Method For Estimating Spontaneous Pulse Rate For Insulators Inside Spacecraft

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Abstract

High energy electrons that penetrate the thin surface materials on spacecraft can be stopped in insulated materials inside spacecraft and thereby generate spacecharge-caused electric fields and high voltages inside the spacecraft. The fields are large enough to induce spontaneous pulsing by insulating materials. Realistic estimates of pulse rates are currently lacking. The frequency of electrostatic discharge pulsing can be estimated by extrapolating the pulse rate measured for insulators on the CRRES spacecraft. The extrapolation is based upon CRRES data which show that: 1) The pulse rate scales with high energy electron flux, and with the area and type of insulator. 2) Samples must be soaked in vacuum for at least six months before being tested so that the results are not biased by species such as water and free radicals that eventually outgas. 3) Insulators containing many large imperfections such as the glass fibers in epoxy fiberglass circuit boards produce the most frequent pulsing. 4) Some insulators pulse only rarely. 5) We have not yet determined a high energy electron flux below which no pulsing occurs.

I. INTRODUCTION

Theoretical concepts are unable to predict the true level of charging that occurs in real spacecraft insulators inside spacecraft. Existing theory [1] indicates that the voltages on surfaces of thick insulators such as circuit boards achieve impossibly large levels. Thus one is ill advised to use theory to predict pulsing rates by internal insulators. Instead, one should use measured pulsing rates from space as a guideline for estimating internal pulse rates.

The NASA design guideline [2] and other documents [3,4] advise that spacecraft surface charging can result in spacecraft anomalies. But spacecraft surfaces are subject to sunlight-caused electron photoemission and ambient plasma which tend to minimize surface charging. Additionally, the energy stored in the surface voltages of charged spacecraft is small because the capacitance of spacecraft to ambient plasma "ground" is small. Differential charging of adjacent surface elements may involve significant capacitance, but only during the occasional surface charging events is differential charging significant. The pulses resulting from discharging of surface elements can often be electrically "shielded" from sensitive circuits. The capacitance of internal insulated surfaces to spacecraft ground is relatively large and the voltages are not minimized by sunlight and ambient plasma. Therefore discharges by internal surfaces are more threatening than spacecraft surface discharging.

The Spacecraft Environmental Anomalies Handbook [4] reports that pulsed discharging of internal spacecraft insulators occurs for high energy (HE) electron flux levels above one picoampere per square centimeter. Existing estimates of pulse rate were based on sparse ground experiments at relatively high flux levels and are not supported by any theory of pulsing. The older guideline was subject to large uncertainty because the tests upon which it was based were of limited duration. Longer duration tests as well as realistic environmental conditions were later achieved with tests on the CRRES spacecraft.

The Internal Discharge Monitor experiment (IDM) on the CRRES spacecraft [5] exposed insulators and circuit boards [6,7] to 14 months in the space radiation belts behind thin (0.2 mm) aluminum shielding. Pulsing of FR4 (fiberglass reinforced epoxy) circuit board material was monitored for 14 months while spectrometers were recording the simultaneous HE electron flux spectrum. The pulsing results are fully documented and were found to correlate with the HE electron flux [7]. Pulsing was seen at fluxes as low as 0.1 picoampere/cm^2 so that we now have a new warning level at a much lower flux. Also, the many anomalies experienced by various systems on CRRES correlated with the IDM pulsing data and with HE electron flux [8] which enhances our concept that anomalies are produced by discharging insulating materials. The wide statistical distribution of pulse rate as a function of incident HE electron flux [7] belies the possibility of rationalization by a simple physical theory; the space data itself forms the basis for prediction.

The CRRES insulator data [7] provides a new point of view for the causes and mitigation of spacecraft anomalies. First, both the flux threshold and the fluence threshold for pulsing occur at lower levels than previously suspected. The fluence threshold is so low that on CRRES the first pulse occurred only 70 hours after launch, while other similar samples quietly waited for six months and then pulsed profusely. Second, pulsing is spontaneous and somewhat random and is best described as a probability rather than as a dependent function. Third, because pulses rarely if ever eliminate the electric fields inside insulators that are the cause for pulsing [9,10], the occurrence of a pulse does not delay the occurrence of the next pulse. For example, the second pulse on CRRES occurred only four hours after the first, and on the same sample; the fourth pulse occurred 100 seconds after the third, again on the same sample. Fourth, the probability for pulsing, and thus the average pulse rate, is proportional to the HE electron flux impacting the insulating material. Finally, the effect of conduction in the insulators is so important, and conductivity is so poorly known, that at this time only actual space test provides meaningful data [1]. Improved understanding of spacecraft anomalies might result from the general application of this point of view.

II. THE H.E. ELECTRON ENVIRONMENT

The insulator pulsing data in this paper was obtained from the CRRES spacecraft which had HE electron flux monitors in a geosynchronous transfer orbit which passed through nearly all of the radiation belts [5]. Most spacecraft do not have HE electron flux monitors. Compared to most other orbits, spacecraft in mid-altitude and transfer orbits experience variable but larger HE electron fluxes and therefore are subject to more charging problems. One must obtain HE electron flux data for each such spacecraft in its particular orbit in order to estimate its pulse rate.

A geosynchronous spacecraft experiences approximately the same trapped environment as any other geosynchronous spacecraft over long time spans of a few days or more. Very low altitude spacecraft experience smaller flux. Most orbits (but not all) experience larger HE electron fluxes than do geosynchronous spacecraft. The geosynchronous case is instructive because there are good radiation monitors available and there are many such spacecraft. Geosynchronous spacecraft operators can compare their experience with these predictions.

First, the general method for estimating pulse rate will be illustrated by using the specific example of a geosynchronous spacecraft where the sensitive insulator is circuitboard material shielded by a thin-walled electronic box. Application to other cases is simple.

The average geosynchronous HE electron flux spectrum during January 12-22, 1994, as measured by several spacecraft [11] is shown in Fig 1. Geosynchronous spacecraft reported unusually large rates of problems during this time period. Each horizontal bar in Fig. 1 represents the ten-day average flux in a channel, and the width of the bar indicates the range of electron energies to which the channel responds. The straight line provides an estimate of the highest day of flux during the ten day period when each day's fluence was at least half this value. It is a straight line with an energy dependence of E^{-3}. The flux dropped rapidly after the ten days. After informally examining outer zone electron data for a 20 year period, it appears that the geosynchronous flux levels in Fig. 1 are achieved for perhaps ten days per year, and perhaps over 30 days per year during two years of declining phase of the sunspot cycle. Normally one expects the HE flux in this orbit to be one-to-ten percent of this level.

We are interested only in the HE flux that impacts the internal insulators. The CRRES data [7] indicates a good correlation between impacting HE electron flux and probability for pulsing. The straight-line electron flux-energy spectrum in figure 1 can be transported through shielding behind which a sensitive insulator is located. There are three levels of shielding on typical spacecraft: the thermal blankets which are thin and typically stop only electrons below 100 keV, the enclosures of circuits and the wrappings of spacecraft wire bundles which are usually thicker and stop electrons between 100 keV and 1 MeV depending on thickness, and the more massive shielding provided by component packaging and other circuitboards within electronic boxes which is sufficient to reduce HE electron flux to negligible levels for the purpose of charging effects.

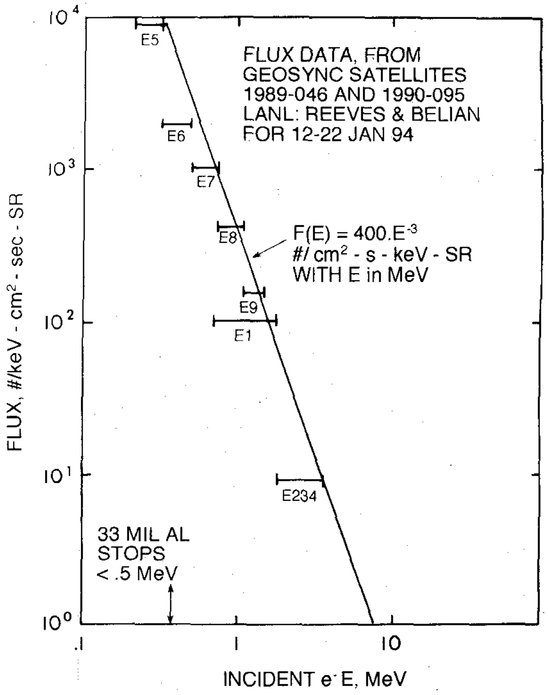

Fig. 1. High intensity electron flux spectrum at geosynchronous altitude.

For our geosynchronous spacecraft example, we consider a circuit board (or other insulator) in a thin electronic box where the box forms a shield of 33 mils (0.84 mm) of aluminum. Penetration of the incident flux can be determined using the algorithm of Tabata and Ito [12]. The flux of electrons is assumed to be semi-isotropic over time periods exceeding a few minutes for spacecraft which move and rotate with respect to the Earth's magnetic field lines. The energy range is divided into bins being 100 keV wide, with electrons at the median energy of the bin. Such bins will provide sufficient accuracy in estimating the penetrating flux for space spectra and spacecraft shielding materials >0.1 mm thick . The electrons in each energy bin are then transported through the shield by integrating the Tabata and Ito transmission function over incident angle (isotropic) from zero to 90 degrees. The method is described in [12,13] and can be rapidly done with most modern software on personal computers.

One might choose other insulators such as cable bundles or interior thermal blankets which are less shielded from space electron flux. Such insulators may be impacted by electrons which are as low as 50 keV in space, and are therefore more likely to pulse.

Figure 2 shows the flux of Fig. 1 which penetrates the aluminum shield and is incident on the circuit board as a function of the energy incident on the outside of the spacecraft. The Tabata-Ito algorithm cannot tell us the energy of the transmitted electrons, it only tells us how many electrons were transmitted. But we do know that negligible electrons below 50 keV were incident on the surface of the insulator; the transmitted spectrum is "hard," as it was in the CRRES IDM space experiment. By summing over all energy bins, and over ten hours, we obtain the ten-hour fluence incident on the circuit board to be $3.3\text{x}10^{10}$ electrons per cm^2 per ten hours. Specifying flux as ten-hour fluence allows immediate comparison with data for insulator pulsing from the CRRES spacecraft.

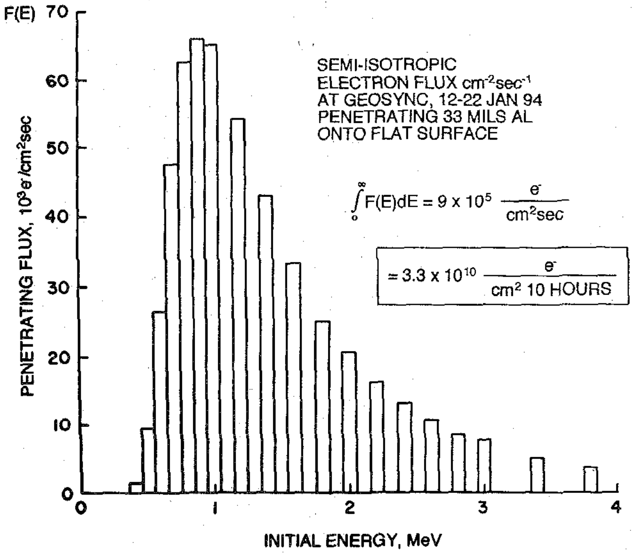

Fig. 2. Penetration of geosynchronous electrons through 0.84 mm Al as a function of incident energy. The total penetrating flux is $3.3\text{x}10^9$ electrons cm^{-2} hour^{-1}.

Information about the impacting electron energy spectrum, at this time, would not help predict the probability for pulsing because pulsing has not been sufficiently investigated as a function of impacting electron energy above 20 keV. The spectrum determines the depths to which HE electrons penetrate. The place where electrons stop as well as where they deposit dose affects the development of the electric fields. This issue has been theoretically addressed to predict that peak electric field strengths are only weakly dependent on electron energy [10]. However, in the case of thin insulators where the vast majority of electrons pass through, the internal electric fields can remain below the threshold for pulsing. Circuit boards, wire harnesses, etc. are geometrically complex, microscopically and macroscopically. The maximum electric field strength [14] as well as the probability for pulsing [9,10] depend far more upon the geometric complexity than on the HE electron spectrum. Complex structures like Space Shuttle Tiles and fiberglass reinforced plastic pulse much more copiously than do simple samples like polymethylmethacrylate (plexiglass). Many pulses are initiated at the sharp edges of samples. The effects of geometrical complexity should be determined before one attempts to determine the effect of spectrum.

III. PULSE RATE PREDICTION

The CRRES-IDM data allow one to estimate the pulse rate from FR4 circuit board material as a function of HE electron flux. Figure 3 is a scatter diagram of the CRRES-IDM insulator pulsing statistics, and other descriptions of the pulsing statistics are available [7]. The vast majority of insulator pulses was generated by the 125 cm^2 of FR4 circuit board samples. Each CRRES orbit was approximately ten hours long. Each datum in Fig. 3 represents the number of pulses during one of the 1061 orbits. There are 1061 points covering 14 months in Fig. 3. For example, during the seven orbits when the orbital fluence was less than $2\text{x}10^{10}$ cm^{-2} there were no pulses. For the orbits with fluence above $2\text{x}10^{11}$ cm^{-2} only two orbits contained no pulses, but approximately fifty orbits contained over ten pulses.

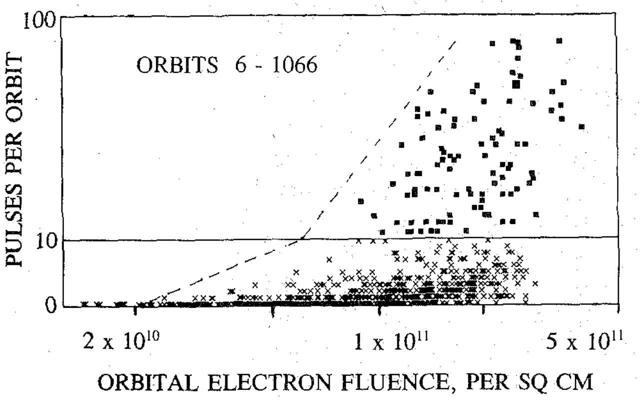

Fig. 3. Pulsing statistics for CRRES/IDM samples, especially FR4 circuitboard. Each point shows the number of pulses in one ten hour orbit. Zero pulses is the most probable number. The scale is linear from 0 to 10 pulses, logarithmic above 10.

Ten-hour fluence, as a flux measurement, is arbitrarily chosen. Substantial charge must be injected to produce pulses, so it is nonsense to monitor instantaneous flux. After extended irradiation in space, if the radiation were instantaneously extinguished, the pulse rate would decay with a decay time constant of from one to ten hours [7]. The CRRES orbit was ten hours, and most data was naturally accumulated in ten hour groups.

For our geosynchronous spacecraft the ten-hour fluence is $3.3\text{x}10^{10}$ cm^{-2}. Figure 3 indicates that for CRRES-IDM roughly one out of ten orbits contained a pulse for orbital fluences near this level. Therefore, a geosynchronous spacecraft with 0.84 mm (33 mils) Al shielding and 125 cm^2 of FR4 circuitboard would experience approximately one pulse per hundred hours during the period from January 12-22, 1994. Indeed, several geosynchronous spacecraft experienced a few anomalies during this time, having had little trouble for years, mostly at one to ten percent of this flux.

The data in Fig. 3 has been corrected for detector dead time to generate Fig. 4. Pulsing statistics are fit to functions in Fig. 4 in order to clearly provide a functional prediction of pulse rate. Orbits with zero pulses can not be included on this log-log plot, but the zeros are included in the fits. The radiation-induced pulse rate must be zero at zero flux. Straight line fits in Fig. 4 correspond to power law functions. The left-most straight line is called the worst case. The histogram is the average pulse rate. The average response straight line is fit to the average pulse rate histogram. If pulse rate is P (pulses per ten hours) and HE electron flux is F (electrons/ten hours cm^2) then the pulse rate is given by

$$P = \alpha F^n \quad .$$

For the worst case fit; $n=1.6$ and $\alpha=2.2\times10^{-17}$.
For average response fit; $n=2.4$ and $\alpha=3.8\times10^{-27}$.

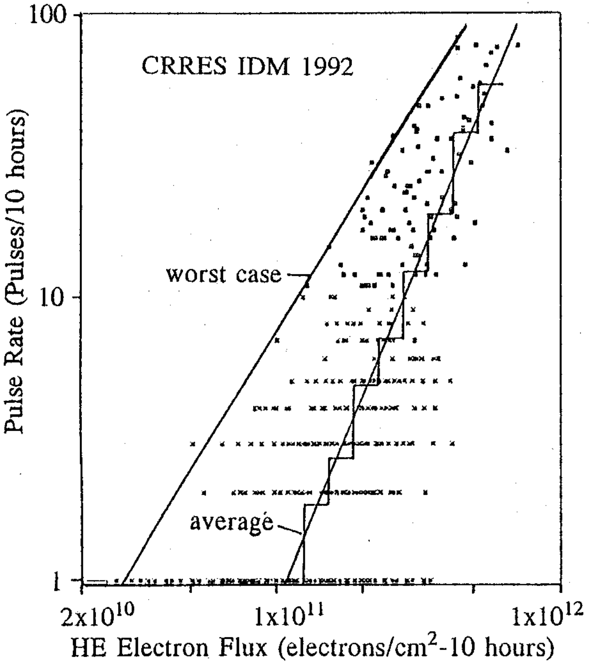

Fig. 4. Pulsing statistics compared with exponential fits. The upper histogram is the average pulse rate, the lower histogram is the median. Each point represents one orbit of ten hours.

The worst case fit applies for up to two days after enhanced radiation levels begin. The CRRES-IDM samples always produced the highest pulse rate per unit flux in the first orbit after the radiation belt flux increased strongly [7]. After two days of constant radiation belt flux, the pulse rate decreases to the average case fit.

These functions are based on CRRES-IDM data which had 125 cm^2 of FR4 circuitboard cut into five samples without electronic components mounted thereon. The FR4 provided most of the CRRES-IDM pulses. One should scale linearly for sample area.

IV. OTHER MATERIALS

CRRES-IDM flew a few samples of other materials. Teflon TFE circuit board with fibers also pulsed frequently. Pure Teflon FEP sheet pulsed less frequently, but if it had been filled with fiberglass reinforcement it probably would have pulsed very frequently. TFE-insulated wire pulsed only early in the CRRES-IDM flight. One may refer to the flight data [7] to estimate a pulse rate for other materials flown on CRRES-IDM. Remember to scale linearly for total sample area.

Testing of cables on CRRES-IDM was statistically weak, but scaling to spacecraft wiring provides a significant threat. Each of the four samples was only ten inches long. There were no cable bundles, only single wires and twisted pair. The geometrical complexity of cable bundles may enhance the pulse rate relative to simple wires. Scaling to similar surface area provides nearly as much pulsing by cables as by the circuitboards. Since spacecraft have large quantities of cables, often radiation-shielded only by thermal control blankets, the insulation of cabling is likely to be a major source of pulsing.

Pulse rates for other materials and samples might be determined by comparing ground tests of FR4 with the other materials/samples using very low flux (5×10^{11} per cm^2 per ten hours) of 100 keV to 1000 keV electrons for several weeks. One must be careful to first expose the samples to vacuum for several months in order to outgas the mobile ions that otherwise may prevent the development of high electric fields inside the insulator. The ground test data could then be extrapolated to space levels of HE electron flux by using the CRRES-IDM data; the functional fits in Fig. 4 provide a method for scaling to low fluxes. Or, one could choose another function if ground tests indicated another function to be appropriate for the particular material.

V. DISCUSSION AND CONCLUSIONS

The major conclusion is that pulse rate by insulators is roughly proportional to the HE electron flux (at the insulator surface) to the power n, where n is between 1.5 and 2.5. Thinner shielding results in greater pulse rate. We have not yet found a "safe" flux below which no pulsing occurs, and thus earlier guidelines are unreliable. The size of a pulse seems to be independent of HE electron flux, but the data is not sufficient to prove this.

The occurrence of a pulse rarely means that the spacecraft will experience an anomaly. The pulses are expected to occasionally disrupt some circuits but rarely burn out a device [4,6]. Many devices would recover from the disruption, unnoticed by the operator, and continue operating. A particular pulse is not expected to uniformly impact all circuits on a board, it will couple more into some circuits than into others. Thus, not every pulse will be noticed by the spacecraft operator. The pulse rate occurring on the spacecraft is likely to be many times larger than the problem rate seen by the ground operators. Small pulses are much more frequent than larger pulses [7]. CRRES IDM insulators pulsed much more frequently than spacecraft experience anomalies, and most of the IDM pulses were smaller than 10 volts. The size of the pulse did not correlate with electron flux.

The functional fits are indicative of a new design guideline. The pulse rate may go to zero for fluxes below $2x10^9$ electrons/cm^2-hour, but the CRRES-IDM data is not sufficient to prove this. This is nearly a factor of ten below our previous guideline [4]. However, note that many ten hour periods occurred without pulses even at five times this flux level. The relationship between flux and pulse rate is not simple. The longer samples remained in space, the more likely they were to pulse [7]. Samples were most likely to pulse within a few days after the HE electron flux increased and changed spectra when worst case pulsing rates were observed.

One can not generate a firm guideline for spacecraft that must operate for 5 years based on only 50 hours of low flux data from CRRES. Our guideline is soft, but it is far superior to previous guidelines. It is based on real space data accumulated over long exposure, 14 months. There is no other space data of measured insulator pulsing. One must be cautioned that the aging history of samples may be very important for the probability for pulsing [7]. In addition, the geometry of the samples may be very important. The CRRES samples had simple geometry, but ground based experience indicates that the more complex the geometry, the more likely that there are weak points that help to initiate pulsing and enhance local fields. An <u>accurate</u> prediction of pulse rates is not available at this time.

Extrapolation to other insulator materials is difficult at this time. The CRRES IDM had other insulators, but the number of samples was too small to provide certainty. One sample of Teflon (PTFE) fiberglass circuitboard also pulsed with similar statistics [7]. Only FR4 circuitboard data is sufficient to provide a guideline. One might wish to test other materials on the ground and extrapolate to space by comparing the ground test to similar ground tests of FR4.

VI. REFERENCES

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