Effects of Cryogenic Temperatures on Spacecraft Internal Dielectric Discharges

Dale C. Ferguson, Todd A. Schneider, and Jason A. Vaughn

***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.

***Index Terms*— Electrostatic discharges, Dielectric breakdown, Cryogenic electronics, Space vehicles.**

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I. Introduction to Cryogenic Dielectric Charging

IT is well known that dielectrics become better insulators at low temperatures. Spacecraft (such as the James Webb Space Telescope [JWST] and Lunar Polar Outposts) are now being designed that will have some dielectric components in permanent darkness and cryogenic temperatures (< 100 K) for months or years. Under these conditions, charges from the natural radiation environment may build up inside insulators until the resultant electric fields exceed the dielectric strength of the material, and one or more electrostatic discharge (ESD) events can occur. These discharges will produce rapid transients in voltage and current that may, in turn, produce electromagnetic interference (EMI) and/or compromise the electrical integrity of the dielectrics concerned.

Traditionally, spacecraft dielectric internal charging has been dismissed as unimportant if the impinging flux is less than 2×10^{10} e^-/cm^2 in 10 hr (NASA-HDBK-4002). The time quoted in these guidelines corresponds to the time it takes charges to bleed off from typical dielectric materials at room temperature. The time for charge bleed off from a plane parallel capacitor can be calculated from the simple formula (see Ferguson et al, 2007)

$$\tau = \varepsilon_0 \kappa \rho \qquad (1)$$

where 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, during this time, the internal electric field exceeds E_{ds} (the dielectric strength), then a discharge may take place. If charges must bleed off across the surface, then the surface resistivity, ρ_S, comes into play. At cryogenic temperatures, it has been established by theory and experiment that ρ and ρ_S 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.

Assuming that all of the incident flux is absorbed in the material, it is easy to calculate the maximum voltage that can develop across a dielectric. This is the voltage at which the charge deposition rate equals the rate of charge loss.

$dQ/dt = (JA-V/R)$, 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. Assume 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. Now ρ = 1/σ, where σ is the bulk conductivity, so that

V/R = VσA/d, and dQ/dt = (JA-V/R) = A(J- Vσ/d).

Finally, since Q = CV and C= A κ ε_0/d, we have

$$dV/dt = (d/\kappa\varepsilon_0)\,(J - V/\rho d), \qquad (2)$$

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

$$V_{max} = Jd/\sigma. \qquad (3)$$

It is usually the electric field that matters in dielectric breakdown, and in our simple model, E = V_{max}/d, so E = J/σ. We may thus expect that if E = J/σ > E_{ds}, then dielectric breakdown is possible. Here σ also includes σ_{RIC}.

In addition to the temperature, the electric field in a dielectric also can modify the conductivity. This effect is usually only important at field strengths comparable to the dielectric field strength of the material. An electric field typically increases the conductivity.

The best way to measure bulk conductivities for high resistivity dielectrics, such as Teflon (FEP and PTFE), is to charge the material up to a certain level and determine the time scale for the voltage decay. A complicating factor for measurements made over short time scales is the fact that for many dielectric materials (i.e. PTFE, FR4, etc.) there is a long polarization time, which mimics a conductivity, but really just allows for charge redistribution within the dielectric. For PTFE and FR4 the decay time at room temperature is at least 18 hours. Thus, hundreds of hours are needed for accurate measurements for these types of materials.

For very low temperatures (parts of JWST are expected to operate at temperatures continuously below 40 K), conductivities may become so low that charges can build up in ordinary dielectrics for years or decades, so that dangerous arcs may occur after years of operation. Measurements of the decay timescales of charge at these low temperatures may take months to determine whether there may be a problem for a spacecraft whose design lifetime is 10-20 years.

II. THEORY OF TEMPERATURE DEPENDENCES

Resistivity in a dielectric material is usually considered to be due to trapping of electrons by potential wells associated with the atomic lattice. Conductivity depends on the ability of some electrons to escape these traps and travel through the material. At relatively high temperatures (above -35 C, for instance) the conductivity is proportional to a Boltzmann factor with a trap depth ΔH (Dennison, 2006):

$$\sigma(T) \propto \exp\left[-\frac{\Delta H}{k_B \cdot T}\right] \quad or \quad \rho(T) \propto \exp\left[\frac{\Delta H}{k_B \cdot T}\right] \qquad (4)$$

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.

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):

$$\sigma(T) \propto \exp\left[-\frac{T_v^{1/4}}{T^{1/4}}\right] \quad or \quad \rho(T) \propto \exp\left[-\frac{T_v^{1/4}}{T^{1/4}}\right] \qquad (5)$$

Here, T_V is a temperature associated with variable range hopping, and is very nearly 11604 K. Here, σ is independent of trap depth, and is nearly the same for all materials. Of special interest is the temperature at which the dependence changes from hopping to variable range behavior, which we will call T_{cr}. The temperature dependence of conductivity with temperature is thus complex, and can be visually represented in Figure 1:

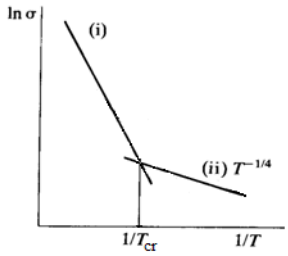

Figure 1. Theoretical dependence of conductivity on 1/T. (i) is the Boltzmann region, (ii) is the Mott region, and T_{cr} is the critical temperature at which transition occurs.

It is instructive to compare this theoretical behavior to that measured by Dennison et al (2009) for LDPE (Figure 2):

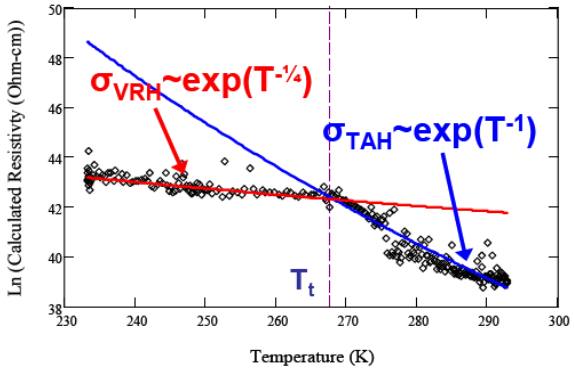

Figure 2. Measured temperature dependence of LDPE resistivity. Here, the transition temperature is T_t, the Boltzmann region is TAH, and the Mott region is VRH.

For LDPE, it can be seen that T_{cr} is about 268 K = - 5 C. For other polymers, T_{cr} is estimated to be about 235 K = - 38 C.

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

$$\sigma_{RIC} = k_{RIC}(T)\, J^{\Delta(T)}. \quad (6)$$

Recent measurements indicate that Δ is approximately one for our purposes, 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.

III. Charge and Discharge Measurements Done at MSFC

Charging and discharging measurements were done in a vacuum chamber at MSFC in September 2006 on candidate cables for the JWST telescope (Ferguson et al, 2008). Some of the wires in these cables employed Teflon insulation of 1 mil thickness (2.54×10^{-3} cm). Charging was accomplished by using a Strontium-90 (Sr-90) source, which emits a broad energy spectrum of electrons. The total current density J of electrons at the sample was 7.6×10^{-14} amps/cm^2. This is about 10^4 times less than the current density in GEO during a substorm event, but 300-1000 times greater than the average current density at L2, where JWST will orbit. For the wire in question, 610 hours of exposure in the laboratory corresponded in total fluence to about 22 years of on-orbit exposure at an energy of 100 keV. During about the first 400 volts of charging, the potential on the wire was monitored continuously in the vacuum by a non-contact electrostatic probe, which was switched out of the circuit eventually to allow arcing to happen at the higher voltages. Measurements were made with the sample both at ambient temperature (~ 20 C = 293 K) and at cryogenic temperatures (~ -183 C = 90 K). The timescales for charging and discharging were quite different at the two temperatures.

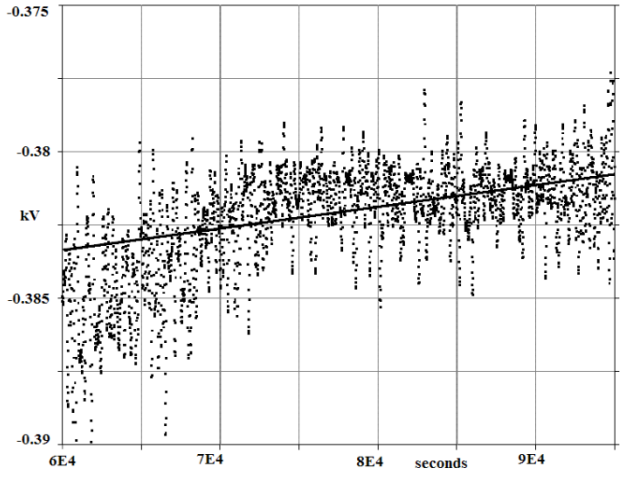

Figure 3. Discharge of 1 mil Teflon material at ambient temperatures. Solid line is an exponential fit.

In Figure 3, the discharge behavior after the source was moved away from the sample under ambient temperature conditions is shown. This type of measurement is cleaner than a charging measurement, where the charging flux is important in producing RIC. Although data were taken over a 28 hour period, we have removed the data from the first 18 hours, since this may involve the lengthy polarization period for Teflon. In addition, data at every tenth second was counted, and the data were smoothed with a Fourier filter. After this processing the data show a time constant of about 1400 hours, yielding a bulk resistivity of about 3×10^{19} ohm-cm. This is to be compared with the Dennison et al (2005) published value of 3.5×10^{19} ohm-cm. The discrepancy is small compared to the errors in the data.

From equation 3, we can use the resistivity at ambient temperatures to predict what might be the maximum voltage we might expect to achieve with our Sr-90 source. Putting in our measured resistivity and flux for a one-mil thickness, we have $V_{max} = (7.6 \times 10^{-14})(2.56 \times 10^{-3})(3.0 \times 10^{19}) = 5800$ volts. This is to be compared with the published breakdown strength of 1 mil Teflon, 6500 volts (DuPont, 2009). So, it is a good question whether with our flux we could make 1 mil Teflon insulation breakdown at ambient temperatures. As a matter of fact, testing for over 600 hours, we did not see any breakdowns at ambient temperature.

When we tested charging, we saw the behavior in Figure 4. Here, there is a significant departure from nonlinearity with time in the charging, with an exponential time constant of about 35.6 hours. Putting in κ = 2.0 (from reference above), and integrating equation 2, this corresponds to a value ρ = 7.3×10^{17} ohm-cm. This is less than even the published value in the DuPont reference (10^{18} ohm-cm), and we believe that we are seeing RIC in the charging data. If so, we can then expect that at our cryogenic temperature of 90 K, the RIC resistivity might increase by a factor of a hundred or so, and be in the range of 7.3×10^{19} ohm-cm at that temperature.

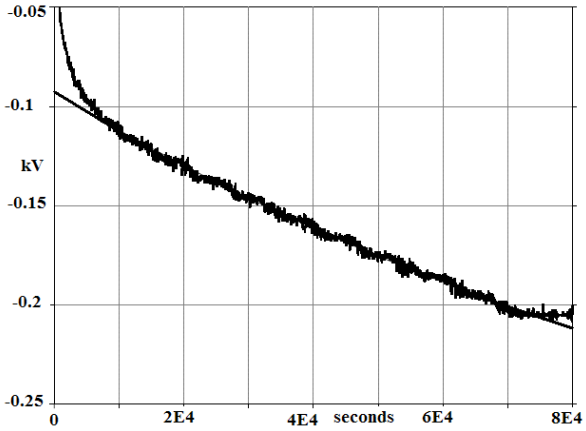

Figure 4. Charging behavior at ambient temperature. Solid line is an exponential fit. Points at beginning (polarization) and at end (retraction of source) were not included.

We also tested the charging behavior of Teflon at cryogenic temperatures (~ 90 K). In all of our tests, we saw no significant non-linearity in the charging curves with time, indicating that the effective resistivity was too great to measure. Formally fitting exponential curves to the data, we found an exponential time constant for charging of about 69

hours, yielding a formal value of resistivity of 1.4×10^{18} ohm-cm. This must be considered a lower limit, as the linear fit to the data was better than the exponential fit. It is interesting that we saw a much lower value of RIC at the cryogenic temperatures, even though our flux was identical, in keeping with our expectations above. Of further interest is the fact that our lower limit on the time constant is longer than the time constant for solar storms, so that at cryogenic temperatures, the charge built up during times of lower flux may not bleed off from RIC effects. From linear fits to the data, we saw $dV/dt = 4.7 \times 10^{-6}$ kV/sec = 17 V/hr.

In addition, after about 300 hours at cryogenic temperatures, we saw arcing in our samples. This indicates that we had reached the breakdown strength of Teflon at that point. At our charging rate above, after 300 hours, we reached about 5100 volts. This can be compared with the short-time dielectric strength of 6500 volts. As that published value is for short times only, we think the agreement is satisfactory. Dennison et al (2008) have seen breakdown in 1 mil FEP Teflon at 4540 ± 850 volts.

IV. Predictions of Dark and Radiation Induced Conductivity

Taking T_{cr} for Teflon to be 235 K, and assuming the room temperature (20 C) value of ρ to be 3.5×10^{19} ohm-cm and ΔH = 1.206 eV, we can find from equations 4 and 5 the following value for the dark resistivity ρ at 90 K:

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

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

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

These values are very dependent on the values of T_{cr} and ΔH. However, they may indicate that at cold temperatures, RIC may be much more important than the hopping conductivity in determining the timescale for charge decay.

Using our "measured" value of resistivity at 90 K and assuming that this is entirely due to RIC, we can estimate the RIC conductivity at average L2 flux values. Taking 2.5×10^{18} ohm-cm to be our minimum value of ρ at 90 K (or $\sigma = 4 \times 10^{19}$ mho/cm) and a Δ of 1.0, we estimate that ρ at average L2 fluxes is $7.5\text{-}25 \times 10^{20}$ ohm-cm, giving a timescale for charge decay of at least 4-14 years.

Clearly, precise measurements of the critical parameters are needed to determine whether cryogenic dielectrics will break down over long times in space conditions. However, if it holds true that Δ = 1 at low temperatures, then from equation 3 the maximum voltage reached in a dielectric is not a function of RIC, and breakdown voltages may be achieved even at high fluxes.

V. Conclusions

Recent measurements of charging and discharging of Teflon at cryogenic temperatures are consistent with charge buildup over many years under space conditions. Radiation induced conductivity, even during brief solar substorms, seems inadequate to prevent charging from eventually reaching breakdown thresholds. New measurements of conductivity parameters and their temperature dependences are needed for typical spacecraft materials under cryogenic conditions.

The present results are important for spacecraft such as probes of the outer planets or the permanently dark cratered areas on the moon. The results will also be of interest to those who must design or operate spacecraft in more moderate cold conditions, such as lunar habitats. 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.

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. In the case of JWST, small amounts of conductive shielding will be used to prevent internal ESD on certain cables.

References

J.R. Dennison, A.R. Frederickson, N.W. Green, C.E. Benson, J. Brunson and P. Swaminanthan, 2005, "FEP- Teflon Full Mcd rept.pdf, *Measurement of Charge Storage Decay Time and Resistivity of Spacecraft Insulators*," in **The Charge Collector**, a NASA SEE Program Publication, Jan. 31, 2005, http://see.msfc.nasa.gov/.

J.R. Dennison, 2006, "Study of High Resistivity Materials Used for JWST at Low Temperatures," James Webb Space Telescope Architecture Working Group, July 24, 2006.

J.R. Dennison et al, 2008, "Temperature, Electric Field and Dose Rate Dependence of the Conductivity of Highly Resistive Materials for Use on the James Webb Space Telescope, Part II: Methods, Models, Errors and Limits of Validity," JWST Spacecraft Charging Working Group Meeting, Feb. 15, 2008.

J.R. Dennison, A. Sim, J. Brunson, J. Gillespie, S. Hart, and J. Dekany, C. Sim and D. Arnfield, 2009, "Engineering Tool for Temperature, Electric Field and Dose Rate Dependence of Low Conductivity Spacecraft Materials," presentation and paper, 47th AIAA Aerospace Sciences Meeting Including The New Horizons Forum and Aerospace Exposition, 5 - 8 January 2009, Orlando, Florida, AIAA 2009-562.

DuPont, 2009, Technical Bulletin H55008, http://www2.dupont.com/Teflon_Industrial/en_US/assets/downloads/h55008.pdf

D.C. Ferguson, T.A. Schneider, and J.A. Vaughn, 2007, "Arc Testing of a Mockup Cable in a Simulated Space Radiation Environment," 45th AIAA Aerospace Sciences Meeting, Reno, NV, Jan. 8-11, 2007. AIAA Paper # 2007-95.

D.C. Ferguson, T.A. Schneider, and J.A. Vaughn, 2008, "Effects of Low Temperature on Charging of Spacecraft Dielectrics," 46th AIAA Aerospace Sciences Meeting and Exhibit, Reno, Nevada, Jan. 7-10, 2008, AIAA-2008-449.

NASA-HDBK-4002, 1999, *Avoiding Problems Caused by Spacecraft On-Orbit Internal Charging Effects*, p. 9.

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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

$$\tau = \varepsilon_o \kappa \rho$$

Here, τ is the 1/e time constant, ε_o 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 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, $R = \rho d/A$, where ρ is the total resistivity, d is the thickness of the film, and A is the area. $\rho = 1/\sigma$, where σ is the bulk conductivity, so

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

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

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

At the maximum voltage V_{max}, $dQ/dt = 0$, so $J - V\sigma/d = 0$, and

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

We may expect that if $E = J/\sigma > E_{ds}$, 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):

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

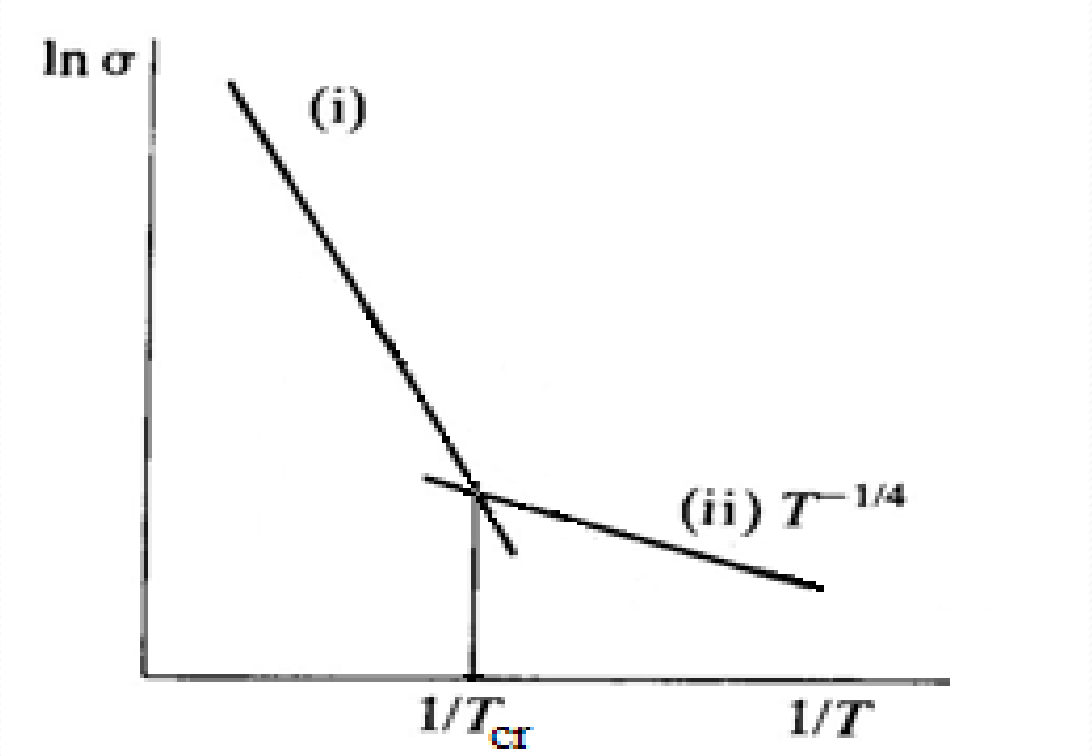
- This trap depth is highly material dependent. For example, Dennison et al (2008) gives the trap depth for Kapton HN as 0.056 eV. For FEP Teflon, he gives ΔH = 1.206 eV. This means that the temperature dependence of conductivity for FEP Teflon is much greater than for Kapton HN.
- As an example, it 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):

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

THEORY OF TEMPERATURE DEPENDENCES (3)

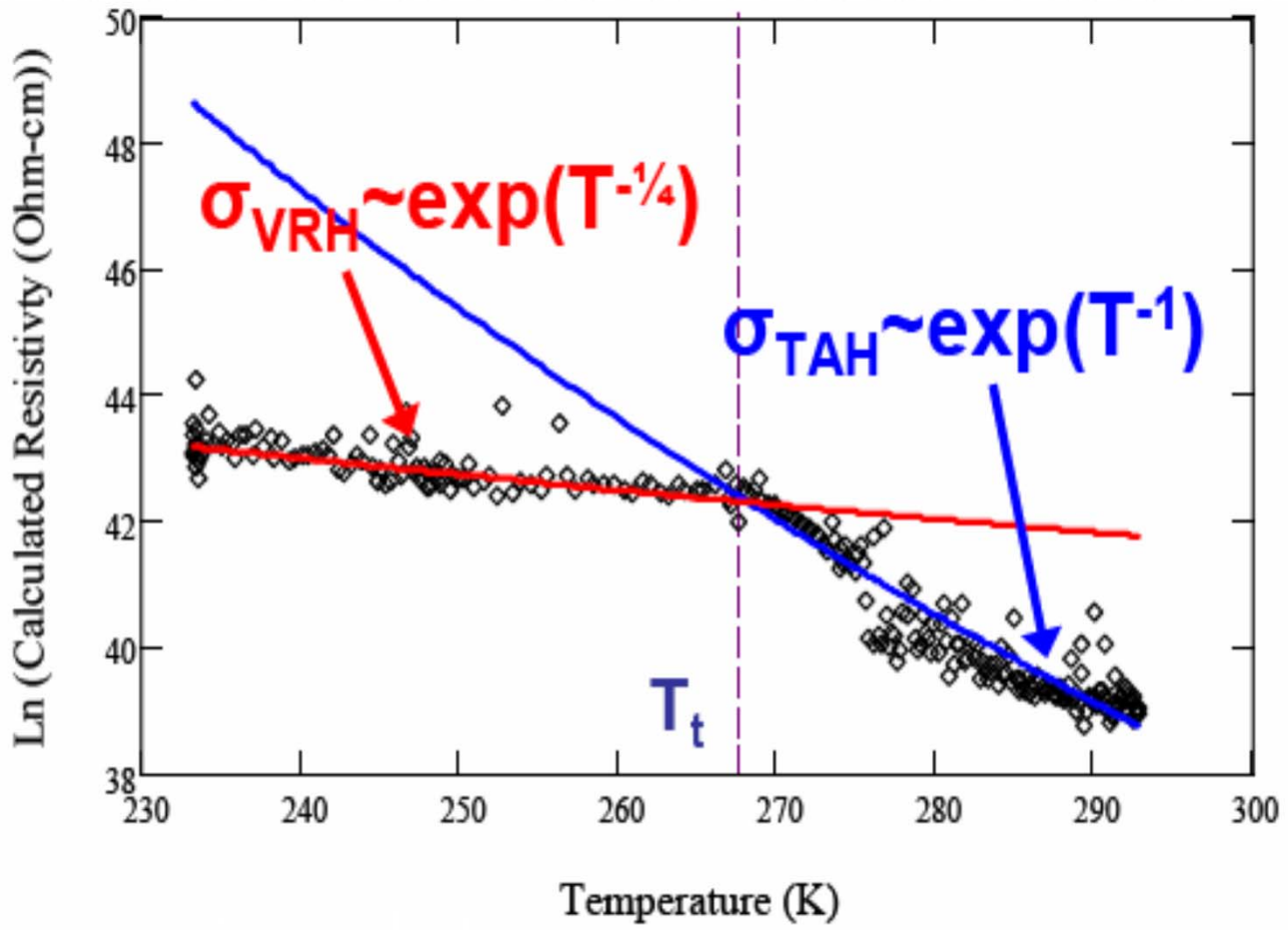


Theoretical dependence of conductivity on 1/T.

(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)

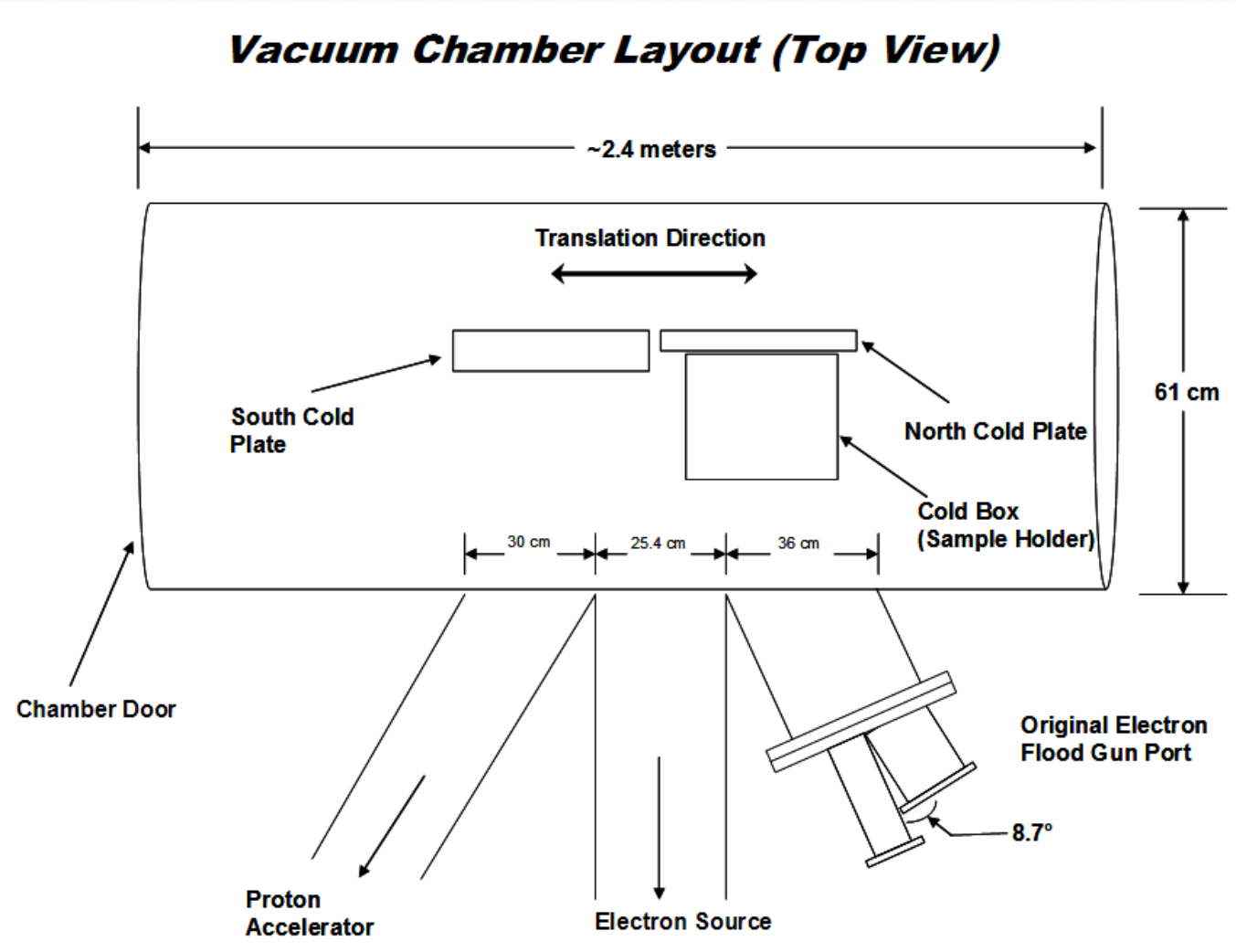
• Radiation Induced Conductivity (RIC) is a complicated matter. Standard theories of RIC predict (Dennison, 2009, presentation) that

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

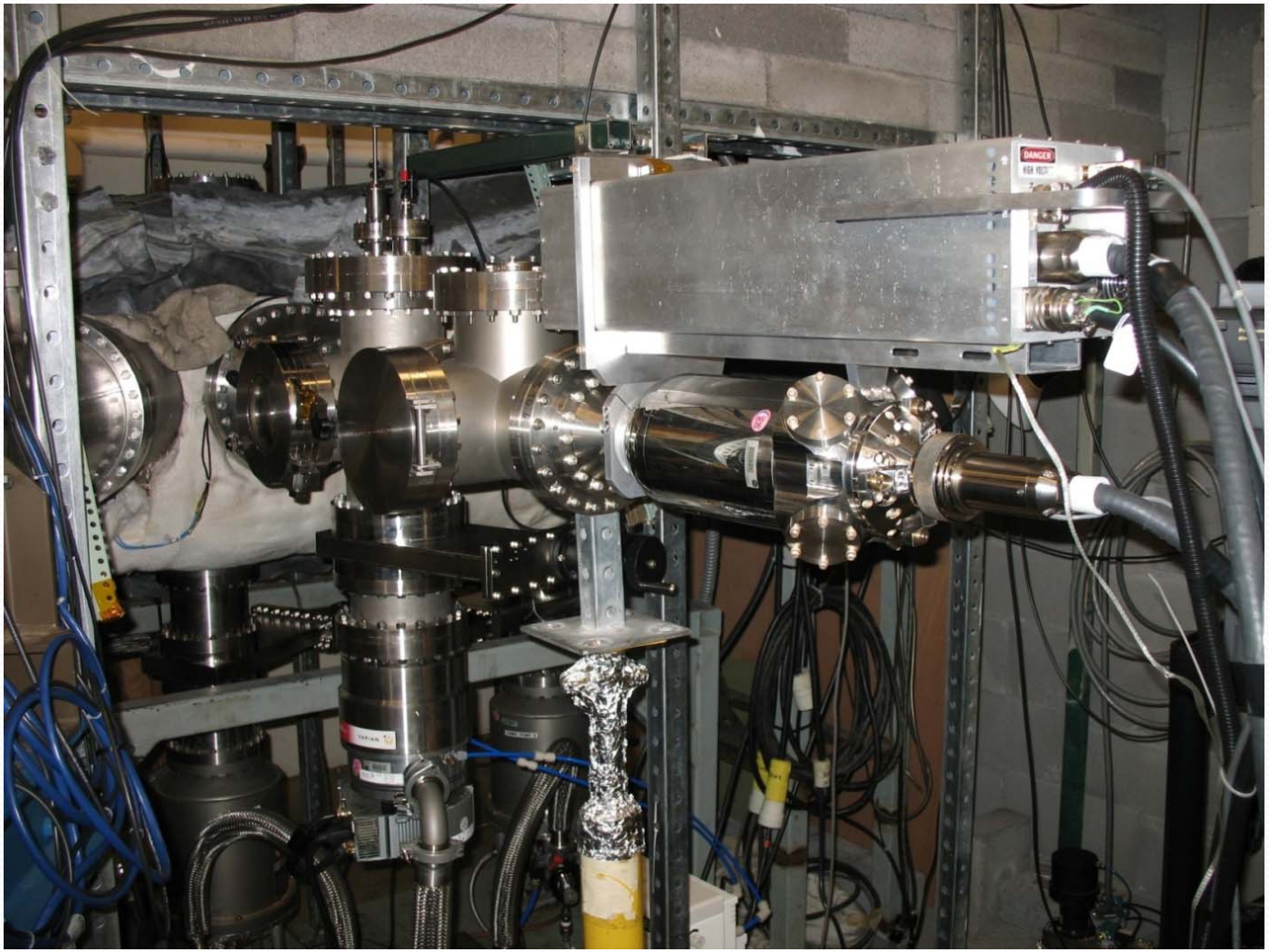
• Recent measurements indicate that $\Delta \approx 1$, and does not depend greatly on temperature. However, k_{RIC} may decrease by two orders of magnitude between room temperature and 90 K for some polymers.

CHARGE AND DISCHARGE MEASUREMENTS

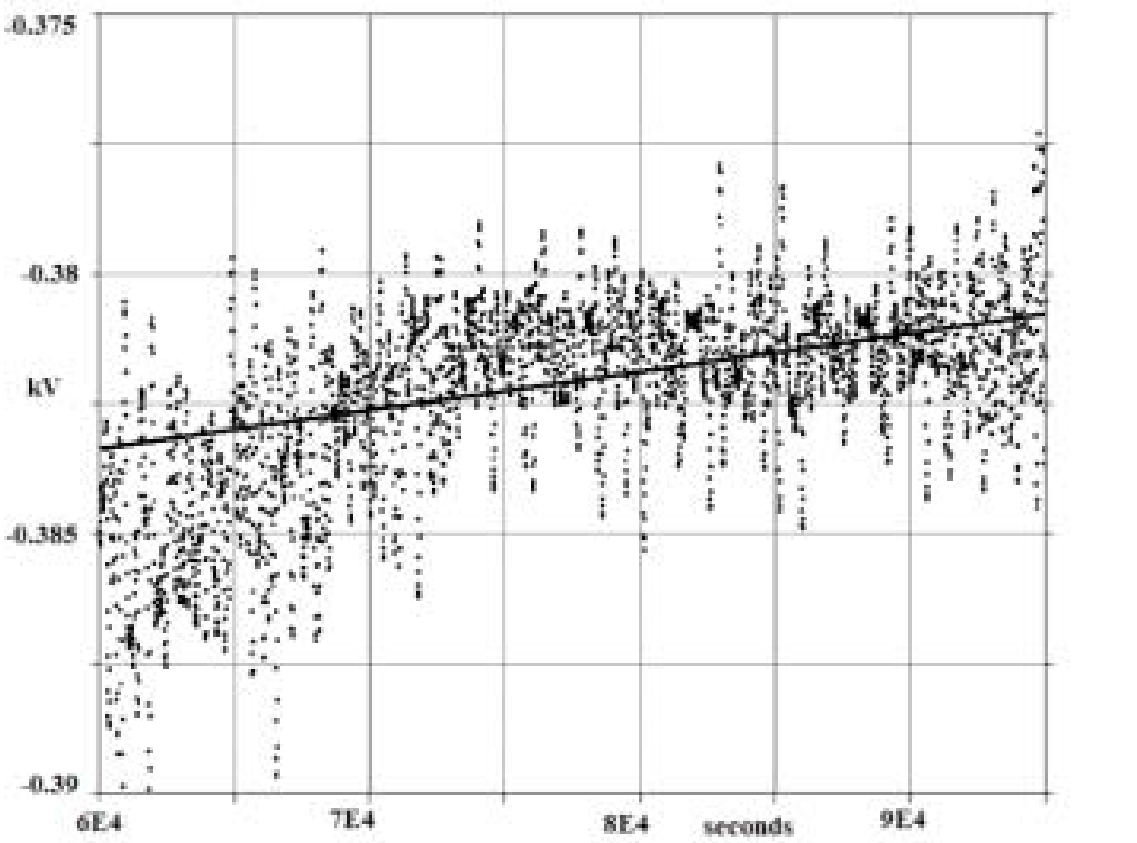
DONE AT MSFC



CHARGE AND DISCHARGE MEASUREMENTS DONE AT MSFC (2)

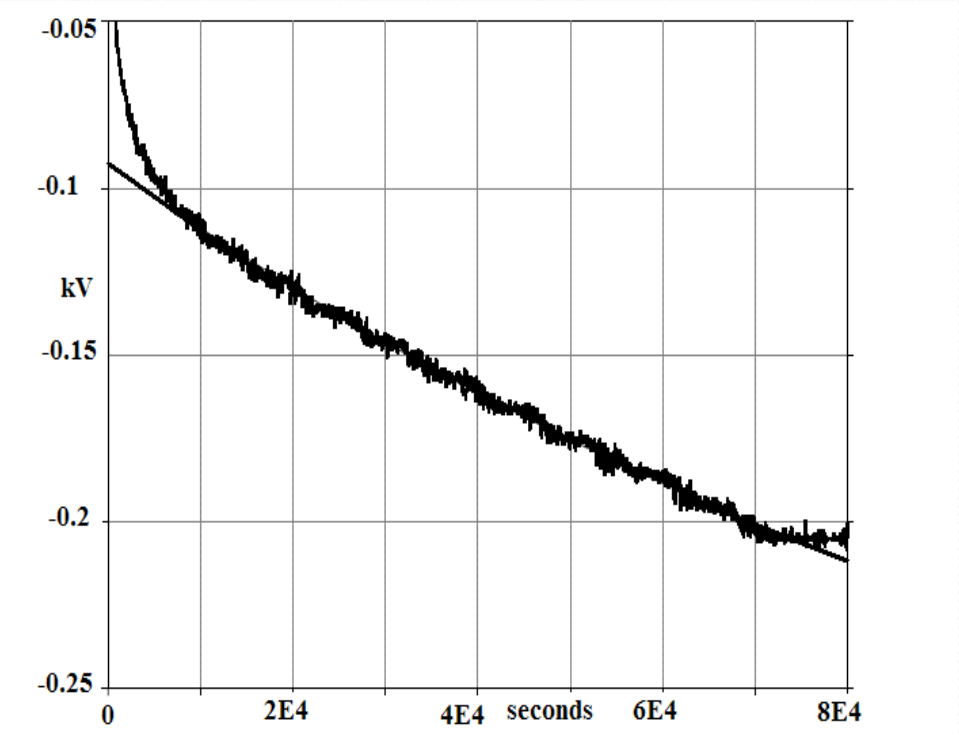


CHARGE AND DISCHARGE MEASUREMENTS DONE AT MSFC (3)



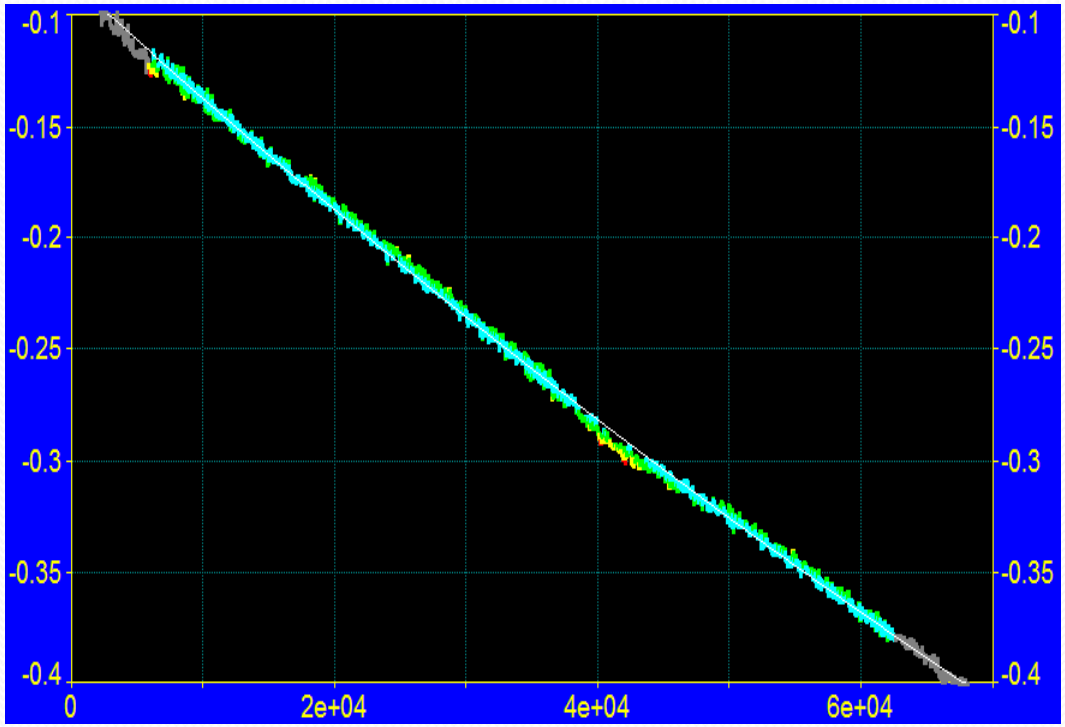
Discharge of 1 mil Teflon material at ambient temperatures. Solid line is an exponential fit. Formal τ = 1400 hours, yielding a formal bulk resistivity of about 3 x 10^{19} ohm-cm. This is to be compared with the Dennison et al (2005) published value of 3.5 x 10^{19} ohm-cm.

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 τ = 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:

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

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

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

- 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 $\rho > 2.5 \times 10^{18}$ ohm-cm at 90 K ($\sigma < 4 \times 10^{19}$ mho/cm) and $\Delta = 1.0$, we estimate that at average L2 fluxes

$$\rho = 7.5\text{-}25 \times 10^{20} \text{ ohm-cm, or}$$

$$\boldsymbol{\tau = 4 - 14 \text{ years.}}$$

- If it holds true that $\Delta = 1$ at low temperatures, from

  $\mathbf{V_{max} = Jd/\sigma}$ and $\mathbf{\sigma_{RIC} = k_{RIC}(T)\, J^{\Delta}(T)}$ then $\mathbf{V_{max} = d/k_{RIC}(T)}$.

- This maximum voltage reached in a dielectric is not a function of RIC, 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.

References

- J.R. Dennison, A.R. Frederickson, N.W. Green, C.E. Benson, J. Brunson and P. Swaminanthan, 2005, "FEP-Teflon Full Mcd rept.pdf, *Measurement of Charge Storage Decay Time and Resistivity of Spacecraft Insulators*," in **The Charge Collector**, a NASA SEE Program Publication, Jan. 31, 2005, http://see.msfc.nasa.gov/.
- J.R. Dennison, 2006, "Study of High Resistivity Materials Used for JWST at Low Temperatures," James Webb Space Telescope Architecture Working Group, July 24, 2006.
- J.R. Dennison et al, 2008, "Temperature, Electric Field and Dose Rate Dependence of the Conductivity of Highly Resistive Materials for Use on the James Webb Space Telescope, Part II: Methods, Models, Errors and Limits of Validity," JWST Spacecraft Charging Working Group Meeting, Feb. 15, 2008.
- J.R. Dennison, A. Sim, J. Brunson, J. Gillespie, S. Hart, and J. Dekany, C. Sim and D. Arnfield, 2009, "Engineering Tool for Temperature, Electric Field and Dose Rate Dependence of Low Conductivity Spacecraft Materials," presentation and paper, 47th AIAA Aerospace Sciences Meeting Including The New Horizons Forum and Aerospace Exposition, 5 - 8 January 2009, Orlando, Florida, AIAA 2009-562.
- DuPont, 2009, Technical Bulletin H55008, http://www2.dupont.com/Teflon_Industrial/en_US/assets/downloads/h55008.pdf
- D.C. Ferguson, T.A. Schneider, and J.A. Vaughn, 2007, "Arc Testing of a Mockup Cable in a Simulated Space Radiation Environment," 45th AIAA Aerospace Sciences Meeting, Reno, NV, Jan. 8-11, 2007. AIAA Paper # 2007-95.
- D.C. Ferguson, T.A. Schneider, and J.A. Vaughn, 2008, "Effects of Low Temperature on Charging of Spacecraft Dielectrics," 46th AIAA Aerospace Sciences Meeting and Exhibit, Reno, Nevada, Jan. 7-10, 2008, AIAA-2008-449.
- NASA-HDBK-4002, 1999, *Avoiding Problems Caused by Spacecraft On-Orbit Internal Charging Effects*, p. 9.