Internal Charging: Principles, Tools and Measurements

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Electrostatic discharge (surface charging)

A significant issue in the 1970s-80s (e.g. MARECS)
Recently again a cause of problems (e.g. solar arrays)

\[ j = j_e - j_{photo} - j_{secondary} - j_{conduct} - j_i \]
BBC

Dara O’Briain’s Science Club

Deep dielectric discharge!
Internal charging and deep dielectric discharge

The plastic object has been irradiated with electrons which do not fully penetrate the width of the material.

- Electron range
- Plane of the Lichtenberg figure (tubes where plastic has vaporised)
- Exit route of discharge – i.e. of the vaporised material in plasma form
- Darkening of the plastic where ionising dose has caused discolouration
Internal charging / Deep dielectric discharge

- Generally occurs in insulating polymers, but can occur in glass
- Energetic, penetrating electrons (>100keV)
- Small currents <1pA cm$^{-2}$
- Slow charge build up (>24 hours) leading to ESD
Internal charging in space

High energy electrons from space environment

Satellite shielding

Dielectric

or

isolated conductor

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Outer belt electron intensity variation and effects on satellites

Note log scale – outer belt is highly dynamic due to buffeting by the solar wind
GEO comsat switching anomaly

Electrons are light and highly scattered within materials

Cause ionization and also deposit charge

Can be shielded out but produce penetrating secondary X-rays (or Bremsstrahlung)

If electrons are stopped in insulator they cannot easily escape
Key factors for internal charging

Space environment and space weather
Electron transport though shielding and into dielectric
Dielectric intrinsic (thermal) conductivity
Radiation induced conductivity
Charge and electric field accumulation
Breakdown strength
Breakdown propagation
Effect on circuit and component
1-D charging equation

\[ \varepsilon_0 \varepsilon_r \frac{dE(x, t)}{dt} + \sigma(x, t)E(x, t) = -J_R(x, t) \]

where:

- $E$ is electric field
- $t$ is time
- $x$ is linear position
- $\sigma$ is conductivity
- $J_R$ is radiation current (density)
- $[dJ/dx]$ is the charge deposition rate at $x$
Charging curve at given depth

At a given depth and assuming non-varying conductivity:

\[ E(t) = \frac{J_R}{\sigma} \left(1 - e^{-\frac{t}{\tau}}\right) \]

where \( \tau = \frac{\varepsilon_0 \varepsilon_r}{\sigma} \)

If \( \sigma \) is small (leading to large equilibrium E-fields) then time constant is long
Thermal / intrinsic / dark conductivity

Activation of electrons across the wide ‘band gap’

Conductivity is determined by Arrhenius-type equation

$$\sigma = \sigma_\infty \exp\left( - \frac{E_A}{kT} \right)$$

Changes rapidly with temperature

- High temperature suppresses charging effect
- Low temperature conductivity can be very small indeed

$E_A = 1.0\text{eV}$ for polythene

$E_A = 1.7\text{eV}$ for PMMA
Changes of temperature greatly affect the internal charging process
Radiation induced conductivity

Ionising dose leads to generation of additional charge carriers
Can be due to primary particles or secondary (bremsstrahlung)

\[ \sigma = \sigma_0 + k_p D^{\Delta} \]

Where \( \sigma_0 \) is the dark conductivity \((\Omega^{-1} \text{cm}^{-1})\)

\( k_p \) is the co-efficient of prompt RIC \((\Omega^{-1} \text{cm}^{-1} \text{ rad}^{-1} \text{ s})\)

\( D \) is ionising dose \((\text{rad})\)

\( \Delta \) is a dimensionless material dependent exponent \((\Delta<1)\)

\( \Delta \) is typically in range 0.6 to 1.0

RIC not a function of temperature
RIC measurements

Figure 12. Measurement of dose rate induced conductivity reported by various authors [27]
Delayed conductivity

**Transient effects**
Conductivity does not reduce to zero instantaneously after irradiation is stopped.
Tends to decay more slowly when sample has been irradiated for a long time.

**Permanent effect**
An increase in conductivity dependent on the ionising dose received.
Few reports
Would indicate that charging is less likely as mission proceeds.
ESADDC model included this effect but was difficult to get conditions where discharge was likely.
Still a research area since some polymers receive very large doses.
Field induced conductivity

Ohmic conductivity breaks down at very high field intensities

\[ \sigma(E,T) = \sigma(T) \left( \frac{2 + \cosh(\beta_F E^{1/2})}{3} \right) \left( \frac{2kT}{eE\delta} \sinh\left(\frac{eE\delta}{2kT}\right)\right) \]

where \( \beta_F = \sqrt{\frac{e^3}{\pi\varepsilon}} \), \( e \) is electron charge, \( k \) is the Boltzmann constant, \( \varepsilon \) is permittivity and \( \delta \) is an experimentally derived jump distance of 10 an
Dielectric breakdown

Electrical breakdown – avalanche effect caused by high fields (>\(10^6\) V)

- Free charge carriers are accelerated
- Lichtenberg figures generated

Deep dielectric discharge produces Lichtenberg figures in transparent materials

Inter-electrode breakdown typically at >\(3 \times 10^7\) Vm\(^{-1}\)

For internal charging, inferred that similar thresholds apply but difficult to confirm

Threshold typically taken as 1 \times 10^7\) Vm\(^{-1}\) and preferred to keep electric fields below 1 \times 10^6\) Vm\(^{-1}\) for safety
Measuring polymer conductivity

Beware of typical conductivities quoted by manufacturers

Measurements of dielectric conductivity typically quoted are usually after 60s of current flow

Current measured will decay over time due to polarisation (capacitive charging)

For internal charging, post-polarisation current is more relevant
Measuring conductivities and polymer parameters

Electron beam method (parameter selective)

- Deposit charge into material and monitor its decay
- RIC can be measured by monitoring rate of decay under fully penetrating beam (e.g. electrons)

Realistic continuous irradiations (multi-parameter measurements)

- Irradiate under various permutations of environmental conditions (high flux, low flux, high temp. low temp., high RIC, low RIC etc.)
- Creates set of simultaneous equations to solve
- Extract parameters using fitting algorithm
Realistic Electron Environment Facility

- Sr-90 beta source, 3 GBq
- High-Vacuum
- Thermal control for sample
- Well matched to GEO spectrum and intensity
- Long test are possible (weeks……months)

- Testing of components for major satellite projects
  - E.g. Galileo

![Sr-90 spectrum](image)

![90Sr spectrum](image)

![Space spectra](image)
Fluence / current threshold

Unfortunately it is not always easy to obtain necessary materials parameters

0.1 pA cm\(^{-2}\) has been established empirically as a ‘general’ charging threshold for safe use of dielectrics (or \(2 \times 10^{10}\) electrons / cm\(^2\) over 10 hours appears to be actual threshold)

[Reduced to 0.02 pA cm\(^{-2}\) below room temperature in ECSS]

Based on absorbed current (often confused with incident current)

Bodeau has suggested that this level is not always safe and that 0.01 pA cm\(^{-2}\) is more suitable
In-orbit measurements of internal charging / discharging

**US CRRES mission**
- various materials exposed in a GTO orbit (various shielding levels etc) – discharges detected and quantified

‘DDD’ experiment (ESA) – no discharges detected

**SURF (STRV and Giove-A)**
- measurement of internal charging rate behind shielding

**Van Allen probes (RBSP)**
- similar to SURF
Sample Wiring Configurations. Heavy lines are electrodes, small circles represent the 50 ohm measuring circuit, and the curly line represents leaky paint in configuration 8. Each sample is Faraday shielded from external fields by 0.2 mm aluminum on the top and 0.5 cm aluminum on the sides and bottom of its container. The feed-through [1] to the external detectors is composed of semi-insulating material which does not pulse. It is not shown in order to simplify the drawing.
IDM results

### TABLE I. DESCRIPTION OF IDM SAMPLES

\( V \text{ max} \) is the maximum pulse voltage during ground tests, CONFIG is the number in figure 1 corresponding to the geometry of electrodes and sample, and PULSE is the number of pulses accumulated in the first 220 days of IDM operations in space, 25 Jul. 90 to 2 Apr. 91. (IDM was turned off from 20 Dec. 90 to 20 Jan. 91 in eclipse during a period of weak electron fluxes.)

<table>
<thead>
<tr>
<th>CHANNEL</th>
<th>SAMPLE DESCRIPTION</th>
<th>( V \text{ max} )</th>
<th>CONFIG</th>
<th>PULSE</th>
</tr>
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<tbody>
<tr>
<td>1</td>
<td>SC18 WIRE, TYPE ET</td>
<td>1</td>
<td>1</td>
<td>10</td>
</tr>
<tr>
<td>2</td>
<td>TS TRIAX CABLE</td>
<td>5</td>
<td>5</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>MEP G10 SOLITHANE COATED ONLY</td>
<td>50</td>
<td>7</td>
<td>0</td>
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<td>4</td>
<td>FR4 FIBERGLASS, 0.317 cm</td>
<td>5</td>
<td>2</td>
<td>265</td>
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<tr>
<td>5</td>
<td>RG 316 CABLE</td>
<td>0.5</td>
<td>3</td>
<td>0</td>
</tr>
<tr>
<td>6</td>
<td>ALJAC CABLE</td>
<td>1</td>
<td>3</td>
<td>0</td>
</tr>
<tr>
<td>7</td>
<td>ALUMINA, 0.102 cm</td>
<td>40</td>
<td>6</td>
<td>0</td>
</tr>
<tr>
<td>8</td>
<td>FR4 FIBERGLASS, 0.317 cm</td>
<td>1</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>9</td>
<td>FEP TEFLOMN, 0.229 cm</td>
<td>100</td>
<td>6</td>
<td>8</td>
</tr>
<tr>
<td>10</td>
<td>FEP TEFLOMN, 0.229 cm</td>
<td>0.2</td>
<td>4</td>
<td>0</td>
</tr>
<tr>
<td>11</td>
<td>PTFE FIBERGLASS, 0.229 cm</td>
<td>1</td>
<td>4</td>
<td>0</td>
</tr>
<tr>
<td>12</td>
<td>FR4 FIBERGLASS, 0.317 cm</td>
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<td>2</td>
<td>126</td>
</tr>
<tr>
<td>13</td>
<td>FR4 FIBERGLASS, 0.317 cm</td>
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<td>6</td>
<td>0</td>
</tr>
<tr>
<td>14</td>
<td>MEP G10 SOLITHANE WITH LEAKY PAINT</td>
<td>&lt;1</td>
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<td>2</td>
<td>62</td>
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<td>PTFE FIBERGLASS, 0.229 cm</td>
<td>0.2</td>
<td>2</td>
<td>186</td>
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</table>
SURF charging current measurements in GTO

- Internal charging current vs depth measurement
- Each plate has unique energy response curve so spectrum can be obtained
- Built and flown on STRV1d
- 300g, 0.3W
SURF results

- GTO orbit
- 500 x 36,000 km
Merlin on Giove-A

Charging current (pA cm\(^{-2}\))

Proton flux / 2000 (cm\(^{-2}\) s\(^{-1}\))

Dose (krad(Si))

Internal charging (bottom plate)

Proton flux (scaled)

'6mm Al' dose

'3mm Al' dose

29/12/2005
29/02/2006
29/04/2006
29/06/2006
29/08/2006
29/10/2006
29/12/2006
28/02/2007
29/04/2007
29/06/2007
29/08/2007
29/10/2007
29/12/2007
29/02/2008
29/04/2008
Orbital regimes of concern for internal charging

NASA HDBK 40002a
Earth, Jupiter and Saturn electron belts

AE8MAX
1 MeV Integral Flux (cm$^2$-s)$^{-1}$

SATRAD Electron
1 MeV Integral Flux (cm$^2$-s)$^{-1}$

GIRE Electron
1 MeV Integral Flux (cm$^2$-s)$^{-1}$
Dielectric Internal Charging Analysis Tool

Developed around 1999 (ESA funding) to provide a fast analysis tool for engineers

Environment - FLUMIC model (new) - analytical

Electron transport – Weber & Sorensen formulae

Temperature effects

RIC/FEC

Cable and Flat geometries

Various grounding arrangements

Electric field calculated in ten layers
FLUMIC

• Empirical model developed specifically for internal charging (2000)

• Based mainly on data from SREM and GOES in 1980s and 1990s

• Give ‘worst-case’ 1-day flux envelope as function of:
  – B
  – L
  – fraction of solar cycle
  – fraction of year (seasonal)

• Latest version 3.0 with flux

Figure 11. Solar Cycle variation of >2MeV electron flux for 1986-2003, normalised to GOES-7 fluxes at L=6.6, plotted against solar cycle phase (fsc). A curve encompasses almost all the enhancements.
FLUMIC 3 for outer belt

OUTER BELT \((L>2.5 \, R_e)\)

\(>2\text{MeV Flux at } L=6.6 \, R_e\)

The peak integral flux above 2 MeV at \(L=6.6\) is taken to be \(8 \times 10^8 \, \text{m}^{-2} \, \text{s}^{-1} \, \text{sr}^{-1}\).

**Solar Cycle**

\[ F(fsc) = 8 \times 10^8 \{0.625 + 0.375 \sin[2\pi (fsc-0.7)] + 0.125 \sin[4\pi (fsc-0.15)]\} \]

where \(fsc\) is the solar cycle phase starting at solar minimum.

**Season**

\[ F(foy, fsc) = F(fsc) \{0.625 - 0.375 \cos[4\pi (foy+0.03)] - 0.125 \cos[2\pi (foy+0.03)]\} \]

where \(foy\) is the fraction of year starting from 1\(^{st}\) January.

**Spectrum**

\[ F(E) = F(>2\text{MeV}) \times \exp[(2-E)/E_0] \]

where

\[ E_0 = 0.25 \quad \text{for } F(>2\text{MeV}) < 10^7 \, \text{m}^{-2} \, \text{s}^{-1} \, \text{sr}^{-1}. \]

\[ E_0 = 0.25 + 0.11((\log[F(>2\text{MeV})] - 7)^{1.3}) \quad \text{for } F(>2\text{MeV}) > 10^7 \, \text{m}^{-2} \, \text{s}^{-1} \, \text{sr}^{-1}. \]

\(E_0\) in the outer belt is the subject of ongoing study and so this aspect of the model may be updated before the model is finalised.

**Flux versus \(L\) profile**

\[ F(E,L) = F(>E,6.6) \times 16 \tanh[0.6(L-2.5)]/\cosh[1.5(L-4.3)] \, \text{m}^{-2} \, \text{s}^{-1} \, \text{sr}^{-1} \]

where \(F(>E,6.6) = F(foy, fsc) \times \exp[(2-E)/E_0]. \)
Comparison of Giove-A data with DICTAT

1.5mm Al shield, 1.0mm Al collector plate

![Graph showing daily averaged charging current (pA/cm²) and smoothed sunspot number over time from 01 Dec 2005 to 02 Jun 2010. The graph includes lines for charging current (1.5mm shield, 1.0mm collector), Flumic plate 3, and smoothed sunspot number.](image-url)
Internal charging at Jupiter

Copious energetic electrons (up to 100 MeV?)
- Order of magnitude more intense at peak of the belt compared to Earth

Potential for very low temperatures in parts of spacecraft

Hard spectrum leads to increased RIC (good)

Voyager and Galileo suffered upsets anomalies attributed to internal charging
JUICE – the European mission to Jupiter

ESA L-class science mission under Cosmic Vision programme

JUICE - Jupiter Icy Moons Explorer

Launch 2022, arrives at Jupiter 2030

Will spend nearly a year in orbit around Ganymede making remote observations of the surface

Also flypasts of Europa and Callisto

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Fig. 1. Charging current versus shielding depth for a planar Aluminium shield as calculated by Mulasis [14]. The FLUMIC model [6] is used to provide a worst case geostationary environment and is compared with a worst-case Jovian environment. Dotted and dashed lines show NASA handbook and ECSS standard critical currents.
Higher energies

- Weber range formula replaced by Tabata (up to 30MeV)

Improved ‘straggling’ approximation

Non-Al shielding (e.g. Ta)

Fig. 9. DICTATv4 calculation of maximum electric field as function of shielding thickness for FR4.

*Rodgers et al, IEEE RADECS, 2011*
On-going challenges

• Long term behaviour of dielectrics in space
• Some materials may have very long time constants (months, years)
  – 0.01 pA cm\(^{-2}\) rather than 0.1 pA cm\(^{-2}\) safe level?
• In-orbit validations still very sparse
• Extreme space weather (Carrington event)
• 3D modelling
• Discharge trigger events – e.g. cosmic rays?
• Jupiter!
Key references

Standards:

- NASA HDBK 4002A Mitigating In-Space Charging Effects
- ECSS-E-ST-20-06C Spacecraft Charging Standard

Book: