Electrostatic Discharge (ESD) Ignition Hazards in Hyperbaric Environments

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Presented By: Nic Linley
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WHA International, Inc.
5605 Doña Ana Road | Las Cruces, NM 88007 | Phone: (575) 523-5623 | Fax: (575) 541-3621 | www.wha-international.com

Outline

- Introduction
- Publications Summary
- ESD Test Data
- ESD Risk Summary

Introduction

- WHA reviewed literature and electrostatic discharge (ESD) test data in order to characterize the ESD ignition risk in hyperbaric chambers.
  - Over 40 publications, test standards, and information based web sites were reviewed.
- Understanding the Risk:
  - Risk of materials igniting due to ESD is based on the materials susceptibility to ignition (minimum ignition energy) and the energy levels that could develop and be discharged in an ESD event.
  - Risk of materials "charging" and transferring charges to a human body or some other capacitive/conductive body that may discharge an incendiary spark.

Noteworthy Publications

- ESDA:
  - *Electrostatic Discharge Sensitivity Testing -- Human Body Model* , ESDA-JEDEC JS-001 (2010)
  - *Calculation of Uncertainty Associated with Measurement of Electrostatic Discharge (ESD) Current,* ESD TR14.0-01-00 (2000)
  - *System Level Electrostatic Discharge (ESD) Simulator Verification Standard Practice,* ANSI/ESD SP14.1-2004 (2004)
- Federal
  - "Static Electricity in the Apollo Spacecraft," NASA TN D-5579 (1969)
  - "Flammability of Materials in Hyperbaric Atmospheres," US Department of the Interior, Explosive Research Center, Bureau of Mines, Appropriation 7560370 (1967)
- Other
  - Zhancheng, Wu et al., "Research on ESD Ignition Hazards of Textiles," Journal of Electrostatics (2002)
  - Andersson, Birgitta et al., "Charging of a Person Exiting a Car Seat," Electrostatics, Journal of Physics: Conference Series 142 (2008)
  - Asanovic, Koviljka A. et al., "Investigation of the Electrical Behavior of Some Textile Materials," Journal of Electrostatics (2006)
  - Chubb, J. N., "A Standard Proposed for Assessing the Electrostatic Suitability of Materials, " Journal of Electrostatics (2007)
  - "Guidelines for the Control of Static Electricity in Industry," Occupational Safety & Health Service (OSH), Department of Labour, New Zealand (1990)

Static Charge Accumulation

Table 1. Maximum body voltages.

Laboratory	Seat / Cover	Garment	Body Voltage (kV)	Stored Energy (mJ)
Renault	Regular Seat in Car / No Additional Cover	Reference Garment (Polyester/Cotton Coverall)	6.66 to 18.00*	3.33 to 24.30*
SP	Leather Seat / No Additional Cover	100% Cotton Coat	10.02	7.53
SP	Polyester Seat / No Additional Cover	Polyester/Cotton Coat	12.40	11.53
SP	Polyester Seat / No Additional Cover	Reference Garment (Polyester/Cotton Coverall)	16.29	19.90
BTTG	Polyester Seat / No Additional Cover	Reference Garment (Polyester/Cotton Coverall)	9.58	6.88
BTTG	Polyester Seat / No Additional Cover	100% Cotton Jeans & Jacket	14.04	14.78

* Dependent on the type of upholstery.

Andersson, Birgitta et al., "Charging of a Person Exiting a Car Seat," Electrostatics, Journal of Physics: Conference Series 142 (2008)

US GOV Data

- NASA Data (1969)
  - “Static Electricity in the Apollo Spacecraft,” NASA TN D-5579 (1969)
  - 9 mJ ignition observed at 16.5 psia in both oxygen environment and oxygen/nitrogen mixed environment (10.0 psia oxygen and 6.5 psia nitrogen partial pressures).
  - No ignitions observed at 6.2 psia oxygen
  - Demonstrates probabilistic nature of ignition testing at low energies
- US DOI (1967)
  - “Flammability of Materials in Hyperbaric Atmospheres,” US Department of the Interior, Explosive Research Center, Bureau of Mines, Appropriation 7560370 (1967)
  - Lowest ignition energy observed was 20 mJ at 0 psig oxygen using an “inductive spark”
  - Demonstrates probabilistic nature of ignition testing at low energies
- Next slide are table extracts from these documents. The red annotations mark the data described in this slide.

NASA Data (1969)

TABLE II. - SPARK IGNITION OF COTTON CLOTH

Spark energy, mJ	Number of sparks	Results
16.5 psia oxygen, Feb. 29, 1968		
12	26	No ignition
20	21	1 ignition
26	28	No ignition
32	14	No ignition
41	21	No ignition
52	21	No ignition
74	5	1 ignition
16.5 psia oxygen, Mar. 6, 1968		
9	8	1 ignition
12	6	1 ignition
20	16	2 ignitions
6.2 psia oxygen, Mar. 6, 1968		
20	20	No ignition
32	20	No ignition
47	20	No ignition
100	20	No ignition
130	20	No ignition
150	21	No ignition
170	22	No ignition
16.5 psia total pressure: 10.0 psia oxygen, 6.5 psia nitrogen, Mar. 6, 1968		
9	10	1 ignition
12	10	1 ignition
20	10	2 ignitions
32	40	1 ignition
42	20	1 ignition
52	12	1 ignition
75	30	1 ignition
100	3	1 ignition

"Static Electricity in the Apollo Spacecraft," NASA TN D-5579 (1969)

US DOI (1967)

TABLE 6. - Summary of Data for Materials Tested Using Various Methods of Spark Formation.

Material	Press. psig	Ignition gap, inch	Ignition energy, mj	Oxidizer	Ignition Source
Rubber sheet, conductive	0	.250	1/	Air	Jacob's Ladder
Cotton sheet	"	"	"	"	" "
Paper drapes	"	"	"	"	" "
Velcro	"	"	"	"	" "
Wood dowel pin	"	"	"	"	" "
Wood dowel pin	"	"	"	Oxygen	" "
Cotton sheet, treated	"	"	2/	Air	" "
Cotton sheet, treated	"	"	1/	Oxygen	" "
Nomex	"	"	"	Air	" "
Nomex	"	"	"	Oxygen	" "
Thread #8, cotton	"	"	"	Air	" "
Thread #8, cotton	"	"	"	Oxygen	" "
Cotton sheet	"	0.015	7050	"	Inductive spark
Velcro	"	0.345	272	"	" "
Cotton balls	"	.500	39	"	" "
Cotton balls	15	.400	136	"	" "
Cotton balls	"	.200	81	"	" "
Cotton sheet	"	.200	109	"	" "
Cotton sheet, treated	"	.200	109	"	" "
Rubber sheet, conductive	"	.200	109	"	" "
Wood dowel pin	"	.200	216	"	" "
Cotton balls	"	.013	122	"	Capacitive spark
" "	0	.005	5230	"	" "
" "	"	.015	1650	"	" "
" "	"	.025	157	"	" "
" "	"	.050	106	"	" "
" "	"	.075	192	"	" "
" "	"	.100	76	"	" "
" "	"	.125	32	"	" "
" "	"	.150	370	"	" "
" "	"	.015	3/	"	Inductive spark
" "	"	.025	272	"	" "
" "	"	.050	56	"	" "
" "	"	.075	24	"	" "
" "	"	.100	20	"	" "
" "	"	.125	34	"	" "
" "	"	.150	41	"	" "

1/ Ignition with one or more passes of arc.
2/ Chars only with 25 passes of arc.
3/ No ignition at 1480 millijoules.

"Flammability of Materials in Hyperbaric Atmospheres," US Department of the Interior, Explosive Research Center, Bureau of Mines, Appropriation 7560370 (1967)

Wu, Zhancheng ESD Data

"Standard atmospheric pressure"

Table 1
The results of ignition experiment in pure oxygen

Voltage (kV)	Stored energy (mJ)	Being ignited or not
8.5	4.34	Not
9.0	4.80	Cotton is ignited
11.5	7.94	Cotton and matas are ignited
30	67.5	Terylene, Chinlon and butyl rubber are not ignited yet

NOTE: "0 Ohm" Resistance

In his paper, Wu also reports

- With 20 Ohm resistance cotton ***ignited*** at 29.04mJ (C=120pF, R=20ohm)
  - Wu references a study that suggests that Human Body resistance can be low as 20 ohm
- With 330 ohm resistor (IEC 61000-4-2 standard), and testing up to 67.5 mJ, cotton could ***not*** ignite. (C=150pF, R=330ohm)

Zhancheng, Wu et al., "Research on ESD Ignition Hazards of Textiles," Journal of Electrostatics (2002)

WHA Data

Oxygen enriched.
Ambient (12.7psia) pressure.

"Parasitic" resistance (low, ~20-80 ohm)

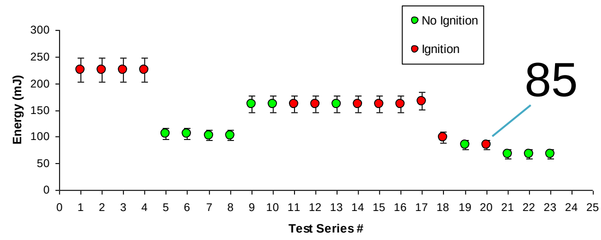


Figure 3: Exemplar Recieving Blanket

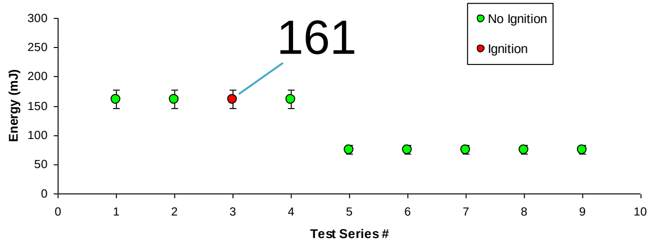
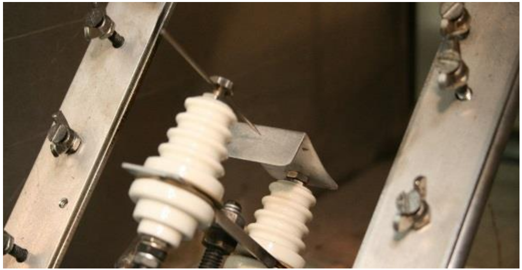


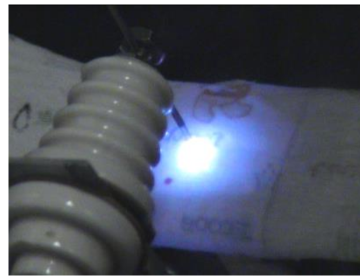
Figure 4: Exemplar Wash Cloth 100% Cotton

WHA Data



3.4 mJ

53 mJ



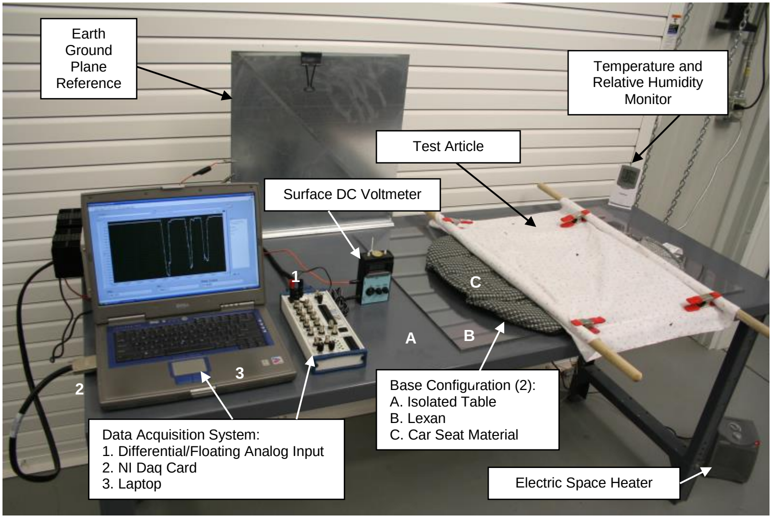
486 mJ

WHA Data

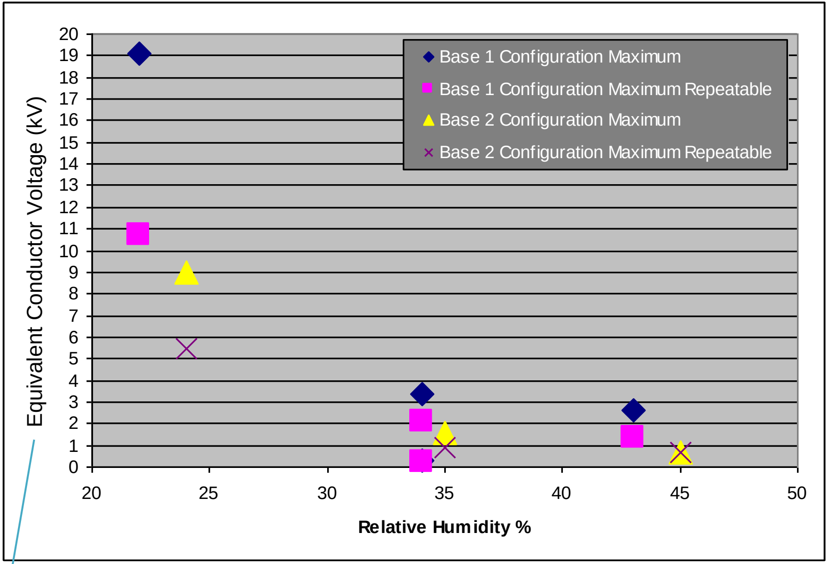
Test Article	Spark Gap (in)	Capacitor (pF)	Charge Voltage (kV)	Spark Energy Level (mJ)	Oxygen Concentration (%)	Number of Sparks	Interval between sparks (seconds)	Comments
Baby Clothing	0.21	3000	18	486	99	60	5	Sample did not ignite
Baby Blanket	0.21	3000	18	486	99	32	5	Sample did not ignite
Baby Clothing w/ Baby Oil	0.25	470	15	52.875	99	3	10	Sample ignited on the 3rd spark.

1.5kohm "Human Body Model" Resistance
Ambient (14.7psia) pressure.

Static Generation Testing (WHA Data)



Static Generation Testing (WHA Data)



NOTE: This is the sensor's raw output. For electrically insulative material, average Q/m^2 where Q is charge in Coulomb and m is length in meters is a more meaningful unit. The trend is what is noteworthy in this plot.

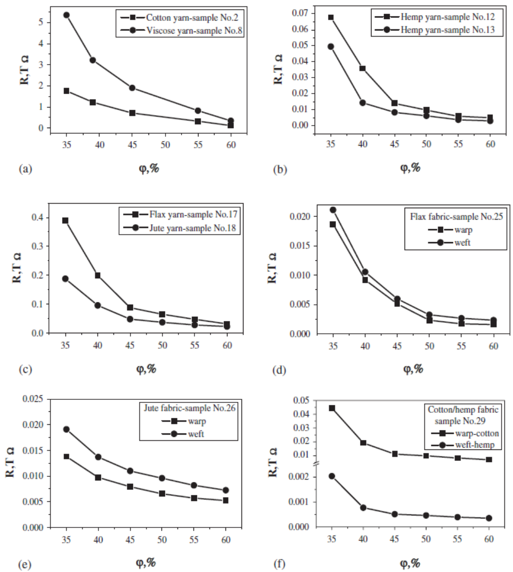
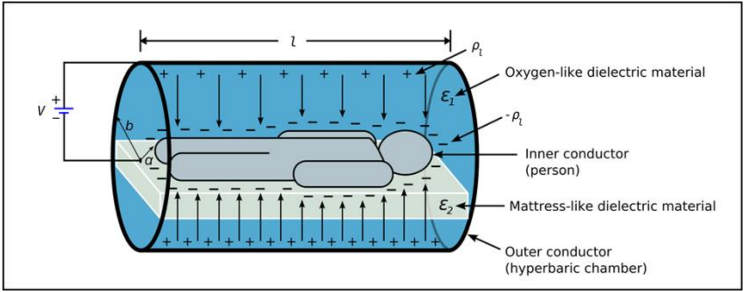


Fig. 2. The dependence of the resistance R with humidity φ for some yarn samples as well as some fabric samples in warp and weft direction.

Asanovic, Koviljka A. et al., “Investigation of the Electrical Behavior of Some Textile Materials,” Journal of Electrostatics (2006)

Estimated Human Body Capacitance in Hyperbaric Chamber Using a Coaxial Capacitor Model



$$C_a := \frac{2\pi \cdot \varepsilon_a \cdot \varepsilon_0 \cdot l_{length}}{\ln\left(\frac{b_{radius}}{a_{radius}}\right)}$$

Parameter	Value
a_radius	8 in
b_radius	15 in
l_length	5.5 ft

Dielectric	Dielectric Constant	Capacitance Calculation (assuming constant dielectric) (pF)
Air	1.006	149
Oxygen (non-compressed)	1.5	223
Polyurethane	5	742

ESD: Recipe for Ignition

- Five general conditions necessary for an electrostatic ignition hazard:
  - Sensitive flammable atmospheres or materials
  - Generation of static charge
    - Based on the data in the previous slides, and multiple other publications, generation of static charge is difficult at humidity levels above 50% and unlikely at >60% humidity. Relaxation rates (charge dissipation rates) is proportional to relative humidity.
  - Accumulation of charge (increased static voltage level) on an isolated conductor that has capacitance.
    - The capacitance of a 6 ft man standing on a dry wooden platform in air has a capacitance of about 103 pF. (Eichel, F. G., "Electrostatics", Chemical Engineering March 13, 1967)
    - The charge density on an isolated conductor must produce an E-Field strong enough for air discharge. Charge density is a function of the conductor's geometry and the charge level measured as a voltage potential between the charged conductor and the conductor that is potentially discharged to ("earth ground", for example).
  - Electrostatic discharge (ESD) from one conductor (i.e., human body) that travels through a flammable material (cotton) to another conductor (chamber).
  - Discharge must have sufficient energy to ignite the flammable material (Discharge Energy > Minimum Ignition Energy). Even when condition is met, ignition has been observed to be probabilistic in nature.

Low Energy Discharge Classifications

- Corona Discharge (non-incendiary)
  - The rate and density of the energy dissipated will always be too low to initiate an ignition of non-gaseous flammable materials.
- Brush Discharge (unlikely incendiary)
  - Typically occurs between two insulators. The total energy may be high, but in most cases either the rate or density of the energy dissipation is too low to cause an ignition. Energy from brush discharge expected to dissipate over a wide area.

ESD Risk Evaluation

- Factors that increase ignition risk and severity in oxygen enriched atmospheres:
  - Oxygen concentration
  - Oxygen pressure
  - Materials exhibiting relatively low oxygen compatibility:
    - E.g., hydrocarbon-based greases and liquids, and finely divided material such as powders.
  - Human body capacitance is dependent on the dielectric constant of the surrounding materials and the geometric configuration of other conductors (i.e., the chamber).
  - The increased use of HBO treatments increases the likelihood of ESD initiated fires in the field based purely on statistics.

ESD Risk Evaluation

- Mitigating factors to consider when evaluating ESD risk:
  - NFPA 99 requirements on chamber and patient grounding.
  - Increased humidity precludes charge development and accumulation.
  - MIE values for a material may be based on the Machine Model (shorter duration, higher current peak) as oppose to the Human Body Model (longer duration, lower current peak).

Summary

- The analysis of risk factors and associated data as a group suggests that the risk is mitigated in current HBO applications.
  - Supported by the successful history of use when implementing the current standard of safety. (e.g., NFPA 99, grounding straps, cleanliness, etc.)
- However, the safety margins are currently uncertain (due to limited data) and therefore should be considered.

Conclusions

- Historic ESD testing performed report ignition energy of cotton fibers in oxygen as low as 9mJ (NASA, 1969) and 4.8mJ (Wu, 2002). Human body static electricity energy levels can be higher than these under certain conditions. NASA data also shows that MIE is inversely proportional to pressure. ESD MIE variability with pressure should be considered.
- These values considered a near 0 resistance spark (“Machine Model”), are not consistent with the standard accepted HBM values. Limited testing performed by Wu and WHA at higher resistance values (more consistent with Human Body Model) suggest higher cotton minimum ignition energy levels. The safety margin between Machine Model and Human Body Mode should be considered.
- Testing has been performed, but is limited. Standards that govern ESD testing for the semiconductor industry should be considered, however, these standards can not be directly applied to ignition testing in oxygen due to configuration limitations. Verification, calibration, and the uncertainty of the energy estimates should be considered in future testing endeavors.