# The Competing Influences of the Radiation Belts on the Charging of Extremely Resistive Spacecraft Materials

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## Abstract

Spacecraft suffer from various types of anomalies caused by space weather. One important source of spacecraft anomalies is internal electrostatic discharge (IESD), which occurs when penetrating electrons deposit charge inside dielectrics faster than that charge can dissipate via conduction currents. This causes the electric field to build up to a breakdown threshold. The most electrically resistive materials, such as PTFE Teflon, are of greatest concern for IESD. Laboratory measurements of the conductivity of Teflon and other highly resistive polymers show that their conventional conductivity is practically negligible. In space, the radiation-induced conductivity (RIC), an alternate source of conduction that is linearly proportional to the ionizing dose rate received by the material, is the dominant form of conductivity. The space radiation environment therefore plays contradictory roles in extremely resistive polymers, both depositing charge and dissipating it. The spectral shape, rather than the total electron flux, becomes the primary consideration for IESD because it determines the relative deposition of charge and ionizing dose in materials. A counterintuitive result is that soft spectra may be a greater risk for IESD, because relative to hard spectra they deposit more charge than dose in materials. This differs from the standard practice of defining the worst-possible environment for charging and IESD as the spectrum in which the electron flux is highest at all energies that could reach the material. We simulate the charging of material samples from the CRRES Internal Discharge Monitor, demonstrating the insensitivity of PTFE Teflon to changes in the electron environment, and contrasting it with a more conventional insulator.

## Background

### Deep Dielectric Charging

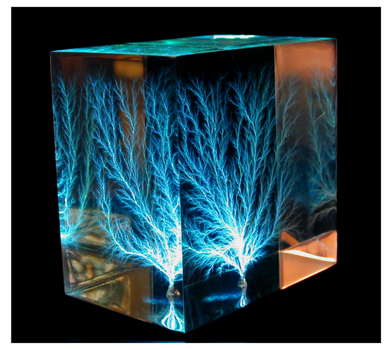
- Deep dielectric charging (aka internal charging or bulk charging) due to penetrating electrons from the space radiation environment presents a risk of electrostatic discharge (ESD) and spacecraft anomalies
- The intuitive picture of deep dielectric charging is a source/loss model in which radiation belt electrons are the source of embedded charge in insulators, and conductive transport to nearby conductors is the loss process
- The resistivity of materials is a critical factor in mitigating charge buildup
- Many common insulators, such as acrylic and mylar, behave according to the intuitive model, which we refer to as conventional insulators
- Extremely resistive materials, notably fluoropolymers such as PTFE Teflon, can take years to dissipate charge in the conventional manner
- In addition, PTFE has a low dielectric constant (2.1), which is desirable for minimizing dielectric losses on circuit boards, but means its electric field will build up rapidly as electrons are deposited
- **The intuitive model of dielectric charging predicts Teflon will frequently experience ESD in the radiation belts**

### CRRES Internal Discharge Monitor (IDM)

- The CRRES IDM experiment measured ESD in numerous insulator samples behind thin shielding in a severe radiation environment, including 2 samples of PTFE Teflon fiberglass, 2 samples of FEP Teflon, and 5 samples of FR4 fiberglass
  - FR4 is approximately 100 times as conductive as PTFE Teflon, is more than twice as polarizable, and has a higher ESD threshold. FR4 "should" be much less of an ESD risk than PTFE
  - The five FR4 samples discharged about 3500 times in total during the CRRES mission lifetime, representing 91% of all discharges measured.
  - The four Teflon samples on IDM discharged a total of 325 times, and **two of the Teflon samples *never* discharged, even during the March 1991 storm.** Teflon samples that did discharge were in geometric configurations that are known to pose a high risk of ESD, but equivalent configurations of FR4 discharged many more times than Teflon

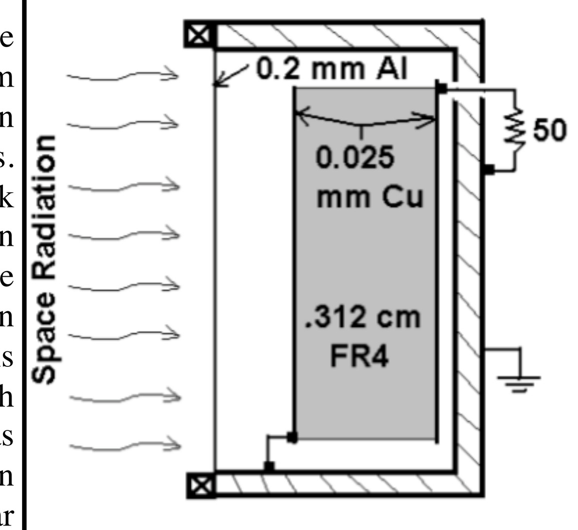
### Radiation-Induced Conductivity (RIC)

- Most of the explanation for Teflon's resilience to ESD appears to be radiation-induced conductivity (RIC), a material property that is well known in the spacecraft charging community
- RIC in PTFE Teflon is proportional to the ionizing dose rate [Khatipov, 2001; Gillespie, 2013], which temporarily creates electron-hole pairs that provide a small amount of charge mobility
- For most insulators, their dark conductivity is high enough that the RIC makes only a small contribution to the total conductivity
- Teflon's dark conductivity is incredibly low, essentially negligible, and it can take years to dissipate charge.
- Teflon's RIC is higher than most common insulators [Khatipov, 2001], considerably higher than many: **the radiation belts are the source of Teflon's conductivity in space**
- Teflon's extremely low dark conductivity and high RIC makes it behave very differently than conventional insulators
- **The nonintuitive behavior of materials like Teflon in response to changes in the radiation belt environment has not, to our knowledge, been previously explored**



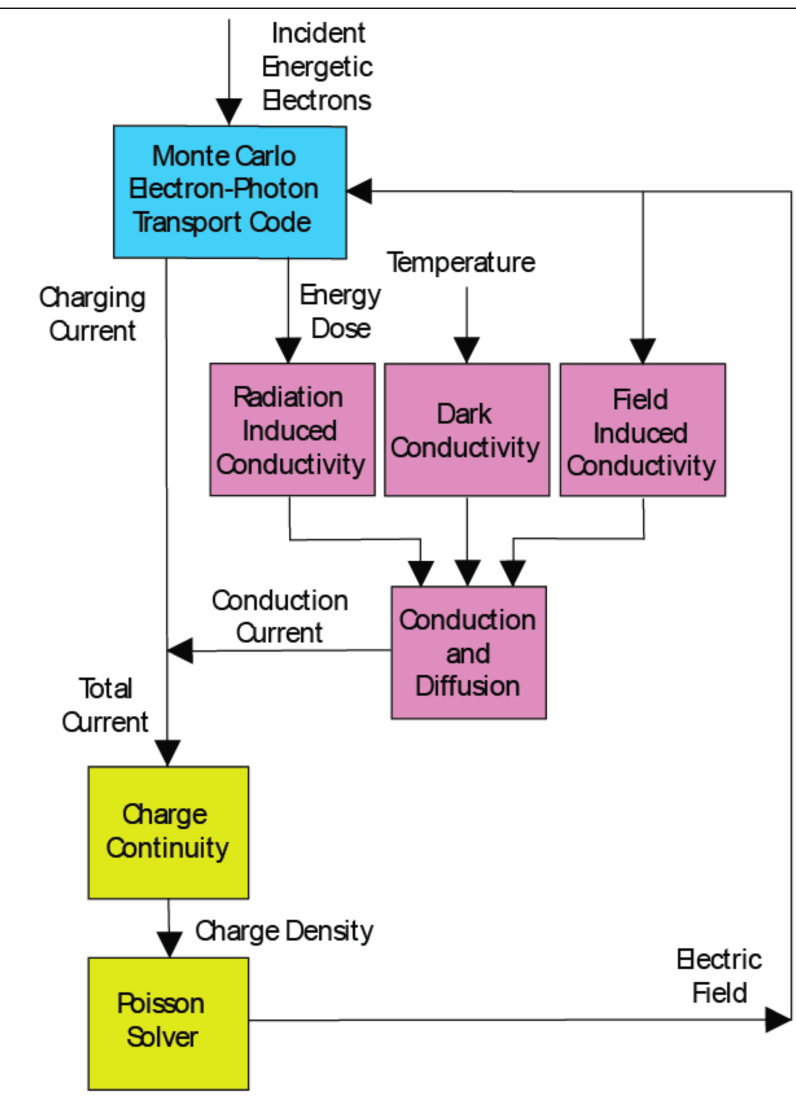
[Left] A Lichtenberg pattern is formed by charging an insulator such as acrylic using an energetic electron beam, and creating an electrostatic discharge. The same phenomenon occurs on spacecraft materials in response to energetic electrons in the radiation belts.

[Right] The CRRES Internal Discharge Monitor (IDM) measured pulses from electrostatic discharge (ESD) events in thinly shielded insulating material samples. Above right illustration is of a 3 mm thick sample of FR4 Fiberglass, a common insulator used in printed circuit boards. The material is sandwiched between very thin copper electrodes to ground each side. This sample is simulated to the right, along with a 2.4 mm sample of FEP Teflon that was also flown on CRRES. Teflon is denser than FR4, so the two samples have similar "equivalent aluminum" shielding thicknesses. (from Frederickson et al., 1993)



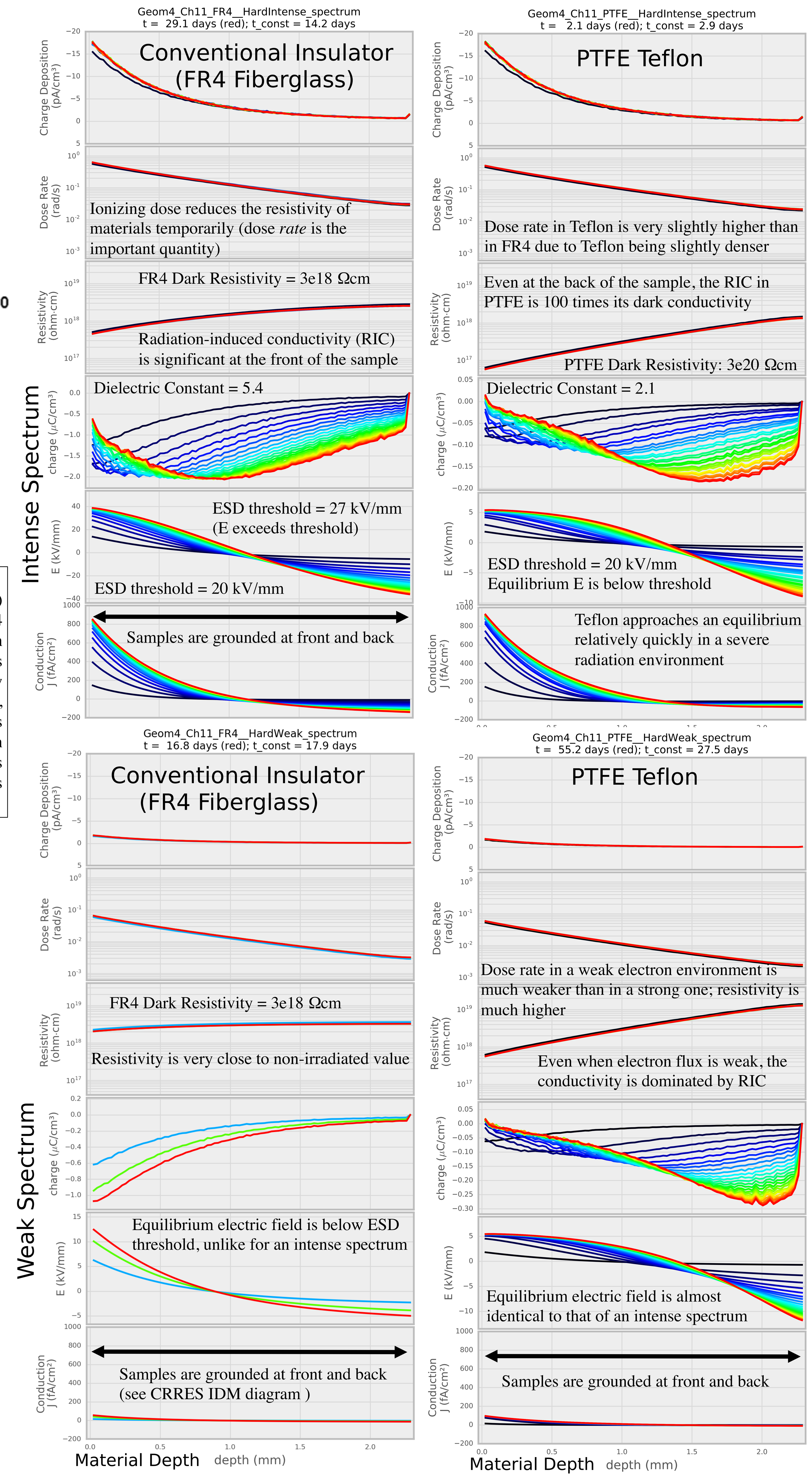

CRRES IDM material sample

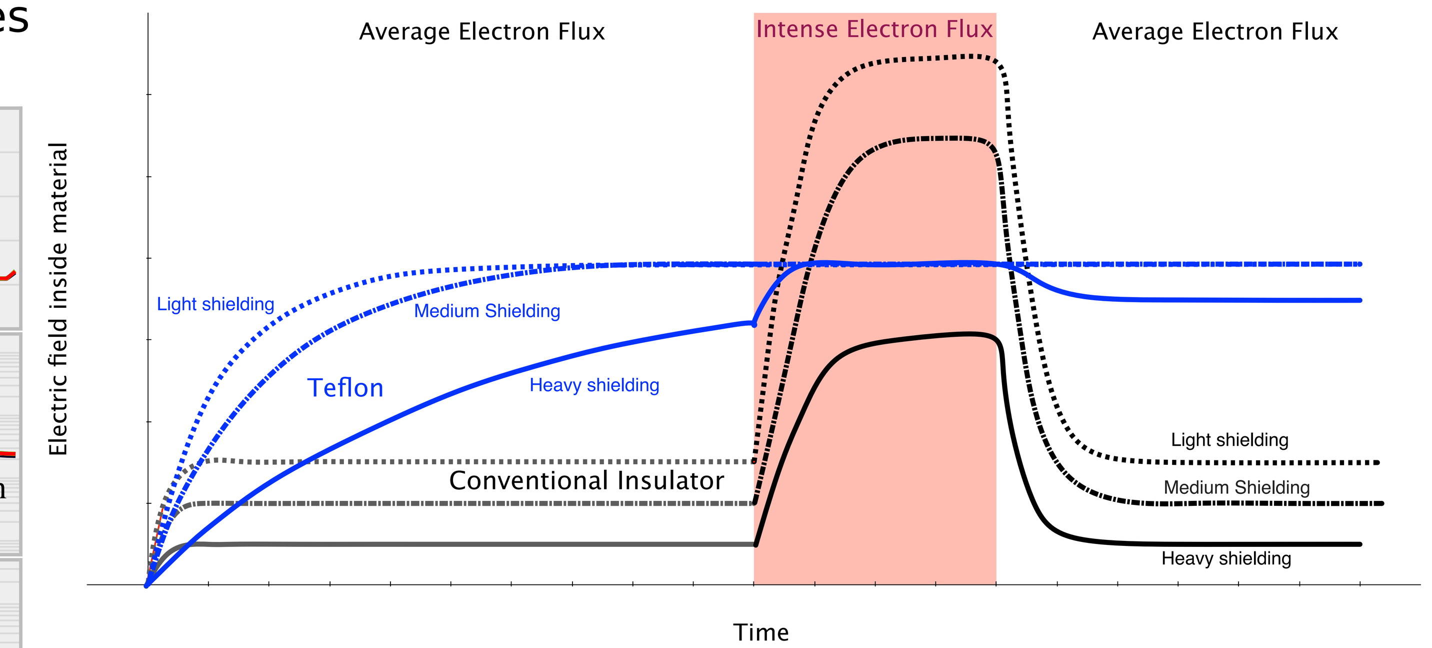
[Right] Four simulations compare the effect of a severe radiation belt spectrum (top) and a weak spectrum (bottom) measured by CRRES on material samples of FR4 fiberglass circuit board (left) and PTFE Teflon (right) in the same configuration as in the CRRES IDM experiment, except FR4 is changed to have the same thickness as the Teflon sample. FR4 is a more conventional insulator. Teflon has extremely low dark conductivity (high resistivity), but is very sensitive to the ionizing dose rate, which severely limits its electric field and charge buildup. The simulated spectrum is constant, and time goes from black to red, with each material approaching an equilibrium. Most charge dissipates to the front electrode, but embedded charge is seen to slowly migrate toward the back of the sample. Teflon's electric field remains considerably weaker than FR4 in the intense electron environment.




[Above] The Simulator To Assess the Threat of Internal Charging (STATIC) model [Lemon et al., 2010] simulates charge deposition due to penetrating electrons using a radiation transport code (EGSnrc or Geant4) combined with an electric field solver and a charge dissipation module. Its coupling is described by this flow diagram.

## Simulations of the CRRES Internal Discharge Monitor material samples




[Above] Based on a variety of simulations similar to (but more comprehensive than) those presented here, this diagram summarizes the qualitative behavior of two classes of material: conventional insulators, and radiation-driven insulators such as Teflon. Teflon (blue) may take weeks or months to build up charge in an orbital environment, but show little change once it reaches a quasi-equilibrium. Adding shielding does not reduce the charge buildup until it is sufficient to reduce the radiation-induced conductivity to low enough values that it is no longer the dominant driver of charge dissipation. The electric field inside conventional insulators, by contrast, rises and falls in response to changes in the radiation belt fluxes, and increasing the shielding always mitigates charge buildup.

## Summary/Discussion

- Radiation belt electrons penetrate spacecraft materials and deposit charge inside insulating materials, potentially causing electrostatic discharge (ESD), damaging electronics or causing other anomalies
- Charge mobility in insulators determines how quickly materials can dissipate charge to nearby conductors

- There are two behavioral regimes of insulating materials:
  - **Conventional insulator**: Material conductivity is constant; charge buildup rises and falls in proportion to changes in the electron flux
  - **Radiation-driven insulator**: Conductivity is almost completely driven by ionizing dose; Increased electron flux deposits both charge and dose faster, leading to no net increase in charge buildup; **Electric field shows little variation even if the radiation belts intensify substantially.**
  - Depending on the electron fluxes in a given orbit, an insulator can operate in one regime or the other, or in the intermediate regime where radiation-induced conductivity and dark conductivity are of comparable importance
  - In the absence of heavy shielding, extremely resistive materials like Teflon operate in the radiation-driven regime. Otherwise they behave like conventional insulators with an extremely long time constant, so that charge buildup and decay occurs very slowly

- In a radiation-driven insulator:
  - The spectral shape (hardness) does affect the electric field, but for a CRRES-like radiation environment, our simulations suggest it's not a dramatic effect.
  - **Increased shielding does not reduce the electric field** unless the shielding is extremely heavy. For a CRRES-like worst case environment, ~4 mm Al shielding would be required to make Teflon behave like a conventional insulator
  - Changing the shielding or the electron fluxes *does* change the time it takes to reach equilibrium. Once an approximate equilibrium is reached, though, the electric field is very stable to further changes.

- In summary, the role of the radiation belts in deep dielectric charging is more complex than simply being a source of charge; it is also responsible for dissipating that charge in extremely resistive materials such as Teflon

## References

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