

# CRÈME: The 2011 Revision of the Cosmic Ray Effects on Micro-Electronics Code

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## **ABSTRACT:**

We describe a tool suite, CRÈME, which combines existing capabilities of CREME96 and CREME86 with new radiation environment models and new Monte Carlo computational capabilities for single event effects and total ionizing dose.

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## I. Introduction

The Cosmic Ray Effects on Microelectronics Code (CRÈME) was first released in 1986 [1]. Over the following ten years there were many advances in our understanding of the space radiation environment.

During this period it was realized that galactic cosmic ray modulation had not only an eleven year cycle but also a twenty-two year cycle [2]. Furthermore it was recognized that the sunspot number is a leading indicator for galactic cosmic ray modulation and could be used to accurately model modulation [3]. Small  $^3\text{He}$ -rich events that were found to be enriched in heavy ions [4], accounting for much of the dispersion in elemental composition reported in CRÈME 86. It was discovered that solar energetic particles (SEPs) were accelerated in coronal mass ejections (CMEs) [5] and this was the source of the largest solar particle events (SPEs) [6]. New data [7],[8] made it possible to model the charge states of solar energetic particles. Also it was shown that rise in the single event upset (SEU) cross section could be described by an integral Weibull distribution [9]. All these and other revisions were included in CRÈME 96 [10].

A decade after the release of CRÈME96 it was becoming obvious that two segments of the site needed to be updated, selected environment models and rate prediction approaches. In this work, we describe the evaluation of environment models and their incorporation into the updated CRÈME web site. We used a chi-squared approach to evaluate three Galactic Cosmic Ray models (a fourth model will be evaluated in the final paper) and selected a single model for the new CRÈME site. We also developed a new model that describes the albedo neutron environment near the surface of the moon. Finally, for environments, this revision also includes a revised description of the transport of the space radiation environment through shielding.

These issues prompted the revision of CREME96 that is described here.. The latest version of CRÈME, together with the two earlier versions, is now available at <https://creme.isde.vanderbilt.edu/>.

## II. Environmental Models

II.a. Galactic Cosmic Ray Model: CREME96 used the Nymmik Model [3], which was adopted as a standard by the International Standards Organization (ISO). To choose a model for this revision, we reviewed the models that are available in the literature and chose those that modeled the differential energy spectra over the energy range from at least 10 MeV/u to 100 GeV/u. The models satisfying these requirements are the revised Nymmik Model [12], the CHIME Model [13], and the Badhwar-O'Neill Model [14].

We evaluated the Badhwar-O'Neill, CHIME and updated Nymmik models by comparing them with measured elemental spectra from an evaluated database we have developed. This database will contain more than 380 measurements of the elemental spectra of GCRs ranging from hydrogen to iron and from 10 MeV/u to 1 TeV/u. These measurements cover the time period from 1960 to the present. We have compared these individual evaluated spectra with each model by calculating the reduced chi-squared between each model and each spectrum, where reduced chi-squared is defined as:

$$\frac{\chi^2}{\nu} = \frac{1}{\nu} \sum_{i=1}^N \frac{1}{\sigma_i^2} [\phi_i - f(E_i)]^2$$

Where  $\phi$  is the measured flux at  $E_i$ ,  $\sigma_i$  is the error in this measurement and  $f(E_i)$  is the flux calculated at  $E_i$  from the model under test.  $\nu$  is  $N-p-1$  where  $N$  is the number of data points in the spectrum,  $p$  is the number of free parameters in the model under test and  $\chi^2/\nu$  is the reduced chi-squared.  $\sigma_i$  is proportional to  $\sqrt{1/n_i}$  where  $n_i$  is the number of detected cosmic rays used to construct  $\phi_i$ . Here we have bounded  $\sigma_i$  to be  $\geq 0.1\phi_i$  to account for systematic errors, especially in the determination of the geometrical factor of the instrument. The results are given in Table 1 below. Based on these results we chose the Nymmik model for the revision. Since this evaluation was made, the Badhwar-O'Neill model has itself been revised [15]. We will evaluate this new model and report the results in the full paper to follow this summary.

Table 1: The weighted mean results on the reduced chi-squared for all the spectral fits. The CRÈME 2009 Nymmik Model gives the best fits overall.

Model Name	Badhwar-O'Neill	Nymmik	CHIME
Hydrogen	3.45	1.28	1.37
Helium	2.21	1.38	1.69
Oxygen	0.71	1.21	0.65
Iron	1.32	1.13	1.32
Overall	2.46	1.31	1.46

The CRÈME 2009 Nymmik model has an added advantage over other models. Because it uses the sunspot number as a proxy for modulation, it has some ability to predict the level of modulation up to a year in advance. This requires current data in the monthly smoothed sunspot number. These data are obtained periodically from the Solar Influences Data Center at the Royal Belgian Observatory (<http://sidc.be/sunspot-data/>). See Figure 1 for a comparison with CREME96.

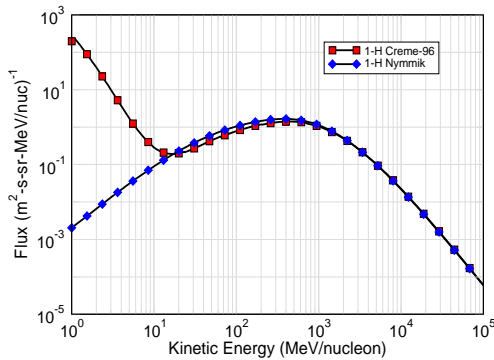


Figure 1. A comparison of the proton flux predicted by CREME96 and CRÈME 2009. Note the large difference for protons below 10 MeV, but the general agreement above 10 MeV.

II.b. Lunar Neutron Albedo: We have added to CRÈME a model for the neutron albedo coming from the lunar surface due to cosmic rays bombarding the surface. This model is based on a GEANT4 calculation of the albedo from protons and helium nuclei striking the lunar surface. The GEANT4 neutron albedo flux calculations were conducted at discrete, logarithmically-spaced energies over the full energy range of the cosmic ray spectrum. The neutron albedo flux was then weighted to match the proton and helium spectra at the Moon calculated by CRÈME. The results of these calculations are compared with the neutron albedo measured on the Lunar Prospector mission in Figure 2.

### III. New Computational Capabilities

III.b. HZETRN 1995/NUCFRG2: We revisited the radiation transport code in CRÈME 96 [10] that is used to determine the radiation environment at the location of the part within the spacecraft for a given radiation environment at the surface of the spacecraft. CREME96 used a radiation transport code called UPROP [16] that was developed for transport of cosmic rays

through cosmic ray detectors and across interstellar space from the cosmic ray sources to Earth. UPROP was chosen because it solves the Boltzmann transport equation using a marching procedure and therefore is much faster than Monte Carlo codes. We compared [17] UPROP with HZETRN (the 1995 version) [18] and two Monte Carlo codes, FLUKA [19] and GEANT4 [20]. Our version of HZETRN was obtained from the NASA COSMIC software collection (currently at <http://www.openchannelfoundation.org/cosmic/>) in the late 1990s.

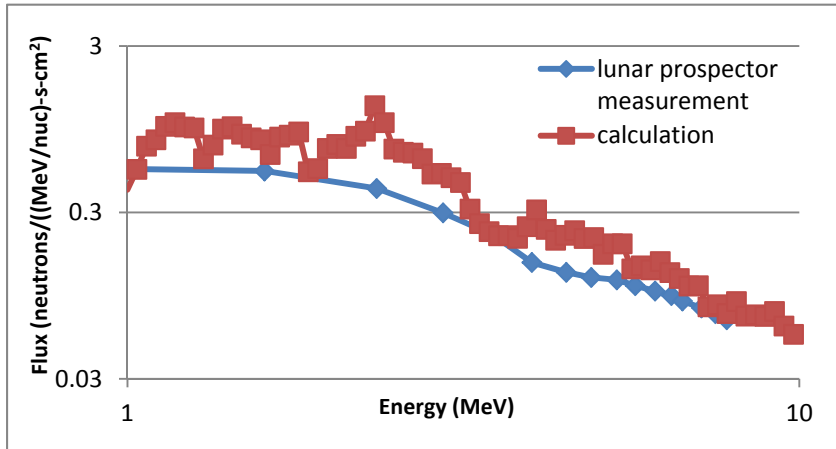


Figure 2: A comparison of the calculated lunar neutron albedo spectrum with spectrum measured on the Lunar Prospector Mission.

HZETRN is a Boltzmann solver that also uses a marching procedure. Our results show that UPROP performed poorer than the other codes for protons and also for heavy ions at low energies. Unlike HZETRN, UPROP does not transport neutrons. This is a deficiency for evaluating radiation effects on the Moon or inside a massive spacecraft like the ISS. We found that HZETRN agreed reasonably well with the Monte Carlo codes except for neutrons at low energies.

As a result of these comparisons we have chosen to include the 1995 version of HZETRN [17] as a users selectable option in the latest revision of CRÈME.

#### IV. Conclusions

Revised models for the CRÈME web site that provide improved fidelity and performance are described. The resulting web-based tool combines existing capabilities of CREME96 and CREME86 along with new Monte Carlo computational capabilities to support improved single event effects and total ionizing dose simulations.

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