Space Experiment Design for Electrostatic Charging and Discharging

Keith G. Balmain
Department of Electrical and Computer Engineering
University of Toronto
10 King's College Road
Toronto, ON, M5S 3G4
Phone: 416-978-3127; Fax: 416-978-4425; E-mail: balmain@waves.utoronto.ca

Abstract

Electrostatic charge accumulation and consequent electrical breakdown of dielectric materials have been implicated in many electronic equipment failures on spacecraft in synchronous orbit. These failures have ranged from temporary anomalies to permanent failures of major subsystems. This paper reviews the relevant background of both surface and internal charging and the factors that lead to the design of a relevant space experiment. The purpose of the planned space experiment is to measure charge buildup and discharge phenomena in ways that will lead eventually to greater immunity in spacecraft electronic circuit design. The paper describes as well how the time derivative of the total current in typical surface discharges can be regarded as a universal constant, considerably simplifying EMC predictions and susceptibility test planning.

1. Introduction

Spacecraft in synchronous orbit (and lower orbits as well) experience significant charge accumulation during periods of unusually high emission of charged particles from the sun [1]. The higher-energy electrons can penetrate into the spacecraft interior where they become lodged in electrical insulators (*deep* or *internal* charging). The lower-energy electrons penetrate just under the surfaces of the exposed dielectrics used for thermal control and for the support of solar cells (*shallow* or *surface* charging). When electrical breakdown occurs in either of these situations, the crucial aspect is the propagation of the discharge. It is this propagation that mobilizes the charge and channels the resulting current, such that, in laboratory simulations, peak ejected-electron currents have reached hundreds or even thousands of amperes [2]. Actual spacecraft discharges are believed to be smaller but still damaging, the consequences ranging from temporary electromagnetic interference to permanent physical damage in spacecraft devices or subsystems, and even loss of entire spacecraft, such cases going back as far as the 1960s or 1970s and continuing into the 1980s and 1990s [3, 4, 5]. Indeed, these "spacecraft anomalies" have been problematic for such a long time that well-organized efforts have been made to record and categorize them [6, 7], those events believed due to electrostatic discharge showing correlation with solar emissions, eclipse conditions, local time (midnight to dawn), and time of year (equinox).

2. Spacecraft Deep Charging and Discharging

Tree-like discharge patterns (sometimes referred to as Lichtenberg figures) were first observed by Gross in borosilicate glass [8] and Plexiglas [9] after exposure to 2 megavolt-level electron beams and subsequent discharge triggering by driving a grounded pin into the side of the specimen, as shown in Fig. 1. The tree patterns are formed within the specimen near the electron stopping distance which is of the order of 10 mm in many of these experiments. Because the discharge occurs deep within the dielectric specimen, it never reaches the specimen surface (except at the grounded pin), with the result that the specimen can be wrapped in thin metallic foil without any effect. Therefore the progress of the discharge is the progress of a breakdown track into an isolated, precharged region.

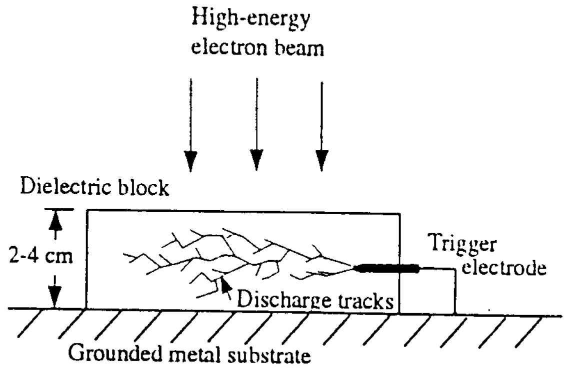

Figure 1. Bright discharge and permanent damage tracks in a thick dielectric block under bombardment by monoenergetic (> 1MeV) electrons.

It has been shown by Cooke *et al.* [10] that the velocity of discharge propagation is dose-dependent, which is to say dependent on the deposited charge density, higher charge densities producing higher local electric fields and faster propagation. Moreover, the same authors observed that a discharge could traverse an uncharged region if that region were narrow enough. By measuring the current to the initiator pin and noting its minima as the discharge crossed narrow uncharged bands, they made absolute measurements of discharge velocity, typically in the range of 1.4 to 6.3×10^5 m/s [11, 12] (it is possible that these velocities are slightly low due to added delays in traversing the uncharged bands).

Deep charging with resultant discharging was demonstrated to be a potential threat to spacecraft, in laboratory experiments on printed circuit boards carried out by Wenaas *et al.* [13]. Moreover, such discharges were shown to occur in space, in a variety of metal-shielded configurations [14]. Evidence suggests that deep charging may be the cause of at least some spacecraft operational anomalies and subsystem failures [3, 4, 5].

3. Spacecraft Surface Charging and Discharging

It is well known [1] that 5-30 kV electron beams incident on thin specimens of spacecraft dielectrics such as Teflon, Kapton and Mylar can produce strong discharges. The scaling of discharge properties with specimen area has proved to be particularly revealing [15]. The proportionality of released charge to specimen area lends support to the notion that most of the deposited charge is somehow mobilized and blown off. More subtle is the proportionality of peak current and discharge duration to the square root of the area (i.e. proportional to the linear dimensions of the specimen). This duration proportionality suggests that the discharge propagates at a finite velocity, typically 7×10^5 m/s (not much greater than the value for deep discharges). For round, disk-shaped specimens, the velocity is calculated as the specimen radius divided by the time between the half-maximum levels of the discharge current. The peak current proportionality to linear dimension suggests that the discharge process is that of a wave expanding from the initiation point, accompanied by electron current ejection proportional to the length of the wavefront. This postulated process is supported by the observation that discharge current waveforms are often symmetric, with roughly equal rise and fall times.

This "burning wavefront" or "brushfire" process is believed to involve the acceleration of discharge-emitted ions over the surface ahead of the wavefront, these ions being attracted to the undisturbed embedded electrons [16, 17]. The embedded electrons are then drawn to the surface by high-field conduction (or possibly by electrical breakdown and plasma eruption through the surface). Excess electrons are then blown off to produce the peak currents that can be over 1000 A for an exposed area of one square meter. This process is depicted in Fig. 2.

In seeming contradiction to the "brushfire" process is the frequent observation of bright, irregular lightning-like traces over the surface during a discharge. Also observed are tunnel-like damage tracks [2] located a few micrometers below the surface and reminiscent of the deep-discharge "tree" structures. These shallow damage tunnels often break through the surface or form surface grooves, thus very likely being the source of dense plasma that could provide ions to support discharge propagation, as well as providing the high current of blowoff electrons. The tunneling process is depicted in Fig. 3.

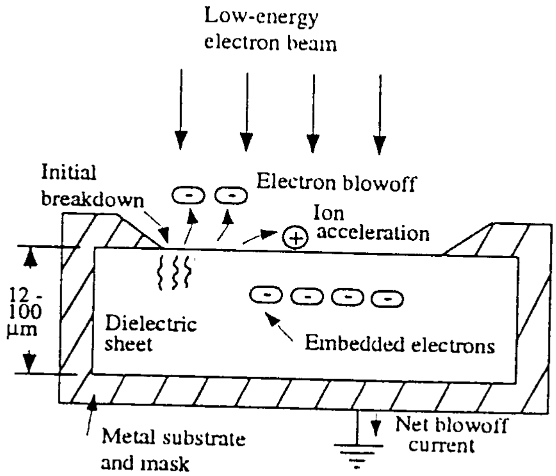

Figure 2. Charge accumulation and discharge processes, showing the accelerated-ion contribution to discharge propagation.

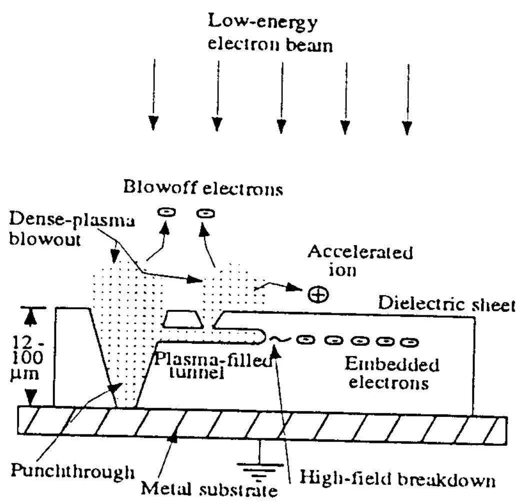

Figure 3. Punchthrough-initiated breakdown and discharge propagation showing tunnel formation in a thin dielectric sheet.

The damage tracks and the lightning-like traces have related directions [18]. However, no one-to-one correspondence between them has been identified.

It is curious that the damage tunnels are usually observed near "punchthroughs" to the underlying metallization which is common in spacecraft thermal blankets. Thus the damage tunnels, although dramatic when seen in scanning electron microscope images, probably do not play a large part in surface discharge propagation.

The significance of discharge-emitted plasma has become somewhat clearer over the years. In his excellent 1983 compendium and interpretation of discharge examples, Frederickson [19] drew attention to the high density of emitted plasma. Recently, in 1992, Frederickson *et al.* [20] noted that the emitted plasma was dense enough to trigger discharges between biased metal plates some distance away from the dielectric arc.

The discharge propagation mechanism has been linked to "barrier-jumping" of surface discharges [21]. More recent advances in this line of thought [22] have led to the conclusion that ejected ions are the principal trigger for "sympathetic" discharges on nearby charged surfaces, thus lending credence to the "brushfire" postulate of ion-assisted discharge propagation.

4. Spacecraft Testing

The only comprehensive spacecraft charging design guideline document is the 1984 NASA report by Purvis *et al.* [23]. Additional insight has been offered in a paper by Whittlesey *et al.* [24] which includes a useful latitude-vs-altitude chart of relative charging threat. The NASA report does not deal with internal charging/discharging but rather focuses on external dielectric charging and surface discharging. Such a discharge produces a pulse of high-current electron blowoff which eventually returns to the spacecraft to form a complete circuit. It is this large current loop that couples EMI into the spacecraft, so it is also this current loop that must be replicated for susceptibility testing.

The NASA document [23] recommends use of the arc generator originally specified for spacecraft testing in MIL-STD-1541 and shown in partial schematic in Fig. 4. At an applied voltage of

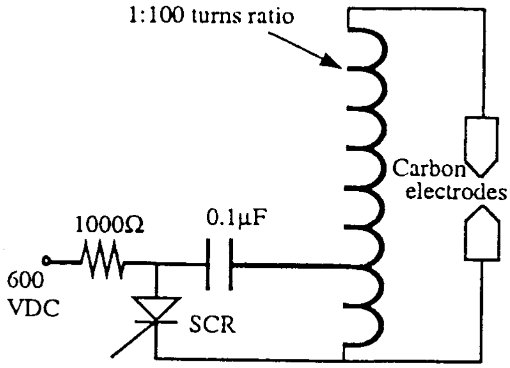

Figure 4. Arc source specified in MIL-STD-1541 and included in NASA TP-2361. The autotransformer has a distributed capacitance of about 50 pF. The DC supply is switched off before the SCR is switched on.

19 kV, it produces a peak current of 80 A, a current pulse risetime of 5 ns and a pulse width of 20 ns. It can be used at a short distance (30 cm) from the spacecraft or in contact with it, the contact test being the more severe of the two, especially if the current is passed between distant points on the spacecraft in simulation of the return current path mentioned in the foregoing paragraph.

Standard arc generators designed to satisfy human ESD standard IEC 801-2 should not be applied directly to spacecraft because the risetime is generally too fast, the decay time is too slow, and the initial high current peak is not representative of spacecraft external discharges. However, it can be argued that the use of indirect discharge (direct discharge to a large metal plate close to the spacecraft) introduces enough pulse smoothing to make the test relevant [25]. Spacecraft surface discharges have wide ranges of peak current and pulse duration on account of the peak current and pulse duration proportionality to the linear dimensions of the charged region, so a range of 1,000:1 is not out of the question, and a range of almost 5 orders of magnitude has been noted [26].

5. A Universal Rate-of-Rise Estimate for Surface Discharge Currents

The simplified "burning wavefront" process discussed in Section 3 implies that the instantaneous total discharge current I is proportional to the length of the wavefront L, making

$$I = k\,L \tag{1}$$

where k is a constant. If the discharge starts at the straight edge of a dielectric sheet lying on a grounded metallic surface, the wavefront length is half the circumference of a circle with radius ρ which is the radius of the wavefront. Further, if the velocity of discharge wavefront propagation is $V = d\rho/dt$, then

$$\frac{dI}{dt} = k\,\pi\,V \tag{2}$$

Applying (1) to a discharge starting at the edge of a circular dielectric specimen of radius r, one finds that

$$k = \frac{\sqrt{2}\,I_{max}}{\pi\,r} \tag{3}$$

which for typical data on specimens 1-3 mil thick of Kapton, Mylar or Teflon leads to

$$k \approx 5\ \text{A/cm} \tag{4}$$

For a velocity approximately equal to $7 \times 10^5\,\text{m/s}$, application of (2) leads to

$$\frac{dI}{dt} \approx 1\ \text{A/ns} \tag{5}$$

Examination of samples of existing data tends to validate (5) within a factor of two, with no strong dependence on physical parameters having been identified so far. Equation (5) could be helpful in estimating worst-case levels of electromagnetic interference in cases where dI/dt coupling is crucial.

Equation (5) is also useful to evaluate susceptibility test techniques. In Section 4, the MIL-STD-1541 arc generator example should produce a current rise rate of roughly 8 to 10 A/ns, which represents overstress related to electromagnetic coupling by perhaps as much as an order of magnitude.

6. Factors Influencing Spacecraft Experiments

The development of design guidelines to prevent spacecraft electrostatic discharge damage is highly desirable. Laboratory experimentation is the primary means to this end. Ultimately, space experiments must be carried out to ensure that the concepts developed in the laboratory are applicable to the space environment.

A parallel objective would be the development of a satellite instrument that could provide advance notice of potentially dangerous charge accumulation. Such an instrument might also provide useful retrospective data in the event that ESD problems did arise.

The detailed study of the ambient energetic-particle environment requires spectrometers whose cost and weight would limit their use to a few scientific satellites. For research purposes, an array of test cells used in conjunction with energetic-particle spectrometers would be appropriate, and such an arrangement was employed in the CRRES experiment [27]. This experiment was aimed at detecting discharge pulses in cases where the dielectrics in question were completely covered with 0.2 mm aluminum foil, such that only electrons with initial energies over 150 KeV could reach the dielectric specimens. The earlier SCATHA experiment [6] included uncovered specimens and also included methods to measure surface potentials.

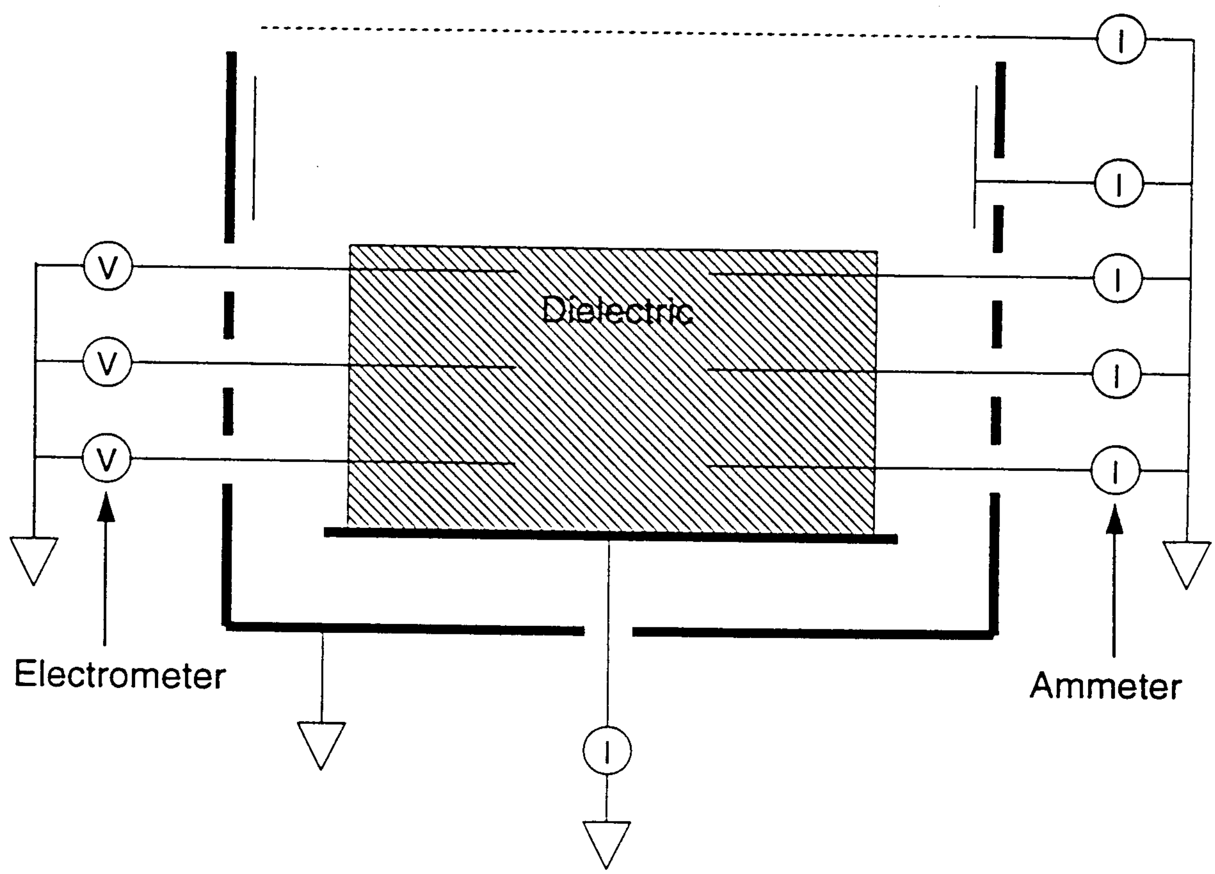

Figure 5. Conceptual design of a test cell for measurement of charge accumulation (slowly varying electrode floating potential) and discharge occurrence (transient current to ground from embedded electrodes and blowoff collectors).

Here, it is suggested that a hybrid test cell could provide some information on the incident electron spectrum while at the same time testing circuit-like configurations for both charge accumulation and discharge occurrence. Specifically, arranging conducting electrodes at various depths in a dielectric specimen could provide information on the depth of penetration of the incident electrons (hence their energies), while at the same time modeling the multilayer circuit boards that are widely used in spacecraft electronics. The electrodes would be in two configurations, floating (for measurement of surface potential using electrometers), and grounded (through a resistor, so that discharge current could be deduced from a measurement of transient voltage across the resistor). The conceptual design is shown in Fig. 5.

A test cell of the type shown in Fig. 5 (but without the blowoff collectors) has been built using Plexiglas 6 mm thick and wire probes at three depths (4 mm, 2 mm and flush with the surface). Floating potentials up to about 3 kV were measured on the surface probe for an incident 20 KeV electron beam, and lower voltages were measured on the deeper probes. For higher energies up to 2 MeV, a Strontium-90 radioisotope source was used: it produced the largest potential on the middle probe, showing that the probe potential variation with depth is an approximate indicator of the incident electron energy.

7. Transient Test Cell Data

The potential of a floating electrode in response to the environment is expected to be slow, having time scales of several minutes to hours. If an electrode loses its charge due to some form of breakdown, our recent experiments show that the result would be a change in its potential with a time scale of a small fraction of a second to a few minutes. If the electrode potential were sampled at 30-second intervals (the same rate as used in the CRRES experiment), then it should be possible to distinguish between rapid discharge events and slow environmental effects.

Actual discharge currents are expected to be very fast, with rise and fall times as short as 10 ns or even shorter. Discharge currents could be monitored by a scheme in which the transient current charges a capacitor whose voltage is periodically sampled at a relatively slow rate. The discharge current to an electrode would depend on the effective capacitance between the stored charge and the electrode, such that a change in the stored charge would induce a detectable current in the electrode. If a discharge produces the release of charge from the specimen surface, then this charge can be categorized as "blowoff" and could be intercepted by the electrode (shown in Fig. 5) that is in the form of a strip or band around the upper part of the cell's inside wall, or the charge could be intercepted in part by the wire grid over the cell. Alternatively, this wire grid could be a metal foil that would function as an energy filter as well as a means to pick up blowoff charge.

8. Conclusions

In principle, it is feasible to design a simple spacecraft test cell that can be instrumented to provide information on the energetic-electron environment and its tendency to charge dielectrics and attached floating metal, thereby to generate potentially disruptive discharges. A design for such a test cell has been outlined, and a laboratory version has been built and tested.

As well, it has been shown that surface discharges on thin spacecraft dielectrics exhibit a characteristic rate of rise of total discharge current of about 1 A/ns. This rate is close to being a universal constant, largely independent of experiment parameters. It enables relatively easy estimation of electromagnetic interference coupling and also permits appraisal of susceptibility test methods with particular attention to electromagnetic coupling aspects.

9. Acknowledgments

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