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THE LET SPECTRUM AND ITS UNCERTAINTY DURING THE CRRES MISSION

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13. ABSTRACT *(Maximum 200 words)*

We present LET spectra calculated for the 1990 - 1991 CRRES mission using the galactic cosmic ray (GGR) and solar energetic particle (SEP) models developed for the CRRES/SPACERAD program and presented by Chen et al. 1992 at this conference /1,2/. We discuss the dependence of the spectra on uncertainties in the galactic cosmic ray and solar energetic particle models and LET calculation methods. Finally, we illustrate the application and significance of these spectra by using them to predict single event upset event rates in a sample integrated circuit memory device, a 256 x 4-bit bipolar static RAM (93L422).

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INTRODUCTION

The Linear-Energy Transfer (LET) spectrum provides the flux of energetic ions as a function of the energy deposited per unit distance (LET) in a medium. Such a spectrum can include contributions from all energetic ion species over a broad energy range. As such it is a valuable summary tool for studies of space radiation effects due to individual ion interactions /3/.

One specific example of this type of single-particle interaction effect is the Single-Event Upset (SEU) or "bit flip", first confirmed as due to the galactic cosmic rays in 1975 /4/. SEUs are random changes in the electronic logic state of a microelectronic circuit (e.g. a bistable flip-flop) caused by the ionization charge deposited when an energetic charged particle penetrates a sensitive region of the circuit (e.g. a specific transistor structure) /5/. Additionally, individual ions have been observed to trigger "SCR latchup" in CMOS devices /6/. This condition is potentially more hazardous to the circuit than a simple SEU.

The avoidance or the detection and correction of these events is an important design goal for modern space flight electronic systems. Accurate estimates of SEU and latchup rates are required to achieve this goal. The basic characteristics which determine these are established /5/. They include both the space radiation environment, as described by the LET spectrum, and the physical layout and electronic design of the specific circuit.

General models of the environment as well as laboratory test and design analysis tools have been developed and are being used widely to guide the engineering design and analysis of space systems /7,8/. A number of experiments have been performed in space to validate these models and methods /9,10/. The CRRES/SPACERAD program includes on-orbit SEU tests of many different microelectronic devices in the CRRES Microelectronics Package /11,12/. In support of this program we have developed improved models of the radiation environment during the CRRES mission based on contemporary measurements of both the galactic cosmic ray and solar energetic particle fluxes.

In this paper we describe the methods used to convert the galactic cosmic ray and solar energetic particle flux measurements into LET spectra. Factors contributing to uncertainties in the results are described. The galactic cosmic ray LET spectra for CRRES are compared to estimates for this period from the CREME code /7/. LET spectra for a pair of large solar energetic particle events are also provided to illustrate the importance of this source. Finally we provide some SEU rate calculations for a specific bipolar memory device, the 93L422, a 256 x 4-bit static RAM.

LET SPECTRUM CALCULATION METHOD

The method used to calculate LET spectra is based on a range-energy software package originally developed to calibrate cosmic ray and solar energetic particle instruments /13/. The range R(E,Z,M) for an ion with kinetic energy E, atomic number Z and mass M is scaled from the proton range tabulation of Janni /14/ at energy E/M by MZ^{-2}. In addition, a range extension correction is applied to account for charge pickup at low velocities based on the results of Heckman *et al.* /15/.

The integral LET spectrum behind a shield of thickness t is determined at fixed values of LET, L_i, by the following procedure, which is repeated for each atomic number from 1 to 92. First, the energy deposit (LET) vs incident energy is calculated for a thin target. The upper and lower "internal" energy range limits, E_i^u and E_i^l, corresponding to each L_i are determined from this curve. The "external" energy range limits are obtained outside the shield, t, by $E_x = E[R(E_i)+t]$. The contribution of this ion to the integral LET spectrum is finally determined as the integral of the differential energy spectrum from E_x^l to E_x^u using the particle flux models presented in the accompanying papers /1,2/. The effects of nuclear interactions are not included in this calculation. As a result, at higher shield thicknesses, when the effects of these interactions become important, the LET spectrum calculated here will over-estimate the real spectrum at high LET values and underestimate the real spectrum at low LET /3/.

In Figure 1 we compare LET spectra for the nominal galactic cosmic ray space environment from several different sources to illustrate the essential features of a typical LET spectrum and to discuss the consistency of the results. Both the present CRRES/SPACERAD spectrum and the CREME spectrum were calculated from their respective ion flux databases for conditions of minimum solar activity, corresponding to the maximum galactic cosmic ray flux. The Heinrich spectrum /3/ is based on 1969-1970 conditions, near the end of a period of maximum solar activity. In addition, the Heinrich spectrum does not include any contributions from protons or alpha particles. These characteristics account for the lower intensity of the Heinrich spectrum both at low and at high LETs. Finally, both the Heinrich spectrum and the Curtis and Wilkinson spectrum /16/ do not include the small contributions of ions heavier than the iron group.

The differences between the present calculation and the LET spectrum from the CREME model are presented more clearly with the ratio plot in Figure 2. Overall, for values of the LET below the iron maximum, the CREME calculation yields a slightly higher flux from thin shields and a slightly lower flux for thick shields. This reflects differences in the shape of the energy spectra between the two models, as illustrated also in Figure 3. The peak in the ratio near 30 MeV cm^2 mg^{-1} reflects a difference in the range-energy curve for iron. The CREME code has a slightly higher maximum LET for iron than the 27.5 MeV cm^2 mg^{-1} in our code. The peak is due to this difference coupled with the steep drop in the spectrum in this region. While this is an apparently spectacular difference it is of little consequence in any practical applications.

Above an LET corresponding to the maximum for iron the spectra are more speculative because the available measurements are scarce. For ions above nickel (Z=28) the CRRES model uses the iron spectrum scaled by the relative composition provided by Cameron /17/.

GCR LET SPECTRA FOR THE CRRES MISSION

As described in the companion papers /1,2/, the GRC model used in this work is based on a model of galactic cosmic ray spectra in the local interstellar medium together with a calculation to transport the galactic cosmic rays to earth orbit under the influence of solar modulation. These local interstellar spectra are assumed to change only on "galactic" time scales. Thus with an adequate model for solar modulation the entire history of results on galactic cosmic ray composition and energy spectra can be accommodated by the proper choice of local interstellar spectrum with all of the local temporal variation attributed to solar modulation with known dependencies on mass, charge, and energy. Predicted flux spectra for all ion species thus can be obtained self-consistently using this method from only a few measurements. An example is shown in Figure 3, where the spectrum of galactic cosmic ray oxygen as measured in the interplanetary medium near earth from August 1990 through March 1991 is compared to results of our solar modulation model as well as to the CREME solar maximum spectrum. The best-fit value of the solar modulation parameter to the measured oxygen spectrum is 1444 ± 42 MV, where the uncertainty quoted is the formal

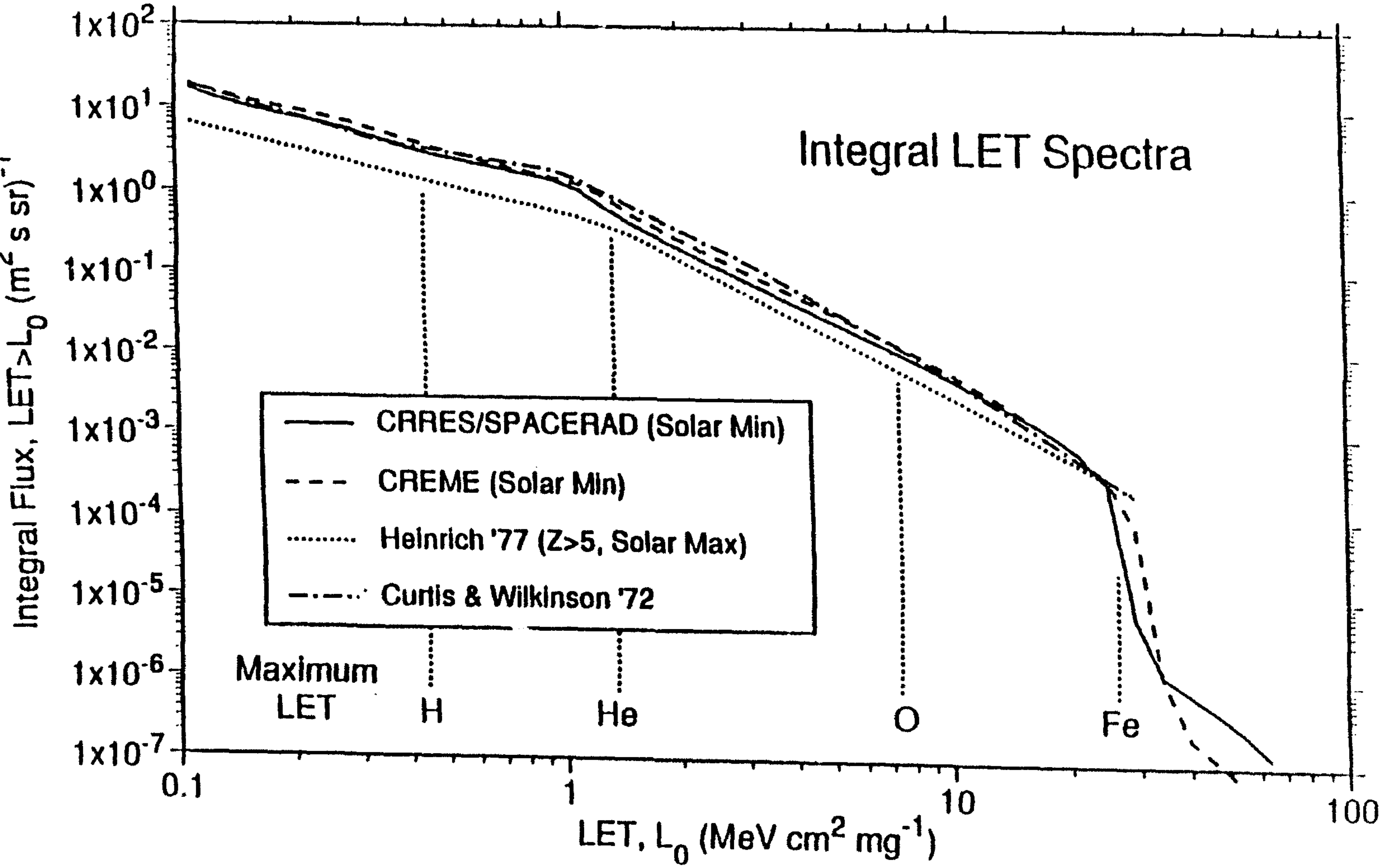

Figure 1. Integral LET spectra from several different sources are compared. The vertical dashed lines and the element symbols indicate the maximum LET that can be produced by the element. Features in the LET spectrum are clearly associated with the helium and iron endpoints.

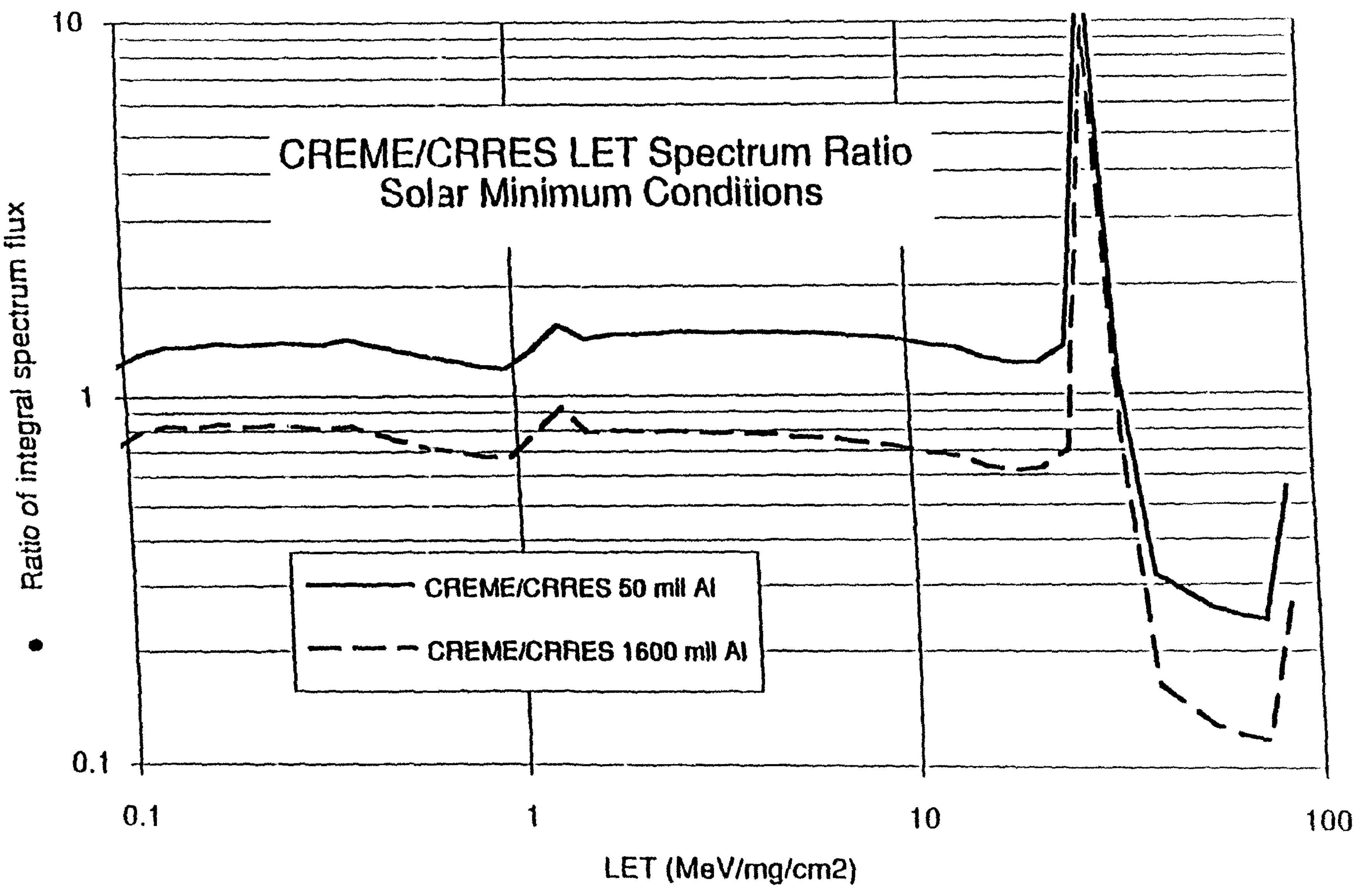

Figure 2. The ratio between the LET spectra of the CREME model and the spectrum calculated from the CRRES/SPACERAD models for solar minimum conditions.

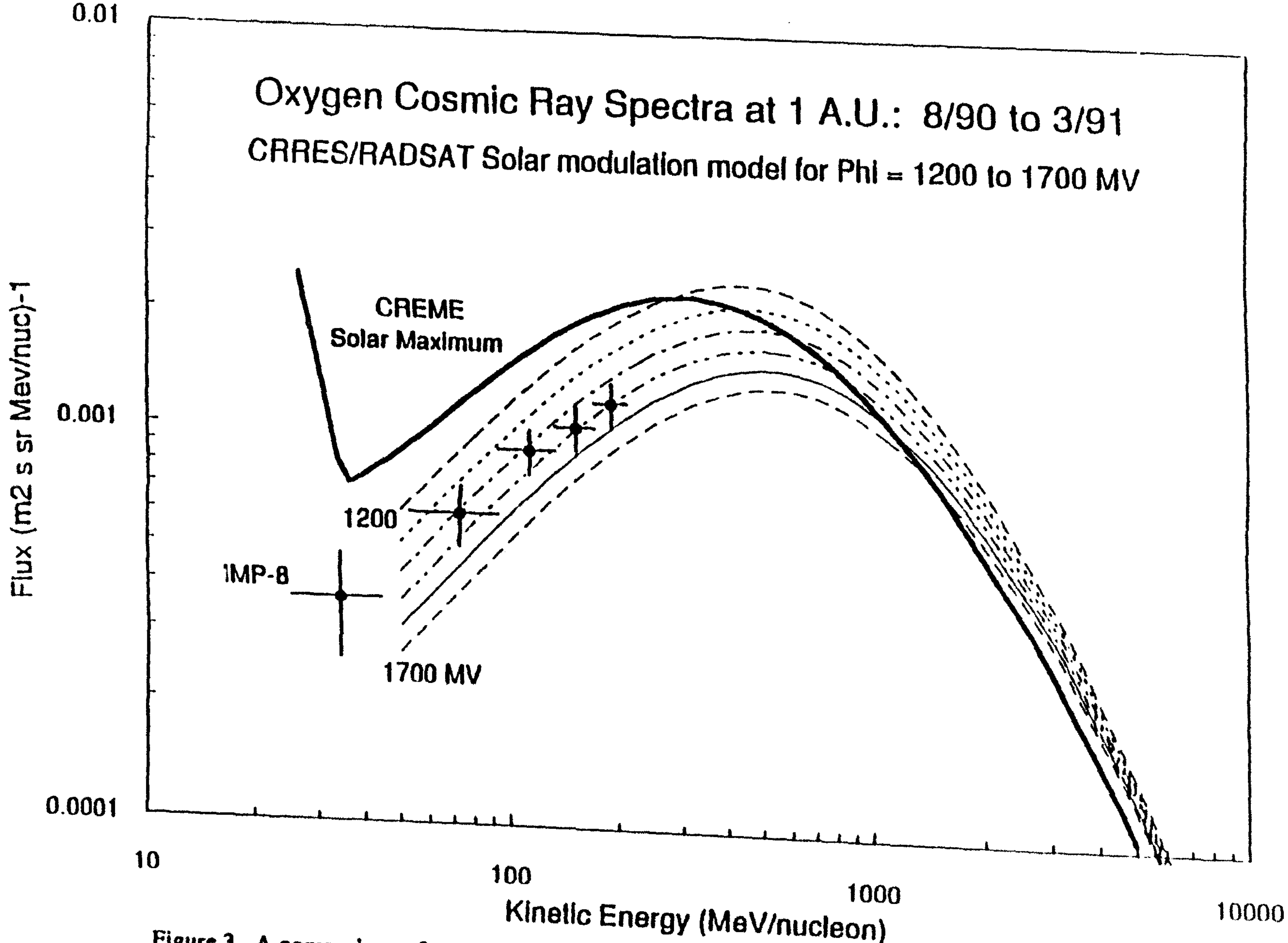

Figure 3. A comparison of measurements and models of the galactic cosmic ray oxygen flux in the interplanetary medium near earth in late 1990 and early 1991. The points labeled "IMP-8" are from The University of Chicago cosmic ray instrument aboard the IMP-8 satellite. The dashed lines are the results of our solar modulation model calculation for a range of the solar modulation parameter (F) chosen to fit the measurements. The heavy solid line is the oxygen spectrum for solar maximum conditions from the CREME model /7/.

flux in this solar maximum is lower than at any time since 1960. LET spectra calculated for this solar modulation level are shown in Figure 4. A graph of the sensitivity of the LET spectrum to changes in solar modulation level is provided in Figure 5. Figure 6 shows the calculated range of variation of LET spectra over a solar cycle for various thicknesses of shielding. Together, Figures 5 and 6 can be used to estimate the magnitudes of solar cycle effects in the LET spectra and, for example, the resulting SEU rates.

SEP LET SPECTRA FOR TWO FLARES DURING THE CRRES MISSION

Chen *et al.* /2/ discussed in detail two of the largest solar energetic particle events observed during the CRRES mission. The flare of 22 March 1991 was "iron rich" and had the highest peak heavy ion intensity at low energy, but a very steep energy spectrum. The flare of 4 June had a smaller peak intensity, but was in an extended series of overlapping flare events which accumulated a large total fluence. Total LET spectra for these events are shown in Figures 7 and 8. These LET spectra correspond to the peak flux intensities during each event. Also shown in the figures are the time factors which can be used to convert the LET flux spectra to fluence spectra for estimating event-integral effects. These ratios of fluence to peak flux were obtained from measurements of helium ions at an energy near 60 MeV/nucleon. The extrapolations to other ions from the measured solar flare oxygen spectra are based on the measured ratio of iron to oxygen following the method described by Chenette and Dietrich /18/.

These flares were large, with total fluences which placed them in the upper few percent of the 1973 - 1984 heavy ion fluence distributions presented in /18/. Because the flare particle flux intensities decrease rapidly with increasing energy, the variation in the intensity of the LET spectrum with shielding is very strong. Additionally, however, the very steep energy spectrum of the March event (power-law energy spectral index of -7.3) meant that the total heavy ion fluence for energies over 100 MeV/nucleon placed this event in the quartile of the smallest flares observed from 1973 - 1984.

SINGLE EVENT UPSET RATE ESTIMATES

To illustrate the use of the LET spectra presented here we provide calculations of the expected upset rate in a 256 x 4-bit bipolar static memory device, part number 93L422. This device has been characterized well in ground-based accelerator tests and was used in a space-based validation study /10/. The measured single-event upset cross-section of this device is provided in /10/ together with a discussion of the device geometry and related issues. The Fairchild version of this part was used in the calculations presented here. At large LET values the upset cross-section of this part is just over 10^{-5} cm^2 per bit, or 10^{-2} cm^2 per device.

The upset rate calculations were performed using the methods of Chenette et al. /19/, which take into account the measured shape of the upset cross-section as a function of effective LET. The results are presented in Table 1. Extreme lower and upper limit bounds surrounding the results shown in the table are typically within about 50% of the tabulated value. These limits are extreme limits of the integration of the cross-section as measured in ground-based accelerator tests. The estimated numerical and measurement error of the procedure used to estimate these upset rates is smaller than these limits.

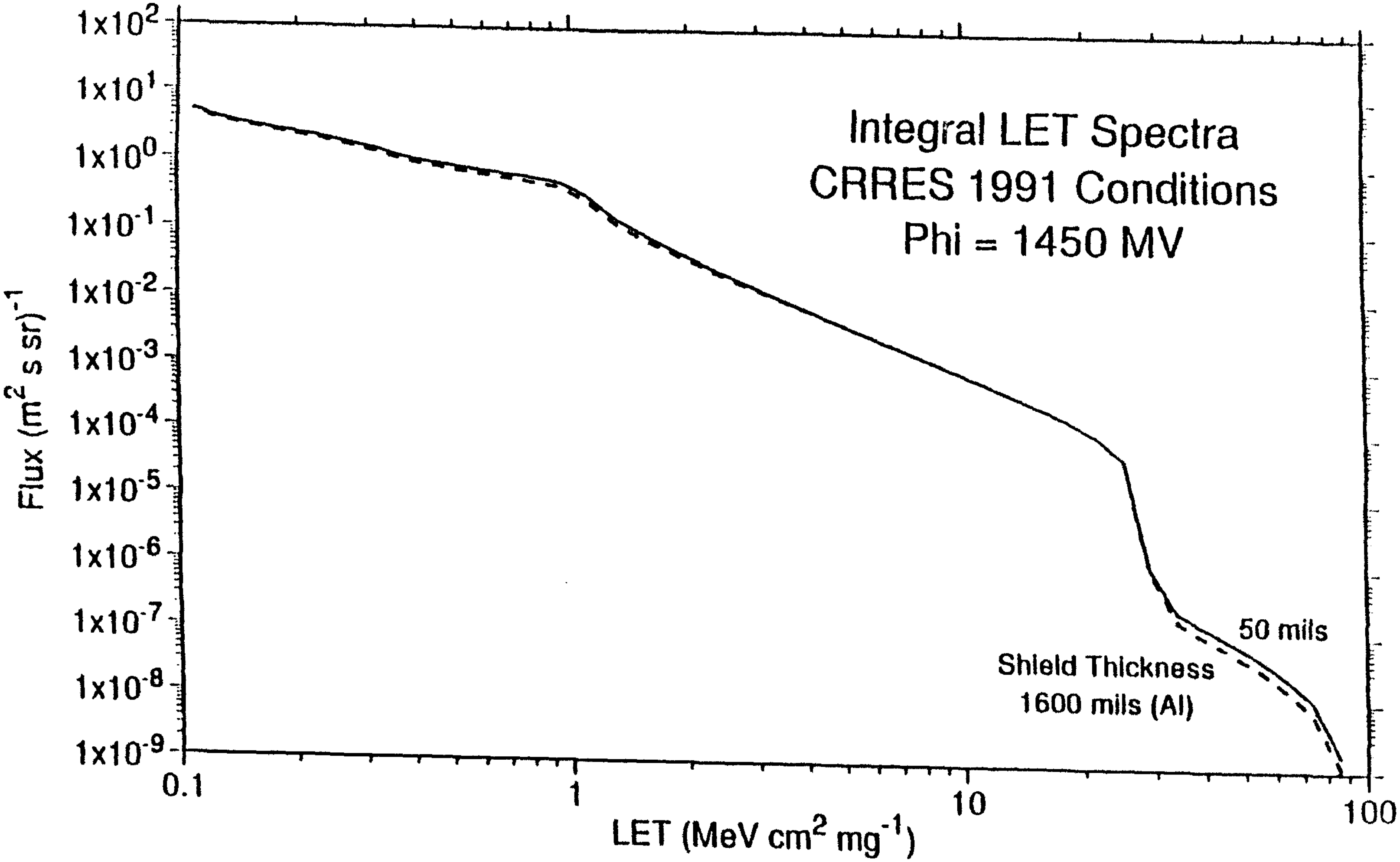

Figure 4: The LET spectrum calculated for the period August 1990 through March 1991. This spectrum is appropriate for periods without significant solar energetic particle fluxes during the early part of the CRRES mission.

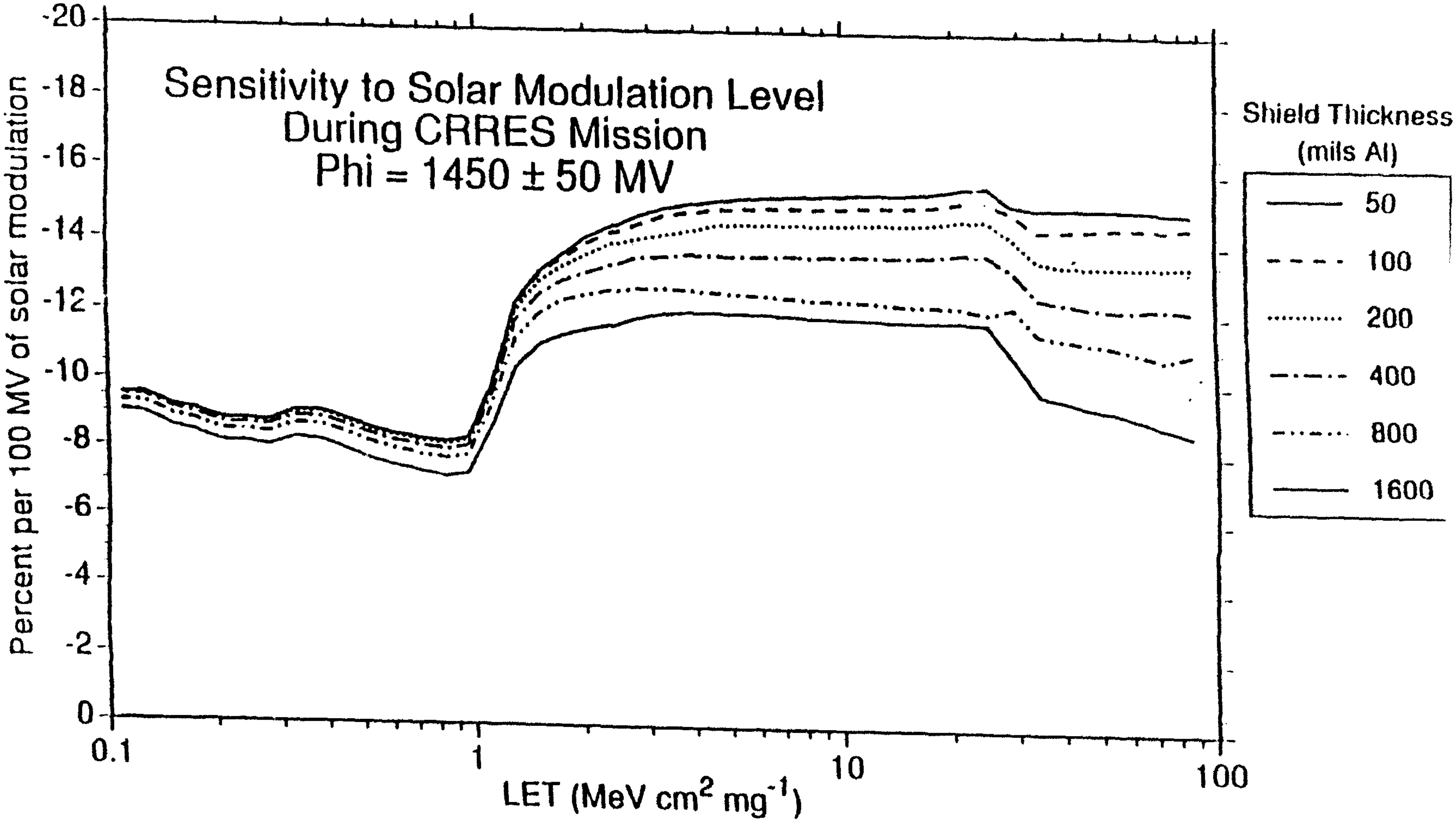

Figure 5: The percent change in LET spectrum which would be obtained for a 100 MV change in the level of solar modulation in the vicinity of the CRRES solar maximum conditions. At high values of the LET the spectrum is more sensitive to the level of modulation for thinner shields.

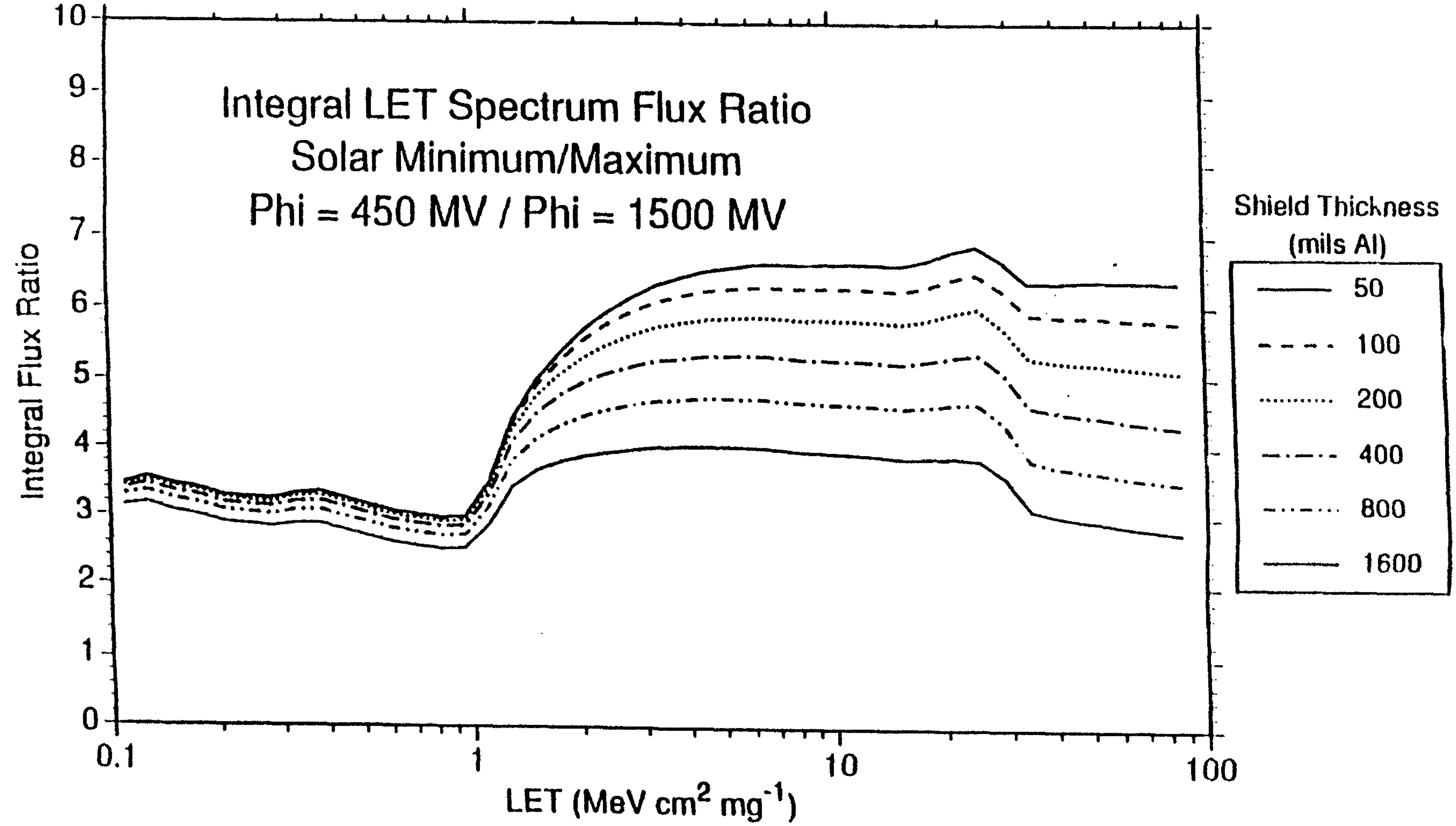

Figure 6. The ratio of LET spectra based on the CRRES/SPACERAD models between solar minimum and solar maximum. At solar minimum the LET spectrum is about 3 times higher than the solar maximum spectrum for low LETs. The ratio increases to a factor of 6 - 7 for thinner shields at high LETs.

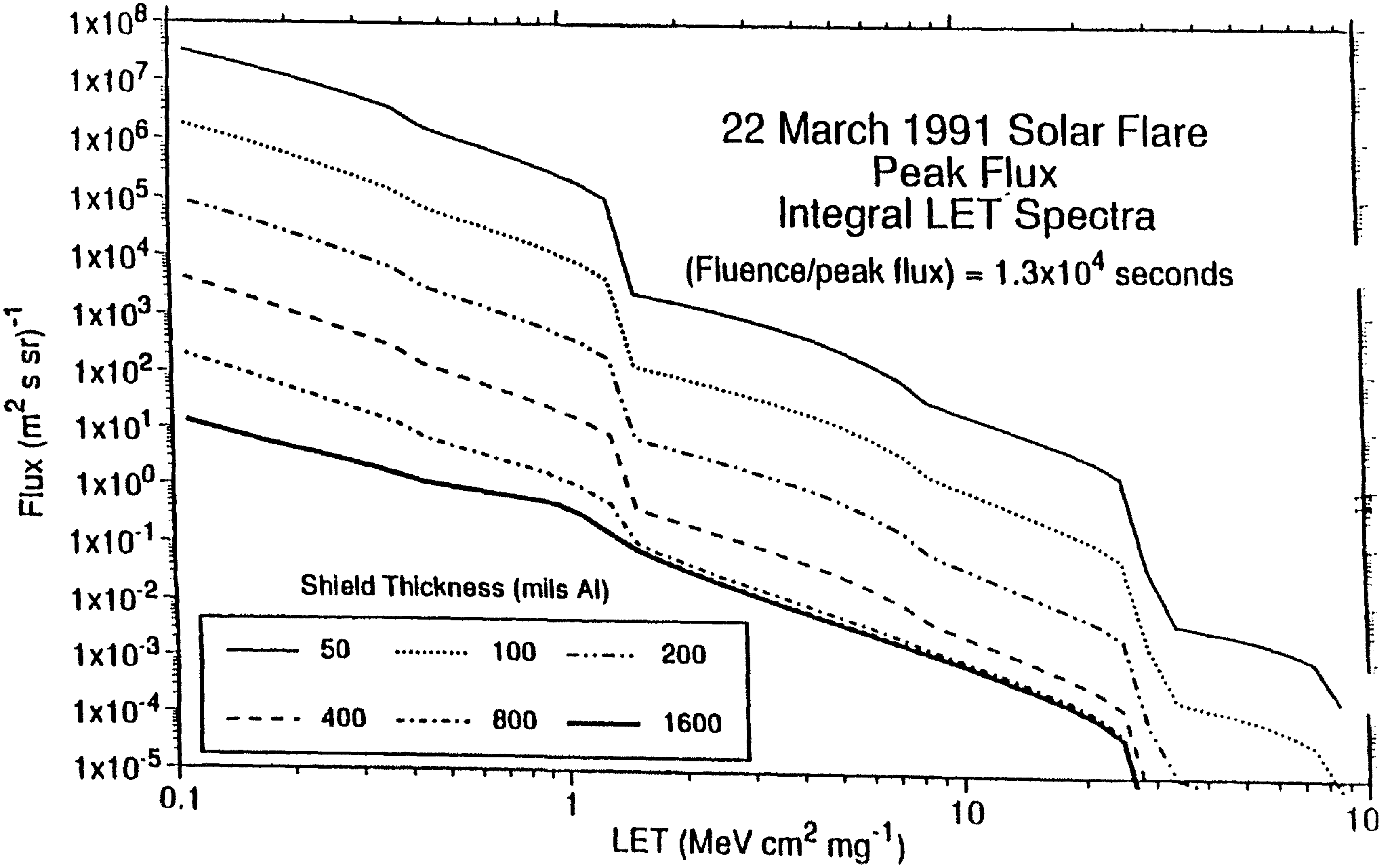

Figure 7. Integral LET spectra for the peak of the 22 March 1991 solar energetic particle event. The fluence to peak flux ratio of 1.3×10^4 seconds is the multiplying factor to use to convert this to a fluence spectrum for estimating event-integrated total effects.

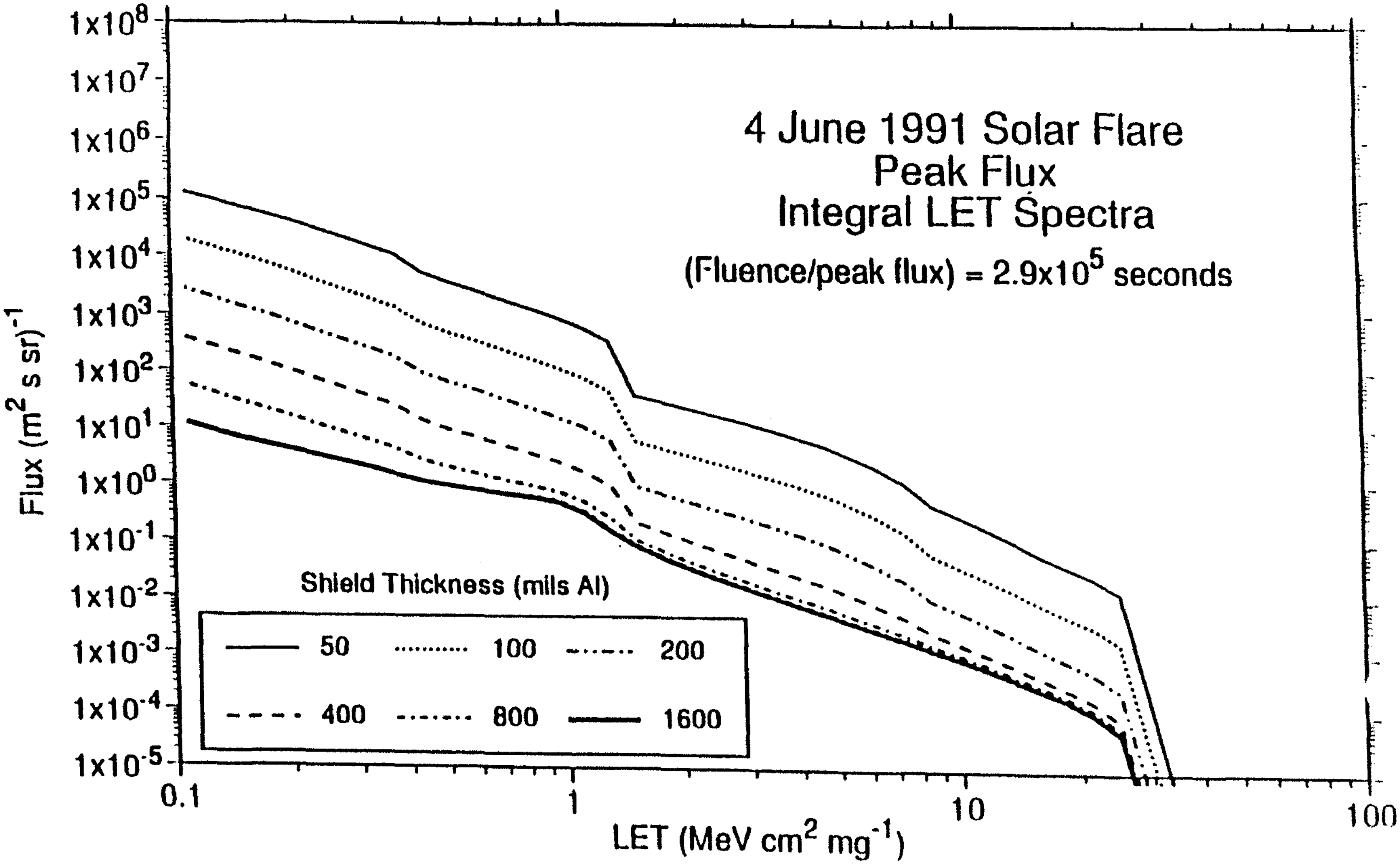

Figure 8. Integral LET spectra for the peak of the 4 June 1991 solar energetic particle event. The fluence to peak flux ratio of 2.9×10^5 seconds is the multiplying factor to use to convert this to a fluence spectrum for estimating event-integrated total effects.

Table 1. Single Event Upset Rate Estimates for a 256 x 4-bit Bipolar Static RAM (93L422)

Environment	Single-Event Upsets per 50 mil (Al) shield	Device(1024 bits) 1600 mil (Al) shield
Solar maximum (Φ = 1500 MV)	0.11 per day	0.10 per day
1990-1991 CRRES (Φ=1444 MV)	0.12 per day	0.11 per day
Solar minimum (Φ = 450 MV)	0.41 per day	0.30 per day
4 June 1991 SEP event peak	35 per hour	0.15 per day
22 March 1991 SEP event peak	3 per second	0.16 per day
4 June 1991 SEP total fluence	2.8×10^3 total	0.14 SEP + 1.0 GCR*
22 March 1991 SEP total fluence	3.5×10^4 total	0.007 SEP + 0.2 GCR*

*At this shield thickness, most of the SEU events during the flares will come from the GCR component.

SUMMARY

LET spectra have been presented to describe the interplanetary heavy ion environment due to galactic cosmic rays and solar energetic particle events during the CRRES mission in 1990 and 1991. These LET spectra were based on the galactic cosmic ray and solar energetic particle models developed for the CRRES/SPACERAD program and presented by Chen, *et al.* 1992 at this conference /1,2/. For solar minimum conditions, the LET spectra developed for CRRES/SPACERAD are within 30% of the CREME results. However, the galactic cosmic ray oxygen spectrum for the period August 1990 to March 1991 is significantly lower than the solar maximum spectrum of the CREME model. As a result, CREME will over-estimate the expected upset rate during these times. LET spectra for a large, heavy-ion rich, but high-energy poor solar particle event (22 March 1991) and a large solar particle event with more typical composition and energy spectrum (4 June 1991) were presented and compared. Predicted single-event upset rates for a bipolar 256 x 4-bit static memory ranged from about 40 per year during solar maximum conditions when no solar energetic particle fluxes were present to about 3 per second at the peak of the 22 March event, for very thinly shielded parts.

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