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Space systems — Space solar panels — Spacecraft charging induced electrostatic discharge test methods

Systèmes spatiaux — Panneaux solaires spatiaux — Matériaux d'essai de décharge électrostatique induite par la charge du vaisseau spatial

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Foreword

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Space systems — Space solar panels — Spacecraft charging induced electrostatic discharge test methods

1 Scope

This International Standard specifies qualification and characterization test methods to simulate plasma interactions and electrostatic discharges on solar array panels in space. This International Standard is applicable to solar array panels made of crystalline silicon, gallium arsenide (GaAs) or multi-junction solar cells. This International Standard addresses only surface discharges on solar panels.

2 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

2.1
active gap
gap between solar cells across which a potential difference is present when the solar array power is available

2.2
blow-off
emission of negative charges into space due to an electrostatic discharge

2.3
collisionless plasma
plasma in which the mean free paths of electron-neutral, ion-neutral and coulomb collisions are longer than the scale length of interest

NOTE Chamber length is an example of a scale length of interest.

2.4
differential charging
spacecraft charging where any two points are charged to different potentials

2.5
differential capacitance
capacitance between any two points in a spacecraft, especially between the insulator surface and the spacecraft body

2.6
differential voltage
potential difference between any two points in a spacecraft during spacecraft charging, especially between the insulator exterior surface potential and the spacecraft chassis potential

2.7
discharge inception voltage
lowest voltage at which discharges of specified magnitude will recur when a DC voltage is applied between any two points in a spacecraft, especially between the insulator surface and the spacecraft body

2.8
electrical breakdown
failure of the insulation properties of a dielectric, resulting in a sudden release of charge with possible damage to the dielectric concerned

2.9
electric propulsion
spacecraft propulsion system in which the thrust is generated by accelerating charged particles that are neutralized before they are ejected in order to produce a jet

2.10
electrostatic discharge
electrical breakdown of dielectric or gas or vacuum gaps, and also of surface interface of dissimilar materials, caused by differential charging of parts of dielectric materials and their interfaces

2.11
gap distance
distance between biased cells or conductors

2.12
glow discharge
gaseous discharge with a surface glow near the cathode surface

NOTE The origin of the ionized gas is mostly ambient neutral gas molecules rather than metal vapour from the cathode surface.

2.13
inverted potential gradient
inverted voltage gradient
result of differential charging where the insulating surface or dielectric reaches a positive potential with respect to the neighbouring conducting surface or metal

NOTE This phenomenon is also known as PDNM (positive dielectric negative metal).

2.14
non-sustained arc
passage of current from an external source through a conductive path that lasts only while the primary discharge current flows

See Figure 1.

2.15
normal potential gradient
normal voltage gradient
result of differential charging where the insulating surface or dielectric reaches a negative potential with respect to the neighbouring conducting surface or metal

NOTE This phenomenon is also known as NDPM (negative dielectric positive metal).

2.16
permanent sustained arc
passage of current from an external source through a conductive path that keeps flowing until the external source is intentionally shut down

See Figure 1.

NOTE Some permanent sustained arcs may leave a permanent conductive path even after the shut-down.

2.17
Poisson process
stochastic process in which events occur independently of one another

2.18
power generation voltage
potential difference between the positive and negative terminals of a solar array string

2.19
primary arc
trigger arc
developed phase of a primary discharge, under an inverted potential gradient, which is associated with cathodic spot formation at a metallic or semiconductor surface

2.20
primary discharge
initial electrostatic discharge which, by creating a conductive path, can trigger a secondary arc

See Figure 1.

NOTE The current can include blow-off current and surface flashover current.

2.21
punch-through
dielectric breakdown between two sides of an insulator material

2.22
ram
space in front of and adjacent to a spacecraft in which the plasma density can be enhanced by the motion of the spacecraft

2.23
satellite capacitance
absolute capacitance
capacitance between a satellite body and the ambient plasma

2.24
secondary arc
passage of current from an external source, such as a solar array, through a conductive path initially generated by a primary discharge

NOTE Figure 1 shows the various stages of a secondary arc.

2.25
snapover
phenomenon caused by secondary electron emission that can lead to electron collection on insulating surfaces in an electric field

2.26
solar array front surface
solar array surface where solar cells are laid down

NOTE Solar cells are laid down on the side of a solar panel that normally faces the sun.

2.27
solar array back surface
solar array surface where solar cells are not laid down

NOTE Solar cells are not laid down on the side of a solar panel that normally faces away from the sun.

2.28
surface charging
deposition of electrical charges onto, or their removal from, external surfaces

2.29
surface flashover

surface discharge propagating laterally over a dielectric material

NOTE Surface flashover is sometimes called a “brushfire discharge”.

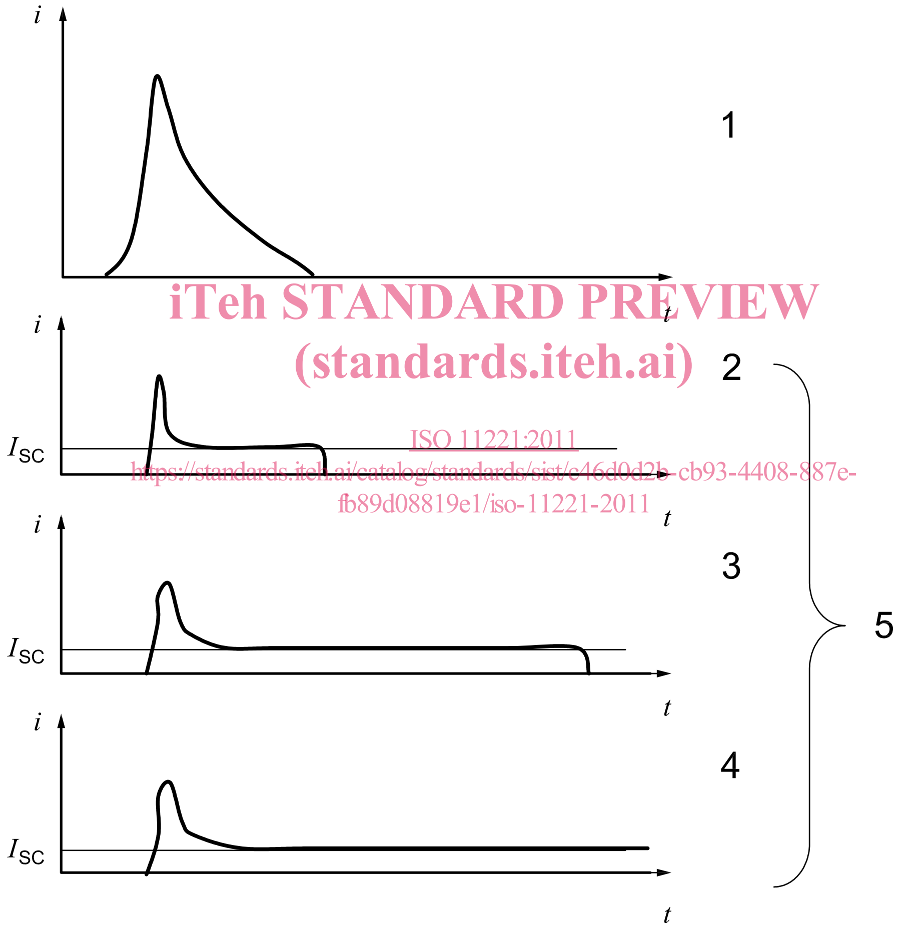
2.30
temporary sustained arc

passage of current from an external source through a conductive path that lasts longer than a primary discharge current pulse but terminates without leaving a permanent conductive path

See Figure 1.

2.31
wake

trail of rarefied plasma left behind by a moving spacecraft



Key

1	primary discharge (blow-off + flashover)
2	non-sustained arc (NSA)
3	temporary sustained arc (TSA)
4	permanent sustained arc (PSA)
5	secondary arc

i	current
I_{sc}	short-circuit current of one or more solar array circuits
t	time

The primary discharge is fed by absolute and differential capacitances. The secondary arc is fed by the solar array power.

Figure 1 — Stages of secondary arc

3 Symbols and abbreviated terms

3.1 Symbols

A_s	area of surface of plasma
C_BC	bypass capacitance
C_CG	differential capacitance
C_GS	capacitor representing capacitance between solar panel structure and ambient plasma
C_kapton	capacitor representing capacitance underneath the cells through the Kapton layer
C_sat	satellite capacitance
C_string	capacitor representing capacitance of solar array string
C_v	capacitance per unit area of coverglass
C_1	capacitor representing capacitance of solar array string and capacitance underneath the cells through the Kapton layer
C_2	capacitor representing capacitance of solar array string and capacitance underneath the cells through the Kapton layer
C_3	capacitor representing capacitance of solar array string and capacitance underneath the cells through the Kapton layer
D_1	fast switching diode
D_2	fast switching diode
D_3	fast switching diode
d_sh	sheath thickness
I_0	reverse saturation-current density, in amperes per square metre (A/m^2)
I_1	power supply representing power generated by the solar array
I_sc	short-circuit current of one or more solar array circuits
I_section	current of a solar array section
I_string	current of a solar array string
i	current
j	number of bins
k	Boltzmann constant
L_ext	inductance to form the pulse current shape
n	diode constant

P_i	probability that an event occurs in the i-th bin
Q	charge
q	elementary charge
R	resistance
R_{ext}	resistance to form the pulse current shape
R_{L}	resistance to adjust the voltage between two strings under test
R_{section}	$U_{\text{section}}/I_{\text{section}}$ resistance needed to get the right voltage and current in the loop simulating the solar panels section
R_{string}	$U_{\text{string}}/I_{\text{string}}$ resistance needed to get the right voltage and current across the solar cells simulating the solar array string under arcing test
r	radius of plasma
T	temperature, in kelvins (K)
T_{e}	electron temperature
T_{i}	ion temperature
t	time
t_{ESD}	time to threshold differential voltage
U_1	constant current source
U_2	constant voltage source
U_{section}	voltage of a solar array section
U_{string}	voltage of a solar array string
V_{b}	power supply representing charging potential of spacecraft body
v_{p}	velocity of plasma wavefront
ΔV	potential difference
θ	angle
λ_{D}	Debye length
ρ_{e}	electron density
ρ_{i}	ion density
ϕ_{CG}	coverglass potential
ϕ_{sat}	satellite body potential

3.2 Abbreviated terms

eV	electron volt (1 eV = 1,602 × 10^{-19} J)
CIC	coverglass interconnect cell
ESD	electrostatic discharge
GEO	geosynchronous orbit
IPG	inverted potential gradient
LEO	low Earth orbit
NPG	normal potential gradient
NSA	non-sustained arc
PA	primary arc
PEO	polar Earth orbit
PI	plasma interaction
PSA	permanent sustained arc
TSA	temporary sustained arc

4 Tailoring

Specifications described in this International Standard are tailorable upon agreement between the customer and the supplier.

5 Test items

NOTE Annex A provides an overview of the subject of spacecraft charging and electrostatic discharge (ESD) phenomena for readers who are not familiar with the subject.

The aims of the plasma interaction (PI) and ESD tests are to simulate the detrimental phenomena anticipated in space for a given solar array design, to evaluate a design's resistance to the phenomena and to provide data necessary for the judgment of qualification and characterization.

Figures 2 and 3 present the test items specified in this International Standard, with flow charts to summarize the logic flow of each test. The purpose of a preliminary test for ESD statistics is to define the statistics helpful for selecting the test parameters (such as the number of primary discharges inflicted upon a test coupon), defining the margins of the test parameters and defining the confidence level of the test results. If proper statistics for these numbers and probabilities are already available, the preliminary test is not required for the qualification of secondary arcs. Annex B provides a brief rationale of the structure of the flow chart in Figure 2.

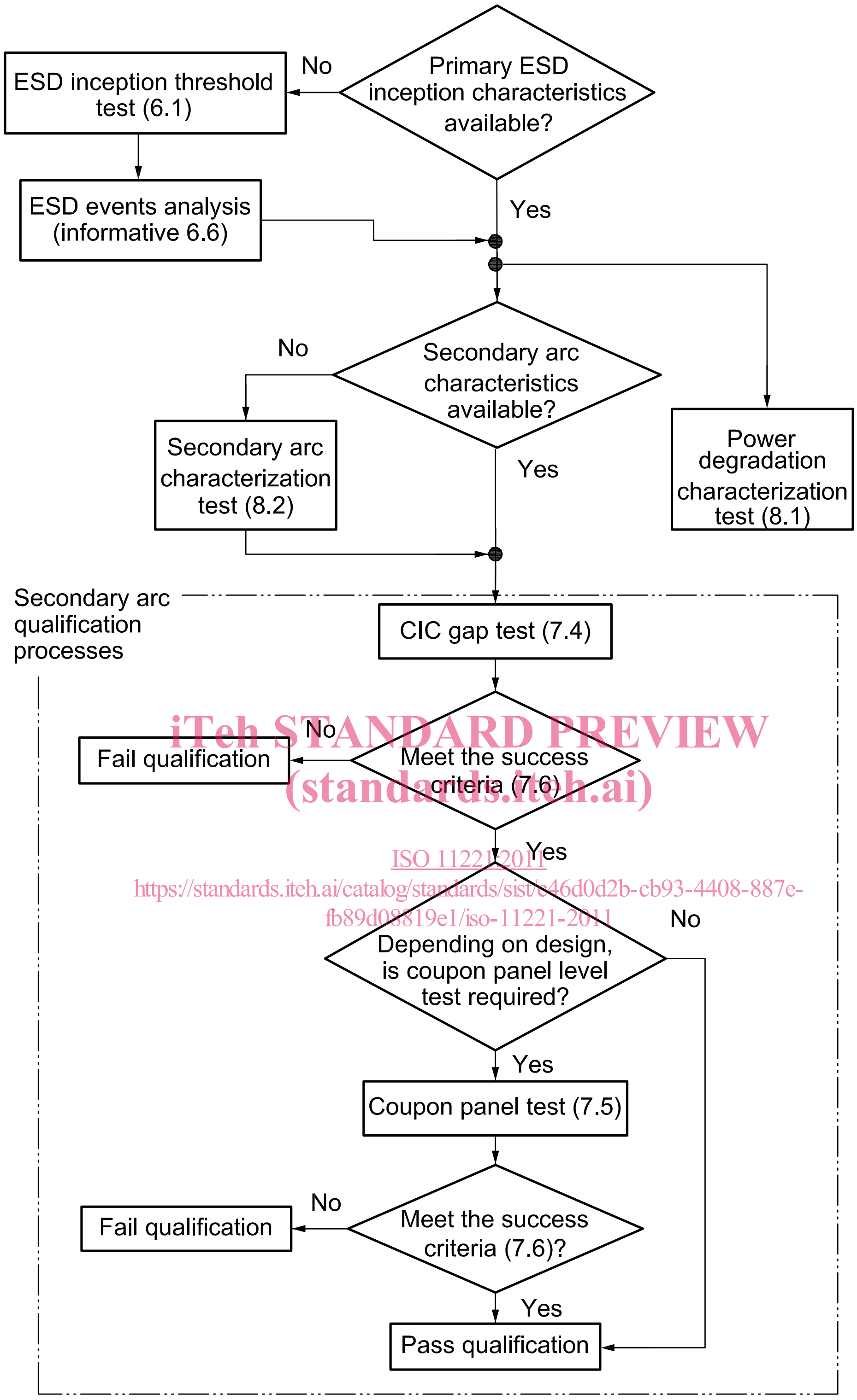


Figure 2 — Logic flow of ESD tests

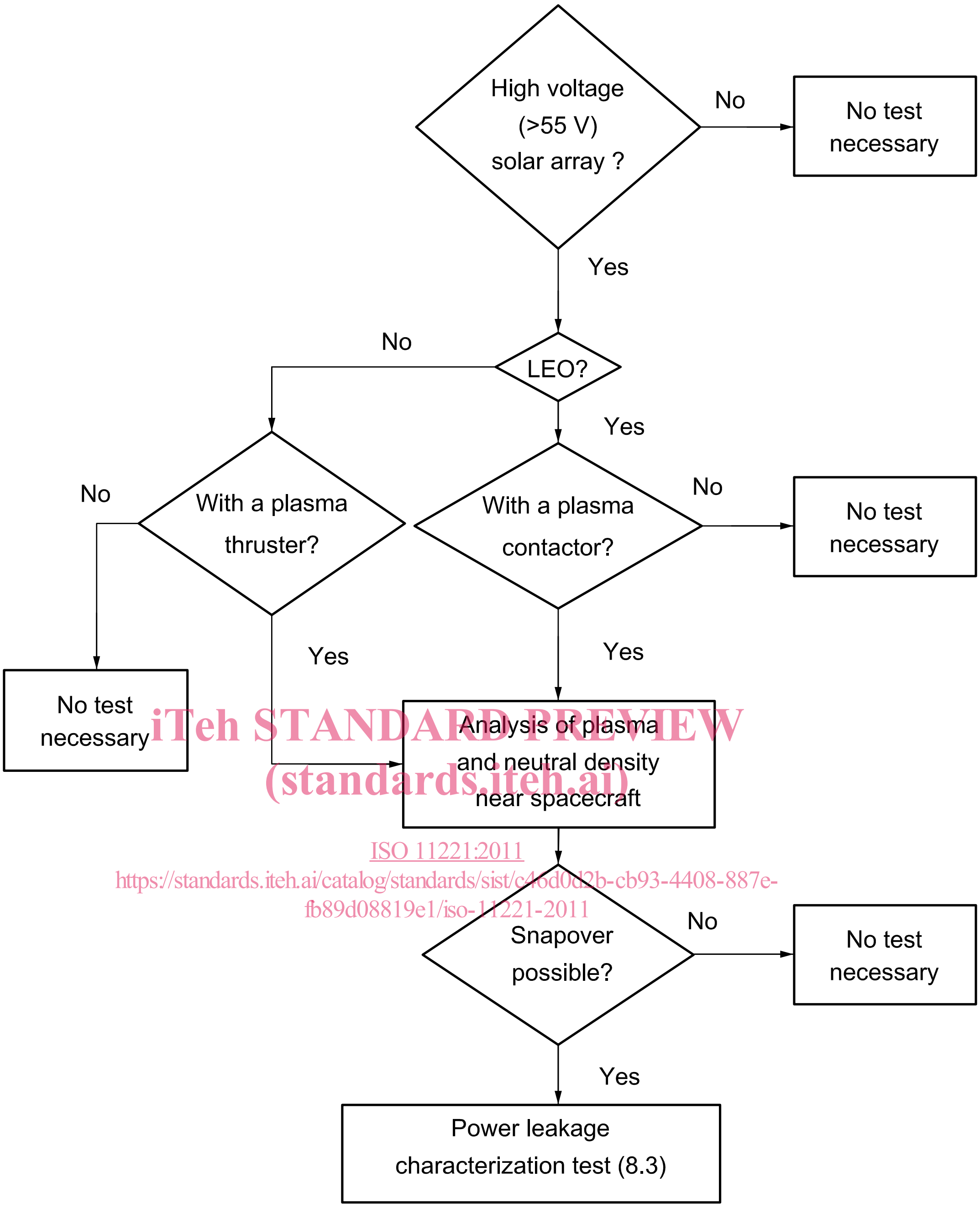


Figure 3 — Logic flow for determining the necessity of a power leakage characterization test

6 Preliminary tests for ESD inception statistics

6.1 Purpose

The purpose of this test is to characterize the ESD (primary discharge) inception threshold in terms of differential voltage between the coverglasses and the solar array circuit. This differential voltage can be used as a tool to estimate the number of ESD events during the mission lifetime in orbit.

6.2 Test facility

The test facility shall be able to simulate the charging processes of a solar array insulator in orbit. If the solar array is for a GEO satellite, the solar array insulator shall be charged using either an energetic electron beam or UV irradiation, or a combination of both, in a vacuum chamber with a pressure lower than 1×10^{-3} Pa ($7{,}5 \times 10^{-6}$ Torr). The electron energy shall be less than 30 keV so that the charging takes place mostly over the insulator surface, and not below it. The vacuum chamber for a geosynchronous orbit (GEO) solar array test shall be equipped with an adequate device to determine the insulator charging potential, such as a non-contacting surface potential probe, preferably mounted on an (x)-(y) scanning device.

If the solar array is for a low Earth orbit (LEO) spacecraft, the solar array insulator shall be charged by a low-energy plasma with a temperature below 10 eV in a vacuum chamber with a pressure that guarantees a collisionless plasma. If the solar array is for a polar Earth orbit (PEO) spacecraft and auroral electrons are responsible for differential charging, the solar array insulator should be charged using an energetic electron beam. If the solar array is for a PEO spacecraft and low-energy ionospheric ions are responsible for differential charging, the solar array insulator should be charged using a low-energy plasma. See Annex C for the minimum chamber size for a low-energy plasma test.

The test facility shall be equipped with a device to record an adequate image of the test coupon during the test so that ESD locations can be identified either during or after the test.

6.3 Test coupon

The test coupon(s) shall consist of at least three strings of three cells to represent a cell surrounded by other cells. The test coupon(s) should

a) reflect the production variation with respect to parameters that can affect the ESD inception threshold, such as degree of grouting, coverglass overhang, cell spacing, etc. on the total number of cells on the test coupon(s),

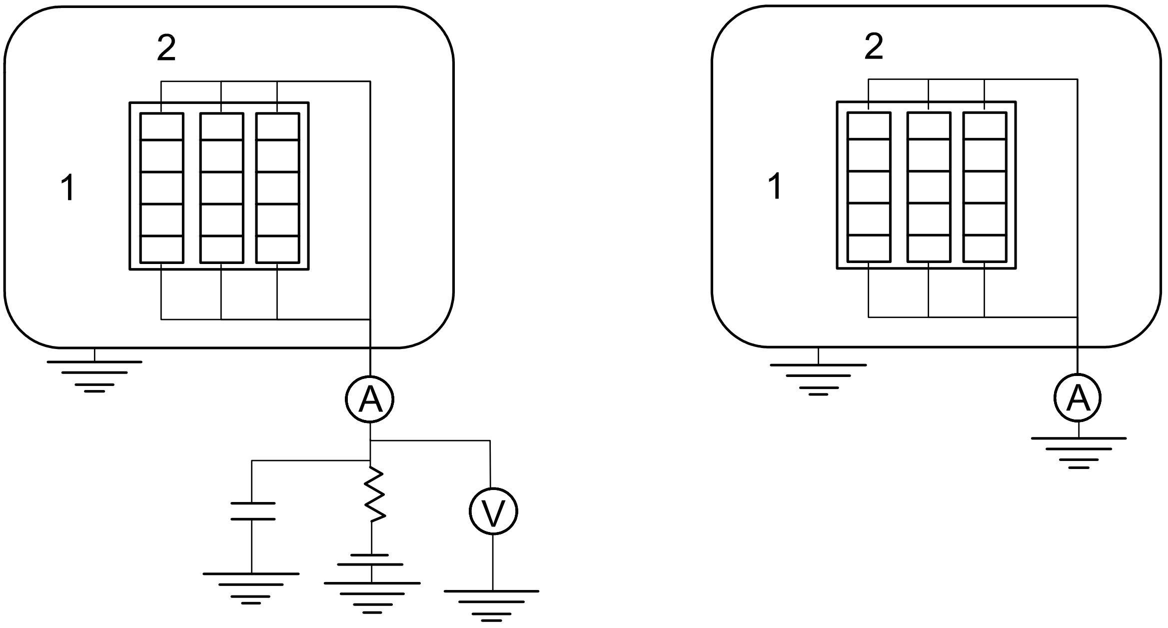
b) include all the features of a flight panel, such as bus bars, through-holes, terminal strips, wire harness, hold-down, etc.,

c) include the mitigation techniques that represent the flight model as closely as possible, if the solar panel design involves ESD mitigation techniques such as a dissipative coating, and

d) consider the worst condition during the life of the spacecraft, such as after thermal cycling, repaired cells, and other conditions that can lead to a greater risk of ESD and secondary arcs.

6.4 External circuit

In the test, the vacuum chamber serves as the circuit ground. If the charging situation in space is the inverted potential gradient, bias the test coupon to a negative potential with a DC power supply. If the charging situation is the normal potential gradient, ground the test coupon. (See Figure 4 for a circuit diagram.) A small amount of capacitance may be connected to the DC power supply if a brighter flash of ESD light is needed to identify its location. Limit the capacitance so that the electrostatic energy dissipated does not cause degradation of the solar cells on the test coupon(s). An energy of less than 5 mJ is recommended. As the capacitance of a coupon alone sometimes exceeds the limit, external capacitance should not be used for a large coupon of more than about 20 cells. To record the ESD in this event, use a sensitive camera.



a) **Inverted potential gradient**

b) **Normal potential gradient**

Key

1	coupon
2	vacuum chamber

Figure 4 — Test set-up for the ESD inception test

6.5 Test procedures

If an electron beam gun or a UV source is used for charging the test coupon, the test shall be carried out until a statistically significant number of ESD events, no less than 10, occur on the test coupon. The test coupon surface potential shall be measured repeatedly during the test by a non-contacting surface potential probe. The coupon surface potential closest to each ESD location shall be identified and recorded. The minimum differential voltage is the minimum value among all the ESD events recorded. Be aware of the uncertainties associated with the spatial resolution of the probe and the temporal variation of the potential depending on the time of measurement from the ESD inception.

If a low-energy plasma source is used, the differential charging voltage can be approximated by the chamber plasma potential, which is usually positive by several times the electron temperature, minus the negative coupon potential. The uncertainty is in the order of the electron temperature. The coupon bias voltage shall be varied to cover all the possible charging potentials in orbit. In the case of PEO spacecraft, the waiting time at each bias voltage should be no less than 20 min. In the case of LEO spacecraft, the waiting time at each bias voltage should be no less than 90 min. At low bias voltages where the probability of ESD is very low, a longer waiting time is recommended to improve the statistics. See Reference [1] for an example of characterizing the arc rate per unit time under a low-energy plasma environment. If the threshold is unknown, plot the arc rates at different bias voltages on a logarithmic scale and find the voltage where the probability of an arc over a given time becomes negligible, assuming that ESD inception is modelled as a Poisson process (see Reference [2] for an example).

6.6 Estimation of number of ESD events in orbit

It can be useful to analyse the number of ESD events expected in orbit as a basis for discussion to determine the number of primary discharges in the subsequent tests. See Annex D for details. Other methods of analysis may also be used to compute the number of ESD events.