Electrostatic Discharge Hazard in Spacesuits

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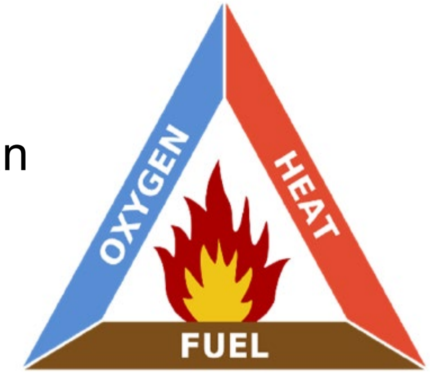
Overview

- Motivation and Purpose
- Review of Suit Conditions and Existing Historical Data
- Materials, Test Methods and Results
  - Surface and Volume Resistivity Results
  - Tribocharging Results
  - Corona Charging Results
  - EMI Magnitude Results
- Findings and Recommendations

Motivation and Purpose

- Motivation:
  - Spacesuits internal atmosphere maintained at 100% O_2 to enable operation down to 3.1 psia (21.4 kPa)
  - Materials within the suit are flammable in 100% O_2
  - Per the fire triangle, control of ignition sources is the only remaining option to mitigate suit fire hazards
    - Historically managed by limiting power to the suit
    - Electrostatic discharge (ESD) historically considered too low energy to be an ignition source, but only limited data
  - Multiple new suit providers have posed questions related to ESD arc ignition

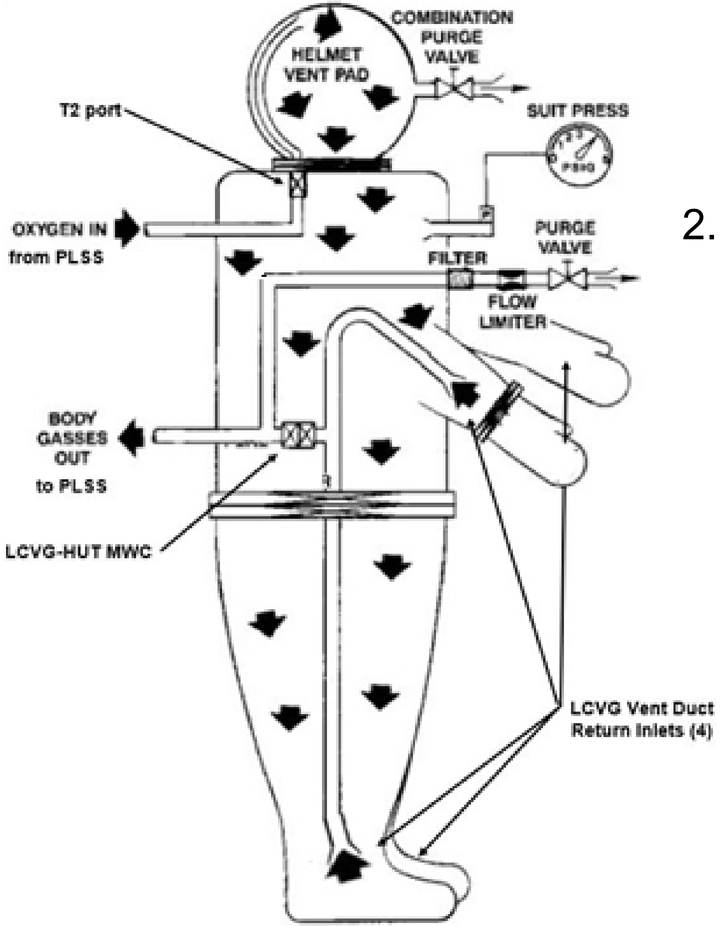
- Purpose:
  - To summarize existing ESD ignition test data
  - To report the results of triboelectric charging assessments of typical internal spacesuit materials
  - To discuss applicability of data to the ISS space suit and other space suit designs.

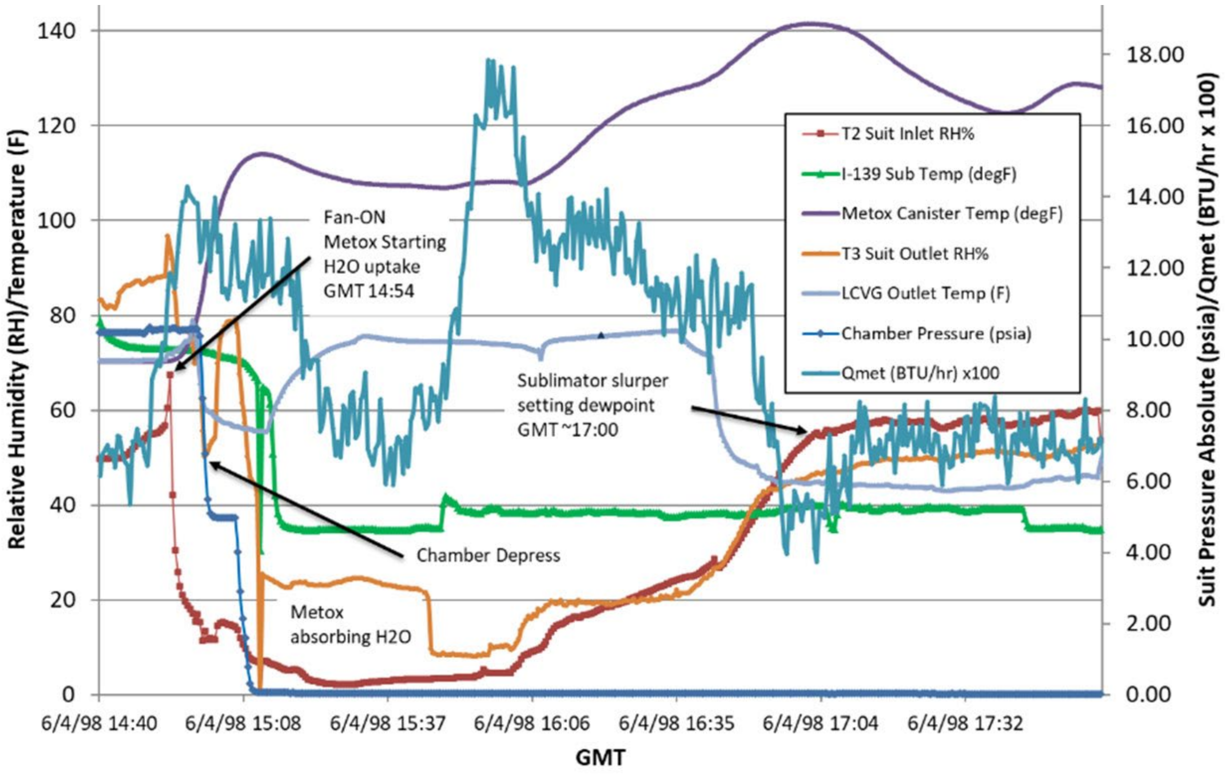


Fire triangle. [Image credit: Wikipedia]

Background: Tribocharging in Suits

- Tribocharging = charging via contact and separation of solid materials, mechanism of concern relevant to suit internal volume
  - Occurs from:
    1. Contact and relative movement of the materials lining the suit and those being worn by the crewmember, or
    2. Contact and relative movement on the outside of the suit with those of the environment





Relative Humidity at T2 (helmet inlet) PLSS 1005 11ft Metox AVT

- Charge **accumulation** then occurs when charging rate > processes that bleed or relax the charge
- Possible mitigations:
  - Grounding/bonding
  - Relative humidity > 50%...not always possible in the suit due to flow path and ventilation system design

Background: Charge Energy and Material Ignition

- Charges accumulated and discharged from human beings can range from 1 to 10's of millijoules
  - 1mJ spark = perceptible
  - 10mJ spark = a prick
  - 30mJ spark = a sharp prick
  - 100mJ = a slight jerk
- The minimum ignition energies (MIE) for combustible vapors and dusts < potential discharges from humans (Table 1)
- Apollo testing:
  - Cotton fabric ignited with 9-20 mJ at 16.5 psia in 100% oxygen
  - No ignitions up to 170 mJ at 6.2 psia in 100%
  - Oxygen
    - Considered only 20 sparks per condition - may or may not address sample and test condition variability.
  - Crew charge in suited tests varied with RH (Table 2)

Table 1 – Minimum Ignition Energies for Selected Fuels in Air and Oxygen

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	---	---

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

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

- Stored energy can be modeled as:
  - C = Capacitance of human
  - V = measured voltage
  - E = available energy

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

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

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

- Result = Apollo concluded ESD not a hazard for suit material ignition (2mJ insufficient to ignite solid materials)
  - Note: Apollo crewmember grounded to prevent discomfort from ESD

Tests Conducted

- Five tests conducted at KSC Electrostatics and Surface Physics Laboratory

1. Surface Resistivity – measures conductivity along a surface
2. Volume Resistivity – measures conductivity through a surface

For Resistivity Measurements:

- Conductive materials $<10^4\ \Omega$
- $10^4\ \Omega <$ Dissipative materials $< 10^{11}\ \Omega$
- Insulative materials $>10^{11}\ \Omega$

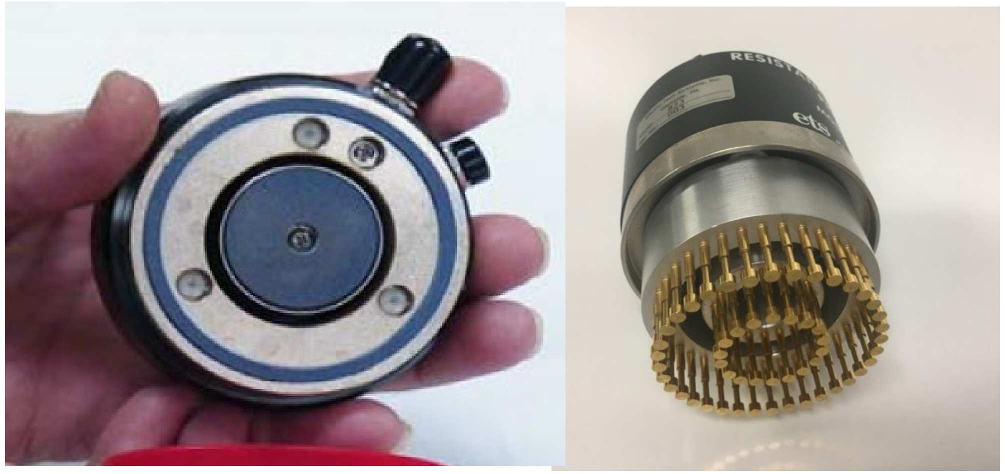
3. Triboelectric Charging
4. Corona Charging
5. Electromagnetic Interference magnitude (during Tribocharging)

Surface and Volume Resistivity Measurements Methods

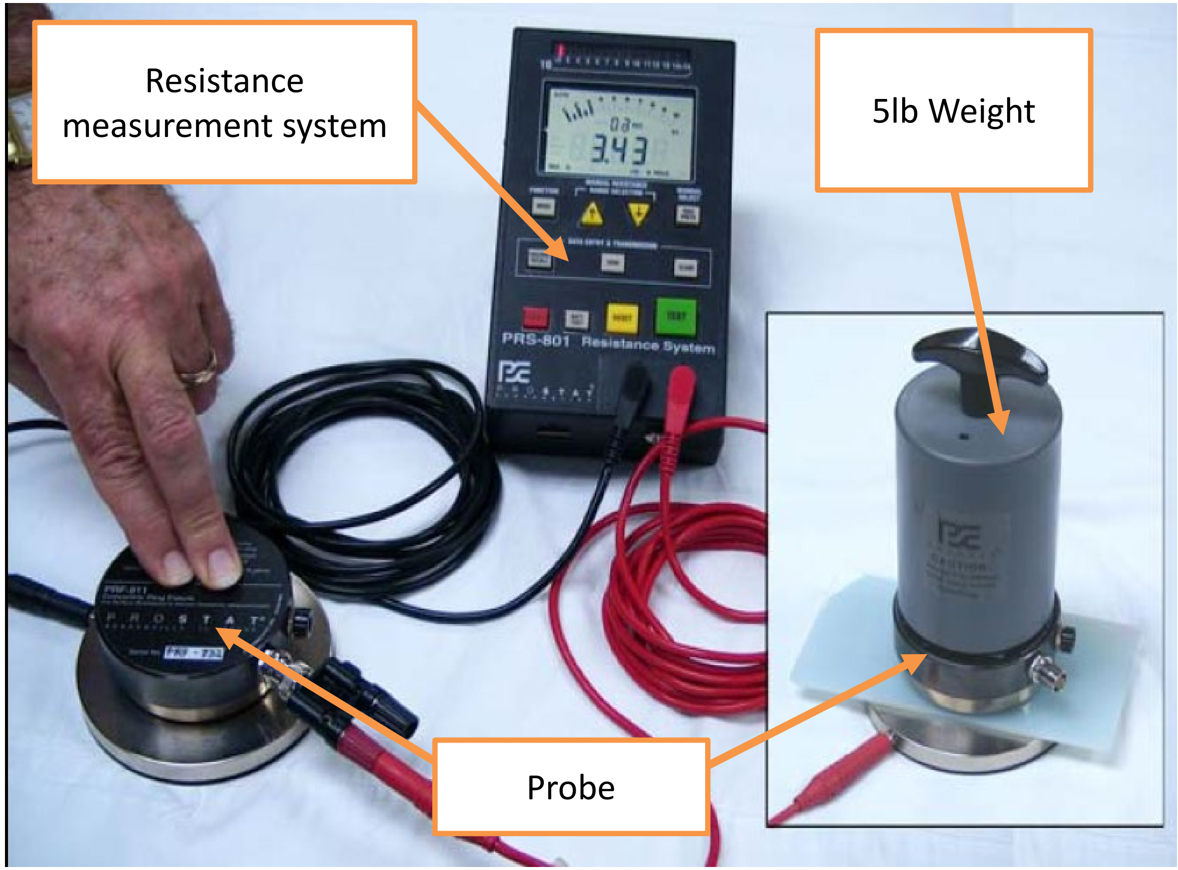
- All resistivity measurements taken at 0% and 40% relative humidity (RH) after 48 hr environmental acclimation
  - Surface Resistivity - measured via ESD STM 11.11
  - Volume Resistivity - measured via ESD STM 11.12
    - Volume resistance measured and converted to volume resistivity (ρ_v) by:

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

where A is electrode area, t is specimen thickness, and R_v is volume resistance



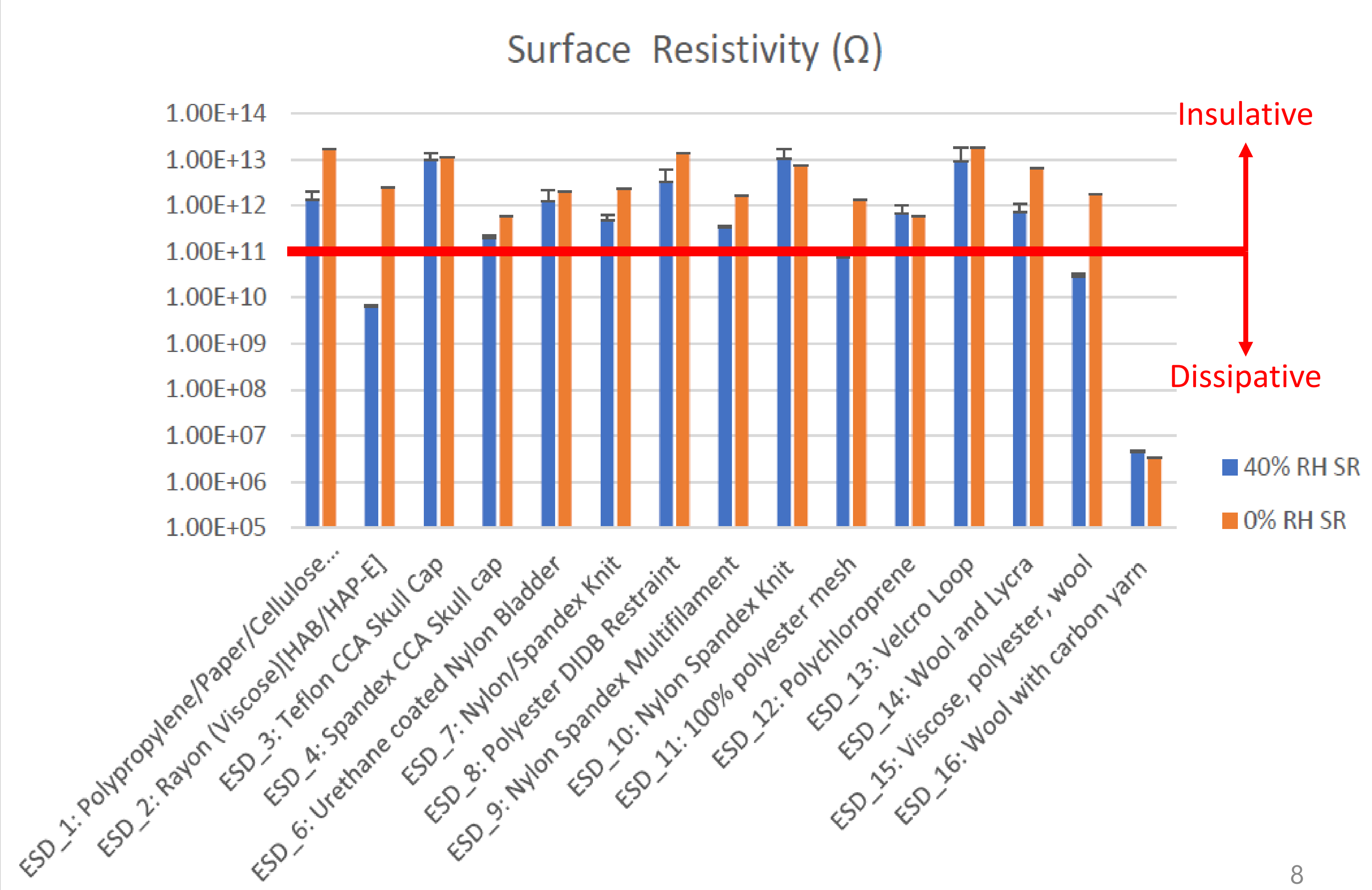
Concentric ring resistance probes used in volume resistivity measurement. *PRF-911 resistance probe (left) and ETS-823 resistance probe (right).* [Image credit: Prostat Corporation (left) and ETS, Inc. (right)]



Example image of surface and volume resistance measurement apparatus. *PRF-911 resistance probe placed on material for testing. 5lb weight placed on probe. PRS-801 resistance system used to capture measurements.* [Image credit: Prostat Corporation]

Surface Resistivity Data

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



Volume Resistivity Data

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
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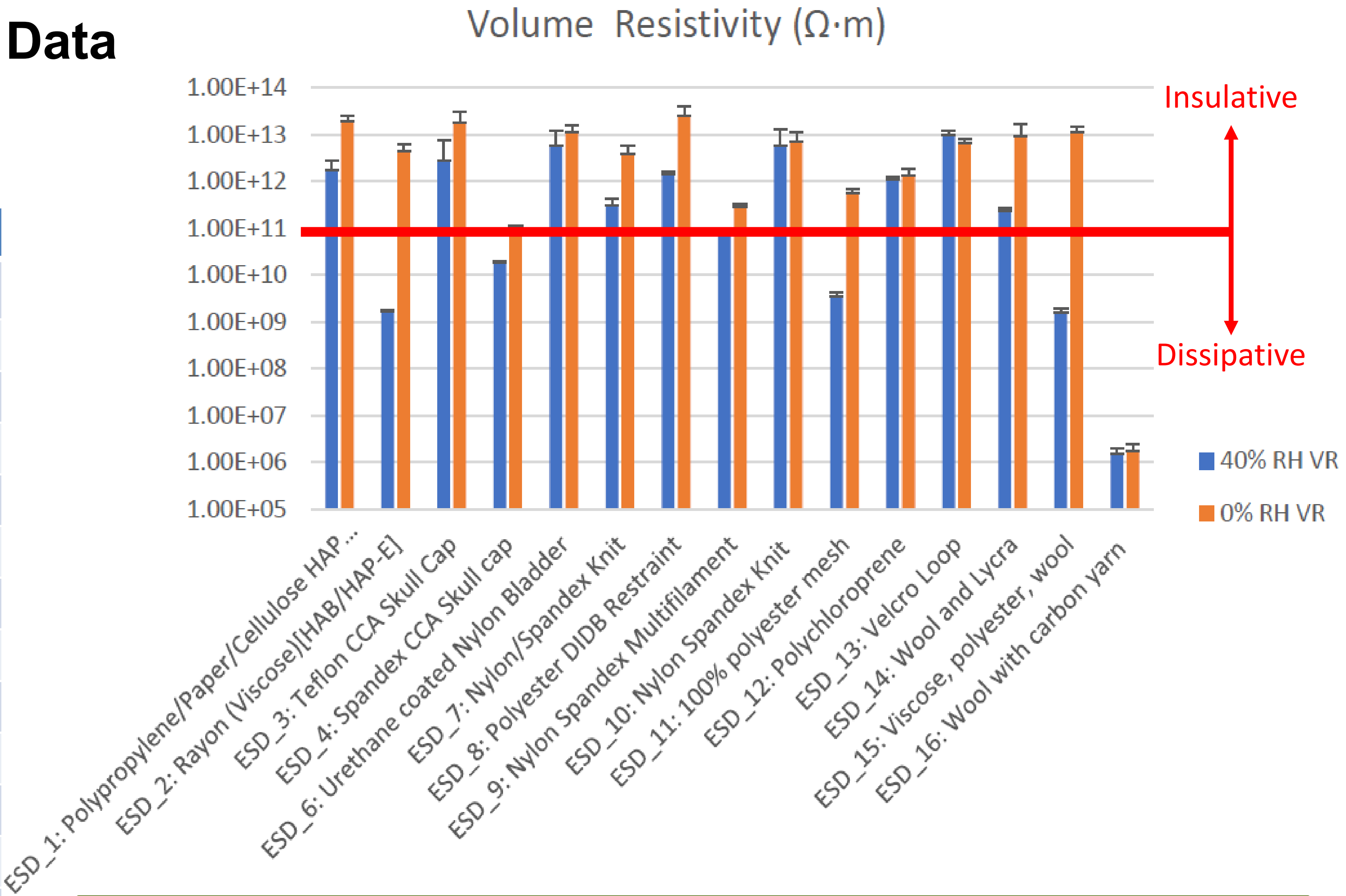


F-1. At low humidity, all materials tested are highly insulating per surface and volume resistivity data except wool impregnated with carbon yarn (dissipative). Electrically bonding or grounding these materials would be ineffective at dissipating charge.

F-2. Addition of new materials such as ESD_16 (wool with carbon yarn) can offer a means for controlling ESD hazard that was not available for Apollo and Shuttle/ISS EMU.

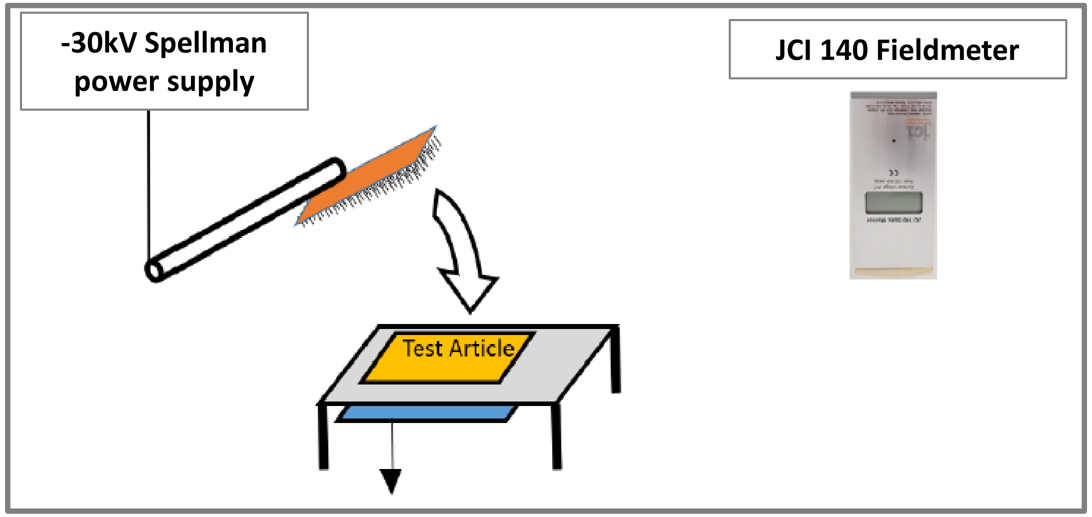
Tribocharging Measurement Methods and Results

- Tribocharging Test Steps:
  1. One material ("tribo" material) is rubbed by hand (vigorously) against a stationary material at 0% RH
  2. Tribo material is placed inside a Faraday cup
  3. Charge measured
- At least 5 experiments were run per sample per test
- Between each experiment both samples were ionized to neutralize static charge from previous test
- Combinations of materials tested based on those expected to occur in typical suit configuration based on ISS EMU (shown with "T")
- Red boxes indicate materials with the highest charging values (over 100 nano coulombs)

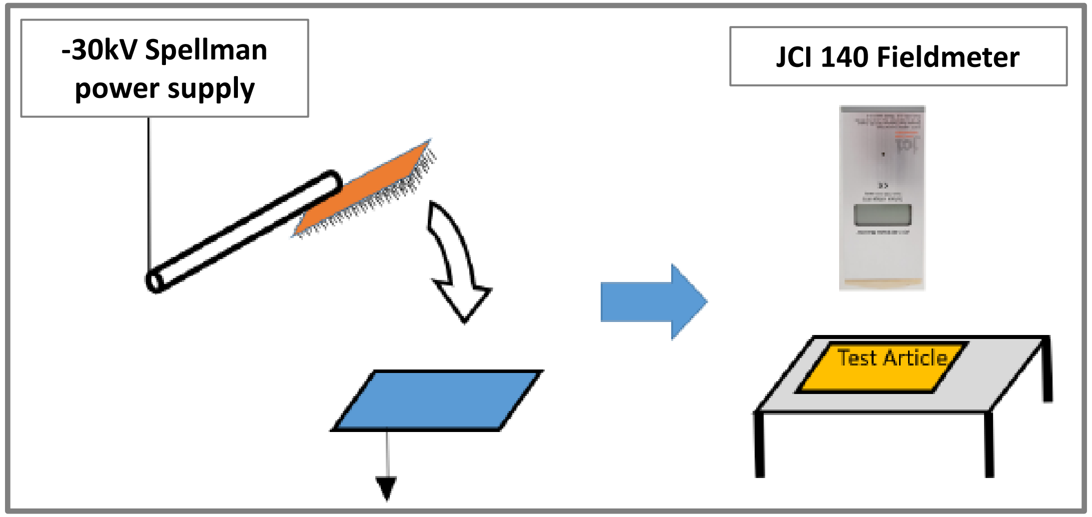
F-3. Eleven combinations of materials known to make intermittent contact based on ISS EMU showed notably higher charging than other configurations, suggesting a higher risk of ESD than other material configurations.

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

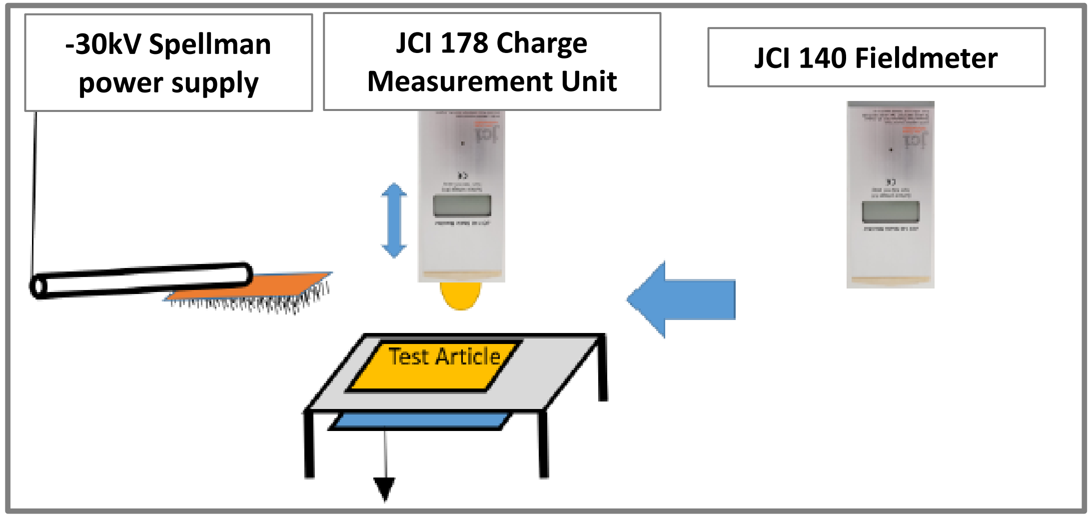
Corona Charging Test Method



1. Corona charging of samples using corona bed of needles space 1 cm apart.



2. Surface potential measurements made using an electrostatic voltmeter after full charge in Step 1.



3. Charge extraction using the Charge Device Monitor. After small discharge is measured, electrostatic voltmeter used to monitor the change in potential.

Corona Charging Results

- Discharges were observed to occur multiple times across a single charged surface (6” x 6”)
  - Limited the total charge in a single discharge
  - Allowed multiple measurements to be taken without requiring recharge (up to 5 discharges)
  - Allowed monitoring of potential drops
- Discharge energy (E in µJ) calculated by:

$$E = \frac{V * Q}{2}$$

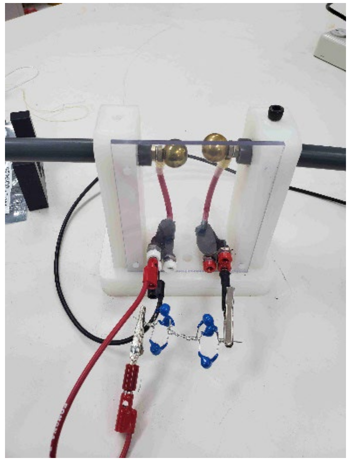
where V is the discharge voltage, and Q is the charge in coulombs.

F-4. Discharges were observed to occur multiple times across a charged surface (6” x 6”) during corona charging testing, which limited the total charge in a single discharge and allowed for multiple readings to be taken following a single charge.

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

EMI Magnitude During Tribocharging Test Method

- EMI magnitudes were measured for each of the triboelectric charging events.
  - Credence Technologies EM Eye - DL device (CTM045)
    - Calibrated using spark gap system generating 20 μJ, average strength = 600V/m
  - Tribocharging tests were repeated while measuring EMI
    - At least 5 experiments were run per sample per test
    - For EMI > 600V/m, "E" is shown in red



Spark gap system used for calibration

EM Eye-DL used to measure the magnitude of EMI generated during tribocharging

Dark red	Both Tribocharging and EMI were high
Peach	Only Tribocharging was high
Yellow	Only EMI was high
Green	EMI was zero

EMI Results Tribo Material → Stationary Material ↓	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
ESD_1: Polypropylene/Paper/ Cellulose HAP Liner			T, E	T, E											
ESD_2: Rayon (Viscose) [HAB/HAP-E]			T, E	T, E											
ESD_3: Teflon CCA Skull Cap	T, E	T, E													
ESD_4: Spandex CCA Skull cap	T, E	T													
ESD_6: Urethane coated Nylon Bladder								T, E		T, E	T, E	T, E	T, E	T, E	T, E
ESD_7: Nylon/Spandex Knit									T, E						
ESD_8: Polyester DIDB Restraint								T, E		T, E	T, E	T, E			
ESD_9: Nylon Spandex Multifilament					T, E		T, E		T, 0			T, E			
ESD_10: Nylon Spandex Knit						T, E		T, E		TE	T, E				
ESD_11: 100% polyester mesh					T, E		T, E		T, E			T, E			
ESD_12: Polychloroprene					T, E		T, E		T, E			T, E			
ESD_13: Velcro Loop					T, E		T, E	T, E		T, E	T, E		T, E	T, E	T, E
ESD_14: Wool and Lycra					T, E							T, E			
ESD_15: Viscose, polyester, wool					T, E							T, E			
ESD_16: Wool with carbon yarn					T, E							T, E			

(Preliminary)* NESC Recommendations

It is recommended that….

R-1. Spacesuit designers evaluate materials and configurations via measurements of surface resistivity, volume resistivity, tribocharging, corona charging, and EMI magnitude to quantify the risk of fire from electrostatic discharge and inform mitigation plans. (*F-1, F-2, F-3, F-5, F-6)*

Additional Information

Tribocharging Tabulated Results

Sample Name
ESD_1: Polypropylene/Paper/Cellulose HAP Liner
ESD_2: Rayon (Viscose)[HAB/HAP-E]
ESD_3: Teflon CCA Skull Cap
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ESD_14: Wool and Lycra
ESD_15: Viscose, polyester, wool
ESD_16: Wool with carbon yarn

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		

EMI Tabulated Results

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
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ESD_12: Polychloroprene
ESD_13: Velcro Loop
ESD_14: Wool and Lycra
ESD_15: Viscose, polyester, wool
ESD_16: Wool with carbon yarn

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

Stationary material	EMI Test Results from EM Eye (V/m)			
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
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		