2009

Engineering Tool for Temperature, Electric Field and Dose Rate Dependence of High Resistivity Spacecraft Materials

JR Dennison  
*Utah State University*

Steven Hart  
*Utah State University*

Jodie Corbridge Gillespie  
*Utah State University*

Justin Dekany  
*Utah State University*

Charles Sim  
*Utah State University*

Dan Arnfield  
*Utah State University*

Follow this and additional works at: [https://digitalcommons.usu.edu/mp_conf](https://digitalcommons.usu.edu/mp_conf)

Part of the [Condensed Matter Physics Commons](https://digitalcommons.usu.edu/mp_conf)

**Recommended Citation**

[https://digitalcommons.usu.edu/mp_conf/31](https://digitalcommons.usu.edu/mp_conf/31)
Engineering Tool for Temperature, Electric Field and Dose Rate Dependence of Low Conductivity Spacecraft Materials

JR Dennison, Alec Sim, Jerilyn Brunson, Jodie Gillespie, Steven Hart, Justin Dekany, Charles Sim, and Dan Arnfield

Materials Physics Group
Utah State University

Study Support by NASA JWST Project

AIAA Aerospace Sciences Meeting
January, 2009
USU Materials Physics Group

Materials Physics Group
JR Dennison
Jon Abbott
Jennifer Albrecht
Jeri Brunson
Kathryn Chapman
Jodie Corbridge
Steve Hart
Josh Hodges
Ryan Hoffmann
Jake Knight
David Oliphant
Tony Thomas
Surface Voltages Predicted by Spacecraft Charging Models

SEE Handbook or NASCAP predicts on-orbit spacecraft charging in GEO and LEO environments

Materials Research

NASCAP Upgrades

Typical SEE Handbook Simulation
USU Resistivity Engineering Tool Inputs

**Mathcad - [USU Resistivity Engineering Tool Ver. 1-3]**

**USU Resistivity Calculator Engineering Tool**

This Mathcad worksheet calculates the resistivity of JWST spacecraft materials as a function of electric field (E), temperature (T), and absorbed dose rate (D) based on parameterized, analytic functions used to model an extensive data set taken by the Utah State University Materials Physics Group.

<table>
<thead>
<tr>
<th>Material</th>
<th>Electric Field</th>
<th>Temperature</th>
<th>Dose Rate</th>
<th>Sample Thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low Density Polyethylene (LDPE)</td>
<td>E_{ev} = 10^6 V m^{-1}</td>
<td>T_{ev} = 290 K</td>
<td>D_{ev} = 0.03 Rad sec^{-1}</td>
<td>d_{ev} = 25 µm</td>
</tr>
<tr>
<td>Kapton HN</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kapton E</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kapton FN (G18)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PFA (Teflon)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>EPR (Teflon)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PTFE (Teflon)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FEP (Teflon)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ECTFE (expanded PTFE or CORELon)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ETFE, (Teeflon)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**List Materials Related Properties Used in Resistivity Calculations**

- **Material name:** Material.name = "Kapton HN (Kapton)"
- **Relative dielectric constant:** ε_r = 3.400
- **Density:** ρ_{den} = 1.42 gm cm^{-3}
- **Electrostatic breakdown field strength and voltage:** E_{esd} = 2700 × 10^6 V m^{-1}, V_{esd} = E_{esd} d_{ev} = 6750 V
- **Fraction of breakdown voltage applied:** F_{ev}/E_{esd} = 1 = 0.37%
# USU Resistivity Engineering Tool Inputs

## Resistivity Database Master Parameter List

### Excel File

<table>
<thead>
<tr>
<th>Material Index</th>
<th>Material</th>
<th>Thermally Activated Hopping Conductivity</th>
<th>Variable Range Hopping Conductivity</th>
<th>Radiation Induced Conductivity</th>
<th>$T_{cr}$ (Low E)</th>
<th>Materials</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$\sigma_{TA,0}$</td>
<td>$T_A$</td>
<td>$E_A$</td>
<td>$\gamma_{PF}$</td>
<td>$\sigma_{VRH,0}$</td>
</tr>
<tr>
<td>1</td>
<td>LDPE</td>
<td>8.00E-08</td>
<td>8860.00</td>
<td>9.52E-08</td>
<td>0.00</td>
<td>1.00E-10</td>
</tr>
<tr>
<td>2</td>
<td>Kapton HN</td>
<td>2.50E-19</td>
<td>650.00</td>
<td>1.50E-08</td>
<td>0.00</td>
<td>1.00E-40</td>
</tr>
<tr>
<td>3</td>
<td>Kapton E</td>
<td>1.10E-17</td>
<td>1800.00</td>
<td>3.80E-08</td>
<td>0.00</td>
<td>1.00E-40</td>
</tr>
<tr>
<td>4</td>
<td>Kapton FN</td>
<td>1.00E-18</td>
<td>1225.00</td>
<td>2.60E+08</td>
<td>0.00</td>
<td>1.00E-40</td>
</tr>
<tr>
<td>5</td>
<td>PFA (Teflon)</td>
<td>3.00E-01</td>
<td>14000.00</td>
<td>5.00E+80</td>
<td>0.00</td>
<td>1.00E-40</td>
</tr>
<tr>
<td>6</td>
<td>FEP (Teflon)</td>
<td>3.00E-01</td>
<td>14000.00</td>
<td>5.00E+80</td>
<td>0.00</td>
<td>1.00E-40</td>
</tr>
<tr>
<td>7</td>
<td>PTFE (Teflon)</td>
<td>3.00E-01</td>
<td>14000.00</td>
<td>5.00E+80</td>
<td>0.00</td>
<td>1.00E-40</td>
</tr>
<tr>
<td>8</td>
<td>ePTFE (Gortex)</td>
<td>3.00E-01</td>
<td>14000.00</td>
<td>5.00E+80</td>
<td>0.00</td>
<td>1.00E-40</td>
</tr>
<tr>
<td>9</td>
<td>ETFE (Tefzel)</td>
<td>3.00E-01</td>
<td>14000.00</td>
<td>5.00E+80</td>
<td>0.00</td>
<td>1.00E-40</td>
</tr>
</tbody>
</table>
USU Resistivity Engineering Tool Outputs

Total Resistivity and resistivity contributions from each mechanism:

\[
\rho_{\text{Tot}} = \sigma_{\text{Tot}}(E_v, T_v, D_v, \sigma_{\text{TAHo}}, E_A, T_A, \gamma_{PF}, \varepsilon_r, \sigma_{\text{VRHo}}, E_o, T_o, k_0, k_1, \Delta_1)^{-1} = 8.159 \times 10^{15} \, \Omega \cdot \text{cm}
\]

TAH:
\[
\rho_{\text{TAH}} = \sigma_{\text{TAH PF2}}(E_v, T_v, \sigma_{\text{TAHo}}, E_A, T_A, \gamma_{PF}, \varepsilon_r)^{-1} = 5.813 \times 10^{16} \, \Omega \cdot \text{cm}
\]

VRH:
\[
\rho_{\text{VRH}} = \sigma_{\text{VRH2}}(E_v, T_v, \sigma_{\text{VRHo}}, E_o, T_o)^{-1} = 5.549 \times 10^{18} \, \Omega \cdot \text{cm}
\]

RIC:
\[
\rho_{\text{RIC}} = \sigma_{\text{RIC}}(T_v, D_v, k_0, k_1, T_{cr}, \Delta_1)^{-1} = 9.507 \times 10^{15} \, \Omega \cdot \text{cm}
\]
Scope of USU Experimental Studies

Determine the resistivity and related materials properties of critical JWST materials over the appropriate range of environmental conditions:

- **Temperature:** \(~100\) K to 365 K
- **Electric field:** low to breakdown field (\(~3\times10^8\) V/m)
- **Radiation dose:** low dose to \(~10\) rad/sec

Appropriate theory has been used to obtain parametric fits to the data and, where necessary, extend the data to experimentally inaccessible regions.

Validity and range of the theories were determined.
Transient Currents

Temporal changes in current as sample comes to equilibrium are not considered in this study.

Polarization Current (short term—10 s to a few hrs)
Diffusion Current (long term—10 min to a few days)
RIC Measurements

- Designed and built an entirely new test system
- Characterized instrumentation and methods
- Used standard model for RIC, augmented with T-dependent k and Δ

- Determined k and Δ for JWST materials over range of dose rates encountered by JWST
  - Measurements made from ~0.01 to ~10 rad/s

- Determined T dependence of k and Δ for JWST materials
  - Measurements made from ~105 K to ~335 K
Electrostatic Breakdown (ESD) Measurements

- Extensive room T measurements (5-20 per material)
- Limited studies completed at $T < T_{rm}$, down to $\sim 140$ K.
- Limited studies completed on endurance (ramp rate) testing

Breakdown fields were mid-$10^7$ V/m to mid-$10^8$ V/m for all materials, except ePTFE.

- Typical results have 10% to 30% variation in $V_{esd}$.

- Typically measured results 10-25% higher than manufacturer’s values. Attributed to slower ramp rate and dry samples.

- Found modest dependence on ramp rate.
Conductivity Mechanisms

Engineering tool considers three conductivity mechanisms.

TAH and VRH depend on $F$ and $T$

RIC depends on $D$ and $T$

$$\sigma_{Total}(F,T,\dot{D}) = \sigma_{TAH}(F,T) + \sigma_{VRH}(F,T) + \sigma_{RIC}(D,T)$$
Conduction Models

Model: T and E Dependence of DC Conductivity

Intrinsic SC  RIC  TAH  VRH
Thermally Activated Hopping Conductivity

**TAH theory is based on thermally assisted quantum tunneling from adjacent trap sites of a single well depth and separation.**

*An E-field favors one direction of motion over another, leading to sinh behavior:*

\[
\sigma_{TAH}(F,T) = \left[ \frac{2N(T)\nu_{TAH} a q_e}{F} \right] \exp \left[ -\frac{\Delta H}{k_B T} \right] \sinh \left[ \frac{a q_e F}{k_B T} \right] = \left\{ \sigma_{TAHo}(T) \left( \frac{T_A}{T} \right) Z_A(\beta_A) \exp \left( -\frac{T_A}{T} \right) \right\}
\]

\[
\beta_A \equiv \frac{4F T_A}{3F_A T} = \frac{q_e F a}{k_B T} \quad \text{with} \quad Z_A(\beta_A) \equiv \frac{1}{\beta_A} \sinh(\beta_A)
\]

**Reduced fitting parameters**

\[
\sigma_{TAHo}(T) \equiv 2 N(T) \nu_{TAH} q_e^2 a^2, \quad T_A \equiv \frac{\Delta H}{k_B} \quad \text{and} \quad F_A \equiv \frac{4\Delta H}{3q_e a}
\]
Temperature and electric field dependence of thermally activated hopping conductivity. (a) Temperature dependence with electric fields of $1\cdot10^7$ V/m (purple), $5\cdot10^7$ V/m (blue), $1\cdot10^8$ V/m (green), $2\cdot10^8$ V/m (orange) and $3\cdot10^8$ V/m (red). (b) Electric field dependence with temperatures of 150 K (purple), 250 K (blue), 300 K (green), 350 K (orange) and 400 K (red). Curves are based on Eq. (2). To approximately match LDPE data we have set $\sigma_{TAHo}=1.4\cdot10^{-10}$ ($\Omega$-cm)$^{-1}$ and $FA=9.5\cdot10^8$ V/m for $TA=6626$ K. FESD is $\sim3\cdot10^8$ V/m.
Conduction Models

Model: T and E Dependence of DC Conductivity

![Diagram of conduction models](image-url)
Theory of Thermally Activated Hopping Conductivity

Theory of thermal assisted hoping conductivity provides a model for the temperature and electric field dependence of the conductivity of polymers:

\[
\sigma_{TAH}(F,T) = \left[ \frac{2N(T)\nu_{TAH} a q_e}{F} \right] \exp \left[ -\frac{\Delta H}{k_B T} \right] \sinh \left[ \frac{a q_e F}{k_B T} \right] = \left\{ \sigma_{TAH_0}(T) \left( \frac{T_A}{T} \right) Z_A(\beta_A) \exp \left( -\frac{T_A}{T} \right) \right\}
\]

\[
\sigma_{TAH_0}(T) \equiv 2 \ N(T) \nu_{TAH} q_e^2 a^2, \quad T_A \equiv \Delta H / k_B \quad \text{and} \quad F_A \equiv 4\Delta H / 3q_e a
\]
E-field Dependence of TAH

Note divergence at $E_{ESD}$
**Variable Range Hopping Conductivity**

Variable range hopping model of Mott and Davis (as extended by Huges and Apsley for E-field dependence), allows hopping at a range of distances over a distribution of trap energy states:

Theory leads to “$T^{1/4}$” behavior

$$\sigma_{\text{VRH}}(F,T) = \left\{ \sigma_{\text{VRHo}}(T) \left( \frac{T_v}{T} \right)^{1/4} \right\} Z_{V1}(\beta_v) \exp \left[ \left( -\frac{T_v}{T} \right)^{1/4} Z_{V2}(\beta_v) \right]$$

$$\beta_v \equiv 4 F T_v / 3 F_v T = q_e F (2\alpha)^{-1} / k_B T$$

$$Z_{V1}(\beta_v) = \left[ 2 / Z_{V0}(\beta_v) \right]^{1/4} \quad \text{and} \quad Z_{V2}(\beta_v) = \left( -\frac{1}{2\beta_v} \right) \cdot \left[ 1 + \frac{Z_{V0}(\beta_v)}{Z_{V0}(\beta_v) - \frac{3}{2} \beta_v} \right] \cdot Z_{V1}(\beta_v) \cdot$$

$$\left[ \frac{3 + \beta_v}{24 \cdot (1 + \beta_v)^3} - \frac{1}{8} - \frac{\beta_v}{3} \right] \cdot \frac{2 + \beta_v}{6 \cdot (1 + \beta_v)^2} + \frac{1 + \frac{1}{3} \beta_v}{2}$$

with  

$$Z_{V0}(\beta_v) = \frac{\left( 1 + \frac{\beta_v}{2} \right)}{(1 + \beta_v)^2} \left[ 1 + \frac{3}{2} \beta_v \right]$$

Reduced fitting parameters

$$\sigma_{\text{VRHo}}(T) = 2 N_{E_F} \nu_{\text{VRH}} q_e^2 / (2\alpha)^2, \quad T_v \equiv 3 (2\alpha)^3 / N_{E_F} \pi k_B \quad \text{and} \quad F_v \equiv 4 (2\alpha)^4 / N_{E_F} \pi q_e$$
Temperature and electric field dependence of variable range hopping conductivity. (a) Temperature dependence with electric fields of $1 \cdot 10^7$ V/m (purple), $5 \cdot 10^7$ V/m (blue), $1 \cdot 10^8$ V/m (green), $2 \cdot 10^8$ V/m (orange) and $3 \cdot 10^8$ V/m (red). (b) Electric field dependence with temperatures of 50 K (purple), 100 K (blue), 150 K (green), 200 K (orange) and 300 K (red). Curves are based on Eq. (4). To approximately match LDPE data we have set $\sigma_{\text{VRH}_0}=1.0 \cdot 10^{-10} (\Omega\cdot\text{cm})^{-1}$ and $F_V=6.9 \cdot 10^{13}$ V/m for $T_V=1.0 \cdot 10^8$ K.
Conduction Models

Model: T and E Dependence of DC Conductivity

VRH
Temperature Dependence of TAH and VRH

\[
\sigma_{\text{VRH}} \sim \exp(T^{-1/4})
\]

\[
\sigma_{\text{TAH}} \sim \exp(T^{-1})
\]

Note change in slope for transition from TAH to VRH.

This occurs near a beta structural phase transition.
Fit for RIC

Basic theory for RIC follows from the Rose, Fowler, Vaiserberg for radiation assisted thermal hopping from a distribution of multiple trap sites

**The key power law relation has T dependant coefficients $k_{RIC}$ and $\Delta$**

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

$$\Delta(T) = \left[1 + \frac{T}{T_{RIC}} \right]^{-1}$$

$$k_{RIC}(T) = q_e \mu_o \left[ \frac{\rho_m}{s \Sigma n_o T_{RIC}} \left( \frac{m_e^*}{3k_B T} \right)^{1/2} \right]^{\Delta(T)} \left[ 2 \left( \frac{\sqrt{m_e^* m_h^*} k_B T}{2 \pi \hbar^2} \right)^{3/2} \right]^{1-\Delta(T)} = k_{RICo} \cdot k_{RIC1}^{\Delta(T)/T_{RIC}} \left[ T / T_{RIC} \right]^{3/2 - 2 \Delta(T)/T_{RIC}}$$

with $k_{RICo} = \left[ \frac{q_e \mu_o}{\pi \sqrt{2 \pi} \hbar^3} \left( \frac{m_e^* m_h^*}{k_B T_{RIC}} \right)^{3/4} \right]$ and $k_{RIC1} = \left[ \frac{\pi \sqrt{2 \pi} \rho_m k_B \hbar^3}{\sqrt{3} s \Sigma n_o} \left( \frac{m_e^* m_h^*}{k_B T_{RIC}} \right)^{3/4} \right]$
Temperature dependence of the RIC parameters. (a) Proportionality constant, $k_{RIC}$, based on Eq. (8). (b) RIC power, $\Delta$, based on Eq. (7). Values shown are for TRIC set to 200 K (purple), 400 K (blue), 600 K (green), 800 K (orange) and 1000 K (red). To approximately match LDPE data we have set $k_{RIC0}=1.8\cdot10^{-14}$ (\(\Omega\cdot\text{cm-Rad/sec}\))-1 and $k_{RIC1}=4.6\cdot10^{-5}$ for TRIC=600 K.
Conduction Models

Model: T and E Dependence of DC Conductivity

RIC
What IS Radiation Induced Conductivity (RIC)

Theoretical Model: T and D Dependence of RIC

Uniform Trap Density

\[ \Delta(T) \rightarrow 1 \]

\[ k(T) \rightarrow k_{RIC0} \]

Exponential Trap Density

\[ \Delta(T) \rightarrow \frac{T_c}{T + T_c} \]

\[ k(T) \rightarrow k_{RIC1} \left[ 2 \left( \frac{m_e k_B T}{2 \pi \hbar^2} \right)^{3/2} \left( \frac{m_e^* m_h^*}{m_e m_e} \right)^{3/4} \right]^\frac{T}{T + T_c} \]

\[ \sigma_{RIC}(T, D) = k_{RIC}(T) \cdot D^{\Delta(T)} \]
Comparison of RIC at Various T

![Graph showing comparison of RIC at various temperatures.](image)
Comparison of RIC at Various T
Comparison of RIC at Various T

![Graph showing comparison of RIC at various temperatures.](image-url)
In real time, when the radiation is turned on, a finite period is required for the measured conductivity to approach the radiation induced conductivity.

Similarly, when the radiation is turned off, the measured conductivity also takes a finite amount of time to decay down to the material’s initial conductivity.
Electrostatic Breakdown Theory

Based on the thermodynamic model for ESD

From an expression for bond disruption, from an expression for charge mobility similar to the TAH model, we get

\[
1 = \left( \frac{k_B T}{h/t_{en}} \right) \exp\left[ -\frac{\Delta G}{k_B T} \right] \sinh\left[ \frac{q_e F_{ESD} \lambda}{k_B T} \right] = \left( \frac{k_B T}{h/t_{en}} \right) \left( \frac{3}{4} \frac{F_{ESD}}{F_{A'}} \right) \frac{T_{A'}}{T} Z_{A'}(\beta_{A'}) \exp\left[ -\frac{T_{A'}}{T} \right]
\]

Reduced fitting parameters

with \quad \beta_{A'} \equiv 4F_{ESD} T_{A'}/3 F_{A'} T = q_e F_{ESD} \lambda / k_B T

\[
T_{A'} \equiv \Delta G / k_B \quad \text{and} \quad F_{A'} \equiv \Delta G / \frac{3}{4} q_e \lambda \rightarrow \frac{3}{4} F_{ESD}
\]

Finally, an expression for breakdown field strength in terms of endurance time and the fitting parameters:

\[
F_{ESD} = \left[ \frac{k_B T}{q_e \left( \frac{3}{4} \lambda \right)} \right] \csc h^{-1} \left[ \left( \frac{h/t_{en}}{k_B T} \right) \exp \left( -\frac{\Delta G}{k_B T} \right) \right] = \left( \frac{3}{4} \frac{F_{A'}}{T_{A'}} \right) \csc h^{-1} \left[ \left( \frac{h/t_{en}}{k_B T} \right) \exp \left( -\frac{T_{A'}}{T} \right) \right]
\]
Temperature dependence of the electrostatic field breakdown strength. (a) Endurance, or time to breakdown, a function of applied electric field, based on Eq. (9). Curves shown are for temperature set to 150 K (purple), 200 K (blue), 250 K (green), 300 K (orange) and 400 K (red). (b) Breakdown field strength as a function of temperature, based on Eq. (10). Curves shown are endurance times set to 100 s (purple), 102 s (blue), 104 s or 2.8 hr (green), 106 s or 11.6 days (orange) and 108 s or 3.2 yr (red). To approximately match LDPE data, we have set $FESD=9.5 \cdot 10^8$ V/m and $\Delta G'=1.22$ eV.
Representative Fitting Parameters for LDPE

Based on the best overall fits to the full data set, Using the equations above, we estimate the fitting parameters to be:

\[ \sigma_{TAHo} = 8.0 \cdot 10^{-8} \text{ } (\Omega\text{-cm})^{-1} \]
\[ E_A = 9.5 \cdot 10^8 \text{ } \text{V/m} \]
\[ T_A = 8.9 \cdot 10^3 \text{ } \text{K} \]

\[ \sigma_{VRHo} = 1.0 \cdot 10^{-10} \text{ } (\Omega\text{-cm})^{-1} \]
\[ E_V = 6.9 \cdot 10^{13} \text{ } \text{V/m} \]
\[ T_V = 1.0 \cdot 10^8 \text{ } \text{K} \]

\[ k_{RICo} = 1.8 \cdot 10^{-14} \text{ } (\Omega\text{-cm-Rad/sec})^{-1} \]
\[ k_{RIC1} = 4.6 \cdot 10^{-5} \]
\[ T_{RIC} = 600 \text{ } \text{K} \]

\[ \Delta G, \text{ of } 1.2 \text{ } \text{eV} \]
Individual Conductivity Components

LDPE Data

TAH

VRH

RIC
Figure 1. Total conductivity as a function of temperature and E-field for various absorbed dose rates. E-field and conductivity are logarithmic. (a) Low absorbed dose rate of $10^{-6}$ Rad·sec$^{-1}$. (b) Approximate average L2 absorbed dose rate of $5.4 \times 10^{-4}$ Rad·sec$^{-1}$. (c) Approximate worst case (storm) L2 absorbed dose rate of $2.7 \times 10^{-1}$ Rad·sec$^{-1}$. (d) High absorbed dose rate of $10^2$ Rad·sec$^{-1}$.
Summary

- Extensive Resistivity measurements made.
- Physics-based parameterized models determined from literature.
- New Engineering tool developed.
  - Tool capabilities are being updated.
  - Hopefully more materials will be added.
  - Looking for mechanism to distribute information.