Radiation Dose Testing on Juno High Voltage Cables

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The Juno mission to Jupiter will have a highly elliptical orbit taking the spacecraft through the radiation belts surrounding the planet. During these passes through the radiation belts, the spacecraft will be subject to high doses of radiation from energetic electrons and protons with energies ranging from 10 keV to 1 GeV. While shielding within the spacecraft main body will reduce the total absorbed dose to much of the spacecraft electronics, instruments and cables on the outside of the spacecraft will receive much higher levels of absorbed dose. In order to estimate the amount of degradation to two such cables, testing has been performed on two coaxial cables intended to provide high voltages to three of the instruments on Juno. Both cables were placed in a vacuum of ~5×10^{-6} torr and cooled to -50°C prior to exposure to the radiation sources. Measurements of the coaxial capacitance per unit length and partial discharge noise floor indicate that increasing levels of radiation make measurable but acceptably small changes to the FEP Teflon utilized in the construction of these cables. In addition to the radiation dose testing, observations were made on the internal electrostatic charging characteristics of these cables and multiple discharges were recorded.

I. Introduction

The Juno mission to Jupiter will continue our exploration of the giant gas planet and extend our knowledge of its composition, including its massive magnetic fields. In order to measure these properties well, however, the mission is designed to orbit Jupiter in a highly elliptical orbit that will bring the spacecraft within 5000 km of the planet surface, passing through and then underneath the radiation belts surrounding the planet. During these close passes to the planet, the spacecraft will be exposed to very high levels of radiation composed of mostly energetic electrons and, to a lesser degree, protons. To protect the sensitive spacecraft electronics from this heavy dose of radiation, a specially designed vault has been constructed to house them. Several of the measurement instruments, however, must have at least a portion of their hardware exposed to this radiation in order to make their measurements that are the purpose of the mission.

A series of cables that carry various electrical signals link these exterior instruments with their corresponding electronics within the vault. Two such cables will provide high voltages to several of the science instruments on the spacecraft top deck to facilitate measurement of the radiation environment of the planet. These cables, intended to transmit voltages as high as +10kV and -10kV, had been flown in space before their selection by the Juno instrument team, but their reaction to high radiation doses, particularly while at cold temperatures, was unknown. The tests described in this paper were conducted to measure the effects radiation had on the electrical properties of these cables and to determine if any extra capabilities needed to be built into the instrument high voltage supplies to mitigate changes to the cables with time. Reports from previous studies suggest that Teflon type materials are particularly susceptible to radiation damage.[1] Specific electrical tests included changes in the cable's capacitance per unit length and their partial discharge characteristics, which give insight to the ability of the insulation to withstand high electric fields before breaking down.

Incidental to these particular tests, but of great importance to the project, the exposure of these cables to energetic electrons also allowed for the measurement of internal electrostatic discharge (IESD) pulses due to the build up of electrons within the non-conducting outer jacket. The pulses thus generated confirmed the supposition

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of the spacecraft design team that conductive outer shielding was required for cables that would receive similar doses of electron radiation.

II. Spacecraft Environment

Since the previous use of these cables was in Earth orbit, any data on their suitability for deep space use needed to be updated. The manufacturer was unable to provide either information regarding the cables' performance in space or information on their degradation due to the effects of radiation. Previous space use of both types of high voltage cable was on propriety spacecraft where flight data and performance specifications were unavailable.

To properly test the radiation properties of these cables, it was necessary to determine a radiation spectrum reflecting the total ionizing dose for the entire mission. Previous experience with the Jupiter radiation environment with Pioneer, Voyager, and Galileo spacecraft provided a baseline value for the types of radiation found around the planet and an energy spectrum. The bulk of the radiation dose around Jupiter is due to energetic electron dose with energies ranging from 10keV to 1GeV. Energetic protons are also present, but due to their reduced flux at higher energies, their effect on the total dose is orders of magnitude less than that of electrons.

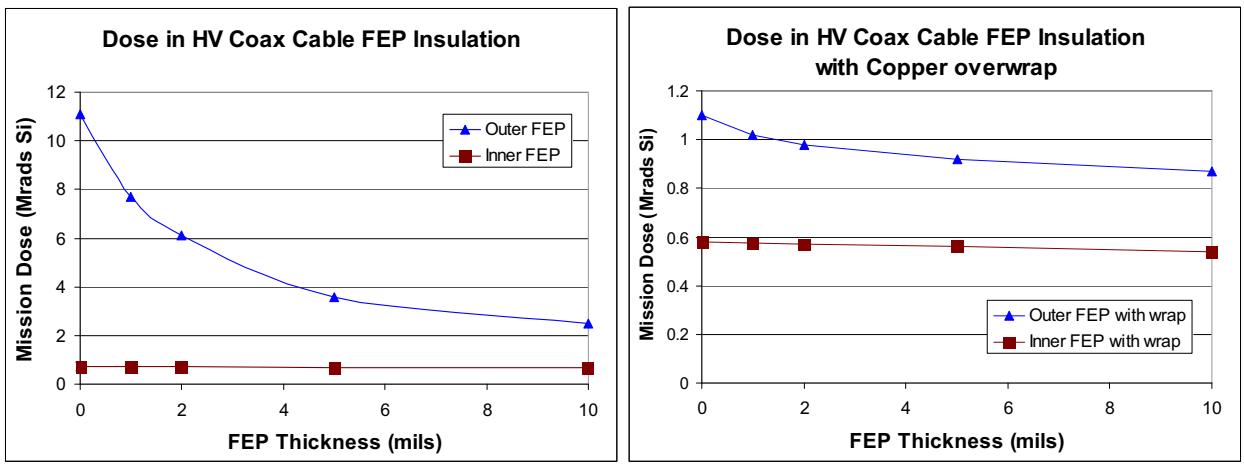

Figure 1. Dose as a function of depth for the high voltage coaxial cables examined in this test. Charts show total mission dose both without and with a protective copper overwrap.

Since the high voltage cables will be routed to the instruments beneath the thermal blankets on the spacecraft deck, the lower end of the radiation spectrum is truncated as the lower energy particles cannot penetrate through the blanket materials. The initial calculations for the total mission dose indicated that the coaxial outer jacket would receive 11 Mrad of dose while the inner dielectric would receive 0.7 Mrad. The difference in dose levels due to the decreasing flux of particles with sufficient energy to penetrate into the interior of the two cables. Since these values were considered high enough to cause concern, the decision was made to wrap the cables in a double helix of thin copper tape as an external shield. As shown in Figure 1, with the copper tape in place, the total outer dose dropped by about a factor of ten to 1.1 Mrad and the internal dose to 0.6 Mrad. This copper shield also had an impact on the charging characteristics of the cables, as will be discussed later.

When installed on the spacecraft, these cables will be routed under the thermal blankets on the instrument deck where they will be held through much of the mission at a temperature of approximately -50°C. Cable runs will be approximately 4 meters in length and will be headed to several locations on the spacecraft. Approximately half of each length will be exposed to the radiation outside of the protective vault at the center of the spacecraft.

III. Sample Selection

The cables chosen for use on the spacecraft are stock high voltage coaxial cables that have been used in space in previous missions. They are designed to deliver high DC voltages with the shielding benefits associated with coaxial cables. Though they have been used in space prior to selection by the Juno instrument teams, their radiation characteristics, particularly at the temperatures associated with orbit around Jupiter, were unknown. Since two types of cables have been incorporated in the design of the spacecraft, both were included in this test. The primary differences between the two cables were their physical size, and thus their voltage rating. The larger cable, with a diameter of ~3mm, was rated for 22 kVdc and the smaller cable, with a diameter of ~2mm, was rated for 18 kVdc.

For the Juno mission, these values were derated to 11 kV and 9kV to increase reliability. In all cases, the voltages to be transmitted through these lines are less than these de-rated voltage maximums.

For both cables, fluoroethylene-propylene (FEP), a type of Teflon, is used as both the inner coaxial insulation and the outer jacket material. Both cables have a nominal impedance near 45 ohms and a capacitance per unit length of approximately 100 pF per meter. For many applications, the capacitance per length of a transmission cable is not of great importance to an instrument designer, but for at least one instrument on the Juno mission, it is important. Part of this particular instrument must establish a constant electric field between a pair of plates, in order to measure the quantity and energy of charged particles around Jupiter. The instrument load, therefore, is strictly capacitive with very little current flow and thus very small resistive losses. The actual capacitive load to the high voltage supplies in the spacecraft vault, is therefore largely due to the capacitance of the cable itself, rather than the instrument's parallel plates. The *change* in capacitance in the cables is of some importance to the power supply designer.

For these tests, a length of each type of cable was obtained from the one of the instrument manufacturers to ensure that the samples tested were as flight-like as possible.

IV. Experimental Procedures

To more closely match the expected radiation dose predicted for these cables, exposure to electrons of multiple energies was planned. Three energies were planned, 75 keV, 750 keV, and 1.5 MeV to implant electrons, and thus dose, into the outer jacket, inner dielectric, and through the cables respectively. Additionally, the cables were to receive a dose of gamma radiation from a Co-60 source to give a wide spread dose from internally generated Compton electrons. Unfortunately, near the start of testing the facility that could produce 750 kev and 1.5 MeV electrons experienced a failure that closed it for half a year. To conduct the test within the allowed time period and budget, we used the Co-60 gamma radiation exposure as the sole inner cable radiation source. The 75 keV electrons were still used to impart dose to the outer jacket dielectrics.

The total radiation dose used in testing was twice that predicted by the environmental study to provide a radiation design factor (RDF) of 2 per standard testing procedures. This choice was made to ensure that the results of the test would be credible while keeping the amount of testing to a reasonable level.

A. Pre-test measurements

Prior to the beginning of radiation testing the capacitance of the cables was recorded and their partial discharge characteristics were measured. A word should be said at this point about partial discharge testing. These tests are performed by applying a high potential across the inner dielectric of the cable while monitoring for small changes in the flow of charge to the cables. The electric potential between the cable braid and center conductor creates an electric field within the inner dielectric similar to what will be seen during cable operations, but less than the breakdown value for the cable. Imperfections in the cable dielectric (and there are microscopic imperfections in all insulators) allow for field intensifications which lead to small discharges within the cable. These discharges do not create a short circuit in the cable, but do induce a small movement of charge in the energized line which is picked up by the measurement system.

The number of these discharges, and the average amount of charge displaced, can be used as an indication of the quality of the insulation. This method is extensively used in the power industry as a non-destructive test for insulation quality, but it is not yet used extensively on space systems. In the power industry, the typical measurement is made with 50-60 hertz systems where the electric fields within the insulation are changing at a regular and predictable rate. Much research has been performed on the relationship between partial discharge measurement and insulation quality and lifetime at these frequencies.

Space systems use dc power delivery. The partial discharge characteristics for constant voltage systems are not as well studied, and there is not presently a recognized technical standard. Therefore, the partial discharge results for these cables cannot be compared to an accepted criterion, nor can the testing method be according to an accepted standard. The testing procedure followed the ramp-and-hold approach developed elsewhere in NASA[2], and this allowed us to learn something about partial discharge measurements with constant electric fields.

Alternating current partial discharge measurements according to IEC Std. 60270[3] were made on the cables prior to any other testing, but the cables did not perform well with AC voltages above 3 kV. It did not seem useful to observe only that the cables did poorly at 60 Hz: DC testing, representative of the application, was clearly called for.

Cable capacitance measurements were made prior to testing with the cables both before and after insertion of the cold plate into the vacuum chambers. Measurements were performed with an inexpensive Inductance, Capacitance,

and Resistance (LCR) meter at 1 kHz. A single LCR meter was used throughout testing and was checked prior to each test run.

B. Sample mounting

Each sample cable was cut to a 4.5 meter length to mimic the flight cable length, and to allow for some of the cable to extend from the test plate to the vacuum chamber feedthrough. The two cables were wound in a flat spiral on a cold plate and clamped in place with thin strips of aluminum. One end of the cable was fed through the cold plate and terminated as an open circuit to simulate the capacitive plates on the spacecraft. The other end was attached to an electrical vacuum feedthrough to allow for in situ testing of the cables at various levels of radiation exposure. An effort was made to maximize the area of the cable exposed to the radiation source while still holding the cables firmly to the cold plate to ensure good thermal contact. Holding the cable in firm contact was particularly important since the cold plate orientation was vertical for all radiation testing.

Thermocouple lines were also attached to the cold plate and cable surfaces to monitor the temperature of the samples during testing. A round shroud was also attached to the cold plate to reduce the thermal load to the cables due to radiative heating from the warm chamber walls.

The cold plate and shroud with the coiled sample cables was mounted in the vacuum chambers available at each radiation source facility with as much thermal isolation as possible while still maintaining a good electrical ground to the chamber. During each test, the vacuum chambers were pumped down to ~5×10^{-6} torr prior to beginning the test. The cables were allowed to outgas overnight to allow for the removal of as much water from the chamber as possible. After an initial warm electrical measurement of the cables, the cold system was activated and the cold plate and cables were cooled by conduction using liquid nitrogen. The thermal objective for the test was a cable temperature of -50°C. Due to the high thermal resistance of the cable FEP insulation, there was a large thermal gradient through the cable structure. The front surfaces of the cable were measured at -45°C while the rear cold plate got as low as -100°C during testing. Since the average temperature was at or below the desired test point, these temperatures were considered sufficient to allow the testing to proceed.

C. Gamma Radiation

As was mentioned above, initial plans for these tests called for energetic electron exposure with some gamma radiation for completeness. With the closure of the available electron accelerator, the entire interior radiation dose had to be applied using gamma radiation from a Co-60 source. This electro-magnetic radiation can be used as a good substitute, however, due to the energetic electrons generated within the materials due to the Compton effect. Energetic electron bombardment would still be preferred, but gamma radiation was deemed sufficient since the goal for these tests was to determine changes due to total ionizing dose rather than strictly the effects of electron bombardment.

The total dose to be imparted to the interior of both cables during testing was set at 1.2 Mrad since the testing dose was set up for an RDF of 2 from the calculated end of mission dose. This total dose was imparted to the cables during two separate test runs of 600 krad each. The first run was the initial dose given to the cables and was intended to be only a portion of the total ionizing dose. When the higher energy electron source became unavailable the cables were again exposed to 600 krad of gamma radiation to complete the inner cable exposure. In both test runs, the samples mounted the cold plate were inserted into a vacuum chamber with a Plexiglas viewport oriented so that the cables were placed in front of the Co-60 source. The effective dose rate was measured at 6 rads/second which mandated a total dose time of 28 hours for 600 krad. Capacitance measurements were made at several intermediate times to try to capture any changes in cable properties as a function of dose.

D. Low Energy Electrons

The gamma radiation from the Co-60 source produces a relatively even radiation dose over the thickness of the cables which is not necessarily mirrored in reality. The dose depth calculations indicated that the dose on the surface of the cables would be larger due to the effects of lower energy electrons. To duplicate this effect the cold plate with the twin coils of sample cables was placed in another vacuum chamber with a lower energy electron gun. The cables were then exposed to 75 keV electrons at a current density of 100 pA/cm^2 to add additional dose to the cable's outer jackets. The calculated dose for the outer jacket behind the copper shielding is 1.1 Mrad. Adding in dose to reach desired RDF of 2, the total dose to be added by the 75 keV electrons was 2.2 Mrad. As with the gamma radiation testing, the cables were held at a surface temperature of -45°C in a vacuum of ~5×10^{-6} torr. Capacitance measurements were taken at intervals in the testing to attempt to see any changes due to increasing dose.

V. Experimental Results

A. Capacitance Measurements

In all cases, the capacitance of the cables did not change appreciably due to radiation dose as can be seen in Figure 2. The initial capacitance measurement and the final measurement showed an increase in capacitance of only 0.7 percent which is more likely to be due to changes in the capacitance meter than shifts in the dielectric properties of the FEP insulation. This slight shift can be seen in the step jump between the final measurement of the first gamma test run and the initial value for the second run. As can be seen in the plot, the capacitance shifted more because of temperature than they did with increasing dose.

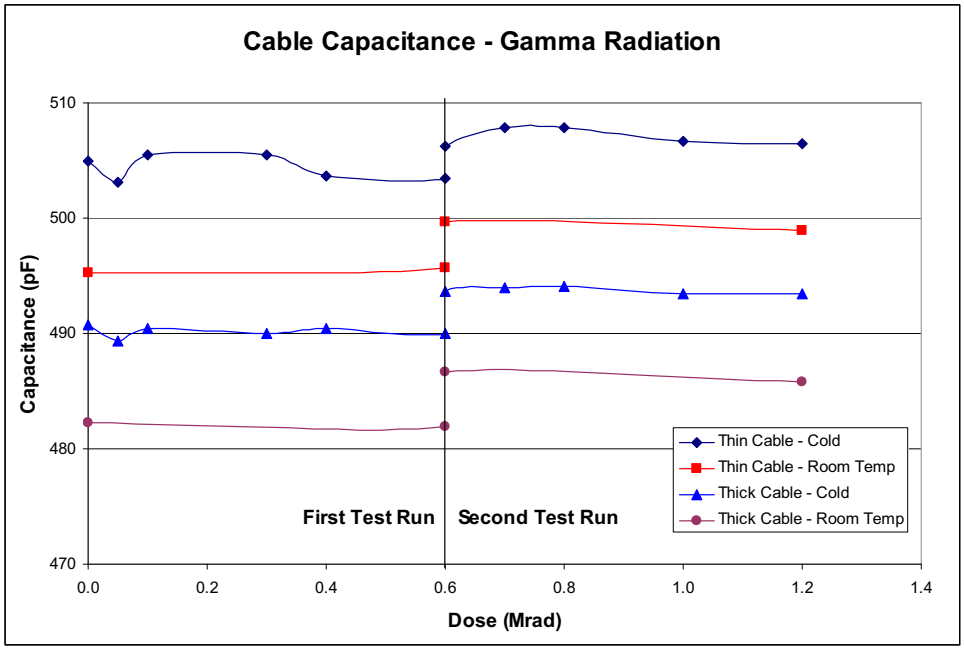

Figure 2. Cable capacitance as a function of dose.

These results are good news for the Juno instrument designers as they indicate that the capacitive load to their power supplies will not change significantly during the mission due to radiation. Since the temperatures on board the spacecraft are not expected to cycle, the shifts due to temperature are not of importance during mission operations.

B. Partial Discharge Testing

It was hoped that partial discharge measurements could also be taken in situ but after an initial attempt, it was found that the electrical noise near the test setup was large enough that no measurements could be taken. Instead, partial discharge measurements were taken in a dedicated Faraday cage at room temperature and pressure before and after each stage of radiation exposure.

Using a method similar to that described by Bever[2], both high voltage cables were tested for partial discharge response to DC voltage as the potential was raised in steps from -1 kV to -10kV. Unfortunately, after the partial discharge measurements of the un-radiated cables were taken, it was discovered that the partial discharge calibration factors used were in error. As a result, the measurements taken prior to the beginning of testing cannot be used as a comparison to the measurements taken after each successive radiation dose. The beginning point for change due increasing dose is thus after the first gamma radiation dose.

Figure 3 shows the measurements taken after the first gamma dose and after all radiation had been applied to the cables. Only the measurements after gamma radiation was applied are shown as the 75 keV electrons affected only the surface insulation which is not part of the cable tested with partial discharge measurements.

As the plots of the applied voltage and partial discharge measurements show, with each increase in voltage across the inner dielectric on the cable, there was a spike in the apparent charge measurement. Since the peaks in charge movement decrease quite rapidly they are likely due to polarization effects with the dielectric rather than an indication of insulation defects. Of more interest is the sustained partial discharge levels than begin to be seen as the

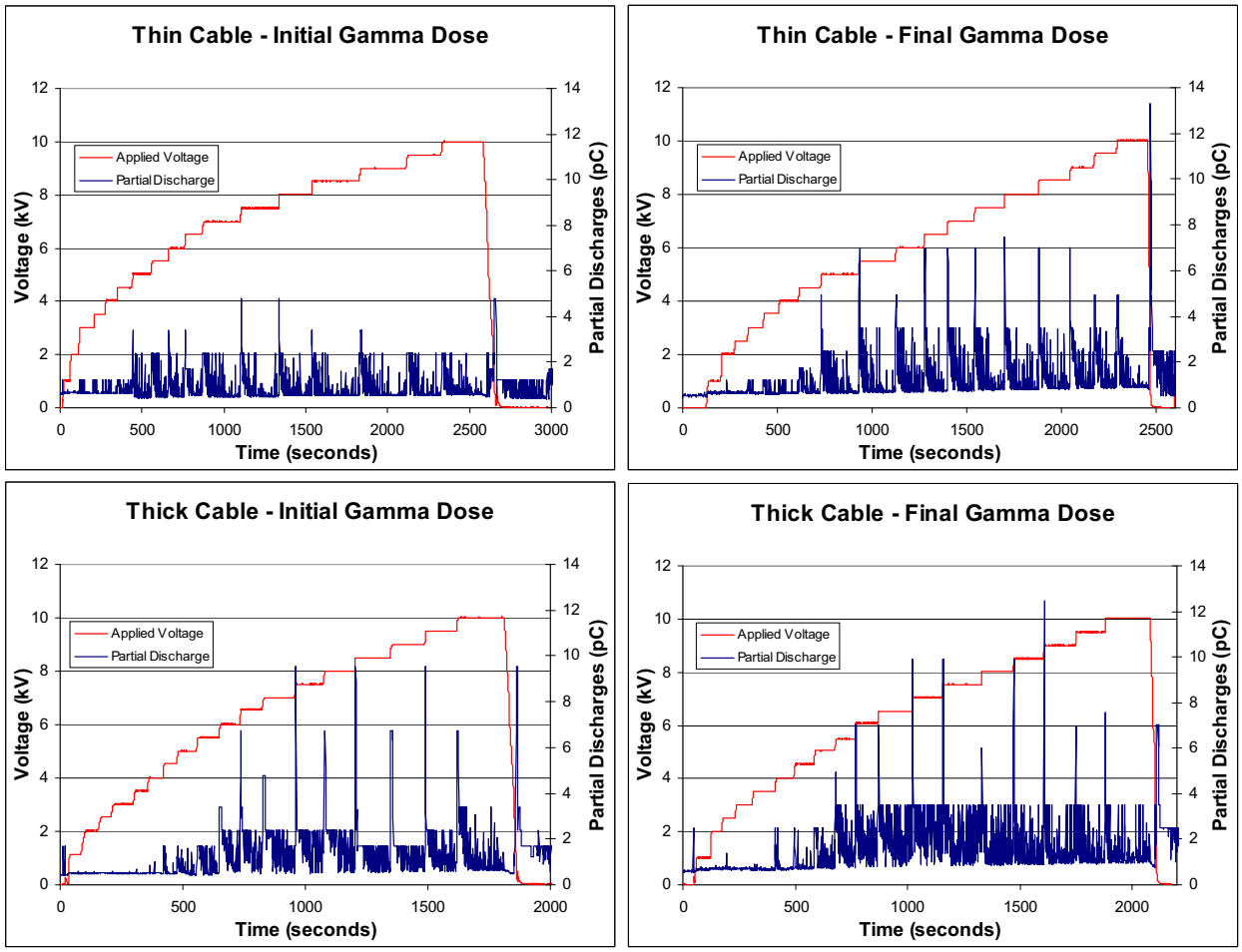

Figure 3. Partial discharge measurement for the two high voltage cables after the initial dose with Co-60 gamma radiation and after the final dose. Note that the base partial discharge levels and the peaks with each voltage jump increased slightly with additional dose.

voltage increased beyond -4.5 kVdc. For the thinner cable, rated for 18 kVdc, the sustained partial discharge level after the initial dose of gamma radiation seems to be about 2 pC over the entire range of voltages tested. In the plot showing the measurements taken after the final dose of gamma radiation, the sustained values have increased to about 3 pC. The height and number of the peaks with each voltage step also became larger and more pronounced between the first and last radiation dose. The effects on the larger cable were similar with an increase in the sustained partial discharge value from around 2 pC to 3 pC and a magnification of the peaks with each voltage step.

In all of these measurements, the partial discharge values would be thought of as quite low – at least, that would be the case if the experience from AC partial discharge testing can be applied to DC testing. In the power industry, insulation is considered to be good if testing with AC voltages yields no apparent charge values above 10 pC. In the case of these cables, the sustained values are considerable less than that limit even with a final radiation dose that is twice the predicted end of mission value. The "spikes" of PD that approach or even exceed 10 pC are almost certainly controlled in magnitude by the rate of increase of the direct voltage.

C. Internal Electrostatic Discharge

Though examination of internal electrostatic discharges (IESD) as a result of 75 keV electron exposure was not a part of the initial planning of this work, adding and oscilloscope to measure the resulting pulses was an easy and painless expansion of the test. One important note at the outset of examining the IESD measurements taken during electron exposure is how these cables differ from the flight configuration. Most notable, these test cables were not wrapped in the exterior copper tape to be used on the flight cables as an additional radiation and electromagnetic interference shield. This omission for the IESD results is key as testing with the copper outer shield would have produced quite different results.

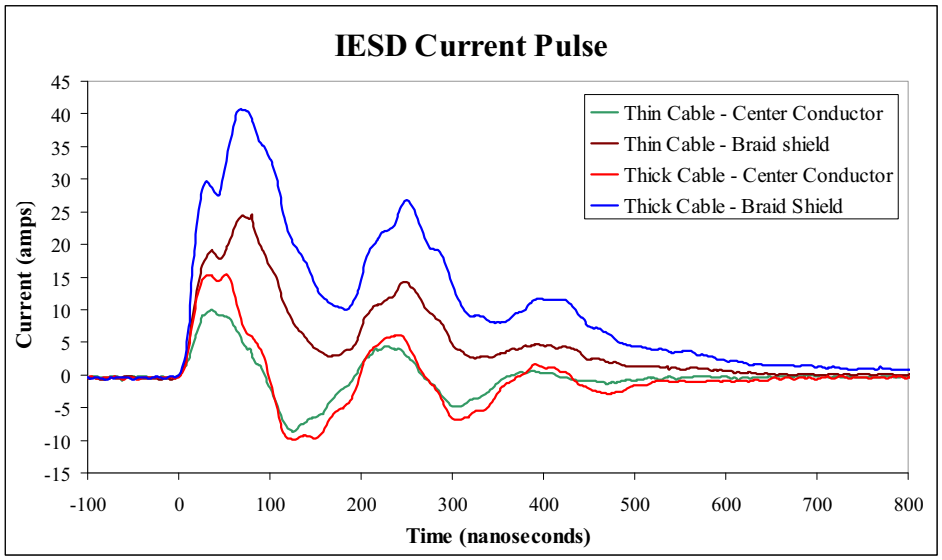

Figure 4. Largest pulse recorded during 75 keV electron exposure. The pulse is due to image charge movement and was initially recorded as volts across a 50 ohm load.

The pulses recorded during the exposure to 75 keV electrons were quite large, with currents reaching peaks of 40 amps, as seen in Figure 4. The measurement technique was to use an oscilloscope to measure the voltage across a 50 ohm terminating resistor.

When a dielectric is exposed to energetic electrons, the charged particles are buried in the interior of the material at a depth related to their initial energy. Electrons implanted in dielectrics do not have an easy migration path to ground because of the high resistivity of the material. Therefore large numbers of electrons can accumulate in the dielectric and create electric fields within the body of the insulator. At some point, either due to large electric fields or some other trigger, the dielectric can no longer withstand the generated fields. The discharge produces a redistribution of charge, and can often result in a release of *plasma* from the surface of the exposed dielectric.

If the dielectric surface is not grounded by an outer shield, portions of the negatively charged surface can be discharged by the nearby plasma as positive ions in the cloud are attracted back to the material. The discharge can produce a large change in the electric fields within the charged dielectric. Grounded conductors near the charged insulator will be directly affected by the redistribution of charge through the movement of image charges. Where conductors are in close proximity to the charged dielectrics, as is the case for the braid shields on these high voltage cables, the resulting image charge movement mirrors the charge released during the IESD event. Where the charged surface area is large, as was the case with over 4 meters each of two cables, the resulting image charge pulse can be quite large. Most of this current is seen on the coaxial braid of the cables, which would be tied to the spacecraft ground, but some of the resulting pulse is coupled into the center conductor via capacitive coupling.

As was pointed out at the beginning of this section, however, the actual flight cables will have grounded copper shields on the outside of the coaxial cables outer FEP jacket. The presence of the outer jacket changes the pulse shapes. Any plasma emitted during an IESD is either contained within the outer conductive wrap or, if it escapes outside of the material, is unable to greatly affect the rest of the charged cable. The negatively charged surfaces are covered by the conductive and grounded copper tape, and not readily available to be discharged.

The pulses observed during the 75 keV electron testing are thus not of great concern to the project for these particular cables, but serve as further justification for the presence of an outer conductive shielding. This is not only true for these high voltage coaxial cables, but hold true for any similar cables used outside of the protective vault.

VI. Conclusion

Increasing levels of radiation do make small changes in the electrical nature of the FEP insulation used in the cables. These changes are mostly easily seen using partial discharge tests rather than capacitance measurements. However, in the absence of a large database comparing measured dc partial discharges and observed insulation lifetime, the most we can say about the results are that they seem encouraging. Space experience with these cables suggest they are adequate for the job in Earth orbit. Results in the lab suggest that radiation affects the partial discharge performance only a little. In addition, the capacitance of the cables tested changed little with radiation dose. Any changes possibly attributable to shifts in the measurement device rather than real changes in the cables.

Thus the two types of high voltage cable chosen for use on the Juno spacecraft appear able to survive the end of mission radiation dose with little difficulty.

Large IESD pulses were observed during exposure to 75 keV electrons which would be a danger for similar cables on the spacecraft without a conductive outer coating. The flight configuration for these cables calls for a copper outer shield which should reduce the incidence of such dielectric discharges and greatly reduce their magnitude. If such shields were not already planned, they would be highly suggested for these cables and any other unshielded insulators on the spacecraft.

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