



**BSI Standards Publication**

## **Space engineering — Photovoltaic assemblies and components**

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## National foreword

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English version

## Space engineering - Photovoltaic assemblies and components

Ingénierie spatiale - Ensembles et composants  
photovoltaïquesRaumfahrttechnik - Fotovoltaische Baugruppen und  
Komponenten

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## European foreword

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This European Standard shall be given the status of a national standard, either by publication of an identical text or by endorsement, at the latest by March 2024, and conflicting national standards shall be withdrawn at the latest by March 2024.

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

This document supersedes EN 16603-20-08:2014.

The main changes with respect to EN 16603-20-08:2014 are listed below:

- Implementation of change requests
- Addition of new clause 12 “Planar Blocking Diodes”
- Check and update of the use of the verb “define” in the document

This document has been prepared under a standardization request given to CEN by the European Commission and the European Free Trade Association.

This document has been developed to cover specifically space systems and has therefore precedence over any EN covering the same scope but with a wider domain of applicability (e.g. : aerospace).

According to the CEN-CENELEC Internal Regulations, the national standards organizations of the following countries are bound to implement this European Standard: Austria, Belgium, Bulgaria, Croatia, Cyprus, Czech Republic, Denmark, Estonia, Finland, Former Yugoslav Republic of Macedonia, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Norway, Poland, Portugal, Romania, Serbia, Slovakia, Slovenia, Spain, Sweden, Switzerland, Turkey and the United Kingdom.

# Introduction

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The qualification, procurement, storage and delivery of space solar arrays are specified in the dedicated solar array specification, where requirements for the solar array electrical layout, structure and mechanism are specified.

This Standard outlines the requirements for the qualification, procurement, storage and delivery of the main assemblies and components of the space solar array electrical layout: photovoltaic assemblies, solar cell assemblies, bare solar cells, coverglass and protection diodes. This Standard does not outline the requirements for the qualification, procurement, storage and delivery of the solar array subsystem, comprising the solar panels, structural parts and mechanisms.

The general requirements are covered in the main part of this Standard (clauses 5 to 11). Annex A to Annex E specify the contents of the source control drawing of photovoltaic and solar cell assemblies, bare solar cells coverglasses and protection diodes and include the inspection data, physical and electrical characteristics, other ratings and acceptance and qualification specific requirements, which can be different for each space project.

This Standard is divided into five specific subjects, each one corresponding to each assembly or component:

- Clause 5 for photovoltaic assemblies,
- Clause 6 for solar cell assemblies,
- Clause 7 for bare solar cells,
- Clause 8 for coverglasses,
- Clause 9 for protection diodes,
- Clause 12 for planar blocking diodes.

Two additional clauses are dedicated to Sun simulators and calibration procedures (clause 10) and capacitance measurement methods (clause 11).

NOTE At the time of the publication of this Standard the handbook ECSS-E-HB-20-08A, that is called in this document, has not yet been published.

# 1

## Scope

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This Standard specifies the general requirements for the qualification, procurement, storage and delivery of photovoltaic assemblies, solar cell assemblies, bare solar cells, coverglasses, protection diodes and planar blocking diodes suitable for space applications.

This standard does not cover the particular qualification requirements for a specific mission.

This Standard is primarily applicable for qualification approval for photovoltaic assemblies, solar cell assemblies, bare solar cells, coverglasses, protection diodes and planar blocking diodes, and to the procurement of these items.

This standard is limited to crystalline Silicon and single and multi-junction GaAs solar cells with a thickness of more than 50  $\mu\text{m}$  and does not include thin film solar cell technologies and poly-crystalline solar cells.

This Standard does not cover the concentration technology, and especially the requirements related to the optical components of a concentrator (e.g. reflector and lens) and their verification (e.g. collimated light source).

This Standard is not applicable for qualification of the solar array subsystem, solar panels, structure and solar array mechanisms.

This standard may be tailored for the specific characteristic and constraints of a space project in conformance with ECSS-S-ST-00.

Qualification is a process to confirm compliance with requirements that have been established with reference to foregoing characterization and engineering test programs. Guidelines for characterization and engineering tests and for relaxation of qualification tests due to similarity with earlier performed qualification are described in the handbook ECSS-E-HB-20-08. Those clauses in this standard, for which the Handbook gives additional information, will refer to the Handbook.

## Normative references

The following normative documents contain provisions which, through reference in this text, constitute provisions of this ECSS Standard. For dated references, subsequent amendments to, or revision of any of these publications do not apply. However, parties to agreements based on this ECSS Standard are encouraged to investigate the possibility of applying the more recent editions of the normative documents indicated below. For undated references, the latest edition of the publication referred to applies.

| EN reference   | Reference in text | Title                                                                                                                                              |
|----------------|-------------------|----------------------------------------------------------------------------------------------------------------------------------------------------|
| EN 16601-00-01 | ECSS-S-ST-00-01   | ECSS system – Glossary of terms                                                                                                                    |
| EN 16603-10-03 | ECSS-E-ST-10-03   | Space engineering – Testing                                                                                                                        |
| EN 16603-20    | ECSS-E-ST-20      | Space engineering –Electrical and electronic                                                                                                       |
| EN 16603-20-06 | ECSS-E-ST-20-06   | Space engineering – Spacecraft charging                                                                                                            |
| EN 16602-60    | ECSS-Q-ST-60      | Space product assurance — Electrical, electronic and electromechanical (EEE) components                                                            |
| EN 16602-70-01 | ECSS-Q-ST-70-01   | Space product assurance – Cleanliness and contamination control                                                                                    |
| EN 16602-70-06 | ECSS-Q-ST-70-06   | Space product assurance – Particle and UV radiation testing for space materials                                                                    |
| EN 16602-70-09 | ECSS-Q-ST-70-09   | Space product assurance – Measurements of thermo-optical properties of thermal control materials                                                   |
|                | ISO 15387         | Space Systems – Single junction space solar cells – Measurement and calibration procedures                                                         |
|                | ISO 14644-1:1999  | Cleanrooms and associated controlled environments – Part 1: Classification of air cleanliness                                                      |
|                | MIL-E-12397B      | Eraser, rubber pumice for testing coated optical elements                                                                                          |
|                | MIL-STD-750       | Test methods for semiconductor devices                                                                                                             |
|                | IEC 60749-26:2006 | Semiconductor devices – Mechanical and climatic test methods - Part 26: Electrostatic discharge (ESD) sensitivity testing – Human body model (HBM) |
|                | IEC 60904-7       | Photovoltaic devices – Part 7: Computation of the spectral mismatch correction for measurements of photovoltaic devices                            |
|                | IEC 60904-10      | Photovoltaic devices – Part 10: Methods of linearity measurement                                                                                   |

| EN reference | Reference in text  | Title                                                                                                                                                                                                                                                                                                                                                                                                                                                       |
|--------------|--------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
|              | ASTM D1193-99      | Standard specification for reagent water                                                                                                                                                                                                                                                                                                                                                                                                                    |
|              | ESCC 23800 Issue 1 | Electrostatic Discharge Sensitivity Test Method;<br>ESCC Basic Specification                                                                                                                                                                                                                                                                                                                                                                                |
|              | ESCC 24900 Issue 2 | Minimum Requirements for Controlling<br>Environmental Contamination of Components;<br>ESCC Basic Specification                                                                                                                                                                                                                                                                                                                                              |
|              | ESCC 2265000       | Evaluation test programme for discrete Non-<br>microwave semiconductors; ESCC Basic<br>Specification                                                                                                                                                                                                                                                                                                                                                        |
|              | EN 1464:2010       | Adhesives - Determination of peel resistance of<br>adhesive bonds - Floating roller method                                                                                                                                                                                                                                                                                                                                                                  |
|              | Gueymard, C., 2018 | Gueymard, C., Revised composite extraterrestrial<br>spectrum based on recent solar irradiance<br>observations Solar Energy, Volume 169, 2018, Pages<br>434-440, ISSN 0038-092X,<br><a href="https://doi.org/10.1016/j.solener.2018.04.067">https://doi.org/10.1016/j.solener.2018.04.067</a> .<br>( <a href="https://www.sciencedirect.com/science/article/pii/S0038092X1830433X">https://www.sciencedirect.com/science/article/pii/S0038092X1830433X</a> ) |

# Terms, definitions and abbreviated terms

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## 3.1 Terms from other standards

For the purpose of this Standard, the terms and definitions from ECSS-S-ST-00-01 apply, in particular for the following terms:

**qualification**

**verification**

## 3.2 Terms specific to the present standard

### 3.2.1 General

#### 3.2.1.1 blistering

forming of multiple small air bubbles inside the perimeter of a finish layer

#### 3.2.1.2 bubbles

gaseous inclusion in the cell, coverglass or coverglass adhesive

#### 3.2.1.3 chip

local absence of material along the edges and corners of a complete component and which extend through the thickness of the component

#### 3.2.1.4 crack

fissure in the component with no separated portion from the remainder

NOTE Cracks can propagate from the edge of the material (edge cracks) or terminate at both ends within the material (surface cracks).

#### 3.2.1.5 delamination

physical separation between two material layers, which are joined in design

#### 3.2.1.6 discolouration

local variation of solar cell anti-reflection coating colour due to the influence of the structure orientation of the cell layer immediately below or the variation of the anti-reflection coating layer thickness

#### 3.2.1.7 dig

cavities in the surface of a component caused by impact with a pointed object or by crushing a material into the surface

#### 3.2.1.8 inclusion

volume contained within the component that is devoid of the substrate material

### **3.2.1.9 in-process testing**

tests performed during the manufacturing of a component or assembly in order to identify, in advance, defects or low performances

### **3.2.1.10 nick**

local absence of material on the surface of a complete component which does not extend through the thickness of the component

### **3.2.1.11 peeling**

forming of a delamination of a finish layer at the edge of the finished area. A blister at the edge of the surface

### **3.2.1.12 procurement lot**

set of shipment lots of solar cells assemblies, bare solar cells and coverglasses, manufactured with the same processes and materials, with identical manufacturing lines, that fill the same purchase order

### **3.2.1.13 scratch**

linear marking of the component that represents a volume devoid of the substrate material emanating from a single face of the component and not penetrating through the whole thickness of the substrate at any point

### **3.2.1.14 shipment lot**

solar cell assemblies, bare solar cells and coverglasses manufactured with the same processes and materials with identical manufacturing lines delivered to the customer as a part of a purchase order

### **3.2.1.15 spatter**

small bits of solid coating material imbedded on or in the coating or substrate

### **3.2.1.16 voids**

absence of deposited materials

NOTE Examples are absence of cell contact material or anti-reflection coating.

## **3.2.2 Photovoltaic assemblies**

### **3.2.2.1 photovoltaic assembly**

power generating network comprising the interconnected solar cell assemblies (strings and sections), the shunt and blocking diodes, the busbars and wiring collection panels, the string, section and panel wiring, the wing transfer harness, connectors, bleed resistors and thermistors

### **3.2.2.2 qualification coupon**

non-flight representative test sample of flight panels, built with flight processes and containing representative materials and components to be used in the manufacture of flight panels, also called DVT coupon

**3.2.2.3 slicing**

procedure to evenly distribute the total number of thermal cycles over temperature domains which are compatible with the temperature excursion on an orbit level rather than on the overall mission temperature envelope

NOTE Normally used for LEO missions.

**3.2.3 Solar cell assemblies****3.2.3.1 cladding**

application of a thin layer of material fully covering the surface, For instance silver cladding of an interconnector

**3.2.3.2 deformed interconnector**

interconnector whose initial conformed shape is modified

**3.2.3.3 interconnected cell**

solar cell with interconnector without coverglass

**3.2.3.4 solar cell assembly**

solar cell together with interconnector, coverglass and with or without by-pass diode

**3.2.3.5 tearing interconnector**

interconnector physically separated from the cell due to a failure of the welding or soldering joint

**3.2.3.6 interconnector tab**

part of the interconnector that is joined, e.g. welded, soldered, ultrasonic, with the solar cell contact pad or the solar cell rear side contact

NOTE Tabs are also known as fingers and interconnectors can be composed of several tabs or fingers.

**3.2.4 Bare solar cells****3.2.4.1 bare solar cell**

photovoltaic component capable to delivering electrical power when illuminated with light

**3.2.4.2 cells nominal size**

cell dimensions of the solar cell procurement lot

**3.2.4.3 component bare solar cell**

specially manufactured solar cell, with only one active junction and the same spectral response as one sub cell of a multi-junction solar cell

**3.2.4.4 contact vacuum evaporation batch**

bare solar cells manufactured in the same contact vacuum evaporation run

**3.2.4.5 drops**

excess of metallization material on the solar cell contacts

#### 3.2.4.6 remaining Factor

ratio of an electrical performance parameter at EOL to its value at BOL

NOTE E.g. maximum power of a solar cell.

#### 3.2.4.7 solar cell anti-reflection coating

single or multi-layer coating which reduces the reflection coefficient of the incident solar radiation

#### 3.2.4.8 uncoated area

area of the solar cell where the bare solar cell is exposed and is devoid of coatings

#### 3.2.4.9 worm shaped bulge

protuberance of contact material shaped in linear irregular paths or single dots where the contact material is locally delaminated from the immediate lower layer

### 3.2.5 Coverglasses

#### 3.2.5.1 coating

dielectric or conductive material applied to the glass substrate by vacuum deposition

NOTE Coatings applied to the external face of the coverglass is termed the “front surface coating”. Coatings applied to the internal face of the glass substrate to be bonded to the solar cell is termed the “rear surface coating”. Commonly used coatings include:

- single-layer anti-reflection coating,
- multi-layer anti-reflection coating,
- ultraviolet reflector,
- infrared reflector, and
- conductive coating.

#### 3.2.5.2 conductive coating

transparent coating used to prevent the exposed surface from charging and consequently protecting the solar cell from the effect of electrostatic discharge

NOTE The coverglass usually comprises a suitable glass substrate and one or more of a combination of the coatings given in the note in clause 3.2.5.1.

#### 3.2.5.3 coverglass

glass substrate and coatings applied to its surfaces

#### 3.2.5.4 coverglass coating lot

collection of glass substrates subjected to the same coating run or runs (for coverglasses which have more than one coating)

#### 3.2.5.5 infrared reflector

multi-layer dielectric coating which has a high reflectance coefficient in the infrared portion of the solar spectrum

**NOTE** The infrared reflector is used to reflect light that is not usefully converted to electrical energy by the solar cell thus reducing the operating temperature and increasing the conversion efficiency of the SCA.

### **3.2.5.6 mark**

See **stain**

### **3.2.5.7 multi-layer anti-reflection coating**

multiple layer coating which has the effect of increasing the transmission coefficient of the coverglass

### **3.2.5.8 single layer anti-reflection coating**

simplest form of coating comprising a single layer of low index dielectric material which minimizes the reflection coefficient of the incident solar radiation thus increasing the transmission coefficient of the coverglass

**NOTE** The single layer of low index dielectrical material is usually done of  $\text{MgF}_2$ .

### **3.2.5.9 stain**

area which under inspection conditions can clearly be defined as not being optically homogeneous with the bulk material, and that cannot be categorized as an inclusion, scratch, crack, chip, dig, void or coating delamination

**NOTE** The term “mark” can be used as a synonymous.

### **3.2.5.10 ultraviolet reflector**

multi-layer dielectric coating which has a high reflectance coefficient in the UV portion of the solar spectrum

**NOTE** The ultraviolet reflector is used to protect the underlying adhesive and to reflect light that is not usefully converted to electrical energy by the solar cell thus reducing the operating temperature of the solar cell and increasing the conversion efficiency of the SCA.

### **3.2.5.11 uncoated area**

area of the coverglass where the bare coverglass substrate is exposed and is devoid of coatings

## **3.2.6 Verification processes**

### **3.2.6.1 accelerated testing**

test in which the life time requirement is verified in an accelerated way by intensifying one parameter of the environment or load.

**NOTE** The following are examples of accelerated tests:

- UV test done with increased sun intensity in the UV part of the spectrum,
- Electron and proton radiation tests with life time fluences in a limited period of time,

- humidity tests done at higher temperature and humidity,
- bake-out done at higher temperature,
- performance parameter degradation at higher temperature,
- thermal cycling with higher/lower cool-down and heat-up rates and without nominal operating dwell time in between.

#### 3.2.6.2 acceptance test

test to determine that a system, subsystem, component or functional part is capable of meeting performance requirements prescribed in purchase specifications or other documents specifying what constitutes the adequate performance capability for the item and to demonstrate the item is free from manufacturing defects

NOTE In this document acceptance is associated with specified requirements which have a defined acceptance safety factor with respect to requirements corresponding with the actual loads and environments

#### 3.2.6.3 delta qualification

qualification performed on an equipment which has undergone minor design modifications or has been qualified to operate in environments less severe than those specified

#### 3.2.6.4 proto flight test

test requirements which have a defined qualification safety factor with respect to requirements corresponding with the actual loads and environments, but with limited test durations

#### 3.2.6.5 qualification by similarity

process to demonstrate the ability to fulfil specified requirements by comparing a new design specification with a similar proven design specification

### 3.3 Abbreviated terms

For the purpose of this standard, the abbreviated terms of ECSS-S-ST-00-01 and the following apply:

| Abbreviation | Meaning                           |
|--------------|-----------------------------------|
| ADP          | acceptance data package           |
| AOCS         | attitude and orbit control system |
| AM0          | air mass 0 (zero)                 |
| APTC         | ambient pressure thermal cycling  |
| AR           | anti-reflection                   |
| ARC          | anti-reflection coating           |
| ATOX         | atomic oxygen                     |
| BOL          | beginning-of-life                 |

| Abbreviation | Meaning                                         |
|--------------|-------------------------------------------------|
| BSC          | bare solar cell                                 |
| BSR          | back surface reflector                          |
| CIBD         | connector integrated blocking diode             |
| CIC          | connector integrated cell                       |
|              | NOTE: U.S. designation of SCA.                  |
| CIDL         | configuration item data list                    |
| CVCM         | collected volatile condensable material         |
| CVG          | coverglass                                      |
| DCR          | documentation change request                    |
| DJF          | design justification file                       |
| DRD          | document requirements definition                |
| DRB          | delivery review board                           |
| DVG          | direct voltage gradient                         |
| DVT          | design verification test                        |
| EMC          | electromagnetic compatibility                   |
| EOL          | end-of-life                                     |
| ELM          | electronluminescence                            |
| EPD          | external protection diode                       |
| ESD          | electrostatic discharge                         |
| FIT          | failure in time                                 |
| FMECA        | failure modes, effects and criticality analysis |
| GaAs         | gallium arsenide                                |
| GEO          | geostationary orbit                             |
| IC           | interconnected cell                             |
| $I_{fw}$     | current in forward direction of the diode       |
| $I_{mp}$     | maximum power current                           |
| $I_{op}$     | current at operational voltage                  |
| $I_{rev}$    | current in reverse direction of the diode       |
| IPD          | integral protection diode                       |
| IRR          | infrared reflector                              |
| $I_{sc}$     | short-circuit current                           |
| IVG          | inverted voltage gradient                       |
| LEO          | low Earth orbit                                 |
| LVDT         | linear voltage displacement transducer          |
| MLAR         | multi-layer anti-reflection coating             |
| NCR          | nonconformance report                           |
| NRB          | nonconformance review board                     |
| OSTC         | on station thermal cycling                      |

| Abbreviation      | Meaning                                               |
|-------------------|-------------------------------------------------------|
| PAD               | part approval document                                |
| PBD               | planar blocking diode                                 |
| PCDU              | power control and distribution unit                   |
| PID               | process identification document                       |
| PLM               | photoluminescence                                     |
| $P_{\max}$        | maximum power                                         |
| PMCF              | product manufacturing and control file                |
| PMP               | parts, materials and processes                        |
| PSA               | permanent sustained arc                               |
| PTH               | power transfer harness                                |
| PVA               | photovoltaic assemblies                               |
| r.m.s.            | root mean square                                      |
| RAMS              | reliability, availability, maintainability and safety |
| RDC               | relative damage coefficients                          |
| RML               | recovered mass loss                                   |
| S.C.              | solar constant                                        |
| S.C. (AM0)        | solar constant at air mass 0                          |
| SCA               | solar cell assembly                                   |
| SCD               | source control drawing figure                         |
| SLAR              | single layer anti-reflection coating                  |
| SMM               | spectral mismatch factor                              |
| SWS               | secondary working standard                            |
| $T_{\text{amb}}$  | ambient temperature                                   |
| TAT               | type approval test                                    |
| TBD               | to be defined                                         |
| TBS               | to be specified                                       |
| TML               | total mass loss                                       |
| TQCM              | thermal quartz crystal microbalance                   |
| TSA               | temporary sustained arc                               |
| UVR               | ultraviolet reflector                                 |
| $V_{\text{fw}}$   | voltage in forward direction of the diode             |
| $V_{\text{mp}}$   | maximum power voltage                                 |
| $V_{\text{oc}}$   | open-circuit voltage                                  |
| $V_{\text{op}}$   | operational voltage                                   |
| $V_{\text{rev}}$  | voltage in reverse direction of the diode             |
| $V_{\text{test}}$ | test voltage                                          |
| WRC               | World Radiation Centre in Davos                       |
| $\Phi_e$          | equivalent fluence used for electron irradiation      |

### 3.4 Nomenclature

The following nomenclature applies throughout this document:

- a. The word “shall” is used in this Standard to express requirements. All the requirements are expressed with the word “shall”.
- b. The word “should” is used in this Standard to express recommendations. All the recommendations are expressed with the word “should”.

NOTE It is expected that, during tailoring, recommendations in this document are either converted into requirements or tailored out.

- c. The words “may” and “need not” are used in this Standard to express positive and negative permissions, respectively. All the positive permissions are expressed with the word “may”. All the negative permissions are expressed with the words “need not”.
- d. The word “can” is used in this Standard to express capabilities or possibilities, and therefore, if not accompanied by one of the previous words, it implies descriptive text.

NOTE In ECSS “may” and “can” have completely different meanings: “may” is normative (permission), and “can” is descriptive.

- e. The present and past tenses are used in this Standard to express statements of fact, and therefore they imply descriptive text.

## 4.1 Overview

### 4.1.1 Objective and organization

The objectives of this Standard are:

- To specify the rules for the flow of technical requirements from a project solar array specification down to component level in order to guarantee that lower level components and sub-assemblies are qualified according to higher level specifications.
- To specify the set of requirements from component level up to solar panel level consisting of photovoltaic assemblies (PVA) and solar panel substrate (rigid or flexible) to achieve generic qualification for each level of assembly for about 90 % of the solar arrays within a given application domain; for example, deployable solar arrays for GEO or LEO applications.

This clause describes the organization of the requirements and how they are applied.

The philosophy behind this Standard is twofold in that respect that:

- Qualification of a specific level of assembly is based on the use of qualified components and sub-assemblies (generically) qualified at lower levels. The specification tree, of which panel substrates, photovoltaic assemblies (PVA) and their components form part is illustrated in Figure 4-1.

OR

- Qualification of components for a specific application can be achieved at a sub-assembly level at which the qualification is unequivocally demonstrated. This means that certain types of qualification tests do not need to be duplicated at different lower level of assembly in case of a unique application of a dedicated design

This Standard specifies the requirements for qualification at each level from components, assemblies and up to and including PVA on Design Verification Test (DVT) coupons. Components, assemblies and coupons are built according to component, assemblies and PVA design requirements and are being qualified with the objective of demonstrating that the design and manufacturing processes are approved and verified for use on solar panels of a flight application.

Together with the PVA qualification on a specific substrate, a material database is needed in order to justify allowable values.

NOTE 1 For a sandwich CFRP type of substrate the material mechanical performance database is needed to complete ECSS-E-ST-32-08 Clause 4.6 and ECSS-E-

HB-32-20\_Part 1A, including stiffness and strength data for CFRP sandwich structures that can be obtained by substrate elementary tests such as

- 4-point bending and/or edgewise compression stiffness and strength tests
- shear and/or skin  $\pm 45^\circ$  tensile stiffness and strength tests
- sandwich flatwise tensile strength tests,
- inserts in-plane and out-of-plane strength tests,
- Kapton peel strength test.

For any other type of substrate, additional or different tests might be needed.

NOTE 2 By having this material data base upfront, potential failures in the substrate design at a late stage or incompatibilities of the design can be avoided.

Generally, with the substrate elementary tests and the solar array mechanical tests, a solar panel substrate is deemed to be mechanically qualified, up to the point of deployment.

In order to qualify a solar panel in view of thermal life time cycling, it is needed to perform a DVT coupon campaign (see clause 5) for qualifying the substrate, PVA and their combination.

The elementary substrate tests will need to be repeated after thermal cycling only if the solar array is subjected to substantial mechanical loading long after deployment, e.g. as a result of main engine firings, docking/undocking manoeuvres, etc.

Minor design modifications as described in the ECSS-E-HB-20-08 do not require the repetition of the DVT thermal life cycling. In the Handbook rules are given with which so-called qualification by similarity or delta qualification can be justified as acceptable for specific cases.

For many parameters in this standard the value to be specified as requirement is dependent on the mission concerning duration and environmental conditions or the implemented solar array design. These parameter values are derived from the higher level subsystem specification and reflected in a dedicated document. In this standard the source control drawing has been selected generically on every level of assembly as an example of a document to reflect the specific requirements. So the source control drawing or equivalent set of documentation is the reference list for physical characteristics, performance requirements and environmental conditions.

Full qualification of an application is not achieved after successful qualification of the solar panel substrate, PVA and its components at coupon level only. Robustness against certain environments can only be demonstrated in the final solar array configuration, that may comprise amongst others full size panel on-station thermal cycling and sine vibration, acoustic noise, and wing deployment testing at subsystem or spacecraft level.

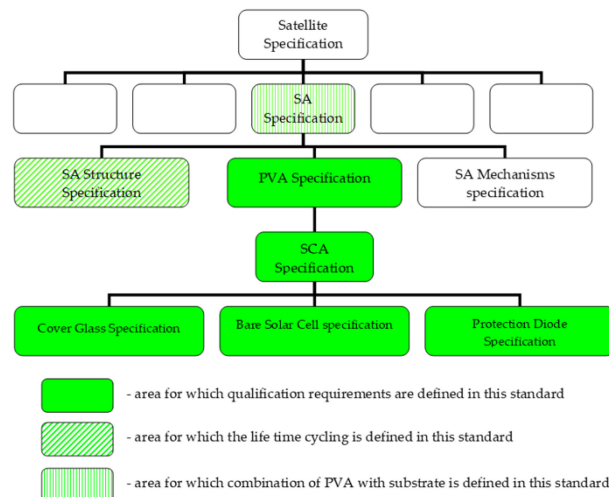


**Figure 4-1: Specification hierarchy**

### 4.1.2 Interfaces with other areas

In the specification hierarchy (Figure 4-1) only the components and assembly levels that are usually dedicated to solar arrays are shown. At every integration step, additional materials and components, not mentioned in the specification hierarchy, are used such as:

- adhesives,
- solder,
- interconnectors and busbars,
- diodes,
- resistors,
- thermistors,
- connectors, and
- wires.

Requirements for these materials and components can be found in their procurement specifications, and in EEE component specifications, which are reviewed as part of the qualification process. For EEE component specifications, see the ECSS-Q-ST-60 series of standards. For Materials Parts and processes specifications, see the ECSS-Q-ST-70.

The qualification of the use of these items is a pre-requisite for the qualification of the assembly they are part of (for example, coverglass adhesive at the SCA level and busbars at the qualification coupon level).

Non-PVA related solar array design, power subsystem interface and mission specific related topics such as grounding, electromagnetic compatibility, magnetic moment, spacecraft related geometrical loss factors and end-of-life performance prediction related topics, including loss factors, are not addressed in this Standard.

Specific design measures to support the solar array in order to satisfy the requirements of this Standard, such as grounding spots and blocking diodes, are however, taken into account.

Specific environmental conditions which can be a limitation in the qualification for general use, are not addressed in this Standard as these aspects are usually the subject of a project dedicated qualification (for example, the chemical contents in local ambient air).

## 4.2 Physical properties

- a. The following physical properties of the components and materials shall be measured:
  1. coefficient of thermal expansion
  2. heat conductivity
  3. specific heat
  4. Young's modulus and Poisson's ratio
  5. Flex strength

NOTE The objective is to establish the boundaries for the qualification test program over the full range of application by means of analysis.
- b. The data specified in requirement 4.2a shall be determined during the development phase of a new component and need not be repeated during the qualification program.

## 4.3 Test and storage

### 4.3.1 Test environment

- a. The atmospheric conditions during all inspection, test operations and storage shorter than 6 months shall be as follows:
  1. Pressure: (1013,25 ± 33) hPa.
  2. Temperature: (23 ± 5) °C.
  3. Average relative humidity: 40 % - 65 %.

NOTE A pressure of (1013,25 ± 33) hPa is equivalent to (760 ± 25) mmHg.
- b. The room cleanliness level should be airborne particle count: Class 8 ISO 14644-1.
- c. Every deviation from requirements 4.3.1a and 4.3.1b during tests shall be recorded in the data documentation package (DDP).
 

NOTE 1 For DDP complete contents, refer to Annex G.

NOTE 2 Semiconductor devices (i.e. planar diodes) can short-circuit if no special precautions are taken

during long storage periods under certain atmospheric conditions. This is because chlorine content, in combination with illumination, can produce metal contact migrations on these semiconductor devices.

- d. For long term storage longer than 6 months qualification coupons shall be kept in the dark in a dry nitrogen environment.

NOTE It is good practice to use light tight coverage to keep the DVT coupons in darkness during periods shorter than 6 months.

### 4.3.2 Test tolerances and accuracies

- a. The accuracy of the instruments and test equipment used to control or measure test parameters shall be one order of magnitude higher than the tolerance on the variable to be measured.

NOTE Examples of where this cannot be achieved include measurements of electrical performance and temperatures.

- b. All instrumentation used for qualification and acceptance tests shall:
1. be calibrated, and
  2. be within the specified calibration period at the time of test.
- c. Instrumentation whose calibration period runs out during the planned test time shall not be used.
- d. The maximum test temperature tolerances for thermal testing shall be as given in Table 4-1.
- e. The accuracy of mass measurements shall be better than  $\pm 1\%$  or 0,01 g, whichever is higher.
- f. The test condition tolerances shall be applied to the nominal test values specified.
- g. The accuracy of the electrical performance test on PVA level shall be better than or equal to the calibration loss factor used in the power analysis.

**Table 4-1: Test tolerances on temperature**

| Temperature range (°C) | tolerance (°C) |
|------------------------|----------------|
| around - 175           | -10 / +0       |
| around - 100           | -10 / +0       |
| around + 90            | -0 / +10       |
| Around +130            | -0 / +10       |

### 4.3.3 <<deleted>>

- a. <<deleted>>

## 4.4 Critical materials

- a. The critical interface information shall be part of the PMP list.

NOTE For PMP, see ECSS-Q-ST-70 Annex B.

- b. Silver cladding shall be annealed and contain a minimum of 99,9 % pure silver.
- c. Pure tin, cadmium and zinc shall not be present in finished space-qualified solar panels.

NOTE Pure tin refers to a tin alloy with less than three atomic percent of an alloying metal, e.g. lead. Pure cadmium and zinc are metals used or applied in a non-mixed metal or unalloyed state.

- d. Solar panels containing Beryllium Oxide shall be clearly identified with the designation BeO.

# Photovoltaic assemblies

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## 5.1 Overview

### 5.1.1 Description

The photovoltaic assembly (PVA) comprises the electrical parts to satisfy the requirements of the solar array specification.

This Clause applies to solar arrays using a planar design without concentration and based on crystalline solar cells.

In case of concentration, this Clause applies to the PVA without the optics, provided that the electrical performance tests are adapted to the light incidence and intensity imposed by the optics.

Usually, a PVA consists of parallel connected strings. A string is the smallest operational component at the PVA level. A string consists of a series interconnected solar cells connected to the spacecraft bus. These strings are supported by a solar array panel substrate or frame.

The parts comprising a PVA usually include:

- interconnected SCAs,
- bleed resistors,
- wiring,
- panel connectors,
- diodes (blocking and shunt),
- thermal sensors,
- telemetry indicator wiring, and
- grounding.

### 5.1.2 Purpose and objective

In this Clause the design limits, including margins, and the responsibilities for PVA manufacturing are specified and include the:

- design requirements (refer to clause 5.3);
- mechanical and electrical interface;
- manufacturing requirements for PVA (refer to clause 5.4);
- qualification requirements for PVA (refer to clause 5.5.1);
- acceptance requirements for PVA (refer to clause 5.5.2).

The values specified for the SCA level are provided by the solar cell assembly supplier and confirmed during the SCA qualification tests (refer to clause 6.4).

In order to design and verify a solar array, data for the following parameters and characteristics at the SCA level or lower are used:

- characteristics of the SCA ( $V_{oc}$ ,  $I_{sc}$ ,  $V_{mp}$  and  $I_{mp}$ );
- spectral response;
- reference calibration standard;
- inputs to describe radiation degradation such as relative damage coefficient and electron-proton equivalence or non-ionising energy loss, according to the approach used;
- temperature coefficients as a function of radiation fluences;
- reverse characteristics versus temperature;
- UV and Sun spectrum characteristics (reflectivity);
- capacitance versus temperature;
- optical properties (hemispherical emissivity, and solar absorptance, and cover gain or loss);
- behaviour with regard to specific mission environments:
  - ATOX sensitivity,
  - thruster erosion sensitivity,
  - micro-meteoroids and debris sensitivity;
- loss factors for interconnecting the cells into a string.

## 5.2 Conditions and method of test

- a. The conditions and methods of testing shall conform to the photovoltaic assembly source control drawing (SCD-PVA).

NOTE The PVA specification consists of two parts, the generic specification (this Standard) and the SCD. For the preparation of the SCD-PVA, refer to Annex A.

- b. The SCD-PVA shall be prepared by the supplier, in conformance with Annex A, and provided to the customer for reviewing and agreement.
- c. Any deviation from in-process, acceptance and qualification test shall be justified.
- d. Deviations from this Standard applicable to the SCD-PVA shall:
1. be agreed between the customer and the supplier;
  2. include alternative requirements equivalent to those of this Standard;
  3. not affect the reliability and performances of the photovoltaic assemblies;
  4. be only those specified in requirement 5.2c.

## 5.3 Photovoltaic assembly design

### 5.3.1 Overview

The objective of this standard at the PVA level is to specify the requirements for the detail design, performance, qualification, manufacture and acceptance testing of coupons equipped with the PVA on the relevant substrate representing all design specifics (e.g. undisturbed area, re-enforced area, edge members, Holddowns, etc.). To cover all the aspects of the solar array, more than one coupon might be needed.

The inputs to these requirements are the solar array specification, which is prepared following the requirements of the mission specification, the ground test programme and the spacecraft design. In this clause the steps which influence specific design characteristics of the PVA have been listed. Requirements which merely determine the sizes of the PVA have not been taken into account, like intensity related loss factors and reliability requirements.

### 5.3.2 Parameters related to parts, materials and processes (PMP)

#### 5.3.2.1 Outgassing

- a. Flight hardware shall be constructed from space qualified materials having the following properties:

1. A recovered mass loss (RML) of 1 % or less.

NOTE See ECSS-Q-ST-70-02.

2. A collected volatile condensable material (CVCM) of 0,1 % or less when heated in a vacuum to 125 °C and collected at 25 °C.

- b. The PMP list shall include the RML and CVCM values for all materials used.

NOTE The mission specification can specify an absolute limit to the total mass loss and volatile condensable material of the solar array sub-system. The fulfilment of this system requirement can be verified either by analysis using the total amount of the applied materials, the individual material RML and CVCM data, outgassing field of view and temperature distribution, or by test of the representative subsystem and measurement of the outgassing product.

#### 5.3.2.2 Toxicity

- a. Any material used in the construction of the PVA that is dangerous to the health of the personnel shall be identified.
- b. Preventive handling measures shall be taken in conformance with a standard approved by the customer.

#### 5.3.2.3 Flammability

- a. Any flammable materials used in the construction of the PVA shall be identified.

#### 5.3.2.4 Corrosion

- a. The supplier and customer shall agree on the measures to be taken to prevent corrosion during storage or in normal operational service.
- b. Standard atmospheric conditions may be assumed for general applications in the spacecraft, over a period of time that is agreed between the supplier and customer.
- c. To avoid electrolytic corrosion, a process, approved by the customer, shall be used.

#### 5.3.2.5 Magnetism

- a. Permanent magnetic materials shall be avoided when specified by the mission.
- b. Non-magnetic materials should be used.

#### 5.3.2.6 Erosion

- a. PVA materials shall be capable of tolerating a specified erosion level resulting from spacecraft operation without degradation in the nominal performance of the PVA, in conformance with the PVA specification.

NOTE Example: thruster plumes.

#### 5.3.2.7 Atomic oxygen (ATOX)

- a. PVA materials shall be capable of tolerating a specified level of degradation resulting from an ATOX environment, without degradation in the nominal performance of the PVA, in conformance with the solar array specification.
- b. The ATOX resistivity shall be determined by the individual resistivities of the used materials and components in their configuration.

### 5.3.3 Parameters related to design

#### 5.3.3.1 Cell integration

- a. The solar cells shall be structured such that the PVA is capable of withstanding all phases of ground handling, transportation, qualification testing and acceptance testing, launch and orbit operations as to conform to the mission requirements.
- b. The capability for replacement of cracked, broken or damaged SCAs shall be included in the design.
- c. Repair method shall be feasible in horizontal and vertical panel positions.

### 5.3.3.2 Stringing

- a. As requested also in the ECSS-E-ST-20 requirement 5.5.2.o, at least individual blocking diodes connected to the end of the strings shall be applied in the design of the panel, consequently the strings of the DVT coupon are protected by blocking diodes in the same way.

NOTE String blocking diodes prevent failures due to power transients from the power sub-system or due to operation in shadow and they mitigate risks linked to ESD secondary arcing.

- b. To enable performance measurement at the lowest level of assembly at the coupon level, strings shall be measured individually.
- c. Potential parallel connections shall not prevent performance measurement specified in requirement 5.3.3.2b.
- d. If the dimensions of the coupon enables the accommodation, the full flight string length shall be represented on the qualification coupon.
- e. Coupon layout shall be as specified in an overall assembly drawing as part of the SCD-PVA.

### 5.3.3.3 Cell interspacing

- a. The cell interspacing shall be compatible, as a minimum, with the following mission requirements:
  1. thermal expansion and contraction within the mission temperature extremes specified in the solar array specification;
  2. panel geometry;
  3. ESD requirements.

### 5.3.3.4 Sectioning

- a. Sections shall not be included at the coupon level.
- b. To test the technique of interconnecting strings, the negative ends of individual strings may be connected in a way that is representative for flight panels.

### 5.3.3.5 Reverse bias protection

- a. The solar cells that are potentially subject to reverse bias shall be protected by shunt diodes unless the solar cells are insensitive to the effects of reverse bias.

NOTE Types of reverse bias include:

- AOCS failure shadowing,
- self shadowing, and
- power management (including maximum power point tracker when direct energy transfer function is acting at BOL).

### 5.3.3.6 Insulation

- a. The following items shall be electrically insulated from each other:
1. Any solar cell circuits to substrate (the grounding reference of the coupon).
  2. Solar cell circuits to solar cell circuits (if not connected at the negative ends).
  3. Thermal sensor to the solar cell circuits and to the substrate (the grounding reference of the coupon).
  4. Conductive coverglass grounding network, if used, to solar cell circuits.

NOTE For fulfilment of reliable insulation (also known as “double insulation”) requirements reference is made to ECSS-E-ST-20.

### 5.3.3.7 Derating

For the derating requirements of components, see ECSS-Q-ST-30-11.

### 5.3.3.8 Redundancy

For redundancy requirements, see ECSS-Q-ST-30.

For failure modes requirements, see ECSS-Q-ST-30-02.

### 5.3.3.9 Fault tolerance

- a. A FMECA shall be performed for the design of the solar array.
- b. The design consequences shall be implemented on the qualification coupon, including:
1. the photovoltaic assembly from solar cell strings to the connector, and
  2. redundant bleed resistors and, if any, redundant PVA assemblies or components.

NOTE 1 Examples: Solar cell strings, blocking diodes, temperature sensors.

NOTE 2 For FMECA, see ECSS-Q-ST-30-02.

- c. No single fault shall result in the following:
1. The loss of integrity of the redundant parts indicated in requirement 5.3.3.9b.2.
  2. The propagation of the fault causing permanent damage or loss of use of the units connected to the PVA.

NOTE Examples: solar array regulator unit, solar array drive mechanism.

- d. No failure shall be propagated from one solar array wiring group to another.

#### 5.3.3.10 Fatigue resistance

- a. The effects of fatigue shall be verified by test as specified in 5.5.1.3.
- b. The design of the PVA shall include the result of the verification specified in requirement 5.3.3.10a.

#### 5.3.3.11 Adherence to substrate

##### 5.3.3.11.1 Measurement

- a. The adherence of SCAs to the substrate shall be measured using representative process samples.

##### 5.3.3.11.2 Property

- a. The SCAs shall stay attached to the panel and conform to all requirements during the test campaign and all the phases of the mission.
- b. The adherence shall be such that the SCAs integrated on the substrate can be repaired, removed and replaced.

#### 5.3.3.12 Adhesive uniformity

- a. The thickness boundaries, including manufacturing and repair tolerances, shall be specified by means of analysis or test.
- b. The boundary requirements on minimum and maximum thickness, in conformance with requirement 5.3.3.12a, shall be guaranteed by a controlled application process demonstrated on separate samples.
- c. The thermal conductance towards the panel substrate shall be such that the specified solar cell and protection diode temperature can be maintained.

#### 5.3.3.13 Electrostatic discharge (ESD)

- a. The solar array design shall be such that it can survive the charging environment and operating conditions as specified by the mission.
- b. Requirement 5.3.3.13a shall be either demonstrated by analysis or by testing.

NOTE During and after launch, the spacecraft is surrounded by a low density plasma of high energy electrons and protons. On insulated surfaces of the spacecraft, the electrons build up a charge which discharges when breakdown of the insulating materials is reached.

#### 5.3.3.14 Electromagnetic compatibility (EMC)

- a. The PVA shall be designed to meet the specific EMC requirements stated in the SCD-PVA.

#### 5.3.3.15 Repairability

- a. The capability of repairing, removing and replacing items down to component level shall be provided.

NOTE For example, for single SCAs, diodes, thermal sensors, wires and connectors.

## 5.4 PVA manufacturing

### 5.4.1 Process validation

- a. The manufacturing and integration processes shall be validated for all the project specific design configurations and to meet the engineering design requirements.

### 5.4.2 Defect acceptability

- a. The acceptability of defects at the PVA level shall be:
  1. agreed with the customer;
  2. specified in a production control document;
  3. validated by qualification testing.

### 5.4.3 In-process testing

#### 5.4.3.1 Overview

The in-process tests are performed during the manufacturing of the PVA to detect or prevent deviations and defects as early as possible. This clause 5.4.3 lists the test to be performed during the manufacturing of the PVA.

#### 5.4.3.2 Mass measurement

- a. To determine the add-on mass of the SCA laydown process, the mass of the substrate shall be measured before and after the substrate is equipped with the SCA's and be in conformance with SCD-PVA.

#### 5.4.3.3 Wet insulation test

- a. A wet insulation test shall be performed by the supplier to prove the integrity of the bare coupon insulation layer, as follows:
  1. Verify continuity between the conductive layer under the insulation to the test connection point.
  2. For the wet insulation test, use ethyl, isopropyl alcohol, or otherwise an equivalent fluid agreed with the customer, as contact fluid during the measurements.

3. Apply a voltage which corresponds to the breakthrough value for short term exposure of the applied insulation material ( $E_{\text{spec}}$  V/ $\mu\text{m}$ ) times the minimum guaranteed thickness.

NOTE For example, for  $E_{\text{spec}} = 20$  V/ $\mu\text{m}$  and a  $(50 \pm 10)$   $\mu\text{m}$  insulation layer, a test voltage of 1000 V applies.

- b. The acceptance criteria shall be an insulation larger than 100 M $\Omega$ .
- c. In case of a failure, the coupon insulator layer shall be repaired.

#### 5.4.3.4 Adherence to substrate

- a. The adherence of the SCAs to the substrate, shall be performed in parallel to panel laydown.
- b. The adherence to substrate shall be verified by means of one of the following two methods:
  1. Method 1
    - (a) Bond 3 SCAs following identical process to a representative PVA substrate of the following dimensions: 200 x 130 mm.
    - (b) After the curing duration and temperature, as specified in the SCD-PVA perform a pull test, with a pull force equal or larger than 1 N/cm<sup>2</sup>.
  2. Method 2
    - (a) In case no solar cell assemblies and substrate are available, bond together 2 Kapton foils of the same material as used in representative PVA and with dimensions of 250 mm x 150 mm.
    - (b) After specified curing duration and temperature, as specified in the SCD-PVA, perform a peel test of the foil according to EN 1464:2010.
    - (c) Use a peel force equal or larger than 1,8 N/cm.
    - (d) Ensure that the separation takes place within the adhesive for an area larger than 50 %.

#### 5.4.3.5 Visual inspection

- a. A visual inspection shall be made before laydown.
 

NOTE This is to determine defects, at the latest as possible before bonding. For example: rear sides of solar cells defects, front sides of solar cells defects.
- b. The visual inspection procedure and criteria shall be agreed with the customer and be described in the SCD-PVA.

#### 5.4.3.6 Continuity check

- a. The continuity of all strings shall be checked after stringing.

- b. Continuity of harness, wires and diodes shall be checked, and measured after final assembly.
- c. The maximum values of resistance shall be given in the SCD-PVA.

#### 5.4.4 Identification and traceability

- a. Components other than SCAs, bare cells and coverglasses shall be identified in conformance with the traceability requirements of Class 1 components, and PAD DRD of ECSS-Q-ST-60.

NOTE For requirements on the identification and traceability of parts and materials, see clauses 6.1.4, 7.1.3 and 8.3.3 for SCAs, bare cells and coverglass, respectively.

#### 5.4.5 Recording

- a. Before start manufacturing, all processes and process variables related to PVA manufacturing that have impact on the performance of the process, shall be identified by the supplier.
- b. The processes variables specified in requirement 5.4.5a shall be recorded during manufacturing.

## 5.5 PVA tests

### 5.5.1 Qualification tests

#### 5.5.1.1 Purpose

Qualification tests are performed to check and qualify the design requirements.

#### 5.5.1.2 Process

- a. Qualification tests shall be preceded by the acceptance tests as listed in clause 5.5.2, in order to be representative of the life of flight hardware.
- b. All results of the qualification test shall be reported in a qualification test report.
- c. Qualification margins shall not exceed component and material specifications unless agreed between supplier and customer.
- d. The following environmental test shall be performed for qualification of PVAs as applied on solar panels:
  - 1. Fatigue thermal cycling test on the qualification coupon.
  - 2. Humidity test performed on dedicated test sample, if specified by the solar array requirements specification.
  - 3. ESD test on a dedicated ESD coupon, if specified by the solar array requirement specification.

4. Erosion of materials, due to thruster plume if specified by the solar array requirement specification.

NOTE The tests to be performed for each qualification are listed in Table 5-1 and described in clauses 5.5.2 and 5.5.3.

- e. In cases where the same coupon is used for the fatigue thermal cycling test and the humidity test, in conformance with requirement 5.5.1.2d the humidity test sequence shall precede the fatigue thermal cycling test sequence.
- f. Except in conformance with requirement 5.5.1.2e, each type of test shall be performed on a dedicated qualification coupon built specifically for the test.
- g. The qualification coupon need not be the same size as the flight panels, but shall contain a representative number of components to enable reliable verification of flight panel processes and materials.
- h. The materials and processes used to build the qualification coupon shall be documented in a parts, materials and process (PMP) list to enable verification that the flight panels are built with identical manufacturers, processes, materials and configurations.
- i. Each qualification coupon shall be flight representative as far as allowed by the dimensions of the qualification coupon
- j. Facilities shall be available to safely store the qualification hardware (included failed samples) for a minimum of 6 years (equivalent to five years in storage and one year in orbit).

**Table 5-1: Qualification test plan for PVA**

| Check                                                                                                                                                          | Fatigue thermal cycling | Humidity test | ESD test |
|----------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------|---------------|----------|
| Full visual inspection (5.5.3.2)                                                                                                                               | 1, 6, 9, 14             | 1, 5          | 1, 4     |
| Electrical health check and performance (5.5.3.3 and 5.5.3.4)                                                                                                  | 2, 7, 10, 15            | 2, 6          | 2, 5     |
| Capacitance (5.5.3.5)                                                                                                                                          | 3, (11), 16             |               |          |
| X-ray photo (5.5.3.9)                                                                                                                                          | 4, (12), 17             |               |          |
| Reflectance (5.5.3.8)                                                                                                                                          |                         | 3, 7          |          |
| Vacuum thermal cycling (5.5.3.11)                                                                                                                              | 5, 13                   |               |          |
| Substrate integrity (5.5.3.10)                                                                                                                                 | 18                      |               |          |
| Fatigue thermal cycling (5.5.1.3)                                                                                                                              | 8                       |               |          |
| Humidity (5.5.1.4)                                                                                                                                             |                         | 4             |          |
| ESD test (5.5.1.5)                                                                                                                                             |                         |               | 3        |
| NOTE 1: The numbers in each column indicate the sequence in which the checks are performed for each test.                                                      |                         |               |          |
| NOTE 2: Guidelines for relaxation of qualification tests due to similarity with earlier performed qualification are described in the handbook ECSS-E-HB-20-08. |                         |               |          |

### 5.5.1.3 Fatigue thermal cycling test

#### 5.5.1.3.1 Purpose

The purpose of the thermal cycling test is to demonstrate the life fatigue compatibility of all components and processes in an assembly.

#### 5.5.1.3.2 General

- a. The PVA manufacturer shall demonstrate that lack of continuity is avoided at any time during cycles specified in requirement 5.5.1.3.4g, both on the solar cell and on the protection shunt diode circuits.
- b. The test conditions, specifically the thermal gradients through the test sample thickness, shall be representative of the distribution predicted in space so that the components are not over-stressed or under-stressed beyond specified limits.
- c. The temperature extremes of the thermal cycling shall be extended or a dedicated structural test be performed in cases where analysis demonstrates that the structural loading results in a greater stress than the thermal cycling.

**NOTE** For example, acoustic and noise can produce greater stress than thermal cycling in certain missions.

#### 5.5.1.3.3 Qualification coupon

- a. The qualification coupon shall be defined by means of a representative drawing, document or matrix in the SCD-PVA.

**NOTE** It is good practice to maximize the number of applied solar cells on the coupon substrate available area. Depending on the complexity of the design and mission, heritage and TRL, the number of required solar cells might lead to more than one qualification coupon.

- b. The representation of the critical areas of the solar array on the qualification coupon shall be agreed with the customer.

**NOTE** For example, the substrate represents a worst-case stress part of the flight panels.

- c. The qualification coupon shall be manufactured using the same design, substrates, materials, processes and manufacturers as for the flight panel, furthermore, any deviation be identified by the PVA/Solar Array supplier.

**NOTE** The same materials means the same material specification, but is not linked to manufacturing batches or lots.

- d. In case the qualification coupon contains more than one PVA technology, fulfilling 5.5.1.2g, the coupon design shall allow to qualify those technologies separately ensuring that:

1. a failure of a given technology does not propagate to the other technologies, and

2. qualification testing is able to discriminate success or failure of each technology independently.
- e. The number of (non-cell) components shall correspond to the number in a flight configuration of the unit they belong to, but with a minimum of two.

NOTE For example, it can be one blocking diode per string, one shunt diodes per shunt interval, and two bleed resistors per panel, but in accordance with this requirement, in all these cases the minimum number is two.

- f. If space is available, additional components and technologies may be included to be tested as separate items.
- g. For every type of solar cell configuration (N-end tab, P-end tab or middle cell) one piece shall be repaired on the coupon after the acceptance test (only visual inspection and electrical health check), unless configurations are identical, in which case at least two cells shall be repaired.
- h. The production of the qualification coupons shall be representative of the full processing of the flight hardware.
- i. At least 3 thermocouples on the front side and 3 on the reverse side of each qualification coupon shall be placed for temperature monitoring.
- j. The qualification coupon subjected to the fatigue thermal cycling test need not follow the acceptance test sequence.
- k. Dedicated electrical test points shall be included in the electrical design of the qualification coupon such that the capacitance of single strings can be measured.

#### 5.5.1.3.4 Test

- a. The number of cycles and temperature deltas may be determined using one of the following criteria:
  1. The number of cycles is four times the number of cycles that occur during the mission with 0 °C temperature delta (at both upper and lower design temperature limit).
  2. The number of cycles is equal to 1,5 times the number of cycles occurring during the mission with a temperature delta of 10 °C at extremes (both upper and lower qualification temperature limit).
- b. If qualification margin temperature exceeds the brittle point of main elements of the PVA, the option to be used in conformance with requirement 5.5.1.3.4a shall be agreed with the customer.
- c. <<deleted>>
- d. The following cycling profiles shall be used:
  1. A temperature profile which envelopes the variation of temperature extremes during the mission.
  2. The total profile can be divided into sub-profiles.

- e. The number of cycles, pressure limit, gas composition and temperature limits of requirements 5.5.1.3.4a and 5.5.1.3.4b shall be stated in the SCD-PVA.
- f. Monitoring of the insulation between the solar cell circuit and the substrate shall:
  - 1. be performed in conformance with clause 5.5.3.3.3, and
  - 2. take place during the cycles with the maximum temperature limits and for a minimum of two cycles at each test interval.
- g. Monitoring of the continuity of the solar cell circuits shall:
  - 1. be performed in conformance with clause 5.5.3.3.2,
  - 2. take place during cycles for the complete activity,
  - 3. be performed on a regularly switching between two polarities, biasing change rate to be agreed with the customer.
  - 4. be performed by measuring both cell circuit continuity, at the beginning and at the end of the cycles in conformance to the relevant percentage specified in requirement 5.5.1.3.4g.3.
- h. Insulation and continuity shall not be measured simultaneously.

#### 5.5.1.3.5 Pass-fail criteria

- a. On completion the test, the following conditions shall be met:
  - 1. there is electrical continuity (no open circuit), and
  - 2. the power output of the test coupon and the insulation is within the limits stated in the SCD-PVA.

### 5.5.1.4 Humidity

#### 5.5.1.4.1 Purpose

The purpose of the humidity test is to demonstrate the endurance of assembled PVA components in a real-life environment against standard environmental conditions using accelerated tests.

#### 5.5.1.4.2 General

- a. If there are requirements on specific environmental conditions, they shall be stated in the SCD-PVA.

NOTE For example, chemical vapour requirements.

#### 5.5.1.4.3 Test Sample

- a. The test sample shall be manufactured using the same qualified materials and processes as the flight panels.
- b. The production of the test sample shall be representative of the full processing of the flight hardware.

#### 5.5.1.4.4 Test

- a. The test sample shall be placed in a chamber at ambient pressure.

- b. The chamber temperature shall then be increased to 60 °C minimum.
- c. Relative humidity shall be higher than 90 %.
- d. The duration of the test shall be 30 days.

NOTE Aluminium containing layers are known to be sensitive to humidity.

- e. <<deleted>>
- f. High-purity water in conformance with ASTM D1193-99, Type I, shall be used.
- g. Water condensation on the surface of the test sample shall be prevented.
- h. If there are requirements on specific environmental conditions, they shall be stated in the SCD-SCA.

NOTE For example, chemical vapour requirements and/or voltage loading to simulate ambient illumination.

#### 5.5.1.4.5 Pass-fail criteria

- a. On completion the test, the following conditions shall be met:
  - 1. there is electrical continuity (no open circuit), and
  - 2. the power output of the test coupon and the insulation is within the limits stated in the SCD-PVA for the specified temperatures.

### 5.5.1.5 Electrostatic discharge (ESD) test

#### 5.5.1.5.1 Purpose

The purpose of the ESD test is to demonstrate that the use of adequate design rules reduces the risk of ESD. This is done by demonstrating that ESD primary discharge does not lead to a secondary arc, which can lead to permanent losses of power and/or insulation in the solar array.

#### 5.5.1.5.2 Pass-fail criteria

- a. No permanent sustained arc (PSA) shall occur during the testing of the conditions as specified in 5.5.1.5.3e.1, 5.5.1.5.3e.2, and 5.5.1.5.3e.3.

NOTE TSA max duration is here assuming a minimum 0,5 mm gap length between solar cells mounted on isolative substrate.

- b. Testing shall demonstrate that the occurred arcs, initiated under 5.5.1.5.3e.1, 5.5.1.5.3e.2 and 5.5.1.5.3e.3, do not produce damage to the cells or the insulation.

NOTE Damage to the cells has to be understood that electrical performance testing demonstrates that no degradation occur with respect to the values found before test (within typical uncertainties related to the reproducibility of the measurement, typically  $\pm 2-3$  %).

- c. During the testing of the worst case nominal operational conditions without margins, as specified in 5.5.1.5.3c, no failure, no permanent sustained arc (PSA) nor a temporary sustained arc (TSA) above 1,2 ms shall occur.

NOTE EMAGS3 European study demonstrated that flashover durations could last up to 800  $\mu$ s on an 8 m<sup>2</sup> panel. This serves up to now as the common reference widely used for ESD testing including flashover. In case new studies, experiments or findings indicate that longer primary ESDs are practically possible on the solar generators, those conditions are currently not covered by this standard.

- d. Dark I-V measurement shall be performed in-situ as a minimum at the beginning and at the end of the ESD test campaign.

NOTE It is recommended to repeat dark I-V measurements after each ESD > 800  $\mu$ s to demonstrate that there is no damage.

#### 5.5.1.5.3 Process

- a. The ESD tests shall be performed on solar array coupons using instrumentation specially designed for that purpose as described in clause 7 of ECSS-E-ST-20-06.
- b. The ESD tests shall cover **worst case nominal operational conditions** as specified in 5.5.1.5.3c and **worst case conditions** (not nominal) as specified in 5.5.1.5.3d and with safety factors as specified in 5.5.1.5.3e.
- c. The worst case nominal operational condition shall cover:
  1. the minimum gap between adjacent strings occurring in the design including any tolerances;
  2. the mission scenarios, whichever yield the highest calculated voltages or currents respectively, between adjacent strings within the PVA network;
  3. the maximum voltage in the gap between any adjacent cells in consideration of the PVA lay-out design;
  4. static operational modes only, without any short term peaks during switching;
  5. shadow cases, partial or full, if any, with corresponding angle of incidence and associated current production;
  6. light reflection cases, if any, which increase the generated current;
  7. the solar array operational modes imposed by the solar array power regulator architecture;
  8. the worst case possible combinations of gap, voltage and current.

NOTE 1 to item 1: Examples of mission scenarios are: best case BOL or worst case EOL).

NOTE 2 to item 3: e.g. parallel strings, U-shaped strings, anti-parallel strings.

NOTE 3 to item 7: e.g. S3R (typically operated between  $[0 \text{ V}, I_{sc}]$  and  $[V_{op}, I_{op}]$ ) or MPPT (typically operated between  $[V_{mp}, I_{mp}]$  and  $[V_{oc}, 0 \text{ A}]$ ).

NOTE 4 to item 8: Combinations of gap, voltage and current can be within a section and between sections where different combinations apply.

d. The worst case condition (not nominal) as specified by 5.5.1.5.2c shall consider the addition of the following:

1. a single hardware failure does not propagate to neighbouring components circuits or interfaces in an undetermined way;
2. the solar array is specified to provide the requested power and ensure the energy balance in each mission phase during operational life including any string loss tolerance defined by the customer, spacecraft charging effects and worst case conditions;
3. provision are made against potential failure propagation in case of short-circuit failure of a solar array section or short circuit of its connection to the power subsystem.

NOTE 1 This means that at least a single non-functionality of any component is part of the worst case condition. E.g. in a PVA design with one blocking diode per string only, the scenarios of a blocking diode being either in short or in open are part of the worst case.

NOTE 2 The solar array is designed to be single-failure tolerant at string level.

e. ESD tests shall be started with the combination of gap, voltage and current as specified in 5.5.1.5.2c and 5.5.1.5.2d, followed by a gradual increase of either the parameter voltage or current, but not simultaneously, until the conditions as specified hereafter are met:

1. For 5.5.1.5.2c (worst case nominal operational condition) a safety factor of 2 or a margin of 50 V, whichever is lower, is demonstrated for the voltage while the current is nominal.
2. For 5.5.1.5.2c (worst case nominal operational condition) a safety factor of 1,2 is demonstrated for the current while the voltage is nominal.
3. For 5.5.1.5.2d (worst case condition) no additional margins need to be demonstrated.

NOTE 1 If the conditions as specified in 5.5.1.5.3e.1, 5.5.1.5.3e.2 and 5.5.1.5.3e.3 were reached without triggering a permanent sustained secondary arc, and after meeting the requirement 5.5.1.5.2c, the parameters voltage and current can be gradually increased until a permanent sustained secondary arc is triggered or until a major power degradation or loss of insulation is detected in order to derive