An Engineering Tool for the Prediction of Internal Dielectric Charging

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Abstract. A practical internal charging tool has been developed. It provides an easy-to-use means for satellite engineers to predict whether on-board dielectrics are vulnerable to electrostatic discharge in the outer radiation belt. The tool is designed to simulate irradiation of single-dielectric planar or cylindrical structures with or without shielding. Analytical equations are used to describe current deposition in the dielectric. This is fast and gives charging currents to sufficient accuracy given the uncertainties in other aspects of the problem - particularly material characteristics. Time-dependent internal electric fields are calculated, taking into account the effect on conductivity of electric field, dose rate and temperature. 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. For output, 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 bring the system below the breakdown threshold. A complementary programme of laboratory irradiations has been carried out to validate the tool. The results for Epoxy-fibreglass 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.

Introduction

The correlation of many spacecraft anomalies with radiation-belt electrons points to internal dielectric charging (IDC) being a major cause of satellite malfunctions (Ref.1). There exist a number of software tools which enable satellite designers to predict the sensitivity of spacecraft structures to *surface* charging. However there has been a lack of a similar tool for internal charging effects. The development of DICTAT (DERA Internal Charging Threat Assessment Tool) was undertaken to fill this gap.

Code development started with an investigation of the in-orbit and laboratory observations described in the existing literature. This led to the identification of the key physical processes that had to be represented in such a tool. The most appropriate theoretical and empirical formulae for these processes were selected and implemented in software.

An existing code, ESADDC (Ref.2), already incorporated most of the relevant physics for the analysis of internal charging. Some aspects, such as particle transport, were handled in a sophisticated manner which, while beneficial for scientific analysis, made the tool too cumbersome for engineering use. However, ESADDC was used to verify some aspects of DICTAT during development.

Software Requirements

DICTAT was designed to be an engineering tool and this is reflected in the key requirements:

- Ease of use - this included helping the user by providing appropriate space environments and eliminating the need for user control of the simulation.
- Speed - since repeated parametric studies were envisaged and simulations of charging throughout an orbit with changing electron flux.
- A Yes/No assessment of whether electrostatic discharge was likely.
- Feedback - what changes to the structure would be needed to make it safe.
- Accurate results - this implied that the tool should represent all the important physics of the problem to an appropriate degree of accuracy.

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. A choice of planar or cylindrical geometry allows PCBs, thermal blankets and cables to be simulated.
- Environment - Mean models of radiation belt electrons, such as AE-8 (Ref.3) are not appropriate. 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.

Figure 1 shows, schematically, an example of the type of problem treated by the code.

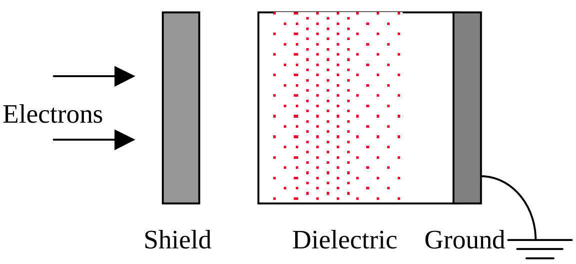

Figure 1 A shielded planar dielectric. Dots are used to suggest the non-uniform deposition of electrons in the dielectric.

Environmental Model – FLUMIC

A suitable model must reflect the characteristic time-period 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.4) electron data (courtesy of Paul Bühler, PSI). The REM data cover energies from 1 to 2.5MeV – probably the most important energy range for IDC. Energy-dependence in the model is given in a simple exponential form. Information on the solar-cycle dependence of fluxes comes from the GOES data. L-shell and Solar cycle variations of FLUMIC are shown in figures 2 and 3.

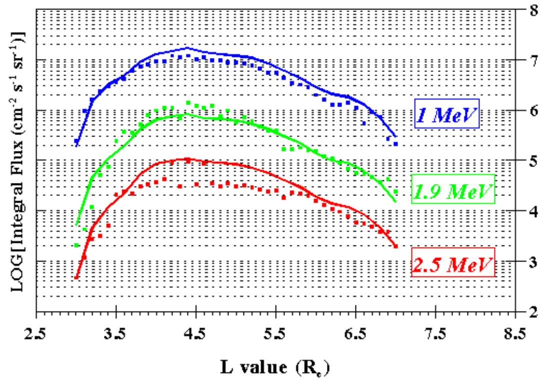

Figure 2 FLUMIC electron flux (line) compared with REM data (dots) at 3 energies.

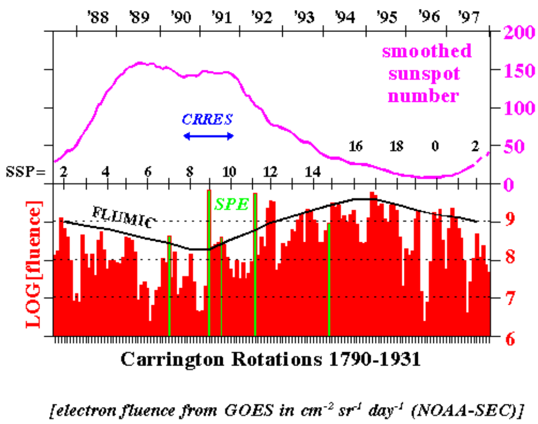

Figure 3 Top panel: Smoothed sunspot number. Bottom panel: Maximum daily (>2MeV) fluence in each Carrington rotation, compared to the FLUMIC model.

In DICTAT, the user can access the FLUMIC model by specifying the orbital parameters of the satellite under study. The code first considers the maximum charging that would result from an orbit-averaged flux. However, if the time-constant for internal charging is found to be shorter than an orbit, then a fully time-dependent environment is used. The user is also able to access

FLUMIC directly by specifying L, B/B_0 and solar cycle phase. For comparisons with laboratory measurements, the user can also directly input an electron spectrum, either isotropic or mono-directional.

Current Deposition

To find the current deposited in the dielectric, DICTAT finds the fraction of the electrons that penetrate the front surface and subtracts the fraction that exit the back surface. These calculations require knowledge of the distribution of penetration depths of the electron population.

The maximum penetration depth at a given energy is the 'range' R. There are a number of alternative analytical equations describing electron range, giving similar results. For DICTAT, the formula of Weber (Ref.5) was chosen:

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

where E is energy (MeV) . This has been shown by Trenkel (Ref.6) to give very good agreement to Monte Carlo simulations for Aluminium.

Sorensen (Ref.7) made the approximation that the electrons are uniformly deposited over a depth 'a' where:

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

Combining these two equations gives the fraction of electrons versus depth, as shown in figure 4.

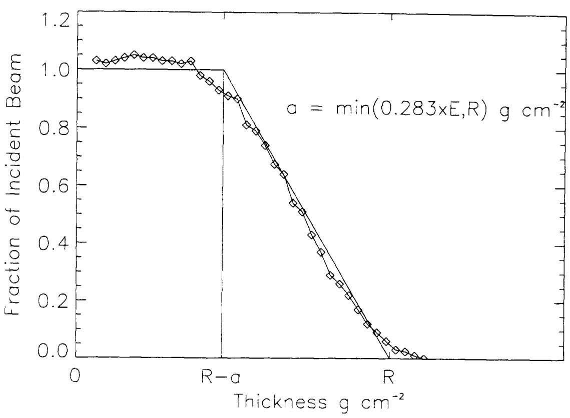

Figure 4 A comparison of electron penetration of Aluminium using a MONTE Carlo simulations (diamonds) and DICTAT's analytical approximation.

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.

In DICTAT, the effect of temperature on conductivity is calculated as follows:

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

where E_A is the activation energy. The value of $const.$ is determined from the room-temperature value of the conductivity. Figure 5 shows the significant effect temperature can have, over a small temperature range.

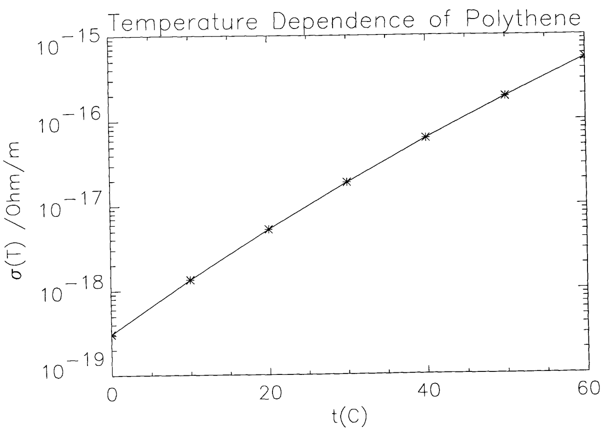

Figure 5 Calculated conductivity of Polythene versus temperature.

Variation of conductivity with electric field is given by a formula from Adamec and Calderwood (Ref.8):

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

where $\beta_F = \sqrt{\frac{e^3}{\pi\varepsilon}}$, e is electron charge, k is the Boltzmann constant, ε is permittivity and δ is an experimentally derived jump distance of 10 angstroms.

As is shown in figure 6, the electric field has no effect on conductivity below 1MV/m but rapidly increases conductivity above this field.

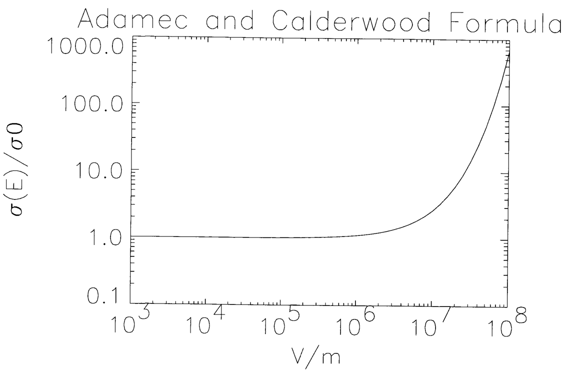

Figure 6 Normalised conductivity versus electric field, according to the Adamec and Calderwood formula.

Radiation-induced conductivity can be a significant effect. Dose-rate induced conductivity is generally described by:

$$\sigma = k_p \dot{D}^{\Delta} \qquad \Omega^{-1}\ m^{-1}$$

where k_p and Δ are experimentally-derived constants of the dielectric material. DICTAT makes the worst-case approximation that delayed and permanent conductivity effects can be ignored, since reliable quantitative formulae for these effects are not available.

A grounded planar dielectric resembles very closely a parallel plate capacitor and has a characteristic time-dependence. The field at time t can be approximated as:

$$E = \frac{J}{\sigma}\left(1 - \exp\frac{-t}{\tau}\right) \qquad \text{where} \quad \tau = \frac{\varepsilon}{\sigma}$$

However, σ is not constant, as shown above.

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 make appropriate laboratory tests.

DICTAT-Laboratory Comparisons

Internal electric fields cannot be easily measured in the laboratory, however we can compare DICTAT and laboratory measurements of surface potential, i.e the integral of the electric field. There were practical constraints on the experimental programme. The experiments were time-limited to a single working day and so higher fluxes were used than found in space and equilibrium was not reached. Temperature was assumed to be 298K but was uncontrolled.

The test facility had a Van de Graaf electron beam source. A realistic severe space-like spectrum, called ‘GEODUR’ could be formed using a combination of scattering plates.

A series of laboratory irradiations of Epoxy-fibreglass 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 initial conductivity σ_0 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’ spectrum are shown in figure 7.

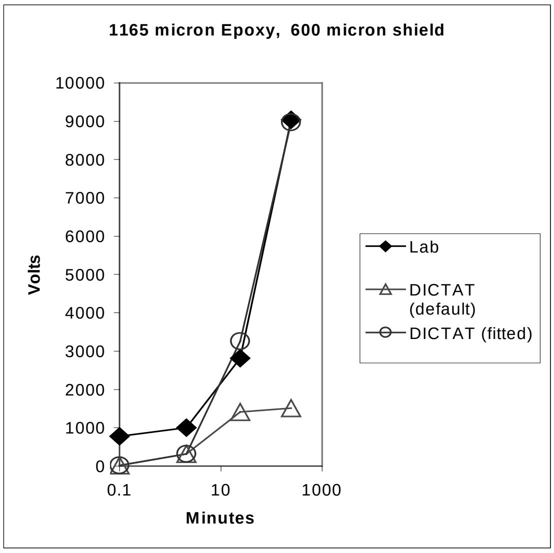

Figure 7 Surface potential versus time for a 1165µ Epoxy sample in the ‘GEODUR’ environment with a 600µ Al shield. The black diamonds are the laboratory measurements. The triangles show the DICTAT result with initial material parameters. The circles show the DICTAT result after fitting to find the best 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 8.

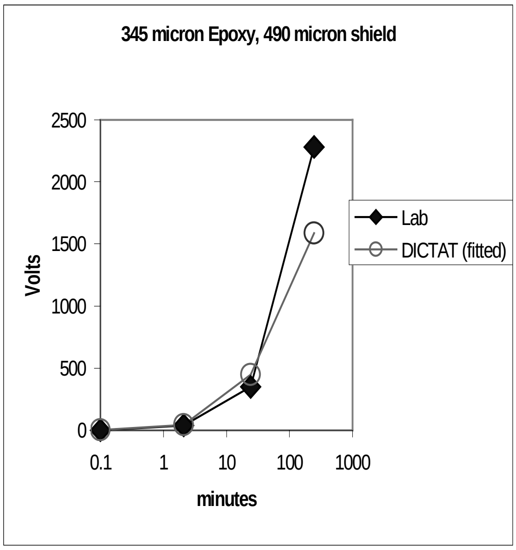

Figure 8 Surface potentials versus time for a 345µ Epoxy sample in a 750keV monoenergetic beam with a 490µ shield. The black diamonds are the laboratory measuremenst. The circles are the DICTAT simulation using the previously fitted values of σ_0 and k_p

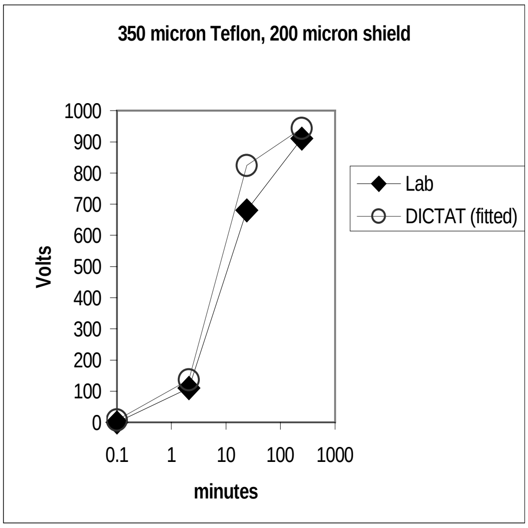

Figure 9 Surface potential versus time for a 350µ Teflon sample in the 'GEODUR' environment with a 200µ Al shield. The black diamonds are the laboratory measurements. The circles shows the DICTAT result after fitting to find the best values of σ_0 and k_p

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 9. Agreement is reasonable, although there is a suggestion that the simulation may be reaching a steady-state more rapidly than the laboratory observation.

However, the fitted material parameters did not produce good agreement for all samples, shields and spectra., as shown in figure 10.

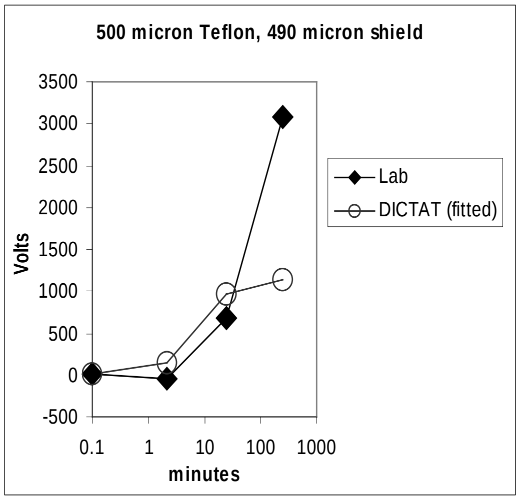

Figure 10 Surface potential versus time for a 500µ Teflon sample in the 'GEODUR' space-like environment with a 490µ shield. The black diamonds are the laboratory measurements. The circles show the DICTAT result using the previously fitted values of σ_0 and k_p

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 and ε to 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 if radiation-induced conductivity is adequately simulated.
– Further tests are required

Breakdown Thresholds

Laboratory observations of the time at which discharge first occurred, in tandem with DICTAT simulations allowed the calculation of breakdown thresholds for the samples tested. Breakdown occurred at electric fields as low as 0.5MV/m. Full results are shown in figures 11 and 12.

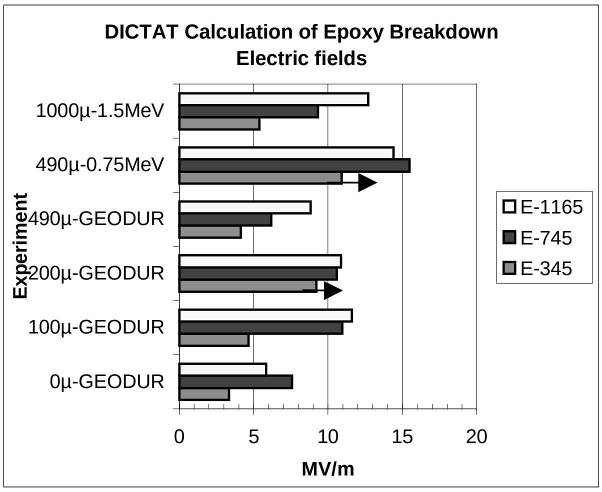

Figure 11Electric field at which breakdown first occurred for three Epoxy thicknesses (345,745 and 1165μ). Al shield thicknesses were 0, 100, 200, 490 and 1000μ. The GEODUR spectrum and 2 monoenergetic beams were used. Arrows show lower limits when the tests ended without discharge.

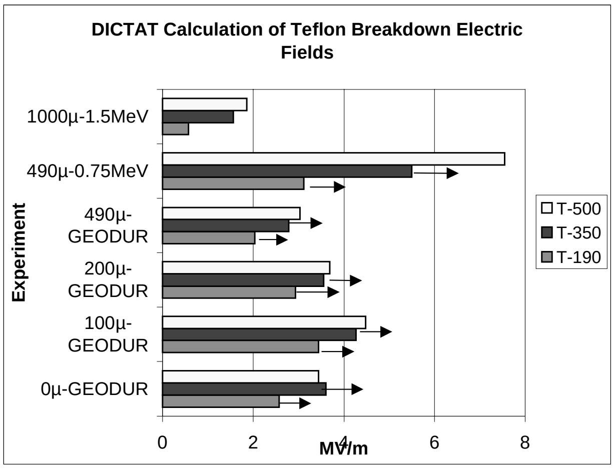

Figure 12 Electric field at which breakdown first occurred for three Teflon thicknesses (190, 350 and 500μ). Al shield thicknesses and spectra were as shown for Epoxy.

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).

Acknowledgments

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