Investigating Premature Ignition of Thruster Pressure Cartridges by Vibration-Induced Electrostatic Discharge

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Pyrotechnic thruster pressure cartridges (TPCs) are used for aeroshell separation on a new NASA crew launch vehicle. Nondestructive evaluation (NDE) during TPC acceptance testing indicated that internal assemblies moved during shock and vibration testing due to an internal bond anomaly. This caused concerns that the launch environment might produce the same movement and release propellant grains that might be prematurely ignited through impact or through electrostatic discharge (ESD) as grains vibrated against internal surfaces. Since a new lot could not be fabricated in time, a determination had to be made as to whether the lot was acceptable to fly. This paper discusses the ESD evaluation and a separate paper addresses the impact problem.

A challenge to straight forward assessment existed due to the unavailability of triboelectric data characterizing the static charging characteristics of the propellants within the TPC. The approach examined the physical limitations for charge buildup within the TPC system geometry and evaluated it for discharge under simulated vibrations used to qualify components for launch. A facsimile TPC was fabricated using SS 301 for the case and surrogate worst case materials for the propellants based on triboelectric data. System discharge behavior was evaluated by applying high voltage to the point of discharge in air and by placing worst case charge accumulations within the facsimile TPC and forcing discharge. The facsimile TPC contained simulated propellant grains and lycopodium, a well characterized indicator for static discharge in dust explosions, and was subjected to accelerations equivalent to the maximum accelerations possible during launch. The magnitude of charge generated within the facsimile TPC system was demonstrated to lie in a range of 100 to 10,000 times smaller than the spark energies measured to ignite propellant grains in industry standard discharge tests. The test apparatus, methodology, and results are described in this paper.

Nomenclature

ABL	=	Allegany Ballistics Laboratory
C	=	capacitance
cm	=	centimeters
D	=	displacement
E	=	electric field
Єo	=	permittivity of free space (8.854 x E^{-12} Coulombs2/n*m^2)
ESD	=	Electrostatic discharge
g	=	grams
HTPB/AP	=	Hydroxyl-terminated polybutadiene/Aluminum Perchlorate
IC	=	charging current
IL	=	leakage current
IR	=	recombination current
J	=	Joules
K	=	dielectric coefficient
nC/J	=	nano-coulombs per Joule
NDE	=	Nondestructive Evaluation
PBD	=	Propagating Brush
pF	=	picofarads

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RH	=	Relative Humidity
RMS	=	root mean square
t	=	time
TPC	=	Thruster Pressure Cartridge

I. Introduction

THIS report documents the efforts, findings, and limitations of the investigation work for potential premature ignition of anomalous thruster pressure cartridges (TPC) by electrostatic discharge (ESD). TPCs are used for payload aeroshell separation.

A substantial limitation affected the nature of this investigation, namely the unavailability of TPC propellant materials to perform a component level test evaluation in time to support the mission timeline. This led to an indirect analysis approach to obtain the necessary information. The analysis approach is described, and it is suggested that similar logic may be applicable to answer ESD questions regarding systems that possess other ESD-sensitive materials.

II. Problem Description

Thruster pressure cartridges (TPC) are pyrotechnically powered devices that function as a powerful piston. The piston action is used to shear pins that secure aeroshell sections to the upper stage, and when actuated, result in aeroshell separation. Pyrotechnic devices are subjected to rigorous testing and inspection to ensure operation under critical flight conditions. However, schedule demands may lead to TPC installation prior to the completion of nondestructive evaluation (NDE) of samples. In one such instance when the NDE results for TPCs from the same lot became available, there was evidence in several units that one of the pyrotechnic components, Hi-Temp™, * could be loose and free to move in volumes internal to the TPCs already installed on the vehicle. TPCs resemble a steel cylinder ~8 inches long and a little more than an inch in diameter. (Fig.1)

Figure 1. Photo of a thruster pressure cartridge unit.

It is well understood that materials brought in contact with each other and then separated have the potential to accrue a static charge. The substantial vibration environment during launch could give rise to triboelectric charging between the Hi-Temp and other propellants within the fixture and could create the conditions for an ESD. This could be sufficient to ignite the propellants, causing an unplanned activation of the TPC.

The primary function of the Hi-Temp is as an intermediary in the ignition chain to ignite the gas generating propellant, hydroxyl-terminated polybutadiene/aluminum perchlorate (HTPB/AP), that drives the piston when combusted. Within the TPC, the HTPB is physically present as a molded material in the shape of a cylinder with seven internal cylindrical passages. Expert opinion expressed early during the evaluation of the problem was that electrostatic ignition of the TPC pyrotechnics was not a concern. However, investigation of the ignition properties of the Hi-Temp found data sufficiently limited and contradictory to warrant a second look. Published data values ranged from 0.095 J[1] to 5.656 J[2]. Further, there was recognition that the Allegany Ballistics Laboratory (ABL) test, which applies a large spark discharge to a substantial sample (30 g) in a cup, would not necessarily model small propellant grains (nominal 0.05 in. diameter, 0.01 in. thickness) bouncing and rubbing against HTPB propellant, within its seven internal passages and elsewhere within the TPC case.

With more time to evaluate the problem, the standard approach would be to conduct a component test with the loose Hi-Temp flaw reproduced under simulated conditions of launch and observe the results for a statistically significant number of repetitions. Testing can also be used to induce more extreme conditions and ensure there is a margin of safety. A variation on this approach that avoids the need for actual TPCs was considered, and that was to duplicate the TPC geometry with the pyrotechnic propellant, introduce the loose Hi-Temp, simulate launch conditions, and then observe the results. However, the hazard classification and quantities of the pyrotechnic materials prevented timely shipment. Hence, an alternative approach was needed and that is the topic of this paper.

* Hi-Temp™ is a registered trademark of Hi-Temp Coatings Technology Company, Inc., Boxborough, Massachusetts.

III. Background

Given the difficulties in employing genuine components or materials, an approach was sought to evaluate spark discharge energies for materials with similar charging properties to bound behavior, and then compare the energies to published limits for Hi-Temp. If sufficient margins were observed, then a reasonable decision could be supported on the use of the TPCs. This had an additional benefit in that experimental efforts could bypass handling of pyrotechnic material, an especially important consideration for materials that require special attention to avoid static discharge.

A. Charging Processes

Charge generation can occur through a variety of means.[3] The primary ones are:

1) Frictional charging or tribocharging that occurs as solids make contact and are drawn apart,
2) Fragmentation of solids that possess non-uniform surface charge densities,
3) Shear working along liquid-solid, liquid-gas, and two-phase boundaries,
4) Separation by gravitation of suspended materials possessing non-uniform size and charge,
5) Induction charging, and
6) Ionic charging.

Mechanisms 5 and 6 require very large electric fields that can transfer charge between electrically isolated systems. Of the first four mechanisms, only the first two pertain to the environment created by releasing Hi-Temp within the vibrating TPC. The Hi-Temp particles are banged back and forth within the TPC inner spaces, repeatedly making contact and separating. Fragmentation of the Hi-Temp is possible. However, we have no reason to suppose non-uniform surface charge densities would exist in the Hi-Temp particles.

B. How Does Static Charging Work?

Equilibrium processes ensue when dissimilar materials are brought into close contact. One well known example is thermal equilibrium, where heat flows from warmer substances to cooler substances until equilibrium is reached. Germane to this work is the natural proclivity of systems brought into contact to try and equalize their electrochemical potential difference. This is a thermodynamic potential that will drive electron movement from the system or material with the higher electrochemical potential to the one of lower potential until equilibrium occurs. The difference in electrochemical potential for most materials is several tenths of a volt.[4]

C. Creation of High Voltages

Mechanical forces acting on materials, or the motions of particles resulting in collisions with materials, supply the energy needed to cause the large voltages, as high as 10^4 or 10^5 volts, observed in static electrification. Consider two dissimilar materials encountering each other, perhaps in a collision. At the moment of contact, a transfer of charge occurs. The geometry of the contact surface could also be considered analogous to the plates of a capacitor. As motions of the materials result in separation, it is similar to drawing apart the plates of a capacitor at a constant charge. Material contact occurs on a dimensional scale of tens of angstrom units. Change in the potential field of a capacitor can be shown to be linearly proportional to the distance of separation between the plates.[4] With the separation of colliding materials to dimensions approaching a millimeter, the potential can grow by an order of 10^6.

Of course, there are a variety of factors that determine what the final voltage will become, including the geometry, surface roughness (determines how close contact between materials will be), the uniformity of charge across the contacting surfaces, and the concentration of charge at sharp edges (which may cause sufficiently high electric fields for dielectric breakdown and subsequent spark discharge).

D. Dielectric Materials

Very generally, a material that has no free charges is an ideal dielectric. Conceptually, in a small volume within a dielectric, application of an electric field will polarize groups of positive and negative charges, i.e., they will attempt to line up with the field. The degree to which polarization occurs will depend both on the electric field and the properties of the molecules in the material. The degree of polarization can be characterized as a displacement that is a function of the material (for a linear dielectric) and the electric field:[4]

$$D = K \epsilon_o E \tag{1}$$

Where E (volts/m) is the electric field, €o is the permittivity of free space (8.854 x E^{-12} Coulombs2/n*m^2), K is a dimensionless quantity called the dielectric coefficient or constant.

If the electric field becomes sufficiently strong, it will begin to pull electrons out of the material. This is known as the dielectric breakdown strength (volts/m) and it is part of the onset of a spark discharge. Some dielectric constants and maximum electric fields are noted for common materials (Table 1).[2]

Table 1. Dielectric constants and breakdown strengths for common materials.

Material	Dielectric Constant (K)	Breakdown Strengths (V/µm)
Air (1 atm - dry)	1.00059	4.5 (1 mm gap)
		3.0 (2 cm gap)
		2.6 (10 cm gap)
Nylon	3.6 - 4.6	12 - 18
PTFE	2.0	19
Water (distilled - 20 °C)	80	

Primary factors correlated to ESD sensitivity are volume resistivity, dielectric constant, and the dielectric strength.[5] Below the point of breakdown, the higher the dielectric constant, the more energy that can be stored (by a material), and therefore, a greater opportunity to approach the breakdown strength. Counter to the buildup of charge is the material's ability to dissipate charge by conduction. The material's volume and surface resistivity affect the rate of charge loss, which can be characterized as a relaxation time (τ) computed as the product of volume resistivity (ρ) and dielectric constant ($\tau = K\epsilon_{\mathbf{o}}\rho$).

There are three materials implicated in a spark discharge within the TPC system: the HTPB/AP, the Hi-Temp, and the air that separates the Hi-Temp from the HTPB/AP. The dielectric breakdown strength for the pyrotechnic materials, Hi-Temp and HTPB/AP, and knowledge of the geometry, would allow determination of the potential at which an arc would occur should sufficient charge accumulate. At the time this analysis was performed, information on the dielectric properties for the pyrotechnic materials was not available. However, the dielectric constant and the dielectric strength of air are known and will be substantially less than the pyrotechnic materials indicating that breakdown will occur in the air first. One other factor to consider is humidity. The presence of water vapor (typically for relative humidity (RH) > 45%) can reduce charging rates for physical circumstances where surface separations are small permitting rapid equilibration of charge. This is certainly a factor for the dimensions within the TPC.

Objects in the "real" world have an associated capacitance, or charge-holding capacity. Assuming the amount of energy discharged is related to the capacitance of the body, an estimate of the discharge energy could be computed and compared to experimental data for initiation. The maximum energy of a capacitor can be expressed as $W = 0.5\ Q_{max}{*}V^2{}_{max}$. Therefore, if the charge the system is capable of holding is known, as well as the voltage which for the worst case would be the discharge voltage, then the discharge energy will be known. Some typical capacitances for common objects[3] are noted in Table 2.

Table 2. Typical capacitances for common objects.

Object	Capacitance (pF)	Comment
Car	500	
Person	100 - 400 (200=average)	
Tank	100,000	3 m diameter tank with insulating lining

For reference purposes, the "human experience" with regard to spark discharge is included to provide a physical sense of what may transpire within the TPC[3] (Table 3).

Table 3. Human spark discharge and consequences.

Charging Action	Voltage kV	Energy mJ	Consequences
Various	3	< 0.5	Below sensation
Carpet, low RH	10	0.5 - 1	Perceptible on hand
Slide on Carpet - Dry air	30	1 - 10	Various levels of discomfort
Auto spark plug	30	15 - 35	Unpleasant
Electric shock	>30*	250	Severe
Electric shock	>30*	1000 - 10,000	Possible unconsciousness
Electric shock	>30*	> 10,000	Possible cardiac arrest

*Or a significant increase in current.

E. Charging Processes

The concern for spark discharge is only valid if sufficient charge can accumulate. There are a variety of mechanisms that can cause charge accumulation[3]:

- Contact and separation (tribocharging, includes friction and adhesives action),
- Fragmentation of solids with non-uniform surface charge densities,
- Shear at phase boundaries,
- Gravitational separation of suspended material,
- Induction charging, and
- Ionic charging.

In the context of vibration of the loose pyrotechnic grains, only the tribocharging mechanism plays a role in TPC systems.

Research performed to develop information that permits control of the amount of charge deposited, not simply reduced, has led to tabulation of relative charging affinities for different insulating materials, given a fixed charging process (Table 4). A level of charge per amount of energy (J) as results from the "pinch/friction" from a roller can be measured for each material. Relevant units are nano-coulombs per Joule (nC/J). This approach allows computation of charging affinity for contact between any two materials as the difference in their individual charging affinity values. Materials with similar charge affinities do not produce charging when brought together and separated. When one of the materials is a conductor, the pressure of contact surface texture produces relatively strong effects such that charge transfer quantification is not consistent. The magnitude of the charging affinities varies with the conditions of test including atmospheric pressure, humidity, etc. Of particular importance is that changing the conditions and method of charging does not affect the relative ranking of the materials. However, the amount of charge per area that can be transferred is limited by two different effects. If the dielectric breakdown strength for air is exceeded, the surfaces will simply short out with a spark discharge. With smaller amounts of charge, affinities less than ~50 nC/J, the charge difference achieved by bringing them together and separating them never exceeds 2 nC/cm^2. Both of these effects are observed experimentally.[6]

Table 4. Triboelectric Table[6]

Insulator Name	Charge Affinity - nC/J (nano ampsec/wattsec of friction)	Charge acquired if rubbed with metal (W=weak, N=normal, or consistent with the affinity)	Notes
Polyurethane foam	+60	+N	All materials are good insulators (>1000 T ohm cm) unless noted.
Sorbothane	+58	-W	Slightly conductive. (120 G ohm cm).
Box sealing tape (BOPP)	+55	+W	Non-sticky side. Becomes more negative if sanded down to the BOPP film.
Hair, oily skin	+45	+N	Skin is conductive. Cannot be charged by metal rubbing.
Solid polyurethane, filled	+40	+N	Slightly conductive. (8 T ohm cm).
Magnesium fluoride (MgF2)	+35	+N	Anti-reflective optical coating.
Nylon, dry skin	+30	+N	Skin is conductive. Cannot be charged by metal rubbing.
Machine oil	+29	+N	
Nylatron (nylon filled with MoS2)	+28	+N	
Glass (soda)	+25	+N	Slightly conductive. (Depends on humidity).
Paper (uncoated copy)	+10	-W	Most papers & cardboard have similar affinity. Slightly conductive.
Wood (pine)	+7	-W	
GE brand Silicone II (hardens in air)	+6	+N	More positive than the other silicone chemistry
Cotton	+5	+N	Slightly conductive. (Depends on humidity).
Nitrile rubber	+3	-W	
Wool	0	-W	
Polycarbonate	-5	-W	
ABS	-5	-N	
Acrylic (polymethyl methacrylate) and adhesive side of clear carton-sealing and office tape	-10	-N	Several clear tape adhesives have an affinity almost identical to acrylic, even though various compositions are listed.
Epoxy (circuit board)	-32	-N	
Styrene-butadiene rubber (SBR, Buna S)	-35	-N	Sometimes inaccurately called "neoprene."

Insulator Name	Charge Affinity - nC/J (nano ampsec/wattsec of friction)	Charge acquired if rubbed with metal (W=weak, N=normal, or consistent with the affinity)	Notes
Solvent-based spray paints	-38	-N	May vary.
PET (mylar) cloth	-40	-W	
PET (mylar) solid	-40	+W	
EVA rubber for gaskets, filled	-55	-N	Slightly conductive. (10 T ohm cm). Filled rubber will usually conduct.
Gum rubber	-60	-N	Barely conductive. (500 T ohm cm).
Hot melt glue	-62	-N	
Polystyrene	-70	-N	
Silicones (air harden & thermoset, but *not* GE)	-72	-N	
Vinyl: flexible (clear tubing)	-75	-N	
Carton-sealing tape (BOPP), sanded down	-85	-N	Raw surface is very + but close to PP when sanded.
Olefins (alkenes): LDPE, HDPE, PP	-90	-N	Against metals, PP is more negative than PE.
Cellulose nitrate	-93	-N	
Office tape backing (vinyl copolymer)	-95	-N	
UHMWPE	-95	-N	
Neoprene (polychloroprene, *not* SBR)	-98	-N	Slightly conductive if filled (1.5 T ohm cm).
PVC (rigid vinyl)	-100	-N	
Latex (natural) rubber	-105	-N	
Viton, filled	-117	-N	Slightly conductive. (40 T ohm cm).
Epichlorohydrin rubber, filled	-118	-N	Slightly conductive. (250 G ohm cm).
Santoprene rubber	-120	-N	
Hypalon rubber, filled	-130	-N	Slightly conductive. (30 T ohm cm).
Butyl rubber, filled	-135	-N	Conductive. (900 M ohm cm).
EDPM rubber, filled	-140	-N	Slightly conductive. (40 T ohm cm).
Teflon®*	-190	-N	Surface possesses fluorine atoms - very electronegative.

* Teflon® is a registered trademark of E. I. du Pont de Nemours & Company, Wilmington, Delaware.

For a spark discharge to occur, charge must accumulate sufficiently to create an electric field that approaches the breakdown strength. The charging process is conceptualized in Fig. 2.

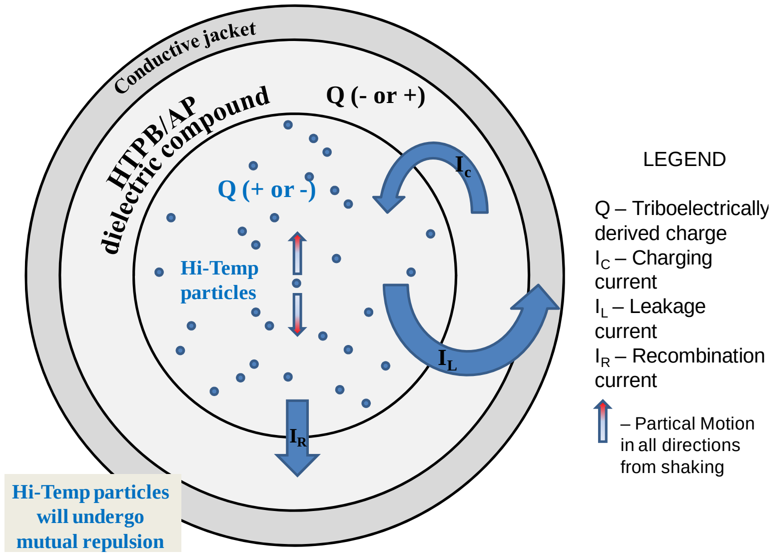

Figure 2. Working triboelectric charging concept.

The HTPB/AP is fabricated as a cylinder with a set of cylindrical passages (boreholes) that penetrate the length. The intended function is for the hot gases from the burning Hi-Temp to initiate combustion of the HTPB/AP. The diagram shows the volume within one of the boreholes and depicts the Hi-Temp grains colliding back and forth against the HTPB/AP walls. The direction of particle motion is depicted for only one moment in time and it should be considered to change as driven by forces induced by the vibration of the TPC and due to collisions. In the envisioned process, each grain is capable of accruing charge. However, it is not clear how many grains of Hi-Temp are available. NDE performed on the TPCs selected for examination revealed that the Hi-Temp had escaped, but not how much. Several charging outcomes are possible with each collision:

- Charging may take place,
- Increased charging may occur if different parts of the particle surface strike an uncharged region,
- Opposite charges may recombine.

Other behaviors that are likely to occur include:

- Repulsion between particles possessing the same charge,
- Particles sticking to surfaces due to induced charges either in the particle or the "wall,"
- Potential differences may form within the TPC system causing charge to flow depending on the resistance along the charge flow path.

From the point of an overall circuit (Fig. 3), the system may be viewed as a "leaky" capacitor.[3] The outer steel case is conductive and surrounds a dielectric material. Several charge flows are possible, including a charging current (IC) due to triboelectric charging, a leakage current through conductive elements in the system (IL), and a recombination current (IR).

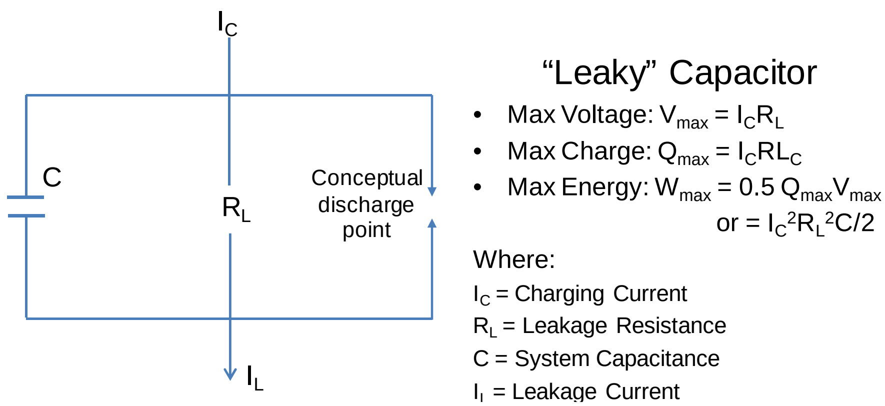

Figure 3. Working electric circuit representation.

The arrows represent the point of discharge, but it is not clear from our knowledge of the TPC geometry which regions are likely to promote discharge. Theoretically, that should be a region with a high radius of curvature like a sharp surface, or a point where the electric field will be concentrated. The overall system has capacitance (C) and should sufficient charge accumulate, such that the electric field exceeds the breakdown threshold, an electric discharge will occur.

F. Ignition of Various Mixtures and Materials

Breakdown conditions in ambient air typically occur when the average electric field within the discharge gap exceeds 0.5 V/µm and where at some point, the field should exceed 3.0 V/µm. There a variety of static discharge mechanisms are influenced by the geometry and composition of what will act as the discharge electrodes. The most common is the spark discharge that acts as a distinct pulse when breakdown conditions occur. It occurs over an unlimited range of energies (Fig. 4). Several different static discharge mechanisms are also shown that release charge in a more distributed fashion as described by their names. These include in order of increasing energy: the corona, brush, propagating brush (PBD), and intermediate forms of discharge.

One obvious observation is that given the grain size of Hi-Temp, a nominal opening approaching that of a sieve mesh size of 10 [ASTM E11 for characterizing powders] would be required to let a grain pass. That implies on the basis of size, the Hi-Temp would be categorized as somewhat larger than sub-200 mesh dusts and therefore, would require an ignition energy falling into the range of 10 to 1000 mJ. Given the distributed nature of the corona and brush discharge mechanisms and the large size of the Hi-Temp grains, the standard spark discharge is the most likely ignition mechanism.

If the spark possesses sufficient energy and is in proximity to a Hi-Temp grain, ignition of the grain will occur. If the grain is sufficiently close to other grains, then more energy will be released, perhaps enough to initiate the HTPB/AP. It is a reasonable assumption that the much greater thermal mass of the HTPB/AP will prevent it from being directly ignited.

G. Single Grain Impact Energy

The source of energy for a discharge will come from the kinetic energy of the particle due to its motion relative to that of the HTPB/AP surface. Several assumptions were used to evaluate a nominal "worst case" to see what upper bound could be placed on charge generation due to motion:

- Worst case path originating on the center axis of the bore
- Constant acceleration between start and impact
- Particle mass was based on nominal dimensions and density
- All three components of acceleration act on the particle simultaneously
- Acceleration data was specified as a distribution. The three sigma RMS acceleration values were used.
- Total kinetic energy transferred to borehole wall during impact
- Total conversion of kinetic energy to charge creation

The findings indicated that under the collision assumptions, the maximum energy should be significantly less than 2.0 µ Joules. By comparison, the minimum ignition energy for a stoichiometric hydrogen-oxygen mixture, one of the most sensitive mixtures to initiation, is published at 8 µ Joules. This is five orders of magnitude smaller than the type of discharge indicated for coarse dusts by the ignition chart (Fig. 4). If a sufficiently energetic discharge is to occur, it must result from charge accumulation involving numerous collisions and not be affected by leakage or recombination currents.

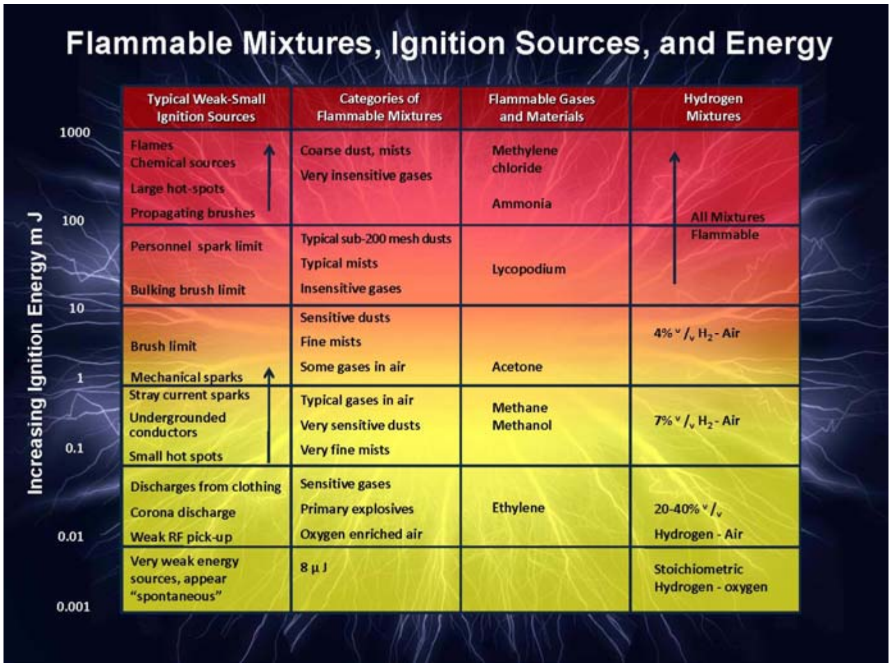

Figure 4. Ignition chart.

H. Inexact Information and the Critical Initiation Energy

A single colliding grain is not capable of igniting the Hi-Temp. Multiple strikes under conditions that favor charge accumulation *may* result in a charge buildup. If there is sufficient charge buildup, it will manifest first with a breakdown in air. This may depend on the capacitive characteristics of the TPC, in its ability to hold a charge. Two separate lines of inquiry are suggested, both with a facsimile TPC as a test article.

A judicious choice of a polymeric material could simulate the capacitive and charge-generating characteristics of a TPC and avoid the use of the actual pyrotechnic materials. Because air breakdown will short circuit unlimited charge buildup, simulating the capacitance may not be as important as demonstrating charge buildup and discharge. Whereas the triboelectric characteristics of Hi-Temp and HTPB/AP are not known, the overall characteristics of the system can be demonstrated if a material were chosen to ensure charging behavior is greater than that of the pyrotechnic materials. If it turns out that materials with greater charging characteristics do not result in a sufficiently energetic discharge to threaten ignition, then we have a basis for concluding that ignition cannot occur. Examination of the triboelectric series[6] shows PTFE Teflon®† to be highly electronegative and polyurethane to be highly electropositive, and more so than almost all other materials. These materials could be fabricated to duplicate the geometry of the HTBP/AP and Hi-Temp and placed within a steel sleeve that duplicates the TPC case. The charging behavior of a facsimile TPC with surrogate materials should bound the pyrotechnic charging behavior and show where air breakdown occurs.

One line of investigation pursued was to evaluate the capability of the facsimile to accumulate charge. By noting the discharge voltage at the point of air breakdown and measuring the system capacitance, the energy of discharge can be determined. Charging can be applied triboelectrically to see what system potentials can be achieved, and applied with a high voltage power supply to see where air breakdown occurs.

A separate line of investigation will subject the facsimile system to vibrations designed to simulate launch conditions. Charge measurement under such conditions is very difficult. Lycopodium[8] is a spore with sub-200 mesh size that readily ignites when exposed to a 20 mJ ignition source, a level an order of magnitude less than the lowest values for the ABL discharge test (Fig. 4). If there is no ignition, this will provide a separate confirmation.

† Teflon® is a registered trademark of E. I. du Pont de Nemours & Company, Wilmington, Delaware.

IV. Experimental Discharge Results

Six test articles were constructed to duplicate TPCs from the standpoint of internal free volume and general overall dimensions. The facsimiles were fabricated to allow mounting to a shaker table and a Teflon (PTFE) block for electrical isolation (Fig. 5). Original TPC case dimensions for the inside and outside diameters and length were fabricated from 304 L SS. Teflon (PTFE) was chosen as a surrogate dielectric material and was machined to have the original dimensions of the HTPB/AP subcomponent. An open cell foam spacer was cut to the same size as assembled within a TPC. Spacers, fabricated from Teflon (PTFE), were used to replace the Hi-Temp container and the first component in the pyrotechnic chain. A screw cap permitted sealing the components and surrogate pyrotechnic grains within the case. Polyurethane was diced into small particles with approximately the same dimensions as Hi-Temp grains. The physical impression of the cut polyurethane is one of minor tackiness. In addition, nylon, while not as electropositive, was prepared in the same fashion because the grains give the appearance of being dry. Aluminum rods were machined to allow their placement within borehole-sized passages machined within the surrogate Teflon subcomponent to facilitate capacitance measurement (Fig. 6).

Figure 5. The capacitance for the facsimile TPC was measured to be 8 pF.

Figure 6. Test article opened posttest showing Lycopodium powder mixed with polyurethane particles and no evidence of ignition.

A. High Voltage Discharge

The test article was placed in a shielded area on a bench designed for high voltage work. High voltage was applied to metal rods placed within the simulated boreholes in the PTFE and voltage measurements were performed on the case. The voltage was incremented to increasing higher values until a discharge occurred as the probe approached the case. The air breakdown was observed for potentials that range between 12 and 15 k.

B. Triboelectric Charging

As a validation test prior to testing with the shaker facility (Fig. 7), the charging action sought by particle collisions was simulated by 30 s of vigorous mechanical rubbing using a small bottle brush with nylon bristles within the borehole passages. Field measurements showed voltages ranging from 300 to 3000 V.

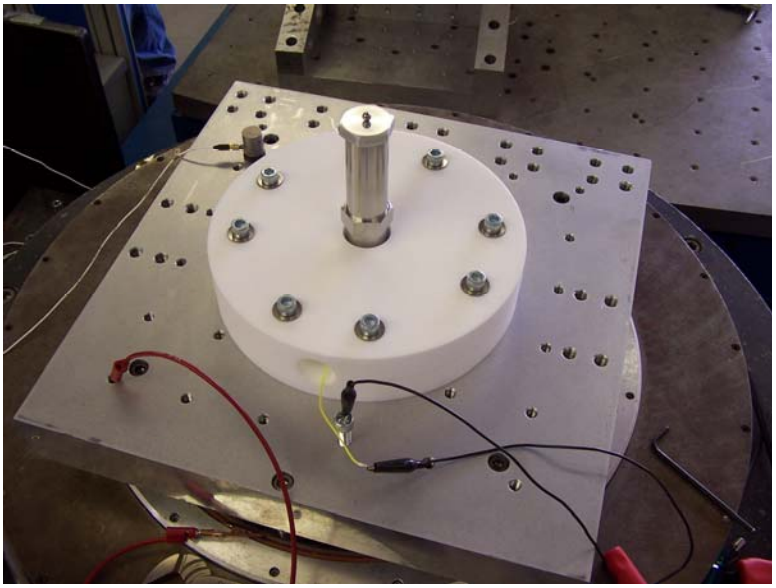

Figure 7. Test article mounted on shaker table.

C. Vibration Excitation of Polyurethane, Nylon, and Lycopodium Powder

The test articles were prepared for travel to the shaker table facility. Polyurethane “grains,” nylon “grains,” and lycopodium powder were loaded into the borehole passages in a glove box under a dry nitrogen purge and then closed. Six TPC test articles were loaded with a matrix combination of two sets of lycopodium alone, lycopodium + nylon, and lycopodium + polyurethane. The shaker facility was programmed to subject the TPCs to a vibration profile that involved three axes and acceleration levels out to 30 g-rms representing accelerational excursions as high as three standard deviations from the nominal acceleration. One set would be tested for 60 s, the duration of the acceleration, and the second set for 180 s, the duration of the entire launch.

The results were negative for all test articles. No evidence of reaction was observed when the test articles were opened and the contents examined.

V. Analysis

The objective of this study is to build confidence for the proper operation of the TPS system despite escape of Hi-Temp within the case. The Hi-Temp pyrotechnic is 80% Royal Demolition Explosive (RDX) by weight. The predominant experience with this energetic material has been that of a relatively insensitive energetic material safely used in many applications. Counter to this experience is the understanding that the behavior of ordnance materials is very specific to a particular environment. Queries within the aerospace pyrotechnic community for experience relevant to this problem did not reduce the concerns for inadvertent ignition.

The results of a survey for ESD sensitivity data for Hi-Temp are shown in Table 5. RDX is shown for comparison purposes. The ATK results are more than 50 times greater than the other findings.

Table 5. ESD sensitivity data for Hi-Temp.*

Material	Test Method	Energy (mJ)	Source	Comment
Hi-Temp	ABL 150	5656	ATK[2]	Results are marked as 20 negative results, which disagrees with UTEC and NAVSEA findings.
Hi-Temp	ARDEC 1032	100	UTEC Corporation	Testing was positive for a 250 mJ, the result is recorded for 20 successive negative results, test samples were 30 mg each[7]
Hi-Temp	ABL 150	95	NAVSEA	
RDX	ABL 150	185	NAVSEA	Used for cross comparison

* The Hi-Temp formulation contains 80% RDX. The initiation energy for RDX is 185 mJ as determined by tests ABL 150 performed by NAVSEA. Ref 4 (put correct ref number).

Given this discrepancy and the values for RDX, it is prudent to disregard the ATK data in favor of an initiation energy of 95 to 100 mJ.

The analysis is performed as a "second best" alternative to testing with flight articles or flight materials. The approach is to demonstrate the nature of static discharge processes given the geometry of the TPC and the vibration environment of launch. Several general findings are:

- Charge accumulation is equilibrium between charging processes and conduction processes that lead to the relaxation of charge.
- The dielectric breakdown strengths of the pyrotechnic materials are greater than that of air. Therefore, air breakdown is likely to be the limiting factor for voltage buildup.
- Objects with a construction similar to a thruster pressure cartridge will have a nominal capacitance dictated by the geometry and the dielectric properties of the encased materials. For the facsimile, a capacitance value of 8 pF was obtained. The properties for the pyrotechnic materials are not expected to substantially increase the capacitance. The capacitance of an object dictates how much charge, and therefore, how much energy can be released.

A summary of findings is presented in Table 6.

Table 6. Summary of ESD findings.

Finding	Initiation Energy Implication (mJ)	Comment
Maximum charge accumulation For a single particle	0.002 Safety factor* > 40,000	Derived from energy of motion considerations for the mass of a single grain of Hi-Temp™
Triboelectric charging in facsimile TPC 300 - 3000 V	0.4 Safety factor* > 200	Determined from system capacitance assuming a discharge occurs. Relaxation of charge is more likely.
Air break down measured for the facsimile TPC Ranges: 12 - 15 kV	2 Safety factor* > 40	Determined from system capacitance. Charge relaxation is more likely to occur before such voltages are achieved.
Lycopodium as a sensitive dust energy indicator is negative	20 Safety factor* > 4	Lycopodium is a test standard that reliably ignites when initiation sources of 20 mJ or greater are present.
Coarse dusts for 200 mesh and greater typically require greater initiation energies	100 - 1000	The nominal grain size for Hi-Temp™ indicates a mesh size much greater than 200 mesh. This information is in agreement with the published spark discharge data.

* Based on 95 mJ initiation energy published by NAVSEA.

VI. Conclusion

The information acquired in this study suggests that charge accumulation by triboelectric mechanisms within the thruster pressure cartridges due to launch vibration or other rough handling will probably relax without a discharge. If a discharge did occur, it would manifest energy several orders of magnitude below that of published spark discharge data for Hi-Temp. Deposited by other means, a larger charge would likely result in an air discharge. A safety factor of greater than 40 would apply to an air discharge, meaning that it would not be sufficient to ignite Hi-Temp. The experimental results using the flammable/explosive dust lycopodium indicate that with reproduction of the worst case launch vibration environment, no reaction would occur even when the duration is extended. The lycopodium initiation threshold indicates a safety factor greater than 4.

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Investigating Premature Ignition of Thruster Pressure Cartridges by Vibration-Induced Electrostatic Discharge

46th AIAA/ASME/SAE/ASEE Joint Propulsion Conference

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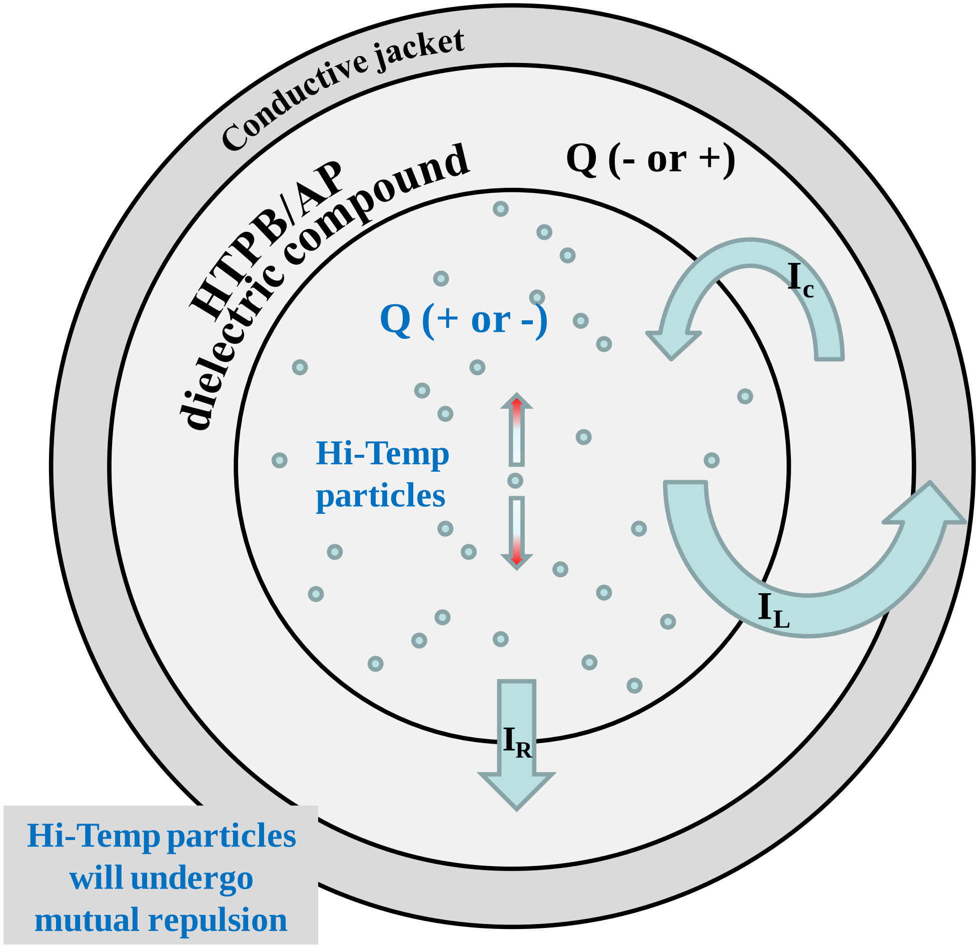
July 26th, 2010

Problem Description

- Launch vehicle uses pyrotechnic thruster pressure cartridges (TPCs) for aeroshell separation
  - Units undergoing acceptance testing had nominal performance, but nondestructive evaluation (NDE) indicated that:
    - Internal assemblies moved during shock testing (failed epoxy bond)
    - Grains of second stage pyrotechnic, Hi-Temp^{TM} were loose
  - Mission timeline precluded fabrication of a new lot
- Concern raised: could launch vibration induce sufficient electrostatic discharge (ESD) to cause premature ignition?
  - Expert opinion: Electrostatic ignition not an issue
  - Contradictory spark ignition data: 0.095 J to 5.656 J
  - Initiation scenario is not modeled by standard test
  - How is ESD from triboelectric charging characterized?
    - No data for Hi-Temp or hydroxyl-terminated polybutadiene/aluminum perchlorate (HTPB/AP)
    - Timely efforts challenged by practical issues of obtaining, transporting, and safely handling pyrotechnics

Triboelectric Charging Concept



LEGEND

Q – Triboelectrically derived charge
I_C – Charging current
I_L – Leakage current
I_R – Recombination current

– Particle Motion in all directions from shaking

TPC ESD Evaluation Approach

- Determine ESD energies possible within system
  - If energies < 0.01 J, then Hi-Temp ignition is not expected
- Characterize how ESD arises from mechanical agitation
  - Triboelectric charging
  - Factors for energy buildup
    - (dielectric, capacitance, relaxation - discharge)
- Sidestep ordnance handling issues
  - Fabricate facsimile test article to duplicate TPC geometry
    - Model energy buildup (capacitive) characteristics
  - Substitute materials for pyrotechnics from a triboelectric charging perspective such that charging > pyrotechnics;
    - Teflon (max -), Polyurethane (max +), & nylon (large +)
  - Simulate launch vibration and use a characterized ignition indicator
    - Lycopodium – 20 mJ

Initiation

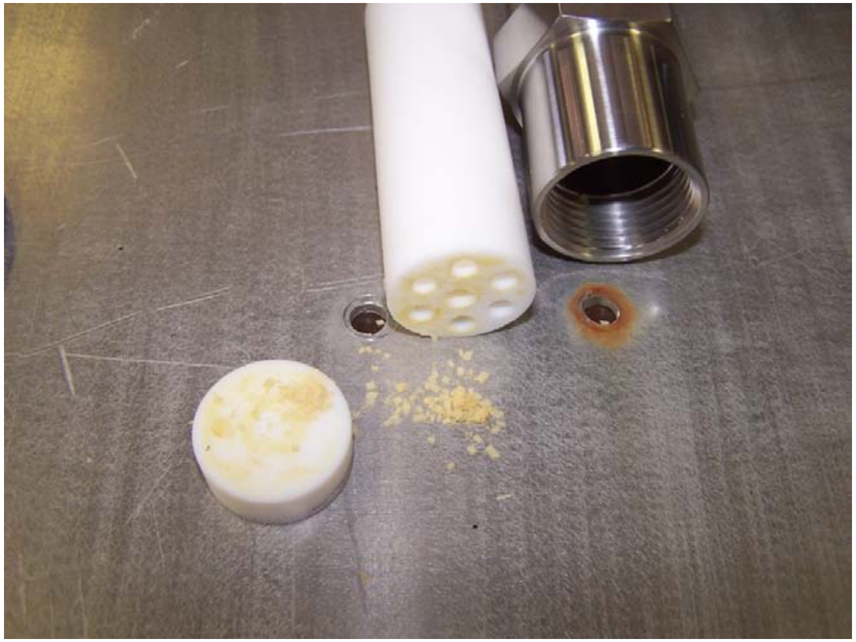
Flammable Mixtures, Ignition Sources, and Energy

Increasing Ignition Energy m J

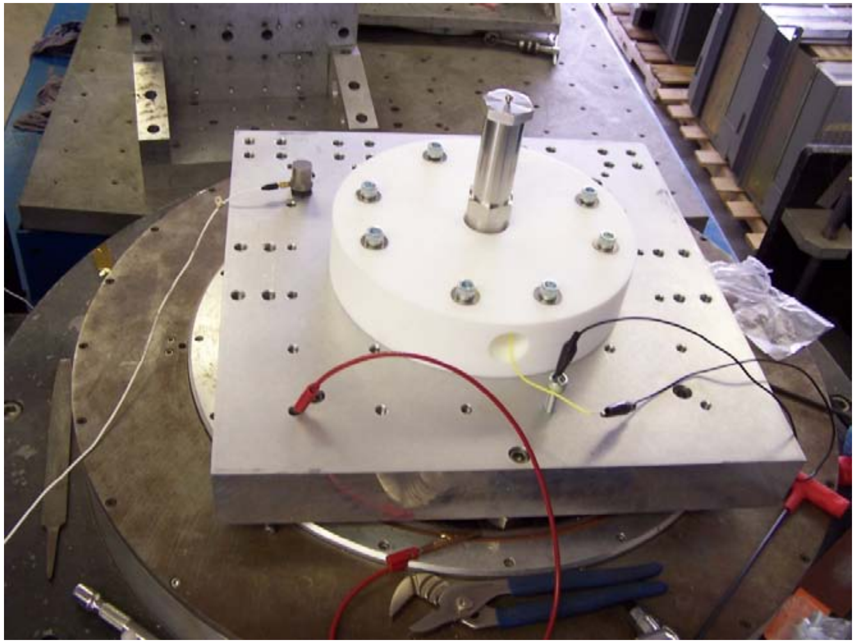
1000, 100, 10, 1, 0.1, 0.01, 0.001

Typical Weak-Small Ignition Sources	Categories of Flammable Mixtures	Flammable Gases and Materials	Hydrogen Mixtures
Flames Chemical sources Large hot-spots Propagating brushes	Coarse dust, mists Very insensitive gases	Methylene chloride Ammonia	All Mixtures Flammable
Personnel spark limit Bulking brush limit	Typical sub-200 mesh dusts Typical mists Insensitive gases	Lycopodium	
Brush limit Mechanical sparks	Sensitive dusts Fine mists Some gases in air	Acetone	4% $^v/_v$ H_2 - Air
Stray current sparks Undergrounded conductors Small hot spots	Typical gases in air Very sensitive dusts Very fine mists	Methane Methanol	7% $^v/_v$ H_2 - Air
Discharges from clothing Corona discharge Weak RF pick-up	Sensitive gases Primary explosives Oxygen enriched air	Ethylene	20-40% $^v/_v$ Hydrogen - Air
Very weak energy sources, appear "spontaneous"	8 µ J		Stoichiometric Hydrogen - oxygen

ESD Vibration Tests



Test article components, posttest, showing unburned lycopodium powder with polyurethane particles



Test article in vertical mount on shaker table

TPC ESD Findings

- Launch vibration evaluated as stimulus for ESD within TPC
  - On a “per grain” basis, discharge energy can’t exceed ~1 µJ/grain (due to charging derived from kinetic energy)
  - Electrical characteristics evaluated with a facsimile TPC & surrogate materials
    - Surrogate materials selected to provide worst case triboelectric properties, greater than pyrotechnics (no data available for pyrotechnic materials)
    - Mechanical simulation of charge buildup within facsimile TPC typically produces 300 to 3000 V fields → maximum discharge energies < ~0.0004 J
    - System capacitance and air breakdown discharge characteristics limit ESD discharge energy < ~0.002 J
  - Shaker tests using surrogate materials + lycopodium to simulate Hi-Temp grains were subjected to worst case (3σ for 3x duration) launch vibration.
    - Result: No initiation of the lycopodium 20 mJ ESD ignition threshold → 5x safety factor
  - Hi-Temp threshold ignition ESD values from literature: 0.1 J (UTEC Corp.), 0.095 J (Navsea)
- Conclusion - ESD energy possible from triboelectric charging is 0.01% to 1% of the realm of concern for Hi-Temp

Conclusions

- Based on theoretical and test considerations, mechanical movement of inner TPC components due to failed epoxy bonds does not appear capable of generating sufficient ESD to cause uncommanded ignition of Hi-Temp during flight
- The analysis provided supports a risk informed assessment process
  - Quantitative risk assessment or determination of a data based safety factor would still require additional information
  - Present assessment gives at least a 5X safety factor, although supporting electrical characterization suggests a much greater factor
- Fabrication of TPCs that prevent movement of the propellant assembly or release of Hi-Temp would preclude the need for ESD analysis

For More Information

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