Internal Electrostatic Discharge Testing of Inert Solid Rocket Motor Materials

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I. Introduction

Jupiter's moon Europa is believed to have a global liquid-water ocean beneath its icy surface. As such, it is a highly interesting destination for explorers seeking signs of life outside of Earth. This interest has given rise to the Europa Lander Mission [Hand, et al., 2017]. The central goal of the Europa Lander Mission is to place a stationary lander on Europa and make surface and sub-surface measurements, dramatically improving understanding of this Jovian moon, and potentially detecting signs of life. Fig. 1 shows an artist's concept of a Europa lander.

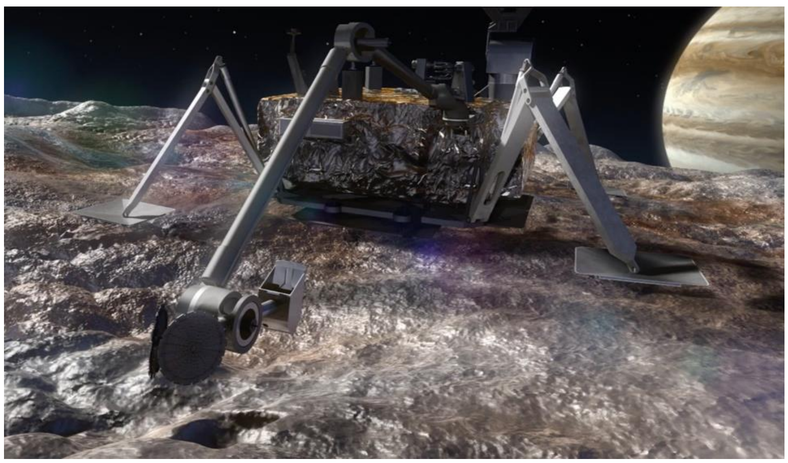


Figure 1. Artist's concept of a Europa lander (credit NASA/JPL/Caltech)

Placing a lander on Europa will require multiple spacecraft elements deployed across a multi-year mission timeline. Fig. 2 provides a summary of the current mission concept [Dooley, 2018]. Some of the key elements include: a large payload capacity rocket, such as the Space Launch System (SLS), capable of providing direct Jupiter orbit insertion; a solar-powered carrier; a de-orbit system; a sky crane landing system; and, of course, the surface lander. A noteworthy fact is that the current design requires a large solid rocket motor to provide the necessary braking thrust for the de-orbit stage. While solid rocket motors have been used extensively by NASA during launch, in-space use has been limited.

In addition to the normal challenges associated with a long-distance planetary mission, the Europa Lander Mission must also contend with the high-radiation environment associated with the Jovian system. The size of Jupiter, combined with its magnetic field strength, and rotation speed, result in a harsh radiation environment composed of high energy charged particles (ions and electrons) as well as high-temperature plasmas [de Soria-Santacruz Pich, 2016].

Due to this high-radiation environment, each component of the Europa Lander spacecraft must be evaluated to determine its radiation dose tolerance and its likelihood for experiencing electrostatic charging (and discharging). In general, metal components in a Jovian environment do not pose a concern for radiation degradation; in fact, metal structures and closeouts can act as radiation shielding for the more sensitive components. Charging of a metal component is only an issue if the component is not properly grounded to the spacecraft chassis. However, electrically insulating materials, such as polymers, are subject to radiation degradation as well as surface and internal charging, and therefore require extra scrutiny.

The focus of this paper will be on the insulating materials that are commonly used inside solid rocket motors. The special application of a solid rocket motor used in space after a relatively long duration flight, combined with the high energy electron environment in the Jovian system, raises concerns about the possibility of significant charging and discharging leading to reduced performance.

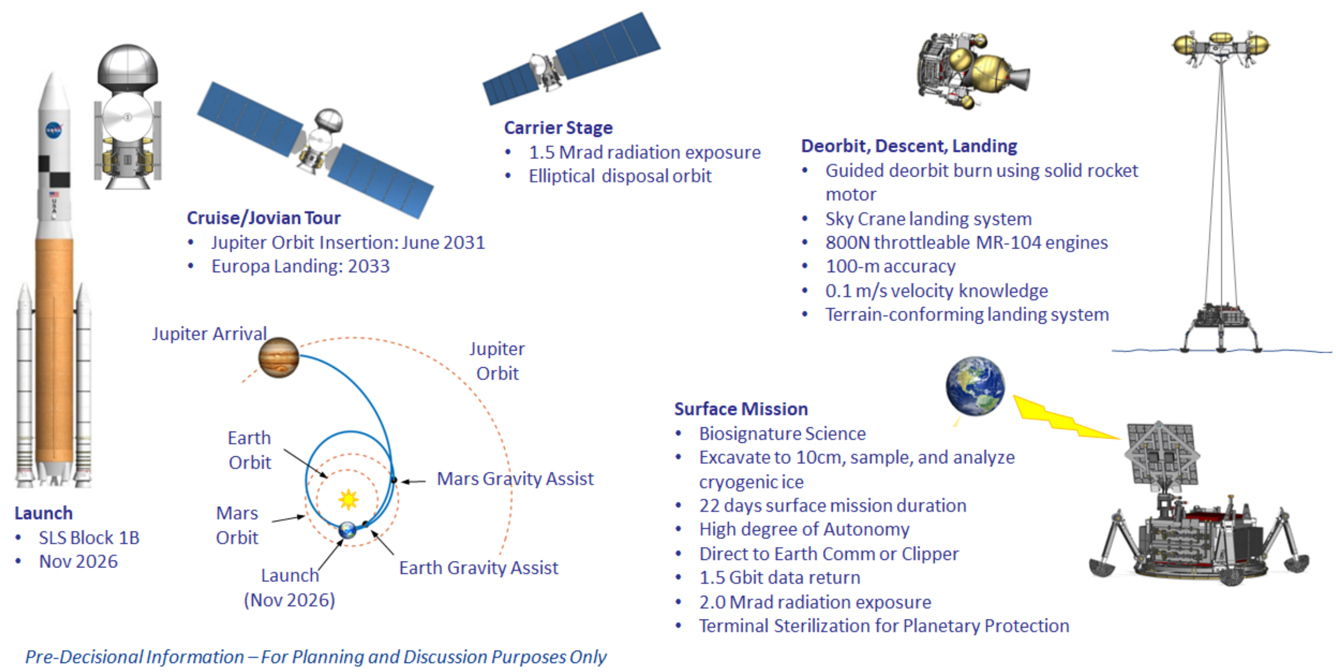


Figure 2. Europa Lander Mission Concept (credit: NASA/JPL/Caltech)

A. Solid Rocket Motor Design

The orbital mechanics of a mission to Europa require significant braking thrust for the de-orbit stage. A solid rocket motor such as shown in Fig. 3 is well suited to slow the lander system. While the metal case of this design does provide some shielding from radiation, Jupiter's environment includes high-energy electrons capable of penetrating deep into the motor.

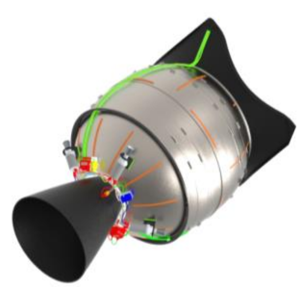


Figure 3. Candidate solid rocket motor assembly for the Europa Lander De-Orbit Stage

Fig. 4 is a notional cross-section of a typical solid rocket motor. Inside the metal case are three key elements of the design: 1) Insulation, 2) Liner, and 3) Propellant. All the internal systems contain electrically insulating materials, also known as dielectric materials. Table I contains details about the internal insulating materials tested during this campaign. It should be noted that the materials tested are very common solid rocket motor materials.

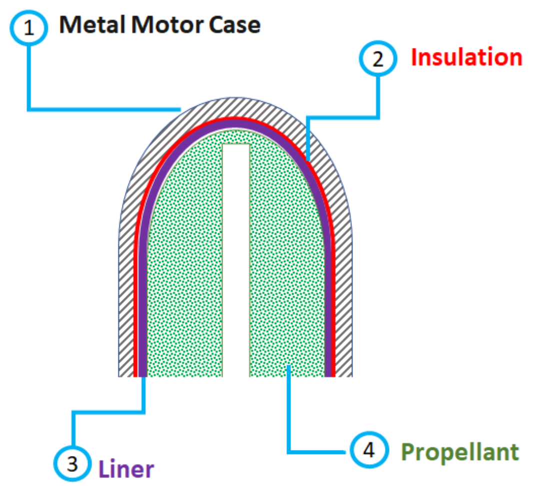


Figure 4. Cross-Section of Typical Solid Rocket Motor

Table I. Solid Rocket Motor test samples

Functional Element	Test Sample Description	Constituents	Comments
Insulation	Silica-Filled EPDM	Silica and EPDM	EPDM: Ethylene Propylene Diene Monomer
Insulation	Kevlar-Filled EPDM	Kevlar and EPDM	EPDM: Ethylene Propylene Diene Monomer
Liner	Custom mixed rubberized bonding agent	Based on HTPB R45	HTPB: Hydroxyl Terminated Poly Butadiene
Inert Propellant	Limited oxidizer, Aluminum fuel, and rubberized binder	Ammonium Sulfate, Aluminum, and HTPB Binder R45	Non-burning formulation with the same mechanical properties as regular "live" propellant

B. Internal Electrostatic Discharge (iESD)

Space environments composed of high energy charged particles, such as the Jovian system, pose a threat to deposit charge deep inside materials [Wang et al., 2019]. This phenomenon, known as internal charging, can be particularly damaging for electrically insulating (dielectric) materials, as the charge mobility may be limited and therefore a substantial amount of charge may accumulate over time. For the situation where a significant amount of charge builds up in a small region in the insulating material, a large electric field may be developed (see Fig. 5). If the magnitude of the electric field exceeds the dielectric strength of the material, an internal Electrostatic Discharge (iESD) will occur [Garrett and Whittlesey, 2011; Rodgers et al., 2011]. The iESD event, sometimes referred to as an “arc”, results in rapid current flow from the charged region to a lower potential (possibly grounded) region. The iESD events, as shown in this paper, are characterized by fast current pulses, which can damage material in the discharge path, and can generate Electromagnetic Interference (EMI). Fig. 6 is an example of a clear acrylic sample damaged due to the generation of multiple iESD events in the material.

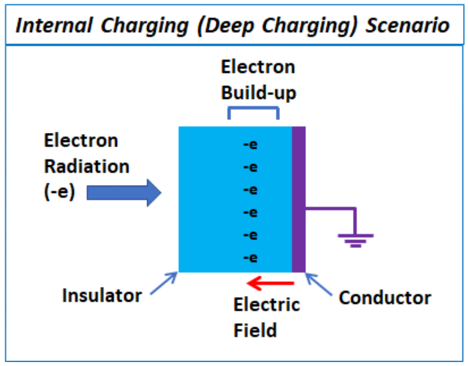


Figure 5. Internal charging due to electron deposition in the electrically insulating (dielectric) material

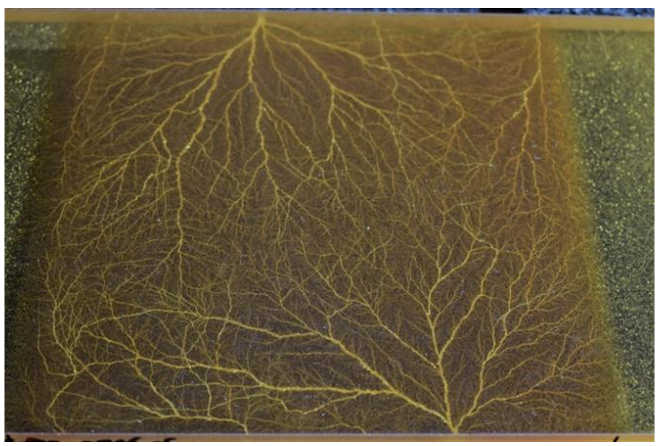


Figure 6. Acrylic sample damaged as a result of the generation of multiple iESD events

II. Laboratory Testing

To gauge the likelihood of iESD occurring in the materials used inside a solid rocket motor, a laboratory test was devised and carried out at NASA’s Marshall Space Flight Center (MSFC). This test was envisioned as a basic screening test to determine if any of the materials exhibited significant iESD generation at low to moderate flux levels. The testing was not intended to simulate the Jovian environment.

A. General Test Procedure

The nature and thickness of the materials selected for testing dictated using a high-energy electron accelerator to deposit charge deep inside a given sample. Therefore, all tests were conducted in MSFC’s Combined Environmental Effects Facility using the 2.5 MeV Pelletron accelerator. Fig. 7 shows the test laboratory.

Testing followed these basic steps:

1. Mount the sample in the vacuum test chamber
2. Apply a low flux electron beam with sufficient energy to deposit charge mid-way through the sample thickness
3. Monitor sample mounting plate for signs of discharge currents (iESD activity)
4. Raise the flux level
5. Repeat steps 3 and 4 until either a large number of iESD events is detected, or the maximum flux level is reached

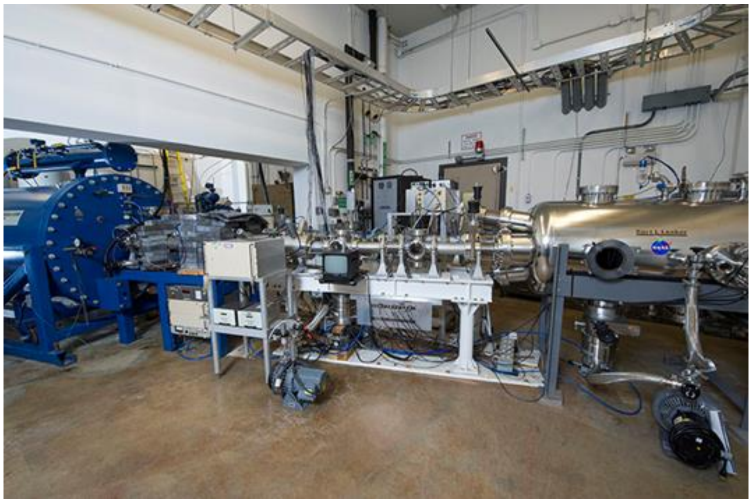


Figure 7. Marshall Space Flight Center's Combined Environmental Effects Facility

B. Test Setup

Fig. 8 shows the sample holder used for positioning the samples in the electron beam. The primary Aluminum assembly plate, with a grid pattern of tapped holes, has dimensions of 45.7 cm x 45.7 cm. Two Faraday cups are mounted in the center of the primary plate as a means to continuously monitor the electron beam flux during the test. The electron beam spot size is 40.6 cm. The iESD test samples are mounted to a secondary Aluminum plate with dimensions of 15.2 cm x 15.2 cm (located near the bottom of the primary plate). The samples are mounted in intimate contact with the secondary Aluminum plate. The secondary Aluminum plate is electrically isolated from the primary plate. A metal encased coaxial test lead is attached to the secondary (sample) mounting plate and connected to a feed-through at the bottom of the chamber.

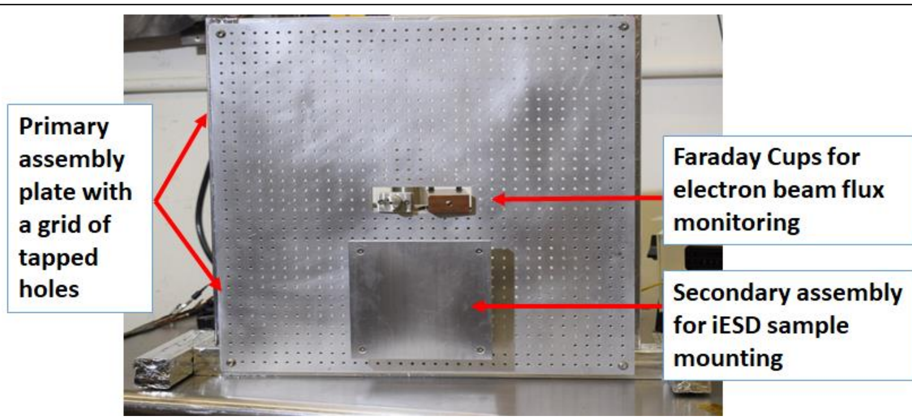


Figure 8. Sample holder with Faraday cups for beam flux monitoring

The electrical circuit schematic is shown in Fig. 9. The detection of an iESD event relies on the rapid movement of charge from deep inside the sample to the mounting plate – which is grounded outside of the chamber via a 50-ohm resistor. The movement of the charge through the 50-ohm resistor gives rise to a voltage that is monitored by a 1 GHz bandwidth oscilloscope.

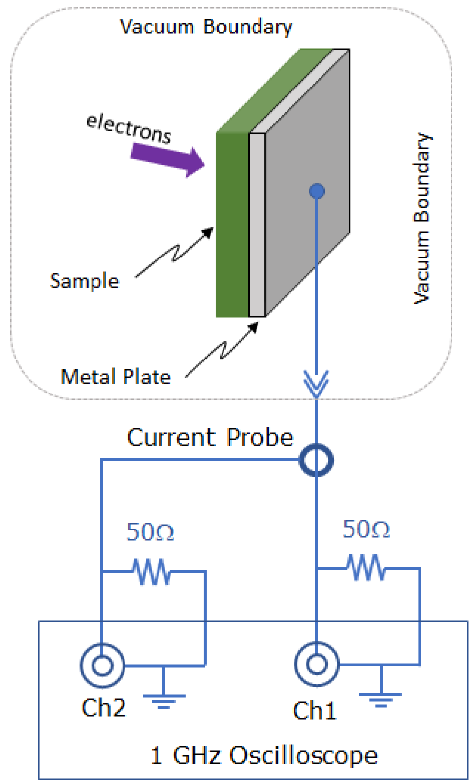
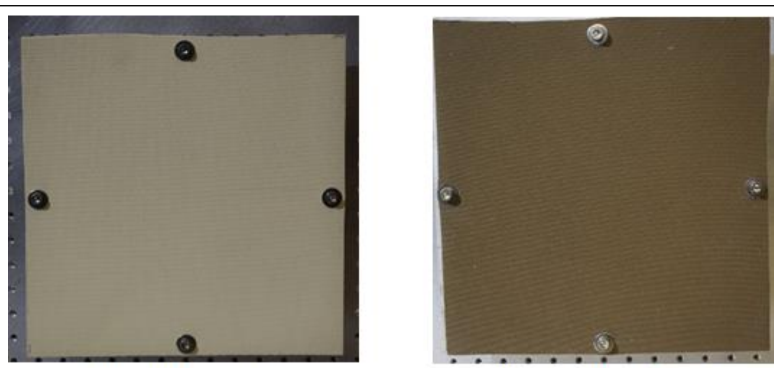


Figure 9. Electrical circuit used to measure iESD events. Ch1 is set to resolve small current signals (high-resolution). Ch2 is used to cover large peak amplitude currents (low-resolution).

C. Test Samples

Four test samples were evaluated and are pictured in Fig. 10 and Fig. 11. Two of the samples were motor insulation materials, one sample represented liner material, and one sample represented inert propellant material. All samples have dimensions of 15.2 cm x 15.2 cm. Details of the samples are described in Table 1.



Silica Filled EPDM **Kevlar Filled EPDM**

Figure 10. Insulation test samples. Each sample is 15.2 cm x 15.2 cm.

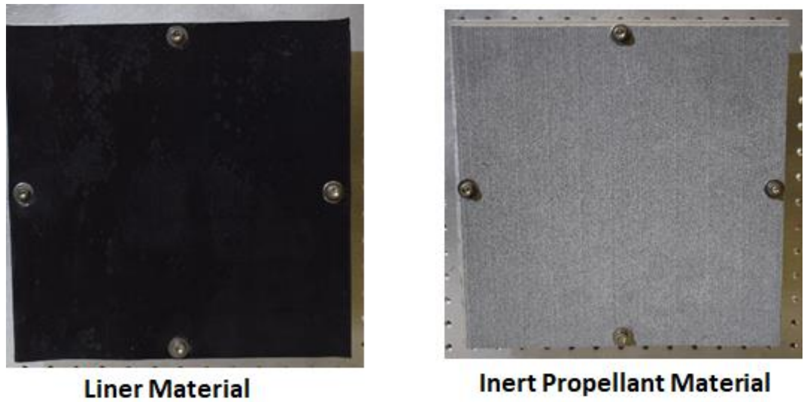


Figure 11. Liner and Inert Propellant samples. Each sample is 15.2 cm x 15.2 cm.

III. Typical Waveforms

Typical iESD waveforms are characterized as fast current pulses with durations ranging from tens of nanoseconds to a few microseconds. Such was the case for the iESD measurements made during this series of tests. Figs. 11 – 14 show typical waveforms acquired for each material tested. As shown in the circuit of Fig. 9, the iESD current is monitored simultaneously in two separate channels. Ch1 directly measures the current through a 50-ohm resistor. Ch2 measures the iESD current through an inductive current loop. Ch1 is dedicated to resolving fine details of the current waveform and is considered the “High Resolution Channel”. However, Ch1 is limited in the peak amplitude it can measure. To ensure the peak amplitude of a large iESD event is captured without saturating, Ch2 is set to a coarse scale – which is considered “Low Resolution”.

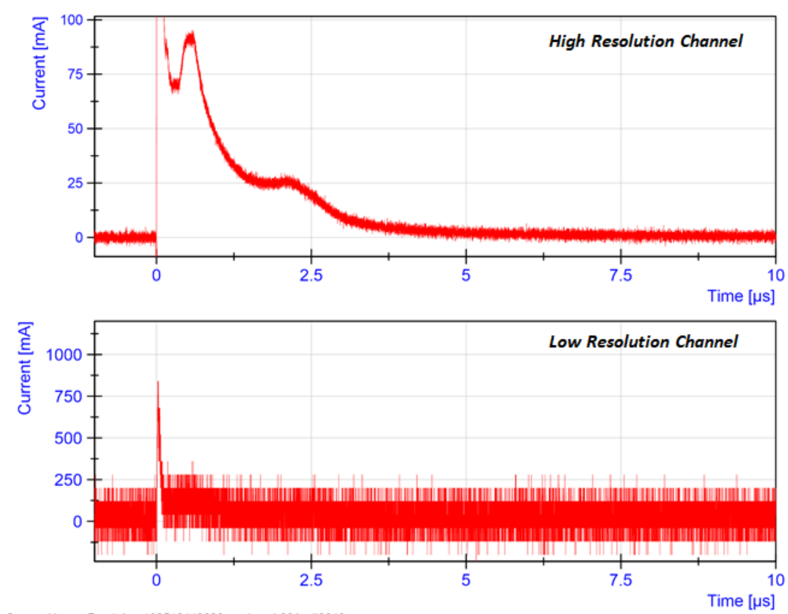


Figure 11. Silica Filled EPDM sample iESD waveform. Peak current = 800 mA. Pulse duration = 3 micro-sec.

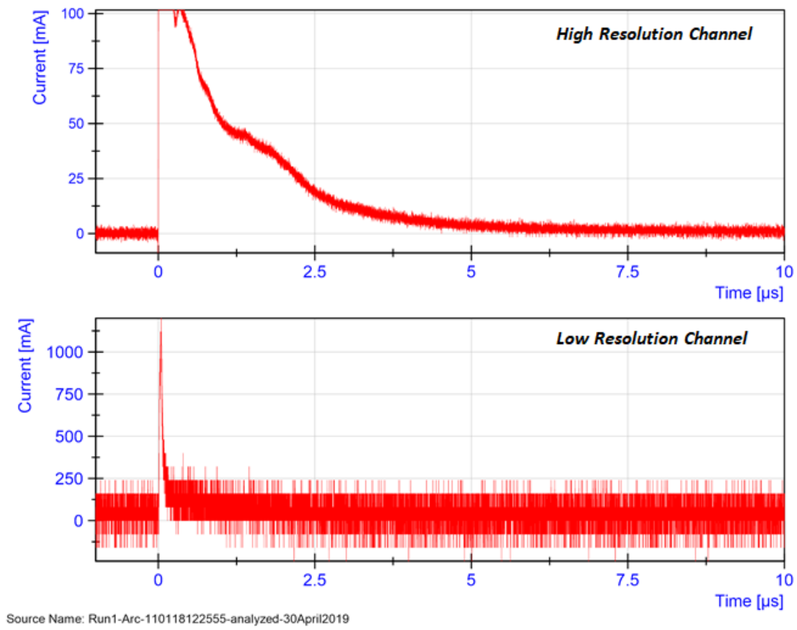


Figure 12. Kevlar Filled EPDM sample iESD waveform. Peak current = 1200 mA. Pulse duration = 5 micro-sec.

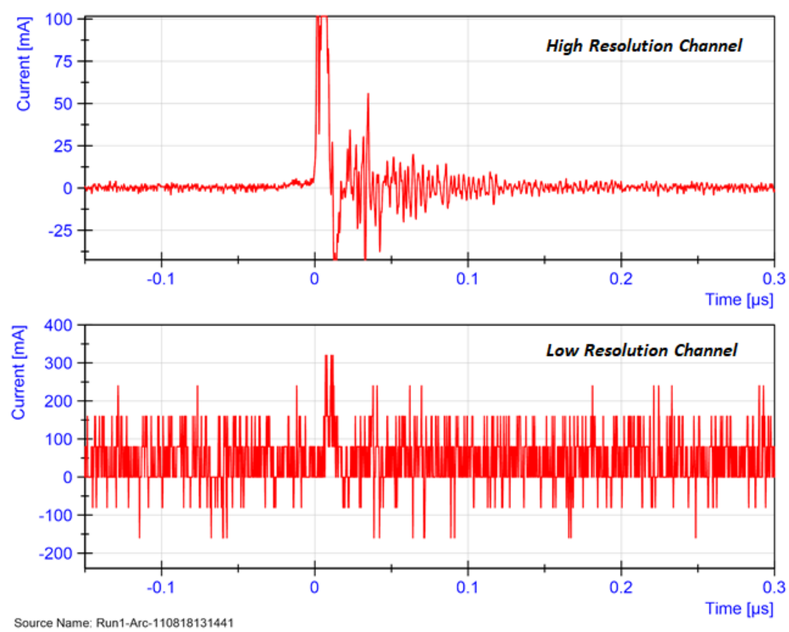


Figure 13. Liner sample iESD waveform. Peak current = 320 mA. Pulse duration = 25 nano-sec.

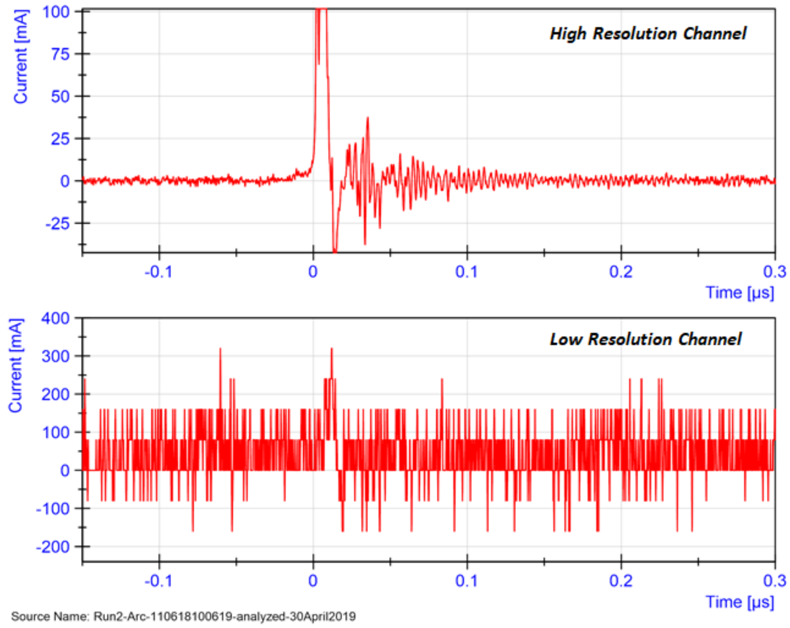


Figure 14. Inert propellant sample iESD waveform. Peak current = 250 mA. Pulse duration = 25 nano-sec.

IV. Test Data Summaries

Presumably due to marked differences in resistivity, each irradiated sample exhibited different behavior with respect to iESD frequency for a given flux application. This behavior is captured in Tables II – V.

Table II. Arc frequency as a function of flux for the Silica-Filled EPDM Insulation sample.

Test Sample: Silica-Filled EPDM			
Test Trial	Energy (MeV)	Flux (nA/cm^2)	Average time between arcs
Run 1	1	0.1	900 sec/1 arc = 900 sec/arc
↓	1	0.25	900 sec/6 arcs = 150 sec/arc
↓	1	0.5	900 sec/16 arcs = 56.3 sec/arc
↓	1	1	2038 sec/200 arcs = 10.2 sec/arc
Run 2	1	0.1	3600 sec/12 arcs = 300 sec/arc
↓	1	0.25	1560 sec/14 arcs = 111.4 sec/arc
↓	1	0.5	6170 sec/84 arcs = 73.5 sec/arc

Table III. Arc frequency as a function of flux for the Kevlar-Filled EPDM Insulation sample.

Test Sample: Kevlar-Filled EPDM Insulation			
Test Trial	Energy (MeV)	Flux (nA/cm^2)	Average time between arcs
Run 1	1	0.1	No arcs in 3600 sec
↓	1	0.25	No arcs in 3600 sec
↓	1	0.5	No arcs in 2100 sec
↓	1	1	No arcs in 1200 sec
↓	1	2	1260 sec/ 21 arcs = 60 sec/arc
↓	1	5	600 sec/40 arcs = 15 sec/arc
Run 2	1	1	No arcs in 1200 sec
↓	1	2	1800 sec/12 arcs = 150 sec/arc
↓	1	3	1800 sec/35 arcs = 51.5 sec/arc

Table IV. Arc frequency as a function of flux for the Liner sample.

Test Sample: Liner (HTPB)			
Test Trial	Energy (MeV)	Flux (nA/cm^2)	Average time between arcs
Run 1	0.8	0.1	No arcs in 1800 sec
↓	0.8	0.25	No arcs in 1800 sec
↓	0.8	0.5	No arcs in 1800 sec
↓	0.8	1	No arcs in 1800 sec
↓	0.8	2	1800 sec/1 arc
↓	0.8	3	1800 sec/1 arc
↓	0.8	4	1800 sec/4 arc = 450 sec/arc
↓	0.8	5	1800 sec/2 arc = 900 sec/arc
↓	0.8	5.5	900 sec/2 arcs = 450 sec/arc

Table V. Arc frequency as a function of flux for the Inert Propellant sample.

Test Sample: Inert Propellant			
Test Trial	Energy (MeV)	Flux (nA/cm^2)	Average time between arcs
Run 1	2.4	0.1	No arcs in 2580 sec
	2.4	0.2	No arcs in 1800 sec
	2.4	0.5	No arcs in 1800 sec
	2.4	1	No arcs in 1800 sec
	2.4	2	No arcs in 1800 sec
	2.4	5	No arcs in 1980 sec
	2.4	10	3600 sec/1 arc
Run 2	2.4	15 +/-2	1200 sec/4 arcs = 300 sec/arc

V. Conclusions

The current mission concept for Europa Lander uses a solid rocket motor to provide braking thrust for the de-orbit stage. As the Jovian system, which includes Europa, can be characterized as a high-radiation environment, critical spacecraft systems like the de-orbit stage motor must be evaluated to determine if the radiation poses a risk of creating damage through total dose effects, or from internal Electrostatic Discharge (iESD). To address iESD concerns for solid rocket motor internal materials, an assessment was undertaken to evaluate inert propellant, liner, and two types of insulation that are common to most motor designs. One of the insulation samples (Silica-Filled EPDM) produced iESD signatures starting at 0.1 nA/cm^2, which was the lowest level applied in the test campaign. As this flux is estimated to be within a factor of ~10 of the anticipated 1 MeV flux at Europa, further study may be warranted to ensure this material will not be compromised due to iESD over the course of the full mission lifetime. The other insulation sample tested (Kevlar-Filled EPDM), as well as the liner sample, required applied fluxes in the 2 - 4 nA/cm^2 range before showing signs of iESD. This high flux threshold, compared to the predicted Europa environment, suggests these materials do not pose a concern for being compromised due to iESD generation. Likewise, the inert propellant sample tested does not pose an iESD concern, as no discharge activity was detected until the applied flux levels reached several hundred times the estimated Europa fluxes.

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