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Investigating the Feasibility of Utilizing Carbon Nanotube Fibers for Spacesuit Dust Mitigation

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Historical data from the Apollo missions has compelled NASA to identify dust mitigation of spacesuits and other components as a critical path prior to sending humans on potential future lunar exploration missions. Several studies thus far have proposed passive and active countermeasures to address this challenge. However, these technologies have been primarily developed and proven for rigid surfaces such as solar cells and thermal radiators. Integration of these technologies for spacesuit dust mitigation has remained an open challenge due to the complexity of suit design.

Current research investigates novel methods to enhance integration of the Electrodynamic Dust Shield (EDS) concept for spacesuits. We leverage previously proven EDS concept developed by NASA for rigid surfaces and apply new techniques to integrate the technology into spacesuits to mitigate dust contamination. The study specifically examines the feasibility of utilizing Carbon Nanotube (CNT) yarns manufactured by Rice University as electrodes in spacesuit material. Proof of concept testing was conducted at NASA Kennedy Space Center using lunar regolith simulant to understand the feasibility of the proposed techniques for spacesuit application. Results from the experiments are detailed in this paper. Potential challenges of applying this technology for spacesuits are also identified.

Nomenclature

KSC	=	Kennedy Space Center
EVA	=	Extra Vehicular Activity
UND	=	University of North Dakota
PTFE	=	Polytetrafluoroethylene
AC	=	Alternating Current
V	=	Voltage applied
μm	=	microns/micrometers

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I. Introduction

SEVERAL anomalies encountered during the Apollo missions revealed the ability of lunar dust to rapidly degrade spacesuits and impact operations[1,2]. Post-flight investigations of the Apollo spacesuits revealed the deleterious effects of dust that abraded spacesuit materials (Figure 1.)[3]. Data from these missions has compelled NASA to identify dust mitigation as its critical path prior to sending humans on potential future lunar, and other planetary and asteroid exploration missions. A recent report published by NASA has also identified dust/particulate mitigation as high priority research for NASA[4]. For future long duration missions it is imperative that spacesuits (and all other systems) that may be exposed to planetary dust/regolith be designed for maintainability in dusty environments. Furthermore, designing suits to be durable would help maximize astronauts' operational time to meet mission objectives rather than having to spend time cleaning and maintaining suits.

Numerous solutions for dust mitigation have been proposed in literature using both active and passive methods. Most of these techniques were demonstrated for use on rigid surfaces such as solar panels, optical planes, glass structures and thermal radiators[5, 6]. However, applying these technologies for spacesuit dust removal has remained a challenge due to the complexity of suit design such as irregular contours of the suit, flexible structure of the soft areas of the suit, and Teflon coated spacesuit materials. Minimal research has been conducted to address the challenge of incorporating existing dust technologies into spacesuits.

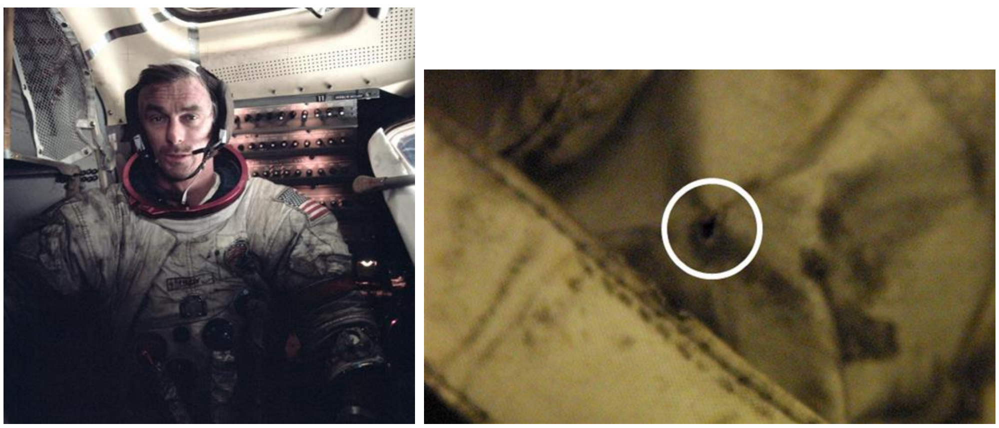


Figure 1.(Left) Gene Cernan during Apollo 17 with dust coated spacesuit after an Extra Vehicular Activity (EVA). (Right) Hole in the knee of Harrison Schmidt's spacesuit caused by abrasion due to lunar dust[7]

The focus of this research is to develop a spacesuit integrated dust mitigation technology leveraging proven active dust mitigation methods, while applying novel materials and techniques to overcome suit integration challenges. The research specifically addresses the technical and fabrication challenges of implementing Electrodynamic Dust Shield (EDS) active electrode technology into spacesuits by utilizing yarns made of Carbon nanotube (CNT) flexible fibers as electrodes.

We investigated proof of concepts of the new materials and techniques through experiments conducted at NASA Electrostatics and Surface Physics Laboratory at Kennedy Space Center (KSC), in both ambient and vacuum conditions. The primary objectives of the experiments presented in this paper are to investigate the feasibility and provide preliminary evaluation of the concepts. Secondary objectives of the experiments include understanding the challenges involved in utilizing these techniques for flight suit implementation and future direction for refining the implementation methods.

II. Technology Overview

A. Electrodynamic Dust Shield

EDS technology was introduced by NASA in the 1960s as the Electric Curtain concept[8]. This concept was further developed at the University of Tokyo in the 1970s and advanced by NASA and the University of Arkansas, specifically addressing dust removal on rigid surfaces[5]. EDS uses electrostatic and dielectrophoretic forces to carry dust particles off surfaces by generating a varying electric field which breaks the adhesive forces due to electrostatics. The shield contains a series of parallel electrodes through which an Alternating Current (AC) of voltage is applied that generates a travelling wave of electric field. This electric field repels the dust particles that travel along or against the direction of the wave, depending on the polarity and prevents further accumulation of dust. The electrodes can be excited by using a single or multi-phase AC voltage to remove charged and uncharged dust particles on the surface of the shield. Specific details on EDS are described in previous studies[5].

In the context of lunar dust particles, the lunar surface is exposed to constant high velocity micrometeoroid impacts, and steady bombardment by charged atomic particles from stars and the sun. These processes lead to electrostatic charge of the lunar dust particles. Additionally, the dryness of the lunar surface and low electrical conductivity effectively make the lunar soil an insulator, and conditions are conducive for these dust particles to hold the static charge developed[9]. The charged particles would have a tendency to adhere to surfaces and could readily coat surfaces soon becoming hazardous to spacesuits and operations including communication failure, discharge breakdown, and other electronic equipment failure etc.

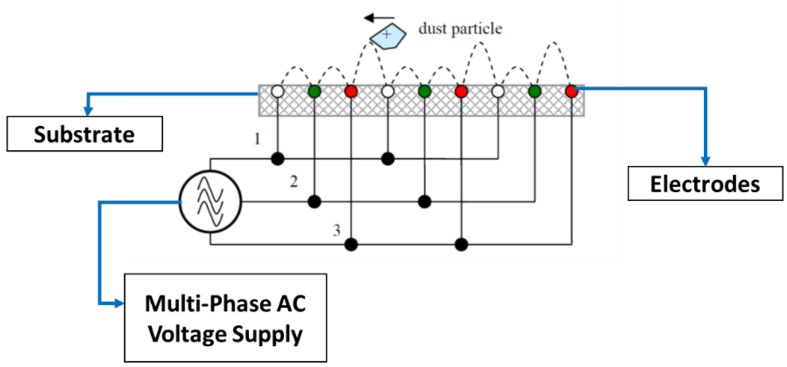


Figure 2. Electrodynamic Dust Shield concept by NASA, adapted from Ref 5. *Three-phase EDS is shown here.*

Several experiments were previously conducted to test the feasibility of the EDS concept demonstrating the high efficiency of the system for surface cleaning on solar panels, optical systems and thermal radiators as shown in Figure 3[5]. For example, in one of the experiments it was shown that when dust loading conditions using lunar dust simulant caused a set of solar cell performance to drop to 11–23% of the baseline performance, activating transparent EDS restored solar cell performance values to above 90%[5].

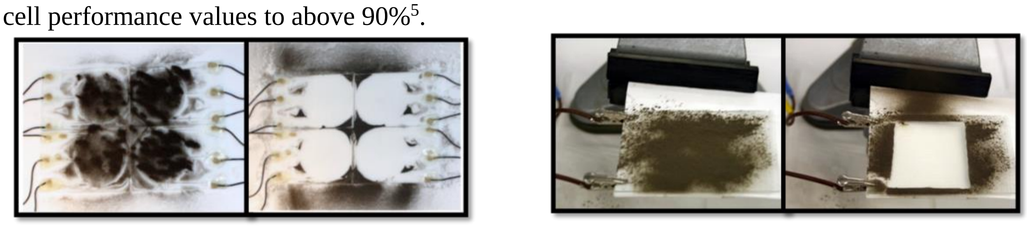


Figure 3. Demonstration of EDS feasibility on Optical surfaces (Left) and Glasses Surfaces (Right)[5]. *These pictures show the before and after EDS activation states of various rigid surfaces. The surfaces are able to repel dust when EDS is activated.*

1. *Feasibility of EDS for Spacesuits*

In spite of proof that EDS performs effectively as a dust mitigation strategy on rigid surfaces, further research is necessary to implement this technology into spacesuits. Initial efforts were made by the EDS research group at KSC to incorporate EDS into flexible structures such as a cotton fabric, but they were challenged by spacesuit fabrics[10]. The complexity of materials used in a spacesuit require new active materials and fabrication methods. This research addresses two specific challenges as described below that prevent the integration of EDS into spacesuits.

a. Electrode material selection

Current materials used as electrodes for EDS are Copper and Indium Tin Oxide. These metallic materials are challenged by fatigue breakage. When flexed, they often exhibit high cycle fatigue due to cyclic loading under repeated mechanical loads. In the context of spacesuits, suits undergo repeated motions that flex, bend, fold or twist suit materials, especially within the leg or arm portions demanding highly flexible and nearly fatigue-free electrode materials.

b. Applying electrodes to the spacesuit system

EDS electrodes are attached to dust prone surfaces which have so far been smooth and flat surfaces (solar panels, radiators) using a dielectric substrate. Traditional methods such as sputtering or ink jet printing have been used to adhere electrode wires to these surfaces. The challenges associated with spacesuits are their irregular contours and non-smooth surfaces. These challenges combined with the Teflon coated spacesuit material (example: beta cloth or orthofabric) that are exposed to dust are not conducive to directly adhering any electrodes to the surface of spacesuits. The spacesuit surfaces are not suitable for deposition of electrodes utilizing traditional methods and new fabrication techniques are required to integrate the EDS system for spacesuits.

B. Carbon nanotube Fibers

CNTs are a high performance technology breakthrough material with applications in nanotechnology, electronics, material science, optics etc. CNTs are an allotrope of carbon with a cylindrical structure with diameters on the order of 1 nanometer (10^{-9}) which were discovered in 1993[11].

CNTs are known for having exceptional properties of mechanical strength and stiffness, electrical and thermal conductivity, and low density (on the order of ~1g/cm^3, verses ~8.96 g/cm^3 for copper), making them ideal multifunctional materials that combine the best properties of polymers, carbon fibers, and metals[12]. While single molecule strength and conductivity of CNTs are far superior to most materials, translating these properties to a macroscopic scale has been a significant challenge. Handling CNTs with sufficient length, stiffness, and chemical inertness introduces major challenges in material processing. However, researchers at Rice University have invented a manufacturing process to continuously produce lightweight CNT fibers on the order of kilometers in length[13]. They have reported the properties of their fibers approaching the high specific strength of polymeric and carbon fibers, while also achieving high specific electrical conductivity of metals and specific thermal conductivity of graphite fibers.

The Ashby plots in figure 4 excerpted from Ref.12 show that the CNT fibers produced by solid-state spinning methods fall in the high strength, low-conductivity region, while metals are in a high conductivity, low strength region. Even though the values shown for electrical conductivity for the CNT fibers are lower than copper and other known highly conductive materials (5 +/- 0.5 MS/m for CNT when compared to 59 MS/m of copper), the advantage of CNTs is their low density and their flexibility providing high resilience to fatigue.

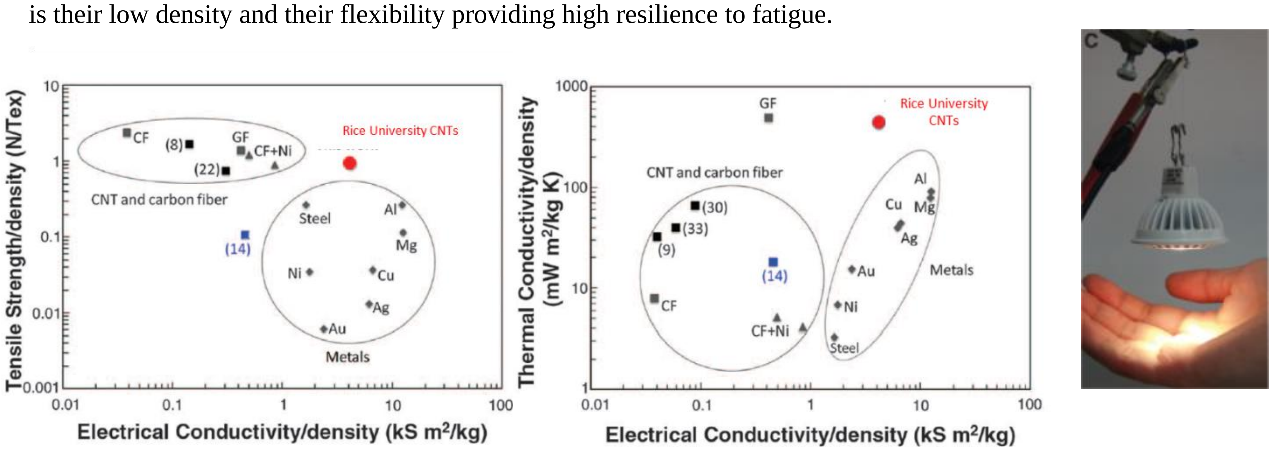


Figure 4. (Left and Middle) Ashby plots showing the CNT fiber properties developed by Rice University. (Right) Demonstration of the mechanical strength of CNT fiber developed by Rice University [12].

In this research, we specifically investigate the use of yarns made of CNT fibers as electrode wires to incorporate EDS into spacesuits. CNTs are proposed to overcome the challenges of integrating the active dust technology over using metal wires or strips as electrodes for the following reasons. (1) The mechanical properties of CNTs are higher than highly conductive metallic materials. (2) The mass of the CNT fiber electrodes is low compared to metal electrodes. (3) The CNT fibers have superior resistance to flex fatigue compared to metal electrodes. Even if thick yarns of CNT fiber is required, the overall mass contribution of the CNT fiber electrodes would be less than that of metal electrodes.

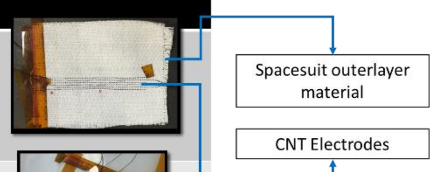
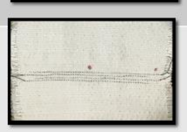
The first use of CNT material for space application was on the Juno spacecraft where dry CNT sheets developed by Nanocomp Technologies Inc. were incorporated as the outermost ply on several composite structures of the spacecraft[14]. The spacecraft has been in operation since 2011 using space qualified CNT material for electrostatic dissipation (ESD) protection. Other previous studies have reported on the ability of the CNT network to withstand high-energy proton irradiation that are comparable to the aerospace radiation environment with no significant compromise in their electrical properties, suggesting the radiation hardness of CNTs[15]. Another study reported the effects of Gamma irradiation treatments of pure CNT yarns in air, which showed significant improvement in the yarn strength and modulus[16]. The electrical properties of macroscopic CNT structures are generally sensitive to defects of constituent CNTs and to the overall structural flaws, which are related to the quality of the as-made material, fiber making process and the presence of foreign molecules/chemical compounds in the fibers. Investigations that reported on the thermo-electrical properties of both pure CNT fibers and CNT composite fibers have shown that the electrical conductivity increases with increasing temperatures, however, much evidence for temperatures beyond 300K are not readily available[17]. The successful technology insertion of a CNT sheet for ESD protection on the Juno spacecraft paves the way for future space applications of CNT. However, further investigation is needed to understand the capability of the CNT fibers used in the EDS system to survive in space environments and the pre- and post-processing treatments of CNTs are to be considered prior to flight suit implementation.

C. Experimental Set-Up

A. Test Samples

Multiple test coupons made of orthofabric material of approximately 76mm x 76mm were applied with multiple configurations of the CNT fiber electrode network. The fibers were embedded using a sewing needle, carefully following through the warp of the orthofabric material. These samples were tested to assess the feasibility of utilizing CNT fibers as electrodes and the dust removal capability when applied with a multi-phase AC voltage. Current ISS EVA suits use orthofabric as the outermost layer and it is a potential material identified for future planetary spacesuits. Orthofabric is a complex weave of Nomex (DuPont) and Kevlar (DuPont) with an outer layer of Gortex (W.L. Gore & Associates), which is made from expanded PTFE. Additionally, one coupon was prepared with copper magnet wire as electrode wires to compare the fabrication process and performance with the CNT fiber embedded coupons. Table 1 provides a high level overview of the test coupons prepared. A test plan was developed to qualitatively evaluate and characterize the EDS system performance with CNT electrodes.

Table 1. Multiple test samples built using Orthofabric spacesuit material and CNT fiber electrodes

#	Electrode Material & Thickness	Number of Electrodes	Electrode Spacing	Number of phases	
1	CNT Fiber ~200µm	6	~1.2mm	3	
2	CNT Fiber ~200µm	6	~2 mm	3	
4	CNT Fiber ~200µm	12	~1.2mm	3	
5	CNT Fiber ~200µm	4	~1.2mm	2	
6	Magnet Wire (Copper) ~200µm	6	~1.2mm	3	

B. CNT Fiber Preparation

Yarns made of CNT fibers for this research were obtained from Rice University. The fibers were produced from concentrated solutions of chlorosulfonic acid via wet-spinning, as described in prior work[12]. CNTs were provided by Meijo Nano Carbon Co. and purified by DexMat, Inc. prior to fiber spinning. The fiber spinning process produced meters of multi-strand filaments that were grouped together. The fibers were assembled into twisted, two-ply, multifilament yarns with a Planetary 3.0 ropemaking apparatus from the Domanoff Workshop to achieve the thicknesses needed for this research. Yarns used for this work consisted of 28 individual CNT filaments plied together (two plies, with each ply having 14 individual filaments. Here the word yarn is interchangeable with fibers since each electrode consisted of 28 filaments.

The individual filaments within each ply were 26 +/- 2 µm in diameter and had an average linear density of 0.82 +/- 0.2 tex. The conductivity of the individual filaments was 2.1 MS/m (specific conductivity was 1390 Sm^2/kg). While the plied yarns (fiber) had approximately the same specific conductivity as individual CNT filaments, the conductivity of the yarns decreased to 1.1 MS/m because the density of the yarns was 0.8 g/cm^3, compared to the 1.5 g/cm^3 density of individual filaments.

Table 2. Characterization of Electrode materials used in the tests

Electrode materials used	Diameter (µm)	Density (g/cm^3)	Linear Density (tex)	Strength (MPa)	Tenacity (mN/tex)	Conductivity (MS/m)	Specific Conductivity (Sm^2/kg)
CNT Fiber	200-215	0.81	29.4	1260* (Single Filament) 760 (2 Ply with 28 filaments)	940	3.1	3850
Copper	218	7.86	280	214	30	49	6275

C. Power Supply

Figure 5. (Top Left) Three phase power supply. (Top Right) Multi-phase waveform timing diagram. (Bottom) Two Phase power supply.

Most of the experiments were conducted using a three-phase AC voltage signal at 120° phase difference. We also tested two samples using two phase voltage at 180° phase shift. Generation of multi-phase voltage was performed using tunable electronics power supplies developed by NASA that can generate up to 3kV on the three phase and 2kV on the two phase power supplies. All tests were conducted at 10Hz frequency using a square waveform for both three phase and two phase. Figure 5 shows the two power supplies used during the experiments. These power supplies were previously used to test and demonstrate EDS for rigid surfaces.

D. Lunar Soil Simulant

Experiments were conducted at room temperature and pressure utilizing the JSC-1A lunar simulant with size ranges of 50-75μm and 10-50μm. The specifications for this simulant developed by Orbital Technologies Corporation are summarized in their specification database[18]. Two conditions of depositing simulant over the coupons were utilized during testing. The first method employed EDS activation as the first step prior to dust deposition, after which dust was continuously dropped (termed 'drop test') over the coupon to represent dynamic dust interacting with the suit during an EVA. With the second method, approximately 10mg of simulant was deposited over the area on the coupon covered with electrodes prior to EDS activation. This represents a scenario where the dust statically adhered to the spacesuits during an EVA.

E. Test Set-up and Procedures

Experiments were conducted at NASA KSC in the Electrostatics and Surface Physics Laboratory using the set-up shown in Figure 6, where the test coupons with the EDS electrode system were placed in a test box.

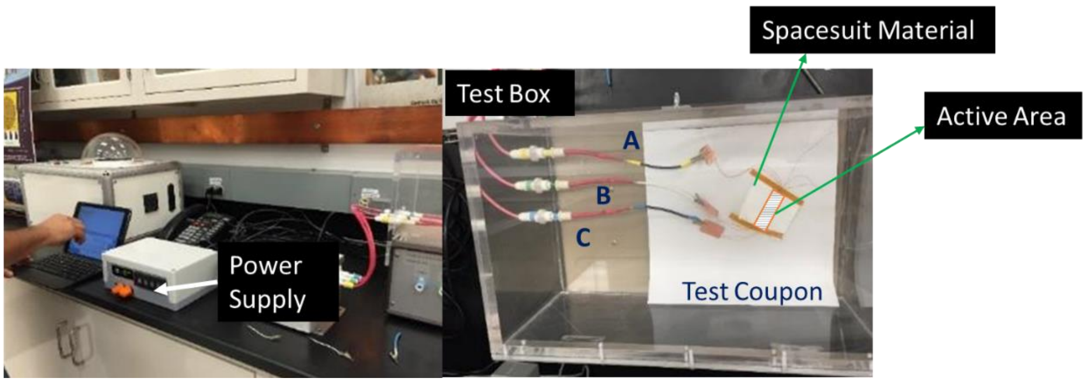


Figure 6. Test Set-up at the NASA Electrostatics and Surface Physics Laboratory in ambient conditions

Each coupon was first cleaned using pressurized air and imaged using a microscope. The coupon was placed horizontally in the test box shown in Figure 6. Each of the three terminals (two terminals for two phase) of the electrodes was connected to the respective phases (A, B, C) of the power supply. The surface of the coupon was neutralized using a 3M Benchtop Air Ionizer unit. For initial characterization of the EDS system, the power supply was activated starting from low voltages (~100V) at 10 Hz in 50V increments.

Two separate evaluations with lunar dust simulant were conducted. Using the drop test method, first the power supply was turned ON and the appropriate voltage and frequency were selected activating the electrodes. Following EDS activation, lunar simulant was continuously dropped over the active area of the coupon with a brush, approximately 6 inches above the coupon. The drop test was conducted for 1-3 minutes to determine if the coupon with the EDS system was capable of repelling the dust. Dust deposition was halted and the power was turned OFF. The coupon was imaged in place for post-test analysis. Using the second method, after the step where the air surrounding the coupon was neutralized, we deposited lunar simulant over the coupon and imaged the coupon with the dust adhered to the fabric. The lid of the test box was then closed, followed by activation of the EDS system by turning ON the power supply at the needed voltage and frequency. EDS was kept activated for approximately 30 seconds or more until no further dust particles visually seemed to repel. The power was then turned OFF and the coupon was imaged in place.

For vacuum chamber testing, we placed the coupons in a Bell Jar that contained a box to mount coupons and connect the terminals as shown in Figure 7. The set-up consisted of an internal dust container which could be loaded with dust and actuated using an external controller to drop dust on the coupon. We cleaned the coupon with pressurized air, imaged using microscope, mounted it in the box, connected terminals, and closed the lid of the box. A camera was placed on the box that had a provision to hold a GoPro session sized camera. Dust was then loaded into the dust container prior to closing the Bell Jar. We activated the pump to draw vacuum. After reaching a pressure level of 6.7e-5 mbar (5e-5 Torr), the electrodes were activated using the power supply situated outside the Bell Jar. The dust from the container inside the jar was dropped by controlling the actuator.

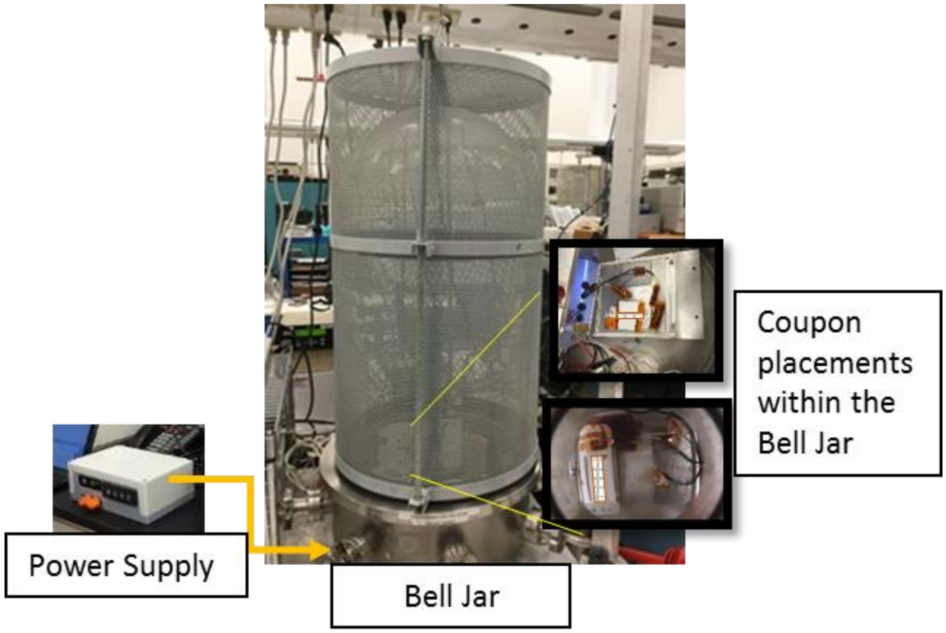


Figure 7. Test Set-up at NASA Electrostatics and Surface Laboratory for vacuum conditions

D. Data Collection and Analysis Methods

For this feasibility study, we qualitatively assessed the capability of the CNT fiber EDS system using experiments. Pre- and post-test analysis was conducted at NASA KSC. Data from the tests was analyzed using 1) Visual Inspection, 2) Optical Microscopy, and 3) ImageJ software.

The pristine coupons were first visually surveyed and then sampled using optical microscopy imaging. For the drop test method, where the EDS was first activated, we recorded continuous video while dust was dropped over the coupon. The coupon was imaged in place after the test using optical microscope. Similarly, for the static test (second method), we imaged the coupon prior to dust deposition, after dust deposition, and after EDS was activated. Videos and photographs were taken to document observable dust removal capability from the coupon. Optical microscopy imaging at 20X magnification was used to record the state of the coupons. ImageJ software was used to estimate the dust particle size and distribution in the captured images that approximated the amount of dust remaining on the coupons post-test.

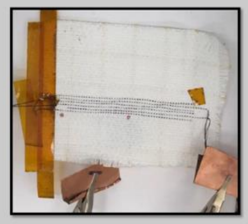
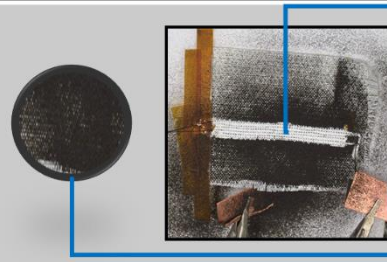
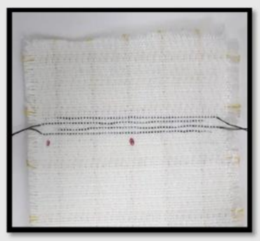
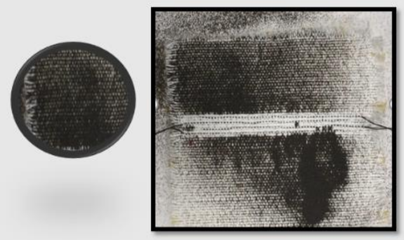
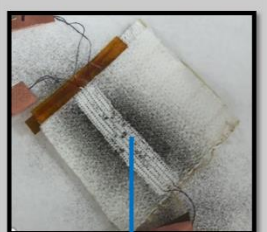
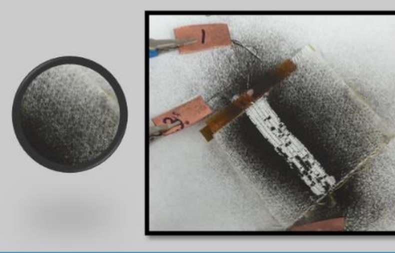
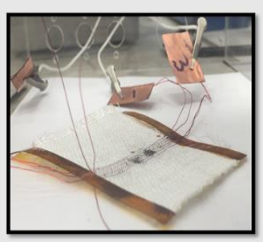
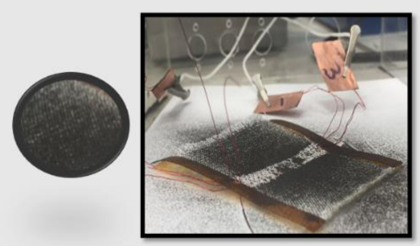
III. Experimental Results and Discussion

A. Part 1: Drop Test

Real time observations of the drop test experiments clearly demonstrated the ability of the EDS system consisting of CNT fiber electrodes to remove dust when applied to spacesuit material using new fabrication techniques. When the EDS system was activated and dust was continuously dropped over the coupon, we observed dust constantly being repelled over the active area of the coupon. Table 3 provides an illustration of the dust removal capability of the system utilized in this study.

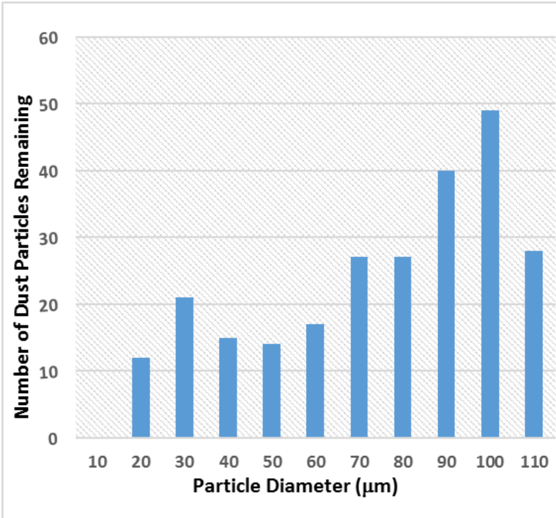
We qualitatively assessed the capability of the system to repel dust during drop tests. We did not measure the amount of dust dropped over the coupon during this test. However, from the figures below, one can notice that the coupon was able to repel greater than 90% of dust as observed by the amount of dust coating outside of the active area. The system was able to reproduce similar cleaning results on repeated drop tests on the same coupons. Experiments showed that cleaning depends on electrode configuration and applied waveform characteristics. As expected, for a respective coupon with specific electrode configuration, the performance of the system was observed to be better (faster clearance of dust and relatively more particles removed) at higher voltages than at lower voltages due to the higher electric field strength generated with increase in the applied voltage. Observations from the tests showed the coupons with CNT electrodes performed on par (or better in some cases) than the Copper magnet wire embedded coupons.

Table 3. Results from Dust Drop Test. (Dust is continuously dropped over the entire coupon while the electrodes are active)

Coupon Information	Voltage	Before Activation	Dust Dropped and EDS Activated
• CNT fiber • 6 electrode lines • ~1.2mm electrode spacing • ~ 200micron electrode thickness	3 phase 1000V		
• CNT fiber • 4 electrode lines • ~1.2mm electrode spacing • ~ 200micron electrode thickness	2 phase 1000V		
• CNT fiber • 6 electrode lines • ~2.0 mm electrode spacing • ~ 200micron electrode thickness • Note that this coupon had preexisting dust prior to the drop test. The amount of dust dropped was also in large quantities, that may not be the case in real EVAs	3 phase 1400V		
• Copper Magnet wire, insulated • 6 electrode lines • ~1.2mm electrode spacing • ~ 200micron electrode thickness • Note that this coupon had preexisting dust prior to the drop test.	3 phase 1600V		

The coupons were able to repel dust particles of both larger (50-75µm) and smaller (10-50µm) grain sizes. However, a characteristic difference noticed between the large grain size (50-75µm) and small grain size (10-50µm) simulant particles was that the smaller grain size simulant was cohesive (particles grouped/stuck together) compared to the larger grain size particles when dropped over the coupon. Cases where the smaller grain size particles were cohesive when dropped on the coupon, it was difficult to repel dust. Nonetheless, these lumps of particles were localized and only covered a minor portion of the coupon.

ImageJ software was used to quantitatively estimate dust particle size and distribution remaining on the coupon after the test. Each coupon was imaged in three separate sections along the longitudinal axis of the electrodes covering the entire active area as shown in the bottom part of Figure 8. This method was adopted due to constraints on imaging the entire coupon with the needed magnification in a single image. ImageJ analysis was performed on each of the three sections of the active area on the coupon. The approximate dimensions of each section was 9.85mm X 6.23mm. Results obtained were averaged over three repeated runs on the same coupon. As an example, Figure 8 provides an estimate of the dust particle size and distribution remaining on the coupons on a single section after EDS activation



was halted using the 3 phase system with 50-75µm simulant. Results similar to that depicted in Figure 8 were obtained for rest of the coupons on all three sections, as well as for the two phase drop tests. No significant difference was observed between the 3 phase and 2 phase voltage signals during the drop test. Note that the dust simulant used, although in the range of 50-75µm, figure 8 shows that the coupon had larger (>75µm) and smaller (<50µm) sized particles remaining on the coupon. This is because we did not sieve the simulant particles used for the experiments prior to test. For the smaller grain size tests (10-50µm), ImageJ analysis was not accurate in estimating particle size and count because particles were cohesively grouped together in a few places making it difficult to accurately distinguish between individual particles. Future tests will address this using improved imaging techniques. Fused

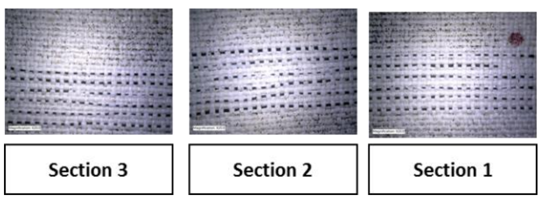


Figure 8. (Top) Dust particle size distribution on one section of a drop test coupon averaged over three sections and three runs. (Bottom)An example of how each coupon was imaged in three sections to perform particle-counting analysis. *Results shown here are for the 3 phase, 1000V, 6 wire, ~1.2mm spacing configuration coupon*

B. Part 2: Static Dust

The second type of experiments were conducted to understand if the system was capable of repelling dust when the fabric was pre-exposed to dust (static dust) prior to EDS activation. Initial runs for the static test were conducted using general distribution of dust over the coupon, where the amount of dust deposited on the coupon was not quantified and the distribution was random. For subsequent runs, we distributed approximately 10mg of dust over the active area using a stencil that matched the dimensions of the active area.

These tests were repeated (average of three repetitions) to examine the reproducibility of system performance. The coupons were capable of repelling dust on repeated test runs. Experiments revealed that the system is able to repel between 80-95% of the dust that was statically attached to the coupon as shown in Table 4. Figure 9 provides a snapshot of the amount of dust particles before and after EDS activation on a section of a coupon for the static test averaged over all three sections and three repeat runs for the same coupon.

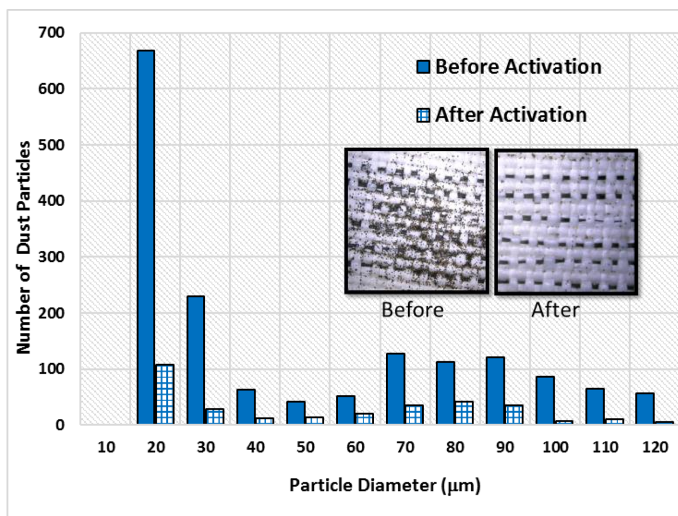
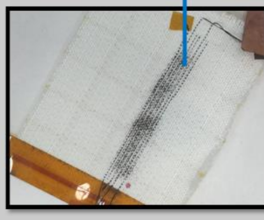
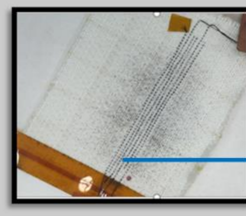
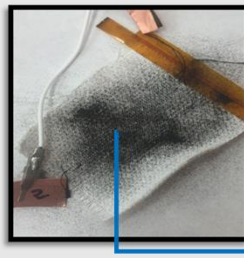
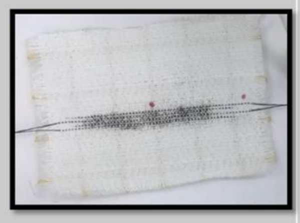
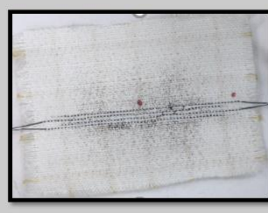
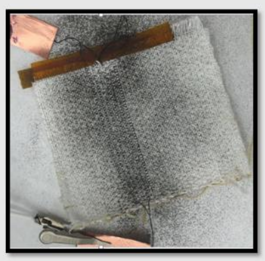
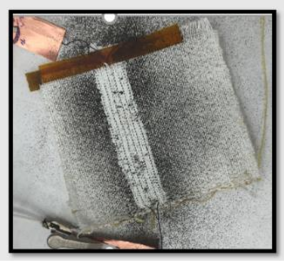
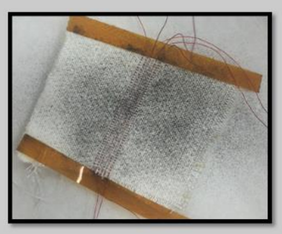
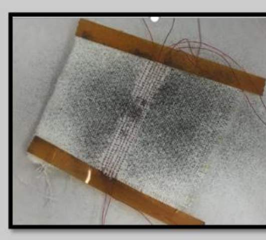


Figure 9. Dust particle size distribution on a section of the coupon before and after activation averaged over three runs. (Inset) Example of before and after picture of a section of the coupon. *Results shown here are for the 3 phase, 1000V, 6 wire, ~1.2mm spacing configuration coupon*

Other observations showed no significant differences between the 3 phase and 2 phase voltage signals. As expected for a given coupon with specific electrode configuration, the system's capability to remove dust was greater (faster clearance of dust and relatively greater number of particles removed) at higher voltages. For example, Table 5 shows the increase in performance of dust clearance as the voltage was increased from 400V to 900V.

Table 4. Results from Static Dust Test (Dust is adhered to the coupon prior to Electrode activation)

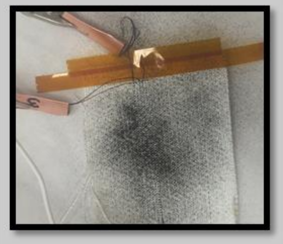
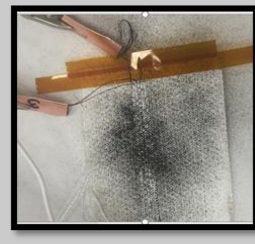
Coupon Information	Voltage	Before Activation	After Activation
• CNT fiber • 6 electrode lines • ~1.2mm electrode spacing • ~ 200micron electrode thickness • 10mg Dust	3 phase 1000V		
• CNT fiber • 6 electrode lines • ~1.2mm electrode spacing • ~ 200micron electrode thickness • Heavy Dust Loading*	3 phase 1000V		
• CNT fiber • 4 electrode lines • ~1.2mm electrode spacing • ~ 200micron electrode thickness • 10mg Dust	2 phase 1000V		
• CNT fiber • 6 electrode lines • ~2.0 mm electrode spacing • ~ 200micron electrode thickness • >10mg Dust	3 phase 1400V		
• Copper Magnet wire, insulated • 6 electrode lines • ~2.0 mm electrode spacing • ~ 200micron electrode thickness • >10mg Dust	3 phase 1600V		

10mg of Lunar Dust Simulant sitting on the Fabric

Active CNT area: Cleared Dust

Heavy Dust Loading

Table 5. Effects of applied voltage on system performance for a specific coupon. *Coupon configuration shown here : ~1.2mm spacing, 6 wires*

Voltage	Before Activation	After Activation
3 phase 400V		
3 phase 800V		
3 phase 900V		

The feasibility of utilizing EDS for spacesuit dust mitigation using CNT technology was demonstrated by experiments conducted in ambient conditions (ambient refers to laboratory conditions with average temperature of 20ºC and relative humidity of 60%). We repeated these tests in vacuum conditions as well, however, due to some inconsistencies in the mounting methods of the coupons in the vacuum test chamber and time limitations, we were unable to complete a comprehensive set of vacuum chamber tests. Therefore, those results are not be presented in this paper. Although, one of the observations made during the initial vacuum chamber testing is the outgassing of the CNT electrodes that was revealed during visual inspection of the coupon after vacuum chamber operations at 1.3e-5 mbar (1e-5 Torr). We have however determined a process to resolve this condition and plan to implement the procedure prior to conducting vacuum chamber experiments in the future.

The ability of the EDS system incorporated into spacesuit fabric using new techniques was shown to be feasible. It was observed that due to the flexibility of CNT, the ability of integrating the CNT fibers into the spacesuit orthofabric material was simple and effective. Additionally, the electrode fibers conformed to the surface of the orthofabric and the existing weaves. In comparison, the Copper magnet wire, due to its rigidity was difficult to conform to the surface of the orthofabric material and the fabrication process was relatively longer than the coupons embedded with CNT fiber. The CNT electrode system performed on par (or better in some cases) with the Copper magnet wire electrode system. The CNT electrode system was capable of reproducing its cleaning results after multiple runs (more than 10). Future tests will be performed to understand the extent of longevity of the CNT electrode system with flexing and re-use of the fabric. Table 6 summarizes the voltages applied that provided the highest dust removal performance for the configurations tested. The CNT fibers utilized in these tests were spun at sub-optimal conditions which reduced the strength and conductivity of the fibers previously reported in literature by Rice University. Nonetheless, the EDS system utilizing these CNT fibers were capable of repelling dust from the spacesuit material. Future tests will be conducted utilizing high quality fibers and the electrodes size and spacing will be optimized based on results numerical modeling.

Table 6. Summary of Voltages applied to the EDS system using CNT technology during experiments.

Coupon electrode material	Electrode Spacing	Phase and Frequency	Voltage applied during experiments	Threshold voltage	Additional Comments
CNT fiber	~1.2mm	3 phase 10Hz	800-1000V	1200V	Uninsulated electrodes
CNT fiber	~2mm	3 phase 10Hz	1200-1500V	1600V	Uninsulated electrodes
CNT Fiber	~1.2mm	2 phase 10Hz	1000V	1200V	Uninsulated electrodes
Copper Magnet wire, insulated	~1.2mm	3 phase 10Hz	1600	1800V	Insulated wire. Capable of taking higher voltage due to insulation

C. Challenges

Besides addressing the physical integration of the EDS electrode system into spacesuits, there are other challenges associated with this technology that need to be resolved prior to spacesuit implementation. Although we have not addressed these other concerns through the experiments presented in this paper, we identify some of the key issues that will need be addressed through future testing and analytical methods. First, while the voltages required for using such a technology are on the order of 600-1200V, the current passing through the electrodes is very low (on the order of micro amps). Nevertheless, application of high voltages needs attention for astronaut safety. Spacesuits are made up of several layers of material (upto 11-13 layers). The fabrics and materials used in the spacesuit system are made of materials such as Orthofabric and Kapton which are insulating and have high dielectric strengths. The assumption is that the layers of the spacesuit will provide the needed protection to the crew in the suit from the electric field forces generated by EDS system. However, issue of electrostatic discharge and interference with life support system electronics and metallic pieces of the spacesuits also pose safety challenges that need to be addressed. Second, an understanding of spacesuit thermal management and increase in the thermal load due to dust contamination is required. This allows identifying the critical areas of the suit that need to be enhanced with the EDS system permitting for an optimized solution to clean the most severe areas from dust. Third, designing a miniaturized high voltage power supply to be portable for the spacesuit system is essential. And finally, additional investigation of the ability of the CNT fibers to survive in space environments and/or post processing or fabrication methods to overcome CNT exposure to extreme environments is required.

IV. Conclusion

The goal of this research is to build a spacesuit integrated dust removal system to protect suits from the deleterious effects of dust (in this case lunar dust) for future long duration missions. We explored new high performance materials and techniques to utilize existing dust removal EDS technology concept for spacesuit dust contamination. The preliminary tests presented in this paper demonstrate the capability of CNT fibers embedded into spacesuit outerlayer to repel greater than 80% lunar dust simulant with particle sizes between 10-75 μm in both dynamic and static dust settings in ambient conditions. We repeated these tests in vacuum conditions, however, due to some challenges with mounting methods of the coupons in the vacuum test chamber and time limitations, we were unable to complete a comprehensive set of vacuum chamber tests and cannot currently provide conclusions on the ability of the system in vacuum conditions. While there are other challenges remaining to be addressed prior to fully implementing the system into spacesuits, we have demonstrated a key part of the integration of the EDS technology for spacesuit application through initial experiments. The experiments demonstrated the feasibility of utilizing CNT fiber technology for repelling lunar dust simulant when applied with a multi-phase AC voltage. Further development of this system continues with additional plans to test the system in vacuum conditions. Furthermore, we are concentrating on optimizing different techniques for implementation of this technology on larger portions of spacesuit prototypes, testing in vacuum conditions, and developing numerical models to help optimize the various technical aspects of the EDS system and materials for spacesuit implementation.

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