

BS ISO 11221:2011



BSI Standards Publication

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

National foreword

This British Standard is the UK implementation of ISO 11221:2011.

The UK participation in its preparation was entrusted to Technical Committee ACE/68/-/1, Space systems and operations - Design, Engineering and Production.

A list of organizations represented on this committee can be obtained on request to its secretary.

This publication does not purport to include all the necessary provisions of a contract. Users are responsible for its correct application.

© BSI 2011

ISBN 978 0 580 66381 9

ICS 49.140

Compliance with a British Standard cannot confer immunity from legal obligations.

This British Standard was published under the authority of the Standards Policy and Strategy Committee on 31 August 2011.

Amendments issued since publication

Date	Text affected
------	---------------

---

# INTERNATIONAL STANDARD

BS ISO 11221:2011

**ISO**  
**11221**

First edition  
2011-08-01

---

---

## 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



Reference number  
ISO 11221:2011(E)

© ISO 2011



## COPYRIGHT PROTECTED DOCUMENT

© ISO 2011

All rights reserved. Unless otherwise specified, no part of this publication may be reproduced or utilized in any form or by any means, electronic or mechanical, including photocopying and microfilm, without permission in writing from either ISO at the address below or ISO's member body in the country of the requester.

ISO copyright office  
Case postale 56 CH-1211 Geneva  
20 Tel. + 41 22 749 01 11 Fax + 41 22  
749 09 47  
E-mail [copyright@iso.org](mailto:copyright@iso.org)  
Web [www.iso.org](http://www.iso.org)

Published in Switzerland



## Contents

Page

Foreword .....	iv
1 Scope.....	1
2 Terms and definitions .....	1
3 Symbols and abbreviated terms.....	5
3.1 Symbols.....	5
3.2 Abbreviated terms.....	7
4 Tailoring .....	7
5 Test Items.....	7
6 Preliminary tests for ESD inception statistics .....	10
6.1 Purpose .....	10
6.2 Test facility.....	10
6.3 Test coupon .....	10
6.4 External circuit.....	10
6.5 Test procedures.....	11
6.6 Estimation of number of ESD events in orbit.....	11
7 Qualification test for secondary arc.....	12
7.1 Purpose .....	12
7.2 Triggering method and test facility .....	12
7.3 External circuit.....	12
7.4 CIC gap test — Test coupon and procedures .....	13
7.5 Panel test — Test coupon and procedures .....	13
7.6 Success criteria.....	13
8 Characterization tests for robustness to ESD and plasma interaction .....	14
8.1 Power degradation .....	14
8.2 Secondary arc.....	15
8.3 Power leakage to plasma.....	15
8.4 Solar array back surface test .....	17
9 Test report.....	17
Annex A (informative) Plasma interaction and electrostatic discharge effects on solar array .....	19
Annex B (informative) Secondary arc qualification processes.....	22
Annex C (normative) Chamber size for a test using LEO-like plasma.....	23
Annex D (informative) ESD events analysis.....	24
Annex E (informative) Spacecraft charging analysis.....	27
Annex F (informative) Derivation of theoretical surface flashover current .....	29
Annex G (normative) External circuit of secondary arc test.....	31
Annex H (informative) Solar cell I-V characteristics measurement.....	36
Annex I (informative) Secondary arc statistics.....	38
Annex J (informative) Solar array back surface test.....	41
Bibliography.....	42

## Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

International Standards are drafted in accordance with the rules given in the ISO/IEC Directives, Part 2.

The main task of technical committees is to prepare International Standards. Draft International Standards adopted by the technical committees are circulated to the member bodies for voting. Publication as an International Standard requires approval by at least 75 % of the member bodies casting a vote.

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. ISO shall not be held responsible for identifying any or all such patent rights.

ISO 11221 was prepared by Technical Committee ISO/TC 20, Aircraft and space vehicles, Subcommittee SC 14, Space systems and operations.



# 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











### 3.2 Abbreviated terms

eV	electron volt (1 eV = 1,602 10 <sup>-19</sup> 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.

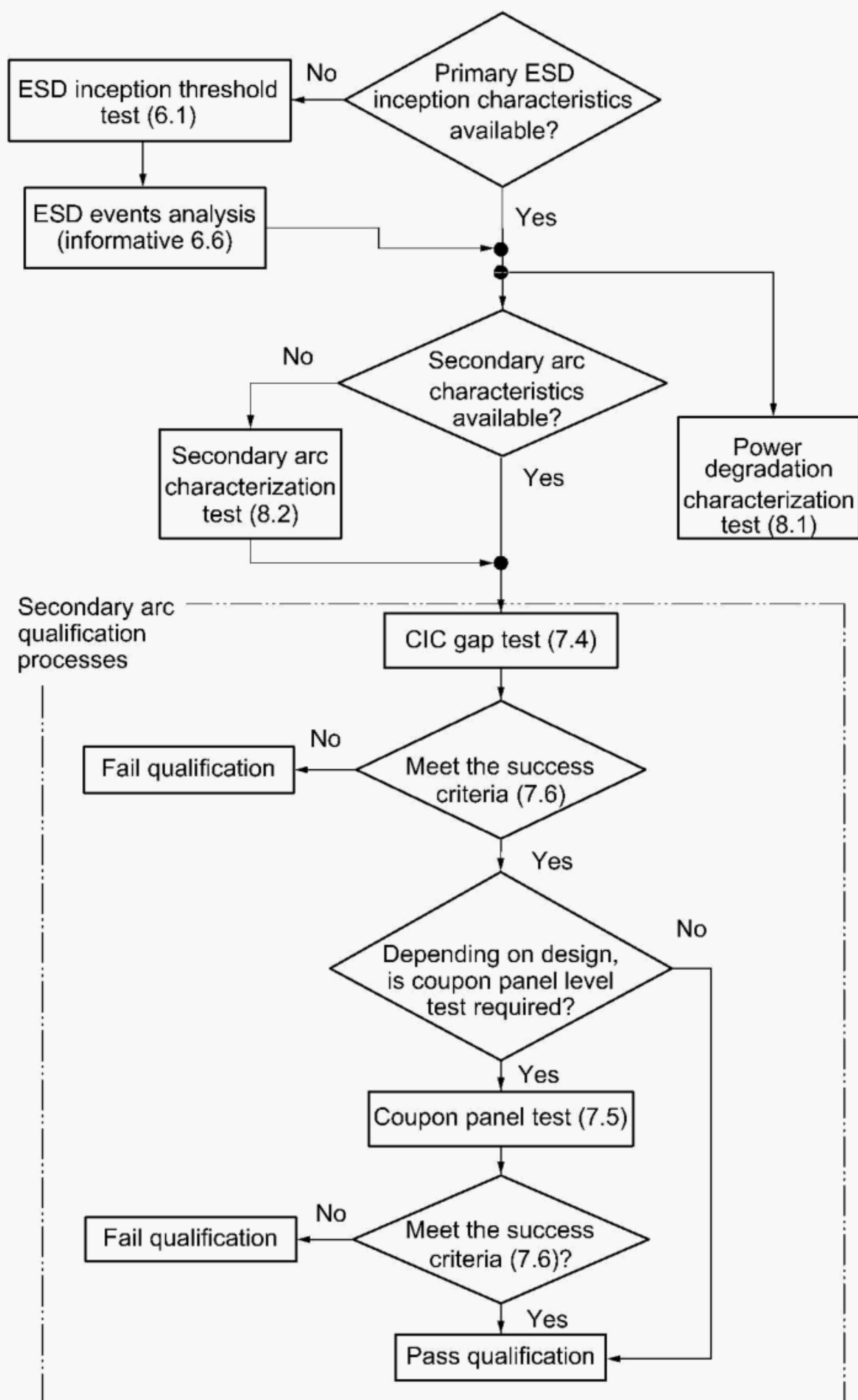


Figure 2 — Logic flow of ESD tests



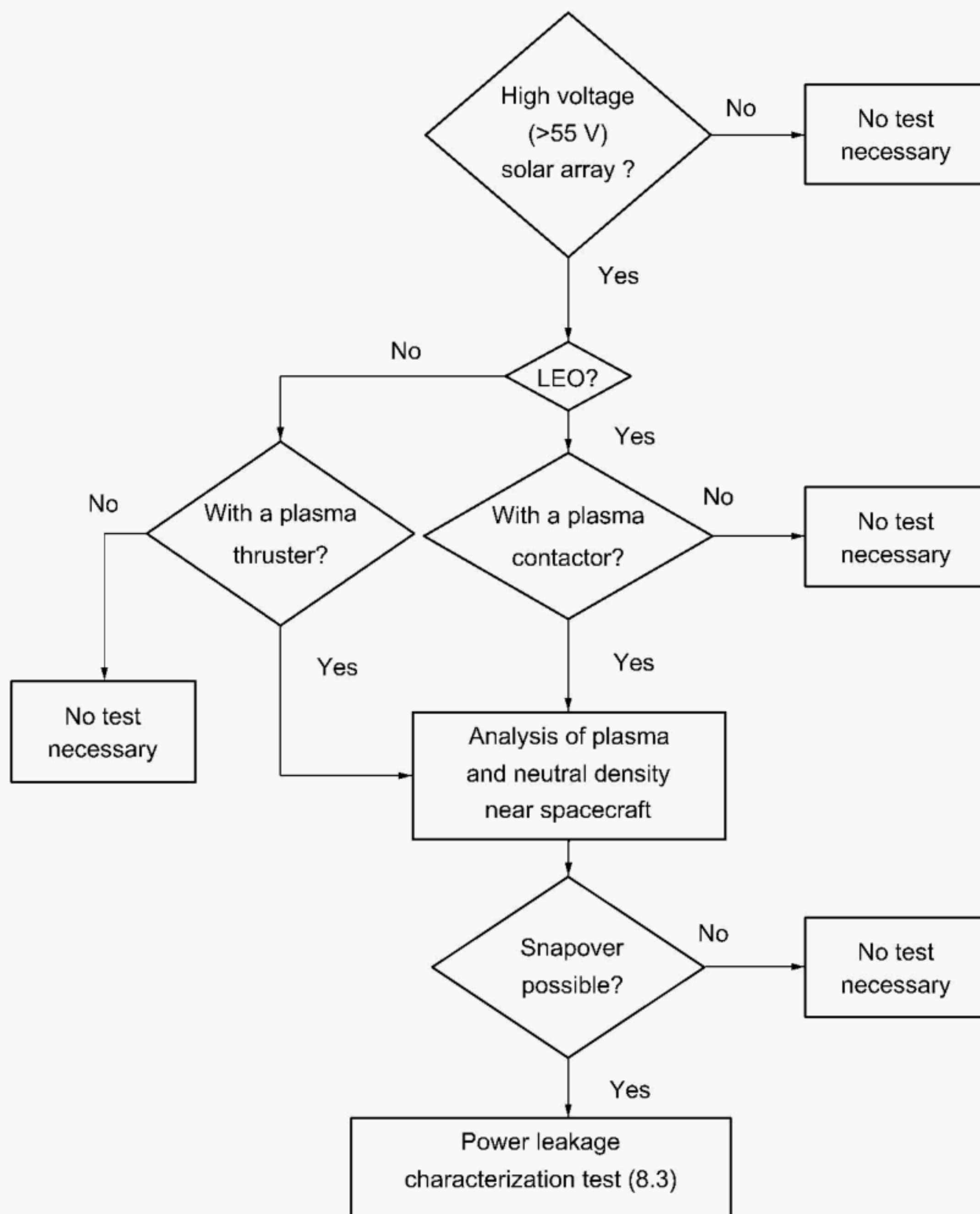
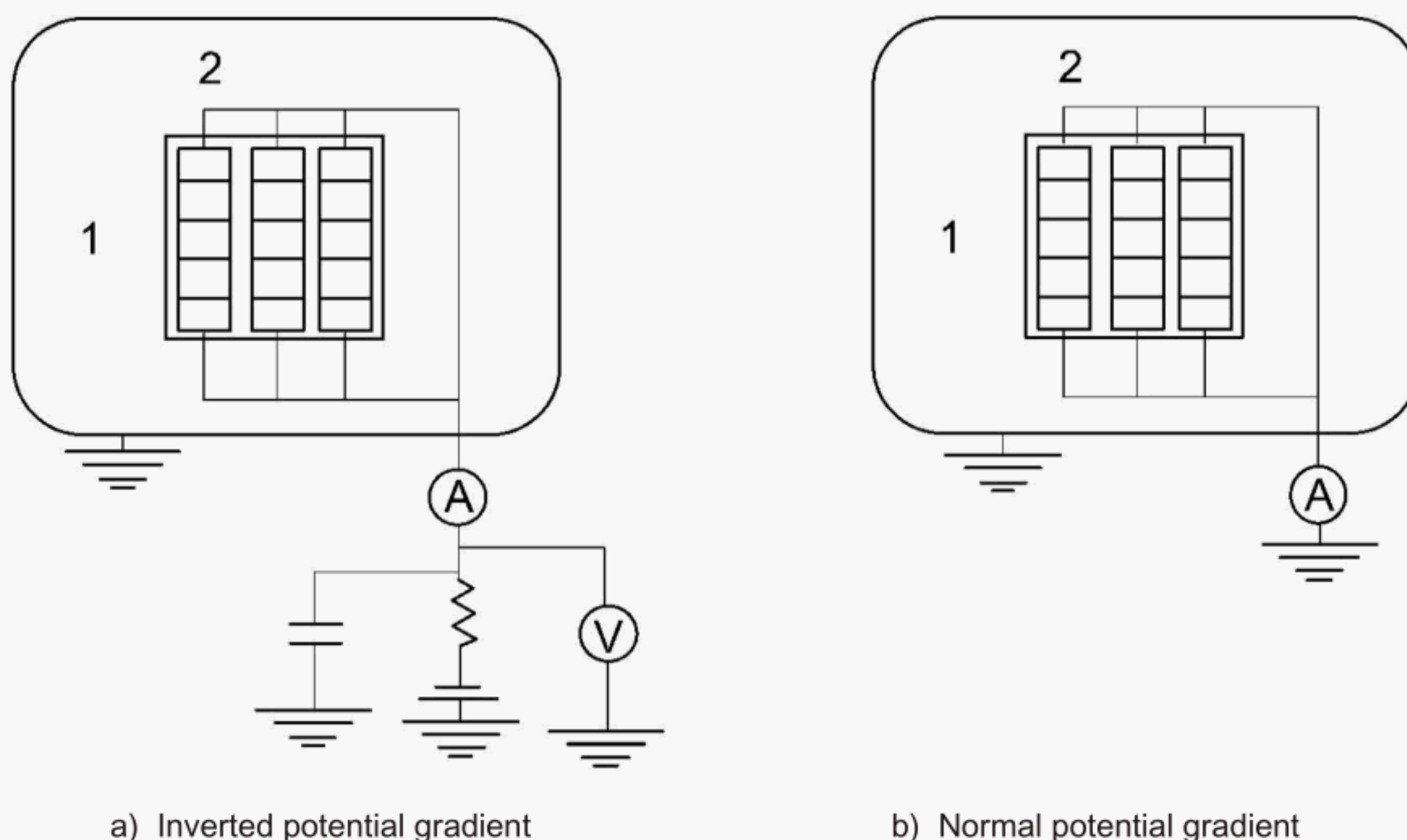


Figure 3 — Logic flow for determining the necessity of a power leakage characterization test







## 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.



## 7 Qualification test for secondary arc

### 7.1 Purpose

The purpose of this test is to qualify a given design of solar panel for flight. The purpose of the coverglass interconnect cell (CIC) gap test (7.4) is to demonstrate that no damaging secondary arc occurs even when primary discharges are forced to occur directly on the active CIC gap, which is a possible worst case scenario. The purpose of the panel test (7.5) is to show that no damaging secondary arc occurs, even after a significant number of primary discharges occur all over the flight-representative test coupon. See Annex B for a more detailed rationale of both tests.

It may not always be possible to replicate the orbital worst case scenario in the laboratory experiment (e.g. low temperature at the end of eclipse, the effects of thermal cycling on gap distance, failure or aging of grouting, and the outgassing time period in orbit). However, every effort shall be made to simulate the worst case scenario or to extrapolate the test results to represent the worst case scenario parametrization.

### 7.2 Triggering method and test facility

If it can be confirmed that the probability of a transition from a primary discharge to a secondary arc does not depend upon the method of primary discharge inception, any method may be used to cause primary discharges, irrespective of the anticipated charging situation in orbit. If the transition probability depends upon the testing plasma environment, the same test facility as used for the primary discharge inception threshold test shall be used. In either case, the shape and amplitude of the primary discharge current in the test shall be plausibly representative of the current expected in orbit.

There is a risk of primary discharge and subsequent secondary arcs in LEO even for a GEO spacecraft as it passes through LEO during the orbit transfer. Also, if a plasma emission device is used, such as a plasma contactor, LEO-type arcing may occur when the device is first turned on or off. Therefore, for a GEO spacecraft, the test should be performed under the conditions in a LEO-type plasma in addition to the GEO-type test. See Annex C for the minimum chamber size for a low-energy plasma test.

The test shall take place under vacuum in a test chamber with a pressure that guarantees the physical state of a collisionless plasma if a low-energy plasma is used, or lower than  $3 \times 10^{-3}$  Pa if other triggering methods, such as an energetic electron beam, UV ray, laser pulse, etc., are used. Care should be taken to choose a power supply capable of reproducing the dynamic response of the array to transient short circuits (such as limited overshoot current and fast recovery to the steady state). Simultaneous ESD current transient monitoring and recording devices and a video imaging device are also required for the test.

### 7.3 External circuit

The cells need not be illuminated, but the available current and capacitance shall be simulated by power sources and external capacitors,  $C_{\text{sat}}$  and  $C_{\text{CG}}$ , representing the satellite capacitance and solar array coverglass capacitance respectively. The capacitance of the missing coverglasses shall also be factored into the test. The current waveform supplied by the external circuit shall be representative of the surface flashover current in orbit. Under the present state of knowledge, the propagation distance is taken to be 2 m, confirmed by a laboratory test using a 4 m  $\times$  1 m coupon panel (see Reference [3]). The present best estimate of the

propagation speed of surface flashover is 10 km/s for a GEO solar array under inverted potential gradient. See Annex F for an example of the current waveform derivation. The electric architecture of a solar paddle shall be taken into account to determine the waveform. If a mitigation method for flashover current is included in the design, the effect shall be taken into account in sizing energy in the capacitance  $C_{\text{CG}}$ .

The inductance of the wire harness should be representative of a flight solar panel. Excessive inductance shall be avoided as it affects the transient current waveform. Short cable lengths or coaxial cables reduce the unwanted inductance. Annex G specifies the external circuit for use in the case of inverted potential gradient. If testing under normal potential gradient is imperative, a representative flashover current to the primary discharge shall be provided.



#### 7.4 CIC gap test — Test coupon and procedures

The test coupon(s) shall consist of at least two strings of two cells to represent a point surrounded by solar cell corner edges. The total number of test coupon(s) shall reflect the production variation, including reworked cells. The solar cells shall be laid down on the substrate in the same manner as for the flight model. The substrate shall also be made of the same material as the flight model. If the solar panel design includes ESD inception mitigation, whether the mitigation design is included in the test coupon or not depends on definition of the worst case scenario in orbit. If failure of the mitigation method is regarded as the worst case scenario, the mitigation method may be removed from the coupon. Before and after the test, the tasks specified in Table 1 shall be carried out.

The primary discharges may be concentrated on the cell gap. The test shall ascertain that a significant number of primary discharges (at least three, or more than three if agreed with the customer on the basis of statistical discussion; see Reference [4] for an example) per given test condition occur in the active gap or in the vicinity of the active gap if a grouted gap is tested.

Table 1 — Required tasks before and after the ESD test

Item	Before test	After test	Comment
Visual inspection of the coupon	x	x	With optical microscope
Output power measurement	x	x	Same light source
Insulation check across the cell gap	x	x	By measurement
Insulation check between the cells and the substrate	x	x	

#### 7.5 Panel test — Test coupon and procedures

The test coupon shall consist of at least three strings of three cells to represent means of cell surrounded by other cells. The coupon shall be a flight-representative qualification coupon covering the production variation of the string gap distance and CIC cell configuration (coverglass overhang, adhesive thickness, etc.), including reworked cells. The solar cells shall be laid down on the substrate in the same manner as for the flight model. The substrate shall also be made of the same material as the flight model. If the solar panel design includes ESD inception mitigation, the mitigation design should be included in the test coupon so as to be as flight-representative as possible. Before and after the test, the tasks specified in Table 1 shall be carried out.

The total number of primary discharges on the coupon shall be determined by means of statistical analysis. The total number of ESD events, as derived in accordance with Annex D, is useful in determining the number of primary discharges. No control shall be carried out at the primary discharge locations.

#### 7.6 Success criteria

The test shall demonstrate that no damaging secondary arc occurs due to ESD.



## 8 Characterization tests for robustness to ESD and plasma interaction

### 8.1 Power degradation

#### 8.1.1 Purpose

The purpose of this test is to characterize power degradation due to repeated ESD events after the desired orbital lifetime. As the present knowledge about the power degradation is not mature enough to list power degradation as a qualification item, the power degradation is measured for characterization purposes only.

This test may be performed simultaneously with the coupon panel test (7.5) provided the test requirements listed in 7.2, 7.3 and 8.1 are satisfied.

#### 8.1.2 Test facility

The test facility shall be the same as the one used for the ESD inception threshold test (6.2).

#### 8.1.3 Test coupon

The CIC solar cells on the test coupon(s) shall be of flight quality. The definition of flight quality shall be agreed upon with the customer prior to the test. The solar cell, coverglass, adhesive (both for coverglass and substrate) and interconnector shall be of the same type and material as for the flight models. The illuminated current-voltage (I-V) characteristics before the test shall be in accordance with the customer's specification of flight quality. The substrate need not be of the same material as the flight model. The total number of test coupon(s) shall reflect the production variation, including reworked cells.

#### 8.1.4 External circuit

An external circuit shall provide additional electrostatic energy that would have been provided by the insulator capacitance not accommodated inside the vacuum chamber. The current waveform supplied by the external circuit shall be representative of the surface flashover current in orbit. Under the present state of knowledge, the propagation distance is taken to be 2 m, confirmed by a laboratory test using a 4 m × 1 m coupon panel (see Reference [3]). The present best estimate of the propagation speed of surface flashover is 10 km/s for a GEO solar array under inverted potential gradient. See Annex F for an example of the current waveform derivation. The electric architecture of a solar paddle shall be taken into account in determining the waveform.

#### 8.1.5 Test procedures

Illuminated current-voltage (I-V) characteristics shall be measured pre- and post-test with an appropriate light source. The intensity of the light source shall be calibrated using a reference cell so that the relative change of the power output can be measured precisely. The exact conditions of the illuminated I-V measurement shall be based on an appropriate solar cell calibration standard, selected in agreement with the customer prior to testing. A visual inspection shall be performed pre- and post-test using an optical microscope. The test can be terminated once it satisfies one of the following:

- a) the estimated number of ESD events during the mission in orbit (see 6.6) occurs;
- b) ten discharges for any one cell do not create cell degradation;
- c) a predetermined number of ESD events, as agreed with the programme customer, occurs.

It is advisable to measure dark current with a DC power supply in order to perform in situ monitoring of the progress of degradation during the test by comparing the dark current with the pre-test value. See Annex H for more information on the measurement of the dark current. The total drop of spacecraft power at the end of its mission lifetime shall be derived and recorded.



## 8.2 Secondary arc

### 8.2.1 Purpose

The purpose of this test is to characterize the secondary arc for a given design of solar panel. The characteristics include the probability of transition from a primary discharge to a secondary arc and the duration of the secondary arcs if the transition probability is not zero. If the characteristics are already known from past experience, this test is not necessary to qualify the solar panel for secondary arcs.

### 8.2.2 Triggering method and test facility

The triggering method and test facility shall be as specified in 7.2.

### 8.2.3 Test coupon

The test coupon(s) shall consist of at least two strings of two cells to represent a point surrounded by solar cell corner edges. The total number of test coupon(s) shall reflect the production variation, including reworked cells. The cell gap spacing should be kept within an allowable design tolerance from the specification. The solar cells shall be laid down on the substrate in the same manner as for the flight model. The substrate shall also be made of the same material as in the flight model.

If the solar panel design includes ESD inception mitigation, whether the mitigation design is included in the test coupon or not depends on the definition of the worst case scenario in orbit. If failure of the mitigation method is regarded as the worst case scenario, the mitigation method may be removed from the coupon.

### 8.2.4 External circuit

The external circuit shall be as specified in 7.3.

### 8.2.5 Test procedures

Before and after the test, the tasks specified in Table 1 shall be carried out. Primary discharges may be concentrated on the cell gap. For each pair of gap voltage and string current agreed upon with the customer, the probability of transition from primary discharge to secondary arc shall be derived. The test shall ascertain that at least ten primary discharges per given test condition occur in the active gap (or in the vicinity of the active gap in the case of a grouted gap). If it is necessary to identify the confidence level of the transition probability, a significant number of primary discharges (as agreed with the customer on the basis of statistical discussion) per the given test condition shall occur in the active gap. If the transition probability is not zero, statistics of secondary arc duration, such as the mean and the standard deviation, are useful to extrapolate the probability of a damaging secondary arc with a very long duration. If any statistical distribution function is proposed to describe the secondary arc duration, its goodness-of-fit shall be determined by an appropriate method, such as the  $\chi^2$  statistic. See Annex I for an example of deriving the statistics.

## 8.3 Power leakage to plasma

### 8.3.1 Purpose

The purpose of this test is to characterize the power leakage from a solar array to the surrounding plasma. The plasma density and neutral gas density near the spacecraft shall be analysed first. Charging analysis tools employing a particle simulation method (see Annex E) can estimate the amount of current for a given plasma density. A rough estimate of the critical neutral gas density for transition of snapover to neutral gas ionization can be obtained using formulas in References [5] and [6]. If the power leakage due to snapover is low and neutral densities are too low for snapover to lead to neutral gas ionization, this test is not necessary.



### 8.3.2 Test facility

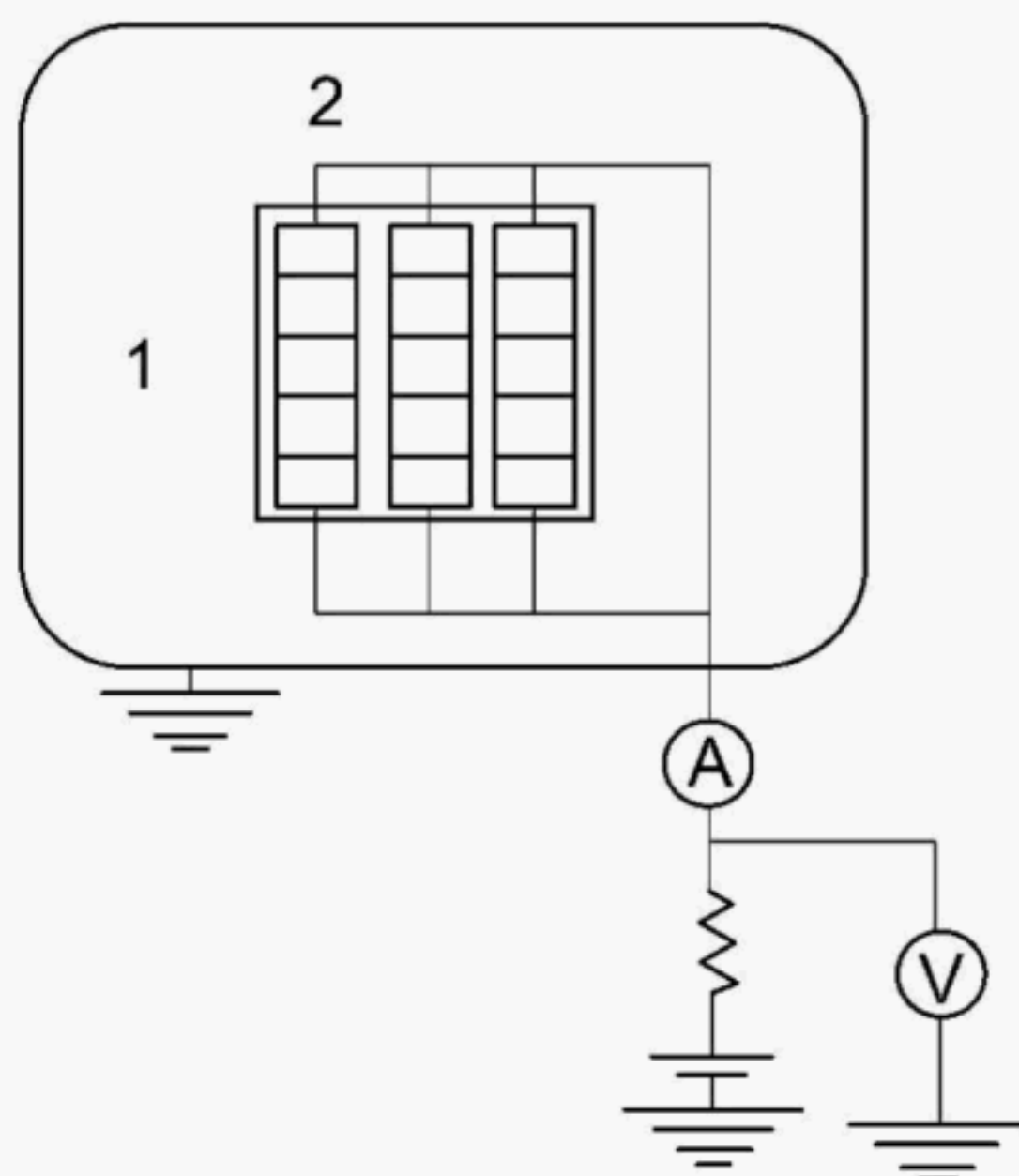
The test shall take place under vacuum in a test chamber equipped with a low-energy plasma source capable of generating the plasma density expected around the solar array in orbit. The plasma species do not have to be the same as those in orbit (see Reference [2]) A best effort shall be made to realize a plasma temperature similar to the value in orbit. If the plasma temperature is higher than that in orbit, the test result on the collected current shall be corrected based on either computer simulation or theory. The neutral background pressure shall be kept below 0,01 Pa so that unrealistic electron-neutral collisions do not affect the test results. The test facility shall be equipped with a DC power supply capable of supplying several amperes of current at several hundred volts, a recording device to monitor the collection current and the coupon potential simultaneously, a video imaging device and a plasma diagnostic device to determine the chamber plasma properties including the plasma potential with respect to the chamber wall. See Annex C for the minimum chamber size for a low-energy plasma test.

### 8.3.3 Test coupon

The number of CIC solar cells per coupon shall be as many as is practical. The minimum number shall be at least three strings of three cells. The use of mechanical CIC cells (not electrically flight-like) is acceptable as long as all the conductive parts, including the cell edge and interconnector, are exposed in the same manner as the flight model. The substrate material shall be flight-representative. The total number of test coupon(s) shall reflect the production variation including reworked cells.

### 8.3.4 External circuit

Both ends of the positive and negative electrodes of an array may be combined and connected to a DC power supply as illustrated in Figure 5. The cells need not be illuminated during the test.



#### Key

- 1 coupon
- 2 plasma chamber

Figure 5 — Schematic of circuit diagram for the characterization test of plasma power leakage



### 8.3.5 Test procedures

Before the test, the solar array coupon shall be visually inspected with an optical microscope. The test coupon bias voltage shall be changed step-wise while monitoring the potential of the coupon with respect to the plasma potential until the potential reaches the maximum solar array output voltage in orbit. The current collected at each potential shall be recorded after the current has become steady. After the test, the visual inspection shall be repeated. The overall power leakage from the spacecraft to the plasma shall be derived and reported.

### 8.4 Solar array back surface test

Although the scope of this International Standard is surface discharge and plasma interaction on the solar array front surface, the possibility of ESD and plasma interaction on the solar array back surface cannot be excluded (see Annex J).

## 9 Test report

The ESD test report shall include the following elements:

- a) a title;
- b) a description of the test facility (i.e. chamber size, chamber pressure, power supply, recording device, etc.) with photographs of the test set-up; verify that all necessary facility criteria are met;
- c) a description of the test coupon (i.e. solar cell type, solar cell output power, number of coupons tested, etc.);
- d) a description of the test conditions as follows:
  - 1) when a low-temperature plasma is used, the plasma conditions, such as plasma density, temperature and potential, shall be listed;
  - 2) when an electron beam is used, the beam energy and current density shall be listed;
  - 3) if the coupon is placed in a vacuum chamber for outgassing purposes prior to the test, the duration, pressure and temperature shall be listed;
  - 4) the coupon temperature during the test shall be reported;
- e) external circuit diagrams for each test case, identifying the value of each circuit element (any floating capacitance and inductance involved in the circuits should be identified);
- f) the test results as follows:
  - 1) summarize all visual inspections and include photographs of the test coupons before and after the tests;
  - 2) ensure that plots of test results have error bars in order to ascertain uncertainties in the test(s) where applicable;
  - 3) include appropriate analyses and discussion of observations and results;

- g) a summary of qualification tests, with an indication whether the solar panel has passed or failed qualification;
- h) a summary of characterization tests where applicable, including the derived total drop of spacecraft power at the end of mission lifetime, the transition probability to a secondary arc, the duration of secondary arc and the derived overall power leakage from the spacecraft to the plasma.



## Annex A (informative)

### Plasma interaction and electrostatic discharge effects on solar array

#### A.1 Plasma environment in orbit

For details of the orbital plasma environment, see References [7], [8], [9], [10], [11] and [12]. Generally speaking, GEO is characterized by the presence of electrons with energies greater than 1 keV. Under quiet conditions, the electron current is less than the photoelectron current, which is of the order of  $1 \mu\text{A}/\text{m}^2$  to  $10 \mu\text{A}/\text{m}^2$ , and there is no serious surface charging issue. Under stormy conditions, the electron current exceeds the photoelectron current, and the risk of electrostatic discharge on the solar array surface increases. Several examples of the worst case GEO plasma environment can be found in Reference [13]. LEO is characterized by the presence of low-energy but dense ionospheric plasma where the particle density is of the order of  $10^8 \text{ m}^{-3}$  to  $10^{12} \text{ m}^{-3}$ . For an object at the plasma potential in LEO, current from electrons of energies 0,1 eV to 0,2 eV dominates over any other current source to the spacecraft. The spacecraft body's potential floats with respect to the ionospheric plasma potential, at an absolute value smaller than the solar array power generation voltage. PEO is characterized by auroral electrons with energies greater than 1 keV that coexist with the low-energy ionospheric plasma. In some cases, the auroral electron current, which can be as large as  $1 \text{ mA}/\text{m}^2$ , may dominate over the other current sources and drive the spacecraft body to a potential more negative than the power generation voltage. When a spacecraft is equipped with an electric propulsion system, the artificial plasma can dominate the plasma environment around the spacecraft, especially in GEO.

#### A.2 Spacecraft surface charging

The spacecraft body that is made of conducting material serves as a grounding point in the spacecraft circuit. Currents to/from conductive parts exposed to space, and the capacitance between the spacecraft body and ambient space, determine the body potential with respect to the ambient space plasma. As the solar array circuit is also grounded to the spacecraft body, any point on the solar array circuit has a potential close to the spacecraft body's potential within the power generation voltage. When the negative end of a solar array circuit is grounded, the potentials on the solar array conductive parts have a distribution from the body potential to the body potential plus the power generation voltage.

In GEO, differential charging on the solar array surface can develop when the spacecraft encounters a high flux of energetic electrons. Conductive parts of the solar array, such as the solar cell electrode, interconnector or bus-bar, have a negative potential bounded by the spacecraft body potential. Insulator parts, such as the coverglass, adhesive or facesheet, also have negative potentials, but the values can be different from the body potential by 1 kV or greater. In PEO, a situation similar to GEO may arise when the spacecraft encounters the aurora and the solar array front surface is facing the wake side. When the solar array front surface is facing the ram side in PEO, the aurora can drive the spacecraft body potential negative and the insulator surface can be charged by ionospheric ions to a potential close to the ambient plasma potential. In LEO, differential charging on the solar array surface appears as the insulator parts have potentials close to the ambient plasma potential and the conductive parts have potentials ranging from the negative of the power generation voltage to the positive of the power generation voltage. Therefore, for LEO spacecraft, ESD and PI issues arise only when the power generation voltage exceeds the primary arc or snapover threshold voltage.

Spacecraft surface charging can be assessed with the aid of computer simulations. There are several computer programs that can calculate the differential voltage for a given set of spacecraft geometry, environmental parameters and surface material properties. As ESD occurs during a transient phase of differential charging in GEO and PEO when a differential voltage develops due to an encounter with a substorm or aurora, it is important for the programs to be able to calculate the transient behavior in addition to the steady state behavior. See Annex E for examples of such software. Although the computer simulation tools can give the differential voltage, they cannot predict the discharge inception voltage.



### A.3 Electrostatic discharge on solar array

ESD on a solar array is a single, fast, high-current transfer of electrostatic charge that results from a strong electrostatic field between two objects in close proximity. Differential charging on solar array exterior surfaces builds up an electric charge on the insulator surface. The electrostatic energy stored on the insulator is partially or fully released once the electric field on any part of the surface exceeds the discharge inception threshold. ESD has three forms of current path. The first is blow-off, which is the emission of negative charges (electrons) into space. The blow-off current discharges electric charge stored in the capacitance between the spacecraft and the ambient plasma. The second is flashover, which is a surface discharge propagating from a starting point as the surface of the dielectric becomes conductive (by the creation of a plasma). The flashover current discharges electric charge stored in the capacitance between the surface of an insulator and the spacecraft ground. The third is punch-through, which is the classic breakdown of a dielectric material, such as the breakdown of a capacitance, for example. The punch-through discharge neutralizes not only electric charge stored in the capacitance between the insulator and spacecraft ground, but also some of the electric charge stored inside the insulator material due to penetrating charged particles. Considering the thickness and dielectric strength of typical insulator materials used on solar arrays, blow-off or flashover-type discharge is more likely to occur than the punch-through discharge.

The inception threshold for ESD on a solar array is often measured by the potential difference between the coverglass surface and the spacecraft ground. Although the threshold depends upon numerous parameters such as polarity, geometry, material, ambient atmosphere, etc., the inverted potential gradient (IPG) situation has a smaller threshold (hundreds of volts) than the normal potential gradient (NPG) situation (thousands of volts). IPG ESD has been more thoroughly investigated than NPG ESD. For high-voltage LEO spacecraft, IPG is the nominal condition. In PEO and GEO, the secondary electron and photoelectron coefficients of insulator material determine the polarity. As the solar array is illuminated by sunlight during power generation, and the coverglass coating, such as  $\text{MgF}_2$ , has a very high secondary electron coefficient, IPG is expected to occur more frequently than NPG. As the situation can differ for each spacecraft, however, a charging analysis should be carried out to determine the polarity on the solar array for each spacecraft unless an identical spacecraft design is employed.

Normal or inverted, ESD originates from a micro-discharge at its inception point. For IPG, it is believed to be due to the field emission and desorption of gas near the so-called triple junction, where the insulator material, conductor and vacuum (plasma) meet together (see References [14], [15] and [16] for more details). For NPG, it may be due to punch-through of a thin dielectric or an electron avalanche triggered by seed electrons produced by various reasons. Due to the negative potential of the spacecraft body and the high mobility of electrons, the blow-off current quickly discharges the satellite capacitance (absolute capacitance), with typical values from 100 pF to 1 000 pF. The flashover current follows the blow-off by neutralizing electric charge on the insulator near the ESD inception point. In the case of IPG, the flashover current flows to the inception point and forms cathode spots, transforming the ESD into a form of vacuum arc. Therefore, IPG ESD is called a primary arc. The primary arc receives its energy from the electrostatic energy stored in the capacitance between the insulator surface and the spacecraft body (differential capacitance), which is typically much greater than the absolute spacecraft capacitance.

### A.4 Detrimental effects of ESD

ESD on a solar array can cause various detrimental effects to the solar array operation. The large transient current can cause electromagnetic interference with spacecraft circuits. As ESD can occur repeatedly during the lifetime of a spacecraft, there can be cumulative effects such as surface degradation, surface contamination via vaporized material or internal damage to solar cells due to surge voltages. When ESD occurs at the edge of a solar cell or bypass diode, it may degrade their electrical performance.

“Primary discharge” includes both IPG ESD (primary arc) and NPG ESD that can trigger a secondary arc. The primary discharge is fed by the absolute and differential capacitances. The primary discharge can create a temporary conductive path between any two cells with different voltages generated by the solar array. The current between the two cells can become sustained when fed from the solar array output power. This resulting phenomenon is called a “secondary arc”. The secondary arc is powered by an illuminated solar array and leads to an important additional damage mechanism since the solar array circuit can become permanently short-circuited.





## Annex B (informative)

### Secondary arc qualification processes

Before drafting of this International Standard on solar panel ESD test procedures began, various styles of ESD tests had already been carried out in various countries (see References [17], [18], [19], [20], [21], [22] and [23] for examples). In some countries, the emphasis was on making sure that the devastating secondary arc would not occur even under the worst possible conditions. In those countries, the worst case scenario was often assumed to be a primary discharge at the active gap and, if the gap was grouted, the worst case scenario was assumed to be failure of grouting, i.e. no grouting. The CIC gap test described in 7.4 is based on the test procedure adopted in those countries. In other countries, the qualification tests had been performed under the philosophy of “test as you fly”. Therefore, the coupon panel test that employs a test coupon which is as flight-representative as possible, without any modification to increase the probability of primary ESD occurrence at the active gaps, has been regarded as mandatory in addition to the CIC gap test. The coupon panel test described in 7.5 is based on the test procedure adopted in those latter countries working on the “test as you fly” principle. Although intensive efforts have been made to absorb the difference between the test methods carried out in different parts of the world, in order to be able to produce this International Standard within a limited time frame, it was necessary to adopt the test flow structure shown in Figure 2.





## Annex D (informative)

### ESD events analysis

In order to have a statistical discussion about the test conditions or the test results, it is useful to know the likelihood of ESD events in orbit. Spacecraft charging in orbit can be analysed to determine whether the predicted voltage differentials will exceed the ESD inception threshold. This can be done by consulting a database to compute the probability of the charging environments the spacecraft may encounter. The charge differential is then computed for these cases together with the time it takes to achieve the differential. There are several computer programs, examples of which are listed in Annex E, that can perform these calculations. At the very least, the charging simulation for the worst charging environment should be run (see References [9] and [24]).

The number of ESD events in orbit can be estimated as follows[25]:

- a) list the space plasma environments that a given spacecraft will encounter in orbit;
- b) carry out spacecraft charging analysis for each type of space plasma environment;
- c) identify plasma environment cases that give a differential voltage exceeding the ESD inception threshold;
- d) for each case identified in c) above, calculate the charging time necessary to reach the threshold value;
- e) derive the probability of occurrence of each case identified in c) and the expected total duration in orbit;
- f) divide the expected total duration obtained in the e) by the charging time obtained in d) to obtain the expected number of ESD events for each case exceeding the ESD inception threshold;
- g) sum the number of ESD events to derive the total number.

More details can be found in Reference [25].

For the steps given in a) and e) above, a proper database relating to the space plasma environment should be consulted. An example of a GEO database is the Los Alamos National Laboratory (LANL) satellite data, which is available on the internet (see Reference [26]), where the magnetospheric plasma analyser (MPA) data are listed for electron density, electron temperature, ion density and ion temperature between 1 eV and 45 keV. These have been measured by multiple LANL satellites every 90 s since 1993. An example of a PEO database is the Defense Meteorological Satellite Program (DMSP) satellite data. These auroral electron data are available on the internet (see Reference [27]), and include the SSJ/4 (Precipitation Electron/Proton Spectrometer) data for the precipitating electron flux between 30 eV and 30 keV, measured by multiple DMSP satellites at an altitude of approximately 840 km every 1 s since 1983. LEO ionospheric data are available on the internet from Reference [28], where the Special Sensor-Ions, Electrons, and Scintillation (SSIES) data are listed for electron density, electron temperature, ion density and ion temperature, measured by multiple DMSP satellites every 4 s since 1987.

In the step given in b) above, a proper spacecraft charging analysis tool should be used. Annex E provides a list of the computer programs currently available. The differential voltage between the coverglass and the spacecraft body should be calculated for a given set of the environmental parameters. The worst case scenario should be calculated first, as there will be no need for further analysis and an ESD test if the worst case simulation shows no possibility of the differential voltage exceeding the ESD inception threshold. (If the ESD threshold is not known, it should be determined by testing.) It should be noted that the result of a charging analysis often depends strongly on spacecraft material properties. Even if the worst case simulation shows no serious charging, the result should be confirmed by varying the material data over the entire possible range of the parameters.









## Annex E (informative)

### Spacecraft charging analysis

#### E.1 General

There are a number of simulation codes available for performing surface charging assessments taking into account surface material processes or 3D effects. Historically, the most common spacecraft charging analysis code in use by the space industry was NASCAP/GEO, developed by NASA and the US Air Force. It has been made available to various users via collaboration agreements with NASA or via commercial arrangement. Although NASCAP/GEO has been replaced by NASCAP-2K in the United States, NASCAP-2K is subject to export restrictions. Recently Japan Aerospace Exploration Agency (JAXA) has sponsored the development of the Multi-Utility Spacecraft Charging Analysis Tool (MUSCAT) and the European Space Agency (ESA) has sponsored the development of the Spacecraft Plasma Interaction System (SPIS).

The basic objective of spacecraft surface charging analysis is to calculate the contribution of each current component by following the trajectories of the ambient plasma particles, calculating the interaction between the incident particles and the surface material and considering the emission of charged particles from the surface, such as secondary electron, photoelectron and artificial plasmas. Then, the surface charge distribution is updated based on the current density and conductivity of each surface element relative to the spacecraft body ground. The surface potentials are calculated by solving the Poisson equation or the Laplace equation. Particle trajectories are recalculated for the renewed surface potential and the processes are repeated until the elapsed time reaches the predetermined time or the steady state is obtained. The important features of the charging analysis code are the capability to model the three-dimensional geometry of the spacecraft and significant surface interactions such as secondary electron and photoelectron emission, and a database relating to spacecraft surface material properties such as conductivity, secondary electron emission yield and photoelectron emission coefficient.

#### E.2 Examples of spacecraft charging analysis codes

##### E.2.1 NASCAP/GEO

NASCAP (also called NASCAP/GEO; see Reference [29]) is commonly used for simulating surface charging in the outer magnetosphere. This code calculates the total current, due to all the current contributions, for each surface on a numerically modelled 3D spacecraft, using a double Maxwellian environment for both ions and electrons. From these currents, the change in potential at each surface is calculated. The current and potential calculations can be performed iteratively until an equilibrium charging state is achieved. The code is available commercially upon request from Science Applications International Corporation, USA.

##### E.2.2 NASCAP/LEO

NASCAP/LEO is aimed at the simulation of high-potential objects with a cold, dense plasma typical of the LEO environment. Like NASCAP/GEO, it employs analytical current collection equations, although these are aimed at sheath-limited current collection and are appropriate for the short Debye-length LEO plasmas. Typical uses are the simulation of parasitic currents from high-potential surfaces, such as solar array interconnects. The geometrical model of the spacecraft is more sophisticated than for NASCAP/GEO, consisting of a finite-element representation. The code is available commercially upon request from Science Applications International Corporation, USA.



### E.2.3 POLAR charging code

The main problem with computing charging in LEO is due to effects associated with the spacecraft sheath. The 3D POLAR code (see Reference [30]) has been designed for the assessment of sheath and wake effects on PEO spacecraft. It uses numerical techniques to track ambient ions inwards from the electrostatic sheath surrounding a negatively charged spacecraft onto the spacecraft surface. The spacecraft velocity is included as an input and ram and wake effects are modelled. One or two Maxwellian components may be used to define the ambient plasma. The electron population in POLAR is a superposition of power-law, Maxwellian, and Gaussian components. Once the surface currents have been found, POLAR calculates potentials and the equilibrium charging state in a similar way to NASCAP. The point of contact for the POLAR charging code is Air Force Research Laboratory, Hanscom Air Force Base, USA.

### E.2.4 NASCAP-2K

The most recent NASCAP code, NASCAP-2K, is available free to US citizens only. This is a comprehensive code with realistic geometry. It combines the capabilities of NASCAP/GEO, NASCAP/LEO and POLAR. The code is not easily available outside the US due to export restrictions.

### E.2.5 SPIS

SPIS (see Reference [31]) is a fully 3D particle-in-cell (PIC) that allows exact computation of the sheath structure and the current collected by spacecraft surfaces for very detailed geometries. Surface interactions including photoelectron emission, back-scattering, secondary electron emission and conduction are modelled. The source code is freely available from [www.spis.org](http://www.spis.org) and a mailing list provides limited support.

### E.2.6 MUSCAT

MUSCAT (see Reference [32]) is a fully 3D particle code that can be applied to spacecraft in LEO, PEO and GEO. Its algorithm is a combination of PIC and particle tracking. A parallel computation technique is used for fast computation. It has a JAVA-3D-based graphical user interface for 3D modelling of spacecraft geometry and output visualization. The surface interactions included in the NASCAP series and SPIS are modelled. A material property database is also included. The code is available commercially upon request from MUSCAT Space Engineering Co., Ltd., Japan.

### E.2.7 Other surface charging codes

There are a number of other codes available to simulate surface charging. Two Russian codes ECO-M[33] and COULOMB[34] perform a very similar function to NASCAP, POLAR and NASCAP/LEO.

### E.2.8 Environment Workbench

Environment Workbench (EWB) is an approximate, quick-look code that includes spacecraft charging in LEO. A variant of EWB is the official charging tool for the International Space Station (ISS). The point of contact for the code is Science Applications International Corporation, USA.

### E.2.9 SPARCS

SPARCS is a code developed and used by Thales Alenia Space for simulating surface charging in the outer magnetosphere (GEO). This code computes the total current, due to all the primary and secondary current contributions, for each surface on a finite-element-type geometrical model of the spacecraft. Physical phenomena accounted for in the secondary current budget are electron photo-emission, back-scattering and secondary cascade emission, and secondary electron recollection. SPARCS uses a double Maxwellian environment for both ions and electrons. From these currents, the change in absolute potential of the spacecraft and in potential at each surface is calculated. Environmental conditions can be changed during computation for a simulation of an end-of-eclipse. SPARCS can be made available commercially upon request from Thales Alenia Space.











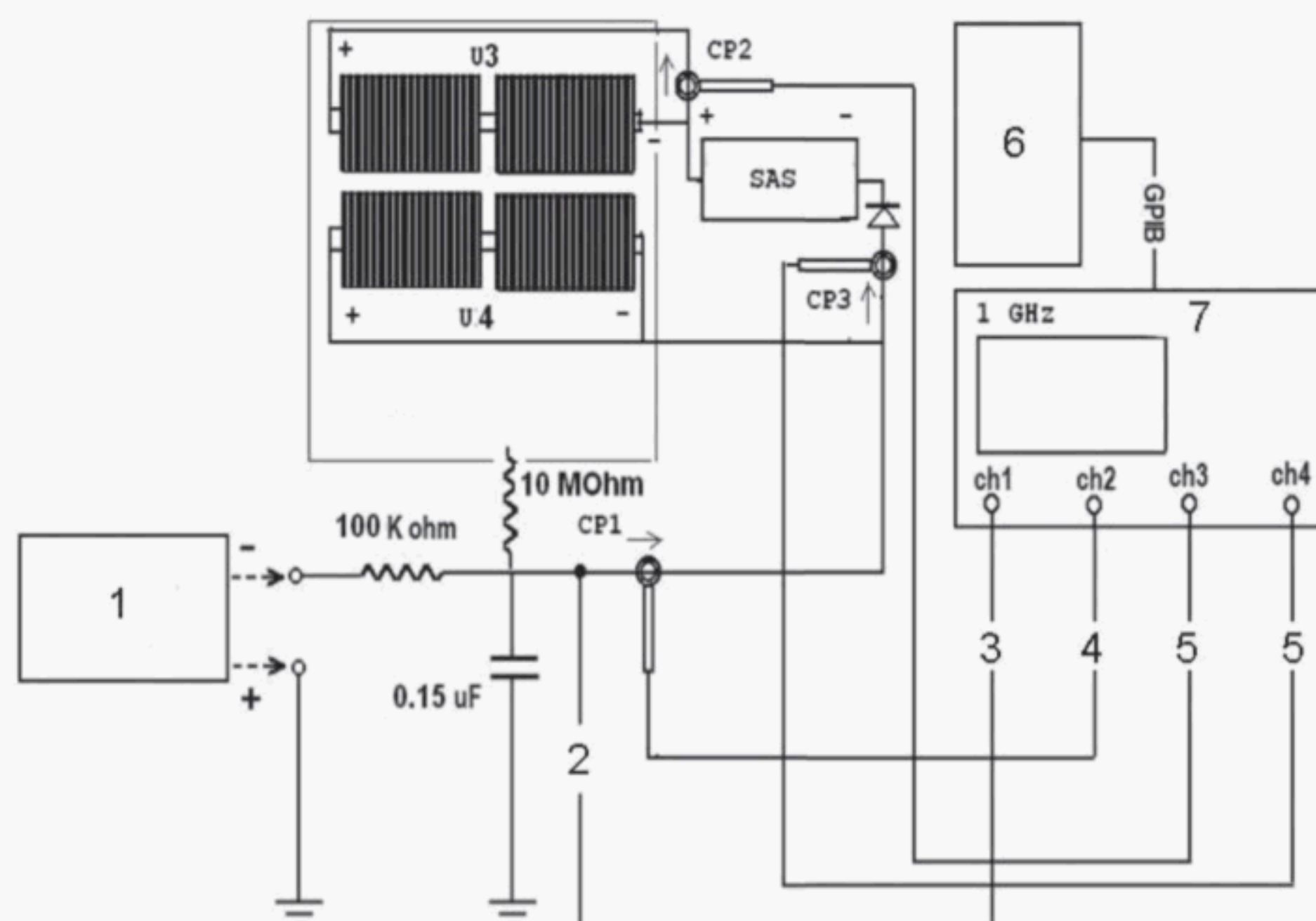












Key

- 1 0-1kV bias supply
- 2 voltage probe
- 3 voltage waveform (voltage WFM)
- 4 trigger pulse (trig. pulse)
- 5 current waveform (current WFM)
- 6 computer
- 7 oscilloscope

- SAS solar array simulator
- GPIB general purpose interface bus
- CP1 current probe
- CP2 current probe
- CP3 current probe
- U3 string
- U4 string

Figure G.4 — Example of the circuit layout for a secondary arc test representing IPG — USA  
© 2008 IEEE. Reprinted with permission from Reference [40]

















## Annex J (informative)

### Solar array back surface test

Although the scope of this International Standard is surface discharge and plasma interaction on the solar array front surface, the possibility of ESD and plasma interaction on the solar array back surface cannot be excluded. Reference [19] describes an example of an ESD test on a solar array back surface.

As there is no solar cell on the back surface, secondary arcs and power leakage are the major concerns. A solar array back surface often has exposed metallic parts such as diodes, connectors, hold-down, etc. If the metallic parts are adjacent to other parts with a different voltage, a primary ESD on the solar array back surface can lead to a secondary arc between the two parts and a subsequent permanent short circuit. The metallic parts may attract electrons from the surrounding plasma if their potential with respect to the plasma is high, resulting in power leakage to the plasma.

Apart from the test coupon, the same test facility and procedure as used for the test on the front surface can be applied to the test on the back surface. The test coupon should be made in the same manner as the flight solar panel, including the substrate. All the features of the flight panel such as diode boards, connectors, etc. should be included. The test flow for a secondary arc is the same as for the front surface. First, the ESD inception threshold should be measured as described in Clause 6, using a charging method representative of the orbital condition. Many charging analysis software programs are capable of calculating the back surface differential charging at the same time as they calculate the front surface charging. Therefore, it is possible to estimate the number of ESD events in orbit as described in Annex D. The secondary arc test on the back surface can be performed in the same manner as given in 7.2 and 7.5, using the flight-representative back surface coupon. The same external circuit as that described in 7.3 and Annex G can be used, although care should be taken to derive the correct value of the external capacitance, because the flashover extension is now over the insulator on the back surface.

The power leakage test on the back surface can be carried out in the same manner as given in 8.3, except for the test coupon. The same test coupon as was used for the back surface ESD test can be used for the plasma leakage test. As most spacecraft use negative grounding of the solar array circuit, power leakage to the solar panel substrate is not a concern. Exposed metallic parts with the same potential as the positive end of the solar array circuit, such as blocking diodes, have the highest risk of serious power leakage. Those parts should be included in the test coupon.



## Bibliography

- [1] VAYNER, B., GALOFARO, J. and FERGUSON, D., Interactions of High-Voltage Solar Arrays with Their Plasma Environment: Ground Tests, *Journal of Spacecraft and Rockets*, Vol. 41, No. 6, 2004, pp. 1031-1051
- [2] FERGUSON, D.C., The voltage threshold for arcing for solar cells in LEO: Flight and ground test results, NASA-TM-87259 or AIAA Paper 86-0362, 1986
- [3] MASHIDORI, H., IWASA, M., WADA, A., NITTA, K., NOMURA, M., TOYODA, K., Preliminary ESD Ground Tests on Meter-Class Solar Panels in Simulated GEO Environments, 4th Space Environment Symposium, Tokyo, Japan, 22-23 January 2008
- [4] CHO, M., KITAMURA, K., OSE, T., MASUI, H., TOYODA, K., Statistical Number of Primary Discharges Required for Solar Array Secondary Arc Tests, *Journal of Spacecraft and Rockets*, Vol. 46, No. 2, 2009, pp. 438-448
- [5] CHO, M., Ionosphere Ionization Effects on Sheath Structure around a High Voltage Spacecraft, *J. Spacecraft and Rockets*, Vol. 32, No. 6, 1995, pp. 1018-1026
- [6] COOKE, D.L. and KATZ, I., Ionization-induced instability in an electron-collecting sheath, *J. Spacecraft and Rockets*, Vol. 25, No. 2, 1988, pp. 132-138
- [7] ISO/TS 16457, Space systems — Space environment (natural and artificial) — The Earth's ionosphere model: international reference ionosphere (IRI) model and extensions to the plasmasphere
- [8] <http://ccmc.gsfc.nasa.gov/modelweb/>
- [9] FERGUSON, D.C. and HILLARD, G.B., Low Earth Orbit Spacecraft Charging Design Guidelines, NASA/TP-2003-212287
- [10] NASA-STD-4005, Low Earth Orbit Spacecraft Charging Design Standard
- [11] NASA-HDBK-4006, Low Earth Orbit Spacecraft Charging Design Handbook
- [12] ECSS-E-ST-20-06C, Space Engineering — Spacecraft Charging, 2008
- [13] PURVIS, C.K., GARRETT H.B., WHITTLESEY, A.C. and STEVENS J.N., Design Guidelines for Assessing and Controlling Spacecraft Charging Effects, NASA Technical Paper 2361, 1984
- [14] PAYAN, D., SEVERIN, F., CATANI, J.P., ROUSSEL, J.F., REULET, R., SARRAIL, D., Electrostatic Discharges on Solar Arrays. Physical Model of Inverted Potential Gradient Electrostatic Discharge, 7th Spacecraft Charging Technology Conference, ESA/ESTEC Noordwijk, The Netherlands, 23-27 April 2001. Available at: <http://dev.spis.org/projects/spine/home/tools/sctc>
- [15] HASTINGS, D.E., CHO, M. and KUNINAKA, H., The Arcing Rate for a High Voltage Solar Array: Theory, Experiment and Predictions, *J. Spacecraft and Rockets*, Vol. 29, 1992, pp. 538-554
- [16] HASTINGS, D.E., WYLE, G. and KAUFMAN, D., Threshold Voltage for Arcing on Negatively Biased Solar Arrays, *J. Spacecraft and Rockets*, Vol. 27, 1990, pp. 539-544
- [17] CHO, M., RAMASAMY, R., MATSUMOTO, T., TOYODA, K., NOZAKI, Y., TAKAHASHI, M., Laboratory Tests on 110-Volt Solar Arrays in Simulated Geosynchronous Orbit Environment, *J. Spacecraft and Rockets*, Vol. 40, No. 2, 2003, pp. 211-220



- [18] CHO, M. and GOKA, T., Japanese practices of solar array ESD ground tests, 9th Spacecraft Charging Technology Conference, Tsukuba, Japan, April 2005, JAXA SP-05-001E. Available at: <http://repository.tksc.jaxa.jp/dr/prc/japan/contents/AA0049206046/49206046.pdf>
- [19] CHO, M., KIM, J.-H., HOSODA, S., NOZAKI, Y., MIURA, T., IWATA, T., Electrostatic Discharge Ground Test of a Polar Orbit Satellite Solar Panel, IEEE Transaction on Plasma Science, Vol. 34, No. 5, 2006, pp. 2011-2030
- [20] BERTHOU, C., BOULANGER, B., LEVY, L., Plasma ESD Qualification Test Procedure of Alcatel Alenia Space Solar Array, IEEE Transaction on Plasma Science, Vol. 34, No. 5, 2006, pp. 2004-2010
- [21] GAILLOT, L., FILLE, M.-L., LEVY, L., Secondary arcs on solar array — Test results of emags 2, 9th Spacecraft Charging Technology Conference, Tsukuba, Japan, April 2005, JAXA SP-05-001E. Available at: <http://airex.tksc.jaxa.jp/pl/dr/AA0049206043/en>
- [22] FERGUSON, D.C., VAYNER, B.V., GALOFARO, J.T., HILLARD, G., VAUGHN, J., SCHNEIDER, T., NASA GRC and MSFC Space Plasma Arc Testing Procedures, IEEE Transaction on Plasma Science, Vol. 34, No. 5, 2006, pp. 1948-1958
- [23] HOEBER, C.F., ROBERTSON, E.A., KATZ, I., DAVIS, V.A. and SNYDER, D.B., Solar Array Augmented Electrostatic Discharge in GEO, AIAA Paper 98-1401, 1998
- [24] ECSS-ST-E10-04C, Space engineering — Space Environment, 2008
- [25] CHO, M., KAWAKITA, S., NAKAMURA, S., TAKAHASHI, M., SATO, T. and NOZAKI, Y., Number of arcs estimated on solar array of a geostationary satellite, Journal of Spacecraft and Rockets, Vol. 42, No. 4, 2005, pp. 740-748
- [26] <http://cdaweb.gsfc.nasa.gov/>
- [27] <http://sd-www.jhuapl.edu/Aurora/index.html>
- [28] <http://cindispace.utdallas.edu/DMSP/>
- [29] KATZ I., CASSIDY, J.J., MANDELL, M.J., SCHNUELLE, G.W., STEEN, P.G. and ROCHE, J.C., The Capabilities of the NASA Charging Analyzer Program, in Spacecraft Charging Technology –1978, Ed. R.C. Finke and C.P. Pike, NASA CP-2071/AFGL TR-79-0082, ADA045459, p. 101, 1979
- [30] LILLEY, J.R., COOKE, D.L., JONGEWARD, G.A. and KATZ, I., POLAR User's Manual, AFGL-TR-85-0246
- [31] FOREST, J., ELIASSON, L. and HILGERS, A., A New Spacecraft Plasma Interactions Simulation Software, PicUp3D/SPIS, Proc. 7th Spacecraft Charging Technology Conf., 2001, pp. 515-520. Available at: <http://dev.spis.org/projects/spine/home/tools/sctc>
- [32] MURANAKA, T., HOSODA, S., KIM, J., HATTA, S., IKEDA, K., HMANAGA, T., CHO, M., USUI, H., UEDA, H.O., KOGA, K. and GOKA, T., Development of Multi-Utility Spacecraft Charging Analysis Tool (MUSCAT), IEEE Transaction on Plasma Sciences, Vol. 36, No. 5, 2008, pp. 2336-2349
- [33] VASILYEV, Ju.V, DANILOV, V.V., DVORYASHIN, V.M., KRAMRENKO, A.M. and SOKOLV, V.S., Computer Modeling of Spacecraft Charging Using ECO-M, Proc. International Conference of Problems of Spacecraft/Environment Interactions, 15-19 June 1992, Novosibirsk, Russia, p. 187, 1993
- [34] SOUBEYRAN, A., DROLSHAGEN, G., LEVY, L., MATUCCI, A., KENSEK, R.P., BETZ, G. and FEHRINGER RUDENHAUER, F.G., Deep Dielectric Charging Simulation New Guidelines, IEEE proceedings of Radiation Effects Data Workshop, IEEE, 21 July 1993, pp. 93-98
- [35] MASUI, H., TOYODA, K. and CHO, M., Electrostatic Discharge Plasma Propagation Speed on Solar Panel in Simulated Geosynchronous Environment, IEEE Transaction on Plasma Science, Vol. 36, No. 5, 2008, pp. 2387-2394



- [36] LEUNG, P., Plasma Phenomena Associated with Solar Array Discharges and their Role in Scaling Coupon Test Results to a Full Panel, AIAA 2002-0628, 40th Aerospace Sciences Meeting & Exhibit, Reno, January 2002
- [37] AMORIM, E., PAYAN, D., REULET, R. and SARRAIL, D., Electrostatic discharges on a 1 m<sup>2</sup> solar array coupon — Influence of the energy stored on coverglass on flashover current, 9th Spacecraft Charging Technology Conference, Tsukuba, Japan, April 2005, JAXA SP-05-001E. Available at: <http://repository.tksc.jaxa.jp/dr/prc/japan/contents/AA0049206042/49206042.pdf>
- [38] PAYAN, D., SCHWANDER, D. and CATANI, J.P., Risks of low voltage arcs sustained by the photovoltaic power of a satellite solar array during an electrostatic discharge. Solar Array Dynamic Simulator, 7th Spacecraft Charging Technology Conference, April 2001. Available at: <http://dev.spis.org/projects/spine/home/tools/sctc>
- [39] MASUI, H., KITAMURA, T., OKUMURA, T., TOYODA, K. and CHO, M., Laboratory Test Campaign for ISO Standardization of Solar Array ESD Test Methods, AIAA 45th Aerospace Science Meeting, 2007
- [40] VAYNER, B., FERGUSON, D.C., GALOFARO, J. T., Emission Spectra of Arc Plasmas, IEEE Transaction on Plasma Science, Vol. 36, No. 5, 2008, pp. 2219-2227
- [41] PAYAN, D., SCHWANDER, D., ROUSSEL, F., INGUIMBERT, V., SARRAIL, D., MATEO-VELEZ, J-C., CNES-ONERA Recommended Test Set-Up to Qualify Solar Array Design against Sustained Arc Triggered by an Electrostatic Discharge, 8th European Space Power Conference, September 2008. Available at: [www.congrex.nl/08a02/abstracts/317600.pdf](http://www.congrex.nl/08a02/abstracts/317600.pdf)
- [42] PAYAN, D., ONERA/CNES Physical Flashover Simulator, Proceedings of 6th Space Environment Symposium, Kitakyushu, October 2009, JAXA SP-09-006











# British Standards Institution (BSI)

BSI is the national body responsible for preparing British Standards and other standards-related publications, information and services.

BSI is incorporated by Royal Charter. British Standards and other standardization products are published by BSI Standards Limited.

## About us

We bring together business, industry, government, consumers, innovators and others to shape their combined experience and expertise into standards-based solutions.

The knowledge embodied in our standards has been carefully assembled in a dependable format and refined through our open consultation process. Organizations of all sizes and across all sectors choose standards to help them achieve their goals.

## Information on standards

We can provide you with the knowledge that your organization needs to succeed. Find out more about British Standards by visiting our website at [bsigroup.com/standards](http://bsigroup.com/standards) or contacting our Customer Services team or Knowledge Centre.

## Buying standards

You can buy and download PDF versions of BSI publications, including British and adopted European and international standards, through our website at [bsigroup.com/shop](http://bsigroup.com/shop), where hard copies can also be purchased.

If you need international and foreign standards from other Standards Development Organizations, hard copies can be ordered from our Customer Services team.

## Subscriptions

Our range of subscription services are designed to make using standards easier for you. For further information on our subscription products go to [bsigroup.com/subscriptions](http://bsigroup.com/subscriptions).

With British Standards Online (BSOL) you'll have instant access to over 55,000 British and adopted European and international standards from your desktop. It's available 24/7 and is refreshed daily so you'll always be up to date.

You can keep in touch with standards developments and receive substantial discounts on the purchase price of standards, both in single copy and subscription format, by becoming a BSI Subscribing Member.

PLUS is an updating service exclusive to BSI Subscribing Members. You will automatically receive the latest hard copy of your standards when they're revised or replaced.

To find out more about becoming a BSI Subscribing Member and the benefits of membership, please visit [bsigroup.com/shop](http://bsigroup.com/shop).

With a Multi-User Network Licence (MUNL) you are able to host standards publications on your intranet. Licences can cover as few or as many users as you wish. With updates supplied as soon as they're available, you can be sure your documentation is current. For further information, email [bsmusales@bsigroup.com](mailto:bsmusales@bsigroup.com).

## Revisions

Our British Standards and other publications are updated by amendment or revision.

We continually improve the quality of our products and services to benefit your business. If you find an inaccuracy or ambiguity within a British Standard or other BSI publication please inform the Knowledge Centre.

## Copyright

All the data, software and documentation set out in all British Standards and other BSI publications are the property of and copyrighted by BSI, or some person

or entity that owns copyright in the information used (such as the international standardization bodies) and has formally licensed such information to BSI for commercial publication and use. Except as permitted under the Copyright, Designs

and Patents Act 1988 no extract may be reproduced, stored in a retrieval system or transmitted in any form or by any means – electronic, photocopying, recording or otherwise – without prior written permission from BSI. Details and advice can be obtained from the Copyright & Licensing Department.

## Useful Contacts:

### Customer Services

Tel: +44 845 086 9001

Email (orders): [orders@bsigroup.com](mailto:orders@bsigroup.com)

Email (enquiries): [cservices@bsigroup.com](mailto:cservices@bsigroup.com)

### Subscriptions

Tel: +44 845 086 9001

Email: [subscriptions@bsigroup.com](mailto:subscriptions@bsigroup.com)

### Knowledge Centre

Tel: +44 20 8996 7004

Email: [knowledgecentre@bsigroup.com](mailto:knowledgecentre@bsigroup.com)

### Copyright & Licensing

Tel: +44 20 8996 7070

Email: [copyright@bsigroup.com](mailto:copyright@bsigroup.com)

## BSI Group Headquarters

389 Chiswick High Road London W4 4AL UK



...making excellence a habit.™