

CONF-870405--3

RADIATION DAMAGE IN SILICON DUE TO ALBEDO NEUTRONS
EMITTED FROM HADRONIC BEAM DUMPS (Fe AND U)*

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CONF-870405--3

DE86 015461

ABSTRACT

Calculations have been carried out to determine the level of radiation damage that can be expected from albedo neutrons when 1- and 5-GeV negative pions are incident on iron and uranium beam dumps. The calculated damage data are presented in several ways including neutron fluence above 0.111 MeV, 1 MeV equivalent neutron fluence, damage energy deposition, and DPA or displacements per atom. Details are presented as to the method of calculation.

I. INTRODUCTION

Radiation damage in electronic equipment and calorimeters containing silicon chips or detectors is becoming a serious problem at all high-energy accelerator facilities.¹ This will be especially true for the proposed Superconducting Super Collider accelerator (SSC). Presented in this paper are the results of calculations which were carried out to determine the level of radiation damage that can be expected from albedo neutrons when 1- and 5-GeV negative pions are incident on iron and uranium beam dumps.

Radiation damage in silicon primarily results from the production of vacancies in the lattice sites and of interstitials.² Elastic, inelastic, or nonelastic collisions of a particle, primarily neutrons, with a silicon atom can result in a displacement of this atom from its normal position in the lattice producing a vacancy. This displacement will occur only if the energy imparted to the knock-on silicon atom exceeds approximately 15- to 25-eV. If this nucleus is unable to find another vacant position within the lattice, the nucleus will come to rest in a nonequilibrium position within the lattice (interstitials). The production of these interstitials and vacancies may result in permanent changes in the physical properties of the silicon.

It is very possible that the kinetic energy transferred to the knock-on silicon atom is sufficient such that it may undergo elastic collisions with other atoms and induce additional interstitials and vacancies. The two basic means by which these atoms may lose energy in the medium are by ionization and excitation of orbital electrons and by Coulomb elastic scattering. At higher knock-on atom energies, approximately greater than 28 keV, the primary energy loss mechanisms is through ionization and excitation. When the kinetic energy of the knock-on is less than 28 keV, the knock-on will lose energy primarily by elastic collisions with other atoms. Hence, the scattering or Coulomb interactions with the material results in a cascade of displaced and ionized atoms.

The calculated damage data are presented in several ways which is proportional to vacancies and interstitials. The data include neutron fluence

above 0.111 MeV, 1 MeV equivalent neutron fluence, damage energy deposition, i.e., that fraction of the total energy deposition that can produce vacancies, and DPA or displacements per atom. The methods of calculation are given in Section II and the results of the calculations are presented and discussed in Section III.

II. METHOD OF CALCULATION

The calculations performed with the CALOR computer system follow approximately the procedures used in previous calculations.^{3,4} A flow diagram of the codes in CALOR is given in Fig. 1. The three-dimensional, multimedia, high-energy nucleon-meson transport code HETC⁵ was used to obtain a detailed description of the nucleon-meson cascade produced in the beam stops considered in this paper and the resulting greater than 20 MeV neutron albedo. This Monte Carlo code takes into account the slowing down of charged particles via the continuous slowing-down approximation, the decay of charged pions and muons, inelastic nucleon-nucleus and charged-pion-nucleus (excluding hydrogen) collisions through the use of the intermediate-energy intranuclear-cascade-evaporation (MECC) model ($E < 3$ GeV) and scaling model ($E > 3$ GeV), and inelastic nucleon-hydrogen and charged-pion-hydrogen collisions via the isobar model ($E < 3$ GeV) and phenomenological fits to experimental data ($E > 3$ GeV). Also accounted for are elastic neutron-nucleus collisions ($E < 100$ MeV), and elastic nucleon and charged-pion collisions with hydrogen.

The intranuclear-cascade-evaporation model as implemented by Bertini is the heart of the HETC code.⁶ This model has been used for a variety of calculations and has been shown to agree quite well with many experimental results. Even when agreement is not very good, the results produced by this model can lead the user to make correct decisions. The underlying assumption of this model is that particle-nuclear interactions can be treated as a series of two-body collisions within the nucleus and that the location of the collision and resulting particles from the collision are governed by experimental and/or theoretical particle-particle total and differential cross-section data. The types of particle collisions included in the calculations are elastic, inelastic and charge exchange. This model incorporates the diffuseness of the nuclear edge, the Fermi motion of the bound nucleons, the exclusion principle, and a local potential for nucleons and pions. The density of the neutrons and protons within the nucleus (which is used with the total cross section to determine interaction locations) are determined from the experimental data of Hofstadter.⁶ Nuclear potentials are determined from these density profiles by using a zero-temperature Fermi distribution. The total well depth is then defined as the Fermi energy plus 7 MeV. Following the cascade part of the interaction, there is excitation energy left in the nucleus. This energy is treated by using an evaporation model which allows for the emission of protons, neutrons, d, ³He, α , and T. Fission induced by high-energy particles is accounted for during this phase of the calculation by allowing it to compete with evaporation. Whether or not a detailed fission model is included has very little effect on the total number of secondary neutrons produced.

The source distribution for the electromagnetic cascade calculation is provided by HETC; it consists of photons from neutral pion decay, electrons

CALOR

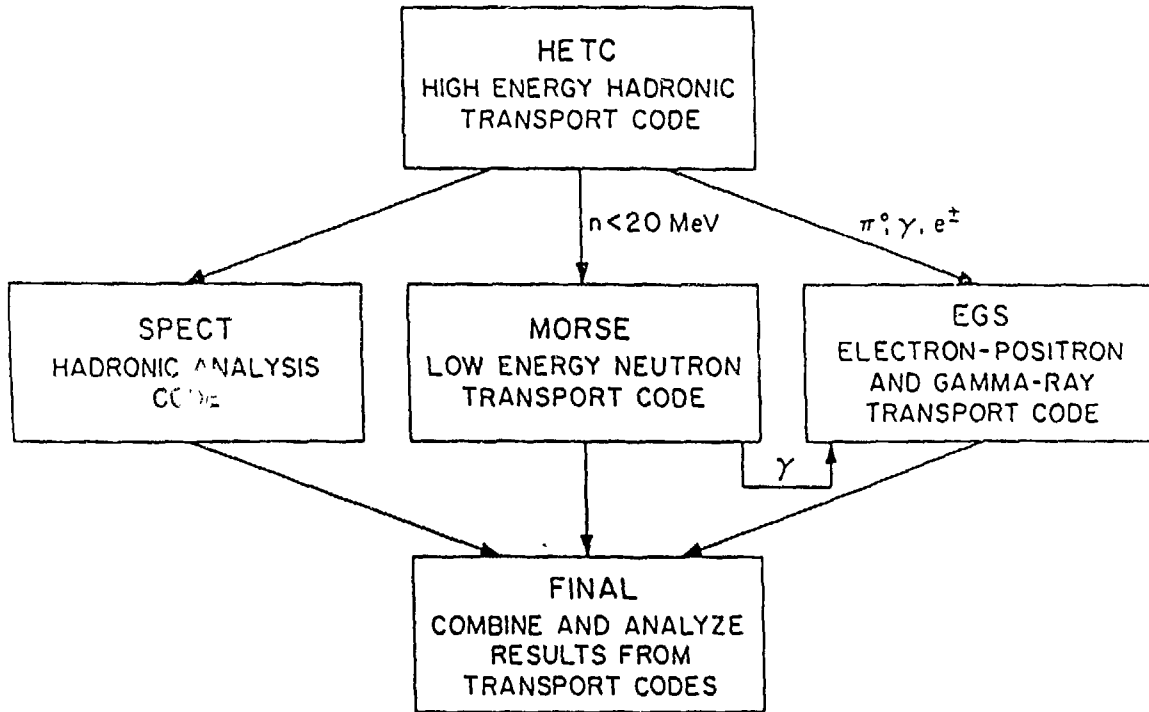


Fig. 1. Flow diagram of the CALOR computer system.

and positrons from muon decay, deexcitation gamma rays from inelastic nuclear collisions, and fission gamma rays. Since the discrete decay energies of the deexcitation gammas are not provided by HETC and only the total energy is known, individual gamma energies are obtained by uniformly sampling from the available energy until it is completely depleted. The transport of the electrons, positrons, and gammas from the above sources is carried out using the EGS system.⁷ Since the production of neutrons by gamma rays is at most a few percent effect, this production has been omitted in the current calculation.

Neutrons which are produced with energies below 20 MeV are transported using the MORSE^{8,9} Monte Carlo transport code. The neutron cross sections used by MORSE were obtained from ENDF/B-IV. Gamma rays (including those from capture, fission, etc.) produced during this phase of the calculations are stored for transport by the EGS code. The MORSE code was developed for reactor application and can treat fissioning and nonfissioning systems in detail.

The Lindhard et al.¹⁰ theory as used by Robinson¹¹ is employed to determine that fraction of the energy of the primary knock-on atom which will produce damage, i.e., further nuclear displacements. The damage-energy cross section can be evaluated from the expression

$$\sigma_{i,damage}(E) = \int_{T_d}^{T_{max}} \frac{d\sigma_i(E,T)}{dT} T_{damage} dT ,$$

where

- $\sigma_{i,damage}(E)$ - the damage energy cross section as a function of neutron energy E for the ith reaction type,
- $\frac{d\sigma_i(E,T)}{dT}$ - the heavy ion primary knock-on atom spectrum for the ith reaction type as a function of recoil energy T and of neutron energy E,
- T_{damage} - that fraction of the energy T which will produce further nuclear displacements, and
- T_d - the effective threshold energy (≈ 15 eV for Si)

T_{damage} can be calculated as follows:

$$T_{damage} = T[1+k g(\epsilon)]^{-1} ,$$

where

$$g(\epsilon) = \epsilon + 0.40244 \epsilon^{3/4} + 3.4008 \epsilon^{1/6}$$

$$k = \frac{0.0793 Z_1^{2/3} Z_2^{1/2} (A_1 + A_2)^{3/2}}{(Z_1^{2/3} + Z_2^{2/3})^{3/4} A_1^{3/2} A_2^{1/2}}$$

$$\epsilon = AT$$

$$A = \frac{0.8853 A_2}{27.2 Z_1 Z_2 (Z_1^{2/3} + Z_2^{2/3})^{1/2} (A_1 + A_2)} \text{ (eV}^{-1}\text{) ,}$$

and

A_1, Z_1 = the atomic weight and number of the recoiling heavy ions, respectively, and

A_2, Z_2 = like quantities for the matrix atoms.

The displacement cross sections are evaluated in a similar way by replacing T_{damage} with N_d , defined as

$$N_d = 0 \quad T < T_d$$

$$N_d = 1 \quad T_d \leq T_{\text{damage}} < 2T_d$$

$$N_d = \frac{\beta T_{\text{damage}}}{2 T_d} \quad 2T_d \geq T_{\text{damage}} ,$$

where

$$\beta = 0.8 .$$

The primary knock-on atom spectrum ($d\sigma/dT$) can be obtained indirectly from experimental data or must be calculated using various models. For elastic, inelastic, (n,2n), (n,3n), (n,np), and (n,n α) reactions a modified version of the XLACS module from the AMPX code system⁹ was used to calculate the primary knock-on atom spectra for neutron energies less than 20 MeV. For elastic and inelastic resolved reactions, where angular distributions are usually available, the spectra are exactly determinable by using two-body kinematics. The effect of gamma rays emitted after inelastic (or nonelastic) collisions on the spectra is small and was not included. For the remaining reactions given above, the spectra were obtained by using a one-neutron emission model¹² and the secondary-neutron spectra (assumed to be applicable at

all angles in the center-of-mass system) given in ENDF/B.

For neutron absorption reactions, such as (n,p), (n, α), etc., the methods of Jenkins,¹² Doran,¹³ and Parkin and Goland¹⁴ were used with one modification: an effective Coulomb barrier was used as the lower energy at which a charged particle can be emitted.

$$C = (1.44 \times 10^{-13} \text{ MeV cm } Z_1 Z_2) / (1.7 \times 10^{-13} \text{ cm } A_2^{1/3}) ,$$

where

- Z_1 = charge of the emitted particle,
- Z_2 = charge of the residual nucleus, and
- A_2 = atomic number of the residual nucleus.

If the Coulomb barrier forced the emission probability of the charged particle to be zero but yet the ENDF/B data showed a nonzero cross section, the Coulomb barrier energy was set to zero.

For (n, γ) reactions, a Monte Carlo program was written. The secondary gamma-ray energies, along with their emission probabilities, were obtained from the nuclear data sheets. In contrast to previous calculations,¹³ the incident neutron energy is used in the kinematic equations for total energy and momentum balance with the gamma rays being emitted isotropically in the rest system. Even though the capture-level probabilities used in the calculations are for thermal-neutron energies, it was assumed that they apply for all neutron energies. It was also assumed that the gamma rays are emitted fast enough so that no interaction with other nuclei takes place until the residual nucleus is fully deexcited.

The damage energy cross sections above 20 MeV could have been calculated using the intranuclear-cascade-evaporation model. However, it was decided for this preliminary study to extrapolate the damage energy cross sections obtained as described above.

III. RESULTS

The beam dumps considered in these calculations are for all practical purposes infinite in the half space, i.e., $-\infty \leq x$ or $y \leq \infty$ and $0 \leq z \leq \infty$. The negative pions are normally incident in the z direction on the beam dump at $z = 0$ and are uniformly distributed over an area of radius 3 cm in the x - y plane. The albedo flux was calculated for the same area and location that the negative pions were incident on, and to a good approximation can be scaled as $1/R^2$ if results are needed back from the beam dump.

The calculated albedo fluxes and damage data results are given in Table 1 and are normalized per source negative pion. The 1 MeV equivalent neutron

Table 1
Albedo Neutron Current and Flux from π^- Incident on Fe and U Targets^a

Neutron Energy Range (MeV)	σ_{damage} (b-eV) ^c	U Target		Fe Target				
		1 GeV π^-		1 GeV π^-		5 GeV π^-		
		Current (n/cm ²)	Flux (n/cm ²)	Current (n/cm ²)	Flux (n/cm ²)	Current (n/cm ²)	Flux (n/cm ²)	
6.40+2 ^b	3.20+2	2.41+5 ^c	0.	0.	0.	0.	1.08-4	1.38-4
3.20+2	1.60+2	2.31+5	1.13-4	2.48-4	1.13-4	1.98-4	6.39-4	8.49-4
1.60+2	8.00+1	2.21+5	7.07-4	1.51-3	3.82-4	1.23-3	1.46-3	1.99-3
8.00+1	4.00+1	2.11+5	1.54-3	2.72-3	5.80-4	9.52-4	1.86-3	2.54-3
4.00+1	2.00+1	1.95+5	1.70-3	2.97-3	8.91-4	1.56-3	2.21-3	3.30-3
2.00+1	1.49+1	1.81+5	1.68-3	3.34-3	6.80-4	1.02-3	1.03-3	1.99-3
1.49+1	1.00+1	1.73+5	4.10-3	7.41-3	9.78-4	2.16-3	1.75-3	2.50-3
1.00+1	4.97+0	1.54+5	1.35-2	2.87-2	2.93-3	5.06-3	3.24-3	5.29-3
4.97+0	2.02+0	1.23+5	2.76-2	5.06-2	4.52-3	9.34-3	5.32-3	8.34-3
2.02+0	1.00+0	9.77+4	2.28-2	3.91-2	3.55-3	6.48-3	5.94-3	1.08-2
1.00+0	4.98-1	7.96+4	2.70-2	4.67-2	3.03-3	5.16-3	5.48-3	8.67-3
4.98-1	2.02-1	5.78+4	2.46-2	4.29-2	2.09-3	3.65-3	3.83-3	6.65-3
2.02-1	1.11-1	2.61+4	7.70-3	1.27-2	5.32-4	8.44-4	1.45-3	2.40-3
Total (n/cm ²)			1.33-1	2.39-1	2.02-2	3.77-2	3.43-2	5.55-2
Damage Energy/Atom (eV)				2.44-20		4.59-21		6.68-21
1-MeV Equivalent Neutron Fluence (9.00+4 b-eV at 1 MeV)				2.71-1		5.10-2		7.42-2
Displacements/Atom (E _d = 15 eV; DPA = 0.8 Damage Energy/2E _d)				6.51-22		1.22-22		1.78-22

^aThe source is normally incident and uniformly distributed over an area of $\pi \times 3^2 \text{cm}^2$. The albedo flux has been averaged over the same location and area. The data are normalized per source π^- .

^bRead as 6.40×10^2 .

^cThe data above 20 MeV have been extrapolated.

fluence is obtained from the damage energy deposition by dividing by the cross section for damage at 1 MeV.

Depending on the type of silicon device, various levels of device failure or degradation of device function can be expected. Very approximately, 10^{12} - 10^{14} n/cm² will produce degradation of device function and 10^{13} - 10^{15} n/cm² will produce device failure.¹ If for this general study 10^{13} n/cm² is used for degradation of device function and 10^{14} n/cm² for device failure, then only 4×10^{13} and 4×10^{14} π^- at 1 GeV incident on U, 3×10^{14} and 3×10^{15} π^- at 1 GeV, and 2×10^{14} and 2×10^{15} π^- at 5 GeV incident on Fe are needed to produce degradation of device function and device failure, respectively. For most high-energy accelerator facilities these are low incident energies and low fluence values, and it can be anticipated that silicon devices located in detectors or close to accelerator beam pipes will show some damage during their operating lifetimes. The sensitivity of silicon to radiation damage becomes more apparent by considering the number of displacements per atom for these π^- fluences. For the uranium beam dump, approximately three displacements per million atoms is sufficient to induce device failure. In general, each time a silicon device is to be used in a radiation environment, a close assessment of the potential damage must be obtained.

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* Research sponsored by Office of High Energy and Nuclear Physics, U.S. Department of Energy under contract number DE-AC05-84OR21400 with Martin Marietta Energy Systems, Inc.

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