ESA PSS-01-604 Issue 1
September 1988

# Generic Specification for silicon solar cells

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Approved by the Inspector General
on the 7th September 1988

Published by ESA Publications Division,
ESTEC, Noordwijk, The Netherlands.

Printed in the Netherlands.

ESA Price code: E1

ISSN 0379 - 4059

## ABSTRACT

This specification outlines the requirements for the qualification, procurement, storage and delivery of silicon solar cells for use in spacecraft applications. The general requirements are covered in the main part of this specification, the generic specification. Moreover, in Annex C, the recommended format is given for the detail specification, covering inspection data, physical and electrical characteristics and other ratings which are expected to be different for each application.

## DOCUMENTATION CHANGE NOTICE

| Rev. Letter | Rev. date | Page | Change Item | Approved DCR no. |
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# SECTION 1: INTRODUCTION

## 1.1 SCOPE

This generic specification covers the general requirements for the qualification, procurement, storage and delivery of monofacial silicon solar cells, bare and covered (assemblies) suitable for space applications.

## 1.2 APPLICABILITY

This specification is primarily applicable to the granting of qualification approval to a solar cell type in accordance with the ESA PSS specification system, and to the procurement of solar cells from qualified manufacturers.

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# SECTION 2: APPLICABLE DOCUMENTS

The following documents form part of this specification. The relevant issues shall be those in effect on the date of placing the purchase order or contract.

## 2.1 ESA SPECIFICATIONS

The following specifications are applicable to the extent specified herein.

**ESA PSS-01-20** Quality assurance of ESA spacecraft and associated equipment.

**ESA PSS-01-202** Preservation, storage, handling and transportation of ESA spacecraft hardware.

**ESA PSS-01-203** Quality assurance of test houses for ESA spacecraft and associated equipment.

**ESA PSS-01-702** A thermal vacuum test for the screening of space materials.

**ESA PSS-01-709** Measurement of thermo-optical properties of thermal-control materials.

**ESA PSS-01-713** Measurement of the peel and pull-off strength of coating and finishes with pressure-sensitive tapes

## 2.2 OTHER DOCUMENTS

**ASTM D 1193-77(83)** Standard specification for reagent water.

**MIL-Std-105** Sampling procedures and tables for inspection by attributes.

## 2.3 ORDER OF PRECEDENCE

For the purposes of interpretation and in the case of conflict with regard to documentation, the following order of precedence shall apply:

(a) Purchase order or contract.

(b) Detail specification.

(c) Generic specification.

(d) Other documents referenced herein.

# SECTION 3: TERMS, DEFINITIONS, ABBREVIATIONS, SYMBOLS AND UNITS

In addition to conventional symbols and units of the ISO System, the following definitions and abbreviations shall apply:

## 3.1 DEFINITIONS

**Solar cell assembly:** Although this term is understood to mean the solar cell together with interconnector and cover, the present specification can also be used for the qualification of bare cells.

**Manufacturing lot:** A solar cell manufacturing lot corresponds to a contacts vacuum evaporation batch.

**Procurement lot:** A procurement lot of solar cells consists of cells manufactured with the same processes and materials on the same manufacturing line to the same purchase order. A procurement lot can consist of one or more manufacturing lots.

## 3.2 ABBREVIATIONS

**ARC** Antireflection coating

**AM0** Air mass zero

**BOL** Beginning of life

**DCR** Documentation Change Request

**EOL** End of life

$I_{sc}$ Short-circuit current

**MRB** Material Review Board

**PID** Process Identification Document

$P_{max}$ Maximum power

**S.C.** Solar constant

**SWS** Secondary working standard

**t.b.s.** To be specified

$V_{oc}$ Open-circuit voltage

# SECTION 4: REQUIREMENTS

## 4.1 GENERAL REQUIREMENTS

### 4.1.1 Test requirements

The test requirements for the qualification of solar cells shall comprise Final Production Tests and Qualification Testing.

The test requirements for the procurement of solar cells so qualified shall comprise Final Production Tests and Verification of Qualification Testing.

### 4.1.2 Specifications

For qualification, procurement, storage and delivery of components in conformity with this specification, the requirements of the documents listed in Section 2 of this specification shall apply.

### 4.1.3 Conditions and methods of test

The conditions and methods of test shall be in accordance with this specification and the applicable detail specification.

### 4.1.4 Manufacturer's quality assurance organisation

The manufacturer shall have a quality assurance organisation established and implemented, which meets the requirements of the specification ESA PSS-01-20.

### 4.1.5 Manufacturer's responsibility for the performance of tests and inspections

The manufacturer shall be responsible for the performance of tests and inspections required by the applicable specifications. These tests and inspections shall be performed at the plant of the manufacturer or at an approved facility, compliant with the requirements of specification ESA PSS-01-203.

### 4.1.6 Inspection rights

ESA and the orderer reserve the right to monitor any of the tests and inspections scheduled in the applicable specifications.

### 4.1.7 Additional tests

If additions to the specified test programme are proposed, the Manufacturer shall supply details to ESA and the Orderer.

These details shall include a description of the modified test methods, procedures and equipment to be used, together with a statement specifying when, in the test sequence, these additional tests will be performed. The Manufacturer shall obtain the approval of ESA and the Orderer before commencing the performance of these tests.

## 4.2 DELIVERABLE COMPONENTS

Components delivered to this specification shall be processed and inspected in accordance with the requirements of the relevant PID and shall have satisfactorily completed all tests and inspections specified herein and in the relevant detail specification.

## 4.3 MARKING

All components (bare cells and cell assemblies) delivered to this specification shall be marked on the rear metal contact with the aid of a code that will make it possible to trace manufacturing date and manufacturing lot as well as silicon crystal. The ink used shall have low outgassing properties, in accordance with the specification ESA PSS-01-702.

All marking shall remain legible after all tests specified herein have been performed, with the exception of the ARC adherence test (Para. 7.4.9).

## SECTION 5: PRODUCTION CONTROL

A Process Identification Document (PID) for the solar cell to be qualified shall be prepared by the manufacturer to the satisfaction of the qualifying space agency. It shall comprise copies of all documents necessary to define the solar cell and fully document the manufacturing and testing procedures.

Where necessary, reference only shall be made to company confidential documents and proprietary information. The PID shall include as a minimum:

— a parts list (including materials);

— full construction details, including any applicable drawings and photographs;

— the production flow chart;

— all relevant process specifications;

— all relevant inspection procedures;

— the overall test programme to comply with the relevant specifications;

— an index of contents by reference number, issue and date.

The qualifying space agency will identify those documents that are to be maintained under configuration control (designated as 'baseline' documents) and will specify the ones it wishes to hold for the effective maintenance of the qualification. From the date of acceptance by the qualifying space agency of the PID, the baseline documents shall be held at the issue references effective at that date. Any intended modifications or changes to baseline documents of the PID, together with any quality and reliability implications, shall be brought to the attention of the qualifying space agency for its review and approval.

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# SECTION 6: FINAL PRODUCTION TESTS

## 6.1 GENERAL

Final production tests shall consist of:

— Visual inspection;

— Control of dimensions and weight;

— Electrical performance measurement.

Unless otherwise specified, all components for delivery and all components used for qualification or verification of qualification tests shall meet the relevant final production-test requirements, and the corresponding data documentation shall be delivered by the manufacturer together with the delivered cells, the qualification test sublot or the verification of qualification test samples in accordance with this specification.

## 6.2 TEST METHODS AND CONDITIONS

The applicable test methods and conditions are specified in Subsection 7.4 of this specification.

## 6.3 DOCUMENTATION

Data documentation for final production tests shall be in accordance with Subsection 9.3 of this specification.

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# SECTION 7: QUALIFICATION AND VERIFICATION-OF-QUALIFICATION TESTS

## 7.1 GENERAL

All solar cell procurement lots shall be qualified. Qualification shall be granted by ESA. The qualification shall consist of the tests specified in this document.

When the cells have been qualified, the qualification shall be maintained by periodic verification of qualification testing during the manufacturing period for a procurement lot. ESA as the qualifying authority shall be informed of the outcome of a verification/qualification programme.

If a purchase order is placed for a procurement lot of a previously qualified solar cell, the qualification tests need not be repeated if:

— no changes are made to the design, function or electrical/mechanical parameters of the solar cell;

— the same detail specification is applicable;

— no changes are made to the PID;

— the last verification of qualification test was performed less than one year ago.

If the qualification is still valid, the qualification test may be replaced by a verification-of-qualification test consisting of all subgroups.

## 7.2 QUALIFICATION

### 7.2.1 Documentation requirements

#### 7.2.1.1 Process Identification Document (PID)

A Process Identification Document (PID) shall be prepared as specified in Section 5.

#### 7.2.1.2 Production and test schedule

Before commencing production of the qualification lot, the manufacturer shall compile a production test schedule. This schedule shall show by date and duration when important production and test activities are to take place including all major processing operations and key points in production and testing. A production flow chart, process schedules and inspection procedures shall be provided.

### 7.2.2 Qualification test samples

The solar cells required for qualification testing shall be produced strictly in accordance with the PID. ESA and the orderer shall have the right to witness the manufacture of these samples. The test samples shall be chosen statistically and at random from the first manufacturing lots of the procurement lot.

### 7.2.3 Qualification testing

Qualification testing shall be in accordance with Table I of this specification. The total quantity of test samples (*n* of Table I) shall be 160 pieces. The qualification tests are divided into subgroups of tests. The samples assigned to a subgroup shall be subjected to the tests in that subgroup in the sequence specified. If bare cells are being qualified, subgroups B and C shall consist of bare cells. The qualification test has failed if more than one failure is detected in any subgroup or if more than two failures in total are detected. For failure definition, see Subsection 8.1.

## 7.3 VERIFICATION OF QUALIFICATION

### 7.3.1 Periodicity

Verification-of-qualification testing shall be performed after 50% of the cells of the procurement lot has been produced or, at the latest, one year after production has started. Verification-of-qualification testing shall be repeated after all the cells of the procurement lot have been produced or, at the latest, two years after production has started. If production of the procurement lot extends over more than two years, verification-of-qualification testings shall be repeated at one-year intervals.

### 7.3.2 Selection of samples

Verification-of-qualification testing shall be performed on samples chosen statistically and at random from the manufacturing lots produced during the periods defined in Paragraph 7.3.1.

### 7.3.3 Verification-of-qualification testing

Verification-of-qualification testing shall be in accordance with Table I of this specification.

The total quantity of test samples (*n* in Table I) shall be 80 pieces. The tests are divided into subgroups. The samples assigned to a subgroup of tests shall be subjected to the tests in that subgroup in the sequence specified.

If more than one failure is detected in a subgroup, the verification of qualification has failed. If one failure is detected, then the subgroup tests shall be repeated on a full qualification sample (20 or 40) pieces. If this second test fails to meet the corresponding qualification criteria, the verification of qualification has failed.

In the case of a verification-of-qualification failure, all manufacturing lots produced since the last verification of qualification (for the same sublot) shall be submitted to verification-of-qualification testing. Any lot showing a failure shall be rejected.

## 7.4 TEST METHODS, CONDITIONS AND MEASUREMENTS

The test methods, conditions and measurement requirements applicable to the tests shown in Table I are detailed in the following paragraphs. For failure criteria, see Subsection 8.1.

### 7.4.1 Visual inspection (all subgroups)

The solar cells shall be examined visually with the aid of a stereo microscope of 5 × to 10 × magnification to verify the applicable requirements for defects on cell, cover glass, adhesive, contacts and interconnector (Subsection 4.4 of the detail specification).

### 7.4.2 Control of dimensions and weight (all subgroups)

The overall lateral dimensions of the cell, contact dimensions or interconnector position when applicable shall be inspected to check compliance with the applicable requirements of Subsection 4.3 of the detail specification.

The thickness of the bare solar cells shall be verified by determination of the average weight per lot, taking into account the contact weight as derived from the contact-uniformity test (Para. 7.4.12). The correct weight of the solar cell assembly shall be verified by determination of the average weight per lot.

### 7.4.3 Electrical performance (all subgroups)

The purpose of this test is to assess the corresponding electrical parameters of the solar cells and to provide data for, say, solar-generator design.

The electrical current of solar cells under 1 S.C. AM0 equivalent illumination shall be measured and recorded digitally at the voltages specified in Subsection 4.5 of the detail specification (Table 1 and Figure 4). During measurement, the cells shall be kept at a constant junction temperature $T_j$, which shall be defined by the relation:

$$(T_s + \Delta T) \leq T_j \leq (T_s + 2\Delta T)$$

where $T_s$ is the nominal test temperature (25°C or operating temperature) specified in Subsection 4.5 of the detail specification, and $\Delta T$ is the inaccuracy of the temperature-control equipment.

A continuous or pulsed light source calibrated in accordance with Annex A shall be used to verify the requirements of Subsection 4.5 of the detail specification.

### 7.4.4 Temperature coefficients

Temperature coefficients shall be measured on all samples of subgroup B and $n/8$ samples of subgroup C.

Test 7.4.3 shall be repeated at six equidistant solar-cell-junction temperatures between two temperature extremes $t_1$ and $t_2$, calculated as follows:

$t_1$ = highest nominal operation temperature + 25°C

$t_2$ = lowest nominal operation temperature − 25°C.

The temperature coefficients of short-circuit current, open-circuit voltage and maximum power shall be derived by least-square curve fitting.

### 7.4.5 Spectral response

Spectral response data are required for sun simulator verification (Subsections 1.1 and 1.2 of Annex A) for performance-measurement error calculation, and for the characterisation of the spectral-response spread of production cells.

Measurement of spectral response shall be performed on all samples of subgroup B and $n/8$ samples of subgroup C by comparison of the short-circuit current of the test cell with the output of a spectral standard of known relative spectral response under monochromatic irradiation. The monochromatic irradiation shall be obtained by one of the following methods:

(a) at (at least) 14 discrete wavelength intervals between 0.3 $\mu$m and 1.1 $\mu$m with the aid of narrow-band interference filters;

(b) by means of a high-intensity monochromator for continuous recording between 0.3 $\mu$m and 1.1 $\mu$m.

The irradiation intensity at all wavelengths shall be such as to ensure that the measurement is made in the region where the cell response short-circuit current versus irradiance is linear.

### 7.4.6 Thermo-optical data (subgroup B)

Thermo-optical data are required for computation of the solar-panel operational temperature. Solar absorptance and hemispherical emittance shall be measured in accordance with specification ESA PSS-01-709.

### 7.4.7 Thermal cycling (subgroups A,E and 0)

The objective of this test is to assure reliability of cells under a thermal stress equivalent to one year in orbit. The number of cycles and the extreme temperatures shall be as defined in Paragraph 4.3.2.2 of the detail specification.

### 7.4.8 Humidity and temperature

This test is an accelerated shelf-life test to check contact and antireflection-coating stability in humid atmosphere.

All cells of subgroups 0 and D (if applicable) shall be placed in a chamber at ambient pressure.

The chamber temperature shall then be increased to 60°C minimum;

relative humidity shall be higher than 90%. The duration of the test shall be four days. High-purity water shall be used (ASTM D 1193-77, Type 1) and precautions shall be taken to avoid water condensation on the surface of the cells.

### 7.4.9 ARC adherence

The objective of this test is to check the adherence of the cell anti-reflection coating. Damage to cell contacts and marking observed after this test or after the subsequent coating adherence test shall therefore be disregarded.

All cells of subgroup U shall be immersed in boiling water for 15 minutes and then dried in hot air ($T_{max}$ = 100°C). Water quality shall be as laid down in Paragraph 7.4.8.

### 7.4.10 Coating adherence

In order to check the durability of the antireflection coating and the contacts, all cells of subgroups O and U shall be subjected to a coating adherence test on both cell faces.

In establishing test conditions, specification ESA PSS-01-713 shall be used as a guideline.

No visible delamination of parts of the contacts (after humidity test) or of the antireflection coating (after humidity or ARC adherence test) shall occur beyond the limits specified in the relevant subparagraphs of Paragraph 4.4 of the detail specification.

### 7.4.11 Adherence of welded interconnectors

The objective of this test is to check the bond strength of interconnectors under mechanical and thermal stresses and to check electrical stability after interconnector welding.

Interconnector tabs shall be welded to the solar cells of subgroups A and E of Table I. Welding parameters and the material and dimensions of the interconnectors shall be as defined in the company's ESA-approved specification of the production process for solar panels for the project responsible for the detail specification.

Front interconnectors shall be welded onto bare cells of subgroups A and E. Rear interconnectors shall be welded onto cells of subgroup E after they have been equipped with front interconnectors and covers. Cementing conditions, adhesive and cover shall be as defined in the company's ESA-approved specification of the production process for solar panels for the project responsible for the detail specification.

After interconnector welding, all cells of subgroups A and E shall be electrically tested according to Paragraph 7.4.3 of this specification and

thermally cycled according to Paragraph 7.4.7 of this specification. After electrical test and thermal cycling, a gradually increasing pull force shall be applied to the interconnector tabs at a pull speed of 30 mm/min.

The ultimate pull strength of each tab shall be as defined in Paragraph 4.3.2.2 of the detail specification.

The pull direction shall in principle be parallel to the cell surface. However, if preliminary experience shows that the interconnector tab breaks before the required pull strength defined above has been reached, the pull direction shall be changed to 90° with respect to the cell surface.

### 7.4.12 Contact uniformity and surface finish

The purpose of this test is, to verify contact thickness uniformity and surface finish of cells of subgroups A and E, in accordance with the requirements of the subsequent interconnection process, as defined in Paragraph 4.3.1.5 of the detail specification.

The uniformity of metal contact thickness in the interconnector weld area shall be checked with the aid of a Betascope or equivalent instrument.

The surface finish in the interconnector weld area shall be checked with the aid of a micro surface roughness tester.

### 7.4.13 Electron irradiation

The solar cells shall be subjected to 1 MeV electron irradiation. The flux density and energy shall be uniform over the cell area within ±10%. During irradiation, the cells shall be kept in a vacuum better than $1 \times 10^{-2}$ Torr at a temperature of (20 ± 10°C). The nominal rate shall be lower than $5 \times 10^{11}$ e cm$^2$ s$^{-1}$. The irradiation facility, dosimetry included, shall be approved by ESA.

The irradiation will, as a minimum, be performed at three doses:

(a) $\phi_p$ = predicted dose for the envisaged application;

(b) $\phi_p/2$

(c $\phi_p \times 2$.

To this end, the sequence of tests in Table I on subgroup C is arranged as follows: Subgroup C is divided in two batches of $n/8$ samples, each one being irradiated twice at $\phi_p/2$ and $\phi_p$ doses. This yields data at $\phi_p/2$ and $\phi_p \times 2$ on $n/8$ samples and data at $\phi_p$ on $n/4$ samples. Cells of subgroup D shall be irradiated at $\phi_p$ only.

After combined electron and photon irradiation, the solar cells shall meet the requirements of Subsection 4.5 of the detail specification.

NOTE 1: An electron irradiation at transfer-orbit dose shall be added when required by the detail specification.
NOTE 2: A proton irradiation shall be added if required, and as defined, by the detail specification.

### 7.4.14 Photon irradiation

The stability of solar cell performance under one solar constant equivalent light shall be demonstrated by this test.

Solar cells of subgroups B and C shall be irradiated with one solar constant for 48 hours. The cells shall be kept at 25 $\pm$5°C during the test. After the test the cells shall be kept at temperatures below 50°C until they have been electrically measured.

### 7.4.15 Surface conductivity

The coverglass surface conductivity of cells of subgroup D shall be measured to demonstrate that the average conductivity across the total surface meets the requirements of the detail specification (Para. 4.6.6). When applicable, this measurement shall be performed between the cover contact dots.

### 7.4.16 Reverse *I/V* characteristics

Information on the reverse voltage behaviour of solar cells is needed for the prediction of shadowing and hot-spot phenomena on solar cell strings. The reverse *I/V* characteristics of the cells of subgroups C and D shall gradually be recorded at temperatures and up to a voltage as defined in the detail specification (Para. 4.5.5), a current-limited power supply being used in order to avoid destructive breakdown.

## 7.5 DOCUMENTATION

Documentation of environmental tests shall be in accordance with Subsection 9.4 of this specification.

TABLE I: QUALIFICATION AND VERIFICATION-OF-QUALIFICATION TEST PLAN

| | | | BARE CELLS (*n*/2 samples) | | | | CELL ASSEMBLIES (*n*/2 samples) | | |
|---|---|---|---|---|---|---|---|---|---|
| Test | Symbol | Method | A (*n*/8) | E (*n*/8) | O (*n*/8) | U (*n*/8) | B (*n*/8) | C (*n*/4) | D (*n*/8) |
| Visual inspection | VI | 7.4.1 | 1,6 | 1,6 | 1,5,7,9 | 1,5,7 | 1 | 1 | 1,9 |
| Dimension & weight | DW | 7.4.2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| Electrical performance | EP | 7.4.3 | 3 | 3 | 3,10 | 3 | 3,5 | 3,5,7,11,13 | 3,7,11 |
| Temperature coeff. | TC | 7.4.4 | | | | | 6 | 8,14 | |
| Spectral response | SR | 7.4.5 | | | | | 7 | 9,15 | |
| Thermo-optical data | TO | 7.4.6 | | | | | 8 | | |
| Thermal cycling | CY | 7.4.7 | 5 | 5 | 6 | | | | 5 |
| Humidity & temperature | HT | 7.4.8 | | | 4 | | | | |
| ARC adherence | AR | 7.4.9 | | | | 4 | | | |
| Coating adherence | CA | 7.4.10 | | | 8 | 6 | | | 6 |
| Intercon. adherence | IA | 7.4.11 | 5 | 5 | | | | | |
| Contact uniformity | CU | 7.4.12 | 4 | 4 | | | | 4,10. | 10 |
| Electron irradiation | EI | 7.4.13 | | | | | | 6,12 | |
| Photon irradiation | PH | 7.4.14 | | | | | 4 | | 4,8,12 |
| Surface conductivity | SC | 7.4.15 | | | | | | | |
| Reverse *I/V* | RV | 7.4.16 | | | | | 9 | 16 | |

## NOTES ON TABLE I

— Figures in subgroup columns indicate test sequence; e.g. for subgroup O, 1st test is VI, 2nd test DW..., 6th is CY, then back to VI (7th), etc.

— General objectives of subgroup division:

- Subgroup A: front interconnector adherence
- Subgroup E: rear interconnector adherence
- Subgroup O: extended storage simulation
- Subgroup U: antireflection coating adherence
- Subgroup B: BOL performance data
- Subgroup C: EOL performance data
- Subgroup D: surface conductivity

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# SECTION 8: FAILURE DEFINITION

## 8.1 FAILURE CRITERIA

The following shall be counted as component failures:

(a) Components which fail during subgroup tests for which the pass/fail criteria are inherent in the test method.

(b) Components failing to comply with the requirements of Subsection 4.4 of the detail specification (visual inspection).

(c) Components whose marking fails to comply with the requirements of Subsection 4.3 of this specification.

(d) Components that fail to meet any stress requirements specified in the detail specification.

(e) Components that, when subjected to electrical performance measurements after qualification tests in accordance with Table 2 of the relevant detail specification, fail one or more of the applicable limits.

## 8.2 FAILED COMPONENTS

A component shall be considered as failed if it exhibits one or more of the failure modes detailed in Subsection 8.1 of this specification. Failed components shall be identified as such and included in the delivery. Failure analysis of these components shall be performed by the manufacturer and the results provided when requested by ESA or the Orderer as part of an MRB procedure (see Subsection 9.5).

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# SECTION 9: DATA DOCUMENTATION

## 9.1 GENERAL REQUIREMENTS

A data-documentation package is required for the qualification-approval records and for each component delivery lot. This package shall consist of the following:

(a) Cover sheet or sheets;

(b) Final production test data;

(c) Qualification testing data (for qualification sublot only);

(d) Failed-component list and failure-analysis report;

(e) Certificate of conformity;

(f) Verification-of-qualification test data.

Items (a) to (f) inclusive shall be grouped preferably as subpackages and, for identification purposes, each page shall include the following information:

— Component type;

— Manufacturer's name;

— Manufacturing lot identification;

— Date of establishment of the document;

— Page number.

## 9.2 COVER SHEET(S)

The cover sheet (or sheets) of the data-documentation package shall include as a minimum:

(a) Reference to the applicable detail specification, including issue and date;

(b) Reference to the applicable generic specification, including issue and date;

(c) Component type;

(d) Procurement-lot identification;

(e) Manufacturing lot-identification;

(f) Number of purchase order or contract;

(g) Additional information if the order specifies deviations from or additions to the applicable detail and generic specifications;

(h) Manufacturer's name and address;

(i) Location of the manufacturing plant;

(j) Signature on behalf of the manufacturer;

(k) Total number of pages of the data package.

## 9.3 FINAL PRODUCTION TEST DATA

A test-result summary shall be compiled, showing the total number of components submitted to, and the total number rejected after, each of the following tests:

— Visual inspection;

— Control of dimensions;

— Electrical-performance measurements.

## 9.4 QUALIFICATION AND VERIFICATION-OF-QUALIFICATION TESTING DATA

All data shall be related to the relevant manufacturing lot numbers. Data shall be provided showing a record of the total number of items submitted for test and the total number rejected from each of the test subgroups. Detailed data shall be provided of all electrical measurements made in accordance with Table 1, Table 2 and Figure 4 of the relevant detail specification. Required data formats are shown in Annex B of this specification.

## 9.5 FAILED-COMPONENT LIST AND FAILURE ANALYSIS

The failed-component list and failure analysis shall provide data in respect of:

(a) the reference number and description of the test or measurement as defined in the applicable generic or detail specification;

(b) the identification of the failed component;

(c) the failed parameter and the failure mode of the component;

(d) a detailed failure analysis, if requested.

## 9.6 CERTIFICATE OF CONFORMITY

A certificate of conformity shall be established and submitted with each delivery.

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## SECTION 10: DELIVERY

All deliverable hardware of the order shall be delivered together with documentation in accordance with the requirements specified in Section 9 of this specification.

One set of documents shall be sent to ESA and two sets to the orderer.

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# SECTION 11: PACKAGING, DESPATCH AND STORAGE REQUIREMENTS

Packaging, despatching, handling and storage of components delivered to this specification shall be in accordance with ESA PSS-01-202.

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# ANNEX A
# SUN SIMULATOR REQUIREMENTS AND CALIBRATION PROCEDURES

The light sources used for electrical performance measurements shall conform to the requirements of the following subsections.

## A.1 SUN SIMULATOR REQUIREMENTS

### A.1.1 Spectral distribution

The AM0 spectrum in the 0.3 $\mu$m to 1.1 $\mu$m wavelength range shall be as defined in Table A.1 of this specification. The spectral distribution of the sun-simulator light incident on the test plane shall be matched to the AM0 spectrum to such an extent that at least one of the two conditions below is fulfilled:

I. The maximum tolerable deviation of total energy per spectral region is defined as follows:
   - 0.35 $\mu$m to 0.5 $\mu$m $\pm 20\%$
   - 0.5 $\mu$m to 0.8 $\mu$m $\pm 10\%$
   - 0.8 $\mu$m to 1.1 $\mu$m $\pm 10\%$

II. The spectral distribution of the simulator light in the test plane is so matched to the AM0 spectrum that errors due to the spectral response spread of the relevant lot of cells are 1% or less.

### A.1.2 VERIFICATION OF SPECTRAL MATCH

The following method shall be used to demonstrate conformance with the requirements of Subsection A.1.1 above:

**For condition I:** direct measurement with a calibrated spectro-radiometer;

or

measurement with a two-channel spectro-radiometer against a calibrated reference light source;

or

measurement using a set of three solar cells to which broadband filters of the corresponding wavelength interval have been attached and which thereafter have been calibrated by ESA or a calibration agency accepted by ESA.

**For condition II:** The short-circuit current of ten solar cells which have been accepted by ESA as representing a worst-case simulation of the spectral-response spread of the cells to be tested shall be measured at constant nominal intensity of the sun simulator.
From the measured spectral response of the cells (according to Para. 7.4.5) and the AM0 spectrum given in Table A.1, the short-circuit current shall be calculated and multiplied by a common factor adjusting the average calculated short-circuit current to the average current resulting from the simulator measurements.
In this case, the difference between calculated and measured current of each individual cell shall not exceed 1% of the measured current.

### A.1.3 Irradiance uniformity

An irradiance of 1 S.C. $\pm 2\%$ is required on an area whose dimensions are at least equal to $D + 2\Delta D + 2d$ with $D$ = dimension of measured cell, $\Delta D$ = cell positioning accuracy and $d$ = dimension of the cell used for irradiance-uniformity checking.

### A.1.4 Irradiance stability

The stability of the simulator shall be sufficient to guarantee a reproducibility of electrical performance measurements of 1%.

## A.2 STANDARD CELL AND SUN-SIMULATOR CALIBRATION

### A.2.1 Primary standards

Primary standards which have been calibrated by a method approved by ESA (orbital, balloon or aircraft flight, ground-level natural sunlight, etc.) will be provided by ESA.

Number and type of primary standard cells shall be mutually agreed upon between the contractor and ESA.

### A.2.2 Secondary working standards (SWS)

Ten solar cells which have been accepted by ESA as representing a spectral response range similar to that of the cells to be tested shall be calibrated for their AM0 equivalent short-circuit current under an ESA approved sun simulator using accepted primary standards.

The spectral response of these SWS shall be measured according to Paragraph 7.4.5 of this specification. From the spectral response and the relevant AM0 and sun-simulator spectral-irradiance curves, the spectral mismatch error shall be calculated. The calculated error shall be not more than 1% for any SWS.

### A.2.3 Stability of the sensitivity of secondary working standards

The stability of the sensitivity of the SWS under operating conditions shall be checked by comparing the short-circuit current of five of the SWS before and after a photon-irradiation test with the short-circuit current of the remaining five SWS which have been kept in the dark. If the average short-circuit current of the photon-irradiated cells deviates by more than 1% from the original values, a new set of SWS shall be selected from a different production process which has been established to yield stable cells. The adequacy of the spectral response range of these cells shall be checked by spectral-response measurements and subsequent calculation of mismatch errors between SWS and production cells. The maximum error shall be less than 1%.

### A.2.4 Sun simulator calibration and maintenance

The irradiance in the test plane shall be adjusted to AM0 equivalent intensity by means of an SWS. The simulator intensity shall be checked with the aid of the SWS at regular intervals. These intervals shall be sufficiently short to guarantee an intensity drift of less than 1% between two subsequent SWS measurements. The length of the intervals shall be specified by the manufacturer in the relevant product assurance plan.

Correlation measurements between the SWS in daily use and a primary standard shall be made at intervals mutually agreed upon between the manufacturer and ESA.

The spectral irradiance of the sun simulator shall be determined periodically by means of one of the procedures specified in Section A.1.2 or an equivalent procedure proposed by the manufacturer. This verification shall be performed on the following occasions:

(a) immediately after the sun-simulator lamp or any part of the optical system has been changed, cleaned or repaired;

(b) every 500 hours (continuous illumination) or every 5000 flashes (pulsed) of lamp use.

### A.2.5 Maintenance of standards

All standard solar cells (primary and SWS) shall be kept at temperatures below 50°C during operation and storage. The standard cells should be kept in the dark during extended storage periods.

TABLE A.1
SPECTRAL SOLAR IRRADIANCE (AM0)
Irradiance integral from 0.3 to 1.1$\mu$m = 1013.12 W.m$^{-2}$

| Wavelength interval ($\mu$m) | Relative spectral irradiance $E(\lambda)$ ref. (%) |
|---|---|
| 0.30 – 0.325 | 1.720 |
| 0.325 – 0.35 | 2.376 |
| 0.35 – 0.375 | 2.557 |
| 0.375 – 0.40 | 2.712 |
| 0.40 – 0.425 | 4.200 |
| – | 4.432 |
| 0.45 – | 5.081 |
| – | 4.975 |
| 0.50 – | 4.819 |
| – | 4.698 |
| 0.55 – | 4.517 |
| – | 4.428 |
| 0.60 – | 4.235 |
| – | 4.035 |
| 0.65 – | 3.851 |
| – | 3.715 |
| 0.70 – | 3.543 |
| – | 3.312 |
| 0.75 – | 3.137 |
| – | 2.955 |
| 0.80 – | 2.775 |
| – | 2.602 |
| 0.85 – | 2.434 |
| – | 2.283 |
| 0.90 – | 2.165 |
| – | 2.074 |
| 0.95 – | 1.978 |
| – | 1.870 |
| 1.00 – | 1.763 |
| – | 1.668 |
| 1.05 – 1.075 | 1.583 |
| 1.075 – 1.10 | 1.506 |
| 0.30 – 1.10 | 100 |

Derived from NASA TT F-803: Makarova, Y.A. and Kharitonov, A.V., Distribution of energy in the solar spectrum and the solar constant.

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# ANNEX B
# REQUIRED DATA FORMATS

This Annex will specify, when available, the required data formats that shall be used in transferring the results of the tests defined in Section 7 of this specification. This annex will also contain the required procedure by which these data shall be transferred to ESA for automated data compilation, storage and processing for the purpose of electrical solar-array design.

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# ANNEX C
# FORMAT FOR DETAIL SPECIFICATION FOR SILICON SOLAR CELLS

Type:

Issue 1:

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# CONTENTS

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## 1. SCOPE

This specification details the ratings, physical and electrical characteristics, test and inspection data for monofacial silicon solar cells.

It shall be read in conjunction with the relevant generic specification, the requirements of which are supplemented herein.

## 2. APPLICABLE DOCUMENTS

The following documents form part of this specification and must be read in conjunction with it:

(a) Generic specification for silicon solar cells. ESA PSS-01-604 Issue 1 (September 1988).

(b) US Military Specification, MIL-0-13830 A or subsequent revision.

## 3. TERMS, DEFINITIONS, ABBREVIATIONS, SYMBOLS AND UNITS

For the purpose of this specification, the terms, definitions, abbreviations, symbols and units as specified in the generic specification (Section 3) shall apply.

## 4. REQUIREMENTS

### 4.1 General requirements

The complete requirements for the procurement of silicon solar cells specified herein are stated in this specification and the generic specification for silicon solar cells (ESA PSS-01-604).

Deviations from the generic specification, which are applicable to this detail specification only and have been formally agreed with specific manufacturers on condition that the alternative requirements are equivalent to those of the generic specification and do not affect the reliability of either solar cells or solar-cell assemblies, are listed in Subsection 4.2 of this detail specification.

### 4.2 DEVIATIONS FROM THE GENERIC SPECIFICATION

#### 4.2.1 Deviations from final production test procedures

To be completed with justification.

#### 4.2.2 Deviations from qualification and verification-of-qualification test procedures

To be completed with justification.

### 4.3 MECHANICAL REQUIREMENTS

#### 4.3.1 Bare cells

##### 4.3.1.1 Lateral dimensions

The dimensions of the solar cells specified herein shall be checked and shall conform to those shown in Figure 1, which shall also indicate configuration of n and p contacts and critical weld areas.

##### 4.3.1.2 Thickness

The thickness of the cell (silicon only) shall be **t.b.s.**

##### 4.3.1.3 Contacts

Before and after completion of the tests on subgroup O of Table I of the generic specification, the cell contacts shall meet the requirements of Paragraphs 4.4.4 and 4.4.5 of this detail specification.

##### 4.3.1.4 Antireflecting coating (ARC)

Before and after completion of the tests on subgroup U of Table I of the generic specification, the ARC shall meet the requirements of Paragraph 4.4.1 of this detail specification.

##### 4.3.1.5 Contact thickness uniformity and surface finish

T.b.s.

### 4.3.2 Solar-cell assemblies

#### 4.3.2.1 Lateral dimensions

The dimensions of the solar cell assemblies specified herein shall be checked and shall conform to those shown in Figure 2.

#### 4.3.2.2 Interconnector adherence

The separation pull strength of interconnectors from cells of subgroups A and E of Table I of the generic specification shall be **t.b.s.** newton. The number of thermal cycles to be performed before pull test and their extreme temperatures shall simulate the number of eclipses occurring during one year in orbit for the project responsible for the detail specification.

#### 4.3.2.3 Cover-glass dimensions

The lateral dimensions of the cover glasses shall be such as to ensure 100% coverage of the bare silicon surface of the cells. The thickness shall be **t.b.s.** (see also Fig. 2).

#### 4.3.2.4 Weight

The maximum average weight (per lot) of solar-cell assemblies specified herein shall be **t.b.s.** grammes including the interconnector.

### 4.3.3 Materials

The detail specification shall indicate the following solar cell characteristics:

- Silicon: growth technique, doping element, base resistivity, thickness;
- Contacts: all metal layers and their thicknesses;
- ARC: materials of all layers;
- Cover glass: material, thickness, ARC, conductive coating (if applicable);
- Cover-glass adhesive: material, outgassing rates (according to the specification ESA PSS-01-702).

## 4.4 DEFECTS (Visual Inspection Requirements)

The requirements on visually observable defects defined in this subsection are primarily applicable to the granting of qualification approval to a solar-cell type of high quality. If for certain applications these defects may be considered cosmetic and do not affect performance or reliability, they may be relaxed accordingly.

### 4.4.1 Cell defects

The location and maximum dimensions of edge chips, corner chips and surface nicks shall be as shown in Figure 3 and the corresponding table. The cumulative area of all defects of these types shall not exceed 5% of the cell area. No defect of these types shall be allowed in the contact weld area.

Cells bearing cracks or fingerprints shall be rejected.

The total area of antireflection coating voids shall not exceed 3% of the total active area of the cell.

### 4.4.2 Coverglass defects

Coverglass chips and nicks are tolerated, provided the bare silicon surface of the solar cell is 100% covered.

No surface defects greater than 80-50 (per Specification: MIL-0-13830 A) are allowed.

Covers with dirty and contaminated surfaces shall be rejected.

The total area of ARC voids shall not exceed 3% of the area of the cover glass, evaporation jig marks included.

The coverglass shall contain no bubble larger than 0.02 $mm^2$ in the projected area.

Cover glasses with hairline cracks are allowed under the following conditions:

(a) no visible separation (see Para. 7.4.1 of generic specification);

(b) no more than three cracks per cover;

(c) meeting cracks allowed if they are separated by more than 2 mm at the nonmeeting end.

### 4.4.3 Defects in cover-glass adhesive

There shall be no delamination or discoloration in the adhesive, except in the area opposite rear welds, where discoloration is tolerated. Adhesive voids along the cover edge shall not exceed 0.6 mm in depth.

The maximum total projected area of additional bubbles shall not exceed 0.2% of cell area.

Bubbles less than 0.02 $mm^2$ in the projected area are to be discounted.

Bubbles, discolorations and voids located at less than 2 mm from the interconnector edges shall be discounted.

#### 4.4.4 Defects of n-contact

The negative n-contact shall be free of interruptions, voids, delaminations, pickles and drops (see Para. 7.4.1 of generic specification) with a smaller dimension larger than 0.1 mm. Missing or noncontinuous grid fingers are allowed.

#### 4.4.5 Defects of p-contact

The positive contact surface of the cell shall be free of edge delaminations deeper than 0.3 mm. Other defects up to a total of 2% of the cell contact area are allowed, except in the interconnector weld area (as defined in Fig. 1) where the same requirements as for the n-contact apply.

#### 4.4.6 Interconnector defects

Breaking, tearing or deformation are not allowed.

### 4.5 ELECTRICAL PERFORMANCE REQUIREMENTS

#### 4.5.1 Electrical performance of individual solar-cell assemblies

The minimum current at test voltage ($V_t$: preferably equal to predicted operating voltage) of each individual cell shall be as specified in Table 1, at a solar-cell temperature of 25°C under AM0 illumination of 1 S.C.

#### 4.5.2 Minimum average electrical performance of electron-irradiated cells

The minimum average current at test voltage shall be as specified in Table 1, at a solar-cell temperature of 25°C under AM0 illumination of 1 S.C. The cells will have been irradiated with 1 MeV electrons at a $\phi_p$ dose **t.b.s.** and exposed to photons according to Paragraphs 7.4.13 and 7.4.14 of ESA PSS-01-604.

#### 4.5.3 Minimum average electrical performance at nominal operating temperature(s)

The minimum average current at test voltage shall be as specified in Table 1, at a cell operational temperature of **t.b.s.** °C under AM0 illumination

of 1 S.C. The cells will have been irradiated with 1 MeV electrons at a $\phi_p$ dose **t.b.s.** and exposed to photons according to Paragraphs 7.4.13 and 7.4.14 of ESA PSS-01-604.

### 4.5.4 Allowed degradations of electrical performance after qualification or verification-of-qualification tests

These shall be as specified in Table 2.

### 4.5.5 Reverse *I/V* characteristics

The reverse *I/V* characteristics shall be recorded up to **t.b.s.** volts at **t.b.s.** temperatures, in darkness and under illumination.

### 4.5.6 Cover conductivity

Cover conductivity before and after qualification tests on solar-cell assemblies of subgroup D in Table I of the generic specification shall be higher than **t.b.s.** and shall not vary by more than $\pm 10\%$ after any of the tests.

*Figure 1 Physical dimensions of uncovered solar cells* - **To be supplied by the Manufacturer (with tolerances)**

*Figure 2 Physical dimensions of solar cell assemblies* - **To be supplied by the Manufacturer (with tolerances)**

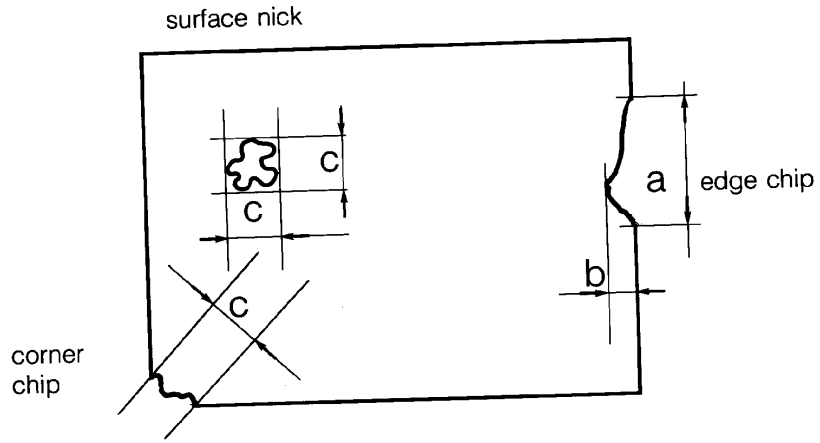


Figure 3 Definition of cell defects

| cell area ($cm^2$) | dimensions of defects (mm) | | |
|---|---|---|---|
| | a | b | c |
| 4 | 4 | 0.7 | 1.5 |
| 8 | 6 | 0.8 | 2 |
| 12 | 8 | 0.9 | 2.5 |
| 25 | 10 | 1 | 4 |

TABLE 1: MINIMUM CURRENT REQUIREMENT FOR SOLAR CELL ASSEMBLIES
(25°C or operating temperature)

| SAMPLE | IRRADIATION DOSE | TEST VOLTAGE $V_t$ (mV) | CURRENT AT $V_t$ (mA) |
|---|---|---|---|
| Minimum for individual solar cell assemblies | B.O.L. | | |
| | E.O.L. | | |
| Minimum average for solar cell assemblies | B.O.L. | | |
| | E.O.L. | | |

E.O.L.: t.b.s. $\phi_p$ 1 MeV electron dose + photons

**NOTE:** Table to be extended if there are several operational voltages and/or E.O.L. **t.b.s.** electron doses, or transfer-orbit doses.

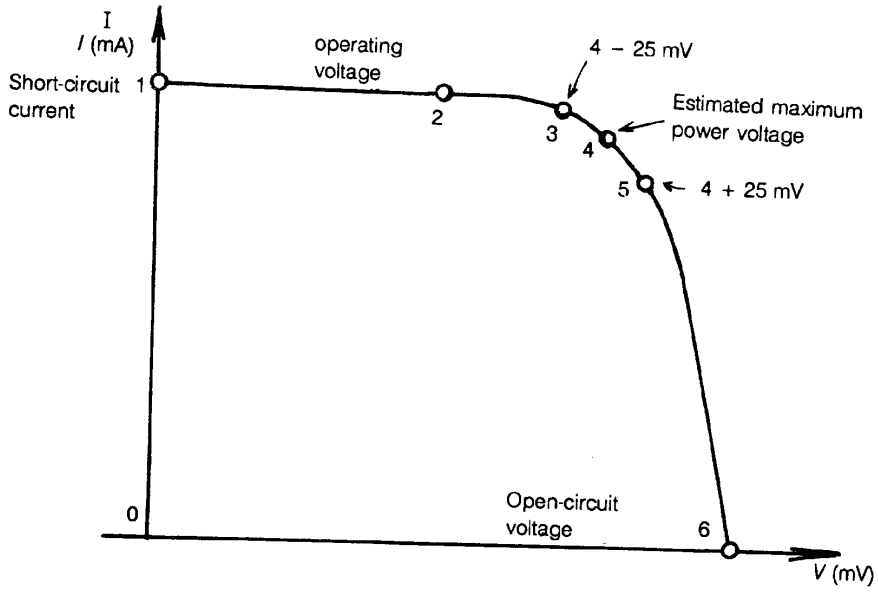


*FIGURE 4 TEST POINTS REQUIRED FOR SOLAR ARRAY DESIGN AND MODELLING*

TABLE 2: ELECTRICAL PERFORMANCE AFTER ENVIRONMENTAL TESTS (25°C)

| MEASUREMENT AFTER | MEASURED PARAMETERS | | MAXIMUM TOLERABLE DEVIATION FROM RESULTS BEFORE TEST |
|---|---|---|---|
| Environmental Test | No. | | |
| Humidity<br>+ thermal cycling<br>+ coating adherence | 7.4.8<br>+ 7.4.7<br>+ 7.4.10 | Current at $V_t$ | 3%* |
| ARC adherence<br>+ thermal cycling<br>+ coating adherence | 7.4.9<br>+ 7.4.7<br>7.4.10 | Current at $V_t$ | 3%* |
| Electron irradiation<br>plus photon irradiation | 7.4.13<br>+ 7.4.14 | Current at $V_t$ | as specified in Table 1 of detail specification. |
| Interconnector adherence | 7.4.11 | Current at $V_t$ | 2%* |

* For each individual cell of the relevant test subject.

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