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Effect of Pin-to-Case Electrostatic Discharge on Electroexplosive Device Insulation Resistance

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In the recent design and testing of the upgraded detonator used in the Titan IVB explosive bolt for jettison of expended strap-on solid rocket motors, it was determined that the 25-kV, 500 pF, pin-to-case electrostatic discharge test without the traditional 5-kΩ series resistor is a destructive test. After this test, pin-to-case insulation resistance in the detonator measured under the traditional 500 V could fail the 2-MΩ minimum requirement. An extensive investigation established a relationship between three phenomena: the electrostatic discharge, the insulation resistance, and the pin-to-case breakdown voltage. Several screening techniques were developed and verified. Parameters and designs for eliminating or reducing the failure were identified for future design of electroexplosive devices.

Introduction

EACH of the twin solid rocket motor upgrade (SRMU) boosters employs two explosive bolts as locking elements in the mechanism attaching the SRMUs to the Titan IVB core vehicle. The design of the bolt was inherited from the original Titan IVA solid rocket motor and reflects 1960s technology but has demonstrated high performance and reliability. Much of the effort on the bolt since then has focused on material control and testing necessary to achieve two seemingly contradictory requirements: high mechanical strength yet efficient severance on actuation.

Figures 1 and 2 show the exterior configuration and interior schematic of the bolt. Redundant explosive trains are designed at both ends of the bolt. Even if only one explosive train fires, the bolt will separate successfully. The train includes an electrical connector, an electrically initiated detonator, and a cyclotrimethylenetrinitramine (RDX) explosive-filled booster charge. Grooves on the surface of the bolt facilitate bolt separation through shear failure of the material due to bolt body expansion caused by the booster charge. The detonator employs state-of-the-art 1960s design: dual bridgewire, a primer pyrotechnic, lead azide, and pentaerythritol tetranitrate (PETN) explosive as an output charge. The pin-header consists of the steel detonator body and two glass sealed pins manufactured using state-of-the art hot furnace technology for glass-to-metal seal. A boron nitride disk (with two through holes for the pins) is then cemented into the bottom of the header, and a cavity for bridgewire installation and primer charge loading is machined in the disk. To complete the detonator, a sleeve loaded with lead azide and PETN is pressed into the header and a steel closure disk is welded in place.

Similar to many Minuteman missile explosive devices designed in the 1960s (Ref. 1), the bridgewire of the detonator adopted a low resistance (0.22–0.32 Ω) and high all-fire current (5.0 A). Therefore, it can meet the 1.0-A, 5-min no-fire standard but not the 1.0-W, 5-min no-fire standard. In 1997, following a recommendation of the Range Safety Offices, the design of this unit was upgraded, including changing the dual bridgewire to single bridgewire, increasing the bridgewire resistance to 0.9–1.08 Ω, performing a 1 A–1 W 5-min no-fire test, and incorporating the new pin-to-case electrostatic discharge (ESD) test. These changes brought the bolt into conformance with the current safety requirements for electroexplosive devices (EEDs).

Measuring the insulation resistance (IR) between the pins and the case is an old safety and reliability requirement. It is widely used in testing EEDs, electrical cables, connectors, and equipment. The IR test is performed with 500-V dc voltage for a duration of 1–2 min. Usually, IR values on the order of 10^7–10^{11} Ω are measured against a standard lower limit of 2 MΩ. This test is also widely in use at the pin-header level as an in-process test prior to the installation of bridgewire. In this case, the measurement is performed between each pin to the pin-header case. The ESD test imposes a voltage of 25-kV dc from a 500-pF capacitor on the EED, either between the pins or between the shorted pins and the case. A 5-kΩ series resistor was originally allowed in the test circuit.[2] However, since the 1970s, the use of the series resistor has been disallowed for the pin-to-case ESD test.[3,4] This change has required the redesign and requalification of many existing EEDs and additional efforts in designing and developing new EEDs. The main concern is that, under such a high voltage, an EED will inevitably break down.

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Fig. 1 Postfunction explosive bolt showing successful break into three segments.

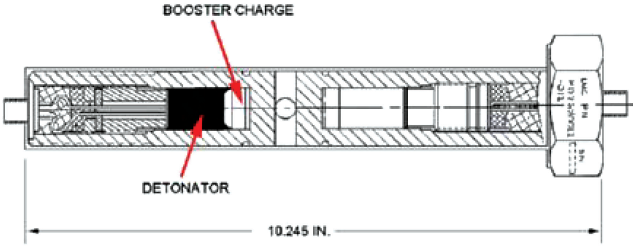

Fig. 2 Interior construction of explosive bolt.

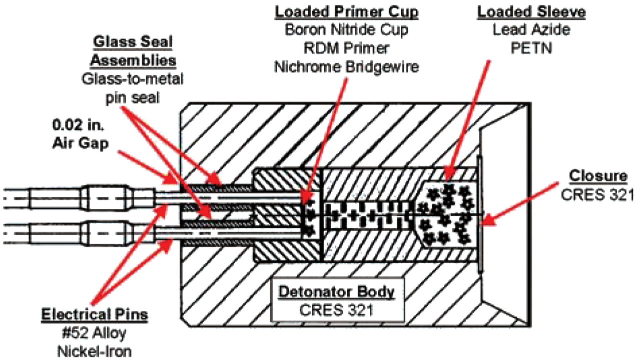

Fig. 3 Schematic diagram of detonator.

A design must provide a preferred discharge path external to the bridgewire/explosive primer area to avoid the inadvertent initiation of the explosive by the large ESD energy (0.156 J).

Figure 3 shows the design of the upgraded detonator for the explosive bolt. The case is made from a single piece of corrosion-resistant steel with glass-to-pin hermetic seals at the bottom of the cup-shaped body. The pins are 1.02 mm. in diameter. The seals are filled with R-6 glass. The glass seal has a length of ∼6.35 mm. and a thickness of ∼0.51 mm. The boron nitride primer cup is cemented to the bottom of the body cavity. Under this configuration, the shortest air path distance between the pins and the steel body exists in the pin/seal area just outside the steel body. To preclude this preferred discharge path from contamination, a meniscus was designed in the seal end surface between the pin and the body. The surface of the meniscus must be clear from solder, potting compound, and the insulation sleeve enclosing the pins.

Emergence of the Problem

The first 35-unit explosive bolt lot containing the upgraded detonator design was successfully manufactured and tested in 1997. ESD and 1 A–1 W no-fire tests were implemented for the first time. The detonator 100% nondestructive acceptance tests consisted of the bridgewire resistance test, pin-to-pin and pin-to-case ESD tests, IR test, leak test, and x-ray inspection. The destructive acceptance tests on 30 detonators consisted of a 1 A–1 W no-fire test, 15 units function tested at 3.25 A, and 15 units function tested at 6.50 A. All tests were performed at ambient temperature. A 100% leak test was also performed at the detonator pin-header level.

The bolt 100% nondestructive acceptance tests covered bridgewire resistance, leak, x-ray inspection, and IR. The destructive acceptance tests on nine units consisted of eight thermal cycles (−35°F and +160°F) and random vibration (50.1 g rms, 180 s per axis). Postenvironmental bridgewire resistance, IR, leak, x-ray, and 1 A–1 W no-fire tests were performed. Three units were function tested with 6.5 A at each temperature (6°F, ambient, and 160°F).

A second follow-on lot of 41 bolts was planned for December 2000 delivery. During the in-process testing, 17 detonators failed the IR test after the ESD test, that is, the measured resistance fell below the required minimum of 2 MΩ. These units had passed the IR test about three months previously using the traditional IR tester, Beckman Model L10A. A new, and much more sophisticated and sensitive IR tester, Slaughter Model 727/205, indicated the failures. When retested by the Beckman tester, 13 of 17 failed units passed the test again. Although this result would seem to indicate that test equipment was the major cause of the problem, this interpretation was not very conclusive because variability or repeatability problems in the test did exist. Whereas IR performance can be screened at the detonator level, a good detonator in one of the assembled bolts also failed the IR test. (IR failure does not mandate the rejection of the entire detonator lot.) The latter failure was not acceptable. The detonator lot (designated here as lot 2A) was disassembled from the bolts and set aside.

A new detonator lot (designated here as lot 2B) was successfully fabricated and tested as the replacement to lot 2A. However, 50% of bolt units assembled with the detonator again exhibited the IR failure when tested with the Slaughter Model 727/205 meter. This test result indicated that failure could occur in the field, if detonator replacement at the factory was used as the solution.

Failure Investigation

Lot 2B was rejected because it also experienced an additional failure: A pin broke during the vibration test. Extensive investigations were performed for both problems. The broken pin is a problem independent of the IR failure; therefore, it is not included in this paper. For the IR failure, more than 80 areas were identified for assessment or test following a fault tree analysis, for example, microcracks and air bubbles in glass, contamination, moisture, test equipment, and manufacturing process. The highlights are summarized in the following sections.

Equipment and Test Method

Common suspects for high-voltage insulation problems (moisture, contaminants, poor wire insulation, leak current around the bridgewire, etc.) were quickly eliminated as the cause for the failure. The pin-to-case ESD was identified as a possible cause. The IR tester was thought to be a factor as has been described earlier.

The ESD tester used a standard construction that consisted of 2.54-cm-diam metal spheres as electrical switch contacts. Lifting a lever manually actuated the discharge. The article under test was connected to the high-voltage output of the machine by a shielded cable approximately 4 ft long containing one twisted pair of insulated wires. The discharge waveform in the setup is complex. At the device under test, the voltage may double due to reflection in the transmission line operation mode. In addition, some energy will be lost to the arc created at the contact point of the spheres. These aspects were not evaluated because the machine used standard construction and had been used extensively in the factory previously.

The Beckman tester Model L10A is a traditional analog readout machine. It has an analog voltage meter to indicate the dialed test voltage and an analog megohmmeter for direct visual readout of the insulation resistance from 50 kΩ up to 5×10^7 MΩ. Its output current is limited to 12 mA under a short circuit condition for personnel safety and equipment protection. Its relatively slow response time can tolerate current fluctuation due to minor arcing or parallel resistive paths. The needle of the megohmmeter exhibits "needle wiggling" under this condition, and an "average" resistance can be read.

The Slaughter Model 727/205 IR tester is microprocessor based. The test voltage, duration, and limiting current can be programmed. Its maximum limiting current is 5 mA, which is not much lower than that of the Beckman L10A, but it has an arc-detection circuit built in that shuts down and indicates a failure in the event of an arc. Therefore, minor current fluctuations due to arcing will cause the machine to shut down automatically and indicate a failure.

A third IR tester, Freed Model 1620, has a limiting current capability of 7 mA and was used for arc resistance characterization for units exhibiting arcing failure during the IR test. Typical voltages

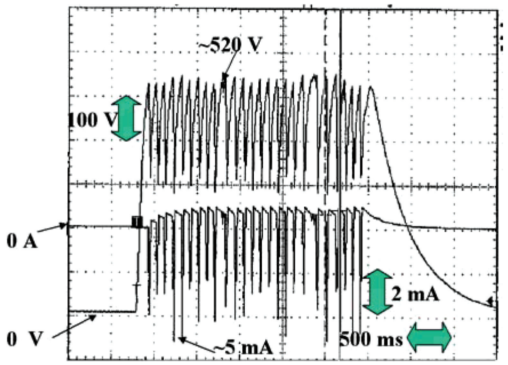

Fig. 4 Typical arcing characteristics of a failed pin-header during 550-V IR test.

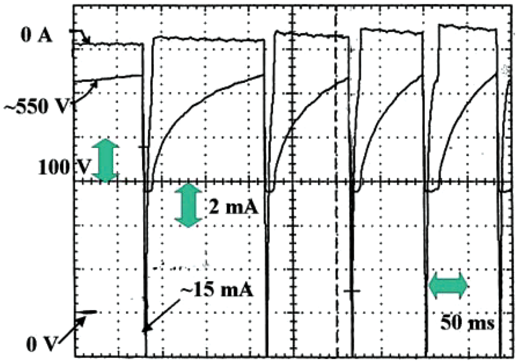

Fig. 5 Typical arcing characteristics in expanded timescale.

and arc currents observed in testing pin-headers are shown in Figs. 4 and 5. It can be seen that the arcing is a periodic phenomenon of frequency 7–14 Hz caused by the recharge rate of the device. Because of the narrow duration of the current spikes, it is quite possible to indicate an average current and, thereby, the resistance, if a slow response analog tester is used.

To test the IR performance effectively, a nondestructive tester other than an IR tester was needed. The readings of IR testers can be affected by many factors, such as the moisture level in the building. In addition, readings may vary by five orders of magnitude above the allowable 2 MΩ, and the 2-min testing duration is too time consuming for diagnostic or screening testing.

Very early in the investigation, it was found that the direct current breakdown voltage of the detonator or the pin-header was highly correlated to the IR. This is not a surprise because, if the IR test voltage is set too high, eventually arcing or breakdown will result.

A thorough evaluation was performed on the breakdown testing to determine the test parameters that could make the test nondestructive, that is, not cause IR to degrade. It was soon clear that this was not achievable if a series resistor cannot be used in the pin-header pin-to-case test. Capacitors rated from 0.00554 to 28 μF all caused IR degradation or arcing. A spark gap breakdown (SGB) voltage tester was found to be satisfactory. This test equipment was originally developed and qualified for testing the spark gap built into the exploding bridgewire detonator used in the now decommissioned Pershing II ballistic missile. Its discharge circuit consisted of a 0.15-μF capacitor and an 830-Ω series resistor. The voltage on the capacitor ramped up linearly from 0 to ~1930 V in 2 s. If breakdown occurred, it automatically reset to 0 V and restarted the ramp if programmed. No degradation in IR was observed in repeated breakdown testing of pin-headers or detonators by this machine. Therefore, it was adopted as the baseline tester for the investigation and subsequent pin-header and detonator screening tests.

Failure Isolation and Characterization

Figures 6–8 summarize the diagnostic testing of a portion of the lot 2B detonators (both failed and good units) using the breakdown technique. In Fig. 6, Serial Numbers (S/Ns) 15 and 32 had failed the IR test and S/Ns 16 and 24 had passed the IR test. The two failed units exhibited low breakdown voltages. S/N 32 data also indicate that IR failure can occur even though the detonator's breakdown voltage was ~650 V. As the teardown continued, there was no significant change in the breakdown voltage in these two failed units. Therefore, the origin of the failure was isolated to the pin-header.

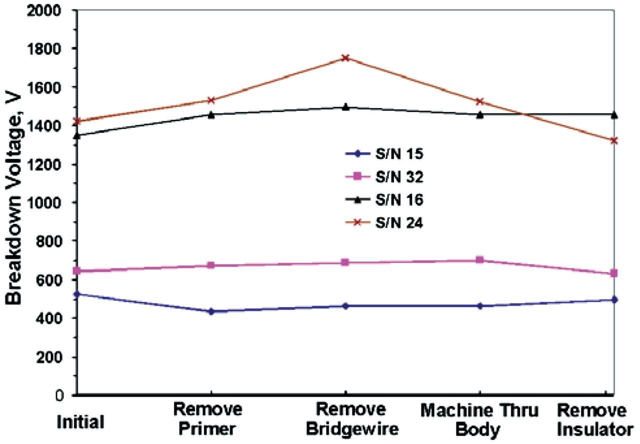

Fig. 6 Detonator pin-to-case breakdown voltage measured during step-by-step teardown, group E data.

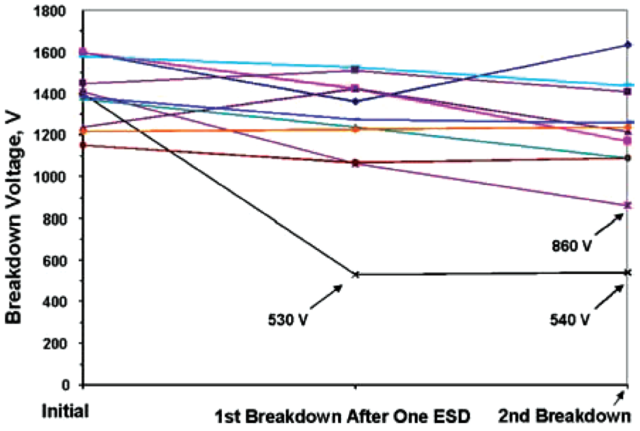

Fig. 7 Detonator pin-to-case breakdown voltage pre- and post-one pin-to-case ESD, group E-1 data.

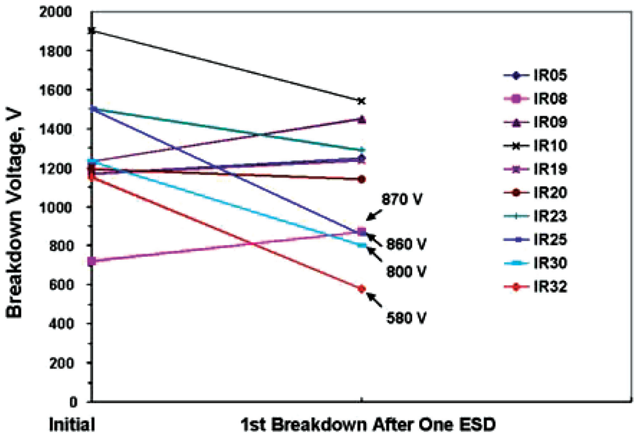

Fig. 8 Detonator pin-to-case breakdown voltage pre- and post-one pin-to-case ESD, group E-2 data.

Figure 7 shows data for detonators that were subjected to one pin-to-case ESD and the subsequent two consecutive IR tests. The low breakdown voltage of 530 V after the ESD correlates with the observed IR failure measured after the ESD. (The pre-ESD IR was successful.) The results for the two back-to-back breakdown voltage tests were within the typical variation for the breakdown voltage test.

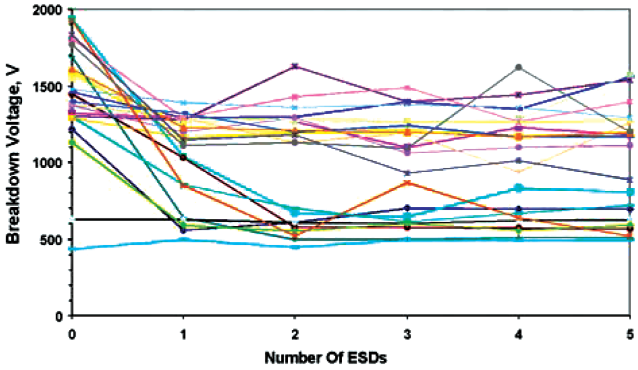

Fig. 9 **Pin-header pin-to-case breakdown voltage as a function of number of pin-to-case ESDs, group J data.**

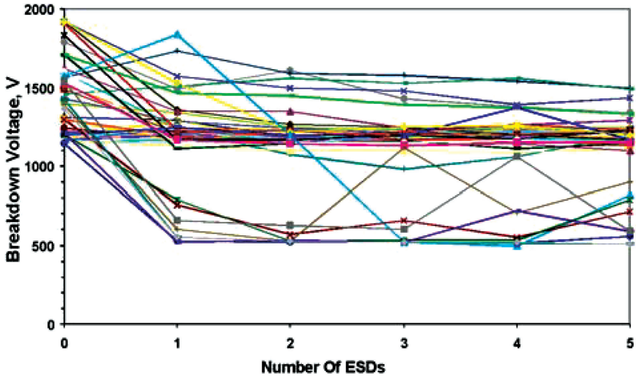

Fig. 10 **Pin-header pin-to-case breakdown voltage as a function of number of pin-to-case ESDs, group L data.**

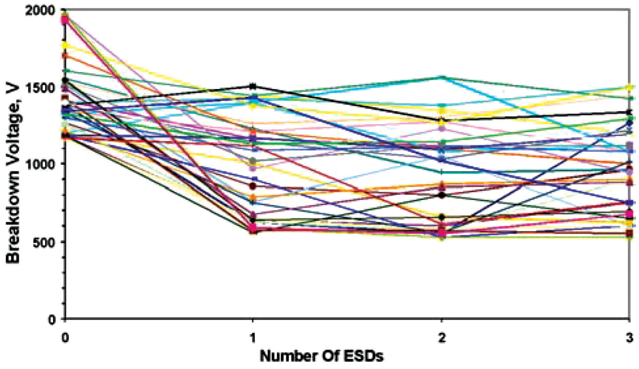

Fig. 11 **Pin-header pin-to-case breakdown voltage as a function of number of pin-to-case ESDs, group O data.**

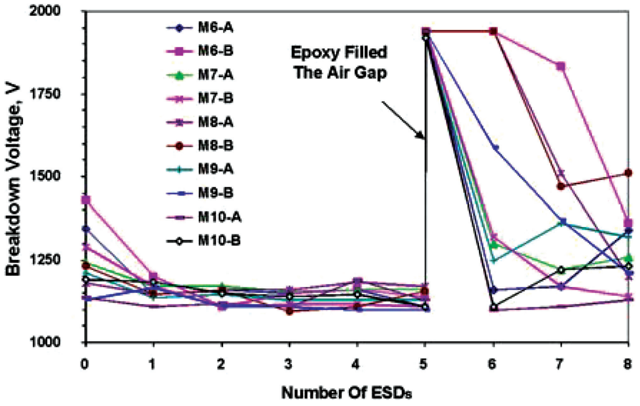

Fig. 12 **Breakdown voltage after each accumulated pin-to-case ESD for pin-header with Schott glass seal and ~2.54-mm deep gap at the inner end, group M data.**

In Fig. 8, many detonators showed a large decrease in breakdown voltage after one pin-to-case ESD. When the breakdown voltage approaches 500 V, IR failure can occur.

Figures 9–11 show the breakdown voltages of pin-headers after multiple pin-to-case ESD tests. The group J headers were pulled out after different steps in glass seal and plating processing; group L headers had shorter electrical pins (another design upgrade feature); and group O headers incorporated some earlier processing improvements.

Similar results were observed for all groups: Some units were not affected by the ESD test with their breakdown voltages remaining well above 1000 V. Some units showed a decrease in breakdown voltage to a range of 1000–1500 V after the first ESD test but remained steady throughout the subsequent ESD tests.

These two types of units were likely to survive the ESD and pass the IR tests that followed. However, a significant portion of units showed large breakdown voltage decreases toward the range of 500–700 V after the first ESD test. These units were likely to fail the IR tests that followed. A few pin-headers registered unfavorable breakdown voltage decreases after the second ESD test. This behavior is detrimental to the attempt to screen out the bad units based on the ESD and a single breakdown test. However, for most pin-headers, the breakdown voltage showed stable values after the first ESD test. As in many spark gap devices, the breakdown voltage can partially recover to higher values in subsequent breakdowns as the spark at times can purge the surface contaminants along its discharge path. This phenomenon can be seen in Fig. 10, in which two pin-header discharges exhibited large breakdown voltage recoveries in #3 and #4 discharge.

Results shown in Fig. 12 are unique. The pin-headers under test were deliberately filled with less glass in the seal to create an air gap of ~2.54 mm in the interior end of the seal. The units did not exhibit any breakdown voltage decrease as a function of number of pin-to-case ESD tests. The voltages, in fact, increased after epoxy was applied to the interior end of the seals. It is suspected that the high and steady breakdown voltage might indicate a robust IR performance. This good result was not pursued further because the purpose of the testing was to evaluate the effect of epoxy fill. Later, the glass fill was increased above the baseline value as one of the corrective actions for reducing the voids and bubbles in the glass.

Root Failure Cause Indication

Determining the root cause of the IR degradation by the pin-to-case ESD test is complicated by the inaccessibility of the small seal region. Visual observation indicated that the spark generated by the discharge appeared to be internal to the glass seal. This was taken to indicate that both ESD and electrical breakdown had occurred inside the glass of the seal. This assessment was supported by the low and scattered initial breakdown voltages of 1200–1950 V dc in these units, which are much lower than the handbook-reported air breakdown voltage corresponding to the 0.51-mm air gap between the pin and the header body in the meniscus region, >2500 V (Ref. 5).

A theoretical assessment indicated that these low initial breakdown voltages could occur in the glass seal if air bubbles of significant size or a mosaic of small bubbles are present for electrical field stratification. Bubbles and voids were observed in some seals. However, a positive correlation between their presence and the IR failure could not be established because some units with visible bubbles performed well in the IR test. Low gas pressure (resulting from the hot processing of the glass seal and subsequent cooling) and possible contamination are possible contributors to the low internal electrical breakdown voltage. The sputtering of metal films on the glass by the high-energy spark may further degrade the IR performance.

Changes in Material, Processing, and Design

Many corrective actions (some were precautionary, focusing on possible seal improvements) were implemented for the next detonator lot. These included changing the glass material from R-6 to Schott glass S-8061, increasing glass fill, eliminating corrosive cleaning solvents, adding preprocessing ultrasonic cleaning of pins by soap and deionized water, handling pins with gloves, adding insulation closure on the primer charge, polishing loading tools to eliminate scratches in the unit interior surfaces, controlling epoxy potting around the exterior pin-to-header air gap area, and changing plating and glass seal processing parameters (temperature, liquid phase dwell time, etc.). Some of these changes were also aimed at correcting the broken pin problem.

Detonator Lot 2C

The foregoing preliminary results seemed to indicate that a combination of process/design improvements and screening may produce detonators that can survive the 25-kV–500-pF pin-to-case ESD and subsequently pass the 500-V IR test. For the next detonator lot (designated here as lot 2C), the screening was focused at the pin-header level, before the installation of the bridgewire: All pin-headers were subjected to a pin-to-case breakdown test by the Pershing EBW SGB tester and a 550-V IR test. The objective was to establish a baseline breakdown voltage. A pin-to-case ESD was performed, and the breakdown test was reperformed, as well as the 550 V IR test. The screen criteria were that the unit must pass the IR test and the breakdown voltage must be beyond 650 V. These tests were performed one pin at a time. The successful units were then processed to detonator assembly. The IR and breakdown tests were also performed on the detonators and the same pass/fail criteria applied.

The results were not very encouraging. Of the 528 units in the pin-header lot, only 248 passed the first test round. A second test series performed on detonators fabricated from these survived headers showed that 45 detonators had failed the screening. These results indicate that the effectiveness of IR and breakdown voltage as screening tools had suffered when the testing continued to a higher level of assembly. The same symptom repeated one more time. Of 86 good detonators, 20 failed the 500-V IR test at the bolt assembly level. The change of physical configuration in different levels of assembly could have contributed to the failure of pin-headers and detonators that had passed the screening tests. Another possible factor was the intrinsic variability in these screening tests. Finally, the relationship between the IR failure and the breakdown voltage was not quantified; that is, the use of 650-V breakdown voltage as a pass/failure criterion was not adequate.

Figures 13–29 show the database generated by the screening tests. The distribution of the breakdown voltage of the 528 new pin-headers is shown in Fig. 13. Voltages are well above 1000 V, indicating excellent prospects for the headers to pass the 500-V IR test. The very high number in the 2000-V increment is an artifact because the SGB tester has a maximum voltage capability of 1950 V, that is, the breakdown voltage of some units could have well exceeded 2000 V. The distribution of the breakdown voltage on these same units after the ESD test is shown in Fig. 14. It is clear that the entire distribution of the breakdown voltage had shifted to the lower voltage values by approximately 500 V. A large number of units registered breakdown voltages below 1000 V. Many voltages were below 650 V. This led to the rejection of nearly half of the units per the 550-V IR and 650-V breakdown voltage-screening criteria.

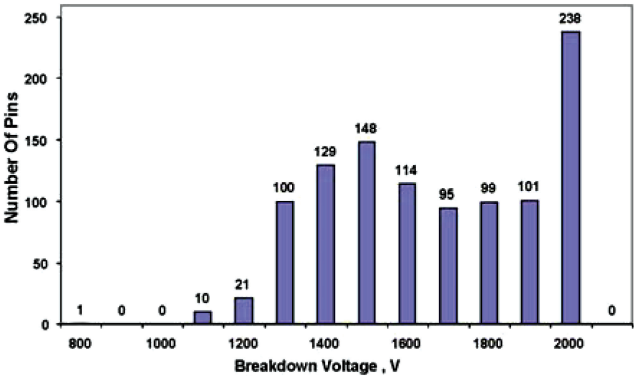

Fig. 13 Pin-header pin-to-case breakdown voltage before pin-to-case ESD.

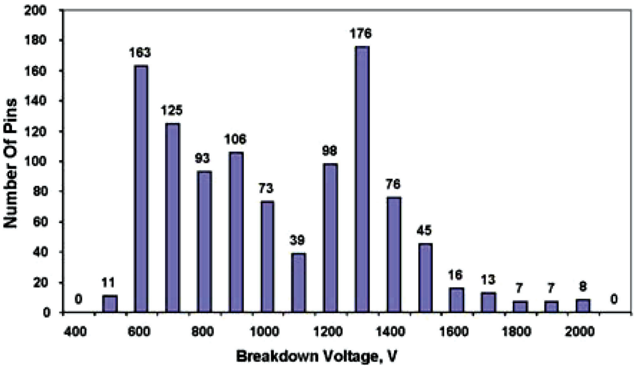

Fig. 14 Pin-header pin-to-case breakdown voltage after pin-to-case ESD.

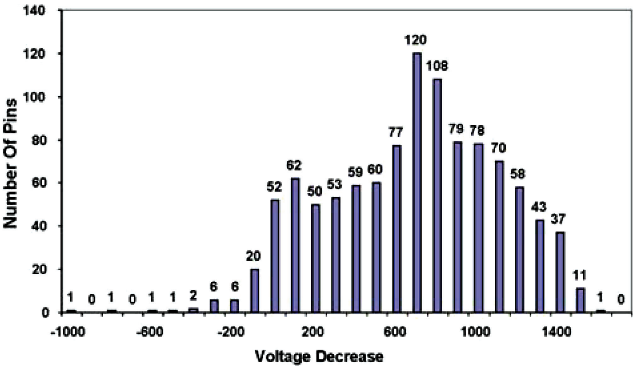

Fig. 15 Decrease in pin-header pin-to-case breakdown voltage due to pin-to-case ESD.

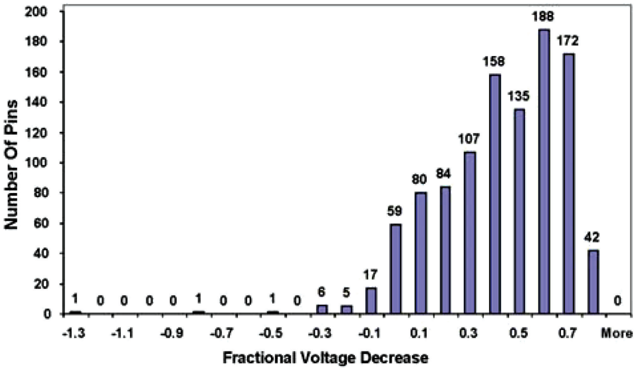

Fig. 16 Fractional decrease in pin-header pin-to-case breakdown voltage due to pin-to-case ESD.

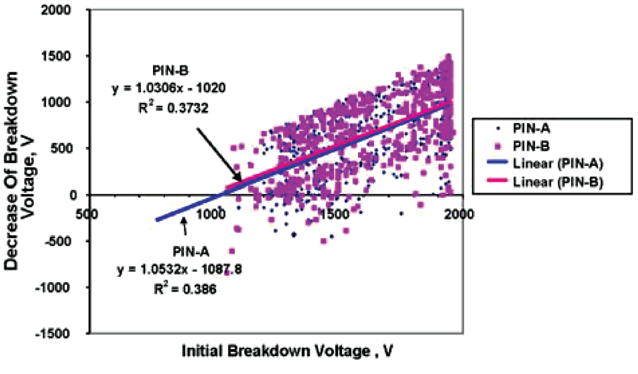

Fig. 17 Correlation between the decrease of the pin-header breakdown voltage induced by pin-to-case ESD and initial breakdown voltage.

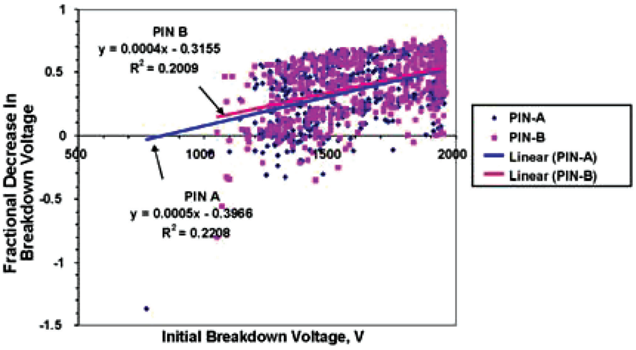

Fig. 18 Correlation between fractional decrease in pin-header breakdown voltage induced by pin-to-case ESD and initial breakdown voltage.

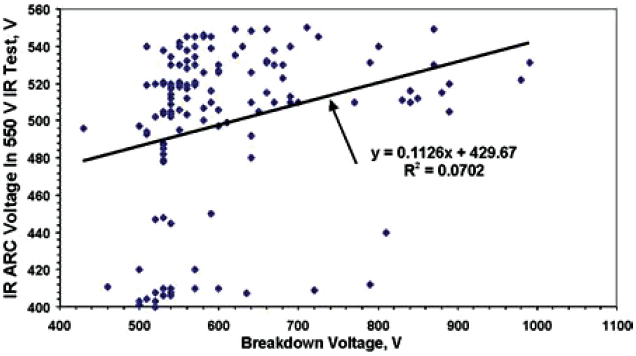

Fig. 19 Pin-header arc voltage in 550-V IR test vs pin-to-case breakdown voltage.

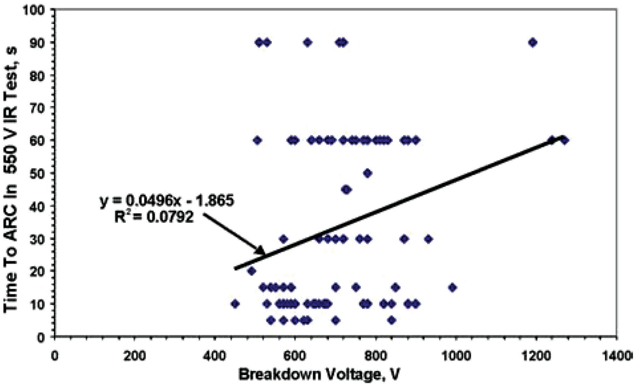

Fig. 20 Pin-header time to arc in 550-V IR test vs pin-to-case breakdown voltage.

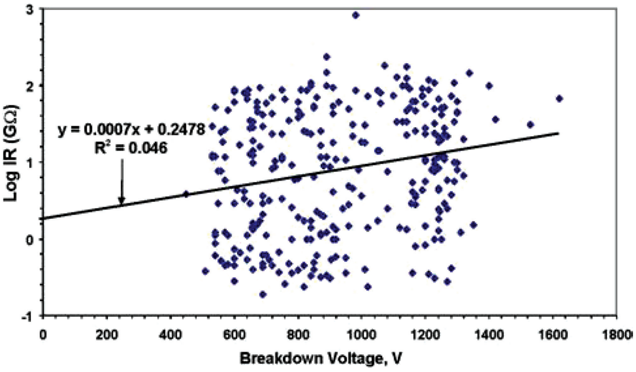

Fig. 21 Pin-header 550-V IR vs breakdown voltage for units passed 550-V IR test.

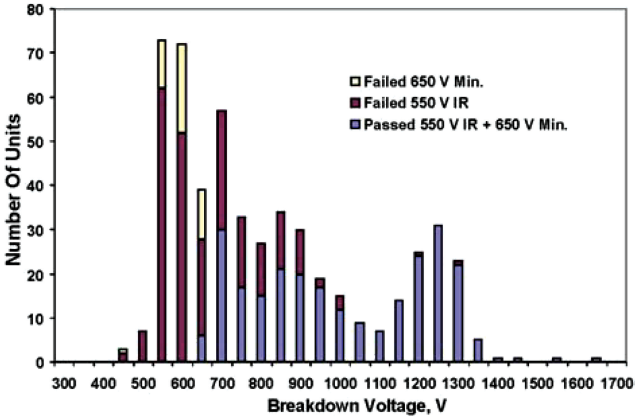

Fig. 22 Pin-header pin-to-case breakdown voltage and IR screening results after pin-to-case ESD.

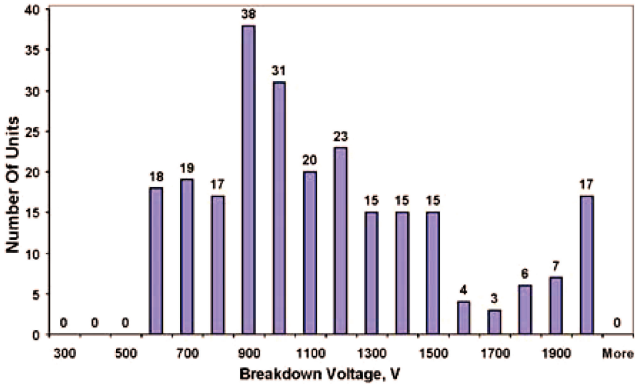

Fig. 23 Detonator pin-to-case breakdown voltage.

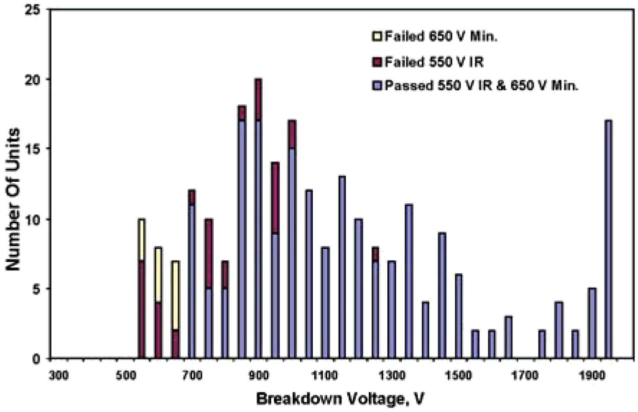

Fig. 24 Detonator pin-to-case breakdown voltage and IR screening results after build.

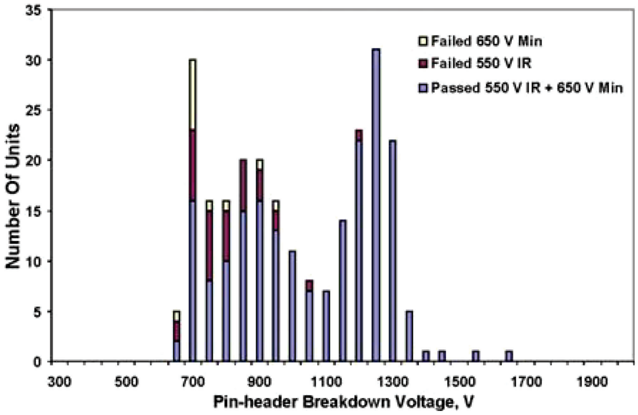

Fig. 25 Detonator performance vs pin-header breakdown voltage.

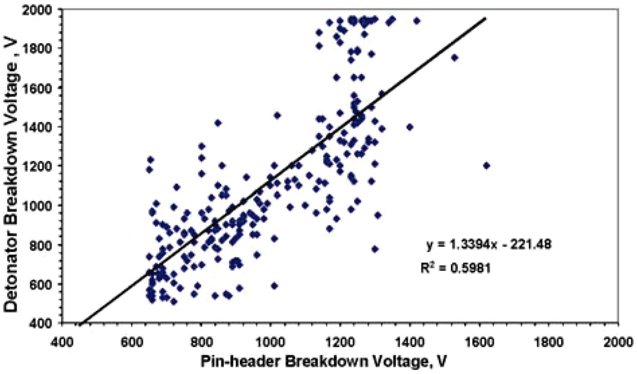

Fig. 26 Correlation between pin-to-case breakdown voltages, pin-header vs detonator.

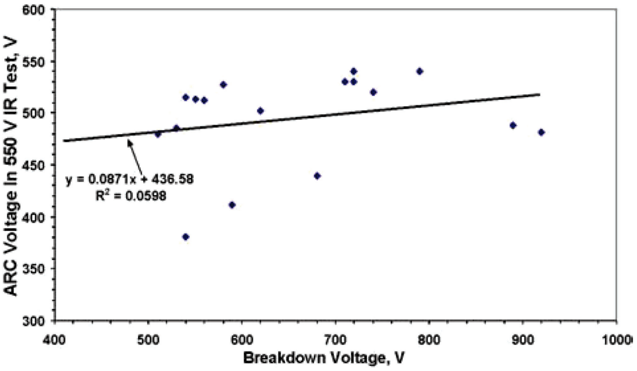

Fig. 27 Detonator arc voltage in 550-V IR test vs pin-to-case breakdown voltage.

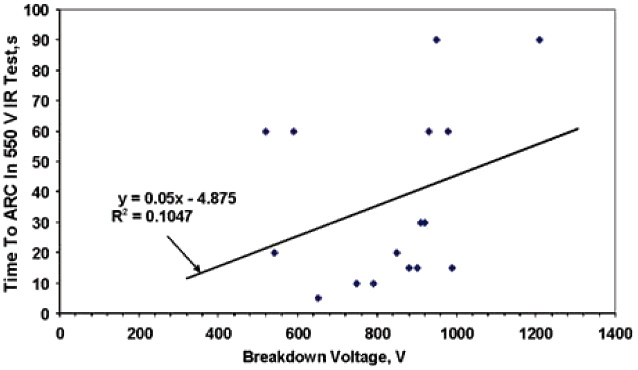

Fig. 28 Detonator time to arc during 550-V IR vs pin-to-case breakdown voltage.

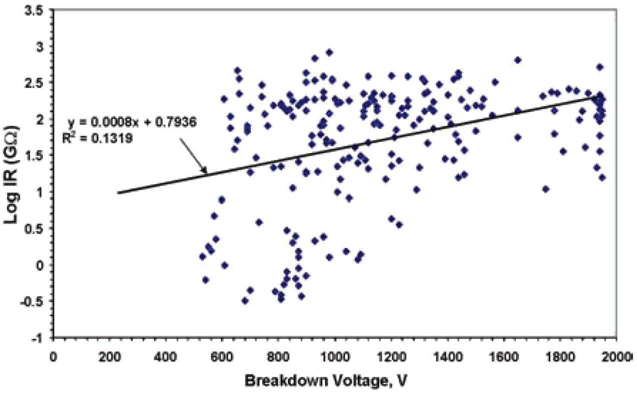

Fig. 29 Detonator IR vs breakdown voltage for units passed the 550-V IR test.

The change in the breakdown voltage is a complex phenomenon, as shown in Figs. 15 and 16. Both the amount of the decrease and fraction of the decrease had wide distributions when viewed as a group. Also note that a handful of units showed increased breakdown voltages after the ESD test. There was no correlation between the pre- and post-ESD breakdown voltages; the coefficient of determination in the least-square straight-line fit, R^2, was 0.001. The decreases per individual pin-header exhibited significant dependence on the initial breakdown voltages as shown in Figs. 17 and 18. This may be an indication that the breakdown was inside the glass in the seal. In that scenario, the smaller the voids or channels in the glass, the higher the breakdown voltage. On the other hand, the small size will receive more concentrated exposure by the contaminants, such as spark-sputtered metal vapor, and result in a much lower subsequent breakdown voltage.

Figures 19–21 plot the arc voltage, time to arc, and IR measured in the post-ESD 550-V IR test, as a function of post-ESD breakdown voltage. Only weak correlation was observed. Figure 22 shows the results of the post-ESD screening, plotted in number of pin-headers as a function of the post-ESD breakdown voltage. It can be seen that IR failure frequently occurs in units with breakdown voltages as high as 1000 V, which proves that breakdown voltage alone cannot reliably screen out units with potential IR problems. It is also evident that a handful of units with breakdown voltages below 550 V passed the 550-V IR test. These results indicate that there are other possible parameters in the observed phenomenon, for example, the duration of the test. The 2-min IR test duration is much longer than the seconds used in the breakdown test. The effect of the pin-header screening was to artificially narrow the width of the distribution in the breakdown voltage. It did not point to the cause that led to this wide distribution.

Figure 23 shows the breakdown voltage distribution of completed detonators using the pin-headers that had passed the screening test. It can be clearly seen that the artificially narrowed new distribution had broadened. As a result, many units failed the 550-V IR and 650-V breakdown voltage screening at the detonator level, as shown in Figs. 24 and 25. The most discouraging result was the frequent IR failure for breakdown voltages as high as 900 V. It casts doubt on whether further screening can prevent IR failure in the field. Figure 26, in which the breakdown voltages of the detonator and pin-header are plotted against each other for a given unit, further illustrates similar results in Figs. 24 and 25. A strong correlation of $R^2 \sim 0.6$ was obtained, but for a significant number of units, the two voltages are not correlated, and so the detonator breakdown voltage cannot be predicted from the pin-header breakdown voltage.

The weak dependence of arcing voltage, time to arc, and IR measured in the detonator 550-V IR test as a function of breakdown voltage is shown in Figs. 27–29. The fact that pin-header level screening could not guarantee success at the detonator level can be understood. Many manufacturing operations are performed in detonator assembly. Some of these procedures, for example, cementing the boron nitride disk, machining the pins and boron disk, welding of bridgewire, loading and drying the explosives, and helium contamination due to hermetic seal testing, can change the breakdown and arcing characteristics.

Tentative Resolution

Explosive bolts were fabricated with lot 2C detonators that had passed the 550-V IR test, that is, failed detonators in the bolt were replaced with good ones and retested for IR satisfactorily. However, during vibration testing in the bolt lot acceptance tests, pins in three bolts broke, causing the entire bolt lot to be rejected. (The bolt body was reusable for loading new good detonators.) The broken pin problem was finally successfully corrected by applying potting compound between the pins and the bolt housing. Therefore, the only remaining problem for bolt production was the ESD-induced IR failure.

The investigation and subsequent retesting effort had consumed 16 months. The problem started to impact the vehicle launch schedule. It is evident that, for this particular detonator design, the pin-to-case ESD is a destructive test. The probability that a unit will fail the 500-V dc IR test following a single ESD test per requirement is finite. After a thorough assessment, the following resolution strategy was implemented. The test voltage for the IR test was lowered following a precedent from the NASA Standard Initiator (NSI). MIL-STD-1576,[3] paragraph 5.5b for the 500-V dc, 2-MΩ IR test requirement for EED states: "For the NSI, the test potential shall not exceed 250 Vdc and only one 250 Vdc test shall be permitted. All other NSI testing should be at 50 Vdc."

A conservative IR testing voltage of 100-V dc for 2 min was adopted for testing the bolt detonator in spite of a detailed system analysis that indicated an insulation voltage as low as 50-V dc is acceptable. Because single ESD-induced breakdown voltage degradation never fell below 400 V in the extensive tests, this adoption represents a 4× margin for the detonator IR test success. Since the program began using the digital Slaughter IR tester, the IR failure mode has manifested itself as arcing rather than low readings below 2 MΩ. (As a matter of fact, the reading was always beyond 100 MΩ when arcing did not occur.) The low resistance during arcing typically ranges from 30 to 100 kΩ, as shown in Figs. 4 and 5. This low resistance occurs only during the arcing and is not detrimental to detonator firing. In Titan IVB ordnance firing circuits, both wires are connected to the system ground by a 100-kΩ resistor as a safeguard against stray voltage buildup.

Because the ESD test is executed in the pin-header and detonator screening tests, the required ESD in the nondestructive inspection portion of the detonator lot acceptance test is considered fulfilled.

The changes were approved for implementation. As a result, two explosive bolt lots of the new design were successfully tested and delivered 19 months after the initial IR failure: There were 9 units for lot acceptance and 26 deliverable for flight. These bolts used the good detonators from detonator lot 2A. There were 9 units for lot acceptance and 14 deliverable for flight. These bolts used the good detonators from detonator lot 2C with the epoxy potting as the corrective action for the broken pin problem. These production units were sufficient to support the remaining Titan IVB flights as Titan IVB was being phased out after a very successful career in government satellite launch service. Therefore, no further bolt production or bolt design improvements were planned at this time.

NSI Pin-Header ESD Evaluation

In an effort to help identify the root cause of the ESD-induced IR degradation, new production NSI (design descriptions in Ref. 6) pin-headers from two qualified NSI pin-header suppliers were evaluated in the same manner as the explosive bolt detonator pin-headers. Very robust results were obtained in spite of the fact that the gap between the pin and the header body is only ~0.356 mm wide. Results are summarized next.

No notable IR degradation was observed after 10 pin-to-case ESD tests. The IR reading remained in the 10^{11}-Ω range. No arcing failure occurred, and the ESD sparks were observed to be external to the seals occurring at either end of the header. The results are summarized in Fig. 30.

The ESD did cause the breakdown voltage to decrease from the initial >1950 V (the maximum voltage available in the SGB tester). However, values still stayed around 1062–1600 V dc after 10 pin-to-case ESD tests. The breakdown sparks were observed to be external to the seals occurring at either end of the header. The results are summarized in Tables 1–3.

Table 1 Breakdown and IR test results of NSI pin-header vendor A number 4, new unit

Test	Test type	Breakdown voltage/IR Pin A	Breakdown voltage/IR Pin B
1	DC[a]	No breakdown at 1925 V	No breakdown at 1914 V
2	DC[a]	No breakdown at 1925 V	Breakdown at 1770 V
3	DC[a]	No breakdown at 1925 V	No breakdown at 1914 V
4	DC[a]	No breakdown at 1925 V	Breakdown at 1881 V
5	DC[a]	No breakdown at 1925 V	Breakdown at 1860 V
6	IR at 550 V	2.12×10^{11} Ω	1.18×10^{11} Ω

[a] Electric breakdown test by the SGB tester.

Table 2 Breakdown and IR test results of NSI pin-header vendor A number 1, after 10 ESD tests

Test	Test type	Breakdown voltage/IR Pin A	Breakdown voltage/IR Pin B
1	DC[a]	1062 V	1065 V
2	DC[a]	1080 V	1200 V
3	DC[a]	1134 V	1161 V
4	DC[a]	1164 V	1260 V
5	DC[a]	1140 V	1245 V
6	IR at 550 V	1.18×10^{11} Ω	9.88×10^{10} Ω

[a] Electric breakdown test by the SGB tester.

Table 3 Breakdown and IR test results of NSI pin-header vendor B number 1, after 10 ESD tests

Test	Test type	Breakdown voltage/IR Pin A	Breakdown voltage/IR Pin B
1	DC[a]	1140 V	1320 V
2	DC[a]	1125 V	1170 V
3	DC[a]	1170 V	1224 V
4	DC[a]	1140 V	1620 V
5	DC[a]	1164 V	1674 V
6	IR at 550 V	1.37×10^{11} Ω	1.27×10^{11} Ω

[a] Electric breakdown test by the SGB tester.

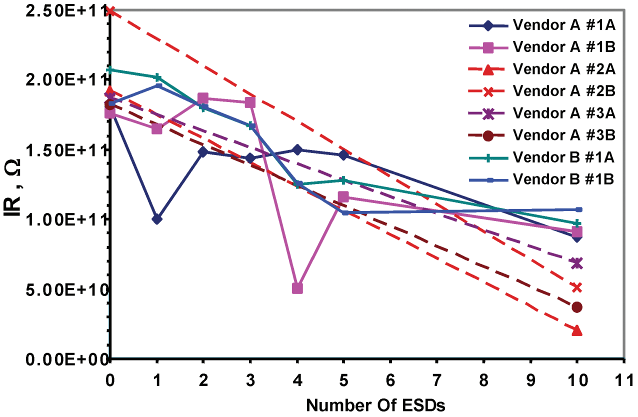

Fig. 30 NSI pin-header 550-V, 1-min IR as a function of number of accumulated pin-to-case ESDs.

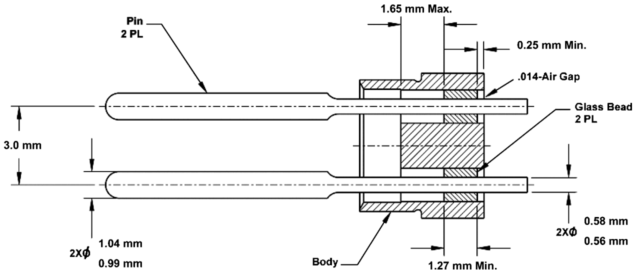

Fig. 31 NSI pin-header schematic diagram.

Two unique features of the NSI pin-header could have contributed to the test success:

1) Both suppliers use their proprietary glass seal materials and glass processing. The finished seals were not transparent, in contrast to R-6 and Schott S-8061 used in the Titan IVB explosive bolt detonator. The frost finish resembles the Sandia National Laboratories–developed S-glass, which is known for its excellent insulation performance. S-glass was used in the Titan IVB high voltage detonator (HVD).[7]

2) Refer to the NSI pin-header design and configuration shown in Figs. 31 and 32. There is an air gap of ~0.25 mm at the bridgewire end of the seal and another air gap of ~1.52 mm at the pin end of the seal. These gaps can buffer the seal end surfaces from spark-induced contamination, thereby reducing the risk of IR degradation.

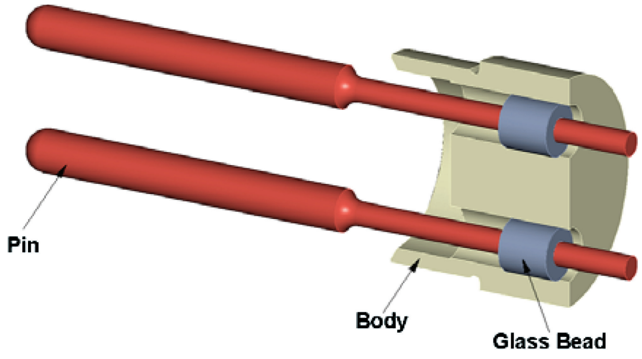

Fig. 32 NSI pin-header construction.

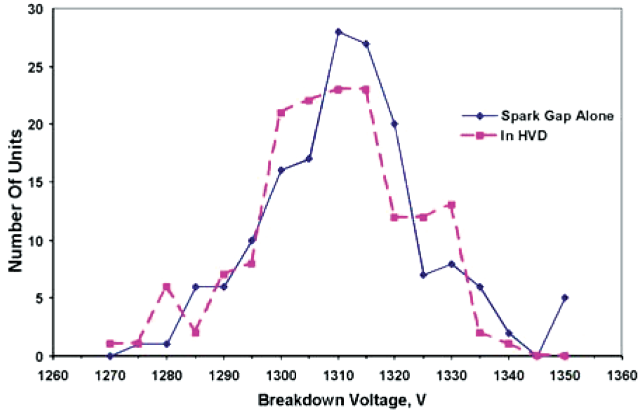

Fig. 33 HVD spark gap average breakdown voltage of five tests.

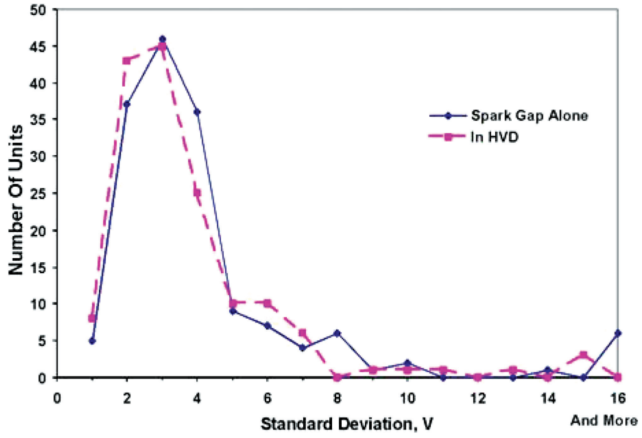

Fig. 34 HVD SGB voltage standard deviation of five tests.

Titan IVB HVD Spark Gap Pefomance

For completeness in assessing the electrical breakdown and ESD and IR phenomena, the performance of the built-in spark gap in the HVD developed and qualified for the Titan IVB SRMU ordnance system is reported in this paper for the first time. (A general description may be found in Ref. 7.) The ruggedized gap designed with precision electrodes is pure gas filled and hermetically sealed. It was originally designed and qualified for the precision control of exploding bridgewire detonator firing voltage. However, in the HVD, its function is explosive safety only. Each unit has gone through many breakdown tests in the factory for burn-in. Figures 33 and 34 show the average breakdown voltage and standard deviation of five acceptance tests, both in gap stand-alone mode and integrated in the detonator. It can be seen that the repeatability was about two orders of magnitude better than that observed in the pin-header/detonator testing in the Titan IV explosive bolt program. The HVD has never had an ESD problem, IR problem, or ESD-induced IR degradation problem. It has been very successful in supporting the Titan IV flight operations. Finally, it demonstrates that precision control of electrical breakdown can be achieved by a good design.

Conclusions

Although further investigation can be performed, the documented effort achieved an interesting understanding of the phenomenon involving the ESD, IR, and breakdown voltage and developed testing and criteria for predicting good ESD performance.

For the existing Titan IVB explosive bolt design, repeated pin-to-case ESD and/or high current/voltage pin-to-case breakdown testing can cause degradation to the IR, thus reducing the detonator's capability to pass a 500-V dc IR test. It is believed that the ESD breakdown occurred in the glass seals and not at the preferred discharge path in open air. This internal breakdown created a path for arcing under the subsequent IR test.

To eliminate or reduce the potential damage by ESD, breakdown in the glass seal should be avoided. The ESD spark can be kept external to the seal by either using a glass material and/or processing with known performances, and/or a good seal configuration, that is, small seal length-to-diameter ratio, deep air gaps near the seal end surface, etc.

To achieve a successful 500-V pin-to-case IR test, the initial pin-to-case breakdown voltage in the EED needs be higher than 1000 V. Two design verification methods can be easily implemented at the pin-header level early in EED development:

1) A 550-V dc IR test should be successful after 10 pin-to-case ESD tests.

2) The pin-to-case breakdown voltage must be sustained at higher than 1000-V dc after multiple ESD tests.

ESD testing was shown to be destructive in this detonator design and thus should be considered destructive in other EED designs. As such, careful consideration of the application of this test to flight assets is warranted. The evaluation of the design and the corrective actions show that the qualification and successful use of EEDs can be accomplished with appropriate use of ESD, breakdown voltage, and IR testing during lot manufacture and acceptance testing.

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