Appendix E
Test Methods

Tests that can be performed to validate some aspects of charging problems are described conceptually below. The focus here is largely on materials with limited descriptions of component, subsystem, and system tests. Details such as test levels, test conditions, instrumentation ranges, bakeout time, pass/fail criteria, etc., should be considered for any tests. Vacuum bakeout/aging of materials before testing is important because apparent surface properties, especially resistivity, quite often increase with aging in space as adsorbed water and other conductive contaminants depart because of outgassing.

E.1 Electron-Beam Tests

Electron-beam test facilities are to be used to test smaller elements of the spacecraft. This test can be used to determine whether a material sample will arc in a given electron environment and can measure the size of the resultant ESD, if any. Electron-beam tests have the advantage that they are real: the electrons can be accelerated to energies that will penetrate and deposit more or less to the depth desired by the experimenter. They have the disadvantage that the beam is usually mono-energetic rather than a spectrum—the electrons initially will be deposited in a diffuse layer dependent on their energy, rather than distributed throughout the exposed material. Usually, the illuminated area is less than 10^3 cm^2 in size. The real area may not be testable, in which case scaling should be applied to the measured results to estimate the real threat. A typical test configuration in a vacuum chamber is shown in Fig. E-1.

The electron source should have both the requisite energy (usually expressed in keV or MeV) and the requisite flux (expressed as a current (pA/cm^2), or flux

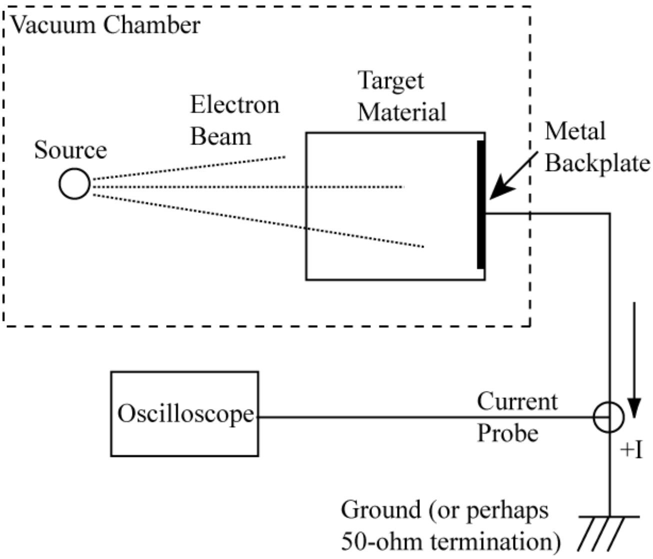


Fig. E-1. Typical electron beam test facility setup.

(e/cm^2-s)). (Note: 1 pA/cm^2 = 6.242 × 10^6 e/cm^2-s). The target material in Fig. E-1 shows a grounded backplate. Some tests may involve a front metal plate, grounded or ungrounded, to simulate the in-flight hardware more closely. In this example, the electrons, after deposition on or in the target material, may leak off to the backplate, or they may remain in the material if its resistivity is high. If they do not leak off to the backplate (harmlessly), they continue accumulating until the electric field exceeds the dielectric strength of the material and an ESD occurs.

The current probe and oscilloscope are used to determine the current waveform of the ESD from the material. If a simple breakdown between the material and the metal backplate occurs, the current probe can measure the discharge directly. From the waveform, the peak current, the pulse width, and the charge are calculated. If there is a 50 Ω termination, the voltage waveform can be measured and the power and energy in the discharge estimated.

The best way to test a dielectric for IESD is to use an electron beam that penetrates to the middle of the thickness. First, dry the sample in vacuum (drying for a month is best), then irradiate at 1 to 10 nA/cm^2 for several hours and monitor all wires. A sample that does not arc after this test will be excellent in space.

Other diagnostics can be included, including a Rogowski coil to measure electrons blown off the front surface of the material to “space” (the chamber walls) or RF field sensors (EMC antennas and receivers) to measure the spectrum of the radiated noise.

E.2 Dielectric Strength/Breakdown Voltage

This number can be used for ESD analyses to determine the magnitude of the ESD. Usually, the dielectric strength (breakdown voltage) of a (dielectric) material is determined from published tables. If necessary, a test can be performed as illustrated in Fig. E-2. ASTM D-3755-97, Standard Test Method for Dielectric Breakdown Voltage and Dielectric Strength of Solid Electrical Insulating Materials Under Direct-Voltage Stress [1], is a standard test method for breakdown voltage. Normal precautions are to use mechanically sound and clean samples of the material under test. Generally, for any materials involved in internal charging studies, it is appropriate to have a vacuum bakeout to remove the adsorbed water and other contaminants. The test is intended to measure the applied voltage until breakdown. The result is the dielectric strength, which is often reported as V/mil of thickness. The result should also report the tested thickness: V/mil at thickness d.

E.3 Resistivity/Conductivity Determination

Volume conductivity and resistivity are reciprocals of each other. Rho (ρ, Ω-m) = 1/sigma (σ, siemens (S), mho/m, or 1/Ω-m). The volume resistivity of a material is a useful parameter for internal charging assessments. Volume resistivity refers to the bulk resistance of a volume of material. Volume resistivity is determined in terms of the equations supporting Fig. E-3. If the material's volume resistivity is not found in existing tables or the manufacturer's data, it can be measured in one of several ways, as described in the following paragraphs. ASTM D-257-07, Standard Test Method for DC Resistance or Conductance of Insulating Materials [2], is a standard test method for dc resistance or conductance.

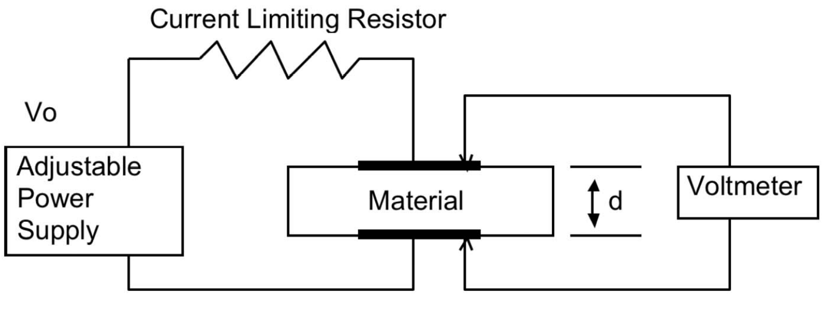


Fig. E-2. Testing for breakdown voltage.

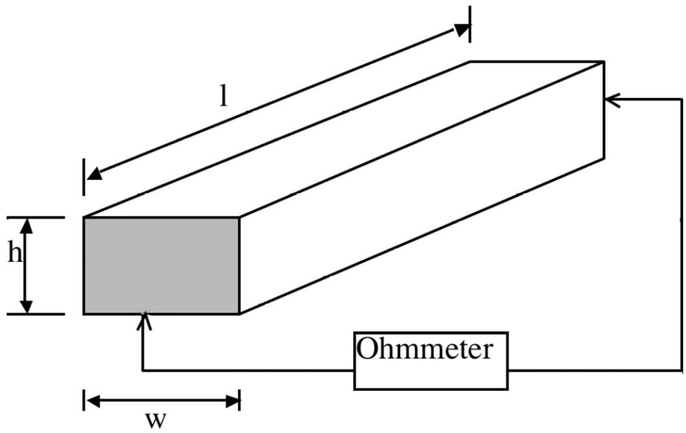


Fig. E-3. Testing for volume resistivity.

There is another resistivity, surface resistivity, which is applicable to thin layers of material or surface coatings. Surface resistivity ρ_S (rho sub s) is the resistance of a flat 2-D square piece of material as measured from one edge to an opposite edge. It may also refer to a surface layer of conductivity on an insulator, which, if the surface has been contaminated by handling or processing, may differ significantly from the bulk resistivity. The resistance of a 2-D surface measured in this manner will be:

$$R = \rho_S \times l/w \qquad \text{(E.3-1)}$$

where:

R = resistance of the sample as measured from end to end (Ω)

ρ_S = surface resistivity (Ω or Ω per square)

l = length of sample, with ground connections at the ends

w = width of sample

For a square sample (length equals width), it can be seen that the resistance from edge to edge will be the same value regardless of the size, so surface resistivity is sometimes called "ohm per square," although the proper unit is simply Ω.

E.4 Simple Volume Resistivity Measurement

Figure E-3 shows the concept of resistivity. The resistance from end to end of the material is as follows:

$$R = \rho \times l/(h \times w) \tag{E.4-1}$$

where:

R	=	resistance of the sample as measured from end to end (Ω)
ρ	=	volume resistivity (ohm-m in SI units); sometimes called ρ_V (rho sub v)
l	=	length of sample (m)
w	=	width of sample (m)
h	=	height of sample (m)

therefore:

$$\rho = R \times (h \times w)/l \tag{E.4-2}$$

Conductivity (S or σ) is the reciprocal of resistivity:

$$S = 1/\rho \text{ (Siemens or } 1/\Omega) \tag{E.4-3}$$

Various difficulties occur when measuring high resistivities, such as higher resistance than can be measured by the ohmmeter, resistivity as a function of voltage stress, resistivity as a function of temperature (more resistive when colder), resistivity modifications related to presence of absorbed moisture, and surface resistivity leakage rather than current flow through the bulk of the material. Test devices, such as the Hewlett-Packard Model 4329A high-resistance meter [3] when used in conjunction with a Model 16008A Resistivity Cell [4], can account for some of these problems. That instrument combination can measure very high resistances, has several user-defined test voltages, and has guard rings to prevent surface leakage effects from contaminating the results. The person doing the test should still bake out the test sample to get rid of moisture-caused conductivity. Testing versus temperature is important for cold situations (on the outside of the spacecraft) because resistance is significantly higher at cold space temperatures. For resistances above 10^{11} Ω, moisture bakeout and vacuum tests are appropriate, because moisture adsorption increases conductivity.

Exposure to radiation may increase conductivity (RIC). That is, materials may have more conductivity than measured in a ground environment. The quantitative details of this phenomenon are too involved for this document but in general should not be assumed to be significant help in the IESD situation.

E.5 Electron Beam Resistivity Test Method

This method has the advantage in that it measures the material in a vacuum and in response to an electron beam applying the voltage stress. With a metal front and backplate or plated contacts (or none at all), an electron beam is directed onto the front surface of a flat sample of the material as in Fig. E-4. A non-contacting voltage probe is used to measure the potential on the front surface of the material. A picoammeter then measures the current flowing from the back surface to ground. The volume resistivity is calculated in the manner of Fig. E-3. Shielding is needed to avoid stray electron false data.

E.6 Non-Contacting Voltmeter Resistivity Test Method

This method, illustrated in Fig. E-5, assumes that the resistivity is a constant with respect to applied voltage stress. The method requires plating the upper and lower surfaces of the material being tested to create a capacitor. The capacitance is determined and the capacitor charged. The power supply is disconnected. The voltage decay is monitored as a function of time as measured by a non-contacting voltmeter. The non-contacting voltmeter is necessary because most voltmeters have lower resistance than the test sample and would lead to incorrect measurements. The resistivity is determined by the equations given earlier and by making use of the voltage-decay versus time-curve given by the equation:

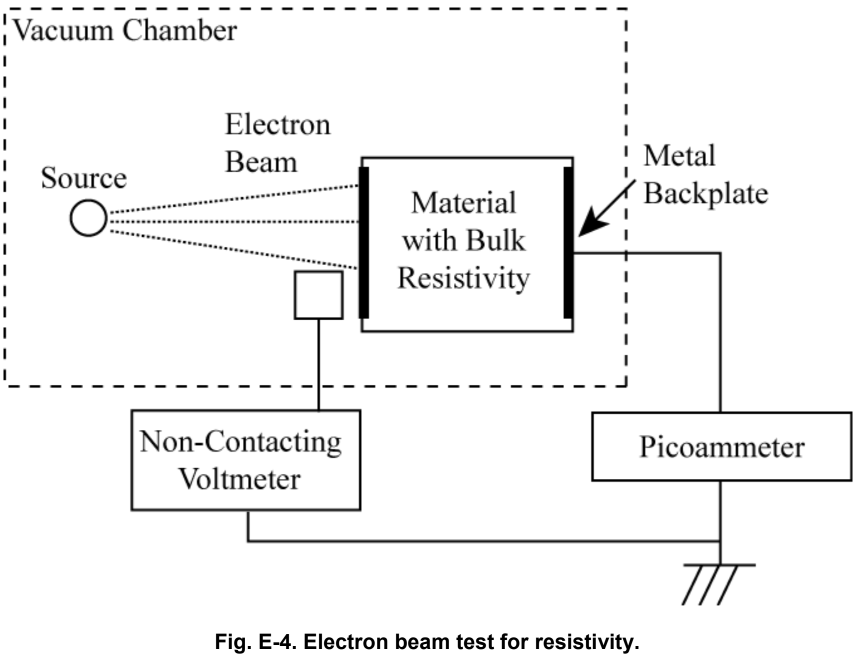


Fig. E-4. Electron beam test for resistivity.

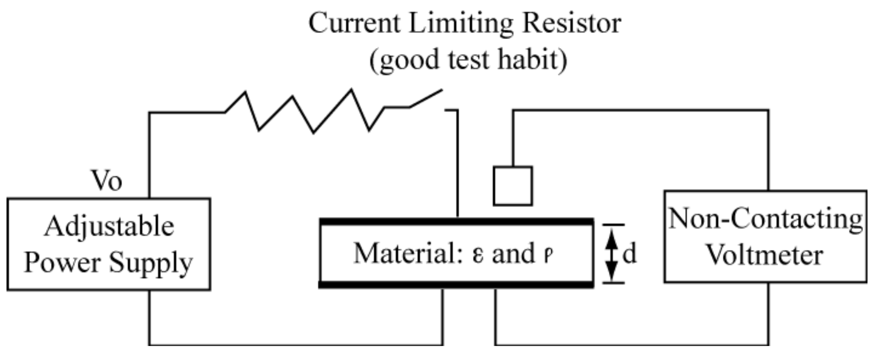


Fig. E-5. Non-contacting voltage decay resistivity test.

$$V = V_o \times e^{-(t/\tau)} \qquad \text{(E-5)}$$

where:

t	=	time (s)
τ	=	R × C time constant (s)
R	=	resistance from top to bottom of the sample (Ω)
C	=	capacitance of the sample (F)

Problems with this method include the sample preparation (cleanliness, absorbed water, and temperature) and surface leakage around the edge; all should be properly considered. The test could be done in a vacuum chamber to reduce water absorption contamination of the sample. An electron beam, as shown in Fig. E-4, can be used to charge the sample. The electron beam is then turned off and the voltage decay rate monitored.

Practicalities limit the maximum resistivities measurable with these conventional methods described above. To measure very high resistivities, special techniques are necessary. Dennison [5] describes these methods as used in his laboratory.

E.7 Dielectric Constant, Time Constant

The dielectric constant, ε, of a material can be determined experimentally, but it almost always can and should be obtained from the manufacturer. From knowledge of permittivity ε and resistivity ρ, the material's relaxation time constant can be determined. One time constant example is the time for a capacitor-resistor combination's voltage to decay to 1/e of its full value or about 37 percent of original voltage (Fig. E-6).

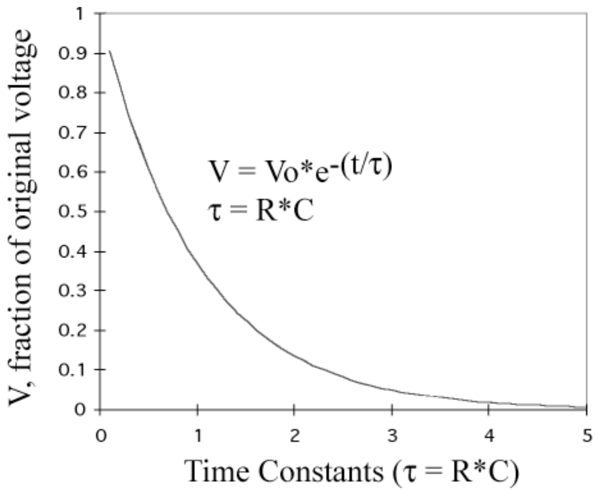


Fig. E-6. RC time constants.

If a rectangular slab of material, as shown in Fig. E-7, has metal electrodes on the top and bottom surfaces, it forms a capacitor, whose value is given by:

$$C = \varepsilon \times A/d \qquad \text{(E.7-1)}$$

where:

ε = permittivity of the material = $\varepsilon_o \times \varepsilon_r$

ε_o = permittivity of free space = 8.85×10^{-12} F/m,

ε_r = relative dielectric constant of the material, usually between 2 and 4

A = area of the sample = length × width

d = thickness, top to bottom

R = a resistor equivalent to the leakage resistance of the capacitor, computed from the resistivity by standard equations

If the units are the International System of Units (SI), the capacitance will be expressed in farads. Usually, capacitance related to space charging is expressed in pF because typical values for space charging are in this range.

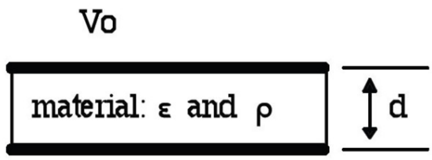


Fig. E-7. Determining material time constant.

The leakage resistance from top to bottom of the same rectangular slab is given by:

$$R = \rho \times d / A \qquad \text{(E.7-2)}$$

where:

ρ = material's volume resistivity, often given in Ω-cm

If the units are consistent, the answer will be in Ω. For the geometry in Fig. E-7, it can be seen that the leakage time constant (τ) is:

$$\tau = \rho \times \varepsilon \qquad \text{(E.7-3)}$$

At five time constants, there is less than 1 percent of the original voltage; at 0.01 time constant, the voltage is still 99 percent of the original. A material time constant of 1 hr or less is desirable to leak off detrimental charges before excessive fields cause ESD breakdown in the material [6].

Materials can thus be characterized by their time constants if both the dielectric constant and the resistivity are known. This is a theoretical description. Many high-resistivity materials behave nonlinearly with applied voltage or applied radiation. Thus, these concepts are introductory and approximate. For example, electron beam tests have found that the discharge time obtained when the beam is turned off (with vacuum maintained) can be hundreds of hours.

E.8 Vzap Test (MIL-STD-883G, Method 3015.7 Human Body Model (HBM))

A Vzap test is a test of an electronic device's capability to withstand the effects of an electrical transient simulating fabrication handling. It is useful when attempting to decide whether a device can withstand an ESD transient. Figure E-8 shows a typical test configuration (MIL-STD-883G, Method 3015.7 [7]). The parameters are intended to represent the threat from an HBM.

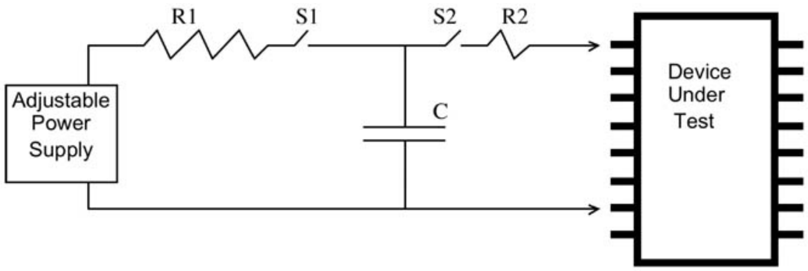


Fig. E-8. Vzap test configuration.

The capacitor in this layout (100 $\pm$ 10 percent pF) is charged through $10^6 < R1 < 10^7$ Ω and the power supply disconnected (switch S1). The capacitor is then discharged (through R2 = 1500 Ω) to the device under test, increasing the voltage until failure. Hardware is classified according to the highest test voltage step that passed without part failure: Class 0 (0-249 V), Class 1A (250-499 V), Class 1B (500-999 V), Class 1C (1000-1999 V), Class 2 (2000-3999 V), Class 3A (4000-7999 V), or Class 3B (>8000 V), depending on its damage threshold.

Although providing some idea of the ESD sensitivity of the part, these broad test ranges may not be as precise as desired. This test is mentioned because device sensitivity information may exist from the manufacturer. For actual space discharge events, the value of R2 appears to be in the range of 10 to 100 Ω and more likely 10 to 50 Ω.

Results obtained by Trigonis [8] for various parts, capacitor sizes, and series resistors (R2) are graphed in Fig. E-9. It illustrates how the damage threshold varies with each of the test parameters. Each point represents a different sample for the same part type subjected to a Vzap capacitor discharge at different voltages for various size capacitors. Both polarities are tested and are applied to the weakest pin pairs. The plotted lines show the least energy that damaged any part under any combination of the variables. One feature of the plot is the existence of a minimum damage voltage threshold for each device. This can be as low as 5 V for some newer devices. The second feature is a constant energy region at low capacitances (not obvious in this chart). The third feature is that the energy appears to go up for the lowest capacitor sizes; this may be an artifact of stray capacitance in the test fixture. It is appropriate to choose the lowest energy as the victim's sensitivity for analyses. It can be seen that, for these parts, the weakest component was damaged by 0.5 μJ. Therefore, based on these test results, an ESD needs to deliver at least 0.5 μJ to damage a part. Of course, having data for the actual parts in question is more desirable.

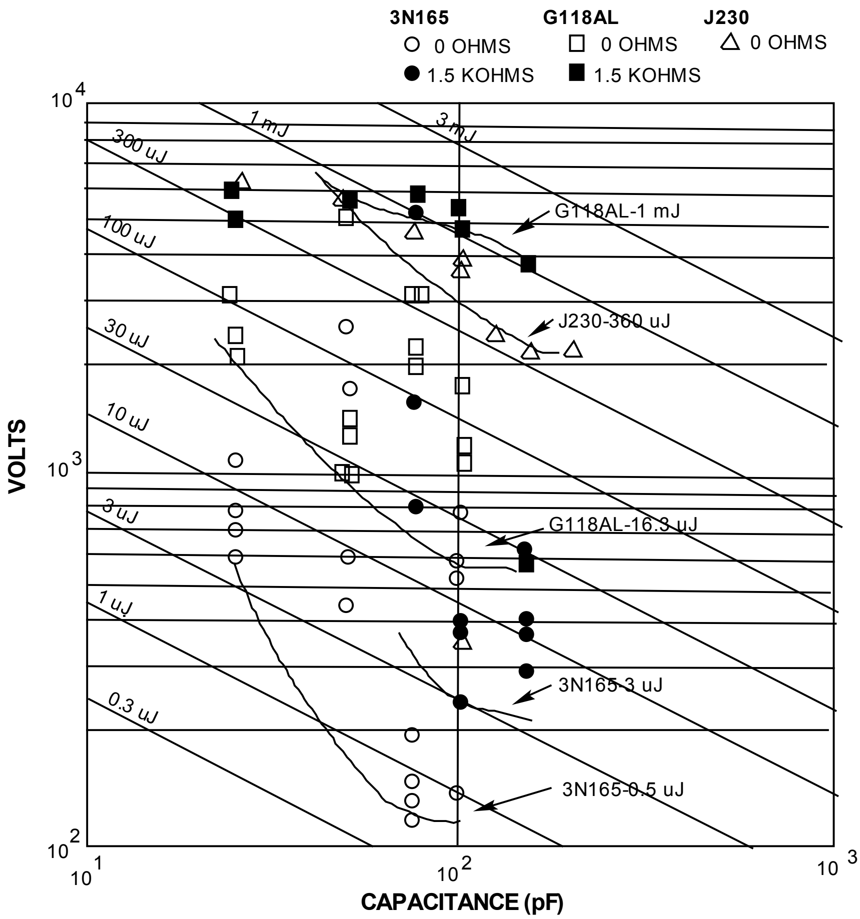


Fig. E-9. Typical results for Vzap test showing lines of minimum damage threshold for given parameters (based on data collected by Arthur Trigonis [8]. Note: Diagonal lines are for constant energy: $E = 0.5\ C\ V^2$.

E.9 Transient Susceptibility Tests

Transient susceptibility tests are very common in the EMC community. Transient injection is done by inductive or capacitive coupling as was shown in MIL-STD-462, *Measurement of Electromagnetic Interference Characteristics* [9], for example. The difference between EMC and ESD is the width of the transient pulses: the EMC pulse is typically 10 µs wide, while an ESD pulse is on the order of 10 to 100 ns. A thorough and comprehensive test of a victim device would include varying the pulse width and then determining the voltage and energy threshold of susceptibility. The test should include all pins on the victim device and both polarities of the transient. Testing should include when the input signal is in the high state, the low state, and/or transitioning states. Such a comprehensive characterization would involve more work than is usually done, but the analyst should understand that anything less will not be complete.

There are two common sources for generating transient pulses for susceptibility testing. The first is the MIL-STD-1541A [10] pulse source shown in Fig. E-10 (repeat of Fig. 4-1). As stated there, this source provides a capacitive discharge with the amplitude set by the voltage used to charge the capacitor and also the electrode separation gap.

The second source is a commercial human body discharge source (Schaeffner supplies one such test device). These sources can be battery operated and also provide a capacitive discharge pulse. The charging voltage is variable so that the amplitude can be controlled. Transients from this source are fast (on the order of 150 ns) and the signal is very clean as opposed to the MIL-STD-1541A ESD transient source [10].

The state of the art is such that ESD test simulators should be improved to better simulate on-orbit ESD pulses. The reader should research for better sources.

E.10 Component/Assembly Testing

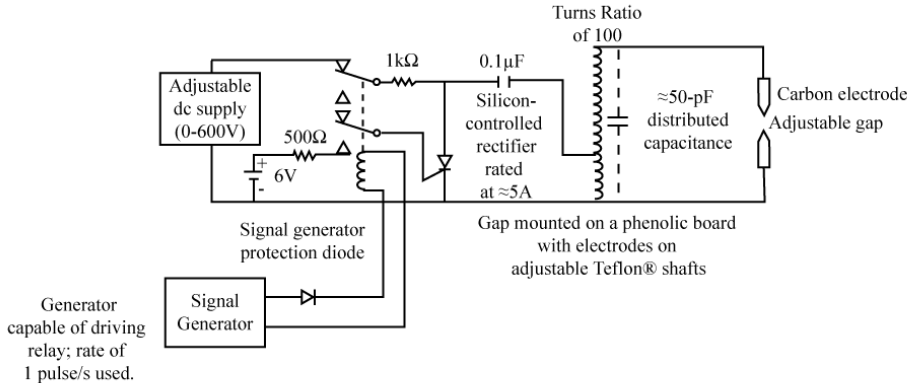
Potentially susceptible components/assemblies should be tested for sensitivity to ESD. The component to be tested is to be mounted on a baseplate and functioning. Pulses are to be injected into the component, and the performance of the device is monitored for upsets. The pulses used are to cover the expected range of current amplitudes, voltages, and pulse durations. It is very important that the pulse device be electrically isolated from the component being tested and the monitoring equipment.

E.11 Surface Charging ESD Test Environments

Monoenergetic electron beam tests have been used to determine approximate surface charging threats of materials.

E.12 System Internal ESD Testing

There is no convenient or cost-effective way to do a system-level internal ESD test.



Typical Gap-Spacing, Voltage, and Energy Levels

Gap (mm)	Vb (kV)	Energy (μJ)
1	1.5	56.5
2.5	3.5	305
5.0	6.0	900
7.5	9.0	2000

Fig. E-10. MIL-STD-1541A [10] pulse source for transient testing.

References

[1] Anonymous, *Standard Test Method for Dielectric Breakdown Voltage and Dielectric Strength of Solid Electrical Insulating Materials Under Direct-Voltage Stress*, ASTM D-3755-97, ASTM International, West Conshohocken, Pennsylvania, 2004.

[2] Anonymous, *Standard Test Method for DC Resistance or Conductance of Insulating Materials*, ASTM D-257-07, ASTM International, West Conshohocken, Pennsylvania, 18 pages, 2007.

[3] Anonymous, *Hewlett-Packard Operating and Service Manual for Model 4329A High-Resistance Meter (and Model 16008A Resistivity Cell)*, 1983. With 16008 Resistivity Cell, directly displays high values of resistivity (saves calculation effort).

[4] Anonymous, Hewlett-Packard Operating Note for Model 16008A Resistivity Cell, Hewlett-Packard, undated.

[5] J. R. Dennison, J. Brunson, P. Swaminathan, N. W. Green, and A. R. Frederickson, "Methods for High Resistivity Measurements Related to Spacecraft Charging," *IEEE Transactions on Plasma Science,* vol. 34, no. 5, pp. 2191–2203, October 2006.

This reference provides a good summary insight into problems of measuring high resistivities for space usage and proposed test methods appropriate to these needs.

[6] A. R. Frederickson, E. G. Holeman, and E. G. Mullen, "Characteristics of Spontaneous Electrical Discharges of Various Insulators in Space Radiations," *IEEE Transactions on Nuclear Science,* vol. 39, no. 6, pp. 1773–1982, December 1992.
This document is a description of the best-known attempt to quantify internal charging effects on orbit, by means of a well-thought-out experiment design. The results were not all that the investigators had hoped, but the data are excellent and very good conclusions can be reached from the data, in spite of the investigators' concerns.

[7] Anonymous, *Test Method Standard for Microcircuits*, MIL-STD-883G, Method 3015.7 (March 22, 1989), United States Department of Defense, 716 pages, February 28, 2006.
Method 3015.7 describes Vzap tests for measuring ESD response of electronic parts to the human body model for ESD.

[8] A. Whittlesey, *Example of Semiconductor Damage Thresholds from Capacitor Discharge*, Interoffice Memorandum 5137-11-042, D-69594 (internal document), Jet Propulsion Laboratory, Pasadena, California, May 10, 2011.
This useful data set was generated from Arthur Trigonis, "JPL Part Evaluation Report Log 3647," May 1981, a JPL internal working document that has been republished as JPL IOM 5137-11-042 for referencing purposes.

[9] Anonymous, *Measurement of Electromagnetic Interference Characteristics*, MIL-STD-462D, United States Department of Defense, 189 pages, January 11, 1993.

[10] Anonymous, *Electromagnetic Compatibility Requirements for Space Systems*, MIL-STD-1541A (USAF), United States Air Force, 42 pages, December 30, 1987.