Effects of Cryogenic Temperatures on Spacecraft Internal Dielectric Discharges

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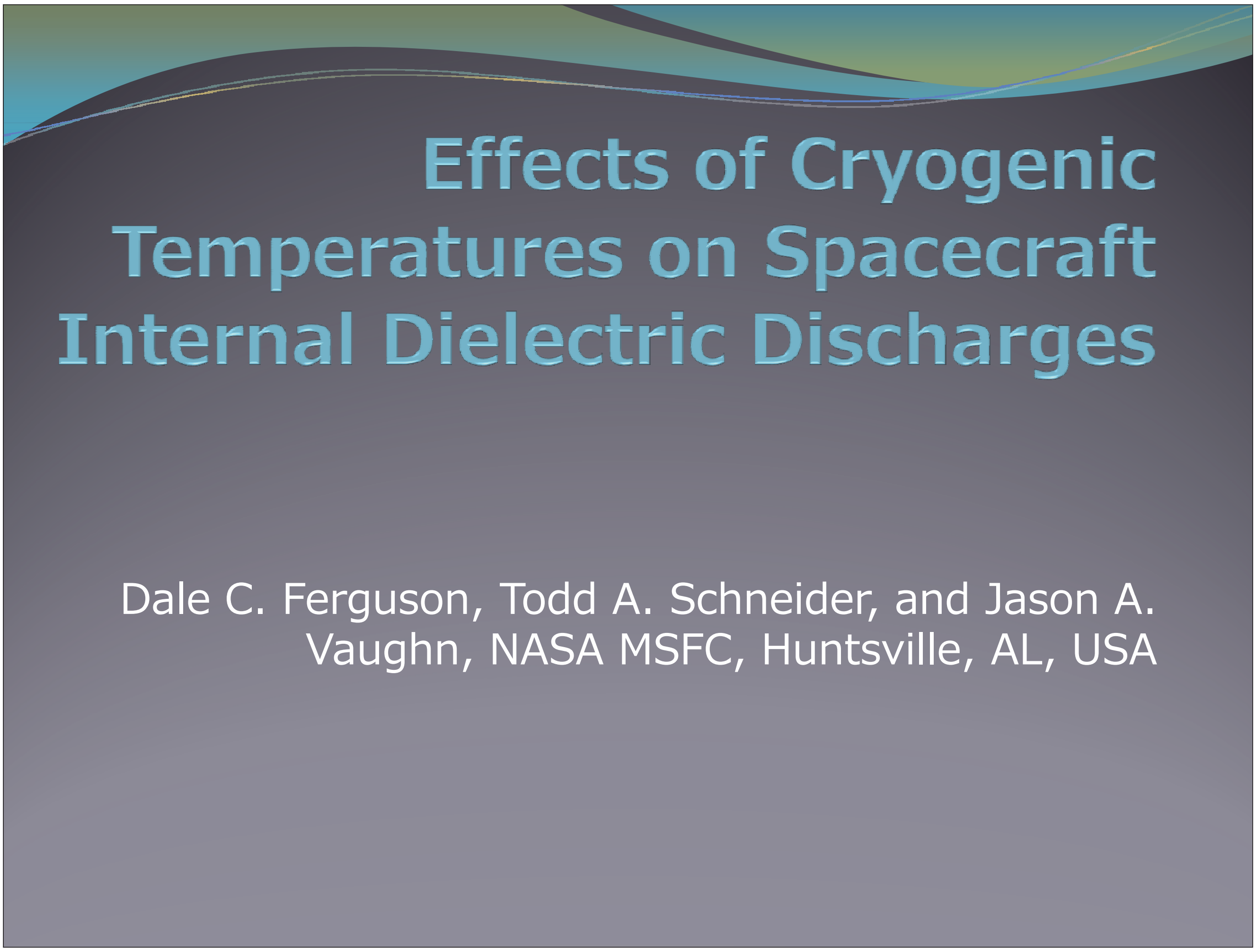
Abstract—Most calculations of internal dielectric charging on spacecraft use tabulated values of material surface and bulk conductivities, dielectric constants, and dielectric breakdown strengths. Many of these properties are functions of temperature, and the temperature dependences are not well known. At cryogenic temperatures, where it is well known that material conductivities decrease dramatically, it is an open question as to the timescales over which buried charge will dissipate and prevent the eventual potentially disastrous discharges of dielectrics.

In this paper, measurements of dielectric charging and discharging for cable insulation materials at cryogenic temperatures (~ 90 K) are presented using a broad spectrum electron source at the NASA Marshall Space Flight Center. The measurements were performed for the James Webb Space Telescope (JWST), which will orbit at the Earth-Sun L2 point, and parts of which will be perennially at temperatures as low as 40 K. Results of these measurements seem to show that Radiation Induced Conductivity (RIC) under cryogenic conditions at L2 will not be sufficient to allow charges to bleed off of some typical cable insulation materials even over the projected JWST lifetime of a dozen years or more.

After the charging and discharging measurements are presented, comparisons are made between the material conductivities that can be inferred from the measured discharges and conductivities calculated from widely used formulae. Furthermore, the measurement-inferred conductivities are compared with extrapolations of recent measurements of materials RIC and dark conductivities performed with the charge-storage method at Utah State University.

Implications of the present measurements are also given for other spacecraft that may operate at cryogenic temperatures, such as probes of the outer planets or the permanently dark cratered areas on the moon. The present results will also be of interest to those who must design or operate spacecraft in more moderate cold conditions. Finally, techniques involving shielding and/or selective use of somewhat conductive insulators are presented to prevent arc-inducing charge buildup even under cryogenic conditions.



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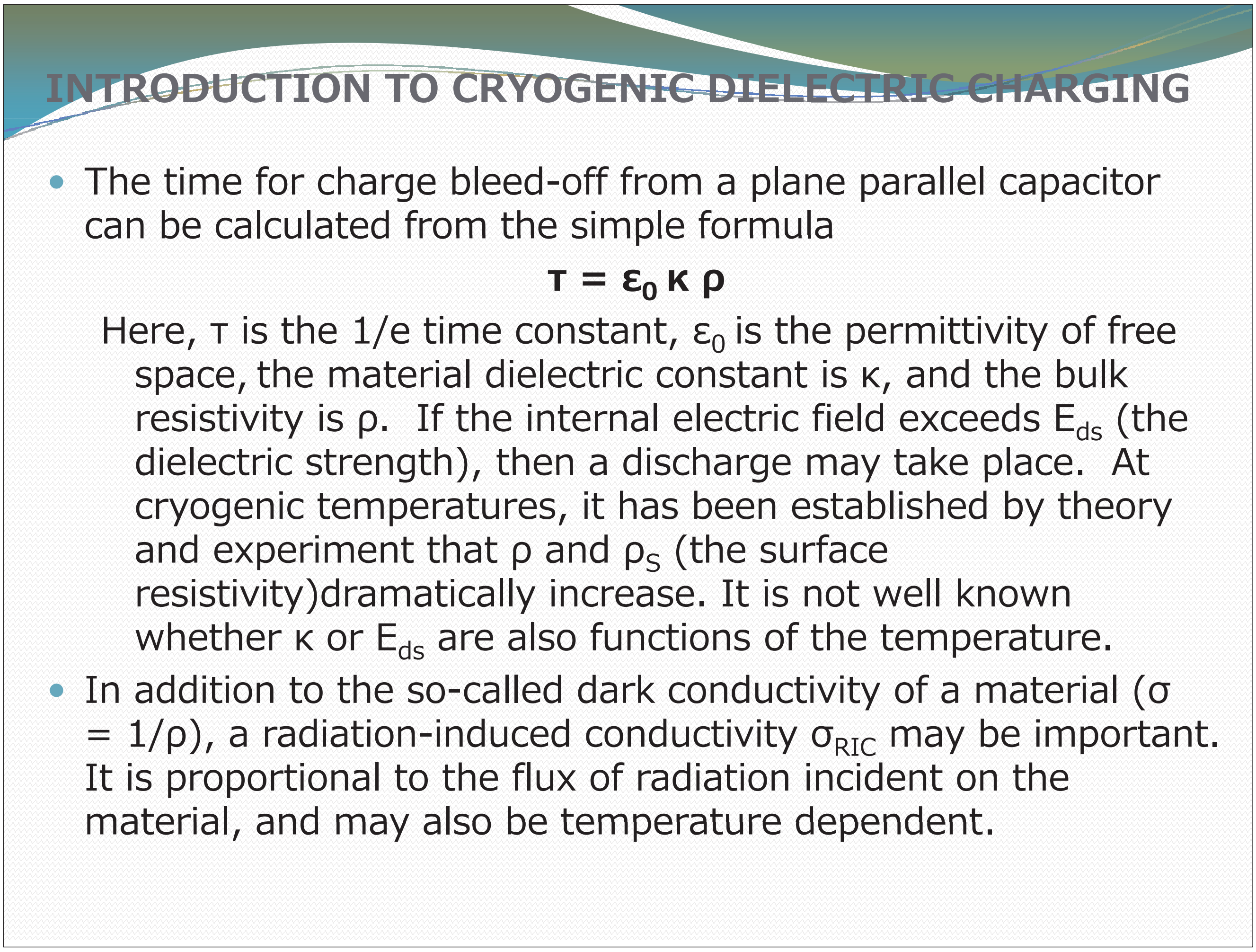


INTRODUCTION TO CRYOGENIC DIELECTRIC CHARGING

- The time for charge bleed-off from a plane parallel capacitor can be calculated from the simple formula

$$\tau = \varepsilon_0 \kappa \rho$$

Here, τ is the 1/e time constant, ε_0 is the permittivity of free space, the material dielectric constant is κ, and the bulk resistivity is ρ. If the internal electric field exceeds E_{ds} (the dielectric strength), then a discharge may take place. At cryogenic temperatures, it has been established by theory and experiment that ρ and ρ_S (the surface resistivity)dramatically increase. It is not well known whether κ or E_{ds} are also functions of the temperature.

- In addition to the so-called dark conductivity of a material ($\sigma = 1/\rho$), a radiation-induced conductivity σ_{RIC} may be important. It is proportional to the flux of radiation incident on the material, and may also be temperature dependent.

INTRODUCTION TO CRYOGENIC DIELECTRIC CHARGING (2)

$$\mathbf{dQ/dt = (JA\text{-}V/R),}$$

where J is the electron beam flux, V is the voltage developed in the insulator layer, Q is charge, and R is the effective resistance. If the insulator acts like a thin film with charge on one side and ground on the other, then, R = ρd/A, where ρ is the total resistivity, d is the thickness of the film, and A is the area. ρ = 1/σ, where σ is the bulk conductivity, so

$$V/R = V\sigma A/d, \text{ and } dQ/dt = (JA - V/R) = A(J - V\sigma/d).$$

$$Q = CV \text{ and } C= A\ \kappa\ \varepsilon_0/d, \text{ so}$$

$$\mathbf{dV/dt = (d/\kappa\varepsilon_0)\ (J - V/\rho d).}$$

At the maximum voltage V_{max}, dQ/dt = 0, so J - Vσ/d = 0, and

$$\mathbf{V_{max} = Jd/\sigma.}$$

We may expect that if E = J/σ > E_{ds}, then dielectric breakdown is possible.

THEORY OF TEMPERATURE DEPENDENCES

- At relatively high temperatures (above -35 C, for instance) the conductivity is proportional to a Boltzmann factor with a trap depth ΔH (Dennison, 2006):

$$\sigma(T) \propto \exp\left[-\frac{\Delta H}{k_B \cdot T}\right] \quad or \quad \rho(T) \propto \exp\left[\frac{\Delta H}{k_B \cdot T}\right]$$

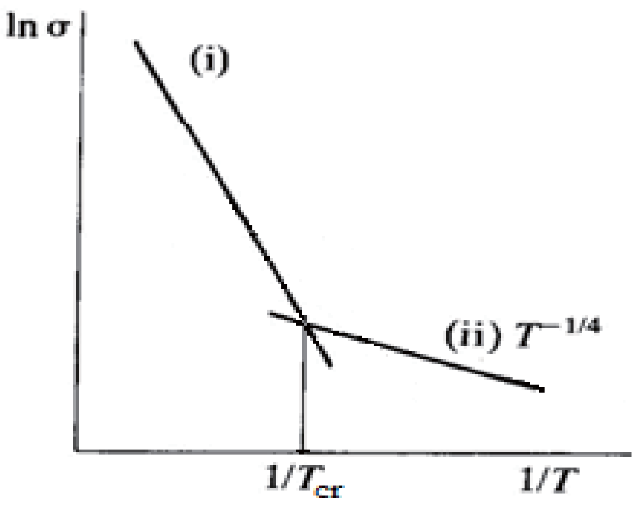
- This trap depth is highly material dependent. For example, Dennison et al (2008) gives the trap depth for Kapton HN as 0.056 eV. For FEP Teflon, he gives ΔH = 1.206 eV. This means that the temperature dependence of conductivity for FEP Teflon is much greater than for Kapton HN.
- As an example, it predicts that at -20 C, the conductivity of FEP Teflon is only about 5 x 10^{-4} of its conductivity at 20 C. However, for Kapton HN, the conductivity at -20 C is predicted to be 0.7 that at 20 C.

THEORY OF TEMPERATURE DEPENDENCES (2)

- At low temperatures, the hopping of electrons out of the traps is modified by a variable range of motion, and the variable-range hopping conductivity is proportional to a Mott factor (Dennison et al, 2009, presentation):

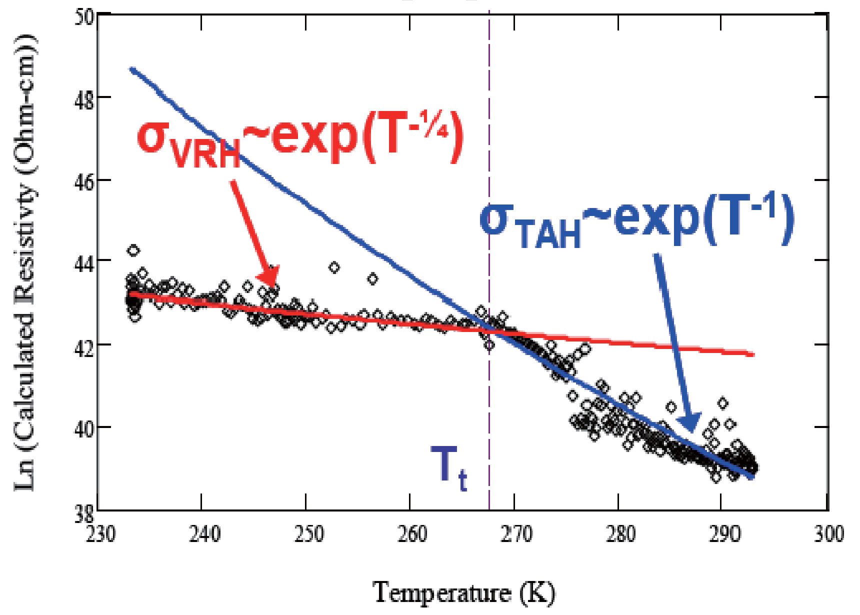
$$\sigma(T) \propto \exp\left[-\frac{T_{\mathrm{VRH}}^{1/4}}{T^{1/4}}\right] \quad or \quad \rho(T) \propto \exp\left[\frac{T_{\mathrm{VRH}}^{1/4}}{T^{1/4}}\right]$$

THEORY OF TEMPERATURE DEPENDENCES (3)



Theoretical dependence of conductivity on 1/T.
(i)is the Boltzmann region, (ii) is the Mott region, and
(ii)T_{cr} is the critical temperature at which transition occurs.

THEORY OF TEMPERATURE DEPENDENCES (4)



Measured temperature dependence of LDPE resistivity. Here, the transition temperature is T_t, the Boltzmann region is TAH, and the Mott region is VRH. From Dennison (2009).

THEORY OF TEMPERATURE DEPENDENCES (5)

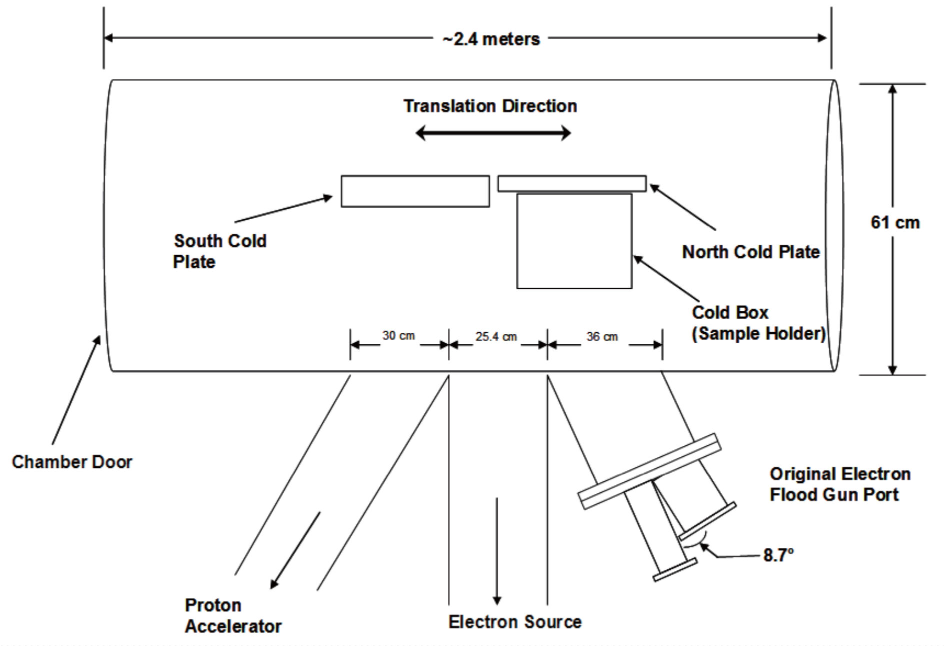
- Radiation Induced Conductivity (RIC) is a complicated matter. Standard theories of RIC predict (Dennison, 2009, presentation) that

$$\sigma_{RIC} = k_{RIC}(T)\ J^{\Delta(T)}$$

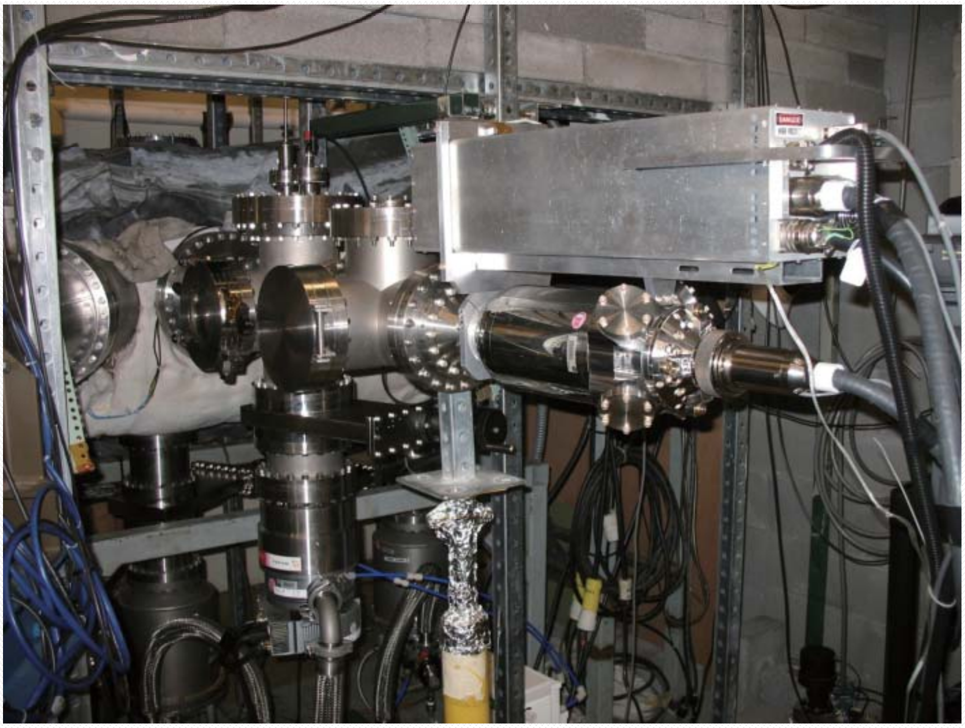
- Recent measurements indicate that $\Delta \approx 1$, and does not depend greatly on temperature. However, k_{RIC} may decrease by two orders of magnitude between room temperature and 90 K for some polymers.

CHARGE AND DISCHARGE MEASUREMENTS DONE AT MSFC

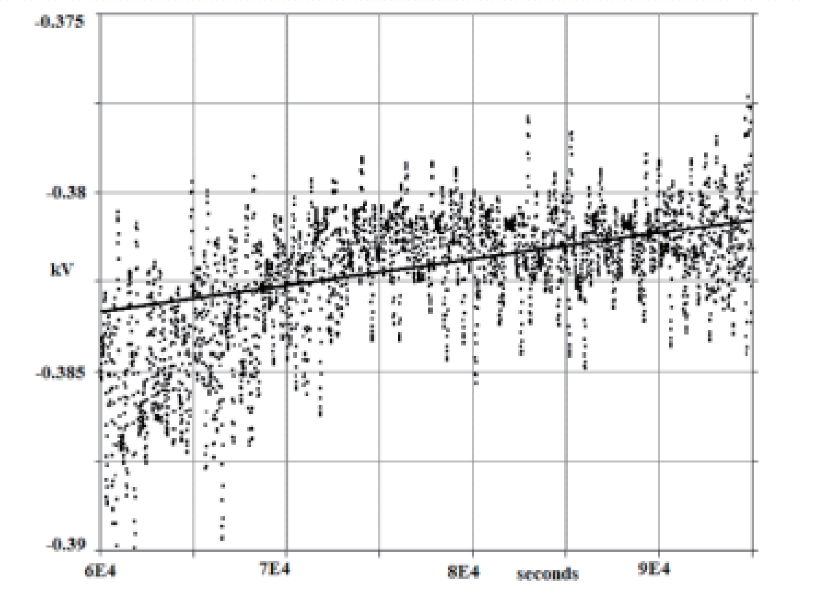
Vacuum Chamber Layout (Top View)



CHARGE AND DISCHARGE MEASUREMENTS DONE AT MSFC (2)

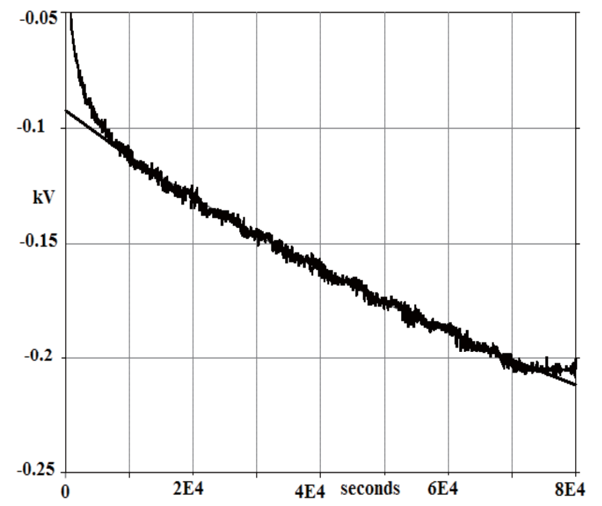


CHARGE AND DISCHARGE MEASUREMENTS DONE AT MSFC (3)



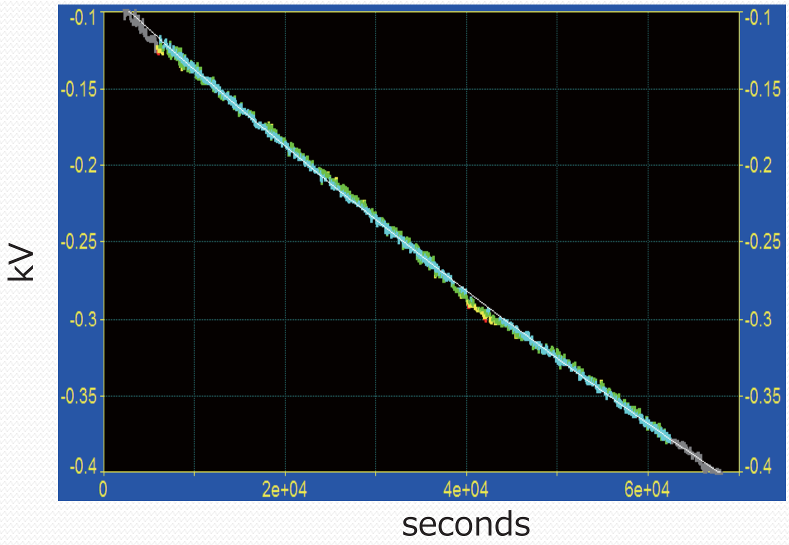
Discharge of 1 mil Teflon material at ambient temperatures. Solid line is an exponential fit. Formal τ = 1400 hours, yielding a formal bulk resistivity of about 3 x 10^{19} ohm-cm. This is to be compared with the Dennison et al (2005) published value of 3.5 x 10^{19} ohm-cm.

CHARGE AND DISCHARGE MEASUREMENTS DONE AT MSFC (4)



**Charging behavior at ambient temperature with Sr-90 electron source. Solid line is an exponential fit. Points at beginning (polarization) and at end (retraction of source) were not included.
τ = 35.6 hours, yielding ρ = 7.3 x 10^{17} ohm-cm. RIC may be involved. We expect that at 90 K the RIC resistivity might be in the range of 7.3 x 10^{19} ohm-cm.**

CHARGE AND DISCHARGE MEASUREMENTS DONE AT MSFC (5)



Charging curve of Teflon at ~90 K – no significant nonlinearity. Formal exponential fit yields $\tau = 69$ hours, or $\rho >> 1.4 \times 10^{18}$ ohm-cm. Arcs were seen after about 300 hours. Assuming linear charging, this corresponds to V = -5100 volts, in agreement with the -4540 +/- 850 V breakdown strength measurement of Dennison (2008).

PREDICTION OF DARK CONDUCTIVITY AT LOW TEMPERATURES

- Taking T_{cr} for Teflon to be 235 K, and assuming at room temperature (20 C), $\rho = 3.5 \times 10^{19}$ ohm-cm and $\Delta H = 1.206$ eV (Dennison et al, 2005 and 2008), we can find from earlier equations the following value for the dark resistivity ρ at 90 K:

$$\rho(235\text{ K}) = 1.92 \times 10^{3}\, \rho(293\text{ K}),$$

$$\rho(90\text{ K}) = 2.07 \times \rho(235\text{ K}) = (3.97 \times 10^{3})(3.5 \times 10^{19})\text{ ohm-cm} = 1.4 \times 10^{23}\text{ ohm-cm}.$$ Thus,

$$\tau = \varepsilon_0\, \kappa\, \rho = 2.5 \times 10^{10}\text{ s} = 780\text{ yrs!}$$

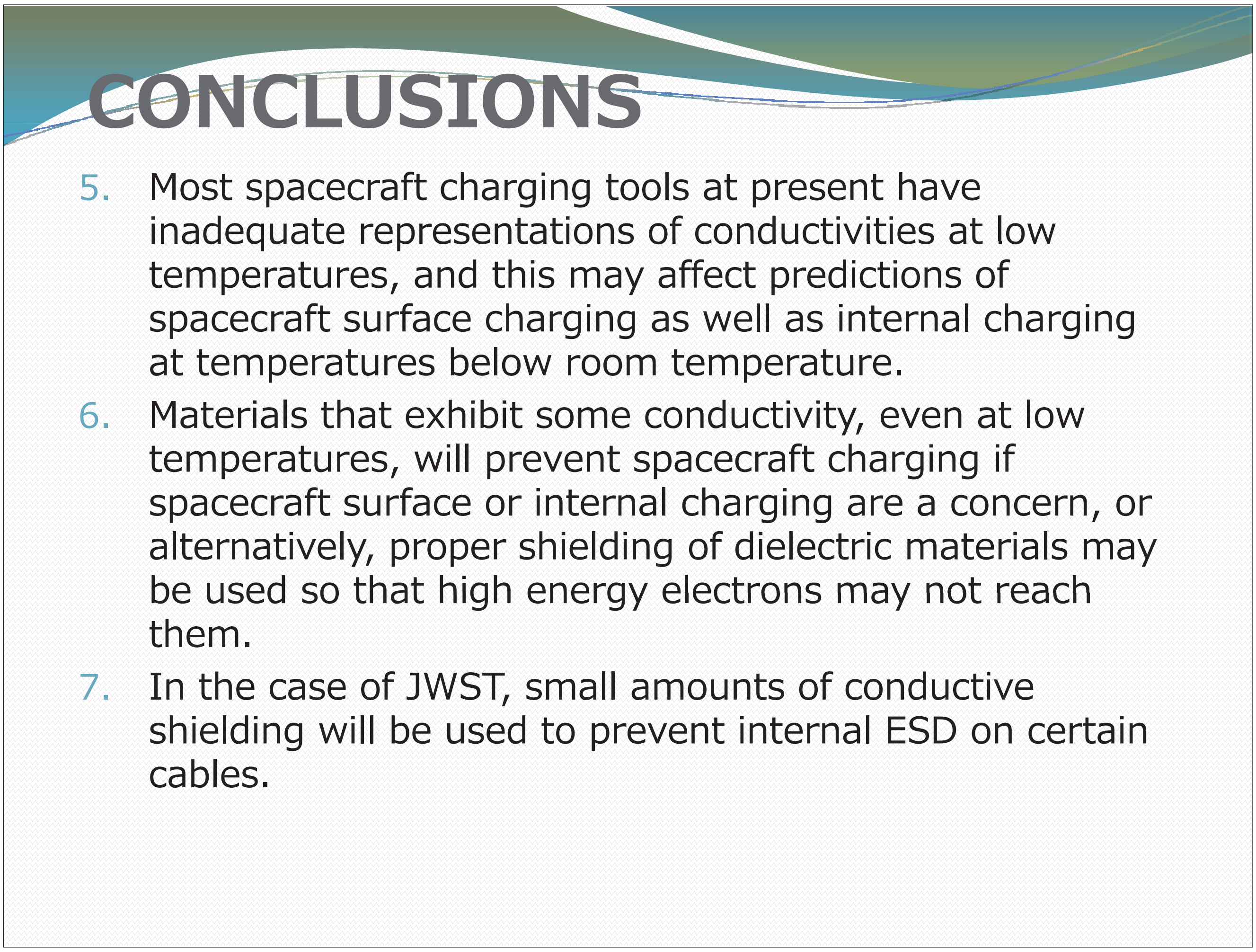
- Thus, dark resistivity is so high at low temperatures that charges will stay intact for a very long time, longer than any conceivable space mission.

PREDICTION OF RADIATION INDUCED CONDUCTIVITY AT LOW TEMPERATURES

- Taking $\rho > 2.5 \text{ x } 10^{18}$ ohm-cm at 90 K ($\sigma < 4 \text{ x } 10^{19}$ mho/cm) and $\Delta = 1.0$, we estimate that at average L2 fluxes
  $\rho = 7.5\text{-}25 \text{ x } 10^{20}$ ohm-cm, or
  $\tau = 4 - 14$ years.
- If it holds true that $\Delta = 1$ at low temperatures, from
  $V_{max} = Jd/\sigma$ and **$\sigma_{RIC} = k_{RIC}(T)\, J^{\Delta}(T)$** then **$V_{max} = d/k_{RIC}(T)$**.
- This maximum voltage reached in a dielectric is not a function of flux, and **if breakdown voltages are achieved at one flux, they will be achieved at any flux.**
- **Breakdown occurred at T ~ 90 K in 1 mil Teflon at our test fluxes, so it will eventually occur at L2 fluxes!**

CONCLUSIONS

1. Measurements of charging and discharging of Teflon at cryogenic temperatures are consistent with charge buildup over many years under space conditions.
2. Radiation induced conductivity, even during brief solar substorms, seems inadequate to prevent charging from eventually reaching breakdown thresholds.
3. New measurements of conductivity parameters and their temperature dependences are needed for typical spacecraft materials under cryogenic conditions.
4. The present results are important for spacecraft such as probes of the outer planets or the permanently dark cratered areas on the moon.
5. The results will also be of interest to those who must design or operate spacecraft in more moderate cold conditions, such as lunar habitats.



CONCLUSIONS

5. Most spacecraft charging tools at present have inadequate representations of conductivities at low temperatures, and this may affect predictions of spacecraft surface charging as well as internal charging at temperatures below room temperature.
6. Materials that exhibit some conductivity, even at low temperatures, will prevent spacecraft charging if spacecraft surface or internal charging are a concern, or alternatively, proper shielding of dielectric materials may be used so that high energy electrons may not reach them.
7. In the case of JWST, small amounts of conductive shielding will be used to prevent internal ESD on certain cables.

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