AIAA S-111A-2014
(Revision of S-111-2005)

# Standard

# Qualification and Quality Requirements for Space Solar Cells

**AIAA S-111A-2014**
**(Revision of AIAA S-111-2005)**

# Standard

# Qualification and Quality Requirements for Space Solar Cells

**Sponsored by**

American Institute of Aeronautics and Astronautics

**Approved**

June 2014

**Abstract**

This standard establishes qualification, characterization, and quality requirements for all solar cells intended for operations in space. It defines terminology and establishes standard tests, environmental conditions, procedures, and systematic methods for verifying the capability of a photovoltaic solar cell device to operate in the environment of space. This standard is intended to be used to establish the minimum level of testing required to demonstrate that a solar cell type will operate in a predictable and understood manner. Success and failure criteria are defined for each qualification test. For the characterization tests, sufficient data is collected to predict electrical performance and behavior as a function of pertinent operational and environmental parameters.

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## Foreword

AIAA Standard S-111-2005, *Qualification and Quality Requirements for Space Solar Panels,* was originally developed to provide a “gold standard” for space solar cell qualification, with provisions included to supplement industry standards for quality.

In this revised version of the standard, effort and care has been taken to update, clarify and resolve controversial provisions that were present in the original. The result is a new standard that the Solar Cells and Solar Panels Committee on Standards has developed and reached consensus that defines the best practices for space solar cell qualification.

At the time of the 2014 revision, the members of the AIAA Solar Cells and Solar Panels CoS were:

| | |
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The above consensus body approved this document for publication in June 2014. The AIAA Standards Executive Council (VP-Standards, Laura McGill, Chairperson) accepted this document for publication in June 2014.

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## Introduction

The purpose for this document is to provide a high level of confidence to the community that a solar cell type is qualified for space applications, and that it is ready for qualification under AIAA-S-112A-2013 *Qualification and Quality Requirements for Electrical Components on Space Solar Panels*.

Bypass diodes, interconnects, covers, and adhesive are not completely qualified by this Standard. Nonetheless, any failure of these components exposed by tests required by this Standard must be reported. In addition, the qualifier must investigate the component failure, determine its cause and take corrective action. The qualifier must also evaluate the component failure with respect to its effect on the cell qualification.

The goal of this document is to standardize testing protocols within the industry that uses, builds, and performs research on space solar cells. The tests included are perceptive to problems seen both in ground testing and on-orbit, and are the first step in including a “test like you fly” protocol in the space solar cell industry. As ground rules for inclusion in this standard, tests had to have been previously documented; experimental tests were disallowed and test equipment had to be available in at least one facility. The order of test execution in this standard was set up to be as close to the sequence of solar cell and panel build, storage, integration and flight as possible.

# 1 Scope

This document establishes qualification and quality requirements for crystalline silicon and gallium arsenide-based single and multiple junction solar cell types for space applications. This includes requirements for solar cell manufacturer quality systems and for characterization of solar cells. Requirements for acceptance testing of lots are not defined in the current version of this document.

Qualification is required when introducing a new solar cell design. Delta qualification is required when making modifications to the materials and processes used to manufacture a qualified cell. If the materials and process changes are limited, these may be considered and evaluated for the scope of a delta qualification. The delta qualification must be based on how the changes might affect the performance and reliability of the cell. The justification for the delta qualification and a detailed description of the changes must be documented per section 11.5, Delta Qualification Report. A change to the lateral dimensions of a qualified cell type does not require delta qualification or re-qualification.

# 2 Tailoring

Unless otherwise specified, this document may not be tailored.

# 3 Applicable Documents

The following documents contain provisions, which, through reference in this text, constitute provisions of this standard. Amendments to, or revisions of, any of these documents do not apply. This standard takes precedence in the event of a conflict between it, the documents cited below, and other documents.

| | |
|---|---|
| ANSI/NCSL Z540.1-1994 | Calibration Laboratories and Measuring and Test Equipment—General Requirements |
| ASTM C1161 | Standard Test Methods for Flexural Strength of Advanced Ceramics at Ambient Temperature |
| ASTM C1239-07 | Standard Practice for Reporting Uniaxial Strength Data and Estimating Weibull Distribution Parameters for Advanced Ceramics |
| ASTM C1683-10 | Standard Practice for Size Scaling of Tensile Strengths Using Weibull Statistics for Advanced Ceramics |
| ASTM E490 | Solar Constant and Zero Air Mass Solar Spectral Irradiance [Notwithstanding the above, the latest version of this document applies.] |
| ASTM E595-93(2003)e2 | Standard Test Method for Total Mass Loss and Collected Volatile Condensable Materials from Outgassing in a Vacuum Environment |
| ASTM E927-10 | Standard Specification for Solar Simulation for Photovoltaic Testing |
| EIA 557 (1995) | Statistical Process Control Systems |
| EIA 625 | Requirements for Handling Electrostatic Discharge Sensitive Devices |
| Jet Propulsion Laboratory Publication 82-69 | Solar Cell Radiation Handbook, Third edition |

| | |
|---|---|
| Jet Propulsion Laboratory Publication 96-9 | GaAs Solar Cell Radiation Handbook and JPL publication 82-69, Solar Cell Radiation Handbook, Third edition |
| MIL-STD-750F | Department of Defense Test Method Standard: Test Methods for Semiconductor Devices |
| Progress in Photovoltaics: Research and Applications, Vol. 9, 2001, pp. 103-121 | Modeling Solar Cell Degradation in Space: A Comparison of the NRL Displacement Damage Dose and the JPL Equivalent Fluence Approaches, S. R. Messenger, et al. |

## 4 Vocabulary

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

**Air Mass Zero (AM0)**
the absence of atmospheric attenuation of the solar irradiance per ASTM E490

**Astronomical Unit (AU)**
the mean distance between the Earth and the Sun, that is, 149,597,890 ± 500 km

**Control limit**
the maximum allowable variation of a process characteristic due to common causes alone

NOTE 1 Variation beyond a control limit may be evidence that special causes are affecting the process.

NOTE 2 Control limits are calculated from process data and are usually represented as a line (or lines) on a control chart.

**Coverglass**
an optically clear component affixed to the active side of a solar cell, typically used to provide radiation shielding and increase emissivity

NOTE A coverglass may have coatings to enhance solar cell performance.

**Coverglass-interconnect-cell assembly (CIC)**
an assembly consisting of a solar cell, interconnect, coverglass, and bypass diode, if present

**Current at the maximum power point (Imp)**
the current a solar cell generates at its maximum power point

**Failure in time (FIT)**
the expected number of component failures per $10^9$ hours

NOTE The FIT rate is a method of specifying component reliability.

**Failure modes and effects analysis (FMEA)**
an analytical technique used as a means to assure that potential failure modes and their associated causes/mechanisms have been considered and addressed

**Interconnect**
a conductive component designed to electrically connect one solar cell to another, or a solar cell to an electrical bus point

**Life-cycle coupon**
a panel sample, built with processes, materials, and components that are flight qualified or proposed for flight qualification

NOTE A coupon consists of a minimum of MSC solar cells and associate components.

**Lot accumulation**
an accumulation of cells that are categorized as a lot for further processing

**Major change**
a change that may affect form, fit, or function of the space-qualified solar cell

**Maximum power point (Pmp)**
the maximum electric power that can be generated by a solar cell, CIC, or string

**Minor change**
a change that will not affect form, fit, or function of the space-qualified solar cell

**MSC**
minimum sample count

**n-factor**
an empirically determined parameter that describes the nonlinear relationship between the energy dependence of the relative damage coefficients (RDCs) and the calculated non-ionizing energy loss (NIEL) for electrons

**Open circuit voltage (Voc)**
the electric potential across the terminals of a solar cell, CIC, or string at zero current

**Short circuit current (Isc)**
the current measured between the terminals of a solar cell, CIC, or string at zero voltage

**Simulated air mass zero**
the output achieved from a solar simulator calibrated to air mass zero (AM0) with a standard, flown at high altitude, of the same type as the solar cell(s) being tested

**Solar cell**
a semiconductor device that produces electric power when illuminated

**Solar cell efficiency**
the percent ratio of the electrical power per unit of total area that a solar cell produces at 28C to one solar constant, which is determined by the latest version of ASTM E490

**Solar cell type**
a set of solar cells so similar in design and construction as to be indistinguishable from each other in terms of nominal power produced per unit area and degradation subsequent to any environmental exposure

NOTE A solar cell type is distinct in that it has a design that consists of a unique combination of epitaxy metallization materials and coatings.

**Solar constant**
the total solar irradiance at normal incidence on a surface in free space at the Earth's mean distance from the Sun (1AU)

**Specification limits**
the requirements for judging acceptability of a particular characteristic as established by this standard

**String**
a number of series-connected solar cells that produces electrical power

**Subcoupon**
a smaller life-cycle coupon

NOTE Several subcoupons may be used in place of a single life-cycle coupon provided the total number of solar cells and associated components are equal to or greater than the MSC.

**Tailoring**
the process by which individual requirements or specifications, standards, and related documents are evaluated and made applicable to a specific program or project by selection, and in some exceptional cases, modification and addition of requirements in the standard.

**Voltage at the maximum power point (Vmp)**
the voltage a solar cell generates at its maximum power point

## 5 Summary of Qualification and Characterization Tests

Table 1 provides a summary of qualification and characterization tests specified under this standard.

Table 1 — Summary of qualification and characterization tests

| Test | Section | Page | Test Article | Minimum Data Requirement |
|---|---|---|---|---|
| Solar Cell Weld or Solder Test | 7.1 | 4 | Top Contact Weld or Solder Samples<br>Bottom Contact Weld or Solder Samples | 484 weld data sets for top and 484 weld data sets for bottom |
| Solar Cell Integration Test | 7.2 | 6 | 2 Coupons/Sets of Subcoupons | MSC CIC data sets per coupon |
| Cell-Level Humidity Test | 7.3 | 7 | Solar Cells | 30 solar cell data sets |
| Electron Radiation Effects | 8.1 | 9 | Solar Cells | 12 solar cell data sets per energy and fluence |
| Proton Radiation Effects | 8.2 | 10 | Solar Cells | 12 solar cell data sets per energy and fluence |
| Bend Test | 8.3 | 12 | Solar Cells | 12 solar cell data sets |
| Mechanical Strength | 8.4 | 12 | Solar Cells | 30 solar cell data sets |
| Light I-V Characterization for Multiple Temperatures | 8.5 | 13 | Solar Cells | 10 solar cell data sets |
| Quantum Efficiency | 8.6 | 13 | Solar Cells | 10 solar cell data sets |
| Dark I-V Characterization | 8.7 | 13 | Solar Cells | 12 solar cell data sets |
| Capacitance Effects | 8.8 | 14 | Solar Cells | 12 solar cell data sets |
| Solar Cell Electrostatic Discharge Sensitivity (ESDS) Test | 8.9 | 14 | Solar Cells | 12 solar cell data sets |
| Accelerated Life Test | 8.10 | 15 | Solar Cells | 22 solar cell data sets |

# 6 Test Requirements

## 6.1 Sample Selection

The coupon/sub-coupon(s) required by section 7, Qualification Tests, and section 8, Characterization Tests, shall be populated using flight quality part types.

Wherever there is a requirement for this Standard, the minimum sample count for certain tests, denoted by MSC in the Standard, defaults to 231. If a non-default MSC is to be required, it must be explicitly specified with the requirement for the Standard, and must be greater than or equal to 116.

Reference this Standard with its default MSC by: AIAA S-111A-2014 Qualification and Quality Requirements for Space Solar Cells.

Reference this Standard with a non-default MSC of for example, 116, by: AIAA S-111A-2014 Qualification and Quality Requirements for Space Solar Cells, with MSC set to 116.

Higher MSCs enable achieving a given reliability for the qualified array and may reduce the power margin for cell or string failure. An MSC greater than 116 does not require tailoring.

It is assumed that the solar cell samples are taken from a population with a binomial distribution. To demonstrate that the qualification tests have a defect rate of less than 1% at a confidence level of 90%, requires a MSC of 231. To demonstrate that the qualification tests have a defect rate of less than 2% at a confidence level of 90% requires a MSC of 116.

Repairs or removals and replacements that are anticipated or that are likely to occur on the flight panel shall be qualified during the course of the testing required herein. At a minimum, 5% of the CICs shall be removed and/or replaced on coupons prior to testing. For CICs, at least one shall be at a string termination and one shall be in the middle of a string.

The solar cell samples must be wired into individual strings for tests. Electrically paralleling of strings is not allowed. This is to increase the ability to find anomalies should they occur. In any event, the test configuration must be such that an open or shorted CIC can be readily identified

## 6.2 Solar Simulation

Where this Standard requires an electrical test of CICs, strings or circuits, the qualifier shall measure output under simulated AM0 irradiance and spectrum as defined by ASTM E927-10, *Standard Specification for Solar Simulation for Photovoltaic Testing,* Class A with the exception of spectral match when testing multi-junction solar cells. For this, the simulator spectrum shall be sufficiently accurate to simultaneously obtain the Isc of each of the sub-solar cell junctions of balloon flown standards (or standards of at least that quality) within +/- 1%, except for multi-junction solar cells having a germanium junction, in which case the simulator shall obtain the Isc of the germanium junction to within +30% -1%.

## 6.3 Electrical Test

Where this standard requires an electrical test, the manufacturer shall measure output under simulated AM0 irradiance and spectrum with a four-wire measurement system

# 7 Qualification Tests

## 7.1 Solar Cell Weld or Solder Test

### 7.1.1 Purpose

The purpose of this test is to demonstrate the ability to attach soldered or welded interconnects to solar cells without significant performance loss.

### 7.1.2 Sample

For this test, a sample is defined as a weld (or solder) joint. A solar cell is used to qualify top contact welds or solder joints and a CIC is used to qualify bottom contact welds or solder joints.

#### 7.1.2.1 Top Contact Weld (or Solder) Samples: Solar Cells

For this test, a sample is defined as an individual weld or solder joint to the top contact of a solar cell. Top contact weld samples shall have flight-like interconnects attached to the sun facing solar cell surfaces with at least 231 weld/solder joints pulled at the conclusion of this test, and at least 22 samples for destructive physical analysis (DPA).

#### 7.1.2.2 Bottom Contact Weld (or Solder) Samples: CICs

For this test, a sample is defined as an individual weld or solder joint to the bottom contact of a CIC. Multiple weld/solder joints may be made on a single CIC, but should be constrained by the principles used to define critical areas for the flight article (e.g. distance from cell edge, not over ink marking, etc.). CICs with a typical flight coverglass attached shall have flight-like interconnects attached to the cell bottom surfaces with at least 231 weld/solder joints pulled at the conclusion of this test, and at least 22 samples for DPA.

### 7.1.3 Procedure

Solar cells may be used with or without bypass diodes. In this section, reverse bias test conditions are set depending on the application of bypass diodes to the solar cells.

#### 7.1.3.1 For All Cells Requiring a Bypass Diode: Establish Test Voltage for Solar Cell Dark Reverse Bias Exposure

The following procedure shall be implemented to establish the test voltage for solar cell dark reverse bias exposure.

a) At less than -165 °C and greater than 110% of the cell's nominal Isc at 28 °C, measure the forward voltage drop of the bypass diode at the first instant of the application of current for 12 welded/soldered diodes or more.

b) Use 110% of the highest forward voltage drop as the solar cell test voltage.

#### 7.1.3.2 For All Cells Not Requiring a Bypass Diode: Establish Test Current for Solar Cell Dark Reverse Bias Exposure

The solar cell test current shall be 110% of the solar cell Isc at 28 °C.

#### 7.1.3.3 Visual Inspection and Electrical Test

##### 7.1.3.3.1 Visual Inspection

The manufacturer shall perform its standard inspection for the basis of acceptance/rejection. In addition the manufacturer shall perform a stereoscopic visual inspection, for clarification only, at 30X magnification under a polarized light source. All cell/CIC discrepancy features including cell anomalies, coverglass and cell cracks, chips, discoloration, and surface contamination shall be mapped. Fail qualification if more than 3% of the cells have cracks propagating from weld or solder sites, or if visual inspection shows a fault related to the parts, materials or processing of the solar cell.

##### 7.1.3.3.2 Electrical Test

An illuminated I-V test shall be performed on each solar cell using simulated AM0 irradiance and spectrum. The cell shall be measured at 28 ±1 °C, and data corrected to 28 °C. Fail qualification if average Pmp degrades more than 2% of the initial average Pmp, or any cell degrades greater than 3% at Pmp.

#### 7.1.3.4 Weld (or Solder) Interconnect

The flight interconnect shall be welded or soldered to the top contacts of the solar cells and to the bottom contacts of the CICs using documented processes that are flight qualified or proposed for flight qualification.

#### 7.1.3.5 Visual Inspection and Electrical Test After Interconnection

Visually inspect and electrically test samples per section 7.1.3.3.

#### 7.1.3.6 Dark Reverse Bias Exposure

Solar cells/CICs shall be temperature controlled to 28 ±1 °C. Samples shall be tested in the following manner.

a) Apply test voltage or test current found in section 7.1.3 to a completely darkened solar cell at 28 °C for ambient temperature for 10 minutes.

b) Repeat procedure at 120 °C.

c) Repeat three times.

#### 7.1.3.7 Visual Inspection and Electrical Test After Dark Reverse Bias Exposure

Visually inspect and electrically test samples per section 7.1.3.3.

#### 7.1.3.8 Pull Test

Select at least 462 top contact weld samples and at least 462 bottom contact weld samples. Perform a pull test on 231 welds at 0 ±10 degrees and a pull test 231 welds at 45 ±10 degrees on both the top and bottom contacts. Record pull strength, failure mode, and percentage of metal peeled on the interconnect and the cell. Repeat for all samples.

The manufacturer shall determine the minimum acceptable pull strengths from a statistical analysis of the pull strengths for each weld type in accordance with the following. The minimum pull strength shall be three standard deviations from the corresponding average pull strength. Fail qualification if the minimum pull strength is less than 300 g. The manufacturer shall consider pull strengths outside of three standard deviations as an out of control condition, which it shall investigate for cause and solution. The manufacturer shall document the out of control condition along with its cause and solution.

#### 7.1.3.9 Destructive Physical Analysis

Using at least 22 top contact weld samples and at least 22 bottom contact weld samples, perform acoustic imaging and cross section analysis to illustrate joint quality. Perform an evaluation of these joints and photograph for documentation of weld solder quality.

### 7.1.4 Reporting Requirements

Report all data, observations, and conclusions. Report data for each electrical test in tabular form. Report pull test data in tabular form. Report test voltage or test current for solar cell dark reverse bias exposure. Summarize all visual inspections. Include test setup block diagram(s) and test setup photograph(s), top and bottom contact acoustic images, and cross-section photomicrographs in the report.

## 7.2 Solar Cell Integration Test

### 7.2.1 Purpose

The purpose of this test is to qualify parts, materials, and processes for flight and to verify that electrically active cells shall survive in a simulated space environment.

### 7.2.2 Sample: Coupon/Subcoupons Requirements

Section 7.2.2.3, Combined Effects Exposure, requires that the qualifier illuminate with AM0 irradiance and spectrum during the hot side of the thermal cycling. The illuminated item shall be a single subcoupon containing the maximum number of solar cells that will fill a uniformly illuminated area of at least 500 square centimeters.

The coupon/subcoupon(s) for the life cycle tests with humidity exposure shall be populated with a MSC of solar cells plus expected attrition. If possible, build the coupon/subcoupon(s) with electrical strings configured to produce flight voltages. Excepting the illuminated subcoupon, the subcoupons shall have a minimum of 18 solar cells. The solar cell samples must be wired into individual strings for this. Electrically paralleling of strings is not allowed even if that is the flight configuration. This is to increase the ability to find anomalies should they occur. In any event, the test configuration must be such that an open or shorted solar cell can be readily identified.

#### 7.2.2.1 Visual Inspection and Electrical Test

##### 7.2.2.1.1 Visual Inspection

The manufacturer shall perform a minimum 10X inspection for acceptance/rejection. All cell/CIC discrepancies including visual anomalies, coverglass and cell cracks, chips, discoloration, and surface contamination shall be mapped. Fail qualification if more than 3% of a coupon or subcoupon cells have cracks propagating from weld or solder sites, or if visual inspection shows a fault related to the parts, materials or processing of the solar cell or bypass diode.

##### 7.2.2.1.2 Electrical Test

An illuminated I-V test shall be performed on each string using simulated AM0 irradiance and spectrum. This shall be done at two temperatures. The string shall be measured at 23 ±5 °C, and data corrected to 28 °C. The string shall also be measured at 80 ±5 °C, and data corrected to 80 °C. Fail qualification if after any functional test the maximum power (Pmp) of any string degrades more than 2% of the initial measurement at ambient test temperature (ATT) based on the extrapolation to 28 °C; or more than 3% of the initial measurement at hot test temperature (HTT) provided the degradation is due to the solar cell, bypass diode, or interconnection joint to the solar cell or bypass diode.

#### 7.2.2.2 Prepare Coupon for Combined Effects Test: Thermal Vacuum Bakeout

Heat coupon to 80 °C for a minimum of 24 hours in a vacuum of $10^{-5}$ Torr or less. Perform 8 thermal vacuum cycles under $10^{-5}$ Torr or less to the temperature ranges specified in the first paragraph of section 7.2.2.3.1. Subject the coupon to the visual inspection and electrical test defined in section 7.2.2.1.

#### 7.2.2.3 Combined Effects Exposures

For the tests specified in sections 7.2.2.3.1 and 7.2.2.3.2, minimize thermal gradients across each coupon.

##### 7.2.2.3.1 Cold Extreme Test Phase

Cycle the coupon or all the subcoupons so that the measured temperature in the cold portion of the cycle is lower than –175 °C -10 °C/+0 °C, the cold test temperature (CTT) and the measured temperature in the hot portion of the cycle is higher than 95 °C +10 °C/-0 °C, the hot test temperature (HTT) for 2,000 cycles. The measured temperature shall be as defined in section 7.2.2.3.3.

At the hot and cold extremes for cycles 100, 1,000, and 2,000, perform the following: in-situ characterize the bypass diode circuits on the coupon or all subcoupons to validate that they are working properly. After these characterizations, remove the coupons from the chamber and subject them to the visual inspection and electrical tests defined in section 7.2.2.1. After the inspection and test regimen, place the coupon/subcoupons in the chamber and resume thermal cycling. Additional test break points may be added for visual and electrical tests.

From the start of the heated portion of each and every cycle and for its duration, illuminate the required one or optionally several solar cell coupon/sub-coupon(s) with simulated AM0, loading such that the solar cells in the string(s). nominally operate at 95% of their maximum power point voltage determined at the highest test temperature Dark forward bias the remainder of the sub-coupon(s) to follow the current profile obtained from the illuminated coupon, multiple chambers may be used. Continue this forward-bias current level until at least 10 °C below the HTT. During the cooling portion of the thermal cycles, monitor the continuity of the solar cell circuits with a forward-bias current of a minimum of 10% of nominal cell Isc at ambient temperature. Monitor the circuit voltages throughout the cycles to detect any changes, which could indicate intermittent or other faults in the circuit. If a solar cell circuit demonstrates a change that would result in its inability to perform nominally, assess to determine if the non-nominal condition warrants qualification failure. Fail qualification if the monitoring shows a fault related to the parts, materials, or processing of the solar cell or if the solar cell circuit opens, shunts, or suffers a significant resistance change.

This test and several of the tests below require that a current be passed through components during the cooled portion of each thermal cycle. If these currents prevent the coupon/sub-coupon(s) from reaching CTT in an acceptable time, the qualifier may substitute lower currents to mitigate the unwanted heating.

Perform the following test every 25 cycles. Douse the illumination. Temporarily suspend the solar cell circuit dark-forward bias and forward bias the bypass diode circuits on all coupons at the highest predicted operating current during the heating portion and through the HTT portion of each cycle. Continue this forward-bias current level until at least 10 °C below the HTT. Monitor the circuit voltages throughout the cycles to detect any changes, which could indicate intermittent or other faults in the circuit. During the cooling portion of the thermal cycles, monitor the continuity of the bypass diode circuits with a forward-bias current of a minimum of 10% of nominal cell Isc at ambient temperature. If a bypass diode circuit demonstrates a change that would result in its inability to perform nominally, assess to determine if the non-nominal condition warrants qualification failure. Fail qualification if the monitoring shows a fault related to the parts, materials, or processing of the bypass diode or if the bypass diode circuit opens, shunts, or suffers a significant resistance change that might cause solar cell failure.

**7.2.2.3.2 Hot Extreme Test Phase**

Then cycle the coupon or all the subcoupons so that the measured temperature in the cold portion of the cycle is lower than -95 °C -10 °C/+0 °C and the measured temperature in the hot portion of the cycle is higher than 140 °C +10 °C/-0 °C for 20,000 cycles. The measured temperature shall be as defined in section 7.2.2.3.2.

At the hot and cold extremes for cycles 100, 5,000, 10,000 and 20,000 for this phase, perform the following: in-situ characterize the bypass diode circuits on the coupon or all subcoupons to validate that they are working properly. After these characterizations, remove the coupons from the chamber and subject them to the visual inspection and electrical tests defined in section 7.2.2.1. After the inspection and test regimen, place the coupon/subcoupons in the chamber and resume thermal cycling. Additional test break points may be added for visual and electrical tests.

From the start of the heated portion of each and every cycle and for its duration, illuminate the required one or optionally several solar cell coupon/sub-coupon(s) with equivalent AM0 irradiance and spectrum, loading such that the solar cells in the string(s) nominally operate at 95% of their maximum power point voltage determined at the highest test temperature. Dark forward bias the remainder of the sub-coupon(s) to follow the current profile obtained from the illuminated coupon, multiple chambers may be used. Continue this forward-bias current level until at least 10 °C below the HTT. During the cooling portion of the thermal cycles, monitor the continuity of the solar cell circuits with a forward-bias current of a minimum of 10% of nominal cell Isc at ambient temperature. Monitor the circuit voltages throughout the cycles to detect any changes, which could indicate intermittent or other faults in the circuit. If a solar cell circuit demonstrates a change that would result in its inability to perform nominally, assess to determine if the non-nominal condition warrants qualification failure. Fail qualification if the monitoring shows a fault related to the parts, materials, or processing of the solar cell or if the solar cell circuit opens, shunts, or suffers a significant resistance change.

This test and several of the tests below require that a current be passed through components during the cooled portion of each thermal cycle. If these currents prevent the coupon/sub-coupon(s) from reaching CTT in an acceptable time, the qualifier may substitute lower currents to mitigate the unwanted heating.

Perform the following test every 25 cycles. Douse the illumination. Temporarily suspend the solar cell circuit dark-forward bias and forward bias the bypass diode circuits on all coupons at the highest predicted operating current during the heating portion and through the HTT portion of each cycle. Continue this forward-bias current level until at least 10 °C below the HTT. Monitor the circuit voltages throughout the cycles to detect any changes, which could indicate intermittent or other faults in the circuit. During the cooling portion of the thermal cycles, monitor the continuity of the bypass diode circuits with a forward-bias current of a minimum of 10% of nominal cell Isc at ambient temperature. If a bypass diode circuit demonstrates a change that would result in its inability to perform nominally, assess to determine if the non-nominal condition warrants qualification failure. Fail qualification if the monitoring shows a fault related to the parts, materials, or processing of the bypass diode or if the bypass diode circuit opens, shunts, or suffers a significant resistance change that might cause solar cell failure.

#### 7.2.2.3.3 Temperature Sensors

The qualifier shall use a minimum of five (5) temperature sensors to measure the test temperatures on each coupon or sub-coupon. The five sensors are to be on the solar cell side of the panel. Alternatively the temperature sensors may be mounted through the back touching the rear of the front facesheet behind a solar cell. Temperature sensors are to be placed near each of the four (4) corners and at the center of the panel. It is preferred and advisable, if space permits, to have redundant, backup temperature sensors co-located with each of the primary five temperature sensors. The average measurement of all properly functioning temperature sensors shall satisfy HTT +10 °C/-0 °C and CTT -10 °C/+0 °C. More than 20% defective or inaccurate temperature sensors shall require that an environmental exposure be interrupted for the purpose of repairing or replacing the problematic sensors. The temperature rate of change for all temperature sensors shall be monitored and is required to be less than 100 °C per minute when measured at a data rate less than or equal to a two (2) second period.

### 7.2.3 Reporting Requirements

Report all data, observations, and conclusions. Report data for each electrical test and bypass diode characterization in tabular form. Summarize all visual inspections. Include test and illumination setup, calibration data, test setup photographs, and life cycle coupon photographs. Report the thermal cycling temperature profile data and the thermal cycling electrical loading profile data.

## 7.3 Cell-Level Humidity Test

### 7.3.1 Purpose

The purpose of this test is to qualify the parts, materials, and processes to be used in manufacturing solar cells by confirming antireflective (AR) coating and metallization integrity on solar cells under adverse storage conditions found between solar cell fabrication and CIC assembly.

### 7.3.2 Sample: Solar Cells

The solar cell sample shall be sufficient in quantity to yield, with attrition, at least 30 complete data sets. Each solar cell shall have an area of at least 20 $cm^2$.

### 7.3.3 Procedure

#### 7.3.3.1 Visual Inspection and Electrical Test

##### 7.3.3.1.1 Visual Inspection

The manufacturer shall perform a minimum 10X inspection for acceptance/rejection. All cell/CIC discrepancies including visual anomalies, coverglass and cell cracks, chips, discoloration, and surface contamination shall be mapped. Fail qualification if more than 3% of a coupon or subcoupon cells have cracks propagating from weld or solder sites, or if visual inspection shows a fault related to the parts, materials or processing of the solar cell or bypass diode.

##### 7.3.3.1.2 Electrical Test

An illuminated I-V test shall be performed on each solar cell using simulated AM0 irradiance and spectrum. The cell shall be measured at 28 ±1 °C, and data corrected to 28 °C. Fail qualification if average Pmp degrades more than 2% of the initial average Pmp, or any cell degrades greater than 3% at Pmp.

#### 7.3.3.2 Humidity Exposure

The humidity exposure shall last 60 days at 95 ±5% relative humidity at 45 °C.

#### 7.3.3.3 Visual Inspection and Electrical Test After Humidity Exposure

Perform visual inspection and electrical test per section 7.3.3.1. Fail qualification if visual inspection shows a fault related to the parts, materials or processing of the solar cells.

#### 7.3.3.4 AR Coating Adhesion/Top Contact Integrity Test

Using half of the solar cell population, apply an adhesive tape (3M type 600 or similar) having a minimum pull-off strength of 490 g/cm to the AR coating and metallization on the front side of the cell so as to cover the whole surface. Peel off the tape at a 90 degree angle to the cell surface.

##### 7.3.3.4.1 Visual Inspection

Perform visual inspection per section 7.3.3.1.1. Fail qualification if more than 5% accumulated area of the AR coating of any solar cell is removed by the tape, or if delamination of the top contact exceeds 10% of the metallization.

#### 7.3.3.5 Bottom Contact Integrity Test

Using half of the solar cell population, apply an adhesive tape (3M type 600 or similar) having a minimum pull-off strength of 490 g/cm to the bottom contact metallization of the cell to cover the whole surface. Peel off the tape at a 90 degree angle to the cell surface.

##### 7.3.3.5.1 Visual Inspection

Perform visual inspection per section 7.3.3.1.1. Fail qualification if delamination of the bottom contact metallization exceeds 10%.

### 7.3.4 Reporting Requirements

Report all data, observations, and conclusions. Report data for each electrical test in tabular form. Summarize all visual inspections. Include the percentage peel for each sample in tabular form for the AR coating test and metal contact integrity tests. Include test setup block diagrams and photographs in the report. Report temperature and humidity profiles for the test.

# 8 Characterization Tests

## 8.1 Electron Radiation Effects

### 8.1.1 Purpose

The purpose of this test is to generate a set of parameters that relate the electrical degradation produced by irradiation by different electron energies to a single, characteristic damage curve. This can be accomplished using two methods. The first is to generate a set of relative damage coefficients (RDCs) according to the “Equivalent Fluence” approach developed by the NASA Jet Propulsion Laboratory (JPL)/California Institute of Technology. This method relates the damage produced by differing electron energies to an equivalent fluence of 1 MeV electrons. The Solar Cell Radiation Handbook (Tada and Carter, 1982) provides a description of this methodology. The second method relies on the “Displacement Damage Dose (DDD)” approach developed by the U.S. Naval Research Laboratory (NRL) and relates the damage produced by differing electron energies to an equivalent 1 MeV electron DDD. This method is referenced in “Modeling Solar Cell Degradation in Space: A comparison of the NRL Displacement Damage Dose and the JPL Equivalent Fluence Approaches” (Messenger et al., 2001). A parameter required in the DDD approach is the electron nonionizing energy loss (NIEL), which can be obtained in tabular form from Jun (2003) and from Summers (1993). The qualifier shall have the choice to use either or both methods for this characterization.

### 8.1.2 Sample: Solar Cells

The solar cell sample shall be sufficient in quantity to yield, with attrition, at least 12 complete data sets for each energy/fluence. Each solar cell shall have an area of at least 4 $cm^2$.

### 8.1.3 Procedure

#### 8.1.3.1 Electrical Test

An illuminated I-V test shall be performed on each solar cell using simulated AM0 irradiance and spectrum. The cell shall be measured at 28 ±1 °C, and data corrected to 28 °C.

#### 8.1.3.2 Electron Radiation Exposure

To produce a set of RDCs referenced to 1 MeV electron degradation in the Equivalent Fluence methodology, degradation due to 1 MeV electron exposure must be measured. To determine the energy dependence of the RDCs, measurements using at least two electron energies, in addition to 1 MeV, shall be performed. The energies shall be chosen to fall within 0.5 and 5 MeV. The degradation data shall contain at least five fluence points to ensure a smooth degradation curve when plotted as a function of the log of the fluence. The fluence range shall be chosen so that the lowest fluence causes approximately 5% degradation of the solar cell maximum power output. The highest fluence shall be at least $1 \times 10^{16}$ 1 MeV electrons per square centimeter. Table 2 gives suggested values for other energies and fluences.

In the Displacement Damage Dose methodology, only one electron energy in addition to 1 MeV is required. Electron energies of 1 and ≥ 2 MeV are suggested for the DDD method.

Post-irradiation cells may be annealed at 60 °C for up to 24 hours per the solar cell manufacturer’s recommendation. The electron radiation shall be conducted at room temperature. The beam currents shall be sufficiently low to prevent significant sample heating. The fluence shall be measured using a calibrated Faraday cup for dosimetry and if desired, supplemented by other methods. The dosimetry shall be accurate to at least ±10%.

Table 2 — Electron energies and fluences*

| Energies (MeV) | Fluences (number of electrons per square centimeter) | | | | | |
|---|---|---|---|---|---|---|
| .6 | $2x10^{13}$ | $2x10^{14}$ | $1x10^{15}$ | $2x10^{15}$ | $4x10^{15}$ | |
| 1.0 | $3x10^{13}$ | $1x10^{14}$ | $5x10^{14}$ | $1x10^{15}$ | $3x10^{15}$ | $1x10^{16}$ |
| 5.0 | $4x10^{12}$ | $1x10^{13}$ | $4x10^{13}$ | $1x10^{14}$ | $4x10^{14}$ | |

*These energies and fluences are recommended except for the fluence of ≥ 1 x $10^{16}$ 1 MeV electrons, which is required.

#### 8.1.3.3 Electrical Test after Radiation

Perform electrical test per Section 8.1.3.1.

#### 8.1.3.4 Dark Reverse Bias Exposure

Apply test voltage or test current found in section 7.1.3.1 or section 7.1.3.2 to a completely darkened solar cell at ambient temperature for 10s after exposure to each fluence.

#### 8.1.3.5 Electrical Test After Reverse Bias

Perform electrical test per section 8.1.3.1.

### 8.1.4 Reporting Requirements

Report data for each electrical test in tabular form. The data shall include the full I-V curve. Plot percentage degradation as a function of fluence for Isc, Voc, Pmp, Vmp and Imp on a semi-log scale in graphical form for each energy. Include test setup block diagrams and photographs in the report. Depending on which methodology is chosen in these tests, the report shall be written as described below.

For the Equivalent Fluence approach, relative damage coefficients for 1 MeV electrons shall be calculated and reported at 90% degradation of Voc, Vmp, Imp and Isc and at 80% for Pmp in accordance with *Jet Propulsion Laboratory publication 96-9, GaAs Solar Cell Radiation Handbook* and *JPL publication 82-69, Solar Cell Radiation Handbook, Third edition*. The qualifier shall maintain the data to compute the RDCs at degradations other than those specified for more refined computation of degradation for specific missions.

For the Displacement Damage Dose approach, the 1 MeV electron equivalent displacement damage dose shall be calculated and reported, as outlined in "Modeling Solar Cell Degradation in Space: A Comparison of the NRL Displacement Damage Dose and the JPL Equivalent Fluence Approaches" and Messenger, S.R., Jackson, E.M., Warner, J.H. and Walters, R.J., "SCREAM: A New Code for Solar Cell Degradation Prediction Using the Displacement Damage Dose Approach," Proc. 35th IEEE Photovoltaic Specialists Conference, pp. 1106-1111, 2010 (the exponent in equation 9 should be n not n-1; see Bibliography). The electron energy dependence shall also be plotted including the n- factor dependence with the calculated NIEL for Voc, Isc, Vmp, Imp and Pmp.

## 8.2 Proton Radiation Effects

### 8.2.1 Purpose

The purpose of this test is to generate a set of parameters that relate the electrical degradation produced by irradiation by different proton energies to a single, characteristic damage curve. This can be accomplished using two methods. The first is to generate a set of relative damage coefficients (RDCs) according to the “Equivalent Fluence” approach used by JPL. This method relates the damage produced by differing proton energies to an equivalent fluence of a given energetic fully penetrating proton. The energy of the fully penetrating proton shall be determined depending on the cell technology of interest. Typically, for III-V based cell technologies, this energy can be chosen to be in the range of 1 to 3 MeV. However, silicon cell technologies typically require 10 MeV protons. The second method relies on the "Displacement Damage Dose (DDD)" approach developed by the U.S. Naval Research Laboratory (NRL) and relates the damage produced by differing proton energies to an equivalent proton DDD. "Modeling Solar Cell Degradation in Space: A Comparison of the NRL Displacement Damage Dose and the JPL Equivalent Fluence Approaches" gives an overview and comparison of these two approaches. An important parameter required in the DDD approach is NIEL. This quantity can be obtained from Jun (see Bibliography). The qualifier shall have the choice to use either or both methods for this characterization.

### 8.2.2 Sample: Solar cells

The solar cell sample shall be sufficient in quantity to yield, with attrition, at least 12 complete data sets for each energy/fluence. Each solar cell shall have an area of at least 4 $cm^2$.

### 8.2.3 Procedure

#### 8.2.3.1 Electrical Test

An illuminated I-V test shall be performed on each solar cell using simulated AM0 irradiance and spectrum. The cell shall be measured at 28 ±1 °C, and data corrected to 28 °C.

#### 8.2.3.2 Proton Radiation Exposure

To produce a set of RDCs referenced to a suitable proton energy, required to be fully penetrating, it is necessary to expose the unshielded solar cell to that proton energy and measure the cell degradation. It is suggested to perform this test using protons with 1-3 MeV as the reference energy. The degradation data shall contain at least five fluence points to ensure a smooth degradation curve when plotted as a function of the log of the fluence. The fluence range shall be chosen so that the lowest fluence causes approximately 5% degradation of the solar cell maximum power output. The highest fluence shall be large enough to cause at least 40% degradation. For most III-V based solar cells, this can be accomplished using 3 MeV protons to a maximum fluence of 1 x $10^{13}$ $p^+cm^2$; lower proton energies allow lower fluence levels. To determine the energy dependence of the RDCs, measurements using at least five proton energies, in addition to the reference proton energy, shall be performed. The energies shall be chosen to fall between 0.02 and 3 MeV. Table 3 gives suggested values of energies and fluences. In the event the required fluences set by this table do not serve this purpose for the solar cell family being qualified, more appropriate energies and fluences may be substituted.

In the Displacement Damage Dose methodology, only one proton energy is required to determine the characteristic degradation curve properties. However another proton energy is suggested for confirmation. It is also suggested that proton energies between 1.0 and 3 MeV be selected when using the DDD approach.

Post-irradiation cells may be annealed at 60 °C for up to 24 hours per solar cell manufacturer's recommendation. The solar cell manufacturer shall ensure that proton radiation is performed at room temperature in a vacuum of 1 x $10^{-5}$ Torr or less. The solar cell manufacturer shall ensure that beam currents are sufficiently low to prevent significant sample heating. The fluence shall be measured using a validated Faraday cup for dosimetry and if desired, supplemented by other methods. The dosimetry shall be accurate to at least ±10%.

Table 3 — Suggested proton energies

| Energies (keV) | Fluences (number of protons per square centimeter) | | | | |
|---|---|---|---|---|---|
| 20 | $3x10^{9}$ | $5x10^{9}$ | $1x10^{10}$ | $3x10^{10}$ | $1x10^{11}$ |
| 50 | $3x10^{9}$ | $5x10^{9}$ | $1x10^{10}$ | $3x10^{10}$ | $1x10^{11}$ |
| 100 | $5x10^{9}$ | $1x10^{10}$ | $5x10^{10}$ | $1x10^{11}$ | $3x10^{11}$ |
| 300 | $3x10^{9}$ | $1x10^{10}$ | $3x10^{10}$ | $5x10^{10}$ | $1x10^{11}$ |
| 1,000 | $5 x10^{10}$ | $2x10^{11}$ | $5x10^{11}$ | $2x10^{12}$ | $5x10^{12}$ |
| 3,000 | $1x10^{11}$ | $4x10^{11}$ | $1x10^{12}$ | $4x10^{12}$ | $1x10^{13}$ |

#### 8.2.3.3 Electrical Test After Radiation

Perform electrical test per section 8.2.3.1.

#### 8.2.3.4 Dark Reverse Bias Exposure

Apply test voltage or test current found in section 7.1.3.1 or 7.1.3.2 to a completely darkened solar cell at ambient temperature for 10s after each fluence.

#### 8.2.3.5 Electrical Test After Reverse Bias

Perform electrical test per section 8.2.3.1.

### 8.2.4 Reporting Requirements

Report data for each electrical test in tabular form. The data shall include the full I-V curve. Plot percentage degradation as a function of fluence for Isc, Voc, Pmp, Vmp and Imp on a semilog scale in graphical form for each energy. Include test setup block diagrams and photographs in the report. The proton damage equivalency ratio shall be calculated and reported in terms of the reference energy chosen. Depending on which methodology is chosen in these tests, the report shall be written as described below.

For the Equivalent Fluence approach, the reference proton energy damage equivalency ratio to the highest energy protons tested shall be calculated and reported. The relative damage coefficients shall also be calculated and reported with respect to the proton reference energy chosen in accordance with the Jet Propulsion Laboratory publication 96-9, GaAs Solar Cell Radiation Handbook and JPL publication 82-69, Solar Cell Radiation Handbook, Third edition.

For the Displacement Damage Dose approach, the proton displacement damage dose shall be calculated and reported as outlined in "Modeling Solar Cell Degradation in Space: A comparison of the NRL Displacement Damage Dose and the JPL Equivalent Fluence Approaches" (see Bibliography). The proton energy dependence also be plotted including the dependence with the calculated NIEL.

## 8.3 Bend Test

### 8.3.1 Purpose

The purpose of this test is to characterize minimum bend radius for a solar cell type.

### 8.3.2 Sample: Solar Cells

The solar cell sample shall be sufficient in quantity to yield, with attrition, at least 12 complete data sets. Each solar cell shall have an area of at least 20 $cm^2$.

#### 8.3.3 Procedure

##### 8.3.3.1 Initial Bend Test

Measure bend radius by bending solar cells around cylinder with a 1,500 mm radius under uniform pressure. Bend cell with the epitaxy pointed away from the foci of the bend and with the gridlines parallel to the axis of the cylinder for no less than 10 s.

##### 8.3.3.2 Visual Inspection

The manufacturer shall perform a minimum 10X inspection for acceptance/rejection. All cell discrepancies including visual anomalies, cell cracks, chips, discoloration, and surface contamination shall be mapped.

##### 8.3.3.3 Multiple Radii Bend Test

Repeat the multiple radius bend test around cylinders of decreasing radii under uniform pressure until first fracture. Bend cell with the epitaxy pointed away from the foci of the bend and with the gridlines parallel to the axis of the cylinder for no less than 10 s.

#### 8.3.4 Reporting Requirements

Report bend radii at which the tests were run and the bend radius at first substrate or epitaxial fracture for each solar cell sample. Include test setup block diagrams and photographs in the report. Report dimensions of solar cell used in test.

### 8.4 Breaking Load Determination

#### 8.4.1 Purpose

The purpose of this test is to characterize, qualitatively, a solar cell type's susceptibility to breaking.

#### 8.4.2 Sample: Solar cells

The solar cell sample shall be sufficient in quantity to yield, with attrition, at least 30 complete data sets. Each solar cell shall be at least 50-mm long and at most 40-mm wide.

#### 8.4.3 Procedure

Determine the flexural strength for the solar cells (without coverglass) using, with the modifications below, ASTM C1161 *Standard Test Methods for Flexural Strength of Advanced Ceramics at Ambient Temperature*. Perform the test on the required 30 solar cells within a single working day. If testing more than one set of samples and more than one working day is required, the samples should be randomly selected from all batches over the entire testing period.

Use a fully articulated ASTM C1161 B-size four-point bend fixture with the following modifications. The fixture shall consist of approximately 50 mm long loading cylinders to prevent sample overhang. This can be achieved by outfitting an existing ASTM C1161 B-size fixture with longer rollers or fabricating a wider fixture that can accommodate longer rollers. When fitting the longer rollers, the springs that hold the rollers in place must be of equal length and tension so that the rollers rest flat. Ensure that the springs do not exert excessive forces on the rollers to allow full articulation and to prevent the rollers from bending. The sample surface in contact with the outer span rollers shall be placed in tension, while the surface in contact with the inner span rollers shall be in compression. The maximum uniform stress shall be centered across the tensile surface contained within the 20-mm inner span.

The load cell and data acquisition system shall have a resolution of at least of 0.1 N.

Conduct the test at 23.5 ± 5 °C and at a humidity of 50% ±10%. Record the nominal size of the solar cells. Do not make any physical measurements on the solar cell that could cause the slightest damage to its edges. Use clean plastic tweezers when handling the solar cells and avoid contact near the central 20 mm of the samples. Load the solar cell with the top side in tension until the cell fractures. Record the thickness of the cell to ±0.01 mm subsequent to the cracking. The flexural strength of the solar cells is inversely related to the square of its thickness.

Compute the flexural strength, $\sigma_f$, in Pascals, of each sample in accordance with equation (1), where P is the applied load in Newtons, L is the outer support span of the test fixture in meters, w is the width of the solar cell in meters, and t is the thickness of the solar cell in meters.

$$\sigma_f = \frac{3PL}{4wt^2} \quad (1)$$

Use ASTM C1239-07 *Standard Practice for Reporting Uniaxial Strength Data and Estimating Weibull Distribution Parameters for Advanced Ceramics* to determine the Weibull modulus and characteristic strength from the raw fracture data.

Only the central 20 mm of the test specimen (i.e., tensile surface contained within the 20-mm inner span) is under the maximum tensile stress. Accordingly, scale each of the raw flexural strengths to determine the strength of the entire specimen, $\sigma_{specimen}$. Use equation (2) to perform the required scaling with reference to ASTM C1683-10, *Standard Practice for Size Scaling of Tensile Strengths Using Weibull Statistics for Advanced Ceramics*.

$$\frac{\sigma_{spectrum}}{\sigma_{test}} = \left(\frac{k \times Area_{test}}{Area_{spectrum}}\right)^{1/\beta} \quad (2a)$$

$$\frac{\sigma_{spectrum}}{\sigma_{test}} = \left(\frac{k \times Volume_{test}}{Volume_{spectrum}}\right)^{1/\beta} \quad (2b)$$

where *k* is the load factor accounting for the stress distribution for four-point bending with quarter point span. Specifically, *k* is given by

$$k = \frac{\beta + 2}{4(\beta + 1)^2} \quad (3)$$

where $\beta$ is the Weibull Scale Parameter as defined in ASTM C1239-07. Equation 2a accounts for flaws with a surface distribution, and equation 2b accounts for flaws with a volume distribution.

#### 8.4.4 8.4.4 Reporting Requirements

Report the average, standard deviation, maximum, and minimum strengths, scaled strengths, and dimensions of the solar cell samples. Report the Weibull characteristic strength and modulus for each of the samples. Include test setup block diagrams and photographs in the report.

## 8.5 Light I-V Characterization for Multiple Temperatures

### 8.5.1 Purpose

The purpose of this test is to characterize solar cell output as a function of temperature.

#### 8.5.2 Sample: Solar cells

The solar cell sample shall be sufficient in quantity to yield, with attrition, at least 10 complete data sets. Each solar cell shall have an area of at least 4 $cm^2$.

#### 8.5.3 Procedure

Measure Isc, Voc, Vmp, Imp, Pmp and the entire I-V curve between -150 °C and 150 °C in 20 °C increments on cells with no fluence, and after 1 MeV electron fluences of 1 x $10^{14}$, 1 x $10^{15}$, and 1 x $10^{16}$.

#### 8.5.4 Reporting Requirements

Report data for each electrical test in tabular form. Plot Isc, Voc, Pmp, Vmp, and Imp as a function of temperature in graphical form for each fluence. Include test setup block diagrams and photographs in the report. Report minimum average I-V curves for each fluence and temperature in tabular form.

### 8.6 Quantum Efficiency

#### 8.6.1 Purpose

The purpose of this test is to characterize the quantum efficiency of the solar cells.

#### 8.6.2 Sample: Solar cells

The solar cell sample shall be sufficient in quantity to yield, with attrition, at least 10 complete data sets. Each solar cell shall have an area of at least 4 $cm^2$.

#### 8.6.3 Procedure

##### 8.6.3.1 Electrical Test

An illuminated I-V test shall be performed on each solar cell using simulated AM0 irradiance and spectrum. The cell shall be measured at 28 ±1 °C, and data corrected to 28 °C.

##### 8.6.3.2 Quantum Efficiency Data

Perform spectral response measurements from 250 to 2,000 nm at 10 nm increments or better, after 1 MeV electron radiation at fluences of 0, 1 x $10^{14}$, 5 x $10^{14}$, 1 x $10^{15}$, and 1 x $10^{16}$. Convert spectral response measurements to quantum efficiency.

##### 8.6.3.3 Electrical Test After Quantum Efficiency Measurement

Perform electrical test per section 8.6.3.1.

#### 8.6.4 Reporting Requirements

Report data for each electrical test shall be in tabular form. Plot quantum efficiency in graphical form as a function of wavelength for each radiation exposure. Include test setup block diagrams and photographs in the report.

### 8.7 Dark I-V Characterization

#### 8.7.1 Purpose

The purpose of this test is to develop a characteristic dark I-V curve of the solar cell.

#### 8.7.2 Sample: Solar Cells

The solar cell sample, which shall include a bypass diode, shall be sufficient in quantity to yield, with attrition, at least 12 complete data sets. Each solar cell shall have an area of at least 20 $cm^2$.

### 8.7.3 Procedure

Using a four-wire measurement system, provide an I-V curve between 110% Isc to -Isc at 28 °C.

### 8.7.4 Reporting Requirements

Report electrical data in both tabular and graphical form. Include test setup block diagrams and photographs in the report.

## 8.8 Capacitance Effects

### 8.8.1 Purpose

The purpose of this test is to characterize the capacitance of the solar cell.

NOTE Knowing solar cell capacitance allows designers to make the spacecraft power control subsystem compatible with the solar array.

### 8.8.2 Sample: Solar Cells

The solar cell sample shall be sufficient in quantity to yield, with attrition, at least 12 complete data sets. Each solar cell shall have an area of at least 20 $cm^2$.

### 8.8.3 Procedure

Characterize solar cell capacitance at room temperature from 10 Hz to 1.5 MHz under simulated AM0 irradiance and spectrum at Vmp and Voc.

### 8.8.4 Reporting Requirements

Report impedance data in both tabular and graphical form as a function of frequency. Include test setup block diagrams and photographs in the report.

## 8.9 Solar Cell Electrostatic Discharge Sensitivity (ESDS) Test

### 8.9.1 Purpose

Characterize the ESDS threshold for the solar cell type.

### 8.9.2 Sample: Solar cells

The solar cell sample shall be sufficient in quantity to yield, with attrition, at least 12 complete data sets. Each solar cell shall have an area of at least 20 $cm^2$.

### 8.9.3 Procedure

Use test method 1020.2 of MILSTD-750, except using a start voltage of 5,000 V. Initiate the test at voltage steps of 1,000V until solar cell failure or 16,000V is attained. Individual solar cell failure is defined as greater than 3% power degradation at Pmp.

### 8.9.4 Reporting Requirements

ESD failure threshold voltage and ESDS class designator per MIL-STD-750 shall be reported for each sample in tabular form. The cell that exhibits the lowest class designator determines the ESD sensitivity of the cell type. Test setup block diagrams and photographs shall be included in the report.

## 8.10 Accelerated Life Test

### 8.10.1 Purpose

The purpose of this test is to develop reliability estimates by characterizing the Mean Time to First Failure (MTTFF), and the Failure in time (FIT) rates of solar cells at 50 °C, 80 °C and 110 °C. A failure is defined as any degradation in on orbit solar cell performance beyond what has been predicted. The failure mechanism is the root cause for the failure

### 8.10.2 Sample: Solar Cells

The solar cell sample shall be sufficient in quantity to yield, with attrition, at least 22 complete data sets. Each solar cell shall have an area of at least 20 $cm^2$.

### 8.10.3 Procedure

Examine all possible solar cell failure modes. This is to be done through a Failure Mode and Effects Analysis (FMEA). An accelerated life test may be done for any of the potential failure mechanisms listed in the FMEA. An accelerated life test must be done in accordance with section 8.10.1.

Solar cell manufacturer shall develop and execute an accelerated life test.

### 8.10.4 Reporting Requirements

Report the FMEA and the rationale behind the choice of accelerated life test(s).Report the calculated MTTFF and FIT rates of solar cells at 50 °C, 80 °C, and 110 °C Include test setup block diagrams and photographs in the report.

# 9 Quality Requirements

The solar cell manufacturer shall comply with ISO 9001 or equivalent.

## 9.1 Performance

The solar cell manufacturer shall demonstrate that parts delivered to this standard are equivalent to those which pass the tests and inspections in section 7.

## 9.2 Solar Cell Reliability

The solar cell manufacturer shall establish the reliability of solar cells produced to this standard, and baseline the methods used for calculating reliability relating to MTTFF, and FIT rates. The solar cell manufacturer shall maintain an ongoing reliability assessment program to ensure the consistent reliability of their solar cells.

### 9.2.1 Failure Modes and Effects Analysis (FMEA)

The solar cell manufacturer shall perform an FMEA for solar cells to be produced under this standard. The FMEA shall identify and address potential failure modes and their causes. The FMEA shall contain a table of potential failures by their likelihood against the severity of their consequences, and from this identify failure modes for corrective measures.

### 9.2.2 Ongoing Reliability Program

The solar cell manufacturer shall maintain an ongoing reliability program. The program shall allow feedback to generate continuous improvement. In this regard, the manufacturer shall constantly evaluate production lines and ensure their stability. The ongoing reliability program shall include the following:

a) formal, routine, reliability testing of each manufacturing process;

b) the ability to tie solar cell failure to manufacturing processes;

c) the integration of the solar cell FMEAs into the reliability program;

d) testing of cells after exposure to key environments at a specified frequency;

e) the tracking of failures to manufacturing process(es);

f) the recording of solar cell failures, their type, root cause, corrective action and responsible manufacturing process.

## 9.3 Certification of Conformance

When solar cells qualified in this document are delivered, a Certificate of Conformance shall document the following:

a) solar cell manufacturer's name and address;

b) customer's name, address and contract number;

c) solar cell type and performance specification sheet number;

d) lot identification codes (including assembly plant code);

e) conformance inspection acceptance date;

f) quantity of solar cells in shipment from solar cell manufacturer;

g) statement certifying product conformance and traceability; and

h) quality assurance manager's signature and date of transaction.

## 9.4 Lot Identification and Traceability

Solar cells delivered to this standard shall be traceable to the applicable manufacturing processes, tools, raw materials, and fabrication dates through the use of build paper, lot codes, and serialization or solar cell manufacturer certification. Specifically, solar cells shall have lot control from wafer processing through screening which provides wafer lot identification; operation (machine), date of operation, operator identification, and quantity; and serial numbers of devices processed.

## 9.5 Test Equipment Maintenance and Calibration System

The solar cell manufacturer shall establish maintenance and calibration systems and the frequency of scheduled actions for gauges and test equipment. The solar cell manufacturer shall use ANSI/NCSL Z540-1-1994 or equivalent as a guideline.

## 9.6 Incoming, In-process, and Outgoing Inventory Control

The solar cell manufacturer shall use procedures to control storage and handling of incoming materials, work in-process, warehoused and outgoing product in order to: (a) achieve such factors as age control of limited-life materials; and (b) prevent inadvertent mixing of conforming and nonconforming materials, work in-process, finished product, resubmitted lots, or customer returns.

## 9.7 Process Control

The solar cell manufacturer shall ensure that manufacturing is carried out as specified. The manufacturer shall monitor and control production processes and solar cell characteristics. Where necessary, due to the complexity or sensitivity of operations, the manufacturer shall consider working environment, workmanship criteria, equipment set-up, and the need for special operator certification or continuous monitoring of critical parameters.

### 9.7.1 Statistical Process Control (SPC)

Where SPC is used to control processes within manufacturing, the methodology shall use EIA-557 as a guide. If a process exhibits an out of control condition, appropriate cause and corrective action shall be undertaken and documented. The solar cell manufacturer shall determine which out-of-control signals to use based on factors such as process capability, control limit proximity to specification limits, false alarm rates, etc. Hardware produced outside the specification limits (not be confused with control limits), shall be considered nonconforming and shall require appropriate disposition.

### 9.7.2 Technology Process Flow Chart

The solar cell manufacturer shall generate a production flow chart for the solar cell type. The flow chart shall diagrammatically depict the sequence of processing steps for the solar cell from material and part receipt to final shipment of the cells.

## 9.8 Environmental Controls

The solar cell manufacturer shall specify, control, and monitor the relative humidity, temperature, and particle count for each critical process step (e.g., wafer fabrication, assembly). The manufacturer shall document the procedures and techniques for measuring these environmental parameters and limits. The manufacturer's procedures shall contain corrective actions for out-of-tolerance environmental conditions. The manufacturer shall handle unsealed parts in such a way as to minimize the introduction of foreign material.

## 9.9 Conformance of Production Solar Cells to Qualified Product

### 9.9.1 Certification of Space-qualified Facilities

The customer shall verify that the solar cell manufacturer's facilities are adequate to produce solar cells to this standard. The verification and certification shall occur no more than once every two years.

### 9.9.2 Validation of Solar Cells Qualified for Space

The quality level for solar cells intended for space applications, and any test samples developed to space-qualify those solar cells under this standard, shall meet the quality requirements specified herein. To validate that solar cells claimed to be qualified under this method are identical to the originally qualified solar cells, the customer, or the customer's representative, reserves the right, with notice, to audit all documentation including, but not limited to, process travelers and test data for compliance with parts, materials, and processes that are qualified under this standard.

The solar cell manufacturer's proprietary documentation shall be reviewed at a facility of the manufacturer's choice.

### 9.9.3 Audit Schedules and Frequencies

Absent serious problems, the customer may conduct audits no more than once per year to ensure that production cells are equivalent to cells qualified under this standard.

## 9.10 Electrostatic Discharge Sensitivity Program

The manufacturer of ESDS class 1 and 2 solar cells shall institute an ESDS program commensurate with the classification. The requirements of EIA-625 apply, but may be tailored for establishing an ESDS program. On customer request, justification for the tailoring shall be made available to the customer for approval.

## 9.11 Reworked Solar Cells

Reworked or repaired product shall be re-inspected in accordance with written procedures. Reworked product shall be documented and traceable. Rework is subject to customer review.

## 9.12 Design Construction and Process Change Control Procedures

Subsequent to solar cell qualification, the manufacturer shall document all changes to design, parts, materials, and processes. The manufacturer shall also document the reasons for changes and shall classify each change as major or minor. The manufacturer shall evaluate the impact of changes against the design, parts, materials, processes and configuration of the cell as it was originally qualified and report the impact. The manufacturer shall document any re-qualification, including but not limited to, delta qualification and proto-qualification.

Upon request, the manufacturer shall provide the above information or “pedigree” to any customer prior to the purchase of cells. Any changes described by the pedigree are to be reported to, and approved by, the customer prior to manufacturing readiness review.

If changes are required during production of cells for a specific customer, the manufacturer shall report minor changes to the customer and shall obtain customer approval, prior to implementation, for major changes.

# 10 Critical Materials

## 10.1 Scope

This information shall identify materials that have proven to be problematic in the space environment or that pose safety hazard.

## 10.2 Requirements

a) For solar cells qualified to this standard, a unique identification is required for each type.

b) Pure tin, cadmium, and zinc shall not be present in finished, space-qualified solar cells. Pure tin refers to a tin alloy with less than three atomic percent of an alloying metal, e.g., lead. Pure cadmium and zinc is defined as these metals used or applied in a non-mixed metal or unalloyed state.

c) The solar cell shall contain materials with less than 1.0% total mass loss and less than 0.1% collected volatile condensable materials, as determined by the procedures of Standard Test Method for Total Mass Loss and Collected Volatile Condensable Materials from Out Gassing in a Vacuum Environment, ASTM E595, unless approved by the customer.

d) Solar cells containing Beryllium Oxide shall be clearly identified with the designation BeO.

# 11 Reporting Requirements

## 11.1 Reports to be Produced

Three products shall be delivered from this requirement: a qualification report, a characterization report, and a quality report. The reporting format is described in sections 11.2 and 11.3.

## 11.2 Qualification Report

Qualification report tests are required by section 7. The qualification report shall be organized in the following manner.

a) Title: The title shall reflect the name of solar cell type; its minimum average power output per unit area, where the area is the total area of the cell including contacts.

   The solar cell type efficiency shall be reported in accordance with the definition of solar cell efficiency in section 4. The version of ASTM E490 used for this computation shall be recorded along with the ASTM E490 determination of the solar constant.

b) Solar cell type description and features: Report the drawings and specifications to which test articles were fabricated.

c) Summary of qualification tests: Indicate whether the solar cell type passed or failed qualification on the first try. If the type did not pass the qualification initially, specify the changes that enabled it to pass.

d) Qualification test results: Qualification test results shall be reported in the following order.

    1) Solar Cell Weld or Solder Test (section 7.1.4)

    2) Solar Cell Integration Test (section 7.2.3)

    3) Cell-level Humidity Test (section 7.3.4)

## 11.3 Characterization Report

Characterization tests are required by section 8. The characterization report shall be organized in the following manner.

a) Title: The title shall reflect the name of the solar cell type and its minimum average power output per unit area, where the area is the total area of the cell including contacts.

b) Solar cell type description and features.

c) Characterization test results: Characterization test results shall be reported in the following order.

    1) Electron Radiation Effects (section 8.1.4)

    2) Proton Radiation Effects (section 8.2.4)

    3) Bend Test (section 8.3.4)

    4) Mechanical Strength (section 8.4.4)

    5) I-V Characteristics for Multiple Temperatures and Temperature Coefficients (section 8.5.4)

    6) Quantum Efficiency (section 8.6.4)

    7) Dark I-V Characterization (section 8.7.4)

    8) Capacitance Effects (section 8.8.4)

    9) Electrostatic Discharge Sensitivity Test (section 8.9.4)

    10) Accelerated Life Test (section 8.10.4)

## 11.4 Quality Report

Quality requirements are found in section 9. The quality report shall be organized in the following manner.

a) Title: The title shall reflect the name of the solar cell type and its minimum average power output per unit area, where the area is the total area of the cell including contacts.

b) Solar cell type description and features.

c) Quality requirements: quality documents shall be arranged in the following order.

    1) Reserved

    2) Report on FMEA (section 9.2.1)

    3) Certificate of Conformance (section 9.3)

4) Flow Chart (section 9.7.2)

## 11.5 Delta Qualification Report

Prepare report in accordance with the requirements of section 1, Scope.

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