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# Electrostatic Discharge Hazard in Spacesuits

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**Triboelectric charging with a resultant electrostatic discharge is a phenomenon with which most people are familiar, especially those living in dry climates. Spacesuits, which are elaborately designed anthropomorphic pressure vessels attempting to match the motions of the human body while providing protections from the harsh environment of space, also must contend with triboelectric charging. But for spacesuits, which operate with elevated oxygen concentrations (usually >95%) in order to enable the lowest reasonable working pressure for the human operator, additional challenges are present with potentially catastrophic results if those challenges are not met successfully. A painful spark discharge can offer as much as 15kV with an energy transfer as high as 15-20mJ. This is well above the level needed to ignite hydrocarbon vapors or fine dusts such as those in grain silos. There have been several test methods beyond the scope of this paper seeking to address the mechanistic ignition energies to ignite suit materials with a wide possible range of results due to the varied test configurations. What is not known is if the suit materials offer sufficient capability for triboelectric charge generation and discharge to generate the potential and the resultant discharge energies within the ranges needed to ignite the suit materials in this operating environment.**

## Nomenclature

| | | |
|---|---|---|
| *Ω* | = | ohms |
| *A* | = | electrode area |
| *ASTM* | = | American Society for Testing Materials |
| *C* | = | capacitance |
| *CCA* | = | communications carrier assembly |
| *CHX* | = | condensing heat exchanger |
| $CO_2$ | = | carbon dioxide |
| *DC* | = | direct current |
| *DCS* | = | decompression sickness |
| *DIDB* | = | disposable in-suit drink bag |
| *E* | = | energy |
| *ECG* | = | Electro-Cardio-Gram |

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| | | |
|---|---|---|
| *ECLSS* | = | Environmental Control Life Support System |
| *EMI* | = | electromagnetic interference |
| *EMU* | = | Extravehicular Mobility Unit |
| *ESD* | = | Electro Static Discharge |
| *ESPL* | = | Electrostatics and Surface Physics Laboratory |
| *EVA* | = | Extra-Vehicular Activity |
| *HAB* | = | Helmet Absorption Band |
| *HAP* | = | Helmet Absorption Pad |
| *HAP-E* | = | Helmet Absorption Pad Extender |
| *ISS* | = | Interational Space Station |
| *IVA* | = | intravehicular activity |
| *JCI* | = | John Chubb Instrumentation |
| *JSC* | = | Johnson Space Center |
| *KSC* | = | Kennedy Space Center |
| *LCVG* | = | Liquid Cooling and Ventilation Garment |
| *LiOH* | = | Lithium Hydroxide |
| *MIE* | = | Minimum Ignition Energy |
| *NASA* | = | National Aeronautics and Space Administration |
| *NBL* | = | Neutral Buoyancy Laboratory |
| $O_2$ | = | oxygen |
| *PLSS* | = | Portable or Primary Life Support System |
| *RH* | = | Relative Humidity |
| $R_v$ | = | volume resistance |
| $t$ | = | electrode thickness |
| *TDL* | = | Technical Discipline Lead |
| $V$ | = | Voltage |

# I. Introduction

For the extra-vehicular activity (EVA) space suit application, the use of 100% oxygen is required in order to enable operation of the total suit pressure at levels down to 3.1 psia [21.4 kPa] with nominal operation for suits such as the Space Shuttle and International Space Station (ISS) extravehicular mobility unit (EMU) at 4.3 psia [29.6 kPa]. As this suit and all other flown or active suit designs use an anthropomorphic pressure vessel approach, the suit is pressurized, the crew operates within that shaped pressure vessel, and they must work against it to perform tasks. Despite the great care and extensive design work implemented in these suit designs, the fact remains that as the suit operating pressure increases, so does the effort the crew must exert and hence so does the fatigue of the crew over the course of an EVA or spacewalk. As a result, the suit operating pressure is lowered as far as possible with the low end based on hypoxia limitations of human physiology. Use of 100% oxygen is required to achieve this lowest possible absolute pressure. Considering that materials within the space suit are flammable in 100% oxygen and that 100% oxygen is required for the functional performance of the space suit, the suit application already includes two of the three legs of the fire triangle (fuel and oxygen, Figure 1). Consequently, the control of ignition sources in the suit volume is the only remaining option for mitigation of the fire hazard in a space suit.

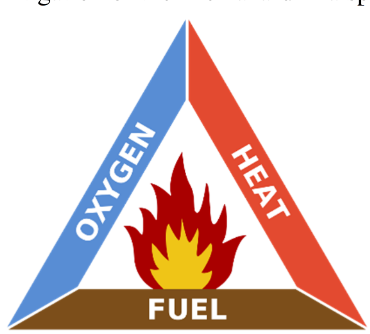



**Figure 1 - Fire Triangle**[1]

With the goal of controlling ignition sources, most of the focus in space suit design, with respect to the low pressure anthropomorphic pressure vessel segments, has been to limit the power sourced into the suit volume[2,3,4]. Given published and historical data, electro static discharges (ESD) have long been considered too low in energy to ignite bulk materials hence, it has not received much attention or focus in the past several decades with respect to consideration of it as a credible ignition mechanism in space suit systems. For the space suit application with textiles in 100% oxygen and pressures ranging from 3.5 to 25 psia, there is limited relevant data related to arc ignition addressing ESD arc ignition. This is one of the reasons multiple new suit providers have posed questions and concerns with respect to this ignition mechanism seeking more information as they mature their respective designs. This paper will summarize existing ESD ignition test data, report out triboelectric charging assessments of typical materials used in space suit internal volumes, and discuss the applicability of these data to EMU and other space suit designs.

## II. Review of Suit Conditions and Existing Historical Data

Of the principal mechanisms of charge generation detailed in the reference 5 paper, the only mechanism applicable to the suit internal volume is charging via contact and separation of solids, also referred to as tribocharging. This can occur from contact and relative movement of the materials lining the suit and those being worn by the crewmember inside the suit volume. This can also occur from contact and relative movement of the materials on the outside of the suit with those of the environment. Charge accumulation then occurs if the processes that bleed or relax the charge between the surfaces are slower than the charging rate from the tribocharging. Charge relaxation mechanisms available in the suited environment include grounding[5]/bonding[6] of conductors as well as maintaining elevated humidity levels greater than 50% RH [6]. For the humidity, the suited volume cannot always guarantee such a condition as the RH can drop lower than 50% depending on how the suit is operated. In the suit ventilation flow path shown in Figure 2, the inlet and frequently low relative humidity source gas typically enters the suit at the helmet location and then progesses down the annular flow paths to each extremity where it is picked up to exhause from the suit. This flow path is common for most EVA spacesuits that seek to achieve $CO_2$ washout from the helmet oro-nasal region by displacing the gas into the suit volume and at the same time, control humidity generated by the body. In this configuration, the gas descending to the extremities is then increased in RH by the water vapor sourced from expiration from the lungs and that picked up from evaporation from the skin, stored condensate on the liquid cooling and ventilation garment (LCVG), or perspiration. However, if the inlet gas humidity is sufficiently low, the volumetric flow rate of the gas is sufficiently high, and the humidity sourced from perspiration/expiration is sufficiently low, then the humidity levels throughout the suit will remain low. The right side of Figure 2 demonstrates an example of this phenomenon. In an ISS EMU with a 6 acfm (170 lpm) volumetric flowrate and an initially anhydrous $CO_2$ scrubber cartridge known as the “Metox” or metal oxide canister, the inlet RH denoted as “T2 Suit Inlet RH%” entered the suit as low as 3-5% and, for the first ~2 hours of operation, the outlet RH denoted at “T3 Suit Outlet RH%” remained below 50% which is coincident with the saturation of the scrubber and the beginning of dewpoint control via the condensing heat exchanger in the EMU. For this period of time, the ability of the RH to aid in charge relaxation is reduced.

This operating mode also pertains to operations of the suit in the Neutral Buoyancy Laboratory (NBL) which operates with 46% Nitrox fed by open loop flow from dry gas expansion[7]. Considering that the relative movement of the crewmember/suit materials and potentially low relative humidity provides an environment for charge accumulation, multiple sources indicate that charges accumulated and discharged from human beings can range from 1 to 10’s of millijoules noting that a “one millijoule spark is perceptible, a ten millijoule spark is a prick, a 30 millijoule spark is is a sharp prick, and a hundred millijoule results in a slight jerk”[8]. Many readers can identify with spark discharges after crossing a room and touching a door knob with low humidity and air. The minimum ignition energies (MIE) for combustible vapors and dusts shown in Table 1[8], suggests that spark discharges from humans can offer enough energy to ignite combustible vapors and dusts in the presence of air and especially in 100% oxygen.

[5] Grounding for the purpose of this discussion is defined as the connection of the conductor to a ground potential such as chassis, earth, etc.

[6] Bonding, for the purpose of this discussion, is defined as the connection between conductors.

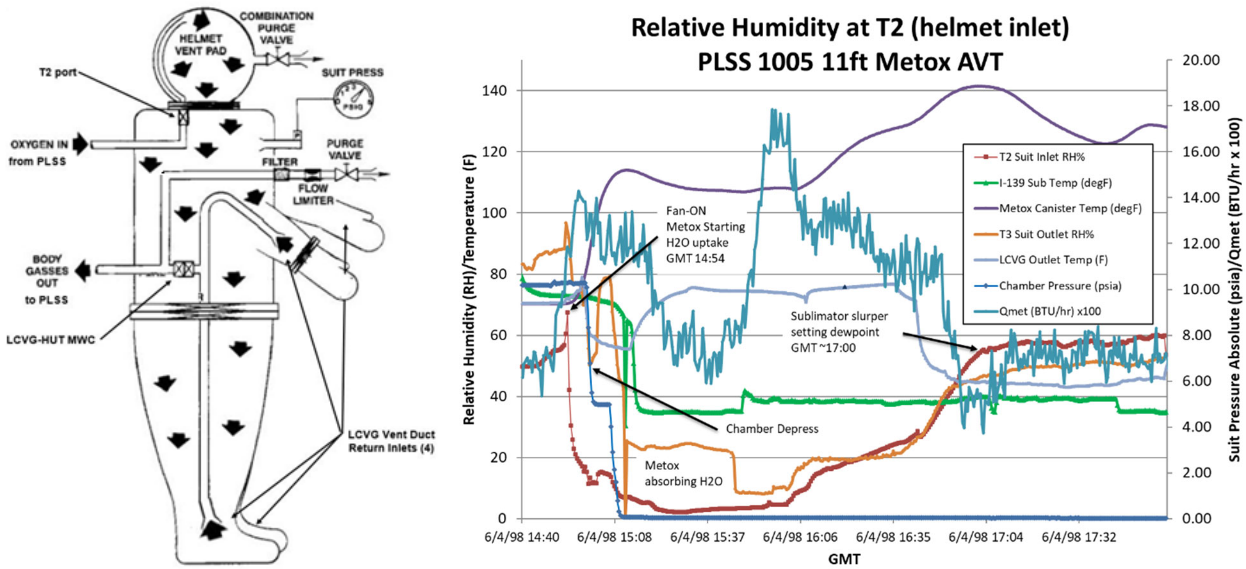



**Figure 2 – Suit Ventilation Flow Path (left) and EMU Altitude Verification Test (right)**

This is corroborated by the testing of various solids (cotton, dacron-cotton fabric, wool, cotton balls, vinyl plastic)[6] in which the investigators were able to ignite the materials in 100% oxygen using 90mJ sparks (number of sparks was unclear as they were tested at 60 sparks per second). Using spark energies of 2.5-20 mJ at 30 sparks/min clean cotton was ignited in 100% oxygen[6]. Noting that spark rate for the testing was likely much higher than would be expected in the suit application it still suggests that a risk exists with respect to the fire hazard with fuels such as cotton and not just combustible vapors and dusts in 100% oxygen. As is thoroughly discussed in the paper in reference 9, the wire break ignition testing that was developed in 2005 to simulate a failure mode in the ISS EMU actually generates a combustible vapor through thermal decomposition of the fuel (surrounding fabric) around a wire that is carrying an excessive current until the potential ignition occurs upon breakage of the wire.

**Table 1 – Minimum Ignition Energies for Selected Fuels in Air and Oxygen[8]**

| Fuel or Dust | MIE, mJ | | |
|---|---|---|---|
| | Air | Oxygen | Ratio |
| **Acetone** | 1.15 | 0.0024 | 479 |
| **Acetylene** | 0.017 | 0.0002 | 85 |
| **n-Butane** | 0.25 | 0.009 | 28 |
| **Cyclopentane** | 0.18 | 0.001 | 180 |
| **Diethyl ether** | 0.20 | 0.0013 | 153 |
| **Ethane** | 0.25 | 0.002 | 125 |
| **Ethylene** | 0.07 | 0.001 | 70 |
| **n-Hexane** | 0.228 | 0.006 | 48 |
| **Hydrogen** | 0.017 | 0.0012 | 14 |
| **Methane** | 0.30 | 0.003 | 100 |
| **Coal** | 60 | 10 | 6 |
| **Aluminum, flake** | 100 | --- | --- |
| **Aluminum, atomized** | 50 | --- | --- |
| **Polycarbonate** | 25 | --- | --- |
| **Polyethylene** | 10 | --- | --- |
| **Polymethylmethacrylate** | 15 | --- | --- |
| **Polypropylene** | 30 | --- | --- |

During the Apollo Program, static discharge events were noted during various activities including donning of the space suit. There was also a report of possible communications interference with the radio from the suit from the discharges. This resulted in an investigation of the static discharge risk[10]. During the testing, the radio interference could not be confirmed. Testing was able to determine that cotton fabric could be ignited with as little as 9-20 mJ of spark energy at 16.5 psia in 100% oxygen; no ignitions were noted up to 170 mJ when tested at 6.2 psia in 100% oxygen with the caveat that this test series considered only 20 sparks per condition which may or may not address sample and test condition variability. Suited test activities with varied RH reflected human-suited crew charge voltages in the 2-4 kV range (Table 2).

**Table 2 - Human-suited Charge Voltage vs RH[10]**

| Relative Humidity (%) | Maximum Voltage (kV) |
|---|---|
| **69** | 2.4 |
| **50** | 3.0 |
| **24** | 3.9 |

Stored electrostatic energy can be modeled considering the source as a capacitor which stores the energy as a function of the capacitance and potential:

$$C = 200 * 10^{-12}\ F$$

$$V = 4.3 * 10^{3}\ V$$

$$E = \frac{1}{2}\ C\ V^2 \quad E = 2\ mJ \tag{1}$$

where E is the available energy, C is the capacitance, and V is the measured voltage.

This results in an energy level of ~ 2 mJ as noted in Equation 1. This is not sufficient to ignite solid fabrics in the suited 100% oxygen environment but it is sufficient for ignition of combustible vapors. Hence, for the Apollo study, the conclusion was made that, absent combustible vapors, that ESD did not present a hazard to ignite the suit materials but that the discharges were undesirable so the crew needed to be grounded via the biomedical system; this also provides a more verifiable control to this hazard. Grounding was implemented to bleed off and preclude the accumulation of charge. During testing, the Apollo study noted large temporary disturbances in the ECG when charges were dissipated through the ground after a discrete charging event.

## III. Summary of Tribocharging Testing for Suit Materials

A series of samples were delivered to the NASA Kennedy Space Center (KSC) for testing. The Electrostatics and Surface Physics Laboratory (ESPL) has performed more than 40 independent ESD evaluations for a variety of programs over the last 25 years. The first series of tests that the ESPL performs to evaluate the electrostatic properties of a material is surface resistivity. Surface resistance measurements are the main test method used in industry to characterize the ESD properties of materials, since it is believed that charge deposited onto the surface of a material will “leave” (or decay) easier from a material with lower surface resistance than from a material with high surface resistance. Surface resistance is the ratio of the direct current (DC) voltage to the current flowing between two electrodes of specified configuration that contact the same side of the material and is expressed in ohms (Ω). The surface resistivity tests are performed per the requirements of the ESD Association Standard Test Method ESD STM11.11[11]. These measurements are taken using a PRS-801 resistance system with an Electro Tech System (ETS) PRF-911 concentric ring resistance probe (Cal # M78447). The tests require a five-pound weight on top of cylindrical electrodes[12]. The resistivity is determined by multiplying the measured resistance by 10 to account for geometric effects of the probe. Materials with a surface resistance less than $10^4$ Ω are considered conductive. Materials between $10^4$ Ω and $10^{11}$ Ω are statically dissipative and materials with a surface resistance above $10^{11}$ Ω are insulating according to ANSI/ESD standards. One simply has to multiply by a factor of 10 to get the older ASTM D-257[13] units of Ω but the same rules apply.

Volume resistivity tests are also conducted to measure conductivity through the material as opposed to conductivity along the surface. These tests are conducted using the same PRS-801 resistance system with the Electro Tech System PRF-911 or ETS-823 concentric ring resistance probe but are performed in accordance with ESD Association Standard Test Method ESD STM11.12[14]. To convert from volume resistance to volume resistivity:

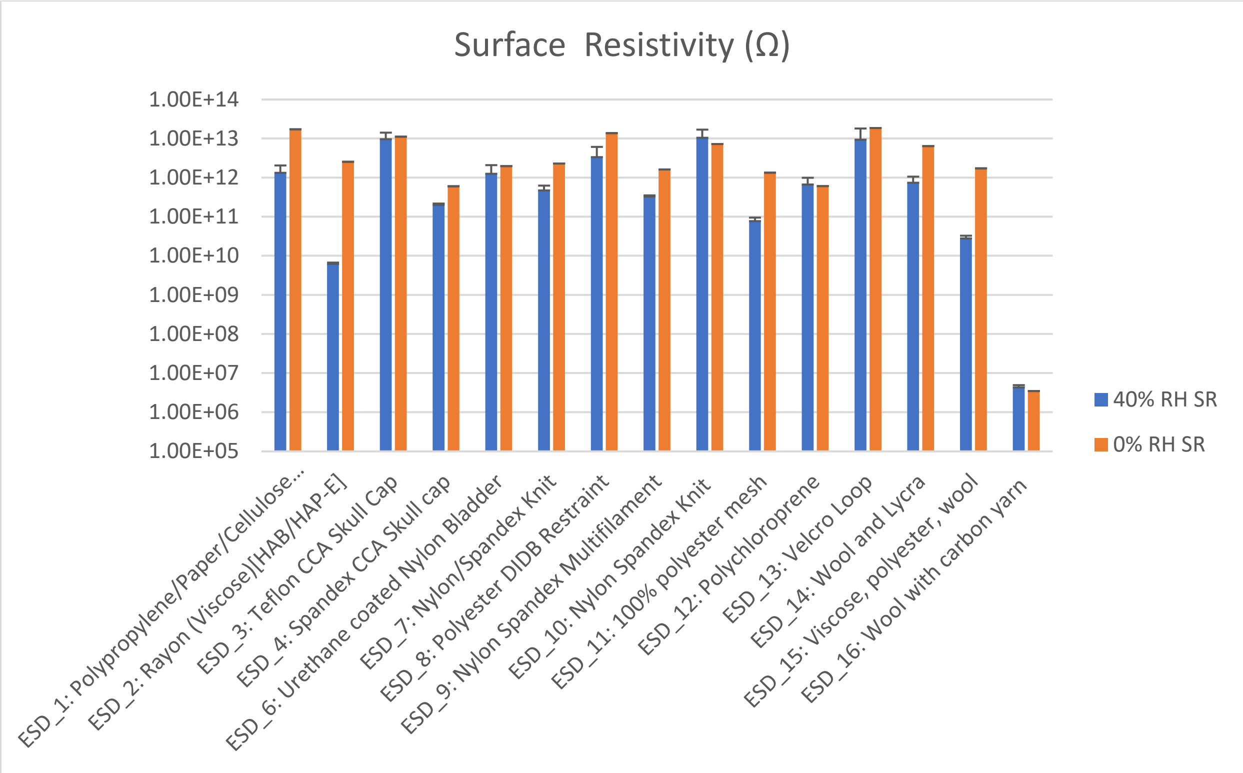
$$\rho_v = \frac{A}{t} R_v \tag{2}$$

where A is the electrode area, t is the specimen thickness, and R is the volume resistance.

Measurements for both surface and volume resistivity were taken at 40% and 0% humidity after acclimating for at least 48 hours in the controlled environment to match similar humidity extremes before and after a donned helmet. The test samples are provided in Table 3. Graphs of results for 40% and 0% relative humidity are in Figure 3.

**Table 3 - Samples provided for ESD testing**

| Sample Name |
|---|
| ESD_1: Polypropylene/Paper/Cellulose HAP Liner |
| ESD_2: Rayon (Viscose)[HAB/HAP-E] |
| ESD_3: Teflon CCA Skull Cap |
| ESD_4: Spandex CCA Skull cap |
| ESD_6: Urethane coated Nylon Bladder |
| ESD_7: Nylon/Spandex Knit |
| ESD_8: Polyester DIDB Restraint |
| ESD_9: Nylon Spandex Multifilament |
| ESD_10: Nylon Spandex Knit |
| ESD_11: 100% polyester mesh |
| ESD_12: Polychloroprene |
| ESD_13: Velcro Loop |
| ESD_14: Wool and Lycra |
| ESD_15: Viscose, polyester, wool |
| ESD_16: Wool with carbon yarn |



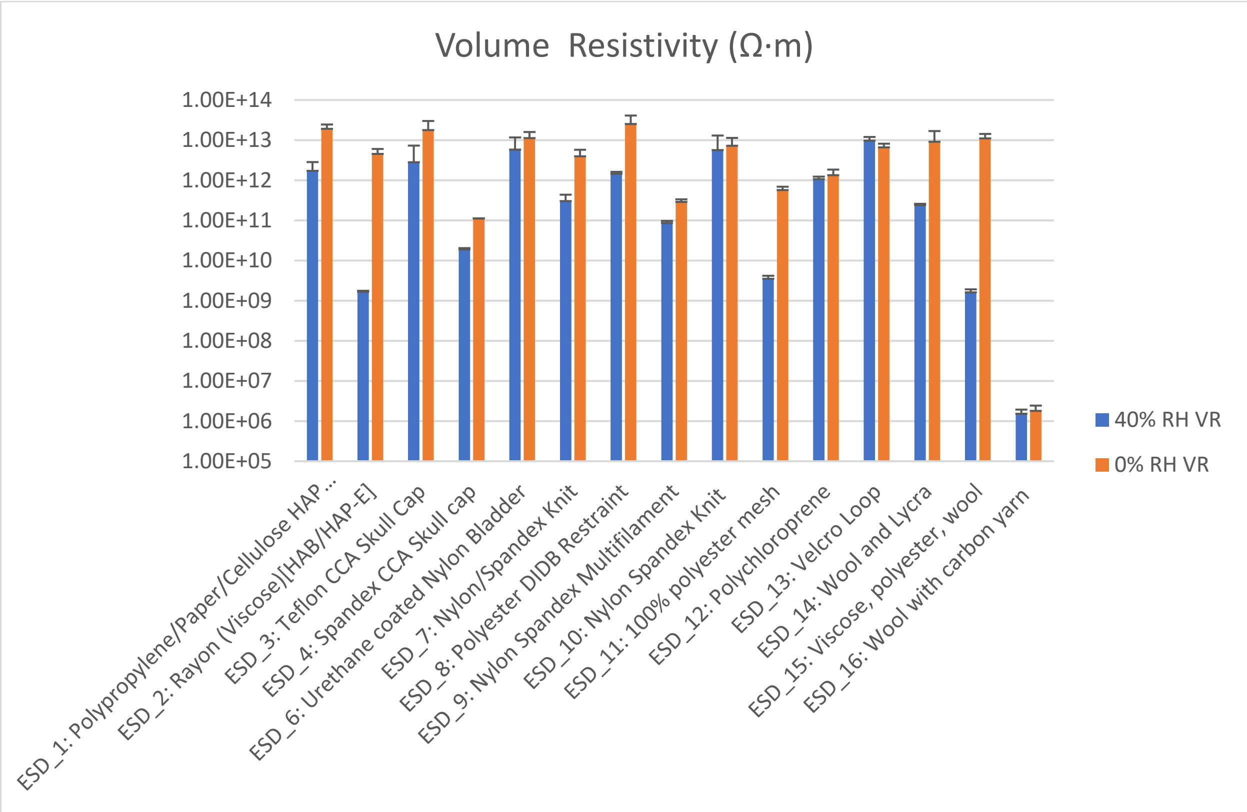




**Figure 3 - Results of the surface (top) and volume (bottom) resisitivity at both 40% and 0% relative humidity**

Some materials are statically dissipative at the higher humidities such as the viscos rayon material as well as the polyester mesh and wool. However, at low humidities all materials are highly insulating according to the surface resistivity data. The only exception is the wool impregnated with carbon yarn which was dissipated with both high and low humidity. The volume resistivity showed a similar trend however, there were more materials that were dissipative through the volume compared to surface resistivity such as the polyester mesh and the spandex skull cap. Under low humidity conditions the resistivities indicate that the materials would not dissipate charge through them according to the volume resistivity results. Hence electrically bonding or grounding such materials would be ineffective except for the carbon yarn woven wool. Although the material may dissipate charge, it is unknown whether it can generate charge. A common misconception is that conductive materials that are well bonded or well grounded cannot generate electrostatic charge. This is simply not true.

The next series of tests that were performed were triboelectric charging tests in which certain materials were rubbed by hand vigorously against a stationary material at 0% humidity conditions. The rubbed material was then placed inside of a Faraday cup and the resulting charge was measured. At least five tribo experiments were done per sample per test. Between each test both the stationary samples and the tribo samples were ionized to neutralize static charges from the previous test. The averages and the results of these tests are shown in Table 4 below.

**Table 4 - Tribocharging Results**

| Stationary material | Tribocharging Results in Coulombs | | | |
|---|---|---|---|---|
| **Suit_ESD_1** | **Suit_ESD_3** | **Suit_ESD_4** | | |
| *AVG* | -1.15E-07 | 1.06E-07 | | |
| *STDEV* | 1.09E-08 | 1.73E-08 | | |
| **Suit_ESD_2** | **Suit_ESD_3** | **Suit_ESD_4** | | |
| *AVG* | -1.15E-07 | -3.34E-08 | | |
| *STDEV* | 7.78E-09 | 6.17E-09 | | |
| **Suit_ESD_3** | **Suit_ESD_1** | **Suit_ESD_2** | | |
| *AVG* | 1.26E-07 | 1.37E-07 | | |
| *STDEV* | 2.44E-08 | 1.66E-08 | | |
| **Suit_ESD_4** | **Suit_ESD_1** | **Suit_ESD_2** | | |
| *AVG* | -1.09E-07 | 2.92E-08 | | |
| *STDEV* | 7.38E-09 | 5.75E-09 | | |
| **Suit_ESD_6** | **Suit_ESD_9** | **Suit_ESD_11** | **Suit_ESD_12** | **Suit_ESD_13** |
| *AVG* | 1.13E-07 | 3.57E-08 | -9.19E-08 | -3.58E-09 |
| *STDEV* | 1.60E-08 | 1.17E-08 | 1.94E-08 | 3.23E-09 |
| | **Suit_ESD_14** | **Suit_ESD_15** | **Suit_ESD_16** | |
| *AVG* | 1.38E-07 | -3.95E-08 | 3.54E-09 | |
| *STDEV* | 1.19E-08 | 1.57E-08 | 1.29E-09 | |
| **Suit_ESD_7** | **Suit_ESD_10** | | | |
| *AVG* | -3.22E-08 | | | |
| *STDEV* | 2.85E-09 | | | |
| **Suit_ESD_8** | **Suit_ESD_9** | **Suit_ESD_11** | **Suit_ESD_12** | **Suit_ESD_13** |
| *AVG* | 1.04E-07 | 5.62E-08 | 1.20E-07 | 6.05E-08 |
| *STDEV* | 1.28E-08 | 5.67E-09 | 2.03E-08 | 1.56E-08 |
| **Suit_ESD_9** | **Suit_ESD_6** | **Suit_ESD_8** | **Suit_ESD_10** | **Suit_ESD_13** |
| *AVG* | -3.22E-08 | -6.10E-08 | 5.34E-09 | -7.87E-08 |

| Stationary material | Tribocharging Results in Coulombs | | | |
|---|---|---|---|---|
| *STDEV* | 1.05E-08 | 1.19E-08 | 1.75E-09 | 2.04E-08 |
| **Suit_ESD_10** | **Suit_ESD_7** | **Suit_ESD_9** | **Suit_ESD_11** | **Suit_ESD_12** |
| *AVG* | 2.34E-08 | 6.41E-08 | 2.44E-08 | -9.36E-08 |
| *STDEV* | 1.43E-08 | 1.48E-08 | 3.31E-09 | 1.49E-08 |
| **Suit_ESD_11** | **Suit_ESD_6** | **Suit_ESD_8** | **Suit_ESD_10** | **Suit_ESD_13** |
| *AVG* | -5.56E-09 | -1.77E-08 | 4.22E-09 | 3.70E-09 |
| *STDEV* | 1.95E-09 | 2.37E-09 | 2.94E-09 | 1.14E-08 |
| **Suit_ESD_12** | **Suit_ESD_6** | **Suit_ESD_8** | **Suit_ESD_10** | **Suit_ESD_13** |
| *AVG* | 3.58E-08 | 4.21E-08 | 4.01E-08 | 4.44E-08 |
| *STDEV* | 1.33E-08 | 8.47E-09 | 1.16E-08 | 8.53E-09 |
| **Suit_ESD_13** | **Suit_ESD_6** | **Suit_ESD_8** | **Suit_ESD_9** | **Suit_ESD_11** |
| *AVG* | 8.18E-09 | -2.47E-08 | 9.64E-08 | 2.25E-08 |
| *STDEV* | 5.49E-09 | 4.79E-09 | 1.69E-08 | 9.30E-09 |
| | **Suit_ESD_12** | **Suit_ESD_14** | **Suit_ESD_15** | **Suit_ESD_16** |
| *AVG* | -1.69E-08 | 1.25E-07 | -3.45E-08 | 4.84E-09 |
| *STDEV* | 1.05E-08 | 3.60E-08 | 1.05E-08 | 8.65E-10 |
| **Suit_ESD_14** | **Suit_ESD_6** | **Suit_ESD_13** | | |
| *AVG* | -3.84E-08 | 1.90E-08 | | |
| *STDEV* | 1.62E-08 | 9.57E-09 | | |
| **Suit_ESD_15** | **Suit_ESD_6** | **Suit_ESD_13** | | |
| *AVG* | 3.45E-08 | 5.96E-08 | | |
| *STDEV* | 3.55E-09 | 5.15E-09 | | |
| **Suit_ESD_16** | **Suit_ESD_6** | **Suit_ESD_13** | | |
| *AVG* | 5.20E-09 | 4.29E-08 | | |
| *STDEV* | 2.39E-09 | 1.02E-08 | | |

Table 4 shows the results of triboelectrically charging materials against one another that are expected to occur in typical suit configuration based on the ISS EMU. The highest charging values are shown in red in which some of the samples charged up to over 100 nano coulombs.

The higher charging scenario suggests that these configurations may want to be avoided if possible since they are the likeliest conditions to represent a potential spark. However, it is not known whether the materials themselves are capable of igniting a brush discharge of sufficient energy although it may help discriminate against certain configurations.

The next series of tests that were performed were corona charging tests. In these tests, each material was charged to a very high level using high voltage corona needles similarly to conventional brush discharge testing. These tests sought to determine whether or not enough charge could be extracted from the test article's surface and possess energies that might be significant in terms of an incendive event. In this case the concern was focused on energies that may ignite materials in the presence of 100% oxygen such as those in the suit internal volume.

The schematic of the test is shown in Figure 4 in which a small corona bed of needles spaced 1cm apart were waved by hand above the test sample which had a grounded backing to maximize charging. The needles were charged up to approximately -30,000 volts to induce a corona to generate electrons and negative ions that deposit onto the test material. Once the material was fully charged, the sample was then placed underneath and JCI 140 Electrostatic Voltmeter to monitor the surface potential that was recorded. The sample was then moved back to the charging location and charge was extracted using a JCI model 178 Charge Measurement Unit. This device was ideally suited to extract the largest amount of charge from a flat surface area in a given condition. After a small discharge has been measured by the dissipation test unit, the sample was then placed underneath the electrostatic voltmeter to monitor the change in potential. Both the amount of charge extracted as well as the drop in potentials were recorded.

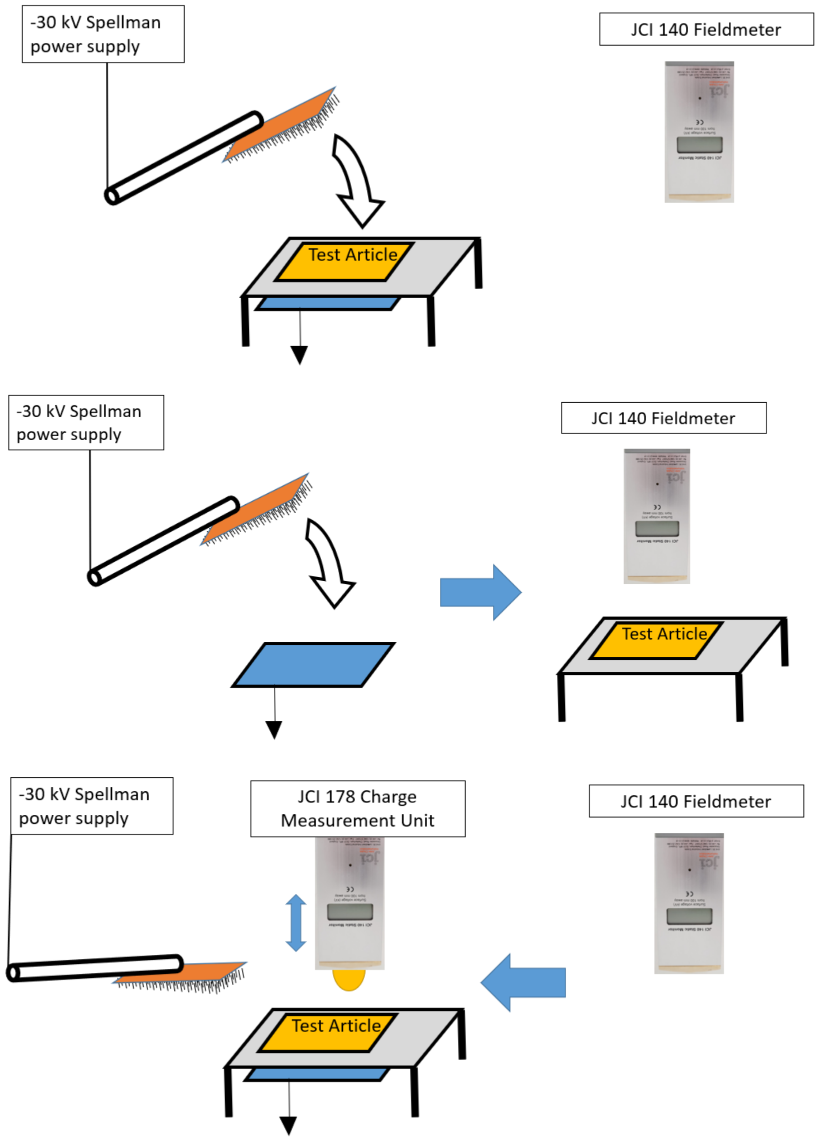



**Figure 4 - (top) Corona charging of samples. (middle) Surface potential measurements and (bottom) Charge extraction step using the Charge Device Monitor**

**Table 5 - Corona Charging Results**

| Sample No/Name | Delta V (VDC) | Ave Q (Coulombs) | Energy (µJ) |
|---|---|---|---|
| ESD_1: Polypropylene/Paper/Celluluse | -537.5 | -1.4E-10 | 0.04 |
| ESD_2: Rayon (Viscose) | -900 | -3.5E-09 | 1.59 |
| ESD_3: Teflon | -570 | -4.1E-09 | 1.17 |
| ESD_4: Spandex | -802.5 | -6.4E-09 | 2.58 |
| ESD_6: Urethane coated Nylon | -190 | -1.4E-10 | 0.01 |
| ESD_7: Nylon/Spandex Knit | -557.5 | -2.6E-09 | 0.72 |
| ESD_8: Polyester | -2615 | -1.3E-09 | 1.73 |
| ESD_9: Nylon Spandex Multifilament | -850 | -3.8E-09 | 1.62 |
| ESD_10: Nylon Spandex Knit | -75 | -1.5E-10 | 0.01 |
| ESD_11: 100% polyester mesh | -12.5 | -4.3E-10 | 0.00 |
| ESD_12: Polychloroprene | -400 | -2.4E-10 | 0.05 |
| ESD_13: Velcro Loop | -240 | -1.4E-10 | 0.02 |
| ESD_14: Wool and Lycra | -365 | -1.2E-10 | 0.02 |
| ESD_15: Viscose, polyester, wool | -362.5 | -1.2E-10 | 0.02 |
| ESD_16: Wool with carbon yarn | -507.5 | -1.2E-09 | 0.30 |

The results of the corona charging tests are shown in Table 5. One very important fact was that the discharges occurred multiple times across a single charged surface. This is significant in that a single discharge was not able to discharge the entire 6" × 6" area thus limiting the amount of total charge in the discharge. This allowed subsequent measurements without the need for recharging with the ability to monitor potential drops each time for up to five discharges. It is interesting according to Table 5 that different materials possess different charge extraction amounts correlating to different drops in the potential. Once the change in potential has been monitored and averaged, the average charge extraction can also be used to calculate the total energy of the discharges which is simply half the product of the charge times the voltage. We note here that the largest energy was caused by the spandex material with an average energy of 2.8 microJoules (µJ).

The next series of tests that were performed were to monitor the electromagnetic interference (EMI) magnitudes for each of the triboelectric charging events. This was done using a credence technologies model EMI device that captures EMI waveforms and assigns a value in volts per meter which is proportional to the electric field magnitude of the incident wave. To calibrate this test a spark gap system was used to generate a 20 µJ spark at a given location from where the triboelectric charging occurs. The average strength of the spark gap EMI was approximately 600 volts per meter. Thus one might expect readings above this value may be of concern for systems that are highly sensitive to ignitions in this energy range.

The repeat of the triboelectric tests of Table 4 are shown below in Table 6 however this time EMI is measured instead of the overall charge left on the sample. Again at least five tests were performed per configuration per sample and the averages and the standard deviations are presented in the table.

The highest readings are highlighted in red to denote values that were above the 600 volts per meter. It is interesting to note that in many cases these overlap quite nicely with the highest triboelectric charging configurations of Table 4. What is more interesting though is that ESD sample 9 is tribocharged with sample 10 EMI is not produced. This configuration should not produce EMI. Thus this table can be used as a guideline to determine which configurations may need to be avoided.

Table 6 - Results of the EMI Testing with EM Eye

| Stationary material | EMI Test Results from EM Eye (V/m) | | | |
|---|---|---|---|---|
| **Suit_ESD_1** | **Suit_ESD_3** | **Sui_ESD_4** | | |
| *AVG* | 4.39E-02 | 5.16E-02 | | |
| *STDEV* | 1.09E-03 | 8.32E-03 | | |
| **Suit_ESD_2** | **Suit_ESD_3** | **Suit_ESD_4** | | |
| *AVG* | 4.51E-02 | 4.65E-02 | | |
| *STDEV* | 4.65E-03 | 2.53E-03 | | |
| **Suit_ESD_3** | **Suit_ESD_1** | **Suit_ESD_2** | | |
| *AVG* | 5.08E-02 | 4.66E-02 | | |
| *STDEV* | 6.92E-03 | 2.36E-03 | | |
| **Suit_ESD_4** | **Suit_ESD_1** | **Suit_ESD_2** | | |
| *AVG* | 6.30E-02 | | | |
| *STDEV* | 2.42E-02 | | | |
| **Suit_ESD_6** | **Suit_ESD_9** | **Suit_ESD_11** | **Suit_ESD_12** | **Suit_ESD_13** |
| *AVG* | 9.16E-02 | 5.96E-02 | 8.82E-02 | 7.23E-02 |
| *STDEV* | 6.20E-02 | 1.24E-02 | 2.99E-02 | 1.15E-02 |
| | **Suit_ESD_14** | **Suit_ESD_15** | **Suit_ESD_16** | |
| *AVG* | 1.08E-01 | 6.17E-02 | 4.57E-02 | |
| *STDEV* | 5.17E-02 | 1.16E-02 | 4.62E-03 | |
| **Suit_ESD_7** | **Suit_ESD_10** | | | |
| *AVG* | 5.04E-02 | | | |
| *STDEV* | 7.62E-03 | | | |
| **Suit_ESD_8** | **Suit_ESD_9** | **Suit_ESD_11** | **Suit_ESD_12** | **Suit_ESD_13** |
| *AVG* | 7.15E-02 | 5.28E-02 | 6.75E-02 | 1.11E-01 |
| *STDEV* | 1.94E-02 | 9.72E-03 | 1.27E-02 | 1.74E-02 |
| **Suit_ESD_9** | **Suit_ESD_6** | **Suit_ESD_8** | **Suit_ESD_10** | **Suit_ESD_13** |
| *AVG* | 9.21E-02 | 7.38E-02 | 0.00E+00 | 4.79E-02 |
| *STDEV* | 2.94E-02 | 2.13E-02 | 0.00E+00 | 4.14E-03 |
| **Suit_ESD_10** | **Suit_ESD_7** | **Suit_ESD_9** | **Suit_ESD_11** | **Suit_ESD_12** |
| *AVG* | 3.48E-02 | 3.47E-02 | 3.04E-02 | 9.17E-02 |
| *STDEV* | 5.16E-03 | 4.51E-03 | 1.78E-03 | 2.75E-02 |
| **Suit_ESD_11** | **Suit_ESD_6** | **Suit_ESD_8** | **Suit_ESD_10** | **Suit_ESD_13** |
| *AVG* | 5.13E-02 | 2.79E-02 | 3.51E-02 | 2.94E-02 |
| *STDEV* | 6.55E-03 | 1.15E-03 | 1.06E-02 | 9.24E-04 |
| **Suit_ESD_12** | **Suit_ESD_6** | **Suit_ESD_8** | **Suit_ESD_10** | **Suit_ESD_13** |
| *AVG* | 3.32E-02 | 3.01E-02 | 3.05E-02 | 3.34E-02 |
| *STDEV* | 1.83E-03 | 4.98E-04 | 2.20E-03 | 6.13E-03 |
| **Suit_ESD_13** | **Suit_ESD_6** | **Suit_ESD_8** | **Suit_ESD_9** | **Suit_ESD_11** |

| Stationary material | EMI Test Results from EM Eye (V/m) | | | |
|---|---|---|---|---|
| *AVG* | 2.76E-02 | 2.88E-02 | 5.90E-02 | 3.07E-02 |
| *STDEV* | 5.41E-04 | 1.60E-03 | 2.22E-02 | 1.71E-03 |
| | **Suit_ESD_12** | **Suit_ESD_14** | **Suit_ESD_15** | **Suit_ESD_16** |
| *AVG* | 7.43E-02 | 4.77E-02 | 6.31E-02 | 2.85E-02 |
| *STDEV* | 1.83E-02 | 1.17E-02 | 2.96E-02 | 1.70E-03 |
| **Suit_ESD_14** | **Suit_ESD_6** | **Suit_ESD_13** | | |
| *AVG* | 3.37E-02 | 2.74E-02 | | |
| *STDEV* | 8.78E-03 | 7.31E-04 | | |
| **Suit_ESD_15** | **Suit_ESD_6** | **Suit_ESD_13** | | |
| *AVG* | 2.87E-02 | 3.00E-02 | | |
| *STDEV* | 5.13E-04 | 8.81E-04 | | |
| **Suit_ESD_16** | **Suit_ESD_6** | **Suit_ESD_13** | | |
| *AVG* | 2.93E-02 | 2.93E-02 | | |
| *STDEV* | 1.19E-03 | 4.36E-04 | | |

## IV. Discussion

Several tests were performed to evaluate the ESD of potential helmet materials and their configurations. The data could be used to discriminate against configurations that may lead to higher potentials of discharges with those of higher energy. It is also useful to show which material configurations do not give rise to high energy discharges or high tribal electric charging. The highest energy discharges were on the order of two to three micro joules which is on the very low end of the brush discharge energy spectrum. These energies are known to only ignite pure hydrogen in an oxygen environment. Energies that are 10 times higher can ignite hydrogen in air are still among the lowest known. As shown in Table 1, in pure oxygen these energies are also capable of igniting combustible hydrocarbon vapors. For combustible dusts such as coal dust energies that are 10,000 times higher even in the presence of 100% oxygen are required for ignition. As can be noted from Figure 3, the surface resistivity results for all materials tested less the wool with carbon yarn indicates that they are not static dissipative with two of the materials ESD_2 (viscose) and ESD_15 (viscose/polyester/wool) transitioning to dissipative with the aid of the 40% RH. ESD_16 (wool with carbon yarn) is dissipative and shows little dependence with a variation from ~0% to 40%. As is shown in Table 4, several typical pairings of these materials like that of the ISS EMU are capable of generating an accumulation of charge via tribo-charging. An important consideration for these materials is then shown in Table 5 which demonstrates that for the material alone, the surface and volume resistivities that enable them to tribo-charge without sufficient dissipation to then accumulate charge also limit the energy produced on a single discharge lowering the available energy in a given arc. In all cases, ESD_16 (wool with carbon yarn) shows improvement over the other materials tested.

In summary, the test data referenced herein confirm the similar results to those presented in the Apollo era report[10] with energy levels capable of igniting combustible vapors but insufficient to ignite solid materials present in the suit. Hence, while the maximum reported electrostatic discharge energies from a human body are reported to be in the 15-20 mJ range[6], which is enough to ignite several of the suit materials in 100% oxygen[10], the selection of the suit materials tested does not produce such a result nor did the suited tests performed and summarized in the Apollo era report. Hence, just as that selected after the Apollo study, grounding/bonding the crew to the suit in order to bleed off charge and preclude excessive charge accumulation provides a verifiable hazard control to address potential variations/permutations not tested given the catastrophic nature of the fire hazard in the space suit.

## V. Application to EMU and other Space Suit Designs

With the development of several new suit designs underway, it is important to consider not that the hazard has been controlled previously, but more precisely the details for how it was controlled and mitigated such that the new suit designs may consider those methods or adapt new ones. Suited applications going back to Gemini have been without incident of a ESD initiated fire aided by multiple controls and mitigating factors:

1. The Apollo EMU and Shuttle/ISS EMU designs grounded the crewmember to the PLSS through the biomedical system. This served to bleed off the charge developed by the crew and preclude in-suit discharges. This is the most direct engineering design control and one that is used throughout industry to mitigate similar hazards from ESD especially in the electronics and semi-conductor industries.
2. MIE for hydrocarbon fuel mixtures increased from 0.002 – 0.004 mJ with 100% $O_2$ at 1 atm to 0.02 – 0.04 mJ with the lowered pressures at 1/3 atm (5 psia). For the suited activities, the only scenarios for which the suit is at elevated pressures at 1 atm and above are during intra-vehicular activities (IVA) such as suit leakage check, purge, and prebreathe or potentially as high as 23-25.2 psia during decompression sickness (DCS) treatment. The most significant portion for tribocharging from relative movement in the suit occurs during the EVA which has been historically operated at 3.5-4.3 psia range.
3. During these IVA tasks, the metabolic rates are generally low and there is limited movement even considering the in-suit light exercise (ISLE) prebreathe protocol added during the ISS Program; this includes frequent but controlled motions of the crew's arms and legs to enhance denitrogenation.
4. Both the Apollo and Shuttle/ISS EMU used a condensing heat exchanger (CHX) designs for EVA operations with 100% oxygen
    a. These CHX take two forms:
        i. The component that is located within the PLSS that condenses out moisture derived from the crew and from the lithium hydroxide (LiOH) scrubber reaction (if present) controlling the dewpoint of the gas recirculated to the helmet inlet to a range just above the reference sink temperature of the sublimator based on the current loading conditions.
        ii. The liquid cooling and ventilation garment (LCVG) which circulates cooling water to extract metabolic waste heat and some environmental heat in-leak (depending on thermal environment) from the crew. As the crew's metabolic rate increases, the cooling water temperature is lowered to increase the differential temperature between skin temperature and transport water temperature enhancing the heat flux. With the lowering of this temperature below the outlet dewpoint from the CHX within the PLSS, the LCVG becomes a second CHX. It also becomes a CHX with increases in the crew expiration rate of moisture from increased minute volume and sweat transition as the crew accumulates heat storage during high metabolic work periods.
    b. Once these CHX are actively controlling the dewpoints, the RH levels are typically >50% in the suit volume permitting increased charge relaxation.
5. The Shuttle/ISS EMU strictly limits the materials and compounds introduced into the suit volume including limitations on personal care products and hygiene products in order to reduce the opportunity for the formation of combustible vapors that can be ignited at lower energy levels. These materials are also limited in the suit volumes to aid in control of trace contaminant accumulation during closed loop operations and damage/impairment of the life support system functions such as hydrophilic coatings in the sublimator condensing heat exchanger. The potential impacts of particular compounds will be suit specific with some level of control likely necessary for all suits.

This is not intended to be a complete list but is worth consideration for new designs with a detailed review that will occur as part of the flight qualification and safety process with specific review of the oxygen fire hazard.

## VI. Conclusion

The review of literature including previous Apollo era testing coupled with surface resistivity, volume resistivity, corona discharge, tribocharging, and EMI signature testing of a selection of current suit materials suggests that the available discharge energies from tribocharging of these materials in the suit application based on the Apollo and Shuttle/ISS EMUs are below the levels needed to ignite all but combustible vapors in the 100% oxygen environment of the suit. Each of these suit designs provided a verifiable design control to bleed off the charge and reduce the likelihood of in-suit discharges via grounding/bonding the crew via the biomedical system. Addition of new materials such as ESD_16 (wool with carbon yarn) can offer additional means not used for Apollo and Shuttle/ISS EMU for controlling this hazard. It is entirely possible that new materials and usage cases could exacerbate some of these factors with enhanced relative tribocharing, lower dissipation with lower humidities, increased tribocharging via increased ambulation or suit design specifics, and so on. For any new system, many factors specific to the suit design and usage cases with some examples presented herein will need to be assessed during the development and qualification phases to determine the best method to control the fire hazard from electrostatic discharge.

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