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

1 Scope

This International Standard 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 Terms and definitions

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

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

2.1
differential energy spectrum
spread of energies of some specific group

NOTE 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.

2.2
electron
e⁻
elementary particle of rest mass m = 9,109 × 10^{-31} kg, having a negative charge of 1,602 × 10^{-19} C

2.3
flux
number of particles passing through a given area in a specified time

NOTE 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).

2.4
fluence
total number of particles per unit area in any given time period

NOTE Fluence is also known as time-integrated flux.

2.5
integral energy spectrum
total number of particles per unit area in a specified group that possess energies greater than, or equal to, a specified value

2.6
irradiation
exposure of a substance to energetic particles that penetrate the material and have the potential to transfer energy to the material

2.7
non-ionizing energy loss
NIEL
rate at which the incident particle transfers energy to the crystal lattice through non-ionizing events

NOTE Typical unit is $\text{MeV} \cdot \text{cm}^{-2} \cdot \text{g}^{-1}$.

2.8
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 Expressed in units of particles per cm^2 per second.

2.9
proton
p^+
positively charged particle of mass number one, having a mass of $1{,}672 \times 10^{-27}$ kg and a charge equal in magnitude but of opposite sign to that of the electron

NOTE A proton is the nucleus of a hydrogen atom.

3 Symbols and abbreviated terms

eV electronvolt

NOTE A unit of energy commonly used for ions, electrons, elementary particles, etc. (1 eV $\approx 1{,}602 \times 10^{-19}$ J.)

4 Space radiation environments

4.1 Space radiation

Primarily electrons and protons with a wide range of energies characterize the space radiation environment. 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 space 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 the Earth's magnetic field to form radiation belts with widely varying intensities [1]. Solar wind is usually associated with particles of low energy (typically below 100 keV), whereas the 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, whereas 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. Owing to the large variability of the involved phenomena, the prediction of the particle spectrum for a given mission is affected by a significant uncertainty. The most widely accepted tools for its calculation are the AP8 (protons) and AE8 (electrons) codes developed by NASA for the trapped particles, whereas the solar flares are modelled with other tools such as the JPL 91 code.

4.2 Shielding effects

Space solar cells are typically flown with some material covering the cell surface, most typically 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 item [2] of the bibliography.

5 General radiation effects in solar cells

5.1 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 non-ionizing events, which result in displacement of the target atom. If enough energy is transferred in a non-ionizing event, then the displaced target atom may, in turn, displace other atoms, creating a cascade of displaced atoms. The displacement damage induced by the non-ionizing 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 non-ionizing events is referred to as the non-ionizing 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.

5.2 Radiation effects on solar-cell cover

Although not specifically a solar-cell radiation effect, it is appropriate in this International Standard to note the effects of irradiation on solar-cell coverglass material. Certain solar-cell coverglass material has been shown to darken under irradiation, thereby absorbing some of the incident light [4]. This increased light absorption can reduce the solar-cell output in one of two ways: reduction of the amount of light that reaches the cell, or increase in operating temperature of array that reduces the cell electrical conversion efficiency.

NOTE Testing cells with attached coverglass or different geometries require special care (see items [7] and [8] in the bibliography).

6 Radiation test methods

6.1 General

As described in Clause 5, the space radiation environment consists of a spectrum of particle energies, and as described in this clause, solar-cell radiation damage is energy dependent. Irradiation by a spectrum of particles in a laboratory is not typical, so most ground radiation testing is done using a monoenergetic beam of particles. Therefore, any space solar-cell radiation testing shall be done in such a way as to enable extrapolation from monoenergetic radiation damage to damage produced by irradiation by a particle spectrum. This is typically done by using the ground test data to reduce the particle spectrum to a fluence of monoenergetic particles that produce an equivalent amount of damage. The determination of the equivalent fluence can be achieved in different ways, the primary ones being the JPL and NRL methodologies [2, 3, 5]. Although it is beyond the scope of this International Standard to discuss these data analysis methods, it is important that the method to be used for a specific experiment be chosen and well understood prior to performing any radiation testing. Similarly, it should be noted that this International Standard gives guidelines on how to perform radiation testing on a space solar cell independent of the device technology. Differing cell technologies might exhibit differing radiation response characteristics that need to be understood in order to perform a meaningful test. On the basis of practical limitations, the recommended energy range for proton irradiations is 30 keV to 30 MeV. The recommended energy range for electron irradiations is 200 keV to 3 MeV. In special cases, lower energies might be achievable. Damage comparisons are usually performed with 10 MeV protons and 1 MeV electrons.

It can be convenient in some cases to perform particle transport calculations before performing the irradiations. These calculations can tell one how far the incident irradiation particle will travel within the solar cell before it stops. For example, if one wanted to irradiate a silicon solar cell, the irradiating particle would need to travel some distance on the order of 100 μm to reach the active region of the solar cell and therefore cause significant damage. Therefore, it is necessary to perform the transport calculation to determine the particle energy required to cover this distance. For proton transport calculations, the Monte Carlo code SRIM [12] should be used; for electron irradiation, ITS TIGER [13] should be used.

Post-irradiation annealing is one specific example. Silicon (Si) 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 h, 60 °C anneal, so such a post-irradiation annealing stage was adopted as the standard protocol for Si solar cells. Issues such as these shall be researched and understood on a technology-specific basis.

6.2 Electron irradiation

6.2.1 Vacuum

Electron irradiation may be performed under vacuum or in air. Scattering of the electrons in air results in an energy spread that is highly dependent on the incident energy and the path length of air travelled by the electrons. Although 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.

6.2.2 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: limiting the particle flux, and 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. After the test, the test samples shall be stored at or below the irradiation temperature until they have been electrically measured. Sample temperature shall be monitored by a thermocouple or similar device.

NOTE If this is not practically possible, the applicability of the results can be affected.

6.2.3 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 might be desired 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 the proper particle energy and beam uniformity on target. Beam uniformity is discussed in 6.2.4. 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 calculated and accounted for. 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. For example, ITS TIGER simulations [13] show that a 1 MeV electron will lose approximately 50 keV as it passes through a 0,127 mm-thick Al foil, so when using such a scattering foil, the accelerator voltage is increased by 50 keV.

An alternative method for increasing the exposure area is to mount the samples on a rotating stage that periodically moves the samples through the beam. A standard implementation of this is to use a rotating wheel attached to a motor much like a phonograph record. When implementing this technique, care shall be taken to adjust the irradiation time to account for the duty cycle of the rotating 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 of the mounting stage.

Because accelerator beam fluxes typically 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 rotating stage. Therefore, special care should be taken in such cases to allow continuous monitoring of the flux, and integrating it over time to calculate fluence.

A third method of achieving beam uniformity over a large area is to use either magnetic or electrostatic deflectors to sweep the beam back and forth and up and down. Care shall be taken to set the deflection frequencies so that the beam sweeps through many cycles (at least 100, but perhaps more if the beam spot size is small and the irradiation area is large). 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. This method can be used for both electrons and protons.

6.2.4 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 is dependent on the specific technology under study. However, experience has shown that 5 % to 10 % uniformity is both acceptable for valid radiation testing and reasonably achievable. It is good to get a beam profile and energy profile from the accelerator before each test. Dosimetry checks shall be done before and after each measurement.

6.2.5 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 solar-cell temperature. As discussed in 6.2.2, the temperature of the solar cells during irradiation should be measured. The typical range for electron flux is 10^9 to 10^{12} electrons per cm^2 per second. It should also be noted that for certain technologies, the magnitude of the flux can affect the amount of degradation observed because of dose-rate effects. This is, again, a technology-specific issue.

6.2.6 Dosimetry

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

For accurate dosimetry with a Faraday cup, the beam-line shall be properly aligned. Integrated current better accommodates beam-current fluctuations. If the beam-line is not aligned properly, the particles can scatter off the sidewalls prior to reaching the target plane. Scattering of the beam off of the beam-line walls will degrade the particle energy. In such a case, the Faraday cup might read a current indicative of the desired flux, but the energy content of particles will be degraded. Furthermore, if the aperture of the Faraday cup is misaligned with the incident beam, the aperture area normal to the beam is decreased and less beam will enter the cup; so, in this case, the current will not be indicative of the desired flux.