

COMPARATIVE ANALYSIS OF RADIATION DEGRADATION OF TRIPLE-JUNCTION SOLAR CELLS USING TWO DIFFERENT APPROACHES

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ABSTRACT

Radiation degradation of solar cells has historically been analysed on the basis of 'relative damage coefficients' using the EQFLUX code developed by NASA/JPL. In recent years, efforts have been made to improve the possibilities for this kind analysis using methods which are more closely similar to the analysis performed on other components. In this paper, we discuss the status of the available tools in the context of the user requirements and expectations.

1. INTRODUCTION AND BACKGROUND

Among the factors which contribute to the degradation of solar cells in space, particle radiation is often the most important. In the case of crystalline Si or, more recently, GaAs based cells, radiation degradation is caused by displacement effects rather than ionisation. The impact upon solar cell characteristics has been thoroughly documented in [1,2] for single junction cells and in elsewhere for the multi-junction cells which are currently the state-of-the art [3,4]. Jet Propulsion Laboratory (JPL) developed the Fortran code EQFLUX to calculate the 'equivalent fluence' of 1MeV electrons over a mission duration, so that lifetime testing could be performed in the laboratory using an electron accelerator [1,2]. However, this approach requires the establishment of a large database of reference information about the degradation of cell characteristics as a function of electron and proton energy and fluence. More recently, Summers et al. proposed a different approach that utilises theoretical understanding of the displacement effects caused by particles with different energies as a function of 'non-ionising energy loss' (NIEL) in order to reduce the required quantity of reference test data [3,4]. This approach has been incorporated in at least two software packages, 'SCREAM' and 'MC-SCREAM' [5,6] which may be used as an alternative to EQFLUX.

From the perspective of the user, any change of approach that has the potential to impact the sizing of a solar array is a major concern that requires careful consideration and validation before possible acceptance. In this paper, we explain the status of the comparison between the results of EQFLUX vs (MC)SCREAM and progress with the validation of the latter, in order to facilitate the decision making process for potential users.

2. FACTORS THAT INFLUENCE ANALYSIS OF RADIATION DEGRADATION

The designer of a space solar array would ideally like to be able to estimate the degradation profile on the basis of reliable inputs with well defined confidence criteria, which can be combined in a statistically meaningful way. In practice, the user tends to make conservative estimates using inputs of variable quality, combined in a way that has no particular mathematical justification [7]. This translates to establishment of margins that have an associated cost.

In the context of this paper, it's important to understand that the method of radiation analysis is one piece in a complicated jigsaw. Regarding the radiation analysis, the principle concern should be that it does not lead to errors in the final array output that are disproportionately high with respect to the other sources of error, and ideally the error associated with the model outputs should be quantified. Historically, there was no alternative to the use of EQFLUX and little published information about how accurate this model is in practice. The situation today is different, as a minimum because we don't want to replace the existing approach with something worse and therefore additional justification is needed.

The analysis in this paper is based on acquisition of radiation test data for the Azur 3G28 triple-junction solar cell, performed as part of an ESA contract [8]. Details about the test philosophy and implementation as well as the generation of the inputs to the EQFLUX and MC-SCREAM models are discussed in [8]. At the time of writing, the 3G28 cell variant within SPENVIS models is available only to a limited number of users on a trial basis for validation purposes.

3. DESCRIPTION OF THE APPROACH WITHIN SPENVIS

3.1. Definition of the mission environment

The reference case for the analysis presented in this paper is a 15 year mission in a geostationary orbit, which is of relevance for commercial telecommunications satellites (though the detailed inputs such as confidence levels used within the relevant models may be different).

The definition of the environment applied within the SPENVIS model is defined in Appendix 1. This is a

good test case to analyse, not only because of its commercial significance but also because it contains all the physically important aspects of the analysis, notably featuring contributions of both electrons and protons to the overall degradation.

The general conclusions regarding the current status of the models are nonetheless true of other mission environments.

3.2. EQFLUX / Definition of relative damage coefficients

Relative damage coefficients had previously been established for several variants of triple-junction solar cells and are typically similar (which naturally follows from the fact that the thickness of the sub-cells is not expected to vary greatly from one cell design to the next). Unidirectional relative damage coefficients for the 3G28 cell which are included in this analysis were calculated by Astrium [8]. Omnidirectional damage coefficients were derived using the calculation tool built into SPENVIS. Using the default mission scenario described in Appendix 1 for the cell variants stated in Figure 1 from the list of options within SPENVIS, the range of ‘equivalent 1 MeV fluence’ for a 100-150micron coverglass was within around 20% (see Fig. 1). Note that this would translate to a difference in output power of <1% for the 3G28 cell. The results obtained using SPENVIS are in line with the conclusions of [8], which were based upon the same data but which did not use the SPENVIS implementation of the degradation models.

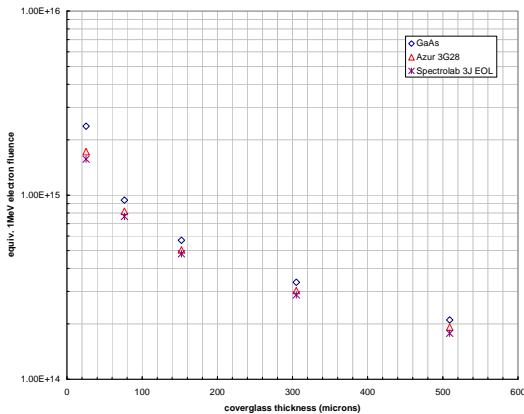


Figure 1. Equivalent fluence for the reference GEO mission described in Appendix 1 using different reference RDCs from the variants available within the SPENVIS application of EQFLUX.

Within EQFLUX, equivalent fluences are calculated at reference energies of 1MeV for electrons and 10MeV for protons. Subsequently, the impact of 10MeV protons is multiplied by a ‘proton to electron conversion ratio’ in order to translate it into an equivalent fluence of

1MeV electrons. Unless the ‘electron-proton conversion ratio’ is forced to be constant by choice of fitting parameters, this parameter varies as a function of the amount of degradation [2], as illustrated in Fig. 2 for the 3G28 cell.

In principle the e-p ratio could be calculated for each value of ‘equivalent fluence’ output within EQFLUX but the published version of the EQ(GA)FLUX code [2] imposes one constant value. In practice the impact on the overall estimates of degradation is <1% for Pmax (nb. The impact upon Voc has not been quantified but would be greater).

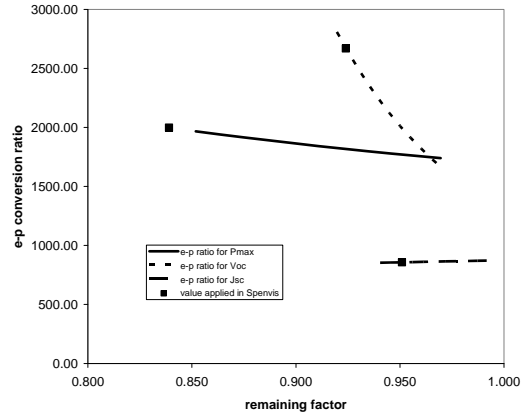


Figure 2. Dependence of the proton to electron conversion ratio as a function of remaining factor of Pmax, Voc, Jsc.

	Azur 3G28 (defined at P/P0=0.8-0.9)	SPL 3JEOL (defined at P/P0=0.8)
Pmax	1999	870
Voc	2669	1020
Isc	857	565

Table 1: conversion factors to translate an equivalent fluence of 10MeV protons to 1MeV electrons as implemented in SPENVIS for the calculations presented. Note that higher numbers do not imply greater degradation, only that the relative impact of the particle energies is different.

The definition of the ratio used to translate an equivalent fluence of 10MeV protons to 1MeV electrons is significantly different for the 3G28 cell in comparison with historical values. This is not in itself good or bad but emphasises the fact that particle environments dominated by electrons are best analysed with reference to electron test data and likewise proton dominated environments are best analysed with reference to proton test data. Within the SPENVIS application of EQFLUX, all the relevant parameters can be entered manually, which allows the proton to electron conversion ratio to be tailored according to the amount of degradation expected.

3.3. NIEL based analysis / MC-SCREAM

The approach described by Messenger et al. [3] has been incorporated in two different software codes. The first, 'SCREAM' ('Solar Cell Radiation Effects and Analysis Model') has been developed and distributed by the Naval Research Laboratories. The second, 'MC-SCREAM', is implemented in ESA's web based software tool SPENVIS [6]. This tool uses a Monte-Carlo approach (hence 'MC') to calculate the displacement damage cause by a given particle input spectrum using the existing MULASSIS tool (Multi-Layered Shielding SIMulation Software), but with a dedicated user interface. More details are provided on the SPENVIS website [6].

Within the NIEL based approach, the degradation produced by electrons and protons is calculated as a function of 'displacement damage dose', which for protons is simply the product (NIEL x fluence). The calculation of degradation produced by electrons involves adjustment by a factor R (analogous to the e-p ratio within EQFLUX) in order to translate the electron data onto the characteristic curve for proton data in terms of displacement damage dose. Both models are therefore similar in terms of their ability to predict the impact of combined electron / proton environments.

Fig. 3 illustrates the characteristic degradation curve calculated using only 1MeV electron data, which is translated onto the characteristic curve for all the proton data. Note that the ratio R which is used within the beta application for the 3G28 cell has been calculated taking into account all electron energies and is therefore not the best fit for 1MeV electrons.

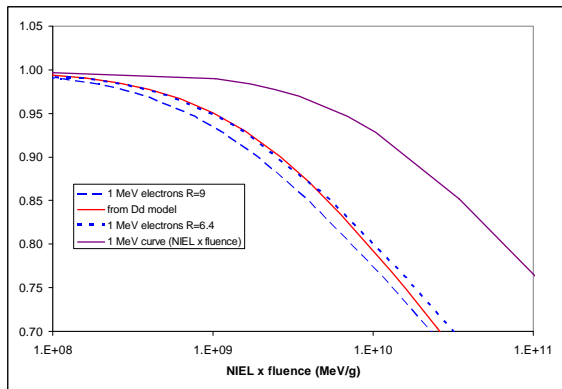


Figure 3. Characteristic degradation curve for protons (red curve) and for 1MeV electrons (black curve) in terms of displacement damage dose (=NIEL x fluence for protons ; see [3]). The dashed lines indicate the translation of the electron curve onto the proton curve (using the ratio $R=6.4$ optimised for 1MeV electrons only, or $R=9$ optimized for all electron energies).

In principle it would be expected that there is no difference whether all the electron data or only the data

at 1MeV are considered, provided that the approach successfully collapses all the electron data onto one characteristic curve. This point is still under investigation but does not have a significant impact on the conclusions presented (the sensitivity depends upon the spectrum of particle energies).

4. RESULTS AND DISCUSSION

Fig. 4 illustrates a comparison of the estimate of solar cell power degradation as calculated using EQFLUX or MC-SCREAM respectively within SPENVIS. The impact upon the maximum power point is illustrated because it is by definition sensitive to degradation of both current and voltage; it is relevant to the case of power conditioning using a maximum power point tracker. At design level, power conditioning based on direct regulation at a fixed voltage is more sensitive to voltage degradation (ie. than current degradation) since accurate understanding of end of life voltage is necessary in order to accurately define the length of series strings.

Typically triple junction cells are designed to be current matched at the end of the life of a commercial mission, which translates to about 10% of degradation of power. The difference between the estimates of the 2 models are within 1% for the case of a 100-150micron coverglass for the test case, when expressed in terms of the 'remaining factor' of available power. This is certainly within the applicable errors, even if the software at present does not provide quantified errors as an output (see section 4).

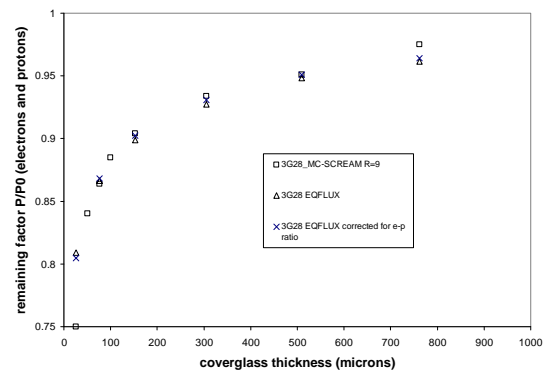


Figure 4. Remaining factor of power for the reference GEO mission described in Appendix 1 for different coverglass thicknesses, as estimated using EQFLUX and MC-SCREAM respectively. Differences are less than 1% for a 100-150micron coverglass.

In order to compare the models for electron and proton environments respectively, the same mission scenario was run within SPENVIS but including either only trapped electrons (Fig. 5) or only protons (Fig. 6). In practice the contribution of trapped protons is negligible for the case in question.

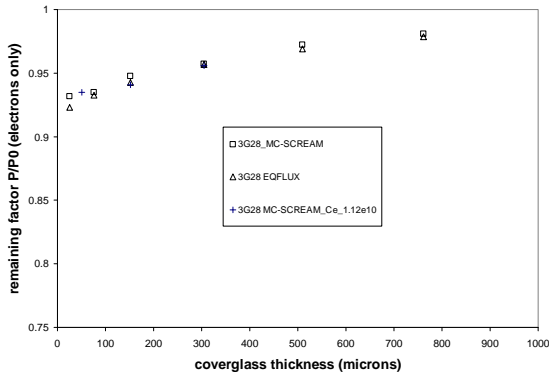


Figure 5. Remaining factor of power for different coverglass thicknesses, as estimated using EQFLUX and MC-SCREAM respectively. Differences are less than 1% for a 100-150micron coverglass. The reference mission environment is the same as for Figure 4 but considers ONLY the electron content of the environment in order to check that the results are equally comparable for both proton and electron dominated environments.

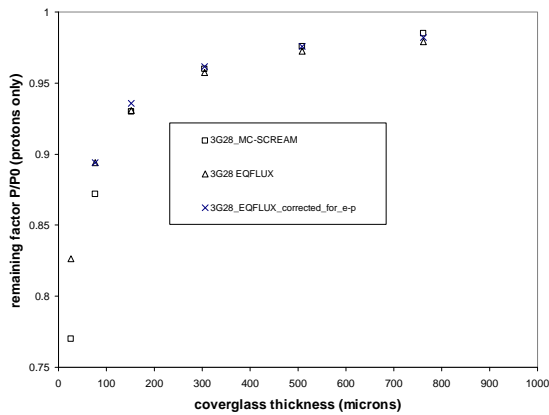


Figure 6. Remaining factor of power for different coverglass thicknesses, as estimated using EQFLUX and MC-SCREAM respectively. Differences are less than 1% for a 100-150micron coverglass. The reference mission environment is the same as for Figure 4 but considers ONLY the proton content of the environment in order to check that the results are equally comparable for both proton and electron dominated environments.

It can be seen that the accuracy of the comparison is similar for both cases within the range of validity. In cases where the estimated degradation is $\gg 10\%$ then the accuracy of the model is significantly worse because the limiting pn junction within the triple-junction cell configuration may no longer be the top junction, but also because the calculations relate to cases where there is progressively less shielding applied and therefore the differences in the treatment of shielding between the

two models become more important. In detail, the impact of the treatment of shielding upon the outputs merits further study.

For the end user, a small difference in the predicted ‘end of life’ performance has a potentially significant cost impact. The validity of the analysis discussed in this paper is fundamentally dependent upon the way that ‘characteristic degradation curves’ are defined, which depends in turn upon the accuracy of the data obtained both at the radiation facility and the cell measurement laboratory. Experimental aspects of this study are discussed in [8].

Changes due to the mathematical approach to fitting or the distribution of cell data can also have a significant impact upon the results. For example, the above discussion relates to the description of the average characteristic degradation of the solar cell characteristics. The degradation of the individual cells within a space solar array is not perfectly uniform and it is known that ‘high grade’ cells tend to degrade more than ‘low grade’ cells [10]. Ultimately cost considerations lead to the definition of tests using limited numbers of samples that may have to be of reduced dimensions with respect to flight cells. Margins need to be introduced to take account of these considerations.

One conclusion of the study conducted by Astrium was that the statistical accuracy of the power prediction using a NIEL based approach is not significantly increased by including the data acquired at more than one energy. However, apart from discussion of statistics, it should be noted that the acquisition of data from different radiation and solar cell measurement facilities greatly reduces the possibility for experimental errors to go undetected. The coherence of the data-set is already a good indication of accuracy.

With reference to the traditional approach to radiation testing, note that an error in the ‘characteristic reference curve’ established using 1MeV electrons would subsequently impact all later analysis. Physically there is no reason to privilege data acquired at one arbitrary reference energy within the analysis – this approach is simply adopted in order to simplify the analysis.

5. MARGINS WITHIN A REAL DESIGN

Finally, note that the solar array designer is typically presented with a requirement for operating voltage without necessarily having any visibility of the voltage margin within the power control and distribution unit. The scope to reduce margins within solar array design is a complicated question that requires system level analysis. In terms of system level priorities, it is striking that typically 5 to 10% of the power generated at beginning of life of a telecom satellite is not accessible if the power conditioning is managed by direct energy

transfer, since in this configuration the operating voltage is fixed at the 'end of life' voltage.

In contrast, a maximum power point tracker (MPPT) allows the best use of the available power over the whole mission life but introduces a different set of problems - notably that unused power can lead to greater thermal dissipation within the spacecraft because of the lower efficiency of the control electronics in comparison with direct regulation. An MPPT based system also has the benefit that, in principle, a new generation of solar cell technology can in principle be introduced into the same array design without requiring re-design of the string length in order to achieve a fixed voltage.

6. FUTURE WORK

It would be valuable to generate via software also performance predictions against laboratory test conditions (ie. using monoenergetic, unidirectional beams) since this would enable direct comparison against test results. It is already possible to do this kind of simulation within the MULASSIS tool within SEPENVIS, but has so far not been implemented within the MC-SCREAM software interface.

Improvement of the estimates of errors within the models would also improve the ability of designers to establish justifiable margins. In this respect, the NIEL based approach is mathematically less complex than analysis of damage coefficients [11].

Fundamentally, the understanding of degradation for mixed electron / proton environments still needs to be improved in order to make the analysis less empirical.

7. CONCLUSIONS

At the time of writing, the results derived from EQFLUX or the alternative MC-SCREAM showed difference of the order of up to 1-2% in end of life power for a typical commercial mission, which is comparable to the uncertainties involved and reasonable in comparison with the other factors which contribute to the design margins for a solar array. This is in line with the conclusions of [8]. It is reasonable to expect that the overall uncertainties associated with end of life performance prediction stem principally from limitations upon our ability to predict the environment, not our ability to predict the response of the solar array. Nevertheless, more can be done to quantify the uncertainties at each step in the evaluation.

For most mission analyses, the EQFLUX and MC-SCREAM models can probably therefore be used interchangeably without impacting the design of a solar array. Nevertheless, it is inevitable that even small differences may potentially imply a change in design such as the definition of the number of cells in a series

string. It is therefore important to specify which model is used and to apply it in a consistent way.

In practice, the scope for error within performance estimates depends less on the choice between these two models and more upon the way that they are applied. Of course, the definition of end of life performance in contractual terms remains subject to the agreement between supplier and customer about how these terms of reference are defined.

For engineers responsible for estimation of radiation analysis, it is useful to be aware of the possible errors involved with the acquisition of the test data as much as with the subsequent data analysis. Cross-checking of data from different radiation and solar cell measurement facilities is strongly recommended.

8. REFERENCES

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9. ACKNOWLEDGEMENT

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10. APPENDIX 1: REFERENCE MISSION

Orbit generator:

SPENVIS 4.6.3_base-v2096 18-Mar-2011
Project: GEO
Mission overview
Orbit around: Earth
Number of mission segments: 1
Mission start: 01/01/2010 00:00:00
Mission end: 28/12/2024 00:00:00
Mission duration: 5475.00 days (15.00 years)
Satellite axis: velocity vector
Mission segment 1:
Orbit type: geostationary
Apogee: 35793.23 km
Perigee: 35793.23 km
Inclination: 0.00°
R. A. Ascending Node: 99.77°
Argument of Perigee: 0.00°
True Anomaly: 0.00°
Period: 23.93 hrs
Number of orbits: 1.00
Duration: 1.00 days
Orbit start: 01/01/2010 00:00: 0.0
Orbit end: 02/01/2010 00:00: 0.0
Segment end: 28/12/2024 00:00: 0.0
Segment length: 5475.00 days
Semi latus rectum: 42164.23 km
Semi major axis: 42164.23 km
Eccentricity: 0.00
Mean motion: 6.30 rad/day
Integration step: 0.50°
Time intervals
60.0 s below 20000.0 km
240.0 s between 20000.0 km and 80000.0 km
3600.0 s above 80000.0 km
Eclipses and bowshock and magnetopause crossings
Orbit Date Time Eclipse Bowshock Magnetopause
1 01/01/2010 12:06:36 35779.5

Radiation

Trapped protons: AP8, solar min
Trapped electrons: AE8, solar max