Mitigation of Electrostatic Hazards on Spacecraft

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Abstract— **Spacecraft are complex systems operating in challenging environments that require customized testing procedures designed to mitigate the unique hazards of a space launch environment. As an example of those testing procedures, we describe the test methodology and recommendations developed to mitigate electrostatic discharges that could have triggered an explosion of the Space Shuttle during launch, return to launch site, abort after one orbit, or during normal landing.**

INTRODUCTION

Rocket fueling operations prior to launch, interaction of rocket surfaces with ice clouds immediately after launch, contact and separation of the insulating surfaces of gas storage tanks aboard spacecraft, and even on orbit operations by astronauts during extra vehicular activities all present possibilities for electrostatic hazards. To mitigate these hazards, our NASA laboratory at the Kennedy Space Center has performed custom testing in relevant environments using actual components and materials for several specific cases.

IGNITION FROM ELECTROSTATIC DISCHARGES

The most important electrostatic hazard for space launch operations is perhaps the possibility of an ignition due to a discharge. For ignition to occur due to an electrostatic discharge event, the discharge must occur in a flammable atmosphere and the energy of the discharge must be greater than the minimum ignition energy of the gas mixture in this atmosphere.

Estimates of the energy associated with a possible spark discharge can be made if the voltages necessary to spark are known, as well as the overall capacitance of the system. For a simple capacitive system such as a parallel-plate capacitor, the energy released is

$$E = \frac{1}{2}CV^2 \tag{1}$$

where C is the capacitance and V is the voltage at which it sparked. For a parallel-plate capacitor configuration,

$$C = \frac{\varepsilon_0 A}{d} \tag{2}$$

where ε_0 is the permittivity of free space, A is the area, and d is the distance between the electrodes.

POSSIBLE HAZARD DUE TO ELECTROSTATIC DISCHARGES IN THE SPACE SHUTTLE

NASA document 21492, titled *Space Shuttle Program Payload Bay Payload User's Guide* [2000], specified that "the major electrostatic discharge (ESD) concern for the orbiter is triggering an explosion of hydrogen gas that might inadvertently leak into the payload bay during launch, Return to Launch Site, Abort Once Around, or normal landing from residuals in the aft equipment bay plumbing. Hydrogen leakage into an enclosure of air at one atmosphere is typically triggered by an arc of 200 microjoules (μJ) [Lewis and von Elbe, 1987]. An ideal mixture could trigger at 17 μJ. Stoichiometric mixtures of pure hydrogen and pure oxygen could be triggered by an arc of 1.2 μJ at one atmosphere."

Although measurements of hydrogen concentrations never exceeded its lower flammability limit for any of the missions that the Space Shuttle flew, increased hydrogen levels above ambient were measured in nearly every launch. Although the Space Shuttle cargo bay was purged with nitrogen prior to fueling and remained purged during launch, the possibility of a hydrogen ignition due to a spark would increase as oxygen leaks into the cargo bay in case of a return to the launch site or of a landing once it completed an orbit. These two contingencies never happened, but because they were planned in case of an emergency, thorough testing of materials that could generate electrostatic discharges was frequently done. In the following sections, we describe the major tests performed and the solutions provided.

ELECTROSTATIC EVALUATION OF THE SPACE SHUTTLE THERMAL CONTROL SYSTEM MULTILAYER INSULATION BLANKETS

The Space Shuttle had more than 5,000 thermal insulation blankets, composed of several layers and were known as Multi-Layer Insulation (MLI) blankets. In general, the MLI blankets were of two main types. One type of blanket, Type I, used to shield the payload cargo bay from the Sun, was a 22-layer blanket consisting of a Teflon-coated beta cloth layer followed by polyimide film aluminized on one side (Fig. 1). These layers were then backed with 19 layers of alternating Dacron mesh or scrim cloth and polyimide film aluminized on both sides. The last layer was also a polyimide film aluminized on both sides, reinforced with a Nomex scrim cloth laminated on the inside. The aluminized covers of these blankets, made by Sheldahl, are complex materials. They are 0.5-mil polyimide film (commonly known as Kapton) that are aluminized on both sides in a high-speed processing chamber. The aluminum, which is 1000 Å thick, readily oxidizes in air and requires an overcoat to protect it from corrosion. The overcoat, made of a transparent polymer, is roughly 2000 to 4000 Å thick. This configuration complicates the electrostatic properties of the materials. The covers also contain 13,500 holes per square foot to allow the passage of air and are fiber-reinforced with Nomex scrim fabric on one side.

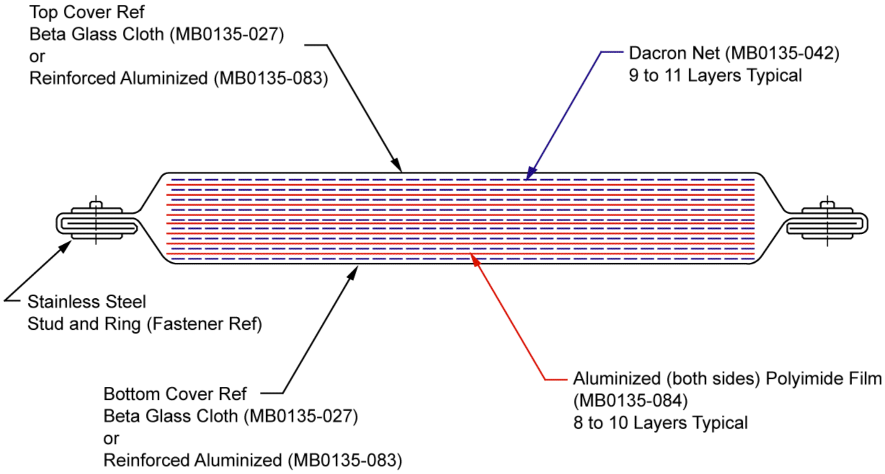


Figure 1. Multilayer insulation blanket designs.

The other type of MLI blanket, Type II, used to thermally insulate the Shuttles in orbit, was similar to the first one except the beta cloth layer and the polyimide film layer aluminized on one side are absent. Instead, the top and bottom of this MLI blanket were covered with polyimide film aluminized on both sides with the reinforced layer with the laminated Nomex scrim cloth on the inside.

The aluminized polyimide layers of the beta cloth-covered Type I MLI blankets were maintained in electrical contact with each other and with the Shuttle structure. The blankets are joined with staples, studs, and sockets or metal grommets. Blankets are also sewn together with polybenzimidazole or Nomex thread. During a thorough inspection of these blankets after the Shuttle Columbia disaster, it was discovered that many of these blankets had a relatively high resistance to ground. If this was the case, charge could build up in these blankets, creating the possibility of a static discharge. Examination of this issue revealed the existence of several possible charging mechanisms not only for this blanket but for the aluminized MLI blankets as well.

A. Grounding Requirements

General electrical grounding requirements for the Shuttle TCS blankets state that the maximum direct current resistance between a given thermal blanket and the vehicle structure, bonding strap, wire, or foil strip or between adjacent thermal blankets must be less than 1000 Ω, according to Rockwell document MA0113-306 [Crawford and Raval, 1996] for Class S bonding or static electricity bonding. NSTS 37330, "Bonding, Electrical and Lightning Specifications" [1999], specifies that any isolated conductor must have a resistance to ground of less than 1 Ω. In addition, NSTS 21492 requires no more than 10-Ω resistance between blankets and the grounded structure. However, several TCS blanket combinations tested did not conform to these requirements, and in several cases the resistance to ground was greater than 1000 Ω [Chambers, 2003].

Surface resistance measurements of the aluminized covers of both Type I and Type II blankets, which are coated with a 2000 to 4000 Å-thick layer of an electrically insulating polymer, were below 20 Ω, well below the 1000 Ω requirement. However, when the blankets were connected together, the insulating layer was doubled and the blanket to blanket resistance increased to values above the 1000-Ω requirement, reaching several hundred kΩ in some cases. These resistances were heavily dependent on the method used to connect the blankets.

Normally a resistance to ground less than 1 MΩ is satisfactory even in the presence of hydrogen, which has unusually low minimum ignition energy [Britton, 1999]. Charge decay experiments performed in the laboratory on the aluminized covers showed that corona charge deposited on these blankets dissipated in less than 2 seconds, indicating that the blanket to blanket grounding for these covers was acceptable. Since charge dissipation took place in less than 2 seconds, the aluminized covers of the MLI blankets are considered to be statically dissipative (MIL-B-81705C and FTMS 4046). A recommendation to change the resistance-to-ground requirement from values less than 1000 Ω to less than 1 MΩ was made.

Spacecraft charging standards state that all internal and external metallic layers of MLI blankets shall be grounded to structure with at least two bonding straps directly to ground, without a daisy chain configuration (ECSS-S-ST-00-01). Table 1 shows the bonding configurations used with the Shuttle MLI blankets. Although avoiding a daisy chain configuration was not possible for the 5,000 Shuttle blankets, our testing revealed that the blanket to blanket connection was acceptable for aluminized covers for all configurations in Table 1, even if only one connection was used instead of the required two. However, all configurations except Configuration 2 did a poor job at grounding the inner layers of the MLI blankets. Since the inner blankets may not be connected to ground, further testing was required.

Table 1. TCS Blanket Configurations and Samples for Testing

Configuration 1	Sample 1 and Sample 2	Aluminized covers folded and attached with PBI thread with an additional aluminized tab sewn with PBI
Configuration 2	Sample 1.1 and Sample 2.1	Folded aluminized covers sewn together with PBI thread
Configuration 3	Sample 3.1 and Sample 4.1	Stud and socket (buttons/snaps) through folded PBI sewn seam
Configuration 4	Sample 5.1 and Sample 6.1	Strip of aluminized sewn cover attached by staples
Configuration 5	Sample 7.1 and Sample 8.1	Same as Configuration 4 except the strip is flipped over
Configuration 6	Sample 9.1 and Sample 10.1	Strip of Beta cloth covered MLI attached by studs and sockets

B. Triboelectric Charging of the MLI Blankets

To produce a charging scenario that would approach what the MLI blankets might encounter during flight, shaker table experiments (Unholtz Dickie Vibrating Test System) were performed that simulated the amplitude, the frequency of vibrations, and the changing accelerations experienced by payloads in the payload bay (Fig. 2). An aluminized TCS (no Beta cloth) MLI blanket that measured 41.5 by 36 inches was custom-built to represent one of the largest blankets used in the Shuttle payload bay. After cutting one side of the blanket to expose the inner layers, resistance measurements between each inner layer and the outer layers were conducted using a PRS-812 meter. The first three inner layers had a resistance between them on the order of a few kΩ, the same as inners layers 4 through 8. However, inner layers 1 through 3 were not connected to inner layers 4 through 8, even though they were stapled together and bound with the Beta glass cloth tape. None of the inner layers were connected to the outer layers of the MLI blanket.

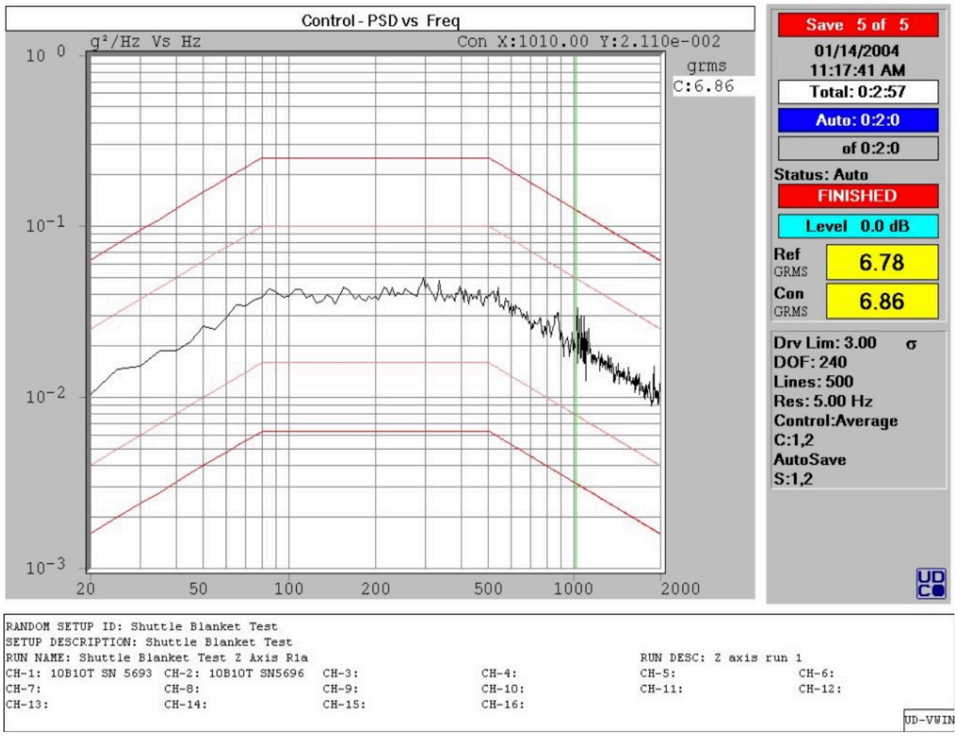
Testing was conducted at room humidity conditions (45% RH) in accordance with NASA-STD-7001 [1996] in order to match the Shuttle profile. The power spectral density profile in the x-y and z axes is 0.01 g2/Hz at 20 Hz, 20 to 80 Hz on a –3-decibel (dB)/oct slope, 0.04 g2/Hz at 80 to 500 Hz, 500 to 2000 Hz on a –3-dB/oct slope, and 0.01 g2/Hz at 2000 Hz, for a 2-minute duration. Accelerometers monitored the acceleration of the table, and a typical test profile is shown in Fig. 3.

Figure 2. Shaker table experiment with aluminized MLI blanket.

Initial tests were performed without wires attached to the blanket to ensure that the signals generated were in fact triboelectric in nature and not generated by the table noise. The ground wires attached to the outer blanket served as shielded cables for the data wires connecting different inner layers of the TCS blanket to an ETS nanocoulomb meter (Model 230). The nanocoulomb meter was monitored using LabView through a data acquisition board. The results for the amount of charged developed during the shaker table test for inner layer 8 are given in Fig. 4. However, since a double-layer was formed due to the insulating Dacron mesh attached to the external aluminized layer, charge measurements were expected to be lower than the actual charge developed on the aluminized layer.

ESD event measurements were also performed with the EM Eye device (Fig. 5). Forty-nine events were recorded during measurements of inner layer 4, and some events were relatively large.

The results of the shaker table experiments above show that it is possible for the MLI inner layers to charge simply as a consequence of vibrations during launch. Although the overall charging magnitudes were low, incendiary discharges resulting from tribocharged inner blanket layers cannot be ruled out based on these magnitudes alone due to the aforementioned double layer formation. There are several competing phenomena occurring that may help or hinder the possibility of igniting a flammable gas mixture, such as gas pressure, fuel mixture, temperature, quenching distance, and humidity.



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RANDOM SETUP ID: Shuttle Blanket Test
SETUP DESCRIPTION: Shuttle Blanket Test
RUN NAME: Shuttle Blanket Test Z Axis R1a                                          RUN DESC: Z axis run 1
CH-1: 10B10T SN 5693  CH-2: 10B10T SN5696  CH-3:              CH-4:              CH-5:              CH-6:
CH-7:                 CH-8:                CH-9:              CH-10:             CH-11:             CH-12:
CH-13:                CH-14:               CH-15:             CH-16:
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Figure 3. Typical z-axis control used for the Shaker Table experiment. The red lines are the ranges minimum and maximum accelerations experienced in the payload bay; the black line is the accelerations experienced during the test run as measured by the accelerometer.

C. *Electrostatic Hazards*

The next step is to measure or estimate the energy associated with a possible spark discharge. Estimates of the energy can be made if the voltages necessary to spark are known, as well as the overall capacitance of the system. For a simple capacitive system such as a parallel-plate capacitor, the energy released is given by Eq. (1), Where V is the voltage at which it sparked. The TCS blankets conform to this parallel-plate geometry, in which the capacitance is $C = \varepsilon_0 A/d$, where ε_0 is the permittivity of free space, A is the area of the blanket (approximately 1 m^2), and d is the distance between the inner layer and the outer layer (approximately 0.001 m). The capacitance of the TCS blanket sample used in the shaker experiments is 8.85×10^4 pF. Measurements of the capacitance using a Sencore Analyzer gave between 12,000 and 15,000 pF, very close to the estimated value.

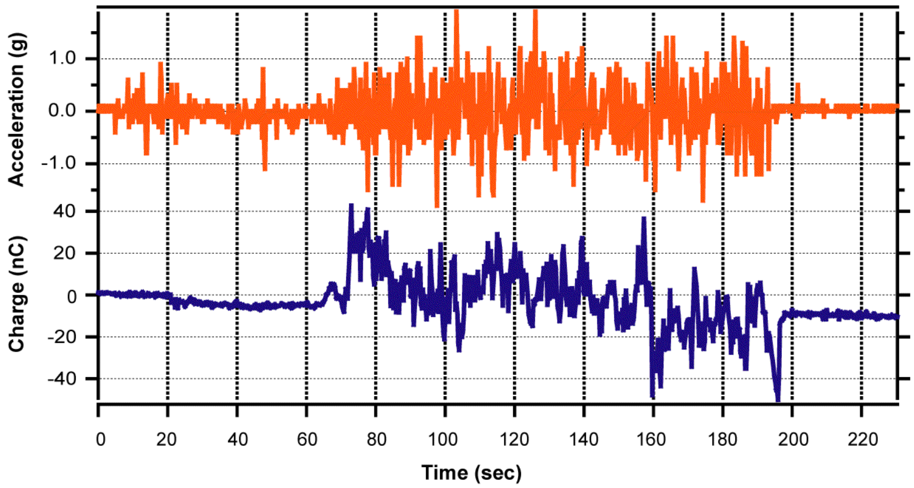

Figure 4. Charge measured on the inner layers of the MLI blanket during vertical vibrations in the Shaker Table.

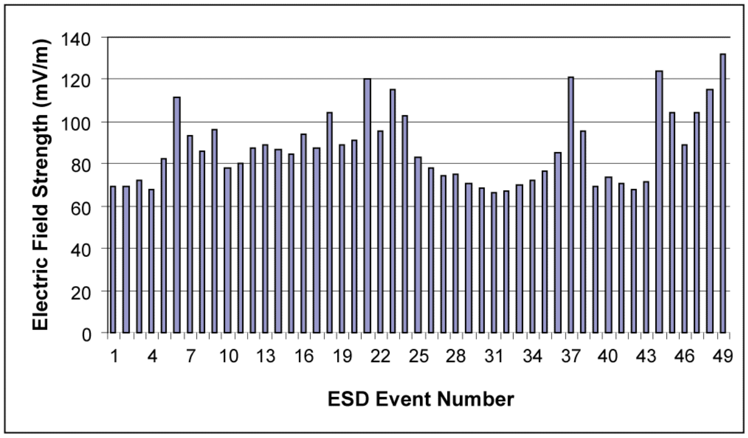

Figure 5. Electrostatic discharge events monitored with an EM Eye instrument during the vertical shaker table experiment.

Electrical breakdown measurements were performed to estimate the maximum allowable voltage the inner layers could handle before sparking to the outer layers of the TCS blankets. A high-voltage power supply (Keithley Model 247) was connected to inner layer 1 of the TCS blanket while the outer layers were electrically grounded. Measurements of the output voltage were made in parallel by first reducing the voltage with a Hewlett Packard High-Voltage Probe model 3411A and then monitored using a Fluke 87 III True RMS Multimeter. The minimum potential at breakdown was approximately 200 V for the large TCS blanket used in the shaker table experiments and approximately 300 V for a sample blanket. All voltage breakdowns were associated with sparks between the inner layers and the outer cover materials.

The theoretical energy released in the spark during breakdown of the large TCS blanket for C=14000 pF and V=100 volts is 1.77 mJ or 1770 μJ. For the sample blanket with a measured capacitance of 3400 pF and V=200 volts, the energy released is 0.153 mJ or 153 μJ. Such energies are more than sufficient to ignite the most easily ignitable hydrogen-oxygen mixture, which has a minimum ignition energy (MIE) of only 17 μJ in air. The shaker table experiments only provided about 4 V maximum between inner and outer blanket layers. But this value was likely much lower due to the formation of a double layer with the Dacron mesh adhered to the aluminized cover. Other tribocharging mechanisms, such as air blowing through the blankets as it rushes out of the payload bay, may lead to higher tribocharging and should not be ruled out.

For the large aluminized TCS blanket with a capacitance of 8.85×10^{-8} F and MIE for the hydrogen-oxygen mixture of 17 μJ, the minimum ignition voltage is only 19 V. Although 19 volts is also far short of the measured breakdown strength of the blanket, breakdown voltage is a function of atmospheric pressure. As the Shuttle rises through the atmosphere, if the electrostatic potential that has developed between the inner layers and the outer layers during launch reaches the electrical breakdown potential of the air, electrical discharges will occur. If at some point during the ascent the breakdown potential reaches 19 V, discharges will occur, provided the blankets have acquired sufficient charge. But once the pressure is lowered, the minimum ignition energy of a hydrogen-oxygen mixture rises, raising the minimum voltage necessary for ignition. Figure 6 shows how the minimum ignition energy changes as a function of pressure for various hydrogen gas mixtures immersed in an oxygen (O_2) and nitrogen (N_2) environment. The ratio of moles of O_2 to moles of O_2 plus moles of N_2 is fixed at 0.21.

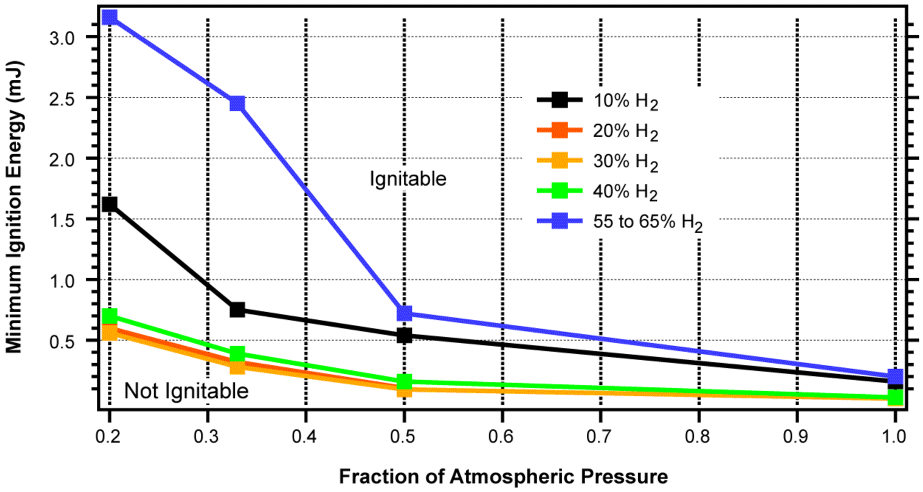

Figure 6. MIE for various hydrogen gas mixtures as a function of pressure [data from Lewis and von Elbe, 1987].

Similar relationships hold for the quenching distance. The quenching distance is the distance at which no ignitions can occur as the electrodes are moved closer together. Experimental quenching distances as a function of pressure for various hydrogen gas mixtures are given in Figure 7.

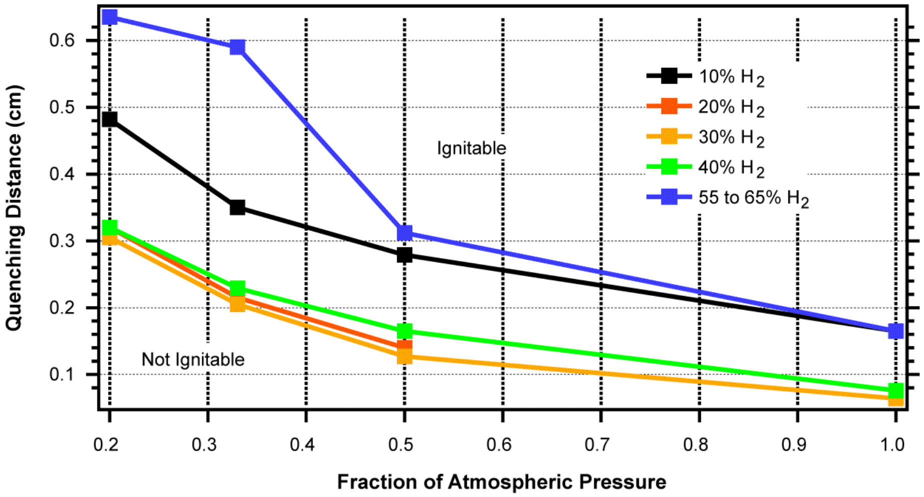

Figure 7. Quenching distance for various hydrogen gas mixtures as a function of pressure [data from Lewis and von Elbe, 1987].

If the blanket layers are too close together when they spark, although the spark may have sufficient energy to ignite the gas, the separation may be below the quenching distance and no ignitions will occur. Even though Tuff buttons are used to minimize billowing, it is possible for the MLI blankets to physically separate above the quenching distances.

Obtaining an ignition of the flammable gas mixture requires a spark above the minimum ignition energy to occur at separations larger than the minimum quenching distance. The preliminary shaker table tests on the MLI blanket were implemented to check the possibility of the existence of a charging mechanism. The actual amount of charge developed on the inner layers of the blankets was most likely underestimated due to double layer effects. Since ESD events were recorded during the shaker table experiments, further testing and evaluation are required.

Incendivity Testing of the International Space Station Blankets

Although additional testing of the Space Shuttle blankets was not performed, similar electrostatic evaluation of the International Space Station (ISS) thermal insulation blankets was performed some time later. The ISS MLI blankets are very similar to the Space Shuttle MLI blankets. The Space Shuttle TCS blankets are comprised of both multi-layer (MLI) blankets and fibrous blankets while the ISS thermal control system blankets are comprised of MLI blankets and thermal shrouds. The STS MLI and fibrous blankets have both reinforced aluminum covers and PTFE-coated fiberglass covers while the ISS MLI blankets only have PTFE covers. The Shuttle's PTFE-coated fiberglass (or Beta cloth) covered MLI and fibrous blankets contain a graphite or stainless steel wire grid sewn within it for electrical grounding purposes. However, the ISS PTFE-coated covers do not contain a wire grid sewn within the material but instead one side of the covers is aluminum coated to enhance thermal properties.

To evaluate any possible ignition hazard associated with the ISS blankets in the cargo bay, the blankets were placed in an environment that represented a leak of hydrogen in the aft and/or cargo bay of the orbiter (NASA NSTS 21492). If the blankets were unable to create a spark of high enough energy to ignite a hazardous gas mixture, then the ISS blankets would be deemed safe in their current configuration. To achieve this environment, an incendivity vacuum chamber was designed and built. This large vacuum chamber (Figure 8) was used to create flammable environments at both ambient and reduced pressures.

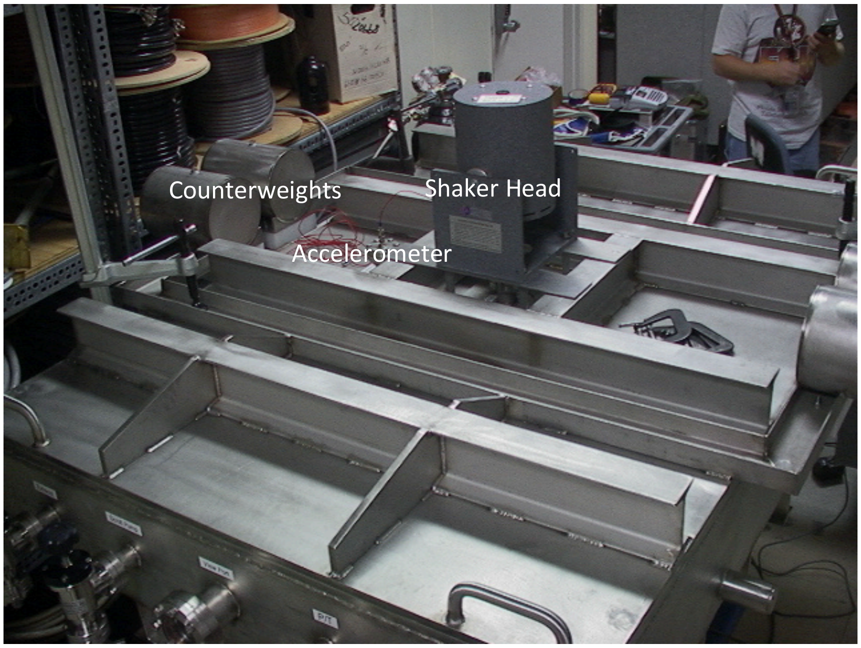

Figure 8. Incendivity vacuum chamber with shaker head and accelerometer.

The ISS MLI blankets were shaken in the incendivity vacuum chamber using the Shuttle vibration profile (Fig. 3). A hydrogen-enriched atmosphere was introduced into the chamber. A full description of this test will be given in a subsequent paper.

The incendivity chamber testing showed that sparking events were never of sufficient energy to ignite a hydrogen-enriched atmosphere even at stoichiometric ratios. Any sparks that occurred between the ungrounded aluminized layer of the betacloth and the Dacron scrim cloth in the case of the MLI blankets, or the sparks that occurred between the betacloth and the anodized plate in the case of the thermal shrouds, must have had energies lower than the MIE of the hydrogen-air mixture. Of the 432 tests performed on the ISS blankets and shrouds, 192 (or 44%) were performed in environments that had MIEs equal to or lower than 25 μJ. The actual number of discharges per test is not known, but according to Table 10 it is very likely that there were several discharges in each test performed, including the 192 tests with the very low MIEs. Therefore, all of the discharges that occurred in these tests must have had energies lower than 25 μJ.

CONCLUSIONS

Rocket fueling operations prior to a launch, contact and separation of the insulating surfaces aboard spacecraft, and even on-orbit operations by astronauts during extra vehicular activities present possibilities for electrostatic hazards. Our NASA laboratory at the Kennedy Space Center performs custom electrostatic testing in relevant environments using actual components and materials. We have described the extensive testing of complex multilayer insulation blankets that were used aboard the Space Shuttle and that are currently used on the International Space Station. These tests require the implementation of electrostatic testing standards to suit relevant environments, such as the vacuum of space or the rapidly atmospheric pressure decrease during a rocket launch. Subsequent papers will describe in more detail the indenditivity testing performed on the ISS MLI blankets, as well as specialized testing performed on several NASA rockets.

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