CREME96: A Revision of the Cosmic Ray Effects on Micro-Electronics Code

Allan J. Tylka[1], James H. Adams, Jr.[1], Paul R. Boberg[2,1], Buddy Brownstein[3,1],
William F. Dietrich[4], Erwin O. Flueckiger[5], Edward L. Petersen[6],
Margaret A. Shea[7], Don F. Smart[7], and Edward C. Smith[8]
[1]Code 7654, E.O. Hulburt Center for Space Research, Naval Research Laboratory,
Washington, DC 20375-5352. *tylka* or *adams@crs2.nrl.navy.mil*
[2]Universities Space Research Association. *boberg@crs2.nrl.navy.mil*
[3]Softech, Inc. *buddy@osse.nrl.navy.mil*
[4]Laboratory for Astrophysics and Space Research, Enrico Fermi Institute,University of Chicago,
Chicago, IL 60637. *dietrich@odysseus.uchicago.edu*
[5]Physikalisches Institut, University of Bern, CH-3012 Bern, Switzerland. *flueckiger@phim.unibe.ch*
[6]Consultant, 9502 Babson Ct., Fairfax VA 22032. *epetersen@epetersen.com*
[7]Phillips Laboratory (OL-AA), Hanscom AFB, Bedford, MA 01731. *shea* or *smart@plh.afl.mil*
[8]Consultant, P.O. Box 880, Monteagle, TN 37356. *ecsmith@edge.net*

Abstract

CREME96 is an update of the Cosmic Ray Effects on Micro-Electronics code, a widely-used suite of programs for creating numerical models of the ionizing-radiation environment in near-Earth orbits and for evaluating radiation effects in spacecraft. CREME96, which is now available over the World-Wide Web (WWW) at http://crsp3.nrl.navy.mil/creme96/, has many significant features, including (1) improved models of the galactic cosmic ray, anomalous cosmic ray, and solar energetic particle ("flare") components of the near-Earth environment; (2) improved geomagnetic transmission calculations; (3) improved nuclear transport routines; (4) improved single-event upset (SEU) calculation techniques, for both proton-induced and direct-ionization-induced SEUs; and (5) an easy-to-use graphical interface, with extensive on-line tutorial information. In this paper we document some of these improvements.

I. Introduction

The space ionizing-radiation environment is tremendously complex: it contains all the naturally-occurring nuclei, from protons (atomic number Z=1) to uranium (Z=92). These particles originate from every imaginable source – Earth's and other planetary magnetospheres, the Sun, accelerators in interplanetary space and at the far-reaches of the heliosphere, our own Milky Way Galaxy, and even powerful, still-unidentified extragalactic objects. These numerous sources combine to produce particle spectra which extend over fifteen orders of magnitude, to more than 10^{21} eV. Most of these nuclei are fully-stripped of electrons, but others are ions which arrive at Earth with a distribution of charge states characteristic of their origin. The intensity, composition, and spectrum of all of these species also vary with time, location, and arrival direction.

The Cosmic Ray Effects on Micro-Electronics (CREME) program [1] was the first computer code to provide a comprehensive description of this complex environment in a numerical form appropriate for calculating effects on electronic systems. Since its first release in 1981, CREME has literally become an industry standard: its use is mandated for DOD systems in MILSTD-1809 and is also a frequent contractual requirement in both NASA and commercial programs. Many of the CREME environment subroutines and calculation techniques have also been incorporated into other widely-used codes, such as Space Radiation [2], NOVICE [3], and MACREE [4].

Since the last CREME update [5] in 1986, there have been many advances, both in our knowledge of the space radiation environment and in understanding how this environment affects spacecraft systems. Increased computer power and new numerical methods now make it possible to routinely undertake more exact radiation-effect calculations, which formerly were prohibitively time-consuming. Graphical-user interfaces have greatly simplified operation of complex computer codes. Moreover, the Internet and World-Wide Web have revolutionized the way in which such programs can be developed, tested, updated, and accessed by the user community. All of these developments have made an update of CREME long overdue.

In this paper we present some of the major features of CREME96. We show how the revised models provide better descriptions of the ionizing radiation environment. We also discuss the significance of these improvements for single-event-upset (SEU) calculations in various orbits. Due to space limitations many details cannot be presented here. Additional information is available at the CREME96 website (http://crsp3.nrl.navy.mil/creme96/).

II. Galactic Cosmic Rays

Galactic cosmic rays (GCRs), whose spectra extend to very high energies, cannot be eliminated by shielding. GCRs are always present, but below ~10 GeV/nuc their intensity varies with the solar-activity cycle. The primary deficiency in the old CREME GCR model [5] was that it gave an inaccurate description of this solar-cycle-variation.

GCRs in CREME96 are based on the semi-empirical model of Nymmik *et al.* [6], which relates the solar-cycle variation in the GCR intensity to the observed time-history of the Wolf (sunspot) number[1]. This empirical relationship is reasonable: sunspots are a general measure of the level of solar activity. When solar activity is high, the solar wind is more dynamic and hence more effective at impeding GCR penetration into the Solar System. Thus, there is an empirical anti-correlation between the number of sunspots and the GCR intensity at Earth. Of course, the anti-correlation is not simple: it varies with the ion's rigidity (momentum per unit charge), since high-rigidity cosmic rays are less effectively scattered and better able to penetrate the heliospheric magnetic field. Moreover, since the solar wind takes $\sim$1 year to propagate to the boundary of the heliosphere, there is a rigidity-dependent time-lag between the sunspot number and the correlated effect on GCR levels at Earth. Finally, in addition to solar-wind effects and the general level of solar activity, GCR penetration into the Solar System is also affected by the large-scale structure of the heliospheric magnetic field. The polarity of the solar magnetic field reverses every 11 years, causing consecutive cosmic-ray maxima to differ significantly in their durations. This pattern is also incorporated into the Nymmik *et al.* GCR model.

We made an independent assessment of how well this GCR model describes the observational database. Figure 1 shows 27-day-averaged solar-quiet fluxes [7] in 1973-96 from the University of Chicago's Cosmic Ray Telescope (CRT) [8] on IMP-8. The solid curve shows the CREME96/Nymmik *et al.* model's predictions for these timelines. Particularly noteworthy here is the relatively good description of the post-1992 data, since these measurements were recorded *after* the model and its parameters (other than the Wolf numbers) were published. Some timelines are described better than others; the mean discrepancy between the datapoints and the solid curves is noted in each panel. Overall, the mean discrepancy is $\sim$25%, somewhat larger than the $<$20% claimed by Nymmik *et al.* but nevertheless adequate for space-system design. For comparison, the dashed curves show the simple sinusoidal variation given by the old CREME GCR model, which clearly shows much more severe disagreement with the data.

Figure 2 shows measurements of the interplanetary spectra of H, He, O, and Fe up to high energies for years near solar minimum. The dashed lines are the old CREME model. The solid lines are the CREME96/Nymmik *et al.* model. At high energies, the two models are quite similar and both

[1] CREME96 uses the historic record of Wolf numbers starting in January 1950 and augmented by NOAA predictions through December 1997. For other times, July 1970-June 1992 is used as a reference period, which is assumed to repeat. The sunspot record will be regularly updated on the CREME96 website, to reflect new values and predictions.

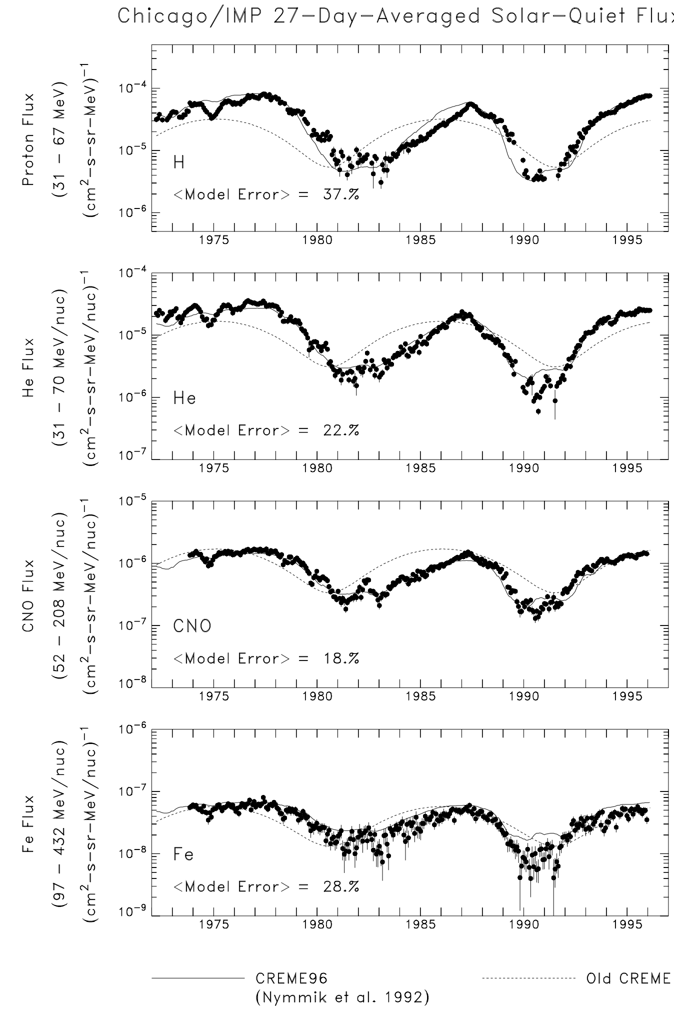

Fig. 1. Solar-cycle variation of Galactic cosmic rays: Chicago IMP-8/CRT data compared to old CREME (dashes) and CREME96 (solid curve). The data and CREME96 curves include small contributions from anomalous cosmic rays, $\sim$10% in the He at solar minimum and much smaller elsewhere. (See Section III.)

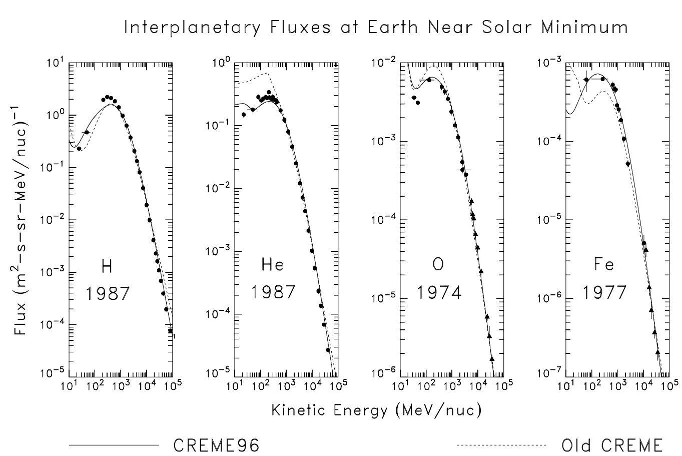

Fig. 2. Solar minimum spectra of H, He, O, and Fe compared to old CREME (dashes) and CREME96 (solid curves). Below $\sim$30 MeV/nuc, the He, O, and (in old CREME) Fe are dominated by anomalous cosmic rays. (See Section III.)

in reasonable agreement with the data. There are clear differences, however, below ~1000 MeV/nuc, with CREME96/Nymmik *et al.* giving a better description of the data. The most significant difference is the increased Fe flux below ~1000 MeV/nuc.

The CREME96/Nymmik *et al.* GCR model also shows comparable improvements over old CREME when compared to a comprehensive database of GCR measurements assembled by Adams and Lee [9]. After screening for quality, this database comprised 2158 GCR measurements in 1963-87 from 65 publications. The database included spectra for the major elements (H, He, C, O, Ne, Mg, Si, and Fe) and elemental ratios for all minor elements through Ni. When compared to this database, old CREME gave a mean error of ~40%; the CREME96/Nymmik *et al.* model, on the other hand, reduced the mean error to ~25% [2].

The solar-minimum GCR environment is generally used as a benchmark in space-system design studies. Although the GCR model in CREME96 gives a much improved description of the solar cycle variation in GCR intensity, Figure 2 suggests that changes in the solar minimum environment *per se* are relatively small. This is confirmed in Figure 3, which shows calculated SEU rates[3] behind 100 mils Al shielding in geosynchronous orbit for a set of representative devices [13]. These devices were chosen to represent a wide range of thresholds, device dimensions, and technologies. They are ordered in the figure roughly according to increasing SEU-vulnerability. The filled circles in Figure 3 were calculated with the CREME96 GCR model[4]; the open circles with the old CREME model. The calculated solar-minimum SEU rates are nearly the same for the two models, with a slight increase (~30%) in the highest-threshold devices, due to the additional Fe flux shown in Figure 2.

III. Anomalous Cosmic Rays

Anomalous cosmic rays (ACRs) were first identified as a "bump" in the spectra of certain elements (He, N, O, and Ne) at ~10 MeV/nuc. Although ACRs are of great interest for particle-acceleration and heliospheric-transport studies, we now know they are relatively unimportant for spacecraft design.

However, this unimportance was not known when the original CREME code was written. In fact, it was thought

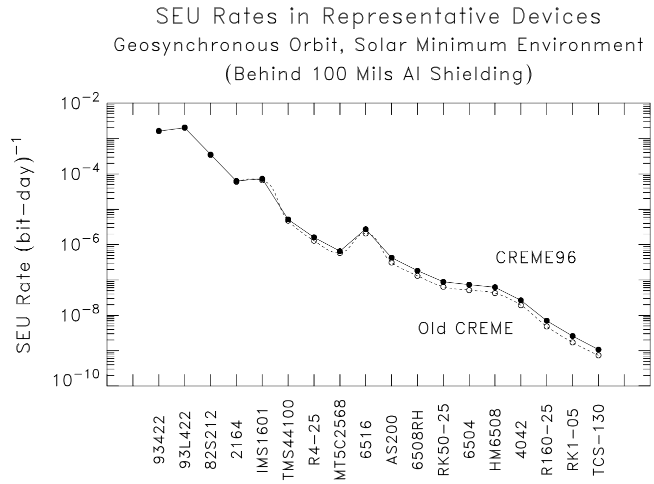

Fig. 3. SEU rates in representative devices at solar minimum, in geosynchronous orbit under 100 mils shielding, calculated with old CREME and CREME96.

that *if* ACRs had hard spectra and included very heavy ions, they would be the dominant part of the high linear-energy-transfer (LET) environment in many low-Earth orbits. The reason for this was that ACRs are singly-ionized ions [18], [19], at least at low energies. This low charge state gives ACRs tremendously enhanced access to low-Earth orbits to which fully-stripped Galactic cosmic rays of the same energy are forbidden[5].

The CREME96 ACR model is primarily based on SAMPEX results [23]. Figure 4 compares the old CREME [5] and CREME96 ACR models[6]. Figure 4 also shows some observed ACR fluxes, including recent high-energy ACR oxygen measurements from SAMPEX. The old CREME model, which was based on the very limited data available at the time, had spectra which were too hard. The old CREME model also included some highly-ionizing species (Mg, Si, and Fe) at levels inconsistent with present observational upper limits[7]. Moreover, old CREME recom-

[2]We note that there are also other recent GCR models [10], [11], [12] which appear to offer comparable improvements over the old CREME GCR model. We have not undertaken a detailed evaluation of these other GCR models, since the comparisons shown here demonstrate that the Nymmik *et al.* [1992] model provides adequate accuracy for space-system design.

[3]The SEU rates in this figure and elsewhere in this paper were calculated with CREME96 routines using the standard integral rectangular parallelepiped (IRPP) formalism [14],[15], [16], with Weibull parameters and rectangular parallelepiped (RPP) depths as given by [13].

[4]The original Nymmik *et al.* model only describes GCRs through nickel (Z=28). The rare, ultraheavy GCRs with Z>28 can be important for low-altitude, low-inclination orbits and latchup analyses. For CREME96 we therefore extended the model through Z=92 using the measured GCR ultraheavy abundances relative to Fe [17], augmented by theoretical estimates in cases where individual elements were not experimentally resolved.

[5]There is another interesting consequence of this singly-ionized charge state and enhanced geomagnetic access. Singly-ionized ACRs penetrate deep into Earth's magnetosphere, where collisions with atoms in the upper atmosphere cause them to lose electrons. The loss of electrons collapses the ions' gyroradii, and the ions become trapped in Earth's magnetic field. Trapped ACRs were discovered as a "third radiation belt" around Earth in 1991 [20] and have been extensively studied by SAMPEX since 1992 [21]. However, because trapped ACRs also have very steep spectra, they are easily eliminated by shielding. They are unlikely to have any impact on spacecraft design except for very lightly-shielded components (<50 mils) and in small portions of certain orbits. See [22] for further details. *Trapped* ACRs are *not* included in CREME96.

[6]This figure shows ACR fluxes near solar-minimum. ACR fluxes vary by a factor of ~500 between solar minimum and solar maximum. Old CREME ignored this solar-cycle variation. CREME96 models the variation from the historical record from 1968-92 given by [30]. The CREME96 software's "solar-quiet" option automatically provides the correct combination of GCRs and ACRs for all times in the solar cycle and for all orbits.

[7]ACR sulfur has very recently been observed below ~20 MeV/nuc near Earth [28]. Anomalous Si and Fe have also been recently reported [29] below 20 MeV/nuc by Voyager spacecraft *in the outer heliosphere* (> 45 AU). These additional ACR species are at energies and flux levels too low to affect spacecraft design. At present they are not included in the CREME96 ACR model.

mended that ACRs be treated as singly-ionized at all energies. Recent SAMPEX results [23], which have been incorporated into CREME96, show that ACRs are multiply charged above ~20 MeV/nuc.

These changes in the ACR model have significant impact on SEU-rate calculations for low-Earth orbits. To demonstrate this, Figure 5 shows SEU rates behind 100 mils Al shielding in 28.5^o, 450 km orbit for the set of representative devices [13]. In low-threshold devices, where relativistic Galactic cosmic rays dominate, the SEU rates are unchanged. However, in the higher threshold devices, the incorrect ACR model in old CREME led to gross overestimates of the SEU rates in this orbit.

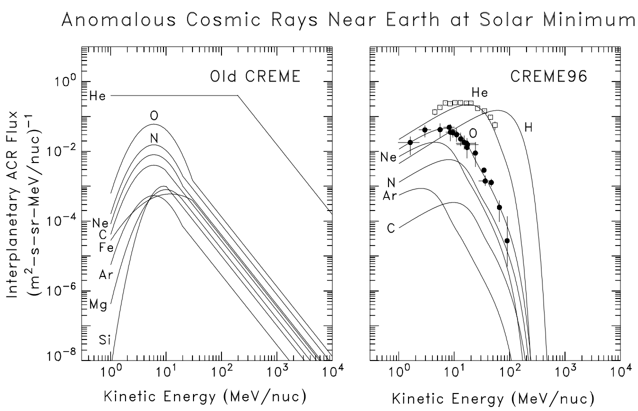

Fig. 4. Anomalous cosmic ray model spectra from old CREME (left) and CREME96 (right). Also shown on the right are measurements of He (open squares) [24] and O (filled circles) [23, 24, 25]. Measurements of other elements [21, 24, 26, 27] have been omitted for clarity.

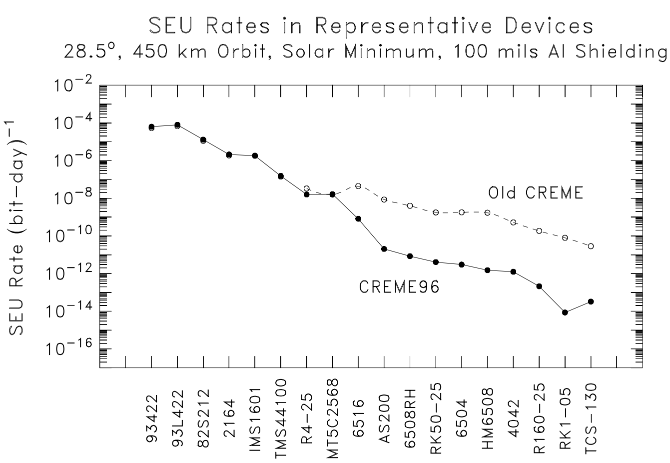

Fig. 5. SEU rates in representative devices, calculated with old CREME and CREME96 GCR+ACR models.

IV. Solar Particle ("Flare") Events

Solar particle events (or, as colloquially but inaccurately known, "flares") are undoubtedly the aspect of the near-Earth ionizing radiation hazard for which the most progress has been made in the past decade. First of all, it is now known that the high-energy, long-duration particle events which are important for spacecraft design are caused by shocks driven by fast coronal mass ejections (CMEs) [31], [32], [33] and *not* by flares. Flares often occur in coincidence with CMEs and thus sometimes provide a useful early-warning, but they are neither the direct cause of these events nor the accelerator which produces the large fluences of high-energy particles which endanger spacecraft. Moreover, during the most-recent solar-active period in 1989-92, there were 25 major solar particle events, all of which were reasonably well-measured [34]. Among these was the October 1989 event, which has provided comprehensive data on a genuine 99%-confidence level [CL] worst-case event [35]. Finally, TDRS-1 and LEASAT reported SEU rates during these particle events, providing on-orbit validation of techniques for accurately calculating SEU rates during solar particle events. (See [34] for further details.)

A. "Worst-Case" Particle Event

It has long been recognized that the solar particle models in old CREME were often unrealistically severe, primarily because they were unconstrained by heavy-ion data at the high energies relevant to space system design. One of the highest priorities of the CREME96 revision was therefore a realistic "worst case" solar particle model, based on the actual measurements of the October 1989 event [34]. Proton and heavy-ion measurements for this event extended to ~500-800 MeV/nuc, depending on species. The October 1989 event is undoubtedly the largest particle event since at least August 1972. [See [35] for further discussion.] The best available data indicate that, in terms of total proton fluence above 10 MeV, the October 1989 event was roughly twice as large as the August 1972 event[8]. According to the event-integrated fluences quoted by Feynman *et al.* [37], the October 1989 event also qualifies as a 99%-CL worst-case event in the three highest energy channels (>10, >30, and >60 MeV) of the JPL91 proton model [37]. The quoted proton fluences for the August 1972 event [37], on the other hand, are at the 99% level for 10 and 30 MeV, but not for 60 MeV [4].

CREME96 presently offers three solar particle models, all based on GOES proton data [40] and high-energy heavy-ion measurements from the Chicago's IMP-8/CRT. These measurements were cross-checked against data at lower- and overlapping energies from other satellites wherever possible [34]. The CREME96 "worst-week" model uses fluences averaged over 180 hours (=7.5 days) of the 19-27 October 1989 event. This "worst-week" model formally

[8] The >10 MeV proton fluence in the October 1989 event was 1.93 x 10^{10} protons/cm^2 [36], according to the GOES-7/MEPAD, which was unaffected by significant instrumental deadtime even in the peak of the 20 October 1989 "shock spike" [35] and which also appears to have minimal electron background in its >10 MeV proton channels. According to [37], the > 10 MeV proton fluence in the August 1972 event was 1.13 x 10^{10} protons/cm^2. This value has been corrected for the substantial electron background (~60% of the apparent fluence) in the IMP-5/6 proton channels [38] which was neglected in earlier reports on the August 1972 event [39]. However, this large electron background implies significant systematic uncertainty in the August 1972 proton fluence, which probably precludes further useful analysis of the event's relative ranking.

corresponds to a ~99%-CL worst-case event [35]. Reference [34] gives further details on validation of this model by comparison with SEU rates observed on TDRS-1.

The other two CREME96 solar particle models focus on shorter-duration, higher-intensity intervals during this worst-case event, which may be more appropriate for evaluating peak-rate (rather than total-fluence) effects. The "worst day" model is based on fluxes averaged over 18 hours beginning at 1300 UT on 20 October 1989. This time corresponded to the arrival near Earth of a powerful interplanetary shock, driven by the fast coronal mass ejection which erupted from near the center of the solar disk on the previous day. This period contained the highest particle fluxes of the entire week-long disturbance, with the shock raising fluxes by roughly another order of magnitude for ~3-6 hours [36],[41].

The CREME96 "peak-flux" model is based on the highest 5-minute-averaged fluxes reported by GOES on 20 October 1989. Since direct heavy-ion measurements are not possible on such a short time scale, heavy-ion fluxes in the "peak-flux" model are scaled from the "worst-day" heavy-ion fluxes, using energy-dependent ratios of the peak-5-minute-flux to the 18-hour-averaged-flux, as determined from the GOES protons. These "peak" fluxes exceed the "worst-day" model by roughly a factor of 5.

Figure 6 shows the predicted SEU rates from these CREME96 solar particle models, as calculated in geosynchronous orbit behind 100 mils Al shielding. For comparison, also shown are the rates calculated with the two old CREME solar particle models (denoted M=9 and M=10), which purported to represent peak rates in the 4 August 1972 event. Even the CREME96 "peak flux" model falls at least one order of magnitude below these old models. All heavy-ion fluxes above ~40 MeV/nuc in the August 1972 event came from a single 4-minute sounding-rocket flight [42], [43], and there were no Fe measurements above ~60 MeV/nuc. (See also [44], [45].) It is quite reasonable to discard the old CREME models in favor of the CREME96. models, which are based on direct measurements throughout the range of energies and atomic numbers relevant to space-system design.

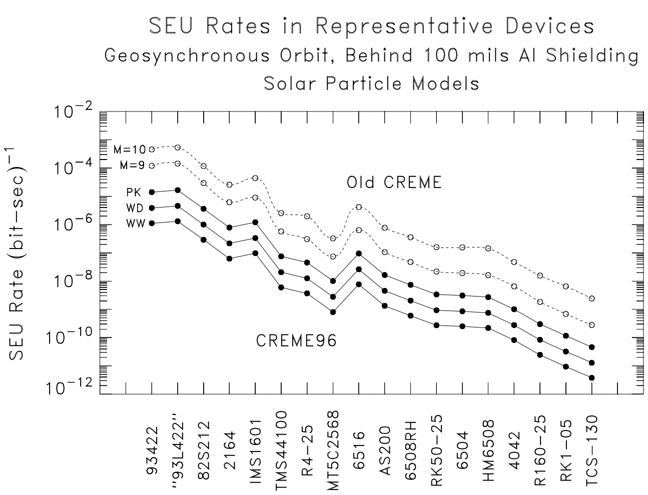

Fig. 6. SEU rates in geosynchronous orbit, behind 100 mils Al shielding as predicted by the three CREME96 solar particle models (peal flux ["PK"], worst-day ["WD"], and worst-week ["WW"]; filled circles and solid lines) and old CREME M=9 and 10 models (open circles and dotted lines). Only elements with atomic number Z > 2 were included in these calculations.

We note that other authors [4],[48] have also recently attempted new solar particle models, based on heavy-ion measurements from Galileo during the last ~40% of the October 1989 event. However, the Galileo measurements did not really extend to sufficiently high energy: for example, the highest-energy Fe measurement from Galileo was at 64 MeV/nuc, but ~85 MeV/nuc is needed to penetrate 100 mils Al shielding. Comparison to Fe measurements from the IMP-8/CRT, which extended to ~800 MeV/nuc, showed that these other models significantly underestimated the high-energy Fe fluence. (See [34] for details.) The potential importance of this discrepancy is illustrated in Figure 7, which compares calculated SEU rates from CREME96 and these other models in representative devices [13] in geosynchronous orbit. To make a realistic comparison, the calculation was carried out using the TDRS-1 shielding distribution [49]. For low-threshold devices, the three models give SEU rates which agree to within a factor of two. However, at higher thresholds, where the penetrating Fe fluence is important, the other models fall as much as an order of magnitude below the CREME96 prediction.

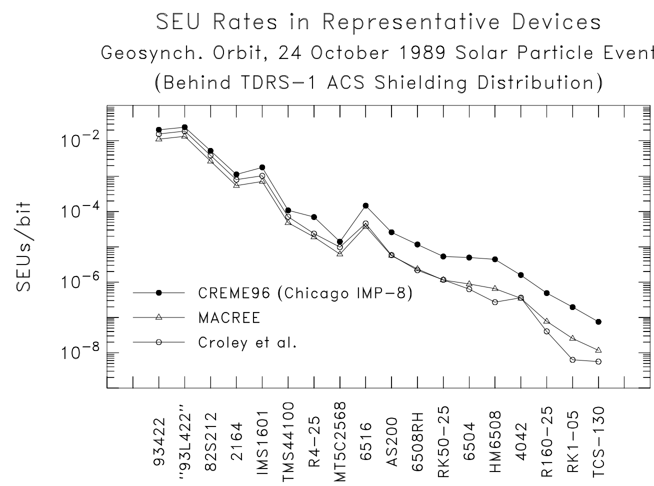

Fig. 7. SEUs during the 24 October 1989 event, as predicted by CREME96 [34], MACREE [4], and the Croley *et al.* model [48] for representative devices, under TDRS-1 shielding in geosychronous orbit. Only elements with atomic number Z > 2 were included in these calculations.

Finally, we also note that the CHIME software package [10] contains new solar particle models based on CRRES observations of the March and June 1991 events. However, those two events were much smaller than the October 1989 event used in CREME96. (The observed SEU rates on TDRS-1, for example, were larger in October 1989 than in March and June 1991 by factors of ~12 and ~8, respectively [34].) CHIME also contains other solar particle models, in which heavy ion fluences are scaled from JPL91 proton fluences [37], using energy-independent average relative abundances. These other CHIME solar-heavy-ion models should probably be used with caution, in that solar protons are known to provide only a poor indicator of high-energy heavy-ion fluence [46], especially Fe[9].

B. Ionic Charge States of Solar Heavy Ions

Another important discovery since old CREME is that high-energy solar heavy ions in these large particle events are not fully-stripped of their electrons. Instead, they have ionic charge states characteristic of the ~2-million kelvin coronal plasma from which they were accelerated [50], [51]. For example, the mean-ionic charge state of solar Fe ions is ~14, rather than 26, as for fully-stripped Galactic cosmic ray Fe nuclei. Moreover, these partially-ionized charge states persist to the very highest energies [52]. In fact, these charge states are one of the key pieces of evidence in establishing CME-driven shocks, rather than flares, as the primary accelerator of solar energetic particles.

The importance of these charge states for spacecraft design is that they greatly enhance the ability of solar heavy ions (especially Fe) to penetrate Earth's magnetic field and to reach low-Earth orbits [53]. This enhancement is illustrated in Figure 8, which shows two calculations of SEU rates in a 28.5^o, ~450 km orbit. The solid circles shows (incorrect) calculations in which the solar heavy ions are assumed to be fully-stripped, like GCRs. The open circles shows (correct) calculations in which the solar heavy ions are partially-ionized. In low-threshold devices, the SEU rates are nearly the same. However, in high-threshold devices, in which the penetrating Fe fluence dominates the SEU rates, ignoring the partially-ionized charge states underestimates the SEU rates by as much as 2-3 orders of magnitude. In the Space Station orbit (51.6^o, ~450 km), partially-ionized charge states increase SEU rates by only a factor of two or so. And, of course, these charge states have no impact on SEU rates in geosynchronous and interplanetary orbits.

V. Geomagnetic Transmission

Geomagnetic transmission refers to the ability of a charged particle to penetrate the near-Earth magnetic field and to reach a point inside Earth's magnetosphere from interplanetary space. Because the near-Earth magnetic field is far from a simple dipole, calculating geomagnetic transmission involves trajectory tracings through a numerical model of the field. These trajectory tracings are generally very time consuming; in fact, they are often done on supercomputers. For spacecraft design, the results of these trajectory tracings are summarized in a world-wide grid, which specifies the minimum ("cutoff") magnetic rigidity a particle must have in order to reach that location from interplanetary space, as a function of latitude, longitude,

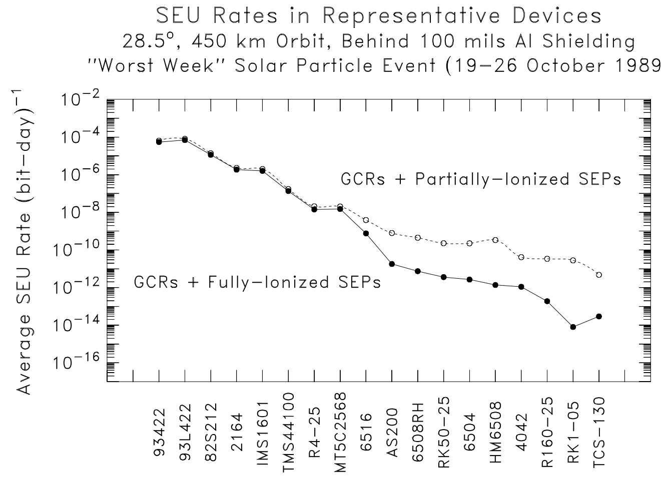

Fig. 8. Effect of solar particle ionic charge states on SEU rates in representative devices in 28.5^o 450 km, behind 100 mils shielding.

altitude, and arrival direction. Old CREME [5] used the 5^o latitude x 15^o longitude world-wide grid of vertical cutoffs at 20 km, as given by Shea and Smart in 1975 [54].

Updated geomagnetic transmission calculations are needed for several reasons. Over the past 25 years, the Earth's magnetic field has decayed and shifted its centroid. In addition, the previous grid calculation considered only the Earth's internal field. Old CREME therefore included an approximate analytic correction to describe enhanced geomagnetic access during large geomagnetic storms. However, there is now a reasonably good empirical model of the magnetospheric current systems [55] which cause this effect[10]. Recent work has also demonstrated how the model can be extended to give accurate geomagnetic transmission calculations even during very large disturbances [56]. The effects of these very large geomagnetic storms are especially important, since they often occur in coincidence with very large solar particle events. (The 20 October 1989 shock event is an example.)

Calculation of a new set of geomagnetic cutoff grids, using the combined International Geomagnetic Reference Field [57] and the extended Tsyganenko model [56] are currently in progress using supercomputer facilities provided by the DOD High Performance Computing (HPC) program. The grid calculations will cover several levels of geomagnetic disturbance. When completed, these grids will allow transmission calculations to arbitrary orbits.

At present, however, results from these new techniques are available in the CREME96 website for only two orbits which are of particular importance to NASA: 51.6^o at 450 km (Mir and International Space Station) and 28.5^o

[9]CHIME also lacks other features included in CREME96. The CHIME User's Guide [47] makes no mention of solar ionic charge states and multiply-charged ACRs. CHIME also uses geomagnetic transmission (based on an offset-tilted dipole field approximation) and nuclear transport routines (which neglect projectile fragments) that are less accurate than those in CREME96.

[10]The complex current systems flowing in Earth's magnetosphere also generate magnetic fields, which tend to partially cancel the Earth's internal field. The most important current system is the so-called "ring current". Even in geomagnetic-quiet periods, these additional magnetic fields allow particles to penetrate to lower latitudes than would be permitted by the Earth's field alone. During geomagnetic storms, the ring current is enhanced, leading to even more geomagnetic penetration.

at 450 km (a common orbit for Shuttle missions). Transmission calculations for these two orbits are available as "pre-calculated" options both for a quiet magnetosphere and for a very large geomagnetic disburbance (Dst = - *300 nT*)[11]. These "pre-calculated" transmission functions take into account the solid angle obstructed by the Earth and averaging over arrival directions. The latter is especially important in the 28.5^o orbit, to which particles approaching from westerly directions have access at significantly lower rigidities. For other orbits, CREME96 presently estimates the geomagnetic transmission from a more recent (Epoch 1980.0) Shea & Smart vertical-cutoff grid, neglecting a formal average over arrival directions, but taking into account the solid-Earth obstruction and using an approximate semi-empirical correction [59] to account for the effect of magnetospheric current systems at high latitudes.

These more-accurate geomagnetic transmission calculations are generally expected to lead to only modest increases in calculated SEU rates in low-Earth orbits. A potentially more important consequence of these improvements is illustrated in Figure 9, which shows the orbit-averaged solar proton flux in the Space Station orbit *behind 10 mils shielding*, roughly appropriate for solar cells. Both calculations use the CREME96 proton fluxes for the 20 October 1989 "worst day" shock event, but they differ in using either the old CREME or CREME96 stormy geomagnetic transmission function (GTF). CREME96's more thorough treatment of cutoff supression during this large storm leads to a large flux of low-energy protons which are not predicted by old CREME. This enhanced low-energy proton flux increases the calculated dose from 0.002 krad to 0.8 krads[12]. Of course, total dose is not the correct parameter for evaluating impact on solar cell performance. However, the difference between these two proton spectra in a proper displacement-damage calculation would probably be even larger than these dose numbers suggest, since the lower-energy flux is even more effective in causing displacement damage [60], [61], [62].

CREME96 also allows calculations of geomagnetic transmission to *segments* of orbits, as delineated by McIlwain L[13]. This capability may be particularly useful in comparing with on-orbit data, since experiments often use such L-bands in analyzing their SEU rates. This capability may also be useful in making operational decisions.

As an example of this capability, Figure 10 shows integral LET spectra observed by the one of the CREDO-II detectors on the APEX satellite [71]. The authors reported their

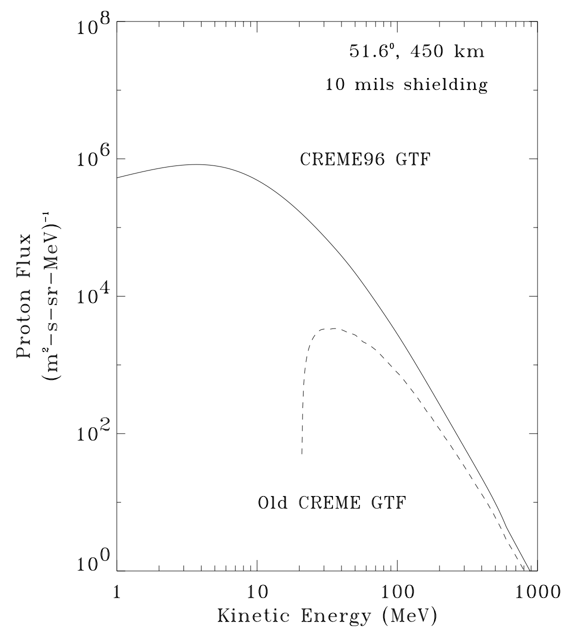

Fig. 9. Effect of improved geomagnetic transmission calculation on orbit-averaged "worst day" solar proton flux in the Space Station orbit behind 10 mils shielding.

results in four orbital sections, corresponding to different geomagnetic-cutoff bands. For purposes of this comparison, we translated these cutoff boundaries into McIlwain L, using the approximate formula $R_c = (14.5\,GV)/L^2$ [72]. These comparisons test not only the CREME96 geomagnetic transmission routine, but also the GCR model and nuclear transport.

The solid lines are the absolute CREME96 predictions, made using only the information specified by [71], namely dates, orbital parameters, and shielding distribution. (See below.) The dashed lines are the CREME96 predictions, but renormalized in each panel to the observed flux at ~900 MeV-cm^2/g. The normalization adjustment factors, which range from 0.80 to 1.11, are noted in the panels[14].

CREME96 accounts reasonably well not only for the absolute flux but also the shapes of the integral LET spectra. Some discrepancies, however, should be noted. The CREDO-II spectra are flatter than the CREME96 predictions below ~200 MeV-cm^2/g. However, the observed flatness seems unreasonable since this is an integral spectrum, suggesting a possible detection inefficiency at low LET. More interestingly, the high-cutoff (low-latitude, low altitude) bins show excess flux in the LET range above ~1500 MeV-cm^2/g. The origin of this discrepancy is not clear. It may be an experimental artifact[15]; or it may reflect the

[11] *Dst* is the change in the horizontal component of Earth's magnetic field at the equator, as determined by averaging over hourly reports from a specific network of magnetometer stations [58]. *Dst* is measured in nanoTesla (nT), where 1 nT = 10^{-5} Gauss.

[12] For comparison, the expected dose due to trapped protons for this orbit and shielding is only ~3 krad per year: this 18-hour event would thus accumulate roughly 3 months worth of dose!

[13] McIlwain L [63] is the geomagnetic coordinate used to label magnetic field lines and (more properly) particle drift shells in the magnetosphere. L corresponds roughly to the distance from the center of the Earth's magnetic dipole to the magnetic field line's location at the magnetic equator, measured in units of Earth radii. For example, geosynchronous orbit is roughly at L = 6.6.

[14] Similar analyses for the other CREDO-II module on APEX and one of the modules on the STRV spacecraft showed normalization adjustments between 0.67-1.31. The worst discrepancy came from the second module on STRV, where the normalization adjustments were ~0.40. However, we found those particular results puzzling, since they purported to show *less* particle flux in a *less-shielded* detector.

[15] The CREDO-II authors say that the discrepancy cannot be due to Si target fragments, since such interactions would not trigger the telescope. They suggest, however, that the discrepancy may be asso-

need for better geomagnetic transmission calculations for this orbit (still under development, as explained above), or an unknown component of the low-Earth environment, not included in CREME96.

VI. Other CREME96 Improvements

A. Nuclear Transport

Accurate nuclear transport is an essential part of space radiation effect calculations, since the external space environment contains a large flux of low-energy particles which do not penetrate to the interior of typical spacecraft. Also, when passing through shielding, fast nuclei slow down, and heavy nuclei can fragment into lighter ones.

The CREME96 nuclear transport module calculates a numerical solution of the one-dimensional continuity equation, taking into account both ionization energy loss (in the continuous-slowing-down approximation) and nuclear fragmentation. CREME96 incorporates accurate stopping power[16] and range-energy routines [64], [65], [66], and uses semi-empirical energy-dependent nuclear fragmentation cross-sections [68], [69], [70]. Unlike the old CREME code, the transport code in CREME96 keeps track of charged nuclear fragments from the cosmic ray projectiles and is therefore more accurate under thick shielding. CREME96 also allows the user to import into the code a *distribution* of shielding thickness (as determined from a sector-shield analysis provided by some other software package). Careful treatment of shielding distributions is critical for accurate calculation of effects due to solar particles [34], [73].

Limitations of the present CREME96 nuclear transport code are: (1) it does not include neutron production in the shielding; (2) it does not include target fragments; (3) at present aluminum is the only available shielding material; and (4) at present silicon is the only available target material. (In general, other shielding and target materials can easily be added, if requested.)

B. SEU-Calculation Techniques

CREME96 contains modules which take the results from the environment and nuclear transport modules and calculate proton- and ionization ("heavy-ion")-induced SEU rates. However, the user must supply the SEU-cross-section data and (for heavy-ions) RPP depth.

ciated with the cutoff-binning of the data.

[16] We compared results from the CREME96 energy-loss routines and the Stopping and Range of Ions in Matter (Version 96.02; SRIM96) [67]. These comparisons showed only minor discrepancies, too small to significantly affect SEU calculations. The largest discrepancy appears near the peak of the Fe stopping power curve at ~1 MeV/nuc, where the SRIM96 value is larger than the CREME96 value by ~15%. The origin of this disrepancy is not yet understood. There is also a systematic discrepancy between CREME96 and SRIM96 below ~0.1 MeV/nuc. At these low energies (where ion ranges are less than 1 micron), SRIM96 shows stopping powers which monotonically decrease with decreasing energy. CREME96, on the other hand, shows stopping powers which increase with decreasing energy below ~0.1 MeV/nuc. This turn-up is expected, as nuclear and atomic collisions (instead of ionization) begin to contribute to the energy loss. In any case, this discrepancy has no impact on SEU calculations.

Heavy-ion SEU rates are calculated in CREME96 with the IRPP method [14],[16]. To specify the cross-section, the user can supply either the Weibull parameters [15] or a table of fully-corrected cross-section values. Funnels [16] may also optionally be specified. In addition, CREME96 retains the "critical charge" option of old CREME, in which the cross-section is treated as a simple step function in LET. Although this technique does not give accurate results for space applications, it may be useful to chip designers. The CREME96 heavy-ion-SEU routine also corrects a minor bug in the old CREME "UPSET" routine and uses more accurate numerical integration techniques.

For proton-induced SEUs, the user can supply Bendel-1 [74], Bendel-2 [75], or Weibull [34] fit parameters for the energy dependence of the cross-section or a table of cross-section values.

C. *http://crsp3.nrl.navy.mil/creme96/*

The primary focus of this work has been developing and validating the model improvements discussed above. However, effective evaluation and dissemination of these models also requires an easy-to-use and widely-accessible interface. Making improved, validated models available as quickly as possible is especially important, given the shortened development cycles under which many projects must nowadays operate.

The CREME96 website (address above) meets these requirements. The website is freely available, although users are required to provide some background information when they first register to use the site. Users provide inputs to the various CREME96 program modules via hypertext-markup-language (HTML) pages, using "point and click" and pull-down menus as much as possible. Results from one program module are automatically forwarded to subsequent modules. The website also provides numerous hyperlinks, which serve as a tutorial on using the CREME96 routines and provide expert-advice on suitable parameter values for various applications. CREME96 output files have extensive header information which record all the inputs into the calculation. The website software can also generate figures and tables of particle fluxes, LET spectra, etc. The user can download these files, figures, and tables to his/her own computer for use with other software.

VII. Future Development

All the models and capabilities of CREME96 are superior to the corresponding elements of the old CREME code. Comparisons to data in this paper and in our previous work on solar-particle SEUs [34] demonstrate the accuracy of the models. Since the website's initial release in December 1996, users have reported no errors. Thus, we recommend use of CREME96 over the old CREME code whenever possible. However, it should be noted that the CREME96 software is not yet complete, and that additional capabilities and improvements (discussed below) are still under development. Also, in that use of the old CREME models is often a contractual requirement, the user should obtain permission from his/her sponsor before utilizing CREME96

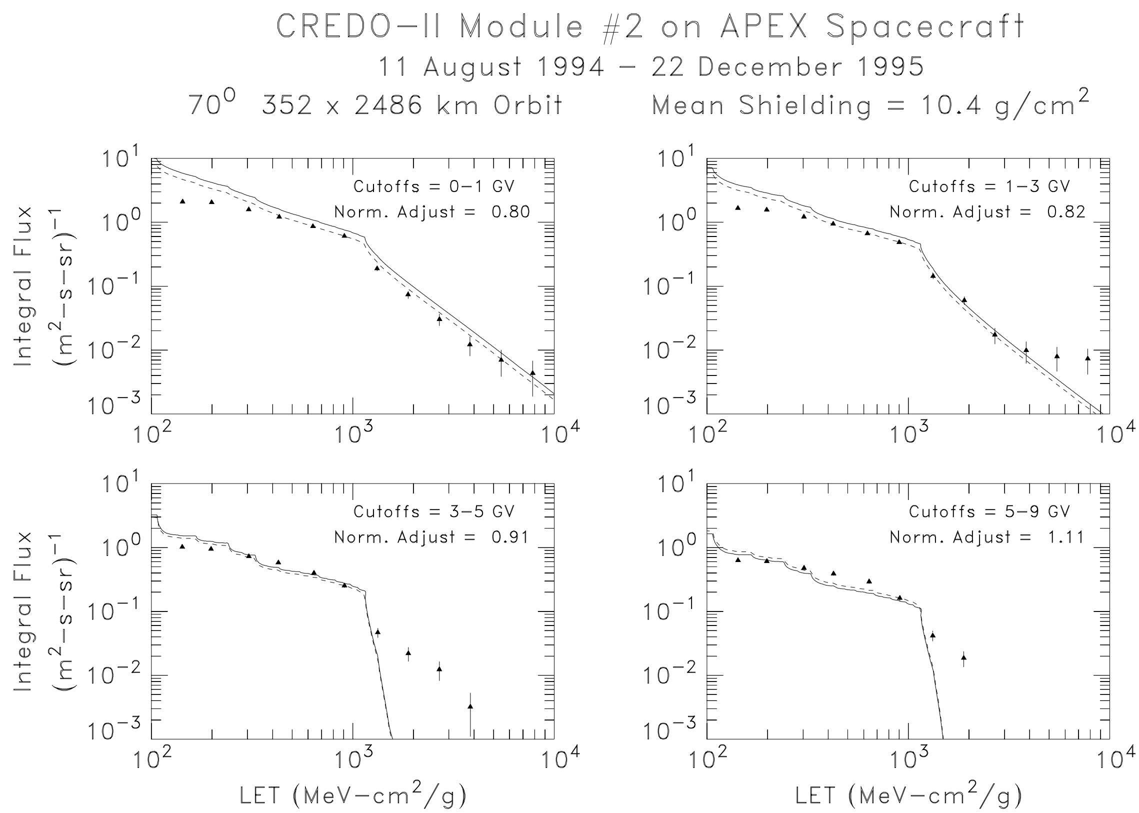

Fig. 10. Observed LET spectra from CREDO-II on APEX (filled triangles with statistical error bars), compared to absolute CREME96 predictions (solid lines) and normalization-adjusted (dashed lines) CREME96 predictions.

for space-system design.

Users have made helpful suggestions for improving the code's ease-of-use. Evaluating and installing these suggestions is in progess. However, most user comments to-date have focused on the need for additional capabilities. The most frequently-requested addition is an interface to a trapped proton model, since trapped protons are the dominant source of SEUs and dose-effects in many low-Earth orbits. Due to funding limitations, no trapped proton interface was included in the original CREME96 release. However, in response to the numerous user requests, work on an interface to the AP8MIN/AP8MAX trapped proton models has been authorized by our sponsors. Work on this interface is also now progress, and the interface should be available in late 1997.

Users have also frequently requested a "90%-confidence-level worst-case environment", similar to that which was available in old CREME code. At low energies, this 90% model reflected genuine variability in the environment. At higher, more-relevant energies, however, flux enhancements in the old CREME code were driven primarily by measurement uncertainties and the large errors in modeling the GCR environment. With the additional data and improved models now available, the effective differences between the solar minimum and 90%-worst case environment will probably be smaller. However, a 90% model is still required, since designing to such a model remains a frequent contractual requirement. Work on a 90% model is also in progress [35], and should be available in early 1998.

We continue to solicit comments from the user community on the accuracy, usefulness, completeness, and user-friendliness of CREME96.

VIII. Acknowledgments

We thank C. Lopate (U. Chicago) for providing the proton and He fluxes shown in Figure 1. This work is sponsored by the NASA Space Environments and Effects (SEE) Program under DPR H-13084D, by the Office of Naval Research, and by NASA contract NAG 5-706 (UC). Two of us (MAS and DFS) are supported in part by AFOSR 6.1. One of us (EOF) acknowledges support by the Swiss National Science Foundation under grant 20-40595.94. Computational support has been provided by the DOD High Performance Computing (HPC) Program.

IX. References

[1] James H. Adams, Jr., R. Silberberg, and C.H. Tsao, "Cosmic Ray Effects on Microelectronics, Part I: The Near-Earth Particle Environment", NRL Memorandum Report 4506, 25 August 1981; J.H. Adams, Jr., J.R. Letaw, and D.F. Smart, "Part II: The Geomagnetic Cutoff Effects", NRL Memorandum Report 5099, 26 May 1983; C.H. Tsao, R. Silberberg, J.H. Adams, Jr., and J.R. Letaw, "Part III: Propagation of Cosmic Rays in the Atmosphere", NRL Memorandum Report 5402, 9 August 1984.

[2] J.R. Letaw, Space Radiation, a commercial code available from Space Radiation Associates.

[3] T.M. Jordan, NOVICE, a commercial code available from E.M.P. Consultants.

[4] Peter P. Majewski, Eugene Normand, and Dennis L. Oberg, "A New Solar Flare Heavy Ion Model and its Implementation Through MACREE, An Improved Modeling Tool to Calculate Single Event Effect Rates in Space", *IEEE Trans. Nucl. Sci.* 42, 2043 (1995).

[5] James H. Adams, Jr., "Cosmic Ray Effects on Microelectronics (CREME), Part IV", Naval Research Laboratory Memorandum Report 5901, 31 December 1986.

[6] R.A. Nymmik, M.I. Panasyuk, T.I. Pervaja, and A.A. Suslov, "A Model of Galactic Cosmic Ray Fluxes", *Nucl. Tracks Radiat. Meas.* 20, 427 (1992). Details of a more recent and slightly different version of this model may be found at http://www.npi.msu.su/gcrf/form.html.

[7] C. Lopate, J. Simpson, and M. Garcia-Munoz, private communication (1997).

[8] M. Garcia-Munoz, G.M. Mason, and J.A. Simpson, "The Isotopic Composition of Galactic Cosmic Ray Lithium, Berylium, and Boron", *Astrophys. J. Letters* 201, L145 (1975).

[9] J.H. Adams, Jr. and J. Lee, "A Model of the Primary Cosmic Ray Spectra", *Radiat. Meas.* 26, 467 (1996).

[10] D.L. Chenette *et al.*, "The CRRES/SPACERAD Heavy Ion Model of the Environment (CHIME) for Cosmic and Solar Particle Effects on Electronic and Biological Systems in Space", *IEEE Trans. Nucl. Sci.* 41, 2332 (1994).

[11] G.D. Badhwar and P.M. O'Neill, "An Improved Model of Galactic Cosmic Radiation for Space Exploration Missions", *Nucl. Tracks Radiat. Meas.* 20 (3)403 (1992).

[12] R.A. Nymmik, M.I. Panasyuk, and A.A. Suslov, "Galactic Cosmic Ray Flux Simulation and Prediction", *Adv. Space Res.* 17 (2)19 (1996).

[13] E.L. Petersen, "SEE Rate Calculations Using the Effective Flux Approach and a Generalized Figure of Merit Approximation", *IEEE Trans. Nucl. Sci.* 42, 1995 (1995).

[14] E.L. Petersen, J.B. Langworthy, and S.E. Diehl, "Suggested Single Event Upset Figure of Merit", *IEEE Trans. Nucl. Sci.* 30, 448 (1983).

[15] E.L. Petersen, J.C. Pickel, J.H. Adams, Jr., and E.C. Smith, " Rate Predictions for Single Event Effects – A Critique", *IEEE Trans. Nucl. Sci.* 39, 1577 (1992).

[16] J.C. Pickel, "Single-Event Effects Rate Predictions", *IEEE Trans. Nucl. Sci.* 32, 483 (1996).

[17] W.R. Binns *et al.*, "Abundances of Ultraheavy Elements in the Cosmic Radiation: Results from HEAO 3", *Astrophys. J.* 346, 997 (1989).

[18] J.H. Adams Jr. *et al.*, "The Charge State of the Anomalous Component of Cosmic Rays", *Astrophys. J. Letters* 375, L48 (1991).

[19] B. Klecker, *et al.*, "Charge State of Anomalous Cosmic Ray Nitrogen, Oxygen, and Neon: SAMPEX Observations", *Astrophys. J. Letters* 442, L69 (1995).

[20] N.L. Grigorov *et al.*, "Evidence for Trapped Anomalous Cosmic Ray Oxygen Ions in the Inner Magnetosphere", *Geophys. Res. Letters* 18, 1959 (1991).

[21] R.S. Selesnick *et al.*, "Geomagnetically Trapped Anomalous Cosmic Rays", *J. Geophys. Res.* 100, 9503 (1995).

[22] A.J. Tylka *et al.*, "LET Spectra of Trapped Anomalous Cosmic Rays in Low-Earth Orbits", *Adv. Space Res.* 17, (2)47 (1996).

[23] R.A. Mewaldt *et al.*, "Evidence for Multiply Charged Anomalous Cosmic Rays", *Astrophys. J. Letters* 466, L43 (1996).

[24] A.C. Cummings, E.C. Stone, and W.R. Webber, "Evidence that the Anomalous Cosmic-Ray Component is Singly-Ionized", *Astrophys. J. Letters* 287, L99 (1984).

[25] A.J. Tylka *et al.*, "*Cosmos* Results on the Altitude Dependence of Geomagnetically Trapped Anomalous Cosmic Rays", *Proc. 24th Internat. Cosmic Ray Conf. (Rome)* 4, 485 (1995).

[26] A.C. Cummings and E.C. Stone, "Elemental Composition of the Anomalous Cosmic-Ray Component", *Proc. 20th Internat. Cosmic Ray Conf. (Moscow)* 3, 413 (1987).

[27] R.A. Mewaldt, "Evidence for Anomalous Cosmic Ray Hydrogen During the 1976-1977 Solar Minimum", *Proc. 24th Internat. Cosmic Ray Conf. (Rome)* 4, 808 (1995).

[28] T. Takashima *et al.*, "The First Observation of Sulfur in Anomalous Cosmic Rays by the *GEOTAIL* and *WIND* Spacecrafts", *Astrophys. J. Letters* 477, L111 (1997).

[29] E.C. Stone and A.C. Cummings, "Evidence for Anomalous Cosmic Ray S, Si, and Fe in the Outer Heliosphere and for a Non-ACR Source of S at 1 AU", *Proc. 25th Internat. Cosmic Ray Conf. (Durban)* 2, 289 (1997).

[30] R.A. Mewaldt *et al.*, "The Return of Anomalous Cosmic Rays to 1 AU in 1992", *Geophys. Res. Letters* 20, 2263 (1993).

[31] J.T. Gosling, "The Solar Flare Myth", *J. Geophys. Research* 98, 18937 (1993); erratum *J. Geophys. Research* 99, 4259 (1994).

[32] S.W. Kahler, "Solar Flares and Coronal Mass Ejections", *Ann. Rev. Astron. Astrophys.* 30, 113 (1992).

[33] D.V. Reames, "Non-Thermal Particles in the Interplanetary Medium", *Adv. Space Research* 13, (9)331 (1993).

[34] A.J. Tylka, W.F. Dietrich, P.R. Boberg, E.C. Smith, and J.H. Adams, Jr., "Single Event Upsets Caused by Solar Energetic Heavy Ions", *IEEE Trans. Nucl. Sci.* 43, 2758 (1996).

[35] A.J. Tylka, W.F. Dietrich, and P.R. Boberg, "Probability Distributions of High-Energy Solar-Heavy-Ion Fluxes from IMP-8: 1973-1996", *IEEE Trans. Nucl. Sci.* (these proceedings).

[36] H.H. Sauer, "GOES Observations of Energetic Protons E>685 MeV: Ground-Level Events from October 1983 to July 1992", *Proc. 23rd Internat. Cosmic Ray Conf. (Calgary)* 3, 254 (1993).

[37] J. Feynman, G. Spitale, and J. Wang, "Interplanetary Proton Fluence Model: JPL 1991", *J. Geophys. Res.* 98, 13281 (1993).

[38] J. Feynman *et al.*, "Solar Proton Events During Solar Cycles 19, 20, and 21", *Solar Physics* 126, 385 (1990).

[39] J.H. King, "Solar Proton Fluences for 1977-82 Space Missions", *J. Spacecr. Rockets* 11, 401 (1974).

[40] Dan Wilkinson and Greg Ushomirsky, "GOES Space Environment Monitor CD-ROM, 1-Minute and 5-Minute Averages, January 1986 - April 1994, User Documentation", NOAA/National Geophysical Data Center, 18 July 1994.

[41] A.J. Tylka *et al.* "HIIS Results on the Mean Ionic Charge State of SEP Fe above 200 MeV per nucleon", *AIP Conf. Proc.* 374, eds. R. Ramaty *et al.*, 96 (1996).

[42] D.L. Bertsch, S. Biswas, and D.V. Reames, "Solar Cosmic Ray Composition above 10 MeV/nucleon and its Energy Dependence in the 4 August 1972 Event", *Solar Physics* 39, 479 (1974).

[43] H.J. Crawford, P.B. Price, B.G. Cartwright, and J.D. Sullivan, "Solar Flare Particles: Energy-Dependent Composition and Relationship to Solar Composition", *Astrophys. J.* 195, 213 (1975).

[44] G.M. Simnett, "Solar Cosmic Radiation During August 1972", *Space Science Reviews* 19, 579 (1976).

[45] W.R. Webber, E.C. Roeloff, F.B. MacDonald, B.J. Teegarden, and J. Trainor, "Pioneer 10 Measurements of the Charge and Energy Spectrum of Solar Cosmic Rays during 1972 August", *Astrophys. J.* 199, 482 (1975).

[46] D.L. Chenette and W.F. Dietrich, "The Solar Flare Heavy Ion Environment for Single Event Upsets", *IEEE Trans. Nucl. Sci.* 31, 1217 (1984).

[47] D.L. Chenette, J.D. Tobin, and S.P. Geller, "CHIME User's Guide for Version 3.4", PL-TR-95-2152, 6 December 1996.

[48] D.R. Croley, H.B. Garrett, G.B. Murphy, and T.L. Garrard, "Solar Particle Induced Upsets in the TDRS-1 Attitude Control System RAM During the October 1989 Solar Particle Events", *IEEE Trans. Nucl. Sci.* 42, 1489 (1995).

[49] E.C. Smith and T.R. Simpson, "Predictions of Cosmic Radiation Induced Single Event Upsets in Digital Logic Devices in Geostationary Orbit", TRW report prepared for INTELSAT, 2 November 1987.

[50] R.A. Leske, J.R. Cummings, R.A. Mewaldt, and E.C. Stone, "Measurements of the Ionic Charge States of Solar Energetic Particles using the Geomagnetic Field", *Astrophys. J. Letters* 452, L149 (1995).

[51] P.R. Boberg, A.J. Tylka, and J.H. Adams, Jr., "Solar Energetic Fe Charge State Measurements: Implications for Acceleration by Coronal Mass Ejection-Driven Shocks", *Astrophys. J. Letters* 471, L65 (1996).

[52] A.J. Tylka, P.R. Boberg, J.H. Adams, Jr., L.P. Beahm, W.F. Dietrich, and T. Kleis, "The Mean Ionic Charge State of Solar Energetic Fe Ions above 200 MeV per Nucleon", *Astrophys. J. Letters* 444, L109 (1995).

[53] A.J. Tylka, P.R. Boberg, J.H. Adams, Jr., L.P. Beahm, and T. Kleis, "Results from the Heavy Ions in Space (HIIS) Experiment on the Ionic Charge State of Solar Energetic Particles", *Proc. 3rd LDEF Post-Retrieval Symposium* 1, 113 (1995).

[54] M.E. Shea and D.F. Smart, "Tables of Asymptotic Directions and Vertical Cutoff Rigidities for a Five Degree by Fifteen Degree World Grid as Calculated Using the International Geomagnetic Reference Field for Epoch 1975.0", AFCRL-TR-75-0185, Hanscom AFB, MA (1975).

[55] N.A. Tsyganenko, "A Magnetospheric Magnetic Field Model with a Warped Tail Current Sheet", *Planet. Space Sci.* 37, 5 (1989).

[56] P.R. Boberg, A.J. Tylka, J.H. Adams, Jr., E.O. Flueckiger, and E. Kobel, "Geomagnetic Transmission of Solar Energetic Protons during the Geomagnetic Disturbances of October 1989", *Geophys. Res. Letters* 22, 1133 (1995).

[57] R. Langel *et al.*, "International Geomagnetic Reference Field, 1991 Revision, *J. Geomag. Geoelectr.* 43 1007 (1991).

[58] P.N. Mayaud, Derivation, Meaning, and Use of Geomagnetic Indices, Geophysical Monograph 22, Washington DC: American Geophysical Union (1980).

[59] R.A. Nymmik, "An Approach to Determination of Real Cosmic Ray Rigidities", *Proc. 22nd Internat. Cosmic Ray Conf. (Dublin)* 3, 652 (1991).

[60] G.P. Summers, E.A. Burke, C.J. Dale, E.A. Wolicki, P.W. Marshall, and M.A. Gehlhausen, "Correlation of Particle-Induced Displacement Damage in Silicon", *IEEE Trans. Nucl. Sci.* 34, 1134 (1987).

[61] G.P. Summers, E.A. Burke, P. Shapiro, S.R. Messenger, and R.J. Walters, "Damage Correlation in Semiconductors Exposed to Gamma, Electron, and Proton Radiations", *IEEE Trans. Nucl. Sci.* 40, 1372 (1993).

[62] C. Dale, P. Marshall, B. Cummings, L. Shamey, and A. Holland, "Displacement Damage Effects in Mixed Particle Environments for Shielded Spacecraft CCDs", *IEEE Trans. Nucl. Sci.* 40, 1628 (1993).

[63] McIlwain, C.E., "Coordinates for Mapping Distributions of Magnetically Trapped Particles", *J. Geophys. Res.* 66, 3681 (1961).

[64] S.P. Ahlen, "Z_1^7 Stopping Power Formulae for Fast Heavy Ions", Phys. Rev. A17, 1236 (1978); "Calculation of the Relativistic Bloch Correction to Stopping Power", *Phys. Rev.* A25, 1856 (1982).

[65] J.D. Jackson and R.L. McCarthy, "Z^3 Corrections to Energy Loss and Range", *Phys. Rev.* B6, 4131 (1972).

[66] R.M. Sternheimer and R.F. Peirels, "General Expression for the Density Effect for the Ionization Loss of Charged Particles", *Phys. Rev.* B3, 3681 (1971).

[67] J.F. Ziegler, J.P. Biersack., and U. Littmark, The Stopping and Range of Ions in Matter, New York: Pergamon Press, 1985; J.F. Ziegler, SRIM Version 96.02 Instruction Manual, 22 December 1995.

[68] C.H. Tsao *et al.*, "Scaling Algorithm to Calculate Heavy-Ion Spallation Cross Sections", *Phys. Rev.* C46, 1257 (1993).

[69] L. Sihver *et al.*, "Total Reaction and Partial Cross-Section Calculations in Proton-Nucleus ($Z_t < 26$) and Nucleus-Nucleus Reactions (Z_p and $Z_t > 26$)", *Phys. Rev.* C47, 1225 (1993).

[70] C.H. Tsao, R. Silberberg, A.F. Barghouty, and M.E. Mattson, "YIELDX: Semi-Empirical Cross-Section Routines", in preparation. Preprints available upon request from *barghouty@acc.roanoke.edu.*

[71] C.S. Dyer, C.J. Watson, C.L. Peerless, A.J. Sims, and J. Barth, "Measurements of the Radiation Environments from CREDO-II on STRV and APEX", *IEEE Trans. Nucl. Sci.* 43, 2751 (1996).

[72] D.F. Smart and M.A. Shea, "The Change in Geomagnetic Cutoffs Due to Changes in the Dipole Equivalent of Earth's Magnetic Field", *Proc. 23rd Internat. Cosmic Ray Conf. (Calgary)* 3, 781 (1993).

[73] E.C. Smith, "Effects of Realistic Satellite Shielding on SEE Rates", *IEEE Trans. Nucl. Sci.* 41, 2396, (1994).

[74] W.L. Bendel and E.L. Petersen, "Proton Upsets in Orbit", *IEEE Trans. Nucl. Sci.* 30, 4481 (1983).

[75] W.J. Stapor, J.P. Meyers, J.B. Langworthy, and E.L. Petersen, "Two Parameter Model Calculations for Predicting Proton Induced Upsets", *IEEE Trans. Nucl. Sci.* 37, 1966 (1990).