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Validation of Two Different Approaches for Solar Cell Degradation under Different Space Environment Conditions

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Abstract- The Prediction of EOL performance for space solar cells is calculated using two different approaches. First approach is EQFLUX based on relative damage coefficients developed by JPL. Second one is NRL Displacement Damage Dose (DDD) realized in two codes (SCREAM and MC-SCREAM). In this paper we validate the three models with flight data, datasheet and compare the EOL efficiency under different space radiation environments.

Keywords- *Solar Cell, Displacement Damage Dose, EQFLUX, SCREAM*

I. INTRODUCTION

Recently Egypt enter space era through series of MisrSat missions. Accordingly, the need for space environment hazards prediction and their effects is essential. Studying different approaches to achieve accurate estimation for threats and their effects.

Solar cell is the main power source for satellites. The space solar cells are subjected to a variety of penetrating energetic radiations present in space that generally have adverse effects on solar cell materials, and these may require some form of radiation protection. If insufficient radiation protection is provided, these effects can result in mission failure or permanent injury to satellite components.

The penetrating space radiations that can have a significant effect on space solar cell are electrons, protons, and, to a lesser extent, heavier charged particles. Protons and electrons present the greatest hazard and are the most difficult to shield against because of their relatively higher intensity and greater penetrability. [1, 2]

For satellites, the design of appropriate protection is done by establishing criteria and procedures for determining doses caused by penetrating space radiation to avoid exceeding specified allowable levels of radiation dose for the duration of the mission. This process is called radiation hardness assurance.

The approach is first to calculate the doses received by each radiation sensitive item, considering the protection inherent in the vehicle structure and contents, and the space radiation environment encountered during the mission. If any doses exceed allowable limits, then the design of shielding is implemented to reduce the doses to meet the specifications, unless the adjustment of mission parameters or system design can eliminate the necessity. [3, 4]

The prevailing types and sources of penetrating space radiation are:

- Solar Cosmic Rays, consisting chiefly of protons, with some alpha particles ejected from the sun during some solar flare events.
- Magnetically trapped protons and electrons in the vicinity of the earth and other planets.
- Galactic Cosmic Rays, consisting of a continuous flux of protons and comparatively fewer heavier nuclei.

The high energy particle radiation environment responsible for effects on electronics is usually considered to consist of electrons with energies greater than 100 KeV, protons or neutrons with energies greater than 1 MeV, and heavy ions with energies above 1 MeV/nucleon.

Effects on electrical and electronic systems and materials are considered in terms of total ionizing dose (TID), displacement damage, and single event effects (SEE).[5]

- **Total Ionizing Dose (TID):** TID degradation in microelectronics results from the buildup of charge in insulating layers, and has a cumulative effect on electronics, resulting in a gradual loss of performance and eventual failure. TID also affects optical components such as cover glasses and fibre optics, and passive materials such as plastics.

- **Displacement Damage Dose (DDD):** DDD is a cumulative radiation damage effect which results from damage to the crystalline structure of semiconductors and some optical materials by energetic particle collisions. DDD is predominantly an issue for semiconductors which rely on minority carrier current flow, such as opto-electronics, bipolar devices, solar cells, *etc*.

- **Single Event Effects (SEE):** Energetic ions passing through integrated circuits semiconductors produce a trail of ionization which induces a variety of physical phenomena known as single event effects (SEE). These failures result from the charge deposited by a single particle crossing a sensitive region in the device and are a function of the amount of charge collected at the sensitive node(s).

The study of radiation damage in semiconductor devices has been an important theme of research of interest to fundamental physics of semiconductor as well as to the applications of semiconductor materials. In space solar cells such studies assume paramount importance in view of the extreme sensitivity of their electronic characteristics to the defects produced by interaction with radiation.

Satellites are mainly powered by solar cells. While high beginning-of-life (BOL) efficiencies are important for space solar cells, the end-of-life (EOL) performance is also a critical factor. Consequently, analysis of proton radiation damage to solar cells is extremely important for predicting output power degradation of solar cell.

Accurate prediction of solar cell performance in a space radiation environment is essential for selecting the appropriate cell technology for a given mission due to gain higher conversion efficiency and better radiation hardness. The exposed outer surfaces of solar cells on spacecraft are usually shielded against radiation damage using specially attached cover glass.

There are two techniques for modeling solar cell performance in a radiation environment: 1) the equivalent fluence (EQFLUX) model developed by the US Jet Propulsion Laboratory (JPL), California Institute of Technology and 2) A Solar Cell Radiation Environment Analysis Models (SCREAM), a Matlab-based executable code, which implements the displacement damage dose (DDD) approach to solar cell degradation prediction in a space radiation environment. The primary goal of both models is the correlation of ground-based degradation data taken after irradiation by different particles at various energies to the particle spectra experienced by the solar cells in the space radiation environment. Both models reduce the available ground test data to single curves from which the effects of particle spectra can be inferred.[6-8]

The main objective of this research is to validate and select the appropriate model for space environment MisrSat series mission analysis. Consequently, the following specific objectives were done:

a. Validate the three models with flight data

b. Comparing the degradation of a GaAs solar cell in different conditions using the three different models according to:

   i. Lifetime of the satellite (1 year, 5 years)

   ii. Solar cycle (minimum, maximum solar cycle)

   iii. Range of cover glass thickness (0.1 to 80 m

c. Validate the three models in case of single junction (GaAs) and multiple junctions (Emcore ATJ) solar cell degradation; comparing the results with their datasheet values.

II. THEORITICAL MODEL

Mission designers and architects use models based on their orbital locations and spacecraft shielding to quantify and predict the expected radiation environment to which their satellites will be exposed. After making a preliminary estimate of the particle flux, we simulate the effects of the space environment using SPENVIS.

Particle radiation causes trapping centers in the base region in solar cells decreasing the minority carrier lifetime and diffusion length. Radiation can damage solar arrays by penetrating through the cover glass (front side) or the substrate (back side). In both cases, the solar cell output (short-circuit current, open-circuit voltage, output power) is reduced. However, the cover glass and the substrate shield the cells from radiation and their thickness has an impact on the damage that the solar array will sustain. To determine the end of life (EOL) solar cell performance for a mission, the beginning of life (BOL) I-V curve must be measured and the effect of the orbital radiation environment must be calculated. [5]

For solar cell radiation damage, there are two methods:

1. EQFLUX: is developed by the Jet Propulsion Laboratory (JPL), calculate 1 MeV and 10 MeV damage equivalent electron and proton fluences, respectively, for exposure to the fluences predicted by the trapped radiation and solar proton models, for a specified duration. [9]

To facilitate simulation and testing of the solar cell degradation, the total damage due to electrons that would be sustained by a solar array in orbit over a particular time span is expressed in terms of equivalent 1 MeV fluence which is the number of normally-incident, mono-energetic 1 MeV electrons per unit area that would produce the same degradation on the array. Similarly, the damage caused by protons of various energies is expressed as an equivalent fluence of 10 MeV protons. Moreover, the 1 MeV and 10 MeV fluences relate to each other by a damage conversion factor. Typically, one 10 MeV proton will cause the same amount of damage as 3000 1 MeV electrons. The exact value depends on the cell type and may range from 2000 to 7000 for silicon based cells.

SPENVIS is ESA's Space ENVironment Information System, a WWW interface to models of the space environment and its effects; including cosmic rays, natural radiation belts, solar energetic particles, plasmas, gases, and "micro-particles. The SPENVIS system consists of an integrated set of models of the space environment, and a set of help pages on both the models and the SPENVIS system itself. [10] The EQFLUX model in SPENVIS calculates 1 MeV electron and 10 MeV proton damage equivalent fluences using data from the solar and trapped particle models. The 10MeV proton fluence is then converted into the equivalent 1 MeV electron fluence (by using a proton/electron damage factor of 3000) and added the total electron fluence. [11]

2. *SCREAM: is a GUI software package written and compiled in the Matlab programming environment which implements the NRL Displacement Damage Dose modeling approach for the prediction of solar cell end-of-life (EOL) performance in a space radiation environment. Equations. [12]*

When given a proton (and/or electron) radiation energy spectrum, SCREAM considers the effect of (multi-layered) shielding and determines the device response associated with that spectrum (spectra). The input radiation spectrum is “slowed down” through the shielding in slab geometry and combined with the nonionizing energy loss (NIEL) to produce a quantity called displacement damage dose (DDD), which is then used to calculate the EOL behavior of the solar cell. Effects of multilayered shielding through both the front and rear sides of the solar array can be also combined to give a total degradation due to the environment.

Displacement damage dose calculation [12]:

$$D_d(E_{ref}) = \Phi(E) \bullet NIEL(E) \left[\frac{NIEL(E)}{NIEL(E_{ref})} \right]^{n-1} \quad (1)$$

$$\frac{P(D_d)}{P_0} = A - C \cdot \log \left[1 + \frac{D_d}{D_x} \right] \quad (2)$$

*Experimentally determined variables (Ap, Ae, Cp, Ce, Dxp, Dxe, n).

Analytical Model Comparison:

Proton DDD to 1 MeV electron equivalent fluence [12]

$$\varphi_{1\ \text{MeV electron}} = \left[10^{\frac{1}{C_e}(A_e - A_p)} \left(1 + \frac{DDD_p}{D_{xp}} \right)^{\frac{C_p}{C_e}} - 1 \right] * \frac{D_{xe}}{NIEL(1)} \quad (3)$$

1 MeV electron DDD to equivalent proton DDD [12]

$$DDD_p = D_{xp} \left[10^{\frac{1}{C_p}(A_p - A_e)} \left(1 + \frac{DDD_e}{D_{xe}} \right)^{\frac{C_e}{C_p}} - 1 \right] \quad (4)$$

III. RESULTS AND DISCUSSIONS

A. Flight Data

In this study, Eureca flight data was used to validate the three models comparison. Eureca, which was launched on July 31st, 1992, will be, in fact, retrieved in June 1993 by STS 57 after a space fight of about 10 months.[12] This flight was specially selected because it was lunched in declined period (solar maximum) which is worst case scenario.

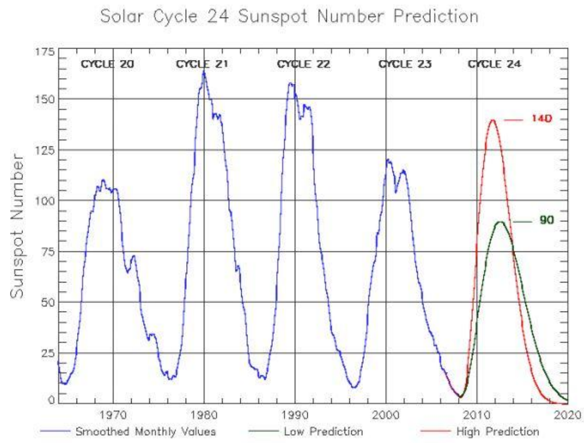

Figure 1. Solar Cycle 24 Sunspot Number Prediction [13]

ASGA, the Advanced GaAs Solar Array, is a reusable test facility designed to fly on board of Eureca, the European Retrievable Carrier. Aim of the ASGA experiment is to provide valuable information on the performance of gallium arsenide solar arrays and on the effects of the Low Earth Orbit on their components. One of the most significant features of the ASGA experiment is the possibility of ground evaluation of the hardware after about one year-stay in space.

After generating orbit using SPENVIS for Eureca mission, solar cell degradation is calculated using EQUFLUX, MC-SCREAM and SCREAM as shown in (fig.1).

TABLE I. ORBITAL PARAMETERS FOR EURECA MISSION

Parameters	Value
Eccentricity	0.00066
Perigee	438 km
Apogee	447 km
Inclination	28.5 degrees
Period	93.4 minutes
Epoch	2 August 1992, 20:00:00 UTC

The degradation was about 0.951 by EQFLUX, 0.941 by MC-SCREAM and 0.935 by SCREAM, good agreement is achieved over a large energy range, thereby validating the cell degradation agreement between models and Eureca flight data.

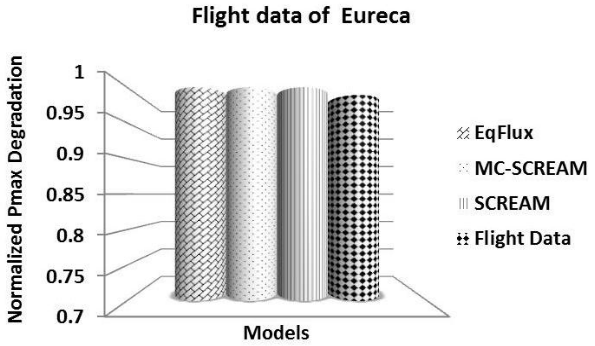

Figure 2. Comparison of Flight data of EURECA 1993 with the same parameters for the three Models

B. Mission Life Time

Figure (2) shows the accuracy of three models in long mission duration 5 years and short mission 1 year. The degradation was about 0.895 by EQFLUX, 0.885 by MC-SCREAM and 0.875 by SCREAM in case of 5 years mission, while for a mission of 1 year lifetime, the degradation was about 0.951 by EQFLUX, 0.941 by MC-SCREAM and 0.935 by SCREAM.

TABLE II. ORBITAL PARAMETERS FOR MISRSAT MISSION

Parameters	Value
Eccentricity	0
Perigee	800 Km
Apogee	800 Km
Inclination	90 degrees
Period	100.8 minutes
Epoch	1-Jan-20

The discrepancy of 1% between the models in both cases is shown. Accordingly, the accuracy of degradation calculated by the models doesn't be affected with changing the mission lifetime. But as expected the degradation is increasing with the longest lifetime.

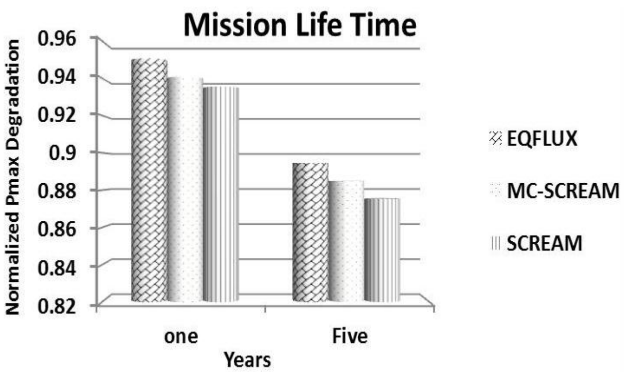

Figure 3. Comparing the degradation for GaAs for a mission of 1 year lifetime and the other with 5 years lifetime using the three models

C. Solar Cycle

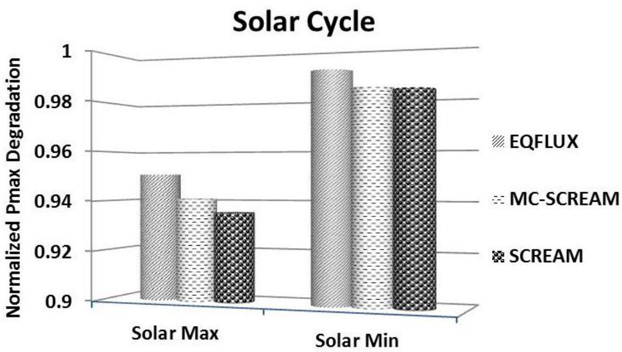

Figure 4. Comparing the degradation for GaAs for a mission is launched in Solar Minimum (2020) and the other in Solar Maximum (2025) using the three models

Figure (3) shows the accuracy of three models in case of launching the mission in solar maximum in 2015, the degradation was about 0.951 by EQFLUX, 0.941 by MC-SCREAM and 0.935 by SCREAM, while in a mission Solar minimum in 2020, the degradation was about 0.991 by EQFLUX, 0.983 by MC-SCREAM and 0.982 by SCREAM, showing discrepancy of 1% between the models in both cases. Accordingly, the accuracy of degradation calculated by the models doesn't be affected with changing the solar cycle. But as expected the figure illustrates that the degradation is increased in the maximum solar activity than the minimum one.

D. Shielding Thickness

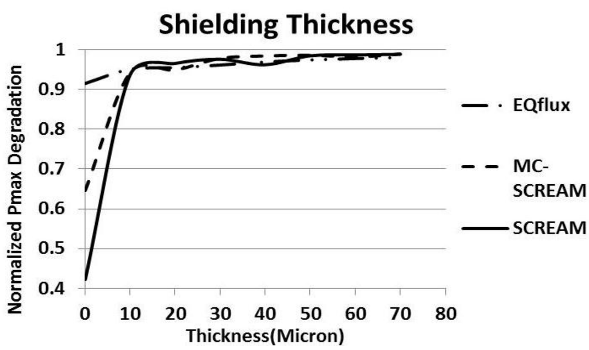

Figure 5. Comparing the degradation for GaAs with a range of SiO2 shielding thickness using the three models

Figure (4) shows the accuracy in case of using a range of cover glass thickness of shielding, the three models are consistent to within ~97% for thicknesses greater than 10 micron but with decreasing thickness less than 10 micron inconsistency between models are increasing which caused by increasing the damage level to the cell. At thickness of 10 micron, the degradation was about 0.951 by EQFLUX, 0.941 by MC-SCREAM and 0.935 by SCREAM, while at thickness of 0.1 micron, the degradation was about 0.914 by EQFLUX, 0.646 by MC-SCREAM and 0.4224 by SCREAM. Accordingly, the accuracy of degradation calculated by the models is affected with changing the cover glass thickness for thicknesses less than 10 micron.

E. Datasheet

In case of comparing a single solar cell (GaAs) [14] and multijunction solar cell (Emcore ATJ) datasheets values [15] with three models results in the same damage levels, Figure 1 is showing that the three models are consistent to within ~97% for both types.

However, EQFLUX was the most accurate results. Which can be described by calculations depending on experimental data that is more accurate than analytical calculating determined by NIEL data in NRL Models.

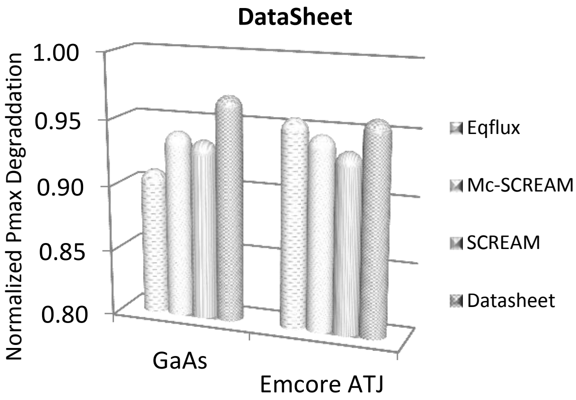

Figure 6. Comparing the degradation of GaAs and Emcore ATJ using the three models with the datasheets values

IV. CONCLUSION

Validating the three models with Eureca flight data shows that, the degradation was about 0.951 by EQFLUX, 0.941 by MC-SCREAM and 0.935 by SCREAM, good agreement is achieved between real flight data and three models.

The accuracy of three models in case of comparing degradation under different mission life time, and minimum and maximum solar cycle is about 2% which can be neglected.

While the accuracy of degradation calculated by the models is affected with changing the cover glass thickness for thicknesses less than 10 micron.

The three models are consistent to within ~97% for both single and multijunction solar cells and with comparing these data with datasheets for them, EQFLUX was the most accurate model, which can be explained by the dependency of its results on experimental data.

In conclusion, the discrepancy between the three models are within <2%, so if we look for low cost and a great variety of solar cells we can use NRL Models, but for accurate calculations with limited types of solar cells the JPL model will be more suitable.

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