PREDICTION OF INTERNAL DIELECTRIC CHARGING USING THE DICTAT CODE

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ABSTRACT

An ESA study has resulted in the development of a new software tool, called DICTAT, to model internal dielectric charging in the outer radiation belt. Analytical equations are used to describe current deposition in simple structures consisting of a single dielectric plus an optional shield. A variety of grounding scenarios are permitted. The analytical approach is fast and gives charging currents to sufficient accuracy given the uncertainties in other aspects of the problem - particularly conductivity characteristics. The variation of these characteristics with temperature, electric field and dose-rate are all modelled by the code. A worst-case model of electron fluxes in the outer belt has been created specifically for the internal charging problem and is built into the code. The tool gives a YES or NO decision on the susceptibility of the structure to internal electrostatic breakdown and if necessary, calculates the required changes to the dielectric and shield thickness that would bring the structure below the breakdown threshold. A complementary programme of laboratory irradiations has been carried out to validate the tool. The results for Epoxy samples show that the code models electric field realistically for a wide variety of shields, dielectric thicknesses and electron spectra. Results for Teflon samples indicate that some further experimentation is required and the radiation-induced conductivity aspects of the code have not been validated.

1. INTRODUCTION

Electrons in the outer belt undergo frequent enhancements. Sustained periods of high flux can create high electric fields in dielectrics, leading to electrostatic breakdown. Many spacecraft anomalies have been associated with these periods.

ESA identified the need for a tool to provide the engineer with a rapid YES/NO answer to possible internal dielectric charging (IDC) problems on a spacecraft. This should cover the range of likely engineering situations such as choice of materials, geometries and shielding. It should also be able to provide the user with data on suitable additional shielding or modification of materials properties required to avoid a possible hazard.

The previously developed tool which ESA had available to analyse internal charging, ESADDC (Ref. 1), already incorporated most of the relevant physics. Some aspects, such as particle transport, were handled in a sophisticated manner which, while beneficial for scientific analysis, made the tool rather cumbersome for the engineering analysis envisaged.

The object of the study was to identify the physical equations to describe all important aspects of the internal charging problem and to incorporate them in a software tool that could be used by engineers and spacecraft designers.

2. PHYSICAL SPECIFICATION

These key elements of the physical model were identified

- Geometry - A simple 1-d model is enough to give a 1st-order solution. A single dielectric enables most sensitive structures to be analysed.
- Environment - A worst-case electron environment is required.
- Current Deposition - It is essential to calculate the currents that pass through any shielding to be deposited in the dielectric.
  - Using a Monte Carlo Method, like ESADDC
  - or analytical equations, like DICTAT
- Electric field calculation – Electric fields will vary throughout the dielectric but, in equilibrium, Ohm's law links deposited current with the maximum electric field, i.e. $E=J/\sigma$ where J is deposited current and σ is conductivity. However, as it can take days (or longer) for sensitive dielectric to reach equilibrium in a constant environment, time-dependence, particularly in an environment which changes with position, must be considered.
- Breakdown assessment – comparison of electric fields with the threshold field for breakdown tells us if breakdown is likely.

The greatest uncertainty in the above process arises due to uncertainty in the material-dependent parameters that control σ and in the breakdown threshold.

3. ENVIRONMENTAL MODEL - FLUMIC

It is necessary to have a model of those electrons which have sufficient energy to critically penetrate spacecraft surface structures. (The role of protons in the charging process is negligibly small by comparison). Mean radiation-belt models, such as AE-8, are not appropriate however.

A suitable model must reflect the characteristic time-periods over which dangerous charging levels can arise. This relates to the conductivity and permittivity of the dielectric materials involved. The FLUMIC model, which was developed for this tool, gives worst-case 1-day fluences throughout the outer belt. It was created from GOES-7 >2MeV electron flux (courtesy of NOAA/SEC) and STRV-1b REM (Ref. 2) electron data (courtesy of Paul Bühler, PSI). L-shell and Solar cycle variations of FLUMIC are shown in figures 1 and 2.

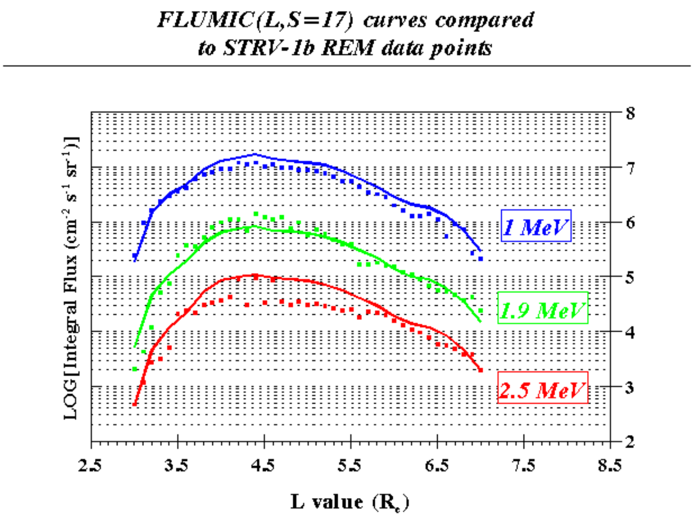

Figure 1. Comparions of FLUMIC (lines) with REM (points) for 3 energies.

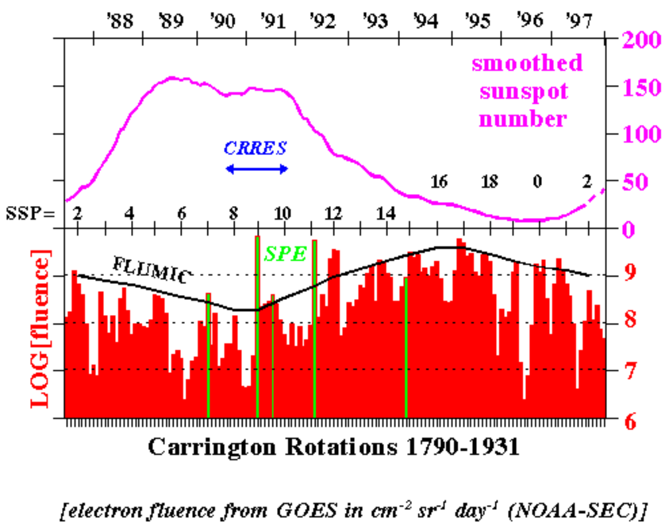

Figure 2. Comparison of FLUMIC with the maximum daily fluence in each Carrington rotation over a solar cycle.

4. ELECTRON DEPOSITION IN THE DIELECTRIC

The transport of electrons through a shield (if present) and their deposition in the dielectric is found from the distribution of electron penetration depths. This can be found to high accuracy using a Monte Carlo transport code but this takes a lot of computer time. Sufficient accuracy can be obtained using radpid analytical equations. The maximum penetration depth R can be expressed as a function of energy E (MeV) as:

$$R = 0.55.E\left(1 - \frac{0.9841}{1+3E}\right) \qquad [\text{g/cm}^2]$$

from Weber (Ref. 3).

Sorensen (Ref. 4) made the approximation that the electrons are uniformly deposited over a depth ‘a’ where:

$$a = 0.238 \times E \qquad [\text{g/cm}^2]$$

The resulting penetration profile is shown in figure 3.

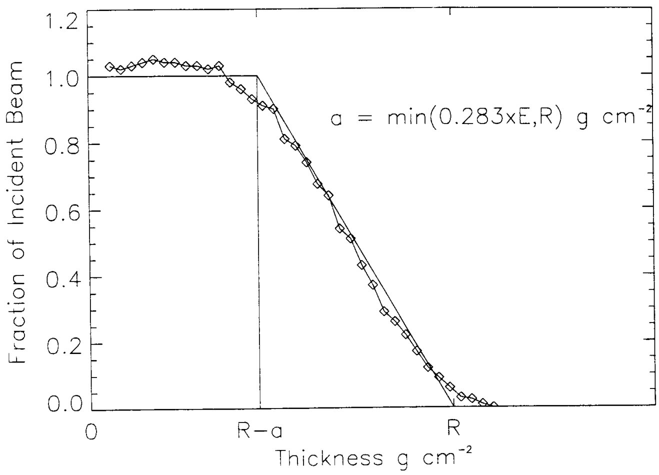

Figure 3. A comparison of electron beam penetration of Aluminium using a Monte Carlo simulation (diamonds) and DICTAT’s analytical approximation

5. CALCULATION OF MAXIMUM ELECTRIC FIELD

Since all the deposited current must, at equilibrium, flow to the ground, Ohm’s Law applies, i.e. $V=IR$, or alternatively, $E=J/\sigma$, where E is electric field and σ is conductivity. However, σ is not constant and DICTAT considers the effects on conductivity of radiation, electric field and temperature.

5.1 Radiation-Induced Conductivity

The following equation is generally used to describe the conductivity σ of irradiated polymers

$$\sigma = \sigma_o + k_p \dot{D}^{\Delta} \qquad [\Omega^{-1}\ \text{cm}^{-1}]$$

where:

σ_o is the dark conductivity [Ω^{-1} cm^{-1}]

k_p is the material-dependant co-efficient of prompt radiation induced conductivity [Ω^{-1} cm^{-1}rad^{-1} s]

Δ is a dimensionless material-dependent exponent

Because energy loss is almost independent of energy, it is possible to calculate the dose-rate from the current J_T transmitted through the dielectric.

$$\dot{D}(x) = 1.93x10^{11}.J_T(x) \qquad [\text{Rads/s}]$$

5.2 Electric Field-Induced Conductivity

The Adamec & Calderwood relation (Ref. 5) between electric field E (V/m) and conductivity is:

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

where E is electric field, $\beta_F = \sqrt{\frac{e^3}{\pi\varepsilon}}$, δ is jump distance, ε is permittivity and e is the charge on an electron. This formula is theoretical, except that δ was chosen to fit experimental data.

5.3 Temperature

Temperature strongly affects the conductivity of dielectrics and is represented in DICTAT (after Adamec and Calderwood) thus:

$$\sigma(T) = \frac{const.}{kT}\exp\left(-\frac{E_A}{kT}\right)$$

5.4 Time Dependence

A planar dielectric resembles a parallel plate capacitor and has a characteristic time-dependence:

$$E = \frac{J}{\sigma}\left(1-\exp\frac{-t}{\tau}\right)$$

i.e. the field exponentially approaches the equilibrium electric field with a time-constant $\tau=\varepsilon/\sigma$. However, σ is not constant, as shown above.

6. BREAKDOWN THRESHOLD

The discharge mechanism is less well understood than the charging mechanism. Assessments of breakdown threshold are empirical and vary widely. The 'dielectric strength' quoted in materials data books is usually higher than the electric field that arise in space, and yet ESD occurs there. The solution is to measure the time before ESD is first observed in laboratory tests.

7. LABORATORY COMPARISONS

A series of laboratory irradiations of Epoxy and Teflon samples was carried out and the results compared to the DICTAT code. These tests used 3 thicknesses of each material and a variety of Aluminium shields and electron spectra. Materials parameters for the DICTAT simulations were initially taken from a list of typical values for various materials. Using the pre-existing estimates for σ and k_p did not result in good agreement between DICTAT and the laboratory observations. However, these two values could be found by fitting and gave good agreement over a wide range of beams and thicknesses of shields and Epoxy samples.

The results of fitting for a 1165µ Epoxy sample behind a 600µ Aluminium shield, using the 'GEODUR' realistic severe space-like spectrum are shown in figure 4.

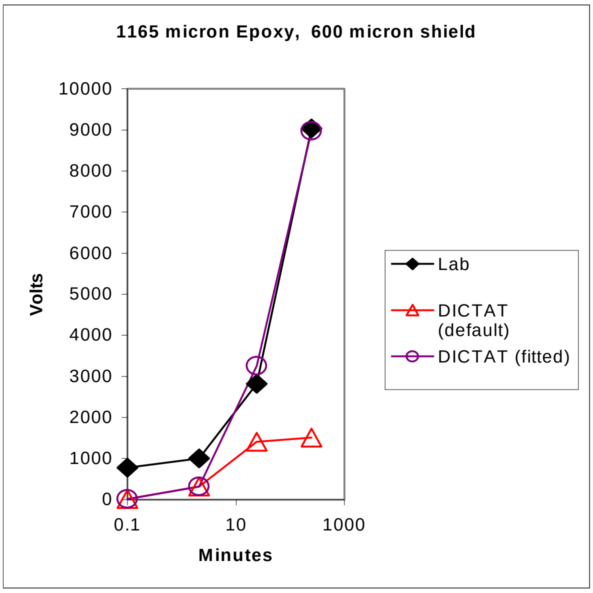

Figure 4. Surface potential versus time for a 1165µ Epoxy sample in the 'GEODUR' environment with a 600µ Al shield. The black diamonds are the laboratory measurements. The triangles show the DICTAT result with initial material parameters. The circles show the DICTAT result after fitting to find the best values of σ_0 and k_p

The Epoxy samples were found to be insensitive to radiation, i.e k_p=0. The material parameters found by fitting to the above experiment, gave good agreement for all other samples, shields and spectra, one of which is shown in figure 5.

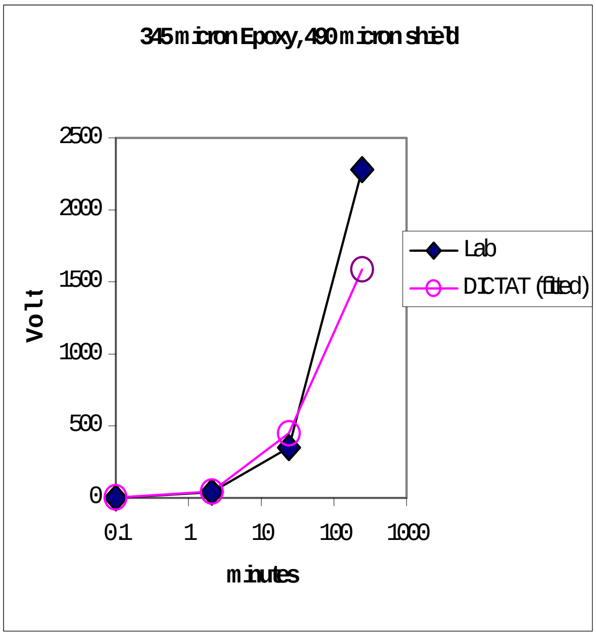

Figure 5. Surface potentials versus time for a 350µ Epoxy sample in a 750keV monoenergetic beam with a 490µ shield. The black doamonds are the laboratory measurenst. The circles are the DICTAT simulation using the previously fitted values of σ_0 and k_p

Epoxy Sample Conclusions

- It is clearly dangerous to use off-the-shelf values of σ_0 and k_p.
- All the Epoxy results are consistent with a single value of σ_0 and k_p=0.
- The final electric field was well simulated in all cases
- Time-dependence was well simulated in all cases
- Nearly all aspects of the code are involved in this comparison – dose rate effects are missing
- Beam tests showed that DICTAT applies both to continuous and mono-energetic spectra.

Comparisons for Teflon samples were not as successful as the Epoxy samples. Fitting of σ and k_p was carried out to provide the result shown in figure 6. Agreement is reasonable, although there is a suggestion that the simulation may be reaching a steady-state more rapidly than the laboratory observation.

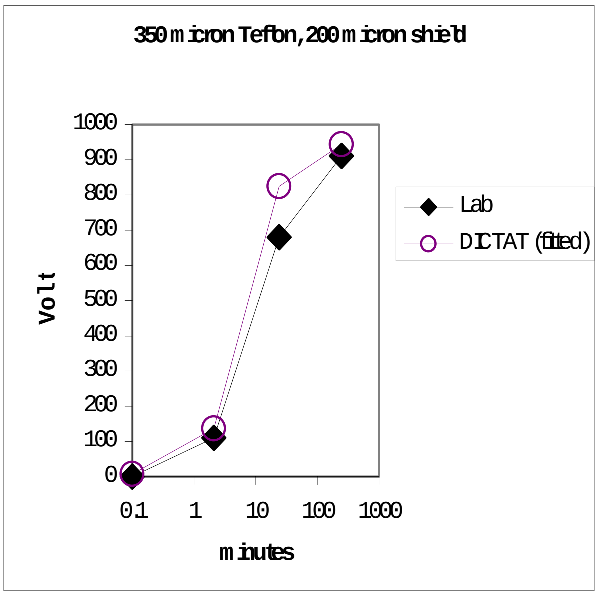

Figure 6. Surface potential versus time for a 350µ Teflon sample in the 'GEODUR' environment with a 200µ Al shield. The black diamonds are the laboratory measurements. The circles shows the DICTAT result after fitting to find the best values of σ_0 and k_p

However, the fitted material parameters did not produce good agreement for all samples, shields and spectra., as shown in figure 7.

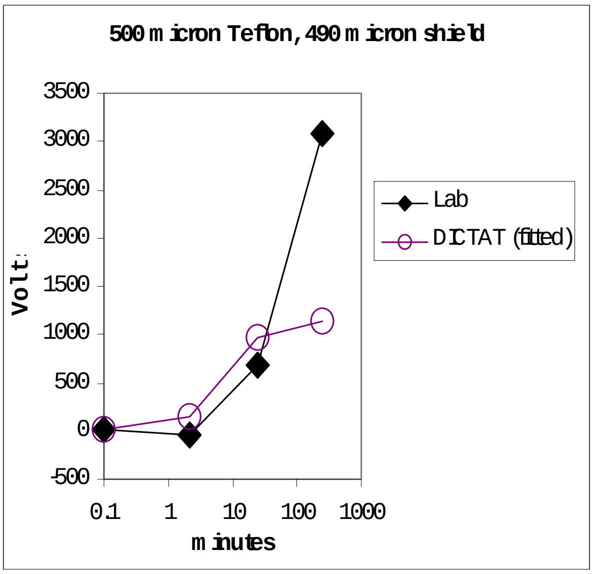

Figure 7. Surface potential versus time for a 500µ Teflon sample in the 'GEODUR' space-like environment with a 490µ shield. The black diamonds are the laboratory measurements. The circles show the DICTAT result using the previously fitted values of σ_0 and k_p

It is likely that fitting with ε is also required for Teflon. Unfortunately the tests carried out so far have not allowed σ_0, k_p anf ε to be be fitted simultaneously. Hence some further tests are planned. At present the radiation-dependent aspects of the code have not been validated.

Teflon Sample Conclusions

- Disagreements of up to a factor 3 remained after fitting of k_p and σ_0.
- Time-dependence was not well simulated - perhaps indicating that ε_r was not as expected.
- It has not been established in radiation-induced conductivity is adequately simulated.
- Further tests are required

Breakdown Thresholds

The laboratory tests, along with DICTAT simulations allowed the calculation of breakdown thresholds for the samples tested. Brekdown occurred at electric fields as low as 0.5MV/m. Full results are shown in figures 8 and 9.

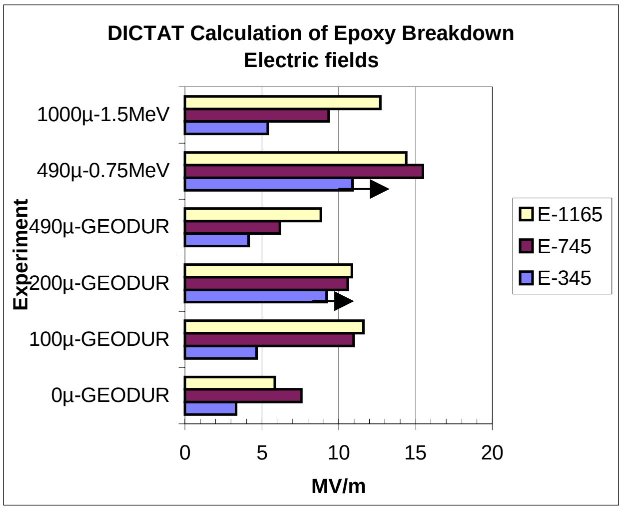

Figure 8. Electric field at which breakdown first occurred for three Epoxy thicknesses (345,745 and 1165µ). Al shield thicknesses were 0, 100, 200, 490 and 1000µ. The GEODUR spectrum and 2 monoenergetic beams were used. Arrows show lower limits when the tests ended without discharge.

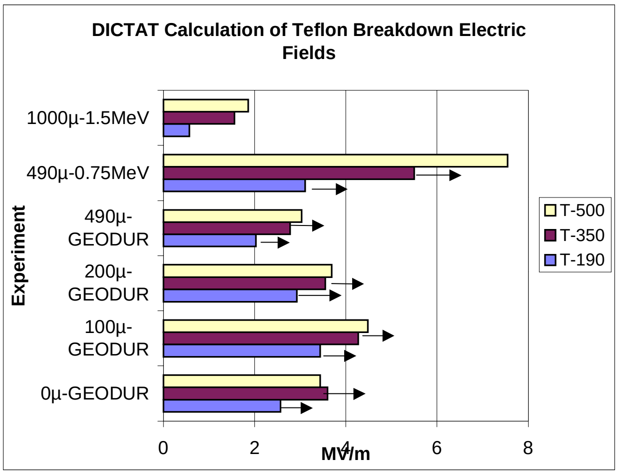

Figure 9. Electric field at which breakdown first occurred for three Teflon thicknesses (190, 350 and 500µ). Al shield thicknesses and spectra were as shown for Epoxy.

8. CONCLUSIONS

- A set of physical equations has been found that together represent a comprehensive physical model of IDC
- DICTAT has been created to implement these equations in a user-friendly form
- Most aspects of the tool have been validated although more work is needed, especially on radiation-induced conductivity.
- Breakdown was typically observed at electric fields of between 1 and 10 MV/m.

Work is in hand to make DICTAT available on ESA's Space Environment Information System (SPENVIS).

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