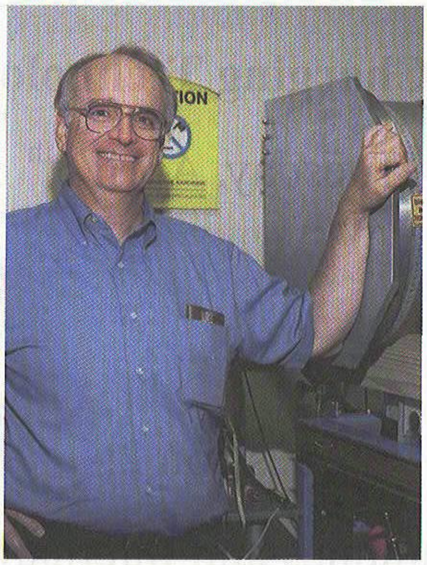
In Memoriam
Arthur Robb Frederickson



A. Robb Frederickson, known as "Robb," died of pancreatic cancer at Huntington Memorial Hospital, Pasadena, California, on April 5, 2004. A Senior Member of IEEE, Robb served as Chairman of the Boston Section IEEE Nuclear and Plasma Sciences Chapter for 10 years and as Secretary for 5 years. In addition, Robb was Treasurer of the 1974 IEEE Radiation Effects Conference.

Robb grew up in Berkeley Heights and Westfield, New Jersey, the son of the former Arthur R. and Bertine B. Frederickson. At Rensselaer Polytechnic Institute he received his B.S. in Physics in 1965. Robb received his MS and PhD degrees in physics from the University of Massachusetts at Lowell. His dissertation, "Recombination-enhanced Defect Diffusion in Semiconductor Devices, Carbon in Silicon," foreshadowed his wide-ranging studies in microelectronic devices and their interactions with the space environment.

After 31 years at Air Force Cambridge Research Laboratory and its reincarnations (AF Rome Air Development Center, AF Geophysics Lab, AF Philips Lab, and AF Research Lab) at Hanscom AFB, Massachusetts, Robb moved to Pasadena, CA, in 1997 when he joined Caltech's Jet Propulsion Laboratory.

He had over 71 publications, presented innumerable talks at conferences worldwide, was granted 5 patents, and authored a well-received book on radiation effects on dielectrics. He capped his Air Force career as Principal Investigator of the CRRES satellite Internal Discharge Monitor. This experiment proved to be a landmark in the study of spacecraft charging and gained him international fame for the seminal findings on the characteristics of internal spacecraft discharges that came from it.

Representative of the way his many friends and colleagues felt about him, one of them recently summarized his contributions: "He demonstrated great physical originality and brought a critical perspective to our spacecraft charging work," and that was merely his first career.

In his second career in Pasadena, he became a recognized expert at JPL and Caltech in spacecraft charging effects. Creating his own plasma physics laboratory, he studied the effects of plasma and space radiation on spacecraft materials and characterized the space radiation belts. Robb consulted for many JPL and commercial spacecraft programs about the effects of plasma and radiation, and helped develop optimum spacecraft designs to avoid the deleterious effects of the space environment. In addition, he took a lead role in training young engineers, helping to develop the next generation of JPL engineers and scientists. His research results, through review papers, scientific meetings, and publications, have permanently secured his place as an international expert in spacecraft design.

Robb received the Air Force Systems Command Technical Achievement Award in 1969. He is listed in *Who's Who in Science and Engineering* and in *Who's Who in America* (Marquis). Robb served the Hanscom Chapter of Sigma Xi as Treasurer and Secretary. In Massachusetts, Robb was active in the Carlisle Boy Scout Troup and in Colonial Wireless. Other memberships include the American Physical Society, ARRL and both the Caltech and JPL Ham Radio Clubs.

Robb leaves his wife of 33 years, Christine, his sons Timothy and Nathan, a daughter Julie, a daughter-in-law Tracey, and a granddaughter Olivia, a great joy of his last year. In addition to his immediate family, he is survived by a brother Alan of New Jersey, four nieces and a nephew, two aunts and many cousins—all on the East Coast.

HENRY GARRETT
Jet Propulsion Laboratory

Spacecraft Charging Phenomena and Spacecraft Design Guidelines

A. Robb Frederickson

JPL Section 513

1–2 May 2003

Outline

- ONE PHENOMENA, But Two Primary Manifestations:
  - Surface Charging
  - Internal Charging
- Existing Design Guidelines for Spacecraft Charging
  - Guidelines are far from complete at this time, yet there are many.
- Wide Assortment of Phenomena in Differing Applications:
  - CASE STUDY 1: In-space Insulator Pulsing,
  - CASE STUDY 2: Coupling from a Breakdown into a Circuit.
- Spacecraft Failure Studies
  - ELECTRIC FIELD FROM CHARGE IN INSULATING MATERIAL IS A PRIMARY CAUSE OF SPACECRAFT ON-ORBIT ANOMALIES.
- Electric Field Controls the ESD Pulse Rate and Pulse Amplitude
- Complete solution of the problem requires knowledge of electric field – very difficult; Ongoing Studies.

CATEGORIES OF SPACECRAFT CHARGING PROBLEMS

Surface Charging (Spacecraft surfaces are charged relative to space.)

- Affects science instruments that measure the space plasma environment by distorting the plasma.
- May present an electrical discharge threat to the spacecraft.
- Creates drag in the space plasma environment.
- Attracts contaminants to the spacecraft surface.
- May cause high-voltage (>50V) solar array failure.
- May generate contamination.

Internal Charging (Internal components, insulators or hardware may become charged relative to spacecraft frame.)

- Insulators are located throughout a spacecraft.
- Thick insulators become charged near breaking point.
- Charging of thin insulators shifts electrical operation. (CMOS)
- Electrical pulsed-discharge threat to the spacecraft.
- Discharges are close-coupled to sensitive circuits.
- Pulse blows-out modern devices similar to human-body model.
- Pulse causes total failure of HV power supplies.

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EXISTING SPACECRAFT DESIGN GUIDELINES (Y-2002)

Surface Charging (Spacecraft surfaces are charged relative to space.)

- Spacecraft are known to charge up to 10 kV relative to space.
- Specific regions of space are known to be worst-case.
- Severe Charging and Discharging have been documented.
- Differential charging among surfaces is documented.
- Classical Design for Electromagnetic Compatibility (EMC) provides most existing mitigation techniques.
- Emit plasma and thereby ground spacecraft. **
- At Earth, sunlight usually prevents negative charging. **
- Calculate surface potential using "current balance method." **
- Make surfaces conductive and ground them. **
- Use old laboratory discharge data to predict pulse threat. ***
- Differential Charging assumed to be calculable. ****

** Reasoning is flawed for certain cases, and may create new problems.

*** Reasoning is fundamentally flawed and leads to severe over-design.

****Reasoning is fundamentally flawed and has led to failing HV solar arrays on commercial spacecraft.

DESIGN GUIDELINES CONTINUE TO BE IMPROVED
SEE YOUR SPECIALIST

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EXISTING SPACECRAFT DESIGN GUIDELINES (Y-2002)

Internal Charging (Internal components, insulators, or hardware may become charged relative to spacecraft frame.)

- Specific regions of space are known to be worst-case.
- Severe Charging and Discharging have been documented.
- Classical Design for Electromagnetic Compatibility (EMC) provides dominant mitigation techniques. *
- Make surfaces conductive and ground them. *
- Calculate surface potential using "current balance method." **
- Use laboratory discharge data to predict pulse threat. ***
- Differential Charging assumed to be calculable. ****

* Will not work in cases where pulse occurs inside the circuit.
** Reasoning is flawed for all cases.
*** Reasoning is fundamentally flawed when lab data is not similar.
**** Reasoning is fundamentally flawed and may lead to under prediction of events, or to failing HV systems.

DESIGN GUIDELINES CONTINUE TO BE IMPROVED
SEE YOUR SPECIALIST

MORE LIMITATIONS OF EXISTING GUIDELINES

- Guidelines do not attempt to predict the number of pulse events that might occur.
- The percentage of orbit time as a function of surface voltage is not predicted, although it has been measured.
- Prediction of the pulse event size distribution is not attempted.
- Amplitudes of both internal charging voltages and pulses are not discussed in guidelines, and have rarely been measured.

Data are available to improve the guidelines, and some specialists sometimes refer to such data when evaluating spacecraft designs.

IMPROVING THE GUIDELINES AND PRACTICES

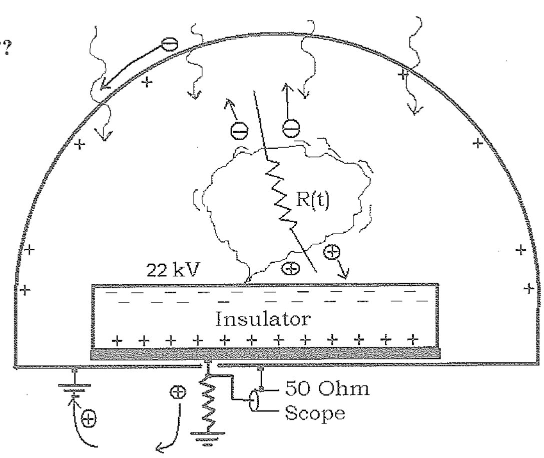
- Several commercial solar array designs have been revised. Even the DS1 solar array required in-production repair. Guidelines are not yet written and experiments are ongoing.
- Discharges allegedly resulting from surface charging have often been cited, yet the sudden drop in surface voltage has not yet been measured in space.
- Internal pulsed-discharges have been cited as causes of spacecraft problems, but their source has not been identified.
- A phased array antenna insulator has arced to burn out the receiver. No direct measurement of antenna arcing has been made.
- Frequent small arcing by thermal blankets in electron belts has been measured by an RF-sensitive spacecraft, but the data and implications have not been published/investigated.

- THESE AND MORE EXAMPLES OF ENVIRONMENTAL PROBLEMS HAVE ACCUMULATED INDIVIDUALLY IN THE LITERATURE, BUT A CENTRAL REPOSITORY DOES NOT EXIST. INSTEAD, SPECIALISTS HAVE ACCUMULATED PERSONAL INFORMATION AND RECIPES FOR BETTER DESIGN.

FOLLOWING ARE SOME SAMPLE CASE STUDIES.

BOTH CASE STUDIES EMPHASIZE PULSED ESD EVENTS (ESD = electrostatic discharge)

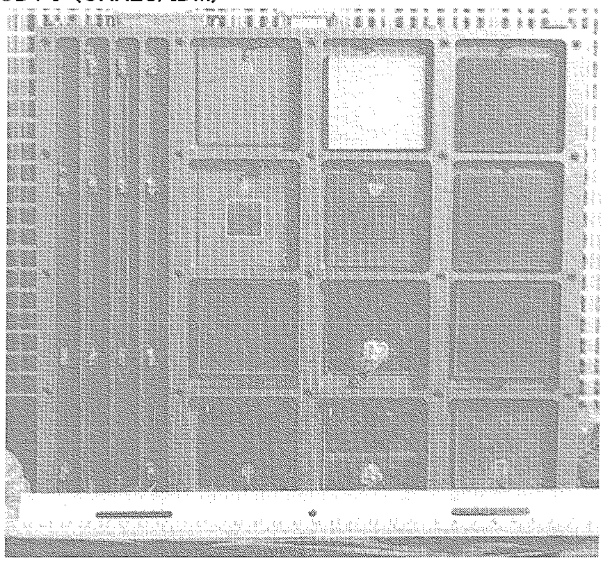
What is an ESD??



Charge Currents in Vacuum During the Pulse. Slightly ionized gas bursts from the insulator and a Townsend avalanche forms a conductive path in vacuum with time dependent resistance R(t).

INTERNAL CHARGING AND DISCHARGING OF CIRCUIT BOARDS ON THE CRRES SPACECRAFT 1990–91

- CASE STUDY I (CRRES/IDM)



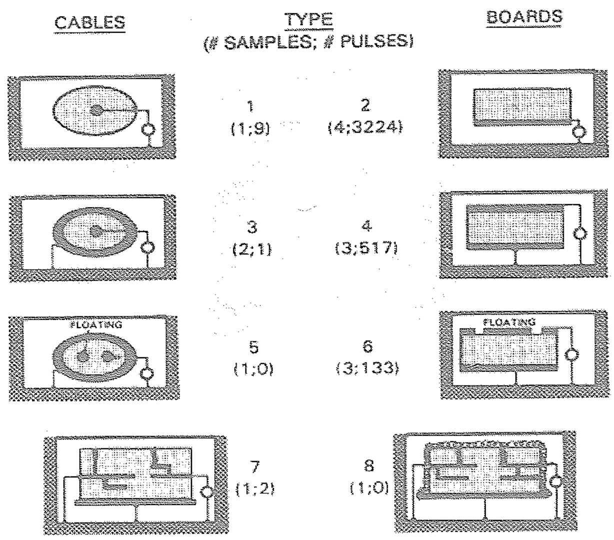
The Aluminum cover is removed to display the twelve circuit board samples and four cable samples. Radiation passed through the 8-mil cover to charge the insulation materials and produce pulsed electrostatic discharges ESD. The pulses were counted.

TABLE OF CRRES/IDM SAMPLES (1990–91)

SAMPLE DESCRIPTION	VM	GEOM	PULSES
SC18 WIRE TYPE ET, 7 mil PTFE	1	1	9, V<16
TS TRIAX CABLE, RAYCHEM 44/2421	5	5	0
MEP G10 SOLITHANE COATED ONLY	50	7	2, V<70
FR4 EPOXY FIBERGLASS, 0.317 cm	5	2	1433, V<25 16, 25<V<60 252, V>60
RG 316 CABLE, BELDEN 83284	0.5	3	0
SOLID AL JACKET RG402 CABLE	1	3	1, V<30
ALUMINA, 0.102 cm, Cu electrodes	40	6	0
FR4 EPOXY FIBERGLASS, 0.317 cm	1	4	516, V<45 1, V>60
FEP TEFLON, 0.229 cm, Al electr.	100	6	23, V<70 1, V>70
FEP TEFLON, 0.229 cm, Al electr.	0.2	4	0
PTFE FIBERGLASS, .229 cm, 3M "250"	1	4	0
FR4 EPOXY FIBERGLASS, 0.317 cm	5	2	903, V<40 2, 40<V<60 4, V>60
FR4 EPOXY FIBERGLASS, 0.317 cm	100	6	101, V<60 8, V>60
MEP G10 SOLITHANE, LEAKY PAINT	<1	8	0
FR4 EPOXY FIBERGLASS, 0.119 cm	0.25	2	294, V<40 19, V>60
PTFE FIBERGLASS, .229 cm, 3M "250"	0.2	2	280, V<30 2, 30<V<60 19, V>60

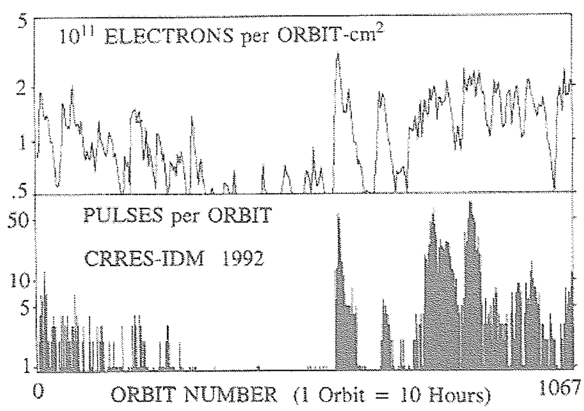
THE IDM CIRCUIT BOARDS HAD SEVERAL METALIZATIONS OR TRACE LAYOUTS

SAMPLE GEOMETRIES



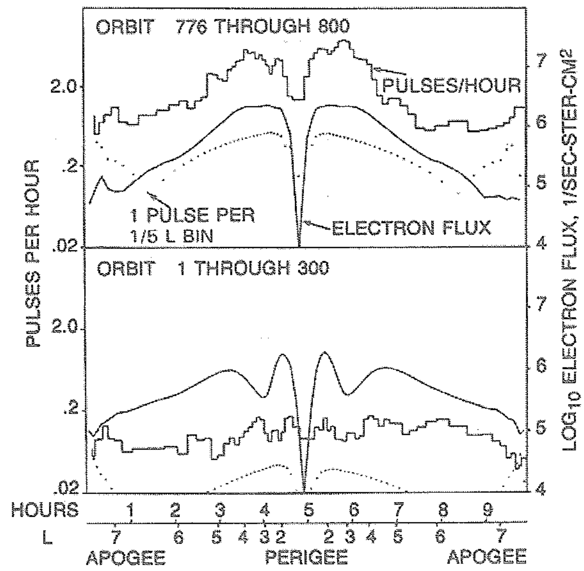
All Sample Pulses vs Space Electron Radiation

Here is plotted the history of pulsing over the 14-month life of the CRRES spacecraft.

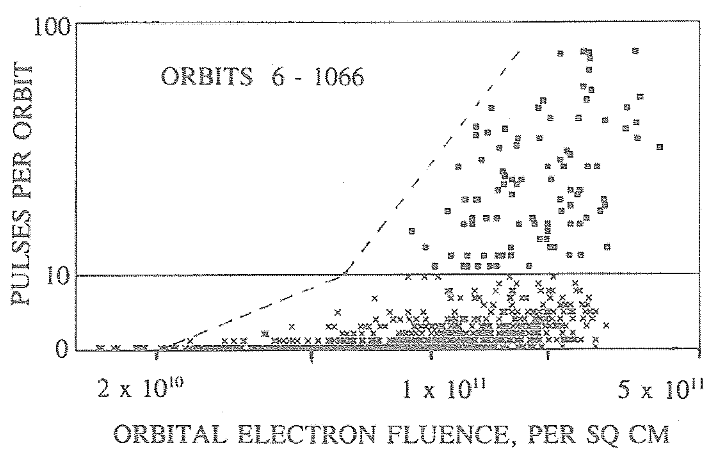


Laboratory testing in 1998-9 demonstrated that the increased pulse rate in the last six months is due to radiation aging of FR4 circuit board.

THE RELATIONSHIP BETWEEN PULSE RATE AND IMMEDIATE ELECTRON FLUX IS INTERESTING. ACCUMULATION OF ELECTRONS OVER PRIOR HOURS DETERMINES HOW MANY PULSES WILL OCCUR NOW.



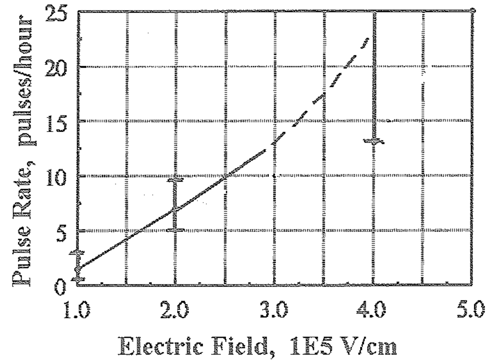
BY PLOTTING THE NUMBER OF PULSES IN EACH 10-HR ORBIT AGAINST THE ELECTRON FLUENCE IN THAT ORBIT, ONE DETERMINES THE (average) DEPENDENCE OF PULSE RATE ON ELECTRON FLUX.



THE IMPORTANCE OF ELECTRIC FIELD

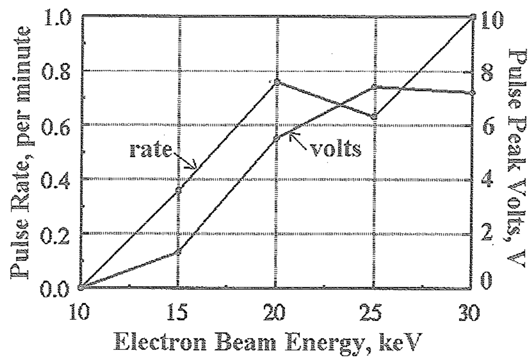
GROUND TESTING IN 1998-9 PROVIDED A RELATIONSHIP BETWEEN PULSE AMPLITUDE AND PULSE RATE. Both the amplitude and pulse rate are strongly dependent upon the electric field strength in the insulator material.

Pulse Rate on FR4 Board in 30 keV Ground Tests at each of the three thickness, 3.18, 1.58 and 0.8 mm. The pulse rate is least in the thickest board



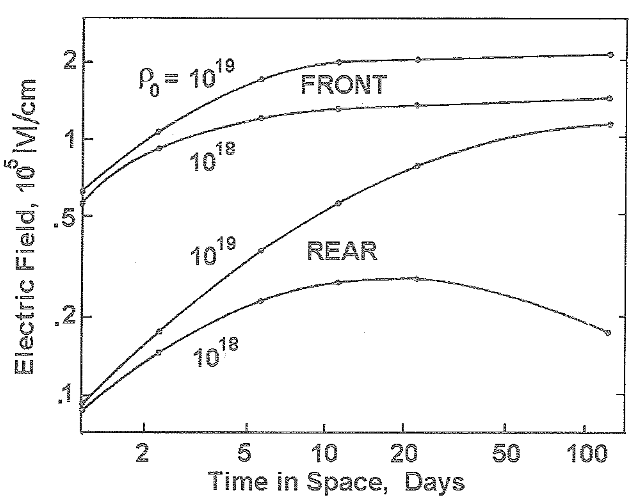
DEPENDENCE OF PULSE RATE AND OF PULSE VOLTAGE UPON BEAM ENERGY.

Beam Energy Is A Surrogate For Internal Electric Field in This Experiment.



The CRRES IDM Spacecraft had a detection threshold of roughly 1-volt.

BOTH THE PULSE RATE AND THE PULSE AMPLITUDE CAN BE RELATED TO THE ELECTRIC FIELD INSIDE AND OUTSIDE THE INSULATOR MATERIAL



Calculated Electric Field in CRRES/IDM Sample Configuration 4 for Two Assumed Values of Dark Resistivity (ohm-cm). Ground testing will soon determine the dark resistivity of several materials using methods recently developed at JPL.

Description of Electric Field Profile in Geometry #4 on CRRES/IDM Spacecraft. Note that the electric field is most negative at the rear copper surface, and most positive at the front copper surface

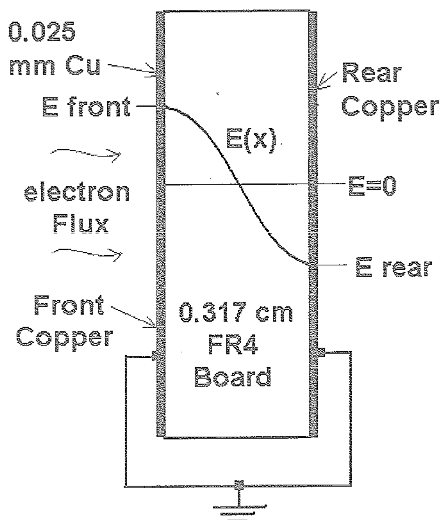


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TABLE OF CRRES/IDM SAMPLES AND PULSES.

The pulses were counted by a 50-Ohm detector when they exceeded a low threshold, typically 1-volt. Some detectors could also determine if the pulses exceeded a higher threshold. The pulse counts and voltage levels are indicated in the Pulses column.

SAMPLE DESCRIPTION	VM	GEOM	PULSES
SC18 WIRE TYPE ET, 7 mil PTFE	1	1	9, V<16
TS TRIAX CABLE, RAYCHEM 44/2421	5	5	0
MEP G10 SOLITHANE COATED ONLY	50	7	2, V<70
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MEP G10 SOLITHANE, LEAKY PAINT	<1	8	0
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PTFE FIBERGLASS, .229 cm, 3M "250"	0.2	2	280, V<30 2, 30<V<60 19, V>60

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CONCLUSIONS FROM CASE STUDY I

Pulses exceeding 1–Ampere peak have been measured in space. They were produced by typical circuit board material.

Pulse amplitudes and waveforms are similar to the human body model that is known to burn-out microcircuits.

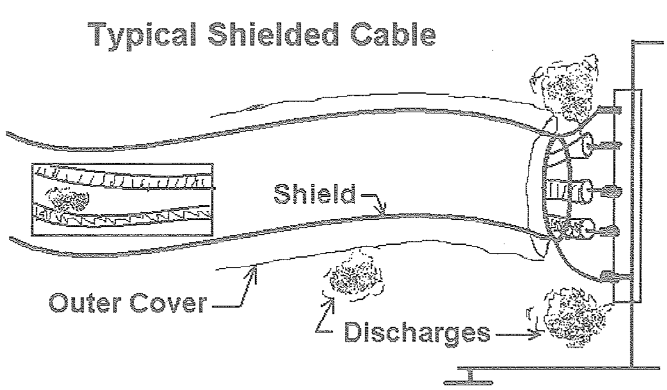
When we determine the electric field generated in the insulator by space radiations we can assess the level of threat produced by the environment.

Initial attempts to relate electric field in space to both pulse rate and pulse amplitude in space are encouraging, but remain embryonic to this time (2003).

The electric field depends strongly on the dark conductivity of the insulating material. This is a parameter that is not generally known. We have recently begun a program to develop methods to determine the values of this parameter in typical insulators.

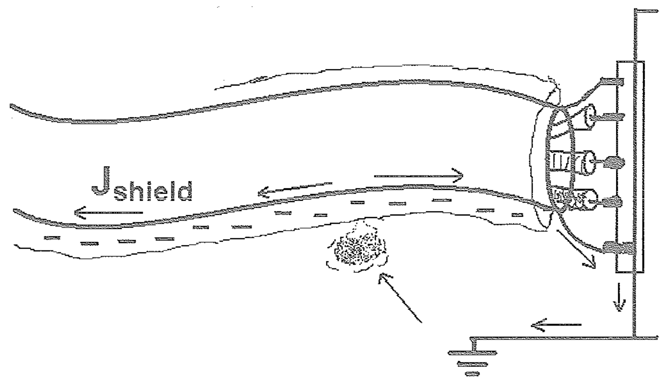
CASE STUDY II

APPLICATION OF THE KNOWLEDGE OF INTERNAL DISCHARGING TO THE DESIGN OF SPACECRAFT CABLING



All four electrostatic pulsed discharge types are depicted as clouds in the drawing. We have learned that with typical tight-braid spacecraft cables the discharge internal to the cable shown in the cutaway view is only very small. In this case study we investigate only the discharge originating on the outer cover.

A discharge originating in the outer cover directly drives a current, J, in the shield. The discharge cloud is partly composed of plasma that carries the current through the vacuum space near the cable. For typical cable outer covers, the worst-case current peaks at less than 3-Amperes. Pulses last less than 100 nanoseconds.



EXPERIMENTAL AND THEORETICAL ANALYSIS OF ELECTROMAGNETIC SHIELDING OF CABLES AND CONNECTORS

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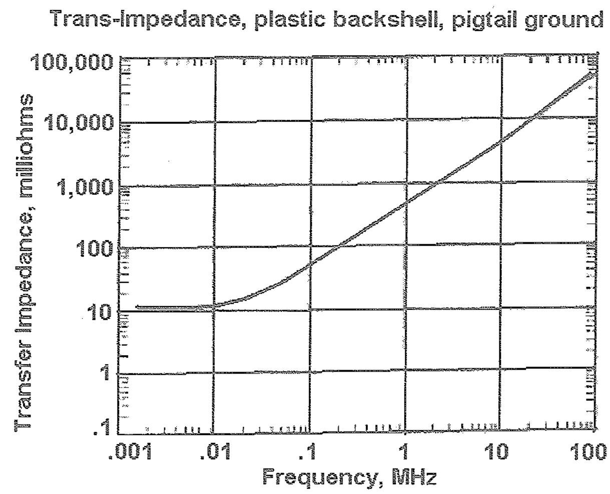
- Trans-impedance is a characteristic of the construction of the cable.
- For electromagnetic energy outside, the coupling to the inside is dominated by the currents induced on the shield. Direct coupling of the external electric field and magnetic field can be ignored.
- Multiply the current induced on the shield by the measured trans-impedance of the cable in order to estimate the voltage in the cable.

One uses the following graph to determine the signal generated inside the cable, in volts. A typical pulse from the outer cover of the cable may be 1-Ampere peak, lasting 50 nanoseconds.

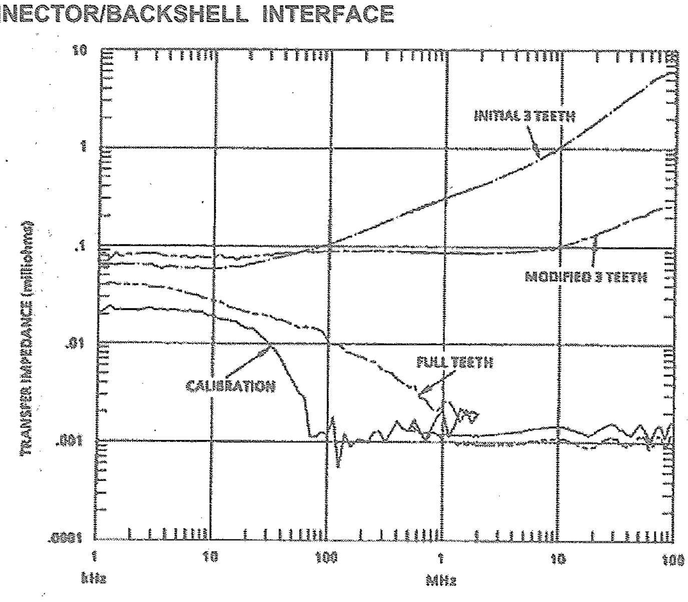
TRANSFER IMPEDANCE OF A DB-25 SUBMINIATURE CONNECTOR/BACKSHELL COMBINATION THAT USED A PLASTIC BACKSHELL AND A PIGTAIL BRAID TERMINATION



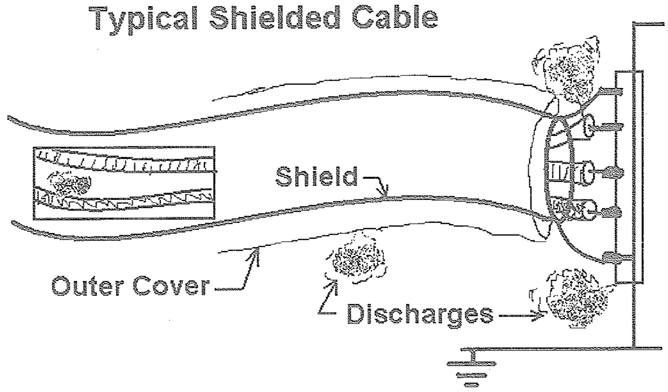
The 1-Ampere pulse has frequency components from 20 MHz through 200 MHz, the cable will produce an internal pulse of 10 to 100 volts.

LOTHAR HOEFT PROVIDES GRAPHS OF TRANSFER IMPEDANCE FOR MANY CABLING SITUATIONS.

TRANSFER IMPEDANCE OF SAMPLES USING THE MS-3155 CONNECTOR/BACKSHELL INTERFACE



Beyond the outer cover there are three more sources of ESD pulsing. Each of those must be measured in a separate experiment. We have determined that the pulses created by the connector body are the largest of the four sources when the electron radiation is at high energy (> 100 keV).



CONCLUSIONS FROM CASE STUDY II (2002)

The pulsed discharge current waveforms have been measured for a variety of samples, and can be measured for new materials.

Recent experiments have provided understanding of the manner in which pulses are created and propagate.

RF propagation theory, antenna theory, EMC guidelines, and other existing information are available to predict the amplitudes of pulses propagating from the pulse itself into nearby sensitive circuits.

Proper cable designs reduce the cable pulses to manageable levels. Pigtail grounding is not proper.

Pulses directly by connectors are of serious concern.

The Success with cables encourages one to feel confident in the future success for other structures as well.

FURTHER RECENT IMPROVEMENTS TO SPACECRAFT CHARGING GUIDELINES

Large Vacuum Tank Test Of Full Spacecraft Surface Charging And Discharging. (Bogorad et al, Lockheed) Demonstrated that the discharge of an entire spacecraft contains factor 100 less energy than scaling of prior lab tests indicated.

More than ten years of measured surface charging and differential surface charging on several Earth spacecraft in various orbits have been collected.

The effectiveness of emission of plasma for reducing surface and differential surface potential has been evaluated in flight. (Mullen et al, AFRL)

The storage of charge in some insulators lasts much longer than old ground-based data would indicate. This by a factor of 1000 in polyimide material. Therefore, we now know that some insulators in space may remain charged for years.

HAS SPACECRAFT CHARGING CAUSED REAL PROBLEMS?

Aerospace Corp. has performed studies to learn that:

Missions Lost or Terminated Due to the Space Environment

Mission	Date	Someone's Diagnosis
DSCS II	Feb 73	ESD
GOES 4	Nov 82	ESD
DSP 7	Jan 85	ESD
Feng Yun 1	Jun 88	ESD
MARECS A	Mar 91	ESD
MSTI	Jan 93	SEE
Hipparcos *	Aug 93	Total Dose
Olympus	Aug 93	Micrometeoroid
SEDS 2 *	Mar 94	Micrometeoroid
MSTI 2	Mar 94	Micrometeoroid
IRON 96	1997	SEE
INSAT 2D	Oct 97	ESD

* Mission Already Completed

Koons, H.C., J. E. Mazur, R. S. Selesnick, J. B. Blake, J. F. Fennell, J. L. Roeder, and P. C. Anderson, "The impact of the Space Environment on Space Systems", presented at Spacecraft Charging Conference, Nov 1998, Hanscom AFB, MA. To be issued as an Aerospace Company Report.

Spacecraft Anomalies but not Failures

Koons *et al.* (1998) at The Aerospace Corporation have compiled data in a systematic way. They report the number of *Forms,* where a single form corresponds to one class of anomalies on a single spacecraft. Thus a single form may represent one or many anomalies of the same type on the spacecraft. The Table is from their report.

Number of Forms by Upset Anomaly Diagnosis

Diagnosis	Number of Forms
ESD - Internal Charging	74
ESD - Surface Charging	59
ESD - Uncategorized	28
Surface Charging	1
Total ESD & Charging	162
SEU - Cosmic Ray	15
SEU - Solar Particle Event	9
SEU - South Atlantic Anomaly	20
SEU - Uncategorized	41
Total SEU	85
Solar Array - Solar Proton Event	9
Total Radiation Dose	3
Materials Damage	3
South Atlantic Anomaly	1
Total Radiation Damage	16
Micrometeorid/Debris Impact	10
Solar Proton Event - Uncategorized	9
Magnetic Field Variability	5
Plasma Effects	4
Atomic Oxygen Erosion	1
Atmospheric Drag	1
Sunlight	1
IR background	1
Ionospheric Scintillation	1
Energetic Electrons	1
Other	2
Total Miscellaneous	36

Lightning Rods for Nanoelectronics

September 16, 2002,

Electrostatic discharges threaten to halt further shrinking and acceleration of electronic devices in the future

By Steven H. Voldman

Some Charging and Discharging References.

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