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Space systems — Space solar cells — Electron and proton irradiation test methods

Systèmes spatiaux — Cellules solaires spatiales — Méthodes d'essai d'irradiation d'électrons et de protons

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Foreword

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The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular the different approval criteria needed for the different types of ISO documents should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2 (see www.iso.org/directives).

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

This second edition cancels and replaces the first edition (ISO 23038:2006), which has been technically revised. The main changes compared to the previous edition are as follows:

— radiation environment models were updated from AE8/AP8 to AE9/AP9;

— threshold energies for atomic displacement for silicon and GaAs were deleted;

— a statement was added that, whatever the method, the duration or intensity level of the electron and proton irradiation test is considered a "destructive test".

Space systems — Space solar cells — Electron and proton irradiation test methods

1 Scope

This document specifies the requirements for electron and proton irradiation test methods of space solar cells. It addresses only test methods for performing electron and proton irradiation of space solar cells and not the method for data analysis.

2 Normative references

There are no normative references in this document.

3 Terms and definitions

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

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

— IEC Electropedia: available at http://www.electropedia.org/

— ISO Online browsing platform: available at http://www.iso.org/obp

NOTE Physical constants are given to four significant figures only and reflect current knowledge.

3.1
differential energy spectrum
spread of energies of some specific group

Note 1 to entry: In this document, this refers to the number of particles possessing an energy value that lies in the infinitesimal range E, $E + dE$ divided by the size of the range (dE). Integration of the differential particle spectrum over all particle energies yields the total number of particles. This quantity is given in units of particles per unit area per unit energy.

3.2
electron
e^-
elementary particle of rest mass m = 9,109 kg × 10^{-31} kg, having a negative charge of 1,602 C × 10^{-19} C

3.3
flux
number of particles passing through a given area in a specified time

Note 1 to entry: Flux may also be specified in terms of the number of particles per unit time passing through a unit area from source directions occupying a unit solid angle. Typical units are particles per cm^2 per second per steradian (sr) (1 sr is the solid angle subtended at the centre of a unit sphere by a unit area of the surface of the sphere).

3.4
fluence
total number of particles in any given time period given in units of particles per unit area

Note 1 to entry: Fluence is also known as time-integrated flux.

3.5
integral energy spectrum
total number of particles in a specified group that possess energies greater than, or equal to, a specified value, given in units of particles per unit area

3.6
irradiation
exposure of a substance to energetic particles that penetrate the material and have the potential to transfer energy to the material

3.7
omnidirectional flux
number of particles of a particular type which have an isotropic distribution over 4π steradians and that would traverse a test sphere of 1 cm^2 cross-sectional area in 1 s

Note 1 to entry: Expressed in units of particles per cm^2 per second.

3.8
proton
p^+
positively charged particle of mass number one, having a mass of 1,672 kg × 10^{-27} kg and a charge equal in magnitude but of opposite sign to the electron

Note 1 to entry: A proton is the nucleus of a hydrogen atom.

4 Symbols and abbreviated terms

eV electronvolt

NIEL nonionizing energy loss

NOTE 1 eV, is a unit of energy commonly used for ions, electrons, elementary particles, etc. (1 eV ≈ 1,602 J × 10^{-19} J.)

NOTE 2 The rate at which the incident particle transfers energy to the crystal lattice through nonionizing events is referred to as the nonionizing energy loss (NIEL), typical unit is MeV · cm^2 · g^{-1}.

5 Space radiation environments

5.1 Space radiation

Primarily, electrons and protons with a wide range of energies characterize the space radiation environment (see References [1] and [2]). Gamma rays can be used as a substitute for electron irradiation with the proper transformation. Some reasonable electron and proton fluence limits usually attained in typical earth orbit conditions are given below. For 1 MeV electrons and 10 MeV protons, these typical but not inclusive fluence limits are 10^{15} and 10^{13} particles per cm^2, respectively. Alpha particles and other charged particles are usually of negligible quantity as far as solar cell damage is concerned. The particles come from the solar wind and are trapped by Earth's magnetic field to form radiation belts with widely varying intensities. Solar wind is usually associated with particles of low energy (typically below 100 keV), while particles of concern for solar cells are generally of higher energies. The inner portion of the belts consists mainly of protons and of an inner electron belt, while the outer portion consists primarily of electrons. Outside of these radiation belts, there is a likelihood of sudden bursts of protons and electrons originating from coronal mass ejections from the Sun, referred to generally as solar flares. Thus, the differential spectrum of electrons and protons for any given mission is dependent on the specific mission orbit. Due to the large variability of the involved phenomena, the prediction of the particle spectrum for a given mission is affected by a significant uncertainty. Widely accepted tools for its calculation include the AP9 (protons) and AE9 (electrons) codes for the trapped particles, while the solar proton events are modelled with other tools such as the JPL 91 code. Note that there is also complementary information in Reference [3]. The definitions of the various particle radiation spectra can be obtained using freely available resources such as the Space Environment Information System (www.spenvis.oma.be).

5.2 Shielding effects

Space solar cells are typically flown with some material covering the cell surface, usually a piece of glass (coverglass), and are mounted on some support structure. These front and rear covering materials act to shield the solar cell from some of the incident irradiation. Because of this, the solar cell in space is actually irradiated by a modified particle spectrum, usually referred to as a slowed down spectrum. An example showing such a slowed down spectrum calculation can be found in References [4] and [5]. Shielding materials may themselves be sensitive to radiation (see 6.2).

The response of the cell to particle radiation is typically tested on unshielded cells. This enables the radiation analysis conducted on the bare solar cell to be made applicable to all combinations of shielding that might be used at solar array level. In practical terms, it also avoids potential complication of the analysis due to broadening by the shielding materials of a nominally monoenergetic particle beam, which can be significant.

6 General radiation effects in solar cells

6.1 Solar-cell radiation damage

Solar cells, like all semiconductor devices, are subject to electrical degradation when exposed to particle irradiation. In terms of radiation damage to solar cells used in space, the primary particles of interest are electrons and protons. When these energetic particles are incident upon the solar cell material, they collide with the atoms of the crystal lattice of the solar cell. In these atomic collisions, energy is transferred from the incident particle to the target atom. This energy can be transferred in several ways. The majority of the energy is transferred through ionization of the target atom, where electrons of the target atom absorb the transferred energy and are promoted to higher energy levels. Another energy transfer mechanism is through nonionizing events, which results in the displacement of the target atom. If enough energy is transferred in a nonionizing event, then the displaced target atom may, in turn, displace other atoms, creating a cascade of displaced atoms. The displacement damage induced by the nonionizing interactions is the primary cause of most solar cell degradation.

When an atom is displaced in a lattice, the electron energy band structure of the material is disturbed, and localized energy levels can be created near the site of the defect. These defect energy levels can act to trap electrical charge carriers, thus restricting their ability to move through the material, which is characterized by a reduction in the minority carrier diffusion length. Since solar cell operation depends on the motion of photogenerated charge carriers through the material, these defect sites tend to degrade the solar cell performance.

The amount of displacement damage caused by an incident particle is a function of the type of incident particle (i.e. electron or proton), the particle energy, and the composition of the crystal lattice. The rate at which the incident particle transfers energy to the crystal lattice through nonionizing events is referred to as the nonionizing energy loss (NIEL). Electrons become more damaging as the incident electron energy increases. The opposite is true for protons, where the lower energy protons are the most damaging. Also, protons are significantly more damaging in comparison to electrons, primarily due to the increased proton differential scattering cross section for atomic displacements. There is a lower limit to displacement damage corresponding to the threshold energy for atomic displacements. This threshold energy is dependent on the semiconductor material that constitutes the solar cell.

6.2 Radiation effects on solar cell cover materials

Although not specifically a solar cell radiation effect, it is appropriate in this document to note the effects of irradiation on solar cell coverglass materials and the adhesives which are typically used to attach them. Certain solar cell coverglass material has been shown to darken under ultraviolet or particle irradiation thereby absorbing some of the incident light[6]. This increased light absorption can reduce the solar cell output in one of two ways: (1) reduction of the amount of light that reaches the cell, and (2) increase in operating temperature of array that reduces the cell electrical conversion efficiency. Whereas crystalline solar cells are typically degraded by atomic displacement damage, coverglasses are typically more sensitive to ionization effects[1]. The "absorbed doses" associated with the radiation environment of a particular mission can be calculated and then simulated by laboratory testing.

Testing cells with attached coverglass or different geometries require special care (see References [1] and [2]).

7 Radiation test methods

7.1 General

As described in Clause 5, the space radiation environment consists of an omnidirectional spectrum of particle energies, and as described in this clause, solar cell radiation damage is energy dependent. The behaviour of solar cells in the real space environment, can nevertheless be calculated from test data acquired under unidirectional, normal incidence, monoenergetic beam conditions on uncovered solar cells. Characteristic parametric damage curves are determined for different particle energies using an unidirectional beam at normal incidence. The determination of the characteristic curve can be achieved currently in two ways described by the methodologies developed, respectively, at the California Institute of Technology/Jet Propulsion Laboratories and the Naval Research Laboratory[1][2][7][8].

While it is beyond the scope of this document to discuss these data analysis methods, it is important that the method to be used for a specific experiment is well understood prior to performing any radiation testing. In particular, for the case of series-connected multi-junction solar cells including the commonly used "triple-junction" GaAs -based solar cells, it is important to understand whether one junction will limit the overall cell current for the whole mission lifetime. The top junction or another junction could become current limiting, in which case the radiation response shall also be characterized in this damage regime. Similarly, it should be noted that this document is written to give guidelines on how to perform radiation testing on a space solar cell independent of the device technology. Differing cell technologies may exhibit differing radiation response characteristics that need to be understood in order to perform a meaningful test.

On the basis of understanding of "slowed down particle spectra" arriving at the surface of a solar cell for satellite missions in earth orbit and practical limitations associated with the availability of test facilities, the recommended energy range for proton irradiations has historically been from 20 keV to 10 MeV. Damage comparisons have historically been performed with 10 MeV protons and 1 MeV electrons[1][2]. However, in practice, it is more convenient to perform ground tests using proton energies below the threshold for nuclear interactions (around 3 MeV in GaAs). Samples irradiated with higher proton energies become radioactive and usually cannot be transported for a period of several weeks or months for safety reasons. The recommended energy range for electron irradiations is 200 keV to 3 MeV. In special cases, lower energies may be desirable. Hereby, care shall be taken that the lowest energy chosen is still higher than the threshold energy for atomic displacements. Threshold energies for atomic displacement are experimentally determined quantities using such techniques as electron spin resonance (ESR) and deep level transient spectroscopy (DLTS). It may also be convenient in some cases to perform particle transport calculations before performing the irradiations. These calculations can indicate how far the incident irradiation particle will travel within the solar cell before it stops. For example, silicon solar cells have an active region on the order of 100 µm. Therefore, the irradiating particle shall have sufficient energy to deposit uniform damage throughout the region. Using a lower energy particle may result in nonuniform damage, which will greatly complicate the data analysis. Therefore, it is often necessary to perform the particle transport calculation to determine the particle energy required to reach this distance. Several such codes are available to perform these calculations. For proton transport calculations, the Monte Carlo code SRIM[9] is freely available. For electron irradiation, available options include CASINO[10] MCNPX[11] and GEANT4[12].

7.2 Electron irradiation

7.2.1 Vacuum

Electron irradiation may be performed under vacuum or in air. Scattering of the electrons in air results in an energy distribution that is highly dependent on the incident energy and the path length of air travelled by the electrons. Though vacuum may be preferred in order to minimize scattering, it should be noted that for electrons the mean free path in air can be acceptably long provided the user is aware of potential sources of error arising from scattering in nonvacuum electron beam environments. Monte Carlo transport studies have been performed to quantify electron energy loss through air[13].

7.2.2 Temperature

Since by its nature, particle irradiation can heat the sample and since heating the sample can affect the nature and extent of the radiation-induced damage, the irradiation temperature shall be maintained at a known temperature. This is typically achieved in two ways (1) limiting the particle flux and (2) mounting the samples on a temperature-controlled plate.

The exact temperature of the irradiation and accuracy of the temperature measurement should be determined with respect to the specific technology under test. To maintain consistency with most ground testing of space solar cells, irradiations are typically performed at room temperature. If there is a possibility of a temperature rise during irradiation, the tested samples shall be kept at a temperature below 40 °C during the test, unless specified otherwise for a special situation. Sample temperature shall be monitored by a thermocouple or similar device. After the irradiation, the test sample shall be stored at a temperature at or below irradiation temperature until they have been electrically measured.

If this is not practically possible, then the applicability of the results may be affected; care shall be taken to ensure that the results are not invalidated by annealing of the radiation induced degradation prior to measurement.

7.2.3 Coverage area

Electron accelerators typically produce particle beams with a circular cross sectional area. To expose samples of larger area or to expose more samples in a single irradiation, it may be desirable to increase the cross sectional area. One typical method for expanding the exposure area is to pass the particle beam through a thin foil that scatters the beam. When implementing a scattering foil, care shall be taken to ensure that the proper particle energy and beam uniformity is incident on the target. Beam uniformity is discussed in 7.2.4. Concerning the beam energy, the particles will lose energy as they pass through the foil. The amount of energy lost is dependent on the foil material, the foil thickness, the incident particle type, and the incident particle energy. The standard method is to use foils consisting of a single element, like aluminium (Al) or copper (Cu), so that energy loss can be quantified. Materials with complex internal structures, like composite graphite materials, are to be specifically avoided as their effect on the particle energy is difficult to quantify. As a practical example, Monte-Carlo simulations[13] show that a monoenergetic 1 MeV electron, transported through a 0,127 mm thick aluminium foil, will be transformed into an electron spectrum having a peak energy about 50 keV lower. Reference [13] gives some guidance on how to properly account for such effects. An alternative method for increasing the exposure area is to mount the samples on a rotating or translating stage that periodically moves the samples through the beam. When implementing this technique, care shall be taken to adjust the irradiation time to account for the duty cycle of the moving stage, since each sample will be exposed only for a fraction of the irradiation time. This is achieved by calculating a constant scale factor based on the geometry and velocity of the mounting stage. Because accelerator beam fluxes can vary significantly over short time periods, large errors in flux and fluence can result without a continuous direct measurement method. This is especially true in the case of irradiating cells on a moving stage. Therefore, special care should be taken in such cases to allow continuous monitoring of the electron beam flux, and integrating it over time to calculate fluence. For example, a Faraday cup co-located on the radiation plate can eliminate the need for a time scale factor. Such a Faraday cup can also be used to modify the velocity of the moving plate to adjust for nonuniform beam current.

A third method of achieving beam uniformity over a large area is beam rastering. This technique uses either magnetic or electrostatic deflectors to uniformly sweep the beam over the irradiation area. Care shall be taken to set the deflection frequencies so that the beam sweeps through many cycles. This is probably the best method to achieve a very uniform beam, but there is the danger of extremely high momentary flux densities and high localized heating over small areas.

7.2.4 Irradiation beam uniformity

To ensure uniform exposure of the solar cell to the electron irradiation beam, care shall be taken to ensure that the electron intensity is uniform over the entire area of the beam. Specification on the acceptable uniformity can be dependent on the specific technology/cell variant under test. However, experience has shown that <10 % uniformity is both acceptable and reasonably achievable for valid radiation testing. It is desirable to obtain beam flux and energy profiles from the accelerator facility before each test. Dosimetry measurements shall be performed with sufficient frequency to ensure beam stability and repeatability (ideally, using an *in situ* measurement but as a minimum before each sequence of experiments).

7.2.5 Flux levels

Most electron accelerators can operate over a wide range of fluxes. The flux is adjusted to obtain the desired total fluence in a desired amount of time. However, care shall be taken since the incident electron beam can cause an increase in the temperature of the solar cell under test. As discussed in 7.2.2, the temperature of the solar cells during irradiation should be measured. The typical range for electron flux is 10^9 – 10^{12} electrons per cm^2 per second. It should also be noted that for certain technologies, the magnitude of the flux may affect the amount of degradation observed due to dose rate effects. This is, again, a technology specific issue. To date, no flux dependent effects have been reported in triple-junction III-V based solar cells[14].

7.2.6 Dosimetry

The fluence for electrons is typically measured using a Faraday Cup connected to a current integrator. Integrated current accommodates beam current fluctuations. The Faraday Cup shall be designed to suppress electron backscattering. This is typically achieved through grounding the external casing of the cup and by designing the cup geometry to maximize recapture of scattered electrons.

For accurate dosimetry, it is recommended that some secondary dosimetry method be employed for each irradiation. The use of “control” samples, which have a known radiation response to a particular particle and/or beam facility, is one method to validate Faraday Cup measurements. Another secondary dosimetry method is to use dosimetric films, from which the amount of discoloration due to an ionizing irradiation dose can be quantified with a known dosimetric film standard. Care shall be taken in order to ensure that dosimetry methods based on ionizing effects provide reliable beam calibration for experiments on solar cells, which are typically sensitive to displacement effects[13]. Uncertainties in beam fluence should be quoted by the beam facility. Uncertainties in beam fluence on the order of 10 % to 20 % are usually achievable.

7.2.7 Other practical test considerations

Regardless the conditions (particle, energy, dose rate, fluence, etc.), radiation test is destructive. Samples shall be flight representative. In order to facilitate the use of an increased number of samples within a limited beam area, it may be desirable to use samples of reduced dimensions. If so, then the equivalence (in terms of radiation response) of the smaller samples to the flight samples should be established by test.

The population of test samples should also reflect any requirements regarding performance distribution or batch level reproducibility. Regardless of the precautions taken to ensure that any radiation experiment is correctly implemented, further confidence can always be provided by acquisition of test data from more than one radiation facility and solar cell measurement facility. In particular, note that when the impact of the all electron and proton energies is calculated relative to the impact of one reference energy then any error in the "characteristic degradation curves" of the solar cell parameters at the reference energy would directly impact the analysis of the cell degradation at all energies.

7.3 Proton irradiation

7.3.1 General

All of the points from the 7.2 also apply to proton irradiation, except as stated in 7.3.2 and 7.3.3.

7.3.2 Vacuum

Because protons experience significant scattering in air, low energy proton (<10 MeV) irradiations shall preferably be done in vacuum in the pressure range of 10^{-3} Pa or lower.

7.3.3 Coverage area

Since low energy proton irradiation shall be performed in vacuum (see 7.3.2), this puts more constraints on the material used as scattering foils. If the beam coverage area is to be enlarged using scattering foils as discussed in 7.2.3, then the foil material shall be chosen so that it can be made thin (to lessen the proton energy loss), but strong so it can withstand vacuum and handling. The foil material shall also have a high heat conductivity and a high melting point in order to withstand the high currents produced by the proton irradiation. The thickness uniformity of the foil material is also important, as significant variations in thickness across a foil have been observed, which can significantly impact the proton beam emerging from the foil.

The beam rastering method described in 7.3.2 can also be used for protons. Again, there is the danger of extremely high momentary flux densities and high localized heating over small areas. However, it has been shown that these conditions do not affect the test results according to the experimental results[14].

7.4 Post irradiation annealing phenomena

It should be noted that accelerated tests that can be performed in a laboratory are, by their nature, an imperfect simulation of the space environment, and the degree to which they are representative depends upon the technology under test. The applicability of annealing phenomena is one specific example. It is understood that defects created by particle irradiation may subsequently be annihilated because of processes which depend upon the temperature of the material and, in addition, energy released during electron-hole recombination events as a result of current injection. Silicon solar cells have been observed to anneal over time at room temperature after irradiation. It was found that the cell electrical output stabilized after a 24 hour, 60 °C anneal, so such a post-irradiation annealing stage was historically adopted as the standard protocol for Si solar cells. However, triple-junction solar cells based on III-V technology seem less susceptible to thermal annealing and show only slightly sensitivity to injection annealing at current levels representative of space operation in earth orbit without optical concentration[14]. For other technologies such as $CuInGaSe_2$ based solar cells, the rates of formation and annihilation of defects may be similar to one another and therefore difficult to simulate in a ground test without careful implementation and subsequently interpretation of the results[15][16]. Issues such as these should therefore be researched and understood on a technology specific basis and with consideration to the application.

8 Test report guidelines

The radiation test report shall normally include the following information:

a) a title (e.g. test report specifying the nature of the samples under test, with document reference, prepared according to the requirements of this document);

b) tested date;