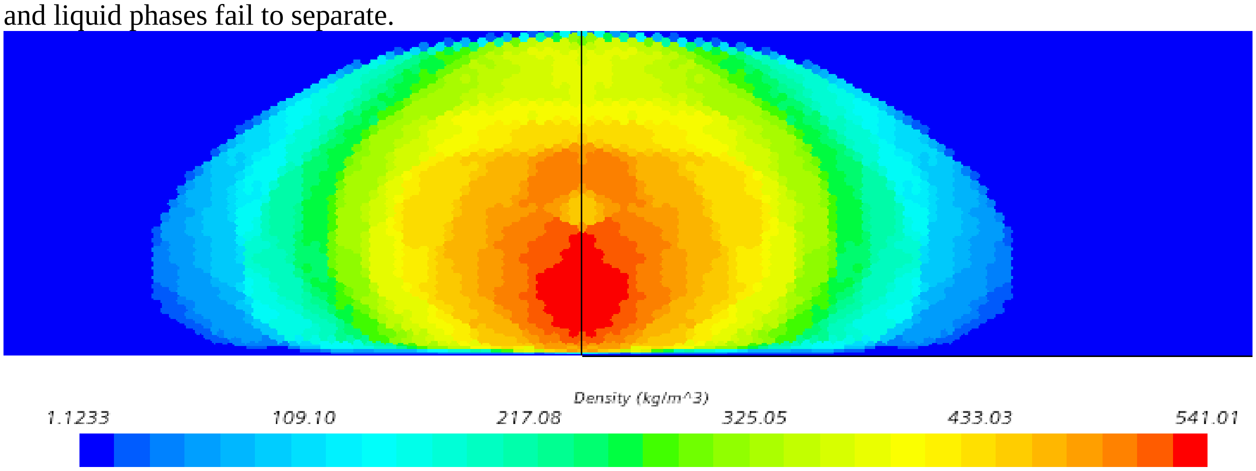

Figure 16: Density-scene of axisymmetric liquid nitrogen droplet on hot (300K surface) from an initial 1 mm radius droplet under earth gravity and standard pressure. Simulated in StarCCM+.

The heat transfer rate at the end of the simulation (after 0.1 seconds) came out to be 0.17 W (over one radian of rotation). If the surface area is taken to be over the initial radius of the droplet (1.0mm), which is roughly the final area of the droplet near to the hot surface, then the heat flux ends up being 340,000 W/m^2 at the end of the simulation. This is significantly different from 30,000 W/m^2, given in literature [15] [16] [17] [18]. However, literature heat fluxes used a pool (large surface) of boiling fluid, instead of a single droplet. It is known that the geometry of the heated surface significantly changes the heat flux, so it is reasonable to assume that a droplet will have a different heat flux than a pool [17] [18].

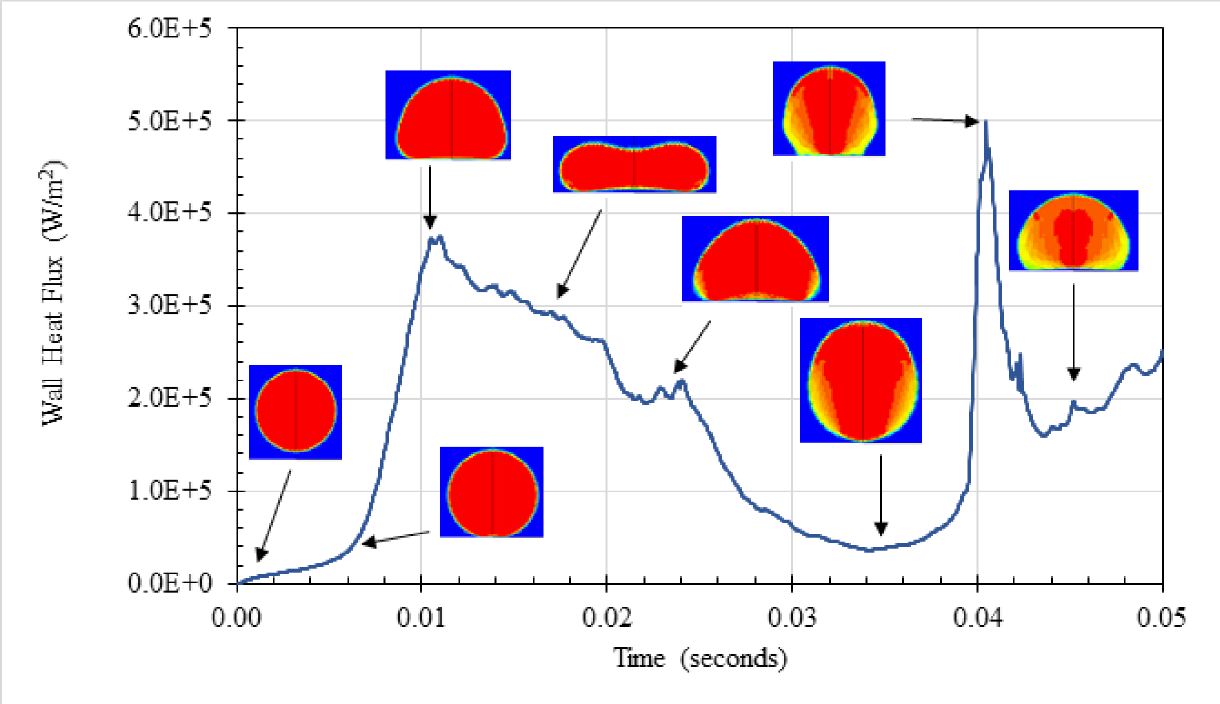

Figure 17: Droplet snapshots of density figure over heat flux (in W/m^2) released from 300K surface when a 1 mm radius droplet of liquid nitrogen is dropped onto it under earth gravity and standard pressure. Simulated in StarCCM+. Surface area assumed constant 1 mm radius.

The amount of liquid in the entire simulation region was monitored. Initial mass was 0.541 mg. By the final time of 0.1 seconds, it decreased to 0.531 mg, an average decrease of 0.1 mg/s.

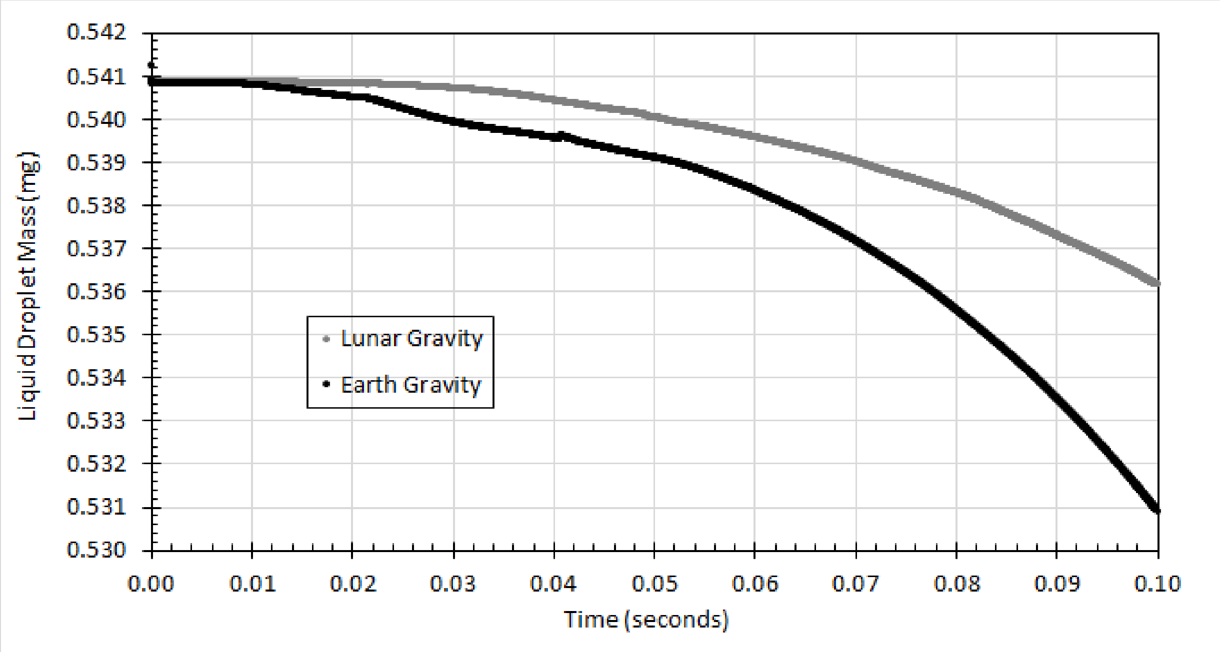

Figure 18: Liquid nitrogen droplet mass over time, after being dropped onto 300K surface in 100 kPa atmosphere with Earth gravity (black) and Lunar gravity (grey). Simulated in StarCCM+.

The simulation was set up to easily allow parameters such as gravity. Using lunar gravity (-1.62m/s^2) instead of earth gravity (-9.81m/s^2) decreased heat flux to 0.11 W after 0.1 seconds (a decrease of 35%) corresponding to 220,000 W/m^2. Literature suggests the heat flux in lunar gravity compared to earthly gravity is between 35% [16] and 40% [15] less. So, our percentage reduction in heat flux is quite close to literature. The initial peak heat transfer rate is decreased by about 50%, and the second highest peak is decreased by about 30% compared to earth gravity.

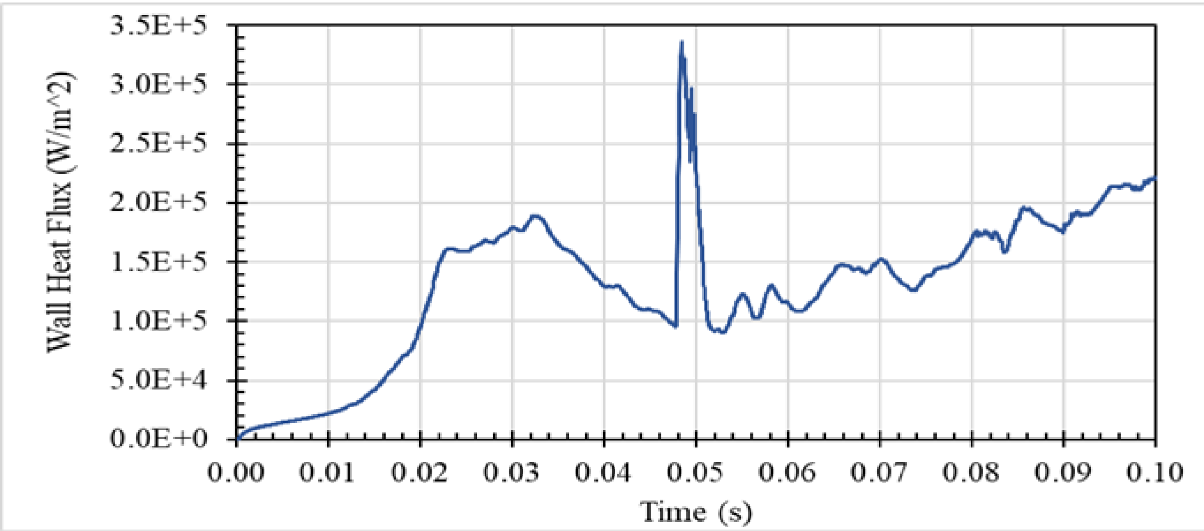

Figure 19: Heat flux (in W/m^2) released from 300K surface when a 1 mm radius droplet of liquid nitrogen is dropped onto it under lunar gravity and standard pressure. Simulated in StarCCM+. Surface area assumes constant 1 mm radius.

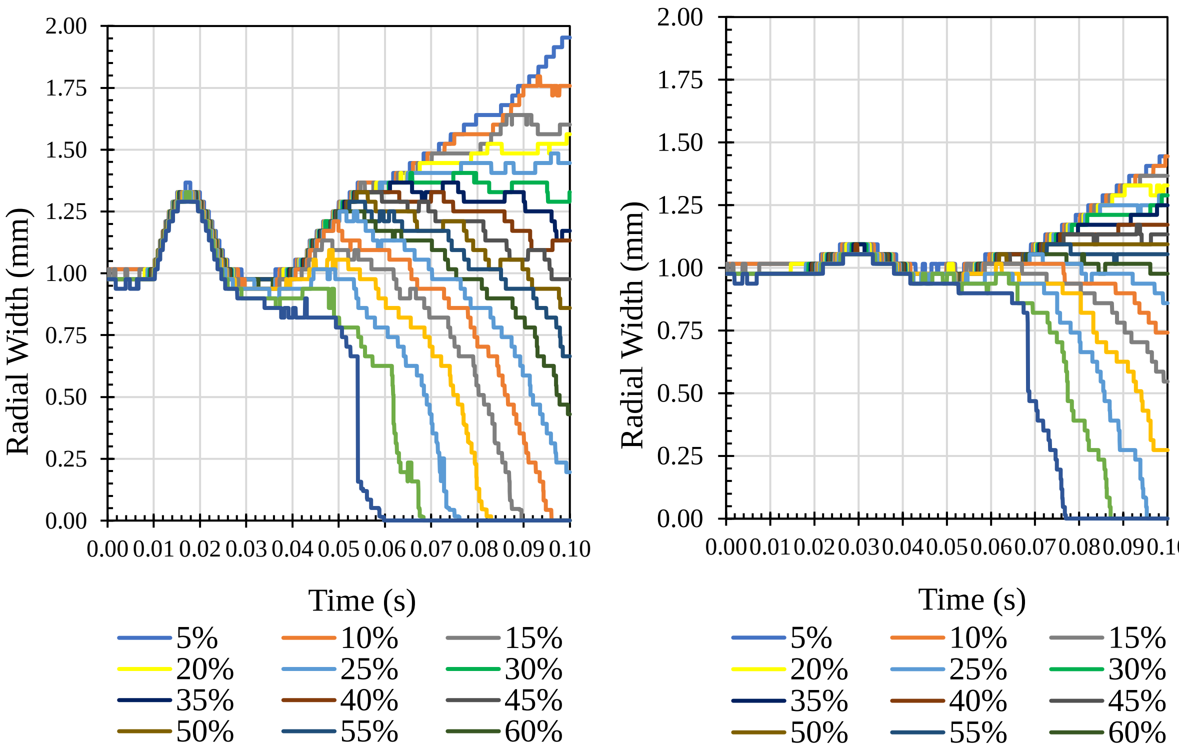

Figure 20: Maximum radius that has at least one cell of the given liquid fraction. Example: the yellow "20%" line shows that if the droplet is defined as having at least 20% liquid in the cell, then the final radius comes to about 1.55 mm. Earth gravity (left) and Lunar gravity (right). Simulated in StarCCM+.

Quantity of boiloff is about half that at lunar gravity compared to earth: a drop of 0.005 mg instead of 0.01 mg over the course of 0.1 s.

Unfortunately, experimental testing clearly showed that liquid nitrogen droplets do not levitate on the surface of the spacesuit simulant cloth material like on solid surfaces. Instead, they absorb into the fabric, possibly wicking into the threads. Our CFD model is currently incapable of simulating such physics. It took several months to develop, and to similarly develop it to include the motion of dust, the porous surface, and the capillary threads would take more time. There is no reason to expect that it cannot be done in the future (given time and resources) but it will not be completed for this project phase.

Modeling Results Summary

A computational fluid dynamic model of a Leidenfrost droplet was developed in StarCCM+. The liquid nitrogen droplet on a hot surface reacted as expected: it bounced and levitated on boiling gas. Lunar gravity showed horizontal-surface boiloff rates to be 40% lower than in earth gravity, so cleaning should still occur but may be slower. Further development will be required to maintain accurate phase boundaries and boiloff rates and to model effects of cleaning, including dust migration and surface permeability.

5.8 Simulating a Relevant Environment

Testing was completed up to a TRL level of 5 (details in 7. Path to Flight). The primary parameters considered from the DNSE were lunar dust and pressure.

Lunar dust and regolith were critical environmental factors simulated. Informed by the Design Specification for Natural Environments [1], the system was tested with a robust portfolio of simulants. These are the two highest fidelity commercially available simulants, Off Planet Research OPRH2N Near Highland simulant and Exolith Labs LHS-1 Lunar Dust simulant, and a WSU provided simulant, Mt. St. Helens ash. Their particle size distributions (see section 5.2) and particle morphologies make them good simulants of lunar dust [1,6, 19, 20, 21]. Similar results for particles less than 10 µm were found for all 3 simulants (see section 5.2). As documented in a presentation at the 10th Lunar Surface Science Workshop and in previous documents given to the BIG Idea team, Mt. St. Helens ash is a medium fidelity simulant [19] [20][21]. This is due to high similarity in the critical parameters of particle size distribution and particle morphology with other similarities in minerology and agglutinate presence (demonstrated by X-ray Computed Tomography) [1,6,20,21]. Both commercial simulants were reviewed by the NASA BIG Idea team, while Mt. St. Helens ash was successfully reviewed by several industry, academia, government scientists, and as approved by NASA BIG Idea Challenge Judges in mid-point report.

The spacesuit ortho-fabric material chosen was a Black Aramid Kevlar. Results on this material were compared with PBI Max LP Ortho-fabric from PBI Performance Products for Liquid Cryogen Sprayer and Vacuum testing phases. Additionally, the BIG Idea Challenge team secured scrap material from spacesuit construction and sent it to the HYPER-Borea Team. Vacuum testing results were verified on these materials. Additionally, microscopy comparisons of the Black Aramid Kevlar and Spacesuit material showed many similarities. Results between the spacesuit simulants and the spacesuit material are similar with cleaning efficacy being slightly lower on the Kevlar, indicating that Kevlar is a similar-enough, if slightly worse spacesuit ortho-fabric testing material.

The lunar surface has a tenuous atmosphere and near-perfect vacuum on the surface. Testing was done down to 0.080 bar pressure. While this is not high vacuum, it brought the liquid nitrogen below its triple point when spraying while maintaining high system efficacy, indicating that the system will work at high vacuum levels, including below the triple point of nitrogen.

Of note, DSNE considerations not accounted for by this testing include lunar gravity and the lunar ionizing radiation environment. Lunar gravity replication was completed minimally with CFD, but experimental verification of the results is lacking. The charged environment was not replicated due to time constraints.

5.9 Further Testing and Recommendations

All testing needed for completion of the project scope was finished, including TRL 2 verification by pouring liquid nitrogen, parametric optimization of handheld cryogen sprayer to prove the cleaning efficacy threshold of >90% of particles less than 10 µm removed (TRL 3), vacuum chamber (relevant environment) testing (TRL 4), testing of a 1/6 scale astronaut in a vacuum (TRL 5), and efficacy verification with multiple particle size distributions and spacesuit simulants. Additional completed testing beyond our project scope includes verification of dust removal from surface-exposed substrates and polymers as well as testing of the effects of multiple washes on removal efficacy.

Due to schedule and budget constraints, some tests outside this project scope are left for further research. This should include a more detailed investigation of the effect of multiple washes on dust removal and whether this adversely affects spacesuit material, tests of removal of electrically charged dust particles, and development of a full-sized array in a large vacuum chamber. Additional exploration of nozzle size, shape, and distance may improve dust removal while limiting dust aerosolization and may narrow down the operational limits of cryogenic spray cleaning. With the current experiments, a maximum range of 900 mm was determined, where droplets did not consistently reach the target. Furthermore, low-gravity testing could be done using hyperbolic aircraft flight, on a so-called "vomit comet", or a suborbital rocket, such as Blue Origin's New Shepard.

Overall, this research has found no significant barriers to implementing liquid cryogen dusting for lunar dust mitigation.

5.10 Challenges

While the project came to a positive resolution, challenges include but are not limited to:

- Reproducibility of cryogen sprayer testing was challenging due to daily variation in the data which we believe resulted from changes in atmospheric conditions (the testing location does not have a Heating Ventilating and Air Conditioning HVAC system for moisture control) and the state of liquid nitrogen within the storage dewar.
- For low mass tests such as those conducted for Smart Materials Solutions, we occasionally had removal percentages over 100%, mostly due to statistical variation, but also sometimes due to other confounding factors.
- Funding delays outside of our institution and programmatic approval challenges were frequent. These led to changes in the project scope and schedule as well as work-arounds to continue the research.
- Time constraints limited the use of Computational Fluid Dynamics (CFD) modeling. This CFD modelling to investigate the effect of gravity on the cleaning technique proved significantly more difficult than expected. The time constraints of this project proved too large for full CFD recommendations.
- Time constraints and the number of available personnel additionally limited the scope of some verification testing of the Cryogen Sprayer, Vacuum, and Scale System.
- Finally, there are unknowns in the precise distribution of the cleaning mechanisms between liquid, vapor, and gas impingement.

As a result of the above challenges as well as unexpected modelling difficulties, some testing remains incomplete. In order to advance this technology, further verification of results in reduced gravity environments indicative of the Moon is required.

As mentioned above, a challenge is holding atmospheric conditions constant. With all tests, the conditions in the room affected the boiloff rate of liquid nitrogen, leading to slight variations in the data from day-to-day. In addition, it was not feasible in the schedule constraints to outfit the vacuum chamber with a thermocouple, making temperature measurement difficult, adding uncertainty to the amount of LN2 added.

Another unique challenge for the technology stems from the nature of liquid nitrogen spray. Initially, we believed the spray worked primarily due to film boiling of liquid cryogens (i.e., the Leidenfrost Effect). We now have reason to believe there are other mechanisms at work, specifically similar to the mechanism behind spray cooling [22]. This uncertainty made certain parts of the project difficult, especially computational modelling. A full understanding of the physical cleaning process is recommended before use on Extra-Vehicular Activity suits.

Additionally, there were several programmatic challenges including delays in money disbursement through WSU and the University of Washington, the primary project Principal Investigator going on professional leave, supply chain delays due to the COVID-19 pandemic, and a new university financial and personnel management system. Phase 2 funds were unable to be dispersed from the Space Grant Consortium until late October, causing significant budgetary issues and delays. Funds were supposed to be dispersed in early July, and frequent, persistent communication did not alleviate the delay. Furthermore, the funds were dispersed in a particularly difficult manner. If more information on delays is of interest, please contact the project principle investigators.

6. SAFETY PLAN AND PROTOCOLS

Prior to performing tests, a thorough risk analysis was completed for each testing system. Before handling and testing with liquid nitrogen (LN2), each team member completed a detailed liquid nitrogen safety training in order to understand how to properly and safely handle LN2 as well as the potential hazards and appropriate emergency procedures. A risk matrix and accompanying safety plan and procedures were completed for TRL 3: Liquid Cryogen Sprayer testing. Prior to completing TRL 4-5: Environmental Testing in a Vacuum, a HAZOP (Hazard and Operability Study) was completed to assess the system's potential hazards and put in place safeguards to lower the risk level of the system. The HAZOP followed the process of determining relevant deviations for process section types followed by evaluating the causes, consequences, recommendations, and safeguards for each potential deviation of each system block. Procedures were then written in accordance with recommendations and safeguards resulting from the HAZOP. The associated safety plan was included with the Mid-Project Report. Due to page-count limits, it is not included here. When performing Liquid Cryogen Sprayer, Vacuum, and Scale System tests, team members closely followed the safety plan and procedures. As a result, there were no near misses and no safety related issues associated with this project. However, many of the funding and supply chain delays listed in the safety plan for this project did arise.

7. PATH-TO-FLIGHT

Current testing places liquid cryogen dusting at a TRL of 5, potentially 6. TRL 5 is defined as component validation in the relevant environment. TRL 6 is defined as system model or prototype demonstration in a relevant environment. As shown in the testing data above, system components have been validated in the relevant environment of a vacuum chamber. In addition, a scale model of the system was tested in a vacuum environment. Furthermore, this scale model of the system was tested on a scale astronaut, proving system and technology efficacy in a relevant environment, arguably raising the TRL of the HYPER-Borea Dust Mitigation System to 6, albeit lacking a verified numerical model.

Planned further testing will investigate the impact of lunar dust on spacesuit materials. This will involve investigating lunar dust saturation in the fabric and degradation of fabric and visor materials via abrasion. These results will give us a better understanding of how the liquid cryogen lunar dust mitigation method interacts with spacesuits.

CFD or low gravity testing, such as through the Space Technology Mission Directorate Flight Opportunities program, is required to advance this lunar dust solution. We also recommend testing with higher vacuum testing facilities and facilities that simulate solar wind to further verify Scale System results.

Additionally, due to the high velocity of the liquid being used, this solution should be investigated for applications on the lunar surface such as cleaning habitat or solar panel substrate surfaces. These solutions will not have the synchronicity of providing airlock pressurization but could be an effective tool for lunar dust mitigation and thus should be investigated. Preliminary results on patterned substrates provided by SMS are briefly discussed in Section 5.2.4.

Liquid nitrogen is a consumable of this system when not recycled. We suggest having a method for nitrogen liquefaction on the lunar surface given the lower temperature there. This will decrease the energy required per system wash and present a way to recycle nitrogen from the atmosphere of the lunar habitat.

In addition, we suggest investigation of other spray bar shapes, especially a curved spray bar, dust collection systems to be placed beneath the astronaut during washing, and other dust mitigation solutions to be used in conjunction with the cryogen dust mitigation technology. On this note, we suggest having a coating or powder applied to the spacesuit surface in advance to system use on an EVA. This will saturate the spacesuit fibers which provide locations for lunar dust to aggregate.

The full system should be tested with simulated lunar gravity and solar wind particle charging to ensure the system remains highly effective in these conditions.

All components (except the hand-held liquid cryogen sprayer) need qualification in a full-scale system. Building a full-scale system and verifying existing results is the primary design modification required to make this technology flight ready.

After component verification at a full-scale, the technology is ready for testing on an EVA suit terrestrially. This testing is recommended to ensure all predictions of material behavior are accurate.

The team has presented the concept of testing this technology in Blue Origin's New Shepard rocket under reduced gravity conditions. Blue Origin is open to further discussions on this topic.

Finally, the technology can be flight ready for use on the Moon by 2026.

8. RESULTS/CONCLUSIONS

The HYPER-Borea Dust Mitigation System can be a highly effective lunar dust mitigation tool on lunar missions. Extensive testing demonstrated technology efficacy above the benchmark of 90% removal of particles below 10 μm, in a simulated lunar airlock. Removal of lunar dust at this high level is necessary due to the challenges the dust causes.

Liquid cryogen dusting utilizes cryogenic droplets to transport dust and remove it from a surface. This effect is harnessed through a cryogen spray bar and shower with a handheld liquid cryogen sprayer for spot treatment. Beyond high removal of lunar dust, this system offers additional benefits. Liquid cryogen dusting has minimal power requirements and no consumables when nitrogen is recycled. This solution also provides synergistic opportunity between dust mitigation and airlock pressurization, as presented in above calculations. This system is not toxic or flammable. Spot treatment using a handheld liquid cryogen sprayer allows for cleaning in areas that other cleaning methods may have difficulty reaching. Furthermore, this system requires few parts, is relatively lightweight and transportable, and fits within planned Lunar and Martian architecture.

Verification testing established optimum parameters, elucidated important variables, and estimated efficacy for this system. Mass removal tests, accompanied by significant microscopy and material characterization, show Mt. St. Helens ash is a medium-fidelity lunar dust simulant and Kevlar-Nomex blend fabric is a medium-fidelity outer-layer spacesuit simulant. For all testing levels, removal efficacy was verified against industry standard fabrics.

The testing process and results moving from TRL 2 to TRL 5 were:

- Initial testing investigated various cleaning methods. Liquid nitrogen spray revealed significantly higher cleaning. 91.99% removal from liquid nitrogen spray exceeded alternate treatment values of 73.77% for a liquid nitrogen pour, and 69.24% for a compressed air treatment.
- Testing investigated a liquid cryogen sprayer. Results showed that the technology was viable when used in a terrestrial environment. Microscopy revealed a large difference in the amount of lunar dust simulant present on the swatches of fabric before and after cleaning. Spectroscopy coupled with particle size distribution analysis indicated cleaning of greater than 90% of particles below 10 μm in size, with primarily particles less than 3 μm in size remaining. Specific recommendations

from liquid cryogen sprayer testing include: 1) spray distance of 40 cm, 2) angle of inclination of ≤90 degrees to the horizontal, and 3) application time of 20-40 seconds. Additional tests revealed minimal substrate surface damage from this cleaning method.

- Vacuum testing allowed for further technology refinement and verification. Removal by mass was found to be 98.38%, corresponding to roughly 95.85% removal of particles below 10 µm. The system appeared to work similar or better in a relevant environment, including at low pressures, than it did terrestrially. Schlieren analysis appeared to show the cleaning is due to vapor or liquid, not gas. Preferable nozzle geometries and precooling processes were also found.
- Final testing observed a prototype spray bar system and 1/6 scale astronaut. These tests brought the system to a TRL of 5. Qualitative analysis of the 1/6 scale astronaut showed visually a mid-to-high level of cleaning. Several recommendations include: 1) inclusion of an additional handheld sprayer, 2) system optimization, 3) reduced gravity testing, and 4) verification of a corresponding numerical model of the removal process.

Computer modeling was also conducted, revealing key insights about cryogenic liquid droplets. There is significant work to pursue with these models, further system testing, and system construction to follow the path-to-flight for liquid cryogen dusting.

This technology is viable, with additional development, for use by 2026 during the NASA Artemis missions, helping ensure the United States returns to the moon to stay. Liquid cryogen dusting has high lunar dust removal, synergy with airlock pressurization, nontoxic characteristics, low material and power requirements, simple path-to-flight, and potential application for lunar dust removal needs beyond the spacesuit. Thus, liquid cryogen dusting is a strong contender for future research and application during NASA's upcoming missions.

9. TIMELINE

Project Goal: To develop lunar dust mitigation technology using the Leidenfrost effect for the NASA Artemis missions.

	Major Objectives and Tasks	QT1			QT2			QT3			QT4		
		Jan-21	Feb-21	Mar-21	Apr-21	May-21	Jun-21	Jul-21	Aug-21	Sep-21	Oct-21	Nov-21	Dec-21
1	**Adhere to the BIG Idea Challenge Timeline**												
1.1	Teams are notified of their selection status	X											
1.2	Mid-Point Report					X	X						
1.3	Forum Registration and Hotel Reservations										N		
1.4	Technical Paper and Verification Demonstration										X		
1.5	Presentation and Digital Poster File											X	
1.6	2021 BIG Idea Forum											X	
2	**Experimental measurements of dust removal efficacy from simulated space suit materials with liquid nitrogen**												
2.1	Table of experimental measurements showing material vs removal percentage				X	X							
2.2	Table of experimental measurements showing angle of inclination vs removal percentage						X						
2.3	Table of experimental measurements showing drop height vs removal percentage						X						
2.4	Peer-reviewed journal publication documenting simulated lunar regolith removal efficacy								X				
3	**Computational modelling of the dust removal measurements to determine the optimal spray angle and impingement velocity**												
3.1	Verification of computational modelling code with experimental measurements								I				
3.2	Recommended impingement velocities								N				
3.3	Recommended spray angles								N				
3.4	Recommended number and distribution of spray nozzles									I			
3.5	Peer-reviewed journal publication documenting computational fluid dynamics modelling code compared to experimental measurements.										I		*X*
4	**Demonstrate a 1/6 scaled prototype of the HYPER-Borea Dust Mitigation System with a model EVA suit covered in regolith simulant.**												
4.1	Washing ash (dust simulant) from Ortho-Fabric (suit simulant) with LN2 in vacuum								X				
4.2	Select high-fidelity spacesuit and lunar regolith simulant					X							
4.3	Construct 1/6 scale system prototype for further testing									X			
4.4	1/6 scale system prototype testing with LN2 wash									X			

Task
Milestone
Go/NoGo

X marks full completion of a task
I marks partial completion of a task
N marks no longer viable
X marks expected full completion

10. Budget Summary

PI Name(s): Jacob Leachman, John McCloy, Konstantin Matveev								
Washington State Unversity								
Leidenfrost Dusting as a Novel Tool for Lunar Dust		**Phase 1 - Budgetted**	**Phase 1 - Actual**	**Phase 2 - Budgetted**	**Phase 2 - Actual**	**TOTAL - Budgetted**	**TOTAL - Actual**	**TOTAL - Difference**
	Start Date	**01/29/21**	**01/29/21**	**07/01/21**	**07/01/21**	**01/29/21**	**01/29/21**	**01/29/21**
Agency Name:	**End Date**	**06/30/21**	**06/30/21**	**11/30/21**	**11/30/21**	**11/30/21**	**11/30/21**	**11/30/21**
Senior Personal Salaries								
	Total Salary	-		-		-		
Other Personnel Salaries and Wages								
	Total Salary	-		-		-		
	Total Wages	21,483	21,984	23,877	33,449	45,360	55,433	-10072.97
	Total Salary & Wages	21,483	21,984	23,877	33,449	45,360	55,433	-10072.97
	Total Fringe Benefits	378	685	420	1,863	798	2,548	-1749.75
	Total Salaries, Wages and Fringe Benefits	**21,861**	**22,669**	**24,297**	**35,311**	**46,158**	**57,981**	**-11822.72**
Domestic Travel								
	Total Domestic Travel	-		**10,329**	**5,100**	**10,329**	**5,100**	**5229.00**
Materials and Supplies								
	Total Materials and Supplies	**12,893**	**6,602**	**7,107**	**3,851**	**20,000**	**10,453**	**9546.87**
Stipends								
	Total Stipends	-		-		-		**0.00**
Tuition								
	Total Tuition	-		-		-		**0.00**
Other Direct Costs								
	Other Direct Costs	**2,500**	**500**	**2,000**	**1,000**	4,500	**1,500**	**3000.00**
Total Direct Costs		**37,254**	**29,772**	**43,733**	**45,262**	**80,987**	**75,034**	**5953.15**
Base		37,254	29,772	43,733	45,262	80,987	75,034	5953.15
Host Univserity Overhead (F&A Rate):	**53%**	19,745	15,779	23,178	23,989	42,923	39,768	3155.17
Space Grant Administration Overhead (F&A Rate):	**0.0%**	-		-		-		
Total Indirect Costs		**19,745**	**15,779**	**23,178**	**23,989**	**42,923**	**39,768**	**3155.17**
Total Costs/Total Amount Requested		**56,999**	**45,551**	**66,911**	**69,251**	**123,910**	**114,802**	**9108.32**
		Estimated Maximum Potential Costs for Salaries, Verification Demonstration, and Lab Fees						

The major relevant expenditures for the project include:

- Student Wages and Benefits
- A professional video in lieu of in person conference attendance
- A new analytical balance
- Vacuum chamber parts and fittings
- Dental use cryogen sprayer device
- McMaster-Carr spray bar

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APPENDIX A: REFERENCES

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