The CRRES IDM Spacecraft Experiment 
For Insulator Discharge Pulses


Abstract—The Internal Discharge Monitor (IDM) is designed to observe electrical pulses from common electrical insulators in space service. The characteristics of the instrument are described. The IDM was flown on the Combined Release and Radiation Effects Satellite (CRRES). The sixteen insulator samples included G10 circuit boards, FR4 and PTFE fiberglass circuit boards, FEP Teflon, alumina, and wires with common insulations. The samples are fully enclosed, mutually isolated, and space radiation penetrates 0.02 cm of aluminum before striking the samples. Published data in the literature provides a simple method for determining the flux of penetrating electrons. The pulse rate is compared to the penetrating flux of electrons.

I. INTRODUCTION

The primary purpose of this paper is to describe the IDM instrument itself. Other papers will describe and interpret the actual pulsing results in space. This paper does not discuss the origins of pulses in irradiated insulators. The IDM focuses its attention on the electrical discharging effects of radiation which penetrates a satellite and stops in the insulating materials, high voltages on other adjacent charged insulator surfaces, a complicated transfer function between the discharging circuit and the sensitive circuit, etc.

The total process is much too complex for the IDM to study. The IDM only detects the number of pulses which occur above a threshold level on simple representative generic circuit elements. Thus, it tells us how often such pulses are occurring but nothing about the nature of the pulses. Our ground tests lead us to believe that these same pulses would occur more frequently on similar samples exposed directly to space on the surface of a satellite (where the radiation flux is highest).

Space radiations acting directly on insulating materials are able to produce electric pulses, independently of the potential of the spacecraft. The radiation intensity in space is so low that the pulse rates can not be predicted with any certainty. Ground testing, extrapolated to space radiation intensities, hinted that pulse rates from small samples might be as high as a few per day in space [1]. However, the extrapolation is very uncertain because the effects of electrical conductivity at high fields in the insulators can not be predicted in space service.

Most of the previous “Spacecraft Charging” work [2] concentrated on the voltages of surfaces on the satellites. Some studies of surface voltages of bodies in space preceded the spacecraft era. E. C. Whipple provides a good review of the phenomena [3]. The most sophisticated attempts at predicting the surface potentials of spacecraft are by the NASCAP code [4] and it has been applied to a number of satellite configurations [4], [5]. NASCAP applies the concepts which were reviewed by Whipple to the complicated structure of a spacecraft by applying 3-D computer simulation of the motion of electrical charges external to the spacecraft materials.

It has become clear that the satellite surface voltages alone are not sufficient to cause the large number of anomalous events seen on satellites. Both theory and in-space measurements (by measuring the shift in the energy of incoming charged particles) find that satellites have not become charged to over 20 kV, rarely become charged as high as 10 kV, and only occasionally are charged to the 1 kV level. References [6]-[9] are indicators of the level of, or perhaps the lack of, correlation between spacecraft anomalies and satellite potentials. Many anomalies have occurred when the potential of satellites were below 1 kV, some when the potential was below 10 V. A large object like a satellite in empty space is not expected to experience a discharge caused by high

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voltage, 20 kV, alone. The differential voltage (usually < 3 kV) possibly developed by radiation between adjacent surface elements of a satellite is not tested on actual satellites to produce discharge pulse events. For the purpose of investigating differential charging effects, in-space anomalies have rarely been properly correlated to ground tests. A proper correlation procedure would determine the in-flight differential voltage between specific spacecraft components, and then see if these differential voltages approached those that produce pulsing in ground tests where the voltage levels are known. To date, we feel that with no confirmation that we know the sources of in-space pulsing beyond the fact that radiation is a cause.

Component level ground tests indicate that irradiated insulators, even with grounded surfaces, produce pulses [1], [10]. Discharge theories, as well as ground tests, tell us that pulses from samples internal to a satellite are potential threats. IDM exists to see if these pulses actually do occur. The IDM results prove that they do; even the grounded-surface samples produce pulses.

The IDM results are teaching us that simple insulators, irradiated by space electrons with energies predominantly above 100 keV produce significant numbers of pulses. The results are adding to the evidence that irradiated insulators are an important cause of spacecraft anomalies. We are also developing a feeling for the magnitude of the pulse rate as a function of space radiation intensity, at least for the IDM samples themselves.

This paper describes the CRRES IDM Experiment. The IDM sample pulse rates can be compared to the simultaneous measurement of space radiation. The paper also describes the pulse detectors, the sample temperature history, and the procedures to verify the data from space. Finally we describe the application of CRRES space radiation data to the analysis of IDM insulator pulsing data.

II. THE EXPERIMENT

The instrument and samples are briefly described in a previous publication [11]. This paper describes them more completely. The samples were chosen for their generic nature; they are representative of the many materials and device structures used in most spacecraft. Fig. 1 is reproduced here to indicate the form of the samples. Table I lists the samples, their configurations and their pulse production in space.

A. IDM Samples

The samples were chosen after an extensive testing program [1]. Table I lists the samples and their electrode configurations. The CHANnel number is the identifying number of the pulse detecting channel to which the sample is wired. There are sixteen samples, one in each of the sixteen channels. \( V_{\text{max}} \) is the maximum pulse voltage measured in ground tests on a 50 ohm line (sometimes 25 ohms): from [1] for configurations 1–6, and from [12] for configurations 7 and 8. CONFIG is the number in Fig. 1 corresponding to the geometry of electrodes and sample. PULSES is the number of pulses accumulated in space, over 13 months (IDM was turned off from 20 Dec. 90 to 20 Jan. 91 during a period of weak electron fluxes.) Most of the insulators and configurations are also described in [1]. However, configuration 1 in [1] is not used in IDM. Configurations 7 and 8 are included to monitor the probability of discharge pulses in another instrument on CRRES, the MEP. However, ground tests were limited by observation time constraints such that most samples experienced only a few ground test pulses. We know of no reason to believe that pulses are limited to \( V_{\text{max}} \).

The planar samples were all square, 5 cm \( \times \) 5 cm. The wires were about 20 cm long. The FR4 epoxy fiberglass circuit board was made by Micaply Co. They no longer make it but it is believed to be similar epoxy to other FR4

<table>
<thead>
<tr>
<th>CHAN</th>
<th>Sample description</th>
<th>( V_{\text{max}} )</th>
<th>CONFIG</th>
<th>PULSES</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>SC18 wire, type ET 7 MIL, PTFE</td>
<td>9</td>
<td>1</td>
<td>4</td>
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<tr>
<td>2</td>
<td>TS Triax Raychem 44/2421</td>
<td>5</td>
<td>5</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>MEP G10 Solithane coated</td>
<td>50</td>
<td>7</td>
<td>2</td>
</tr>
<tr>
<td>4</td>
<td>FR4 Epoxy fiberglass, 0.317 cm, Cu</td>
<td>5</td>
<td>2</td>
<td>1701</td>
</tr>
<tr>
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<td>RG 316 Belden 83284</td>
<td>0.5</td>
<td>3</td>
<td>0</td>
</tr>
<tr>
<td>6</td>
<td>AJAC Cable RG 402</td>
<td>1</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>7</td>
<td>ALUMINA, 0.102 cm, Cu electrode</td>
<td>40</td>
<td>6</td>
<td>0</td>
</tr>
<tr>
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<td>FR4 epoxy fiberglass, 0.317 cm, Cu</td>
<td>1</td>
<td>4</td>
<td>517</td>
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<tr>
<td>9</td>
<td>FEP Teflon, 0.229 cm, Al Electrode</td>
<td>100</td>
<td>6</td>
<td>24</td>
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<tr>
<td>10</td>
<td>FEP TEFILON, 0.229 cm, Al Electrode</td>
<td>0.2</td>
<td>4</td>
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<tr>
<td>11</td>
<td>PTFE Fiberglass, 0.229 cm, SM-250&quot;</td>
<td>1</td>
<td>4</td>
<td>0</td>
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<tr>
<td>12</td>
<td>FR4 Epoxy Fiberglass, 0.317 cm, Cu</td>
<td>5</td>
<td>2</td>
<td>909</td>
</tr>
<tr>
<td>13</td>
<td>FR4 Epoxy Fiberglass, 0.317 cm, Cu</td>
<td>100</td>
<td>6</td>
<td>109</td>
</tr>
<tr>
<td>14</td>
<td>MEP G10 Solithane with leaky paint</td>
<td>8</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>15</td>
<td>FR4 Epoxy Fiber glass, 0.119 cm, Cu</td>
<td>0.25</td>
<td>2</td>
<td>313</td>
</tr>
<tr>
<td>16</td>
<td>PTFE Fiberglass, 0.229 cm, SM-250&quot;</td>
<td>0.2</td>
<td>2</td>
<td>301</td>
</tr>
</tbody>
</table>
material. The PTFE fiberglass circuit board, type 250, is made by 3-M Co. The SC-18 type ET wire is made by Teledyne Thermatics Co., Elm City, NC. It is a 0.018 cm thick PTFE insulated no. 18 hook-up wire with a specially treated PTFE surface. The alumina and the FEP samples are glued to their electrodes using silver filled epoxy. The dimensions listed in Table I are the thicknesses of the insulating material alone. The nine layer G10 circuit boards, including solithane coating are roughly 1.5" thick.

Because the pulse voltage is so dependent upon many external factors, it is not the exact voltage which is of interest. The occurrence of a pulse of sufficient energy to interrupt normal circuits is of interest. Thus, even pulses of order 1 V on 50 ohms could be of significance for a different geometry or transfer function. In different configurations the pulsed voltage, or energy, from the same kind of material could be much larger. This is especially important where the vacuum space surrounding the sample contains high electric fields (>100 V/cm) from any source [13].

Channel 3 contains a configuration 7 sample of circuit board made of G10 material. This is a nine layer board without any components mounted. Approximately one quarter of the circuit traces are connected to the pulse detector, the rest of the traces are connected to the instrument ground. The surface of the board is treated with urethane (solithane, tm) conformal coating. A ground plane is conductively glued to most of the back side of the board. Under electron beam testing, similar circuits were found to produce 20-40 V pulses several nanoseconds wide [12]. Channel 14 contains a configuration 8 sample of MEP board which is covered with "leaky paint". Samples with leaky paint were seen to pulse only rarely and with pulses less than 1 V in ground tests [12].

**B. Pulse Sensitivity**

Signal generators (square pulse) were used to determine the thresholds for pulse detection in each channel. The pulses in ground tests vary in width from less than 1 ns to as much as 10 ns [1, 12]. Most pulses are between 2 and 5 ns wide. Fig. 2 gives the detector thresholds. Broadly speaking, the thresholds vary from a tenth of a volt to fifteen volts on the 50 ohm detectors. All detectors have two sensitivity settings, full or attenuated. Channels 3, 7, 9, 13 are less sensitive than the other channels. Channels 3, 9, 13 have thresholds of order 15 V when they are attenuated. The detectors were set to full sensitivity during most of the 14 month flight.

Much larger pulses would result from the same phenomena occurring on larger samples or on samples with applied voltage on the electrodes [10], [13], [14]. The pulses monitored on these samples are assumed to reflect the phenomena of satellite anomalies produced by discharges on wiring, solar array insulator, thermal blankets, antenna insulators, circuit boards, feed-thru insulators, and other electrical component insulation. It is widely known that the maximum size (total energy) of such pulses scales linearly with the area of the charged dielectric [14]. Therefore, since the size of IDM samples is small relative to many spacecraft applications, it is wise to make the IDM instrument sensitive to small pulsed voltages.

**C. Crosstalk Between Channels**

Five-nanosecond pulses were applied to each channel, one at a time, to measure the crosstalk between channels. Although the samples are fully isolated from one another, the detectors use a common power supply and are in a common enclosure. The signal levels which produce crosstalk were determined empirically. Table II provides the crosstalk data. The pulse voltage was raised until

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### TABLE II

<table>
<thead>
<tr>
<th>Channel tested</th>
<th>Threshold volts</th>
<th>Xtalk channel</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>+16; -16</td>
<td>2; 2</td>
</tr>
<tr>
<td>2</td>
<td>+31; -54</td>
<td>1; 3</td>
</tr>
<tr>
<td>3</td>
<td>&gt; +70; &lt; -70</td>
<td>none; none</td>
</tr>
<tr>
<td>4</td>
<td>+26; -59</td>
<td>2; 1, 2</td>
</tr>
<tr>
<td>5</td>
<td>+11; -25</td>
<td>6; 6</td>
</tr>
<tr>
<td>6</td>
<td>+21; -36</td>
<td>5; 5, 8</td>
</tr>
<tr>
<td>7</td>
<td>&gt; +70; -70</td>
<td>none; 5</td>
</tr>
<tr>
<td>8</td>
<td>+48; -45</td>
<td>5; 7; 6, 7</td>
</tr>
<tr>
<td>9</td>
<td>&gt; +70; &lt; -70</td>
<td>none; none</td>
</tr>
<tr>
<td>10</td>
<td>+47; -54</td>
<td>9; 11</td>
</tr>
<tr>
<td>11</td>
<td>+70; -54</td>
<td>9; 12; 9</td>
</tr>
<tr>
<td>12</td>
<td>+39; -44</td>
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</tr>
<tr>
<td>13</td>
<td>&gt; +70; -70</td>
<td>none; 13</td>
</tr>
<tr>
<td>14</td>
<td>+27; -24</td>
<td>13; 16</td>
</tr>
<tr>
<td>15</td>
<td>+35; -46</td>
<td>16; 14</td>
</tr>
<tr>
<td>16</td>
<td>+30; -30</td>
<td>13; 13</td>
</tr>
</tbody>
</table>

**Fig. 2. Pulse detection thresholds.**

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crosstalk began to occur, and hence the voltage was not raised further. The pulse generator was limited to 70 V.

The crosstalk data may be used to determine if some pulses exceed the threshold for producing crosstalk. In fact, this has happened in space and the pattern of crosstalk mimics that seen in Table II. The crosstalk produced by pulses of less than 70 V is confined within 9-12, and 13-16. This occurs because the pulse detectors responded simultaneously. This test was performed according to MIL STD 1541 on the test bench, not on the satellite. Thus we know that events seen in all 16 channels of IDM. Multiple channels, as well as all sixteen channels, responded simultaneously. This test was performed according to MIL STD 1541 on the test bench, not on the satellite. Thus we know that events seen in all 16 channels may have occurred externally to the IDM during flight. This test technique is not easily related to detection levels on the satellite in space, so we don't pretend to have calibrated the external-pulse all-channel detection sensitivity. We only know that external arcs produce all-channel pulse counts.

### III. INSTRUMENT TESTING

Extensive tests were performed on the instrument, both as a stand alone instrument and on the satellite, to determine if it is compatible with the entire satellite. Through many days of testing there were no false events due to operations of the other parts of the CRRES satellite. Because the IDM is a self shielded structure, false events can only be introduced by the power or telemetry lines. The power lines are well filtered, mostly because of the constant-power IDM power supply which isolates the IDM circuits from short power line transients. Large power line transients produce obvious multiple interference signals on many data sets in IDM (such as power supply voltage readings) and therefore such events can be determined and subsequently ignored. Noise pulses on the telemetry lines which are large enough to produce a signal on the IDM detectors are already a false event on the telemetry stream and can not be filtered anyway. During the satellite ground tests the IDM operated exactly as expected and accumulated no false events from satellite operations which were chosen to maximize the emission of noise from all CRRES satellite instruments. The space data has also been very clean.

The IDM was run for several days at its lowest design temperature, -10°C, and again at its highest design temperature, 40°C. There were no flaws in its operation. The IDM has operated satisfactorily for close to 100 full days spread over a 4-year period while waiting for launch, and for the 14 mo CRRES satellite life in space.

The IDM results can be checked for errors. The pulse counter within the IDM would increment its count only when it received a pulse from one or more channels. Once a day every channel is tested four times by a separate pulse generator in IDM. The IDM transmits the data in its raw format to the ground where the detailed form of the data can be inspected. The IDM did not generate any false counts while it was in the daily self-testing mode. It missed at most 0.2 percent of the test pulses. The data stream was checked by hand for a time span before, during and after every calibration pulse and every reported event.

It is unlikely for flipped bits in the telemetry stream to produce a false count. The IDM reports its latest results again and again every 32 sec. If a false event to be scored from a telemetry error, the pulse counter would have to accidently increment itself and the next reports would have to have the same bit flip telemetry error sequence. This is very unlikely. There were very few once-only telemetry errors, and negligible repeated telemetry errors. All of the IDM results were checked by hand and we believe that no false counts were collected.

We did find a number of counts where the pulse counter did count a pulse, but the channel of origin and the time of occurrence were not known because the telemetry was lost for a substantial time (several minutes to an hour). These counts are not reported in our publications. Because of lost telemetry the actual number of events in space was two or three percent higher than the verified events reported by us.

### IV. RESULTS IN SPACE

This paper describes the IDM instrument and its experiment protocol, it does not report the in-space insulator
sample results. Those results are lengthy and detailed and will be reported elsewhere in the literature. Reports on sample pulsing data will be associated with “analysis and explanations” about why the insulators responded the way that they did. However, some in-space data are common to all of the samples and are therefore reported here.

A. Sample Temperature History:

Four thermistors were mounted near the samples. They consistently gave good agreement with one another (2°C) and they were originally calibrated to within 2 degrees C in the IDM itself. The temperature history of the samples is provided in Fig. 3.

B. Comparison with High Energy Electron Fluence

The radiation detectors on CRRES provide a measurement of the radiation spectra which impinge on the IDM. The spectra of electrons incident on the samples should be calculated by transporting the incident CRRES spectra through the 0.20 mm aluminum cover sheet. Pulse rates may then be correlated with the spectra which directly impact the samples. The cover sheet stops all electrons below 150 keV, and passes almost unimpeded an isotropic electron electron flux above 1 MeV. The effect of the cover sheet is small for electrons above 1 MeV.

We are well aware that electron energy is an important parameter for insulator charging. Very high energy electrons pass through the samples providing little charging while adding to the conductivity of the material by exciting electron hole pairs. Low energy electrons may be stopped in the grounded front electrode on the sample and thereby contribute nothing to insulator charging. For now, we simply determine the number of electrons penetrate the aluminum cover plate. We note that the cover plate severely reduces the flux of electrons incident at energies below 200 keV from that which is incident at the surface of CRRES. One of us (ARF) has experience relating the charging and discharging of insulators with the details of the radiation spectrum [10]. We have learned that irradiated insulators are often on the “hairy edge” for pulsing and that more careful modeling can improve the determination of the time evolution of electric fields. But pulsing is another matter; one cannot predict whether or not a pulse will occur, nor what the pulse rate will be, even if perfect prediction of the electric fields can be made [15]. The materials are not being stressed to the fundamental breakdown strength, they are only approaching a practical breakdown strength where one expects them to last from hours to perhaps years before the breakdown event actually happens. We have state of the art prediction capabilities for electric fields in irradiated insulators and we feel that electron energy spectrum is a first order measure of the electrons which are absorbed in the IDM samples. If needed, the count data is temporarily available in time increments as small as a half second, and will be permanently available in time increments of roughly 15 min.

The HEEF also provides a measure of the energy spectrum of the electron flux. Primarily HEEF measures the spectrum above 1 MeV, but the first two detectors in HEEF provide a measure of lower energy fluxes, down to 200 keV. HEEF is presently being calibrated for this lower energy region. Another instrument, the MEA, provides a measure of the electron flux between 200 keV and 1 MeV, but it is subject to false counts when the proton or high energy electron flux is too high. The MEA can be used in conjunction with HEEF in the radiation belts where the fluxes are not too high.

In general, one would estimate the energy spectrum to first order as a power law spectrum, \( N(E) = CE^{-\alpha} \). The power \( \alpha \) varies strongly through one CRRES orbit. It also varies strongly from orbit to orbit. We have made preliminary measures of \( n \), averaged over each orbit, from raw uncorrected HEEF data above 1 MeV. We find that orbits vary from a low average \( n = 3 \) to a high average \( n = 7 \). More accurate measures of \( n \) will be available in the future.

Instantaneously, the electrons impacting the surface of the IDM are not isotropic. However, averaged over several spins of the satellite (one spin takes 30 sec) we assume an isotropic distribution. The CRRES orbit is near equatorial and spins about an axis which points to the sun. Thus the spin axis is approximately perpendicular...
to the earth's magnetic field. The instruments face outward from the equator (belly band) of CRESS. Thus the instruments' surface normals have an approximately uniform distribution of angles with respect to the magnetic field when averaged over time \( \gg 30 \) seconds. This, combined with the pitch angle distribution of electrons about the magnetic field, results in a crude approximation to a hemispherical isotropic flux of electrons impinging on the surface of the IDM. One could include detailed angular distribution functions which are available from the CRRES spectrometers, but we see no reason to do this for the IDM.

Pulsing first began on one sample on the seventh orbit. The second sample began pulsing on the ninth orbit. The third sample began pulsing on the eleventh orbit. It takes time to get the samples charged up to a pulsing level, and there are strong differences among samples. Thus, spin averaging over 30 sec is not compromising our data.

At this stage in our work it seems unnecessary to maintain spectral details with time increments finer than one orbit (10 h) for the initial comparisons of IDM results to predictions. The electric fields in the IDM insulators build up very slowly, taking days to months (depending on location in the insulator) to reach the large values which can induce pulses. The IDM electron data files are being recorded and stored in 1/5 magnetic L shell bins. For the CRRES orbit these bins are typically 10-15 min of flight. It is expected that the assumption of a constant intensity and energy spectrum during fifteen minute time bins is adequate for all IDM analysis in the future.

C. Determination of Penetrating Flux

Interpolation of Tabulated Data: The effect of the cover sheet on electrons can be determined. For the first IDM studies we chose to extrapolate existing data concerning the number of electrons transmitted, but not their energy. Later, we provide a crude recipe for estimating the energy spectrum as well. Seltzer [16] provides the important information that we may extrapolate between incident energies based on the parameter \( L/R_p \) where \( L \) is the sheet thickness and \( R_p \) is the continuous slowing down approximation (csda) range. The csda range is tabulated [17] as a function of electron energy. Watts and Burrell [18] provide the fraction of electrons penetrating a sheet as a function of angle of incidence and sheet thickness for incident 500 keV electrons. We extrapolate to energies from 150 keV to 1200 keV through the parameter \( L/R_p \). Additionally, Tabata and Ito provide an expression [19], [20] for calculating the transmission of electrons as a function of energy and angle. Interpolated data from Table B1, pg. 53 of Watts and Burrell [18] for 500 keV electrons is reproduced here in the asterisk (*) columns of Table III. We divide our isotropic incident electrons into angular bins as shown in Table III and interpolate from Watts and Burrell to the center of the bin.

The honeycomb structure which fastens the thin aluminum sheet prevents electrons from being incident at angles above 80 degrees, blocks half the electrons at 74 deg, blocks 1/4 at 60 deg, etc. No electrons can penetrate the satellite to be incident at the back of the samples. The effect of these factors is that we have roughly 4.2 steradians of view from the sample surfaces, not the full \( 4\pi \) steradians.

Table IV, the fraction transmitted for each value of \( L/R_p \) is calculated from Table III by summing over angle the fraction transmitted times the factor \( F \). With these approximations we can correlate the pulses with the electron flux hitting the samples. The data are in units of electrons/cm²-Steradian-second-keV. Integrating over the time of one orbit provides electrons/cm²-Steradian-keV-orbit. Multiplying by factor \( 2\pi N \) provides electrons/cm²-keV-orbit. The factor \( 2\pi N \) is obtained for any energy from 150 keV to 1200 keV by interpolation in Table IV. Integrating over the electron energy range provides electrons/cm²-orbit.

We determine the number of electrons incident on the samples per orbit from the CRRES High Energy Electron Fluxmeter (HEEF) data by transmitting them through the 0.2 mm aluminum sheet in narrow energy bins and summing over the energy bins. Each energy bin corresponds to an energy channel of the HEEF instrument. We assume that all electrons are at the center of their energy bin. The transmission factor for each energy bin is interpolated from Table IV. The orbital electron fluence transmitted through the IDM cover for incident electrons from 0.85 MeV to 8 MeV is shown in Fig. 4. This is the range of energies covered by the HEEF Instrument. The range will soon be extended down to 200 keV.

Transmission Data From Tabata and Ito: An alternate Method for computing the parameter \( 2\pi N \) is to use Tabata and Ito's expression for electron transmission. The expression [19] of Tabata and Ito can be numerically integrated over incident angle to obtain the fraction of electrons transmitted through thin foils for incident energies from 0.5 to 10 MeV. Although the expression is an analytic function, we have not analytically integrated it over the incident angles. Instead, we used a numerical integration technique commonly available on personal computers to determine the fraction transmitted at closely spaced energy intervals. Because the expression is constructed using the parameter \( L/R \), we find that it is reasonably safe for our purpose to use it down to 0.2 MeV. Many works have shown that penetration of electrons varies only slowly with energy if the penetration length \( L \) is scaled by the range \( R \) [16], [18], [19]. It is necessary to use their term \( R_{csda} \) extrapolated range, in this expression. \( R_{csda} \) is obtained from another paper [20] and is slightly different from the csda range discussed earlier.

We determine the factor \( 2\pi N \) from Tabata and Ito [19], [20] as follows.

\[
2\pi N = 2\pi \int_{0}^{72^\circ} \eta(\theta) \sin \theta \, d\theta,
\]

where \( \theta \) is the polar incidence angle measured from the surface normal and \( 72^\circ \) is the cutoff angle assumed for the
honeycomb shadowing. The term \( \eta(\theta) \), the fraction transmitted, is given [19] by

\[
\eta(\theta) = \frac{1 + \exp[-s(\theta)]}{1 + \exp\left[\frac{L}{R_{cs}(\theta)} - s(\theta)\right]}
\]

The terms in this equation are determined from the incident electron energy and from the cover plate as follows.

\[
s(\theta) = a_1 \cos^2 \theta,
R_{cs}(\theta) = R_{cs}(T, Z) \cos \theta.
\]

\( R_{cs}(T, Z) \), the extrapolated range, is obtained from [20]. \( Z \) is the atomic number of the cover plate and \( T \) is the energy of the incident electron in MeV. We reduce the energy to units of the rest mass energy of the electron,

\[
\tau = \frac{T}{0.511}.
\]

The rest of the terms are functions of the cover material and electron energy as follows:

\[
a_1 = b_1 \exp \frac{-b_2}{1 + .042r_{1.86}},
a_3 = \frac{b_3}{\tau^{0.86}},
a_5 = \frac{b_5}{\tau^{0.56}}.
\]

The constants for aluminum are: \( b_1 = 6.929, b_2 = 0.652, b_3 = 1.711, b_4 = 0.086, b_5 = 0.5237, b_6 = 0.0191 \). Reference [19] provides the \( b \) constants only for aluminum, we are not aware of constants for any other material. We have reproduced the equations of Tabata and Ito so that the reader might see why we took the approach that we did. Refer to the references [19], [20] concerning the accuracy of the expression or for leads to other approaches [21] in the literature.

The honeycomb structure which supports the 0.2 mm cover plate provides a soft cut-off to the electron flux produced by electrons incident above 45 degrees. When integrating the expression over incident angle we used a hard cut-off at 72 degrees. This provides the value of 4.2 steradians of view which we mentioned above.

Fig. 5 plots the factor \( 2\pi N \) as a function of incident energy. WB is from Watts and Burrell and TI is Tabata and Ito.

The constants for aluminum are: \( b_1 = 6.929, b_2 = 0.652, b_3 = 1.711, b_4 = 0.086, b_5 = 0.5237, b_6 = 0.0191 \). Reference [19] provides the \( b \) constants only for aluminum, we are not aware of constants for any other material. We have reproduced the equations of Tabata and Ito so that the reader might see why we took the approach that we did. Refer to the references [19], [20] concerning the accuracy of the expression or for leads to other approaches [21] in the literature.

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proportion to distance travelled, \( L \), as \( E(L) = E_{\text{inc}}(1 - L/R) \) for distances \( L < R \). For \( L > R \), \( E(L) = 0 \). This function was obtained by inspection of transmission data for normally incident electrons [21]-[24]. One may then assume that all the electrons with \( E_{\text{inc}} \) are transmitted with this mean energy, \( E(L) \). We have not found a correction for non-normal incidence in the literature, but we feel it is not a substantial correction considering the other approximations implicit in this method. The number of electrons transmitted with initial energy \( E_{\text{inc}} \) has already been determined above in Fig. 5. For example, the electrons above 1 MeV have been transmitted without significant loss of energy, and the loss of flux is only a factor of 4.2/2\( \pi \). At 310 keV incident electron energy \( L/R = 0.5 \) so the transmitted energy is 155 keV and the fraction of flux transmitted (Fig. 5 or Table IV) is 1.04/2\( \pi \).

More accurate transmission data could be determined by use of one of the several Monte Carlo transport codes available. However, for several reasons discussed earlier, there is not likely to be a helpful finding even if one does the more careful analysis of electron spectra. Comparison of IDM data with the simple electron flux estimates described above should be adequate.

V. SPACE PULSING SUMMARY

Summing over all samples, we find [25] that the pulse rate correlates positively with electron fluence per orbit. However, each sample has shown its own peculiar response. Some samples pulsed often early in the flight and rarely pulsed after that. Other samples began pulsing only much later [11], [25]. Approximately 4300 pulses have been seen in the fourteen months since launch. The total sample area is about 300 cm\(^2\). Scaling to full satellite insulator surface area exposed to space electrons could result in much higher pulse rates.

Samples with floating metal are pulsing, but not as often as the simple samples without floating metal. The simple samples, configurations 1 and 2, are pulsing most frequently. Note that all of these samples are unbiased. Applied bias might enhance both the pulse rate and the pulse magnitude [13].

Pulses occur even hours after passing through the electron belts [11], [25]. There have been weeks of low electron flux where the pulse rate approaches zero. Maximum pulse rates have been approximately five per hour. The minimum pulse rate data appears to have determined a floor in electron flux levels below which pulses are unlikely [11], [25].

VI. SUMMARY

We have described the salient features and the purpose of the IDM Experiment. The IDM counts pulses from each of several space insulating structures. The pulse statistics of each insulator can be compared with simultaneous measurement of the space radiation flux. The results from space, published elsewhere [25], have been excellent and are very informative.

All indications from the actual space data are that electrons alone are responsible for the pulsing. The effects of protons or cosmic rays are too small to be separated from the overwhelming influence of electrons on the IDM space data.

We have found two simple methods for determining the transmission of electrons through our cover plate. Both methods provide adequate results so that the uncertainty in flux measurements is not controlled by the uncertainty in transmission (±10%) through the cover. The uncertainty in flux measurements now resides with the electron flux spectrometers elsewhere on the CRRES satellite. Additionally, the HEEF instrument first detector provides a direct reading of the electron flux (and the proton flux separately) which has penetrated a thickness equivalent to the IDM cover plate.

The IDM instrument has worked well for the life of the satellite. The on-board pulse generator verified the instrument daily. The data stream was quiet most of the time so that very few of the pulses were unidentified.

IDM has detected 4300 pulses from its 16 samples during its 14 mo flight. Thus, IDM has proven that even at the low radiation fluxes in space, insulator discharge pulses are common. However, IDM provides little information on the magnitude of the pulses. Ground based measurements have already provided the only good quantitative information about voltage magnitudes [1], [2], [10], [12]-[14]. Only very crude estimates of pulse voltages in space have been determined from channel crosstalk in space [25].

REFERENCES


