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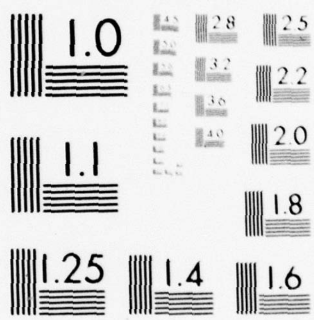

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Neutron induced displacement damage in silicon has been calculated and measured for a number of threat and simulator neutron spectra. The results in each case are presented as the ratio of damage produced by the source neutrons to that produced by 14 MeV (fusion) neutrons. The program to calculate damage, ~~formulated at BRL~~, determines the Lindhard nuclear stopping fraction corrected for multiple collisions, thus providing the fraction of the recoil energy available for displacement damage. For the measurements, wide-base silicon → next page

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered) diodes were exposed to appropriate neutron fluences at each of the simulators. Diode changes that reflected the degradation in injected carrier lifetimes were observed. The results have produced both calculated and experimental ratios that are in generally good agreement with each other, and they are considerably smaller than the currently accepted values.

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I. INTRODUCTION

Neutron damage in silicon plays a central role in radiation effects of military interest, and a knowledge of the energy dependence of this neutron damage is required to relate threat and simulator spectra as well as to provide a basis for a 1-MeV equivalence definition for hardness assurance. To meet this requirement, a model has been formulated to effectively utilize all available neutron cross section information to calculate the energy available for displacement damage,[1,2] and the calculated results have been compared with experimentally determined damage (lifetime degradation)[3]. In this report calculated and experimentally measured results for both threat and simulator spectra will be presented.

Neutron irradiation of silicon produces changes in the electrical properties of the material, and these changes manifest themselves in two ways, as a degradation of minority-carrier lifetime and as a reduction of the equilibrium charge-carrier concentration. Radiation-induced neutron damage causes permanent changes in the operating characteristics of silicon devices and the extent of this permanent damage is neutron-energy dependent. The evaluation of energy dependence is complicated by the annealing of unstable damage, by effects peculiar to devices if devices are used in the evaluation, and by the superposition of lifetime and carrier-concentration effects if both change significantly. Past research by many investigators has produced substantial information on energy dependence and this will be discussed in the following paragraphs of this introduction. Then an experimental technique for measuring lifetime degradation without interference from carrier-removal and a calculational procedure that utilizes all available neutron cross section information to determine the energy available for displacement damage will be described, and both calculated and measured results will be presented.

Calculation of displacement damage as a function of neutron energy, with consideration of the different reactions and angular distributions

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1. J.E. Youngblood, W.R. Van Antwerp, and R.M. Tapphorn, "Displacement Damage in Silicon Irradiated with 6- to 10-MeV Neutrons", USABRL Memorandum Report No. 2738, April 1977. (AD #A039774)
2. J.E. Youngblood and W.R. Van Antwerp, "Calculated Energy Dependence of Neutron-Induced Displacement Damage in Silicon", USABRL Memorandum Report No. 2759, June 1977. (AD #041465)
3. J.E. Youngblood, C.E. Hollandsworth, and W.R. Van Antwerp, "Neutron Damage in Silicon From Neutrons With Energy Near 1-MeV", USABRL Memorandum Report No. 2768, July 1977. (AD #A043268)

of the neutrons, evolved through the work of Smith et al.,[4] Stein,[5] and Holmes.[6] These efforts and the more recent work of Guenzer and Manning[7] and of Rogers et al.[8] determine the fraction of energy available for displacement damage using the stopping-power theory of Lindhard, Scharff, and Schiott (LSS).[9] The LSS theory provided a more realistic basis for energy partition than earlier theories and it was experimentally confirmed (by measuring the ionization fraction) by Satler and Vook.[10] In efforts to proceed beyond the energy available, Holmes,[6] Curtis,[11] and Gregory[12] have attempted to analyze in detail the electrical behavior at disordered regions. Both point and cluster defects have been considered and a recent review of work in this area has been presented by van Lint and Leadon.[13] Cluster formation and

4. E.C. Smith, et al., "Theoretical and Experimental Determinations of Neutron Energy Deposition in Silicon", IEEE Trans. Nucl. Sci., NS-13, No. 6, (1966). D. Binder, et al., "Analytical and Experimental Predictions of Fusion Neutron Radiation Effects", AFWL-TR-66-41, Vol. 1, Hughes-Fullerton, (1966).
5. H.J. Stein, "Energy Dependence of Neutron Damage in Silicon", J. Appl. Phys., 38, No. 1, (1967).
6. R.R. Holmes, "Energy Dependence for Carrier Removal and Lifetime Damage by Fast Neutrons in Silicon", Bell Telephone Laboratories Weapons Effects Studies, Report to ABMDA, Vol. II, Supplement III, pp 67-88, October 1, 1970.
7. C.S. Guenzer and Irwin Manning, "Calculated Displacement Damage by Neutrons in InSb", IEEE Trans. Nucl. Sci., NS-21, No. 6, (1971).
8. V.C. Rogers, L. Harris, Jr., D.K. Steinman, and D.E. Bryan, "Silicon Ionization and Displacement Kerma for Neutrons from Thermal to 20 MeV", IEEE Trans. Nucl. Sci., NS-22, No. 6, (1975). Also, Op. Cit., NS-23, No. 1, 875, (1976).
9. J. Lindhard, M. Scharff, and H.E. Schiott, "Range Concepts and Heavy Ion Ranges", Kg. Danske Videnskeb Selskab, Mat. Fys. Medd., 33, No. 14, 1-42, (1963).
10. A.R. Sattler and F.L. Vook, "Partition of the Average Energy Deposited in Silicon as a Function of Incident Neutron Energy", Phys. Rev., 155, No. 2, 211 (1967).
11. O.L. Curtis, Jr., "Statistics of Carrier Recombination at Disordered Regions in Semiconductors", J. Appl. Phys., 39, 3109, (1968).
12. B.L. Gregory, "Minority Carrier Recombination in Neutron-Irradiated Silicon", IEEE Trans. Nucl. Sci., NS-16, No. 6, 53-62, December (1969).
13. V.A. J. van Lint and R.E. Leadon, "Implications of Cluster Model of Neutron Effects in Silicon", Lattice Defects in Semiconductors, 1974, Inst. Phys. Conf. Ser., No. 23, The Institute of Physics, London and Bristol, pp 227-232, (1975).

annealing is receiving considerable current interest because of its relation to fusion-energy studies. Recent results[14,15] imply that there is a threshold energy for the formation of stable clusters, that there is much diffusion out of clusters, and (thus) that there is a limited significance to clustering. In the calculations on which the present results are based, the damage is modeled only to the extent of determining the fraction of the energy available for displacements, and emphasis has been placed on the detailed use of all available neutron cross section data.

Experimental work on the energy dependence of neutron damage has been very limited. Work with monoenergetic neutrons has been done by Smits and Stein,[16] Cleland et al.,[17] and Speers.[18] Working with selected-average energies from polychromatic sources, Kantz[19] and Lohkamp and McKenzie[20] have obtained experimental results related to energy dependence. Smits and Stein[16] compared the damage in silicon produced by 14 MeV neutrons relative to reactor neutrons. They found a ratio of 3.0 for carrier removal and a ratio of 3.5 for charge carrier lifetime degradation. One should note, however, that Coppage[21] has shown that errors of

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14. Yu. V. Martynenko, "Annealing and Clustering of Defects in Cascades", Rad. Effects, 29, 192, (1976).
15. V.L. Vinetskii and A.V. Kondrachuk, "The Kinetics of Formation and the Parameters of Radiation Defect Clusters in Silicon", Rad. Effects, 30, 227, (1976).
16. F.M. Smits and H.J. Stein, "Energy Dependence of Neutron Damage in Silicon-Experimental", Bull. Am. Phys. Soc. 9, No. 3, 238, (1964). F.M. Smits, "On the Energy Dependence of Neutron Damage in Semiconductors", Sandia Report No. SC-R-64-196, (1964).
17. J.W. Cleland, R.E. Bass, and J.H. Crawford, Jr., "The Nature and Yield of Neutron-Induced Defects in Semiconductors", Conference on Radiation Damage in Semiconductors, Paris, (1964), Proc. of the 7th Int. Conf. on the Physics of Semiconductors, Vol. 3, Radiation Damage in Semiconductors, Paris-Royaument 1964, pp 401-406, Academic Press, New York, (1965).
18. R.R. Speers, "Neutron Energy Dependence of Excess Charge Carrier Lifetime Degradation in Silicon", IEEE Trans. Nucl. Sci., NS-15, No. 5, 9-17, (1968).
19. A.D. Kantz, "Average Neutron Energy of Reactor Spectra and Its Influence on Displacement", J. Appl. Phys. 34, No. 7, 1944-1952, (1963).
20. J.E. Lohkamp and J.M McKenzie, "Measurement of the Energy Dependence of Neutron Damage in Silicon Devices", IEEE Trans. Nucl. Sci. NS-22, No. 6, 2319-2325, December (1975).
21. F.N. Coppage, "The Influence of Dosimetry on Earlier Damage Equivalence Ratios", IEEE Trans. Nucl. Sci., NS-22, No. 6, 2336-2339, December (1975).

30 percent are likely in early fluence measurements at reactors and these would result in equal errors in quoted damage ratios. Cleland et al.[17] used monoenergetic neutrons from an accelerator but based their conclusions on observations of carrier removal and thus required high fluences and attendant long runs. The present experimental work is most closely related to that of Speers,[18] but uses different readout techniques and better fluence measurements.

II. EXPERIMENTAL TECHNIQUE

The experimental measurements of damage were done with wide-base silicon diodes operating at a fixed forward current of 0.1A to maintain a constant, high level of charge injection and a high sensitivity to neutron damage. All diodes were made from 100 ohm-cm p-type silicon and had a cross-sectional area of about 0.1 cm^2. However, two base widths, about 1.27 mm (0.050 inch, "50-mil") and about 0.76 mm (0.030 inch, "30-mil"), were used. In both cases a constant injection level existed because the low level of neutron exposures used changed the injected-carrier lifetime without significantly changing the equilibrium carrier density. Observations were made on the change in forward voltage (with fixed current) induced by neutron irradiations. We have shown[1] this is a direct evaluation of lifetime degradation. The 50-mil diodes, and the readout technique used with them here, were used extensively in past work[1,2,3] and this use will be described next. Special efforts were made with the 30-mil diodes to control annealing and injection effects and these will be described at the end of this section.

An analysis of the current-voltage characteristics of wide-based silicon diodes and the effects of neutron irradiation can be found in the paper by Swartz and Thurston.[22] They combine the neutron induced changes in base and junction voltages at high injection to obtain theoretical results that agree with the current-voltage characteristics of actual diodes, including neutron effects. With a modest history of irradiation, the base voltage change with neutron exposure will dominate, and:

$$\frac{1}{\tau} = \frac{1}{\tau_o} + K \phi \qquad (1)$$

with

$$L = \sqrt{Dt} \qquad (2)$$

22. J.M. Swartz and M.O. Thurston, "Analysis of the Effect of Fast-Neutron Bombardment on the Current-Voltage Characteristic of a Conductivity-Modulated p-i-n Diode", J. Appl. Phys., 37, No. 2, 745-755, (1966).

and $$V_{base} = \frac{2kT}{e} \sinh \left(\frac{W}{2L}\right) \tan^{-1} \left[\sinh\left(\frac{W}{2L}\right)\right] \quad (3)$$

where τ_o = initial carrier lifetime

τ = carrier lifetime after irradiation

K = damage constant

ϕ = neutron fluence

D = diffusion constant

L = ambipolar diffusion length

k = Boltzman's constant

T = temperature

e = electron charge

W = width of the base region of the diode.

Equations 1, 2 and 3 relate the observed diode property (base voltage), carrier lifetime, and neutron fluence. These relations, and the lifetime measurements presented by Speers,[18] indicate clearly why the voltage observation is a measure of lifetime degradation. However, the explicit correctness of the formulae is not required for the damage measurements here. With the allowance of interpolations on the order of 10% of the observed changes, damage from neutrons from a particular source is compared with an equal amount of damage from 14 MeV neutrons.

The 50-mil diode exposure-readout procedure, developed for measurements made with monoenergetic neutrons,[1,3] consisted of an initial exposure to 14 MeV neutrons (about 10^{11} n/cm^2), necessary to put the diodes in a response range where damage measurements are the result of neutron exposure rather than material and device-fabrication history. After this initial irradiation, the diodes were annealed for several hours at a temperature of at least 50°C and then they were allowed to stabilize at room temperature for at least one week. At a subsequent exposure, the diodes were irradiated with a fluence of neutrons with a selected energy spectrum (fusion or fission simulator). Following each such exposure, the forward voltage was measured at selected times for a period well in excess of 100 hours and the value of the forward voltage 100 hours after mid-exposure time was determined. Typical before and after voltages were 1.2 and 1.4 volts. The individual readings were ± 2 mV and thus a 200 mV damage-induced change could be determined to about ± 2% (this does not include the errors in determining neutron fluences). The diodes were exposed in sets of 5 and they were maintained, except for the period of transport, at 30°C after exposure to control annealing. A very long-term (8000 hours) anneal curve, at 30°C, has been measured for these devices. This curve was used to make few-percent corrections to diode voltages when they were returned from exposure too late to read at the 100-hour point. The nonlinear response of the diodes was corrected for by a polynomial fit to experimental calibration (14 MeV) data, and, of course, this nonlinearity precludes quoting a single sensitivity factor.

The neutron fluence measurement techniques include use of activation foils, a proton-recoil telescope, and an associated-particle counter at the BRL Cockcroft-Walton accelerator. A weighted-average of these techniques was used for the initial evaluation of diode response to 14 MeV neutrons. Also, there was a subsequent exposure[†] of diodes to the intense 14-MeV neutron source at Livermore.[23] For equal amounts of damage, the fluences for the Livermore exposures were found to be 5 percent less (0.947). Because it is a more generally available source, all fluences were corrected to agree with the Livermore value. The fluence measurements at the APRF reactor[††] were obtained using techniques given by McGarry et al.[24] The fluences for exposures at a californium-252 source were determined by exposure-time and position with a prior calibration against APRF.[24] In all these measurements advantage was taken of very recent spectrum evaluations by McGarry et al.[25] The importance of spectra in fluence determinations has been discussed by Dunn, Kazi, and Saccenti.[26] The fluence measurements for exposures at the DORF reactor are based on older spectrum measurements and may be less reliable as a result.

Annealing is an important aspect of damage measurement and three areas of concern will be mentioned with regard to the 50-mil measurements. First, a stable pre-irradiation evaluation and a time and temperature controlled post-irradiation evaluation are required. Second, if annealing depended on neutron energy, then the energy dependence would depend

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† The authors would like to thank E.D. McGarry and P.A. Trimmer of HDL for including this exposure in their experiments.

23. R. Booth, H.H. Barschall, and E. Goldberg, "Rotating Target for Intense 14-MeV Neutron Source", IEEE Trans. Nucl. Sci., NS-20, No. 3, 472-474, June (1973).

†† The exposures and fluence measurements at the APRF were done by the reactor staff under the direction of Dr. A.H. Kazi.

24. E.D. McGarry, A.H. Kazi, G.S. Davis, and D.M. Gilliam, "Absolute Neutron Flux Measurements at Fast Pulse Reactors With Calibration Against Californium-252", IEEE Trans. Nucl. Sci., NS-23, No. 6, 2002-2006, December (1976).

25. E.D. McGarry, C.R. Heimbach, A.H. Kazi, and G.W. Morrison, "Fast Pulse Reactor Neutron Spectrum Measurement and Calculations", preprint (unpublished) July (1977).

26. T.A. Dunn, A.H. Kazi, and J. Saccenti, "Fluence-to-Dose Conversion Factors for APRF Fast Pulse Reactor Neutron Spectra", USABRL Report No. 1832, September (1975). (AD #B007605L)

on the time. We have proven this is not the case.[1] Third, annealing due to carrier injection, such as that noted by Gregory and Sander,[27] by Barnes,[28] and by Mallon and Harrity,[29] is an area we have not investigated. It can be said, however, that a consistent amount of injection was involved in all the (50-mil) measurements presented.

Very great care is necessary in characterizing permanent damage in neutron irradiated devices. The stable damage observed at room temperature many hours after irradiation depends in a complex way on the time, temperature, and charge injection history. As indicated in the paragraphs above, for the 50-mil measurements each of these (time, temperature, and injection history) was kept constant. The result was to require a very lengthy and careful series of measurements. To provide an alternate procedure, and additional measurements, a different test technique was used with a set of thirty-six 30-mil diodes. Rather than maintain a constant temperature in an oven, the 30-mil diodes were kept in a controlled lab (24 to 28°C) and careful measurements of the temperature at readout were used to make small (few-tenths-of-a-percent) corrections. A procedure suggested by Kruger et al.[30] was used to eliminate the need to interpolate to a 100-hour-after-exposure value.[1] These authors found (for diodes from a different manufacturer) that diodes annealed for 2 minutes at 100°C gave a constant result from 1 to 300 hours after exposure. The procedure used was to expose the diodes to 100°C (boiling water, the diodes were kept dry by plastic foil) for 2.5 minutes and to determine the forward voltage change 20 days after exposure. Tests indicated that the observed forward voltage change, when compared with the value 20 days after irradiation, was 2% high at 10 days and 2% low at 40 days. Data at 20 days after exposure was available for all runs so no correction was required for time of observation.

27. B.L. Gregory and H.H. Sander, "Injection Dependence of Transient Annealing in Neutron-Irradiated Silicon Devices", IEEE Trans. Nucl. Sci., NS-14, No. 6, 116-126, December (1967).
28. C.E. Barnes, "Thermal and Injection Annealing of Neutron-Irradiated P-type Silicon Between 76°K and 300°K", IEEE Trans. Nucl. Sci., NS-16, No. 6, 28-32, December (1969).
29. C.E. Mallon and J.W. Harrity, "Short-Term Annealing in Transistors Irradiated in the Biased-off Mode", IEEE Trans. Nucl. Sci., NS-18, No. 6, 45-49, December (1971).
30. H. Kruger, G. Tumbragel, R. Metzner, and H. Koch, "Fast-Neutron Dosimetry With Silicon Diodes", Neutron Monitoring for Radiation Protection Purposes, Vol. II, IAEA-SM-167/53, 401-409, International Atomic Energy Agency, Vienna (1973).

The injection dependence of the time, temperature, injection-history influence on annealing is the least understood aspect of this complex interaction. In addition to the studies previously noted,[27,28] an increase in forward voltage or "reverse anneal" has been observed.[31] An investigation of this effect showed that the forward voltage after irradiation (and thus the measured voltage change) will increase significantly with continued current injection for protracted periods. For example, several diodes with very-permanent neutron damage (12 years after irradiation) were found to increase from 1.19 to 1.25 V when injected for several hours. This is a 5% increase in the forward voltage and a 15% increase in the neutron-induced voltage change. This effect was found to saturate after 150 to 300 minutes of injection, and it was found to increase with an increase in the amount of neutron damage. No effect was observed for unirradiated diodes and the effect was reduced when some neutron damage was annealed at high temperature. A few months at room temperature, or a few minutes at 100°C, was found to bleach this effect. The 30-mil diodes were injected (standard forward current of 0.1A) for a period in excess of 300 minutes in sets of 10. They were then transferred to a different circuit configuration and read at 5, 30, and 50 seconds after the start of current injection. The 30s values were used to determine damage and the other values were used to insure that injection effects were stabilized.

To summarize the diode exposure-readout procedures, the 50-mil diode measurements were made with the same techniques used for studies with monoenergetic neutrons. These techniques are described in the first paragraphs of this chapter, and they have been presented in previous reports.[1,3] The same careful procedures were followed with the 30-mil diodes. However, the 30-mil diodes were read after they had been annealed 2.5 minutes at 100°C, after they had been current injected for at least 300 minutes, and after 20 days at room temperature subsequent to exposure. Exact readout temperature and injection dependent stability were noted.

III. CALCULATIONAL PROCEDURES

In our first efforts to determine the energy dependence of neutron-induced displacement damage in silicon[1,32] a limited (unevaluated) set of cross section data for specific neutron reactions was used with an

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31. E. Grober, Private Communication.
32. W.R. Van Antwerp and J.E. Youngblood, "Displacement Damage in Silicon Irradiated With 6- to 10-MeV Neutrons", Bull. Am. Phys. Soc., 17, p. 678, June (1972).

approximation for the LSS displacement fraction taken from Bertin et al.[33] This approximation, an empirical fit to the LSS[9] nuclear energy loss, is given by:

$$\left.\frac{d\varepsilon}{d\rho}\right|_{\text{nucl}} = \frac{\varepsilon^{\frac{1}{2}}}{0.67+2.07\varepsilon+0.03\varepsilon^2} \tag{4}$$

where ε and ρ are the dimensionless parameters defined by LSS in terms of particle energy, E, and displacement, X, as

$$\varepsilon = \frac{aA_2}{Z_1Z_2e^2(A_1+A_2)}\,E\ ,\ \rho = \frac{4\pi a^2NA_1A_2}{(A_1+A_2)^2}\,X \tag{5}$$

with Z_1,A_1 = atomic number and mass of projectile

Z_2,A_2 = atomic number and mass of stopping medium

N = number of stopping atoms per unit volume

$a = 0.8853\ a_o/(Z_1^{2/3}+Z_2^{2/3})^{\frac{1}{2}}$

a_o = the Bohr radius, 0.529×10^{-8} cm

e = the electron charge.

The LSS electronic energy loss was taken as proportional to the square root of the energy parameter, ε, and the formulation of an integral for the nuclear-stopping fraction followed in a straightforward way (details can be found in reference 2).

In integrating the formulae for energy, nuclear stopping is being treated as a continuous process and this is an approximation as the energy lost in a single collision can be a substantial fraction of the total recoil energy. Also, LSS as used in the preliminary calculations provides the fraction of energy of the primary recoil that goes into nuclear scattering and no correction was made in the preliminary calculations for multiple collisions. That is, no correction was made for energy lost to ionization in secondary, tertiary, et seq., collisions. The preliminary program was designed with particular emphasis on determining the effects of various parts of the input neutron cross section information and it served this purpose well. Despite its shortcomings, it also served as a base for the more elaborate subsequent effort.

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33. M.C. Bertin, N. Benczer-Koller, G.G. Seaman, and J.R. MacDonald, "Electromagnetic Transition Rates in ^{58}Ni", Phys. Rev., 183, 964-977, (1969).

The final program for damage calculations was formulated with a desire to improve the evaluation of the displacement fraction and with a continued interest in the sensitivity of damage calculations to cross section inputs. The ability to read an evaluated cross section set from magnetic tape was considered necessary, and there was a need for very good neutron energy resolution for use in analyzing accelerator neutron damage experiments.

The partial cross section, solid angle, and primary recoil energy calculations were done in the same way as for the preliminary calculations, but with the neutron cross sections and angular distributions taken from a tape. The preliminary program calculated the final displacement energy for each neutron reaction at each of 60 angles and summed the results. The present program made similar calculations, then doubled the number of angles and repeated the calculation with a test (0.5%) for convergence, with further doubling of the number of angles when required. Also, there was a substantive change in the calculation of the fraction of the primary recoil energy available for displacements. A correction was made for the energy lost to ionization in the collision sequence and, for this, a numerical-integration technique was used in an iterative process. Many collisions were followed for the higher-energy recoils and several tens of values were determined, geometrically spread across each decade of recoil energy. A few hundred values were stored, then, for table lookup and interpolation.

Calculations of the silicon recoils in silicon were supplemented with calculations of the aluminum and magnesium recoils in silicon to account for the heavy recoil products of the (n,α) and (n,ρ) reactions. The proton and alpha recoils were not included in the final calculations. There are two reasons, other than convenience and simplicity, for omitting these light-particle recoils. First, the contributions from these light particles were evaluated in a few cases and found to be no more than 1 or 2% of the total damage (similar results were obtained by Smith et al.[4]). Second, these particles have ranges significant when compared to typical device dimensions, and a realistic calculation of the p and α damage would have to account for losses and gains of p's and α's with the surrounding materials. The cross section tape used was the DNA file designated as DNA 4151 MOD 3. Except for editorial changes, this cross section information is the same as that in ENDF/B, Version IV, MAT 1194. The calculations include elastic scattering, inelastic scattering (22 excited states + continuum), (n,p) reaction (15 excited states+continuum), (n,α) reaction (12 excited states+continuum), (n,2n), (n,np), and $(n,n\alpha)$. In the last three reactions, the heavy reaction product was assumed to be at rest in the center of mass frame, and, in all cases, the reaction was assumed to be isotropic in the center of mass system if no other information was available.

Although the above 'present-work' formulation provided excellent results, a simple approximation taken from Doran[34] will produce almost identical results, and it seems most important to point out that this part of the computation does not contribute to differences between the present results and those of others. The formula given by Doran, when reduced to a single constituent (silicon recoil in silicon) is:

$$f = \frac{1}{1+kg(E_r)} \tag{6}$$

with $$k = 0.1334 Z^{2/3} A^{-1/2} \tag{7}$$

and $$g(E_r) = E_r + 0.40244 E_r^{3/4} + 3.4008 E_r^{1/6} \tag{8}$$

where f = fraction of recoil energy going into displacements, corrected for multiple collisions.

Z, A = atomic number and mass of silicon (14,28).

E_r = recoil (or PKA, primary knock-on atom) energy.

Table I provides a comparison of the displacement-fraction estimates obtained from Equation (4), from present-work, and from Equation (6).

TABLE I. Comparison of Estimates of Displacement Energy E_d, at Several Recoil Energies, E_r (all values in keV).

E_r (keV)	E_d (Equation 4)	E_d (Present-Work)	E_d (From Equation 6)
1	0.91	0.79	0.78
3	2.7	2.3	2.24
10	8.8	7.0	6.9
30	25.	19.	18.4
100	68.	50.	49.
300	141.	101.	99.
1000	240.	167.	165.

34. D.C. Doran, "Neutron Displacement Cross Sections for Stainless Steel and Tantalum Based on a Lindhard Model", Nucl. Sci. Eng., 49, No. 2 130-144, October (1972).

The table shows both the importance of the multiple-collision correction and the close correspondence of the present calculations to those (including any future ones) based on the Doran[34] approximation. This approximation, Equation (6), is in a convenient form and equally convenient expressions could be obtained for aluminum recoils in silicon and magnesium recoils in silicon. The comparison between present-work and Doran is somewhat better than the previous used comparison[2] taken from Mayer et al.[35]

The results of the calculations on energy dependence, in complete tabular form, are required in order to calculate the displacement damage to be expected from an accelerator produced neutron experiment, from a simulator spectrum, or from a threat spectrum. For these uses the tables of calculated results, presented in a previous report,[2] are included in the appendix. The calculations were done for each 5 keV interval from 0.1 to 20 MeV and these results, for 0.1 to 16 MeV, are given in the first four tables. There are also tables providing 25 keV interval averages for 0.1 to 16 MeV and 100 keV interval average values for the energy range 0.1 to 20 MeV. The appendix also contains tables of the calculated response for various group structures used in subsequent sections of this report.

IV. COMPARISON OF CALCULATIONS AND MEASUREMENTS

Prior to presenting the results for more complex neutron spectra, some of the calculations and measurements done for accelerator-produced neutrons will be compared. This will provide the reader with a better feel for the level of agreement that might be expected between calculated and observed values. A graphic presentation of the totality of calculated results is given in Figures 1 and 2. The fractional contributions from the various neutron reactions are shown as well as the total calculated damage. Figure 1 covers the neutron energy range 0.1 to 10 MeV while Figure 2 covers 10 to 20 MeV. To calculate the expected damage the (5-keV interval) tabulated damage values are averaged over the appropriate energy interval (for the energy range of an accelerator run) or over each of the appropriate energy intervals (for a given group structure). The resulting damage factor(s) is multiplied by the neutron fluence (or fraction of a neutron in each group).

35. J.W. Mayer, L. Eriksson, and J.A. Davies, Ion Implantation in Semiconductors, p. 68, Academic Press, NY, (1970).

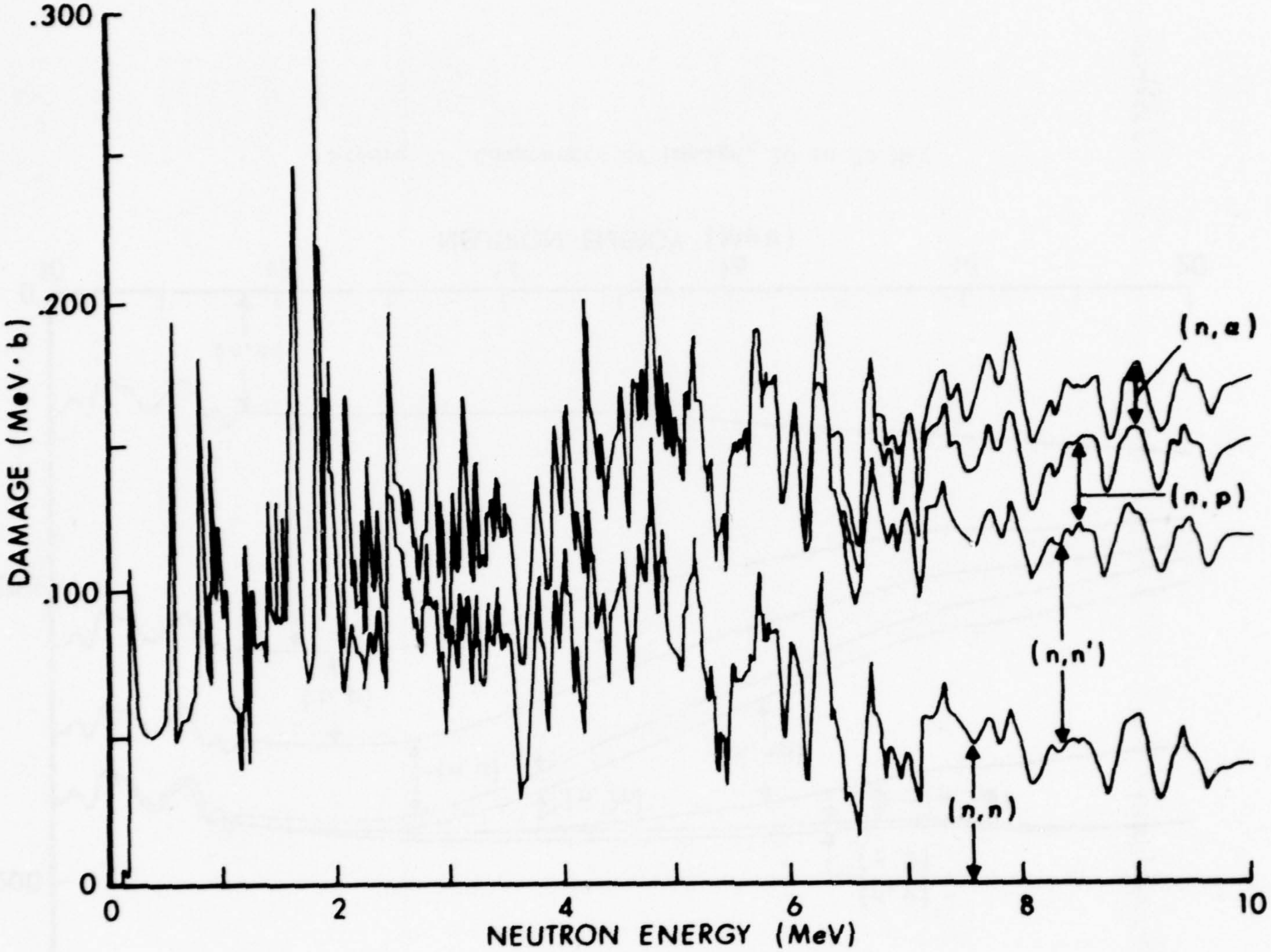

Figure 1. Components of Damage, 0.1 to 10 MeV

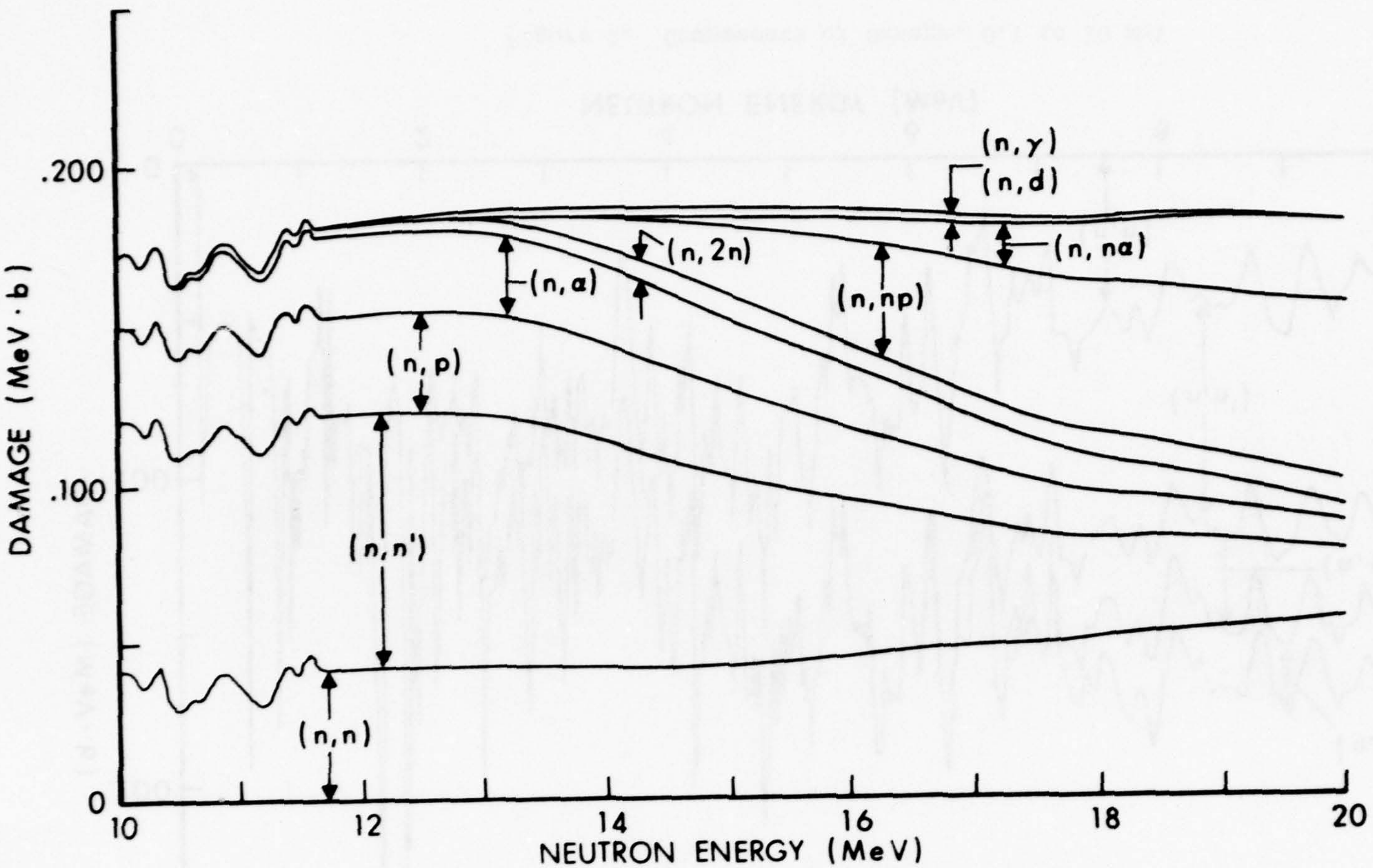

Figure 2. Components of Damage, 10 to 20 MeV

The results of damage calculations are, typically, 0.1 to 0.2 MeV·b (100 to 200 MeV·m b), with the specific value of 0.187 MeV·b for 14.2 MeV neutrons. The techniques used to process experimental data,[1,3] corrected for non-linear response and normalized to a neutron fluence of 2.357 X 10^{10} m/cm^2, produced measured damage results that ranged from 1.4 to 5.7. The measured values divided by calculated values for the same neutron energy (e.g., 5/0.2) produced numbers of the magnitude 25, and the constancy of this ratio is an indication of the adequacy of the model used to calculate the damage. A comparison of calculated and measured results for neutron energies near 1 MeV is illustrative of the facts just described and these are shown in Table II.

TABLE II. Comparison of Calculated and Measured Damage Near 1 MeV.

Neutron Energy (MeV)	Energy Spread[a)] (keV)	Calc. Dam. (MeV·b)	Ratio[b)] (Exp/calc)	Error (%)
0.696	60	0.0582	24.4	13
0.957	49	0.114	23.7	13
1.157	44	0.0502	30.3	13
1.630	38	0.193	26.4	13
2.370	37	0.108	24.7	13
3.990	35	0.131	20.8	12
4.990	30	0.152	18.9	12
14.2	-	0.187	22.7	7

a) The energy spread includes line-shape effects. The stated energy widths define an interval that contains 90% of the total neutrons incident on the diode samples.

b) The ratios given include experimental values (see text for units) obtained using fluences measured with a long counter except for 14.2 MeV. The 14.2 MeV value was obtained using a fluence determined by proton-recoil telescope.

These results are shown graphically in Figure 3, and the results for 4.0 to 7.5 MeV for experiments done at the BRL tandem Van de Graaff are shown in Figure 4. For both Figures 3 and 4 the calculated (left) and experimental (right) scales are for a ratio of 26.1/1. This is the average value for the 25 results shown.

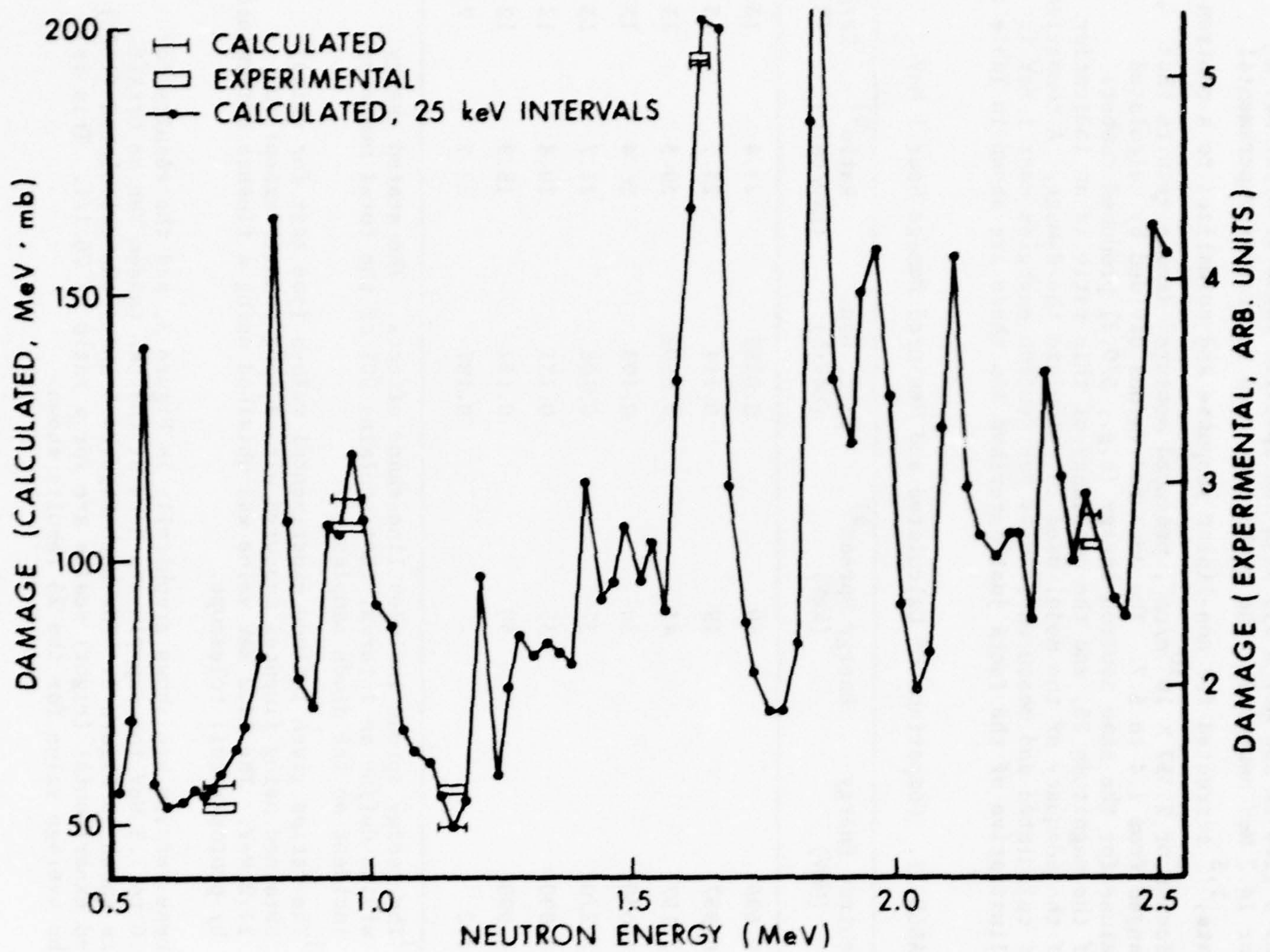

Figure 3. Calculated and Measured Damage Near 1 MeV

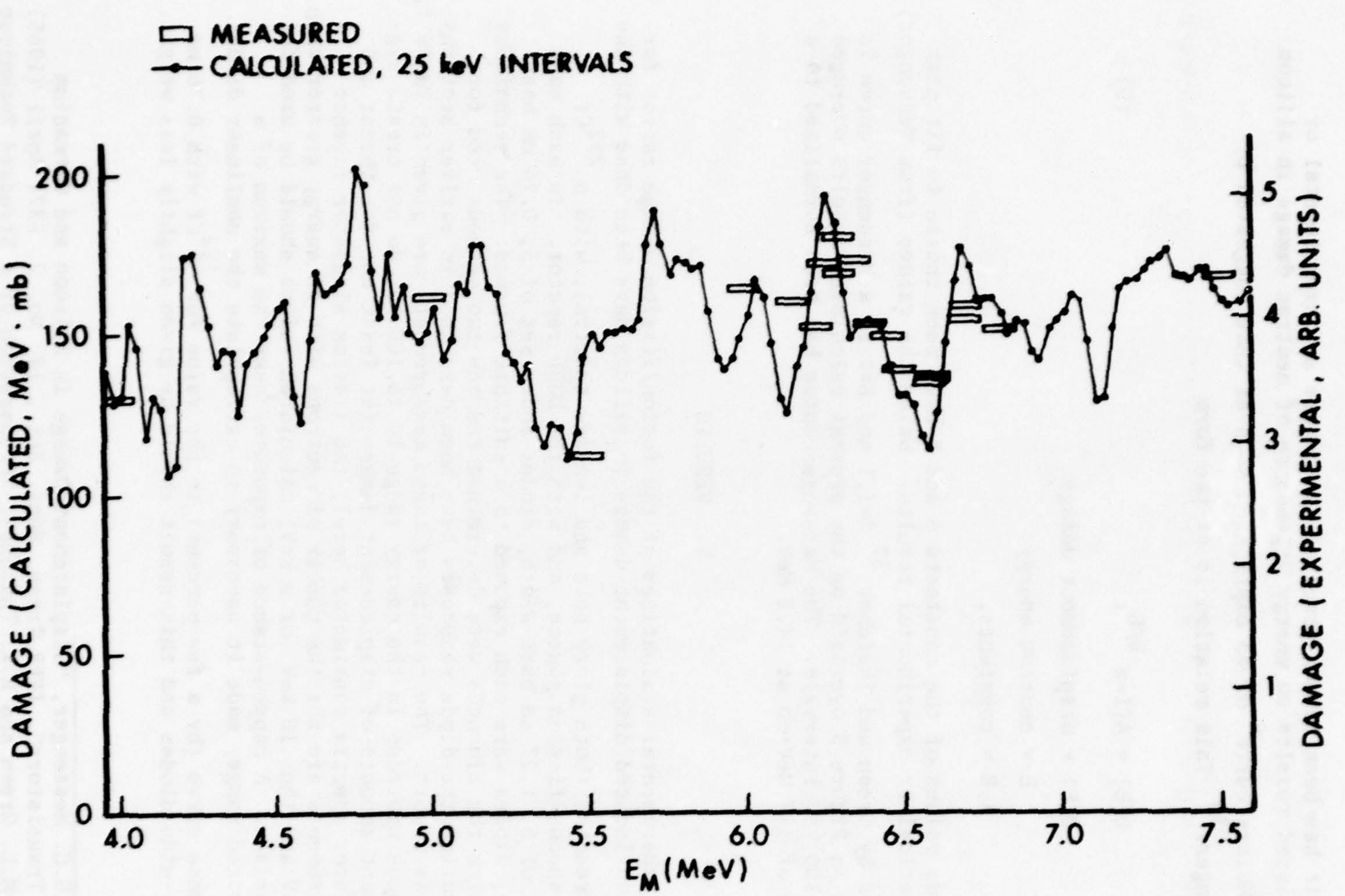

Figure 4. Calculated and Measured Damage, 4 to 7.5 MeV

It has been common practice to compare all experimental or calculated results on energy dependence of neutron damage in silicon to a Holmes curve[6] or an expression such as that suggested by Messenger.[36] This relation is of the form

$$D(E) = A(1-e^{-B/E}) \tag{9}$$

where $D(E)$ = displacement damage

E = neutron energy

A, B = constants.

Various values of the constants A and B have been chosen to fit past theoretical or experimental results. Using the values (from Messenger) quoted by Green and Thatcher,[37] $A=1.1$ and $B=2.2$, a Messenger curve is shown in Figure 5 overlaid on the present calculated results averaged over 100 keV intervals. The Messenger curve has been normalized to a value of 187 MeV·mb at 14.2 MeV.

V. RESULTS

Experimental evaluations of the fusion/fission damage ratios for neutron-induced displacement damage in silicon have been done with the APRF reactor (both glory hole and leakage spectra), with a ^{252}Cf spontaneous-fission source, and with the DORF reactor. In each case a set of 5, 1.27 mm base-width, diodes and a set of 5, 0.76 mm base-width, diodes were each exposed to a suitable fluence. The techniques by which the fluences were determined and the two methods used for evaluating the diode responses have been described in earlier sections of this report. The results of these measurements are given in Table III. Although neutrons in the energy range 10 to 100 keV do not create significant amounts of displacement damage (at least not for threat and simulator spectra considered here), the fission simulator fluence measurements are for the number of neutrons with an energy greater than 10 keV and thus 10 keV (or 9 keV) calculated values should be used for comparison. A happen-stance of exposure, near the maximum of a suggested range, made it necessary to extrapolate the nonlinear diode-response curve (by a few percent) to the value for ^{252}Cf with 0.76 mm base -wide diodes and this result should be given slightly less weight.

36. G.C. Messenger, "Displacement Damage in Silicon and Germanium Transistors", IEEE Trans. Nucl. Sci., 12, No. 2, 5374 April (1965).
37. M.L. Green and R.K. Thatcher, "Preparation of a Standard Technique for Determination of Neutron Equivalence for Bulk Damage in Silicon", IEEE Trans. Nucl. Sci., NS-19, No. 6, 200-208, December, (1972).

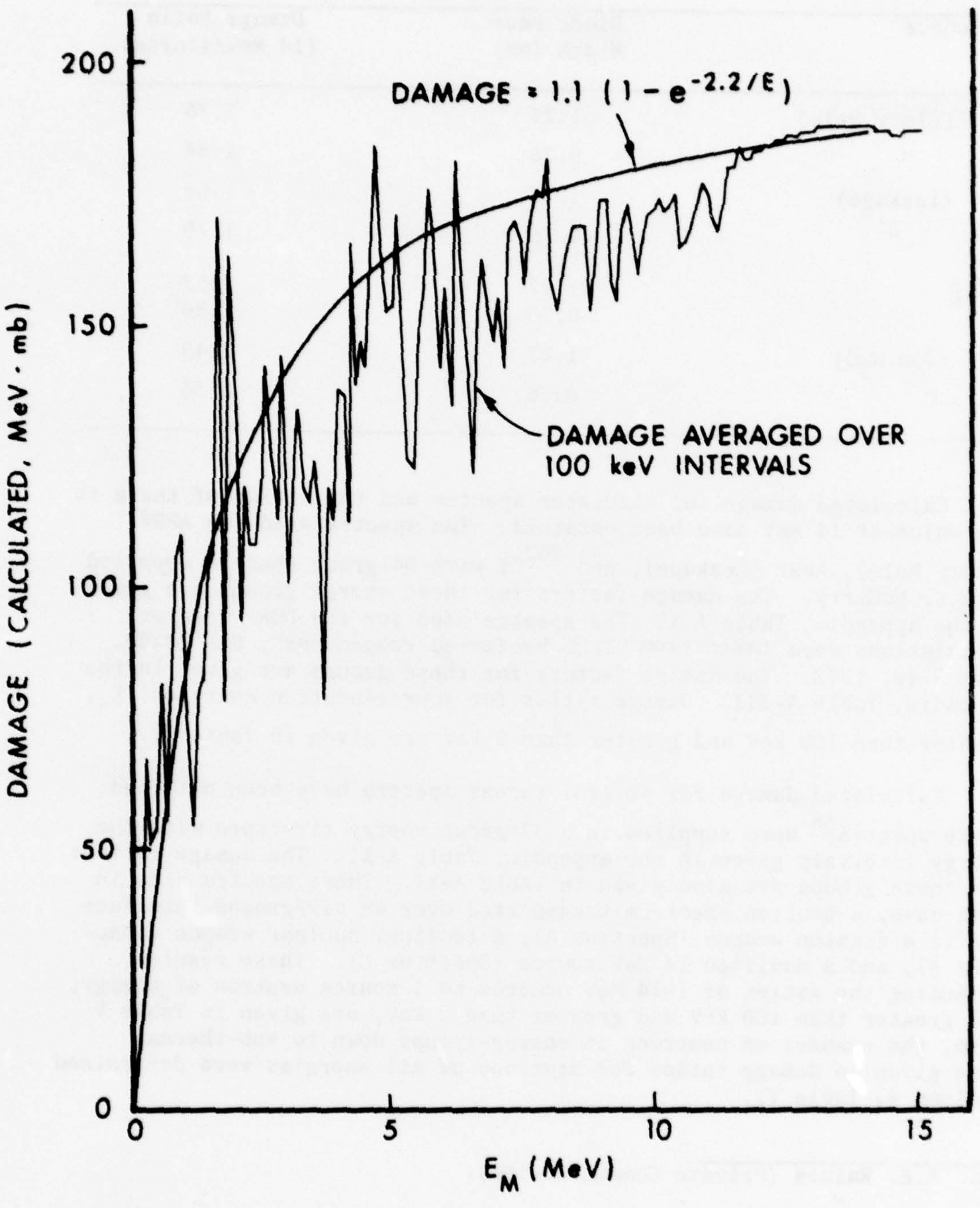

Figure 5. Calculated Damage Averaged Over 100 keV Intervals

TABLE III. Measured Fusion/Fission Damage Ratios.

Source	Diode Base Width (mm)	Damage Ratio (14 MeV/source)
APRF (Glory Hole)	1.27	1.75
" " "	0.76	1.84
" (leakage)	1.27	1.66
" "	0.76	1.70
^{252}Cf	1.27	1.52
"	0.76	1.80
DORF (2cm H_2O)	1.27	2.45
"	0.76	2.58

Calculated damage for simulator spectra and the ratios of these to the value at 14 MeV have been obtained. The spectra used for APRF (Glory Hole), APRF (Leakage), and ^{252}Cf were 94-group spectra supplied by E.D. McGarry. The damage factors for these energy groups are given in the appendix, Table A-X. The spectra used for the DORF reactor calculations were taken from "TREE Preferred Procedures", DNA 2028H, page 5-49, 1972. The damage factors for these groups are given in the appendix, Table A-XII. Damage ratios for source-neutron energies, E_n, greater than 100 keV and greater than 9 keV are given in Table IV.

Calculated damage for several threat spectra have been obtained. These spectra[38] were supplied in a 37-group energy structure with the energy intervals given in the appendix, Table A-XI. The damage factors for these groups are also given in TABLE A-XI. These spectra are, in each case, a neutron spectrum transported over an air/ground interface due to a fission weapon (Spectrum A), a tactical nuclear weapon (Spectrum B), and a modified 14 MeV source (Spectrum C). These results, including the ratios of 1-14 MeV neutron to 1-source neutron of energy, E_n, greater than 100 keV and greater than 9 keV, are given in Table V. Also, the numbers of neutrons in energy-groups down to sub-thermal were given so damage ratios for neutrons of all energies were determined (column 4, Table V).

38. A.E. Rainis (Private Communication).

TABLE IV. Calculated Ratios of Damage for Simulator Spectra.

Source	Damage Ratio (1-14 MeV neutron to 1 source neutron with $E_n \geq 100$ keV)	Damage Ratio (1-14 MeV neutron to 1 source neutron with $E_n \geq 9$ keV)
APRF (Glory Hole)	2.13	2.19
APRF (Leakage)	2.07	2.12
^{252}Cf	1.80	1.82
DORF (Center of Core)	2.13	2.54
DORF (2 cm in H_2O)	2.10	2.54
14 MeV	1.00	1.00

TABLE V. Calculated Ratios of Damage for Typical Threat Spectra.

Source*	Damage Ratio (14 MeV/source) $E_n \geq 100$ keV	Damage Ratio (14 MeV/source) $E_n \geq 9$ keV	Damage Ratio (14 MeV/source) $E_n \geq 0$ keV
Threat Spectrum A	2.58	7.06	10.4
Threat Spectrum B	2.74	6.47	9.40
Threat Spectrum C	1.98	3.90	5.32
14 MeV	1.00	1.00	1.00

*Spectrum A = fission weapon, transported over air/ground interface
Spectrum B = tactical nuclear weapon, transported over air/ground interface
Spectrum C = modified 14 MeV source, transported over air/ground interface.

VI. DISCUSSION

The nature of modeling permanent neutron damage in materials can readily be divided into four phases:

a. Model the nuclear reaction cross sections, combine these with measured cross sections, and form a self-consistent evaluated neutron cross section set.

b. Apply the known kinematics (and model where necessary) for each nuclear reaction at each angle and obtain the energy distribution of primary recoils.

c. Model the fractioning of primary-recoil energy into electronic stopping (not producing permanent damage) and energy available for displacements.

d. Model the conversion of displacement energy into the number and geometry of displaced atoms.

In the frame of these four phases, the calculations of damage presented in this report are based on a particularly thorough and detailed consideration of phases a and b. These phases are discussed in detail in the section on calculational procedures. Phase c has been done using the fractioning of LSS,[9] and, in addition to the confirmation by Sattler and Vook,[10] the work of Chaseman, et al.,[39,40] has shown that the ionization losses for germanium atoms moving in germanium agree with LSS (electronic stopping proportional to velocity) for the energy range 10 to 100 keV. Jones and Kraner[41] have extended this with measurements in the range 1 to 2 keV and[42] with a final check at 254 eV. Even at 254 eV Jones and Kraner[42] find an inelastic loss of ca. 40 eV in good agreement with LSS. With regard to phase d, it has been assumed that the number of defects initially formed is proportional to the energy available for displacements, that the number of permanent defects is proportional to the number initially formed and independent of their geometry, and that the mechanical or electrical property of interest does not depend on the geometry (clustering) of defects.

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39. C. Chasman, K.W. Jones, and R.A. Ristinen, "Measurement of the Energy Loss of Germanium Atoms to Electrons in Germanium at Energies Below 100 keV," Phys. Rev. Letters, 15, No. 6, 245-249, August, (1965).
40. C. Chasman, K.W. Jones, and H.W. Kraner, "Band-Gap Effects in the Stopping of Ge^{72*} Atoms in Germanium", Phys. Rev. Letters, 21, No. 20, 1430-1433, November (1968).
41. K.W. Jones and H.W. Kraner, "Stopping of 1- to 1.8-keV ^{73}Ge Atoms in Germanium", Phys. Rev. C, 4, 125-129, January, (1971).
42. K.W. Jones and H.W. Kraner, "Energy Lost to Ionization by 254-eV ^{73}Ge Atoms Stopping in Ge", Phys. Rev. A, 11, No. 4, 1347-1353, April, (1975).

The measured values of damage ratios are primarily limited by fluence determinations. Although neutron-induced voltage changes can be measured to 1 or 2 percent, an error of 10% is possible in the fluence evaluations at 14 MeV. For pulsed reactor neutron fluence measurements the neutron spectrum is involved. The spectra are used, for example, to determine the fluence ratio, $\phi(E_n > 10\ \mathrm{keV})/\phi(E_n > 3\ \mathrm{MeV})$ and this ratio is used to convert activation foil measurements to fluences.

The experimental results in Table III show slight but consistently higher damage ratios from the 0.76 mm diodes. If the value for ^{252}Cf is discounted, the difference is about 4% and cannot be considered significant. This would be worth a careful check if the exposures are repeated, however. When the measurements in Table III are compared with the calculated ($E_n > 9$ keV) results in Table IV, spectrum and fluence measurements are again brought into question. The three results on the APRF and ^{252}Cf simulators are based on the recent, carefully determined 94-group spectra and they are self-consistent to about 7%, but the measured ratios are 15% less than the calculated ratios. The more limited and dated spectral information on the DORF, meanwhile, has produced an experimental-to-calculated ratio of 1.00. It has been noted that (especially with non-monoenergetic sources) the spectrum used affects both the calculated damage and the fluence measurement.

VII. CONCLUSIONS

Despite the limitations cited in the discussion above, excellent results have been obtained on the energy dependence of neutron damage in silicon and a modeling technique of general applicability to damage calculations has been presented. Neutron-induced displacement damage in silicon has been calculated and measured for a representative selection of simulator and threat neutron spectra. The calculated damage is based on the Lindhard nuclear stopping fraction corrected for multiple collisions and it thus provides the energy available for displacement damage. Tables of calculated damage in 5, 25 and 100 keV intervals are presented as well as tables of calculated damage for several frequently used group structures. An experimental check of the damage has been obtained using wide-base silicon diodes at a high injection level. The changes in forward voltage at a fixed current, reflecting the degradation of injected carrier lifetime, were observed.

The uncertainties in the measurements we have presented of fusion/fission damage ratios for neutron induced displacement damage in silicon are generally less than 20%. The comparison of measurements and calculations is also less than 20% and this is sufficient for most military applications. The problems with a 1 MeV hardness-assurance criteria, delineated most concisely in an earlier report,[3] remain. However, if adequate spectral information is folded into the damage table presented, any equivalence definition can be accommodated.

ACKNOWLEDGEMENTS

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APPENDIX

TABLES

The basic damage calculations were done in 5-keV intervals from 0.1 to 20 MeV and the results, stored on disc, remain available. To provide the information necessary for others to obtain a set of damage factors for any neutron energy group structure of interest, the complete 5-keV interval results from 0.1 to 16 MeV are presented in Tables A-I, A-II, A-III and A-IV. Tables A-V and A-VI provide 25-keV interval averages for 0.1 to 16 MeV, and Table A-VII has 100-keV average values for 0.1 to 20 MeV. The results for a 22-group structure (Table VIII), a 94-group structure (Table IX), a 36-group structure (Table X) and a 24-group structure (Table XI) are also presented.

TABLE A-1. Relative Neutron Damage (MeV·b) Averaged Over 5 keV Intervals - 0.1 to 4 MeV

NEUTRON ENERGY MEV	INTERVAL BOUNDARIES IN KEV 0	5	10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100
0.000																					
0.100	.005	.005	.005	.005	.004	.004	.003	.003	.003	.002	.003	.005	.009	.016	.030	.051	.075	.098	.112	.111	
0.200	.104	.097	.090	.083	.077	.072	.069	.066	.063	.061	.040	.058	.057	.056	.055	.055	.054	.053	.053	.053	
0.300	.057	.052	.052	.052	.051	.051	.051	.051	.051	.051	.051	.051	.051	.051	.051	.052	.052	.052	.052	.052	
0.400	.052	.052	.053	.053	.053	.053	.053	.054	.054	.054	.054	.054	.055	.055	.055	.055	.056	.056	.056	.057	
0.500	.057	.057	.057	.058	.058	.062	.082	.064	.068	.074	.088	.113	.182	.195	.115	.074	.057	.048	.056	.054	
0.600	.055	.052	.052	.053	.053	.053	.053	.053	.055	.058	.057	.056	.056	.056	.056	.057	.057	.057	.058	.058	
0.700	.059	.059	.059	.060	.060	.061	.062	.063	.066	.069	.068	.068	.068	.070	.071	.070	.073	.077	.085	.106	
0.800	.136	.166	.182	.179	.160	.138	.116	.098	.095	.092	.081	.079	.078	.076	.075	.075	.074	.073	.070	.068	
0.900	.069	.099	.153	.114	.100	.098	.100	.104	.108	.113	.117	.120	.122	.123	.120	.117	.113	.108	.104	.100	
1.000	.095	.094	.092	.090	.088	.086	.086	.088	.097	.084	.078	.070	.068	.067	.065	.065	.064	.064	.063	.063	
1.100	.063	.062	.062	.062	.062	.060	.058	.055	.052	.050	.047	.039	.046	.061	.056	.052	.050	.050	.054	.070	
1.200	.103	.115	.098	.087	.080	.074	.069	.061	.050	.041	.043	.061	.089	.099	.088	.087	.088	.087	.086	.084	
1.300	.083	.082	.082	.082	.083	.083	.084	.084	.085	.084	.084	.083	.083	.082	.082	.082	.082	.080	.078	.082	
1.400	.099	.129	.135	.113	.102	.098	.094	.092	.091	.091	.091	.091	.091	.095	.109	.133	.120	.099	.093	.091	
1.500	.091	.091	.093	.097	.110	.127	.113	.097	.092	.090	.089	.090	.090	.091	.094	.104	.114	.116	.146	.192	
1.600	.179	.161	.158	.160	.174	.200	.217	.212	.187	.196	.247	.242	.197	.163	.146	.132	.121	.112	.105	.099	
1.700	.094	.090	.087	.085	.083	.082	.080	.079	.077	.076	.074	.073	.072	.072	.071	.070	.069	.069	.073	.079	
1.800	.083	.082	.078	.082	.095	.115	.140	.172	.216	.266	.302	.291	.249	.218	.197	.177	.154	.130	.110	.097	
1.900	.093	.100	.117	.140	.160	.166	.157	.146	.141	.139	.141	.147	.157	.170	.178	.165	.142	.124	.112	.105	
2.000	.100	.096	.093	.089	.085	.081	.078	.075	.073	.073	.078	.084	.089	.085	.079	.084	.102	.129	.153	.159	
2.100	.152	.154	.164	.165	.151	.134	.120	.110	.104	.100	.099	.101	.103	.108	.112	.112	.106	.100	.097	.092	
2.200	.097	.099	.100	.109	.120	.123	.116	.105	.094	.086	.082	.082	.085	.092	.102	.115	.130	.142	.146	.141	
2.300	.132	.121	.113	.108	.105	.103	.101	.099	.098	.098	.102	.106	.111	.119	.127	.122	.111	.102	.097	.095	
2.400	.094	.094	.093	.092	.090	.088	.086	.086	.089	.101	.124	.146	.148	.141	.130	.141	.148	.159	.175	.193	
2.500	.192	.172	.151	.140	.137	.137	.137	.137	.136	.136	.136	.136	.136	.136	.136	.136	.136	.136	.135	.135	
2.600	.134	.133	.131	.129	.126	.123	.121	.121	.122	.126	.130	.134	.134	.130	.123	.116	.113	.118	.122	.125	
2.700	.124	.121	.117	.114	.111	.108	.104	.101	.104	.109	.110	.109	.107	.108	.112	.119	.123	.120	.117	.118	
2.800	.121	.125	.128	.131	.134	.138	.145	.154	.162	.170	.175	.176	.175	.169	.157	.141	.128	.120	.116	.112	
2.900	.109	.104	.102	.108	.111	.115	.122	.128	.126	.116	.103	.093	.086	.081	.079	.079	.081	.084	.089	.096	
3.000	.107	.120	.128	.131	.130	.125	.118	.116	.120	.122	.119	.117	.119	.121	.116	.109	.104	.107	.116	.127	
3.100	.139	.148	.150	.146	.140	.139	.146	.157	.165	.165	.154	.137	.123	.117	.116	.115	.113	.110	.105	.101	
3.200	.100	.105	.110	.116	.124	.133	.142	.146	.143	.136	.127	.117	.110	.106	.107	.110	.113	.115	.114	.112	
3.300	.109	.106	.105	.105	.107	.109	.111	.113	.115	.117	.120	.124	.127	.130	.131	.129	.126	.122	.118	.117	
3.400	.117	.118	.121	.126	.131	.136	.137	.135	.131	.127	.123	.120	.118	.118	.118	.120	.121	.122	.124	.126	
3.500	.129	.130	.129	.126	.124	.121	.120	.119	.119	.119	.118	.117	.115	.113	.111	.108	.106	.104	.101	.097	
3.600	.092	.087	.081	.076	.073	.073	.074	.076	.076	.076	.076	.076	.076	.076	.075	.076	.077	.081	.087	.092	
3.700	.096	.098	.098	.097	.098	.099	.102	.107	.115	.123	.130	.136	.140	.141	.139	.137	.135	.133	.131	.129	
3.800	.127	.127	.127	.127	.127	.126	.123	.119	.114	.110	.105	.101	.099	.099	.100	.100	.101	.103	.107	.112	
3.900	.118	.125	.131	.138	.143	.147	.149	.151	.151	.150	.149	.148	.147	.141	.133	.128	.126	.128	.130	.131	

TABLE A-II. Relative Neutron Damage (MeV.b) Averaged Over 5 keV Intervals - 4 to 8 MeV

NEUTRON ENERGY MEV	INTERVAL BOUNDARIES IN KEV 0-5	5-10	10-15	15-20	20-25	25-30	30-35	35-40	40-45	45-50	50-55	55-60	60-65	65-70	70-75	75-80	80-85	85-90	90-95	95-100
4.000	.131	.128	.129	.132	.137	.143	.150	.155	.159	.160	.158	.152	.146	.139	.132	.126	.121	.117	.114	.113
4.100	.114	.117	.126	.124	.127	.127	.122	.116	.112	.110	.110	.109	.108	.105	.100	.098	.101	.105	.112	.128
4.200	.147	.165	.179	.188	.190	.187	.181	.174	.168	.164	.164	.165	.165	.165	.162	.159	.155	.151	.147	.145
4.300	.144	.142	.140	.139	.137	.138	.141	.145	.149	.151	.152	.149	.145	.140	.134	.129	.124	.122	.123	.127
4.400	.132	.138	.143	.146	.145	.142	.141	.145	.149	.149	.148	.148	.148	.150	.153	.155	.155	.152	.150	.150
4.500	.152	.154	.158	.161	.164	.166	.165	.163	.157	.150	.141	.134	.128	.125	.124	.124	.122	.120	.122	.126
4.600	.133	.140	.148	.155	.161	.166	.169	.171	.171	.170	.168	.165	.162	.159	.158	.158	.160	.163	.168	.172
4.700	.173	.171	.166	.161	.158	.159	.163	.171	.180	.189	.196	.200	.201	.201	.210	.212	.203	.193	.188	.184
4.800	.180	.176	.171	.165	.160	.155	.152	.151	.154	.161	.169	.176	.180	.178	.173	.166	.158	.151	.148	.150
4.900	.154	.161	.167	.171	.170	.163	.153	.146	.144	.146	.148	.148	.147	.146	.144	.143	.146	.150	.154	.157
5.000	.160	.162	.160	.156	.153	.149	.146	.142	.138	.136	.137	.141	.147	.154	.160	.166	.168	.169	.165	.161
5.100	.159	.161	.163	.165	.167	.170	.174	.179	.183	.186	.186	.183	.179	.174	.169	.164	.162	.163	.165	.167
5.200	.167	.166	.163	.159	.154	.150	.145	.143	.142	.142	.143	.142	.141	.140	.138	.136	.135	.134	.135	.137
5.300	.140	.142	.143	.142	.139	.133	.126	.120	.115	.112	.111	.113	.115	.118	.120	.121	.122	.123	.123	.123
5.400	.123	.122	.122	.121	.119	.117	.113	.110	.107	.106	.108	.112	.118	.124	.130	.136	.141	.144	.147	.149
5.500	.151	.151	.151	.150	.149	.147	.146	.145	.144	.145	.147	.149	.152	.152	.151	.151	.151	.152	.151	.148
5.600	.146	.147	.150	.153	.156	.157	.155	.151	.148	.146	.147	.149	.153	.158	.163	.168	.173	.177	.181	.184
5.700	.187	.189	.189	.188	.186	.184	.180	.176	.173	.170	.168	.167	.167	.169	.170	.171	.172	.173	.174	.174
5.800	.174	.173	.172	.171	.169	.168	.169	.170	.171	.173	.174	.173	.172	.170	.167	.163	.160	.156	.153	.149
5.900	.146	.143	.141	.139	.138	.137	.137	.137	.138	.138	.139	.141	.142	.143	.144	.146	.147	.148	.149	.150
6.000	.150	.150	.154	.158	.161	.164	.166	.167	.167	.167	.165	.164	.161	.158	.155	.152	.149	.146	.142	.139
6.100	.135	.132	.129	.126	.124	.122	.122	.124	.127	.131	.135	.139	.141	.142	.142	.143	.144	.145	.148	.151
6.200	.154	.158	.162	.167	.171	.175	.180	.183	.187	.190	.191	.193	.194	.194	.193	.191	.188	.184	.180	.175
6.300	.171	.166	.161	.157	.153	.150	.149	.147	.147	.148	.149	.151	.153	.155	.156	.156	.155	.154	.153	.153
6.400	.152	.152	.152	.153	.154	.154	.153	.152	.150	.148	.145	.142	.139	.136	.134	.132	.130	.130	.130	.130
6.500	.131	.132	.132	.131	.131	.130	.129	.127	.125	.123	.122	.120	.118	.116	.114	.113	.112	.112	.113	.115
6.600	.117	.121	.124	.129	.133	.138	.142	.147	.152	.157	.161	.165	.167	.169	.170	.172	.173	.175	.176	.177
6.700	.175	.173	.170	.167	.164	.162	.160	.159	.159	.159	.160	.160	.161	.161	.160	.160	.160	.160	.160	.160
6.800	.159	.157	.155	.153	.150	.148	.147	.147	.148	.150	.151	.152	.154	.155	.155	.155	.154	.153	.151	.149
6.900	.147	.145	.143	.140	.139	.138	.139	.140	.142	.145	.147	.150	.151	.152	.152	.152	.152	.152	.152	.152
7.000	.152	.153	.155	.157	.158	.159	.160	.161	.161	.162	.162	.161	.160	.158	.156	.153	.150	.146	.142	.138
7.100	.134	.130	.127	.125	.124	.124	.125	.128	.131	.136	.140	.145	.150	.154	.158	.160	.162	.163	.164	.165
7.200	.165	.165	.165	.165	.165	.166	.166	.167	.167	.167	.167	.167	.167	.168	.169	.170	.171	.171	.171	.171
7.300	.171	.171	.172	.173	.174	.176	.176	.176	.174	.171	.169	.167	.166	.167	.166	.166	.166	.166	.166	.165
7.400	.165	.165	.164	.164	.165	.166	.168	.169	.170	.170	.170	.171	.170	.169	.167	.166	.164	.162	.161	.159
7.500	.158	.158	.158	.157	.157	.157	.157	.157	.157	.157	.157	.158	.158	.159	.159	.160	.160	.161	.162	.162
7.600	.163	.163	.164	.164	.165	.165	.166	.166	.167	.169	.169	.170	.171	.172	.174	.175	.176	.177	.179	.180
7.700	.181	.180	.180	.180	.179	.178	.176	.175	.175	.174	.174	.174	.175	.175	.174	.174	.173	.173	.173	.172
7.800	.171	.171	.170	.169	.168	.168	.169	.170	.171	.172	.173	.175	.176	.178	.180	.182	.183	.183	.184	.185
7.900	.186	.186	.186	.186	.186	.186	.185	.185	.184	.184	.183	.182	.181	.180	.179	.178	.177	.176	.174	.173

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TABLE A-III. Relative Neutron Damage (MeV·b) Averaged Over 5 keV Intervals - 8 to 12 MeV

INTERVAL BOUNDARIES IN KEV: 0 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80 85 90 95 100

NEUTRON ENERGY MEV																				
8.000	.172	.171	.169	.168	.166	.165	.163	.162	.160	.159	.158	.156	.154	.153	.152	.150	.149	.149	.149	.149
8.100	.149	.150	.150	.150	.151	.152	.152	.153	.153	.154	.154	.155	.155	.155	.155	.155	.156	.156	.156	.157
8.200	.157	.157	.158	.159	.160	.161	.161	.162	.163	.163	.163	.162	.161	.161	.160	.160	.159	.159	.159	.159
8.300	.158	.158	.158	.158	.158	.159	.160	.161	.162	.164	.166	.167	.169	.170	.170	.170	.171	.171	.171	.171
8.400	.171	.171	.171	.170	.170	.169	.169	.169	.169	.169	.169	.169	.169	.169	.169	.169	.169	.169	.169	.169
8.500	.170	.170	.170	.170	.170	.170	.170	.170	.169	.169	.169	.169	.168	.168	.168	.168	.168	.168	.168	.168
8.600	.168	.168	.168	.168	.168	.169	.169	.170	.171	.171	.171	.171	.171	.171	.170	.170	.169	.168	.167	.166
8.700	.164	.162	.161	.159	.157	.155	.153	.151	.150	.150	.149	.149	.149	.150	.150	.150	.151	.151	.152	.152
8.800	.153	.154	.155	.156	.157	.158	.159	.160	.161	.161	.162	.163	.164	.165	.166	.167	.168	.169	.170	.171
8.900	.171	.171	.172	.172	.172	.172	.173	.173	.173	.173	.174	.174	.174	.174	.175	.175	.175	.175	.176	.176
9.000	.176	.177	.177	.177	.177	.177	.177	.177	.176	.175	.175	.174	.173	.172	.172	.171	.170	.169	.168	.167
9.100	.167	.166	.166	.165	.164	.164	.163	.162	.161	.160	.159	.158	.157	.156	.155	.154	.153	.153	.152	.152
9.200	.152	.152	.152	.152	.152	.152	.153	.153	.153	.154	.154	.154	.155	.155	.155	.157	.158	.159	.160	.161
9.300	.163	.164	.165	.166	.167	.168	.169	.169	.169	.169	.169	.169	.169	.169	.169	.170	.172	.173	.174	.175
9.400	.176	.176	.176	.176	.175	.174	.173	.172	.172	.172	.171	.171	.171	.171	.171	.171	.172	.172	.172	.172
9.500	.172	.172	.172	.171	.171	.170	.170	.170	.169	.169	.169	.168	.167	.166	.165	.165	.164	.163	.162	.162
9.600	.161	.160	.159	.159	.158	.158	.158	.158	.158	.159	.159	.160	.160	.161	.162	.162	.163	.163	.164	.164
9.700	.165	.166	.166	.166	.166	.167	.167	.167	.167	.167	.168	.168	.168	.168	.169	.169	.169	.169	.169	.170
9.800	.170	.170	.170	.170	.170	.170	.170	.170	.171	.171	.171	.171	.171	.171	.171	.171	.171	.171	.171	.171
9.900	.171	.171	.171	.171	.171	.171	.171	.171	.171	.171	.172	.172	.172	.172	.172	.172	.172	.172	.172	.173
10.000	.173	.173	.173	.173	.173	.174	.174	.174	.174	.174	.174	.174	.175	.175	.174	.174	.174	.174	.174	.174
10.100	.174	.174	.174	.173	.173	.173	.173	.173	.172	.172	.172	.172	.172	.171	.171	.171	.170	.170	.170	.169
10.200	.169	.170	.170	.171	.171	.172	.172	.172	.172	.173	.173	.173	.173	.173	.174	.174	.175	.175	.175	.176
10.300	.176	.177	.177	.177	.177	.177	.177	.177	.177	.176	.175	.175	.174	.173	.173	.172	.171	.171	.170	.170
10.400	.169	.168	.168	.167	.167	.166	.166	.166	.165	.165	.165	.164	.164	.164	.164	.164	.164	.164	.164	.164
10.500	.164	.164	.164	.164	.165	.165	.165	.165	.166	.166	.166	.166	.167	.167	.167	.168	.168	.168	.168	.169
10.600	.169	.168	.168	.168	.168	.168	.168	.168	.168	.168	.168	.167	.167	.167	.167	.167	.168	.168	.168	.168
10.700	.169	.169	.169	.170	.170	.171	.171	.171	.172	.172	.173	.173	.173	.174	.174	.175	.175	.175	.176	.176
10.800	.176	.176	.177	.177	.177	.177	.177	.178	.178	.178	.178	.178	.178	.177	.177	.177	.177	.177	.177	.177
10.900	.177	.177	.177	.176	.176	.176	.176	.175	.175	.175	.175	.174	.174	.174	.174	.173	.173	.173	.173	.172
11.000	.172	.172	.172	.172	.172	.172	.171	.171	.171	.171	.171	.171	.170	.170	.170	.170	.170	.170	.170	.169
11.100	.169	.169	.169	.169	.169	.169	.168	.168	.168	.168	.168	.168	.168	.168	.168	.168	.168	.168	.168	.168
11.200	.169	.169	.170	.170	.171	.171	.172	.172	.173	.173	.174	.174	.174	.175	.175	.175	.176	.176	.176	.176
11.300	.177	.177	.178	.178	.178	.179	.179	.180	.180	.181	.181	.181	.182	.182	.182	.182	.182	.182	.182	.182
11.400	.182	.182	.181	.181	.181	.180	.180	.180	.180	.179	.179	.179	.179	.179	.179	.180	.180	.181	.181	.182
11.500	.182	.183	.183	.184	.185	.185	.186	.186	.185	.185	.185	.185	.185	.184	.184	.184	.183	.183	.183	.182
11.600	.182	.182	.182	.182	.182	.182	.182	.182	.182	.182	.182	.182	.182	.182	.182	.182	.182	.182	.182	.182
11.700	.182	.182	.182	.182	.182	.182	.182	.182	.182	.182	.182	.182	.183	.183	.183	.183	.183	.183	.183	.183
11.800	.183	.183	.183	.183	.183	.183	.183	.183	.183	.183	.183	.183	.183	.183	.183	.183	.183	.183	.183	.183
11.900	.183	.183	.183	.183	.183	.183	.183	.183	.183	.183	.184	.184	.184	.184	.184	.184	.184	.184	.184	.184

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TABLE A-IV. Relative Neutron Damage (MeV·b) Averaged Over 5 keV Intervals - 12 to 16 MeV

INTERVAL BOUNDARIES IN KEV

0 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80 85 90 95 100

NEUTRON ENERGY MEV																				
12.000	.184	.184	.184	.184	.184	.184	.184	.184	.184	.184	.184	.184	.184	.184	.184	.184	.184	.184	.184	.184
12.100	.184	.184	.184	.184	.184	.184	.184	.184	.184	.184	.184	.184	.184	.184	.184	.184	.185	.185	.185	.185
12.200	.185	.185	.185	.185	.185	.185	.185	.185	.185	.185	.185	.185	.185	.185	.185	.185	.185	.185	.185	.185
12.300	.185	.185	.185	.185	.185	.185	.185	.185	.185	.185	.185	.185	.185	.185	.185	.185	.185	.185	.185	.185
12.400	.185	.185	.185	.185	.185	.185	.186	.186	.186	.186	.186	.186	.186	.186	.186	.186	.186	.186	.186	.186
12.500	.186	.186	.186	.186	.186	.186	.186	.186	.186	.186	.186	.186	.186	.186	.186	.186	.186	.186	.186	.186
12.600	.186	.186	.186	.186	.186	.186	.186	.186	.186	.186	.186	.186	.186	.186	.186	.186	.186	.186	.187	.187
12.700	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187
12.800	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187
12.900	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187	.188	.188	.188	.188	.188	.188	.188	.188	.188	.188
13.000	.188	.188	.188	.188	.188	.188	.188	.188	.188	.188	.188	.188	.188	.188	.188	.188	.188	.188	.188	.188
13.100	.188	.188	.188	.188	.188	.188	.188	.188	.188	.188	.188	.188	.188	.188	.188	.188	.188	.188	.188	.188
13.200	.188	.188	.188	.188	.188	.188	.188	.188	.188	.188	.188	.188	.188	.188	.188	.188	.188	.188	.188	.188
13.300	.188	.188	.188	.188	.188	.188	.188	.188	.188	.188	.188	.188	.188	.188	.188	.188	.188	.188	.188	.188
13.400	.188	.188	.188	.188	.188	.188	.188	.188	.188	.188	.188	.188	.188	.188	.188	.188	.188	.188	.188	.188
13.500	.188	.188	.188	.188	.188	.188	.188	.188	.188	.188	.188	.188	.188	.188	.188	.188	.188	.188	.188	.188
13.600	.188	.188	.188	.188	.188	.188	.188	.188	.188	.188	.188	.188	.188	.188	.188	.188	.188	.188	.188	.188
13.700	.188	.188	.188	.188	.188	.188	.188	.188	.188	.188	.188	.188	.188	.188	.188	.188	.188	.188	.188	.188
13.800	.188	.188	.188	.188	.188	.188	.188	.188	.188	.188	.188	.188	.188	.188	.188	.188	.188	.188	.188	.188
13.900	.188	.188	.188	.188	.188	.188	.188	.188	.188	.188	.188	.188	.188	.188	.188	.188	.188	.188	.188	.188
14.000	.188	.188	.188	.188	.188	.188	.188	.188	.188	.188	.188	.188	.188	.188	.188	.188	.188	.188	.187	.187
14.100	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187
14.200	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187
14.300	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187
14.400	.187	.187	.187	.187	.187	.187	.187	.187	.187	.186	.186	.186	.186	.186	.186	.186	.186	.186	.186	.186
14.500	.186	.186	.186	.186	.186	.186	.186	.186	.186	.186	.186	.186	.186	.186	.186	.186	.186	.186	.186	.187
14.600	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187
14.700	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187
14.800	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187
14.900	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187
15.000	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187
15.100	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187
15.200	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187
15.300	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187
15.400	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187
15.500	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187
15.600	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187
15.700	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187
15.800	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187
15.900	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187

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TABLE A-V. Relative Neutron Damage (MeV·b) Averaged Over 25 keV Intervals - 0.1 to 8 MeV

NEUTRON ENERGY MEV	INTERVAL BOUNDARIES IN KEV 0–25	25–50	50–75	75–100
0.000				
0.100	.005	.003	.012	.090
0.200	.090	.066	.057	.053
0.300	.052	.051	.051	.052
0.400	.053	.054	.055	.056
0.500	.057	.070	.139	.058
0.600	.053	.054	.056	.057
0.700	.059	.064	.069	.082
0.800	.164	.108	.078	.072
0.900	.107	.105	.120	.108
1.000	.092	.088	.068	.064
1.100	.062	.055	.050	.055
1.200	.097	.059	.076	.086
1.300	.082	.084	.083	.081
1.400	.115	.093	.046	.107
1.500	.096	.104	.091	.134
1.600	.166	.202	.199	.114
1.700	.088	.079	.072	.072
1.800	.084	.182	.251	.134
1.900	.122	.150	.158	.130
2.000	.092	.076	.083	.125
2.100	.157	.114	.105	.101
2.200	.105	.105	.089	.135
2.300	.116	.108	.113	.105
2.400	.093	.090	.139	.163
2.500	.158	.137	.136	.136
2.600	.131	.123	.130	.119
2.700	.117	.105	.149	.119
2.800	.128	.154	.170	.124
2.900	.107	.121	.089	.086
3.000	.123	.120	.118	.113
3.100	.145	.155	.129	.109
3.200	.111	.140	.113	.113
3.300	.107	.113	.126	.122
3.400	.123	.133	.119	.123
3.500	.128	.120	.115	.103
3.600	.082	.075	.076	.083
3.700	.097	.109	.137	.133
3.800	.127	.118	.101	.105
3.900	.131	.150	.144	.124
4.000	.131	.153	.146	.118
4.100	.121	.117	.106	.109
4.200	.174	.175	.164	.152
4.300	.140	.145	.144	.125
4.400	.141	.145	.149	.153
4.500	.150	.160	.131	.123
4.600	.140	.170	.162	.164
4.700	.166	.172	.202	.196
4.800	.170	.155	.175	.155
4.900	.165	.150	.147	.150
5.000	.150	.142	.140	.166
5.100	.163	.170	.178	.164
5.200	.162	.144	.141	.135
5.300	.141	.121	.115	.122
5.400	.121	.111	.119	.143
5.500	.150	.145	.150	.150
5.600	.151	.151	.154	.177
5.700	.188	.177	.168	.173
5.800	.172	.170	.171	.156
5.900	.142	.130	.142	.140
6.000	.155	.166	.161	.146
6.100	.129	.125	.140	.146
6.200	.162	.183	.193	.184
6.300	.162	.140	.153	.154
6.400	.153	.151	.139	.130
6.500	.131	.127	.118	.113
6.600	.125	.147	.166	.175
6.700	.170	.160	.160	.160
6.800	.155	.140	.153	.152
6.900	.143	.141	.150	.152
7.000	.155	.161	.159	.146
7.100	.128	.129	.150	.162
7.200	.165	.166	.168	.171
7.300	.172	.175	.167	.166
7.400	.165	.169	.169	.162
7.500	.158	.157	.158	.161
7.600	.164	.167	.171	.177
7.700	.180	.176	.174	.173
7.800	.170	.170	.177	.183
7.900	.186	.185	.181	.176

TABLE A-VI. Relative Neutron Damage (MeV.b) Averaged Over 25 keV Intervals - 8 to 16 MeV

NEUTRON ENERGY MEV	INTERVAL BOUNDARIES IN KEV 0 25	50	75	100
8.000	.169	.162	.155	.149
8.100	.150	.153	.155	.156
8.200	.158	.162	.161	.159
8.300	.158	.161	.168	.171
8.400	.170	.169	.169	.169
8.500	.170	.169	.168	.168
8.600	.168	.170	.171	.168
8.700	.161	.152	.149	.151
8.800	.155	.160	.164	.169
8.900	.172	.173	.174	.176
9.000	.177	.176	.173	.169
9.100	.166	.162	.157	.153
9.200	.152	.153	.155	.159
9.300	.165	.169	.169	.173
9.400	.176	.172	.171	.172
9.500	.171	.170	.167	.163
9.600	.159	.158	.160	.163
9.700	.166	.167	.168	.169
9.800	.170	.170	.171	.171
9.900	.171	.171	.172	.172
10.000	.173	.174	.174	.174
10.100	.174	.173	.172	.170
10.200	.170	.172	.173	.175
10.300	.177	.177	.174	.171
10.400	.168	.166	.164	.164
10.500	.164	.165	.167	.168
10.600	.168	.168	.167	.168
10.700	.169	.171	.173	.175
10.800	.177	.178	.178	.177
10.900	.177	.175	.174	.173
11.000	.172	.171	.170	.170
11.100	.169	.168	.168	.168
11.200	.170	.172	.174	.176
11.300	.178	.180	.182	.182
11.400	.181	.180	.179	.181
11.500	.183	.185	.185	.183
11.600	.182	.182	.182	.182
11.700	.182	.182	.183	.183
11.800	.183	.183	.183	.183
11.900	.183	.183	.184	.184

NEUTRON ENERGY MEV	INTERVAL BOUNDARIES IN KEV 0 25	50	75	100
12.000	.184	.184	.184	.184
12.100	.184	.184	.184	.185
12.200	.185	.185	.185	.185
12.300	.185	.185	.185	.185
12.400	.185	.186	.186	.186
12.500	.186	.186	.186	.186
12.600	.186	.186	.186	.186
12.700	.187	.187	.187	.187
12.800	.187	.187	.187	.187
12.900	.187	.187	.188	.188
13.000	.188	.188	.188	.188
13.100	.188	.188	.188	.188
13.200	.188	.188	.188	.188
13.300	.188	.188	.188	.188
13.400	.188	.188	.188	.188
13.500	.188	.188	.188	.188
13.600	.188	.188	.188	.188
13.700	.188	.188	.188	.188
13.800	.188	.188	.188	.188
13.900	.188	.188	.188	.188
14.000	.188	.188	.188	.188
14.100	.187	.187	.187	.187
14.200	.187	.187	.187	.187
14.300	.187	.187	.187	.187
14.400	.187	.187	.186	.186
14.500	.186	.186	.186	.186
14.600	.187	.187	.187	.187
14.700	.187	.187	.187	.187
14.800	.187	.187	.187	.187
14.900	.187	.187	.187	.187
15.000	.187	.187	.187	.187
15.100	.187	.187	.187	.187
15.200	.187	.187	.187	.187
15.300	.187	.187	.187	.187
15.400	.187	.187	.187	.187
15.500	.187	.187	.187	.187
15.600	.187	.187	.187	.187
15.700	.187	.187	.187	.187
15.800	.187	.187	.187	.187
15.900	.187	.187	.187	.187

TABLE A-VII. Relative Neutron Damage (MeV·b) Averaged Over 0.1 MeV Intervals - 0.1 to 20 MeV

NEUTRON ENERGY MEV	INTERVAL BOUNDARIES IN MEV									
	.0 .1	.2	.3	.4	.5	.6	.7	.8	.9	1.
0.0		.027	.067	.051	.054	.081	.055	.069	.106	.110
1.0	.078	.055	.079	.083	.103	.106	.170	.078	.163	.140
2.0	.094	.119	.108	.108	.121	.142	.126	.113	.144	.101
3.0	.119	.134	.119	.117	.124	.116	.079	.119	.113	.138
4.0	.137	.113	.166	.139	.147	.143	.161	.184	.164	.153
5.0	.154	.171	.146	.125	.124	.149	.158	.176	.167	.142
6.0	.157	.135	.181	.154	.143	.122	.153	.162	.152	.147
7.0	.155	.142	.168	.170	.166	.158	.170	.176	.175	.182
8.0	.159	.153	.160	.165	.169	.169	.169	.153	.162	.174
9.0	.174	.159	.155	.169	.173	.168	.160	.167	.171	.172
10.0	.174	.172	.173	.175	.165	.166	.168	.172	.177	.175
11.0	.171	.168	.173	.180	.180	.184	.182	.182	.183	.183
12.0	.184	.184	.185	.185	.186	.186	.186	.187	.187	.187
13.0	.188	.188	.188	.188	.188	.188	.188	.188	.188	.188
14.0	.188	.187	.187	.187	.186	.186	.187	.187	.187	.187
15.0	.187	.187	.187	.187	.187	.187	.187	.187	.187	.187
16.0	.187	.187	.187	.187	.187	.186	.186	.185	.185	.184
17.0	.184	.184	.183	.183	.182	.182	.183	.183	.183	.183
18.0	.184	.184	.184	.184	.185	.185	.185	.184	.184	.184
19.0	.184	.184	.184	.183	.183	.183	.183	.183	.183	.182

TABLE A-VIII. **Calculated Damage Results in 22-Group Structure.**

Group Number	ΔE_n (MeV)	Damage (MeV·mb)
1-9	$E_n < .1$	--
10	.11 - .55	53
11	.55 - 1.11	84
12	1.11 - 1.83	97
13	1.83 - 2.35	125
14	2.35 - 2.46	103
15	2.46 - 3.01	127
16	3.01 - 4.07	120
17	4.07 - 4.97	151
18	4.97 - 6.36	153
19	6.36 - 8.19	158
20	8.19 - 10.0	166
21	10.0 - 12.2	176
22	12.2 - 15.0	187

TABLE A-IX. Calculated Damage Results in 94-Group Structure.

Group Number	ΔE_n (MeV)	Damage (MeV·mb)
1-25	E_n<·1	--
26	.100-.111	5
27	.111-.136	4
28	.136-.183	18
29	.183-.200	104
30	.200-.224	91
31	.224-.250	67
32	.250-.302	55
33	.302-.400	51
34	.400-.408	52
35	.408-.498	54
36	.498-.600	80
37	.600-.672	54
38	.672-.800	66
39	.800-.821	165
40	.821-1.00	101
41	1.00-1.11	77
42	1.11-1.20	55
43	1.20-1.35	81
44	1.35-1.40	82
45	1.40-1.50	103
46	1.50-1.60	106
47	1.60-1.80	124
48	1.80-2.00	151
49	2.00-2.20	107
50	2.20-2.23	108
51	2.23-2.30	108
52	2.30-2.40	108
53	2.40-2.60	131
54	2.60-2.73	124
55	2.73-2.80	111
56	2.80-3.00	122
57	3.00-3.20	126
58	3.20-3.40	118

Continued

TABLE A-IX. (Continued)

Group Number	ΔE_n (MeV)	Damage (MeV·mb)
59	3.40-3.60	120
60	3.60-3.68	78
61	3.68-3.70	84
62	3.70-3.80	119
63	3.80-4.00	125
64	4.00-4.20	125
65	4.20-440	152
66	4.40-4.60	145
67	4.60-4.80	172
68	4.80-5.00	158
69	5.00-5.20	162
70	5.20-5.40	135
71	5.40-5.60	136
72	5.60-5.80	167
73	5.80-6.00	155
74	6.00-6.07	161
75	6.07-6.50	153
76	6.50-7.00	147
77	7.00-7.50	160
78	7.50-8.00	172
79	8.00-8.50	161
80	8.50-9.00	165
81	9.00-9.50	166
82	9.50-10.0	168
83	10.0-10.5	172
84	10.5-11.0	172
85	11.0-11.5	175
86	11.5-12.0	183
87	12.0-13.0	186
88	13.0-14.0	188
89	14.0-14.9	187
90	14.9-15.0	187
91	15.0-16.0	187
92	16.0-17.0	186
93	17.0-18.0	183
94	18.0-20.0	184

TABLE A-X. Calculated Damage Results in 37-Group Structure.

Group Number	ΔE_n (MeV)	Damage (MeV·mb)
1-14	E_n<•1	--
15	.111-.158	4
16	.158-.550	59
17	.550-1.00	85
18	1.11-1.83	96
19	1.83-2.31	127
20	2.31-2.39	109
21	2.39-3.01	124
22	3.01-4.07	120
23	4.07-4.72	144
24	4.72-4.97	170
25	4.97-6.38	153
26	6.38-7.41	152
27	7.41-8.19	168
28	8.19-9.05	166
29	9.05-10.0	166
30	10.0-11.1	172
31	11.1-12.2	180
32	12.2-12.8	186
33	12.8-13.8	188
34	13.8-14.2	188
35	14.2-14.9	187
36	14.9-16.9	187
37	16.9-19.6	184

TABLE A-XI. **Calculated Damage Results in 24-Group Structure.**

Group Number	ΔE_n (MeV)	Damage (MeV·mb)
1	10.0 - 7.79	166
2	7.79 - 6.07	156
3	6.07 - 4.72	152
4	4.72 - 3.68	138
5	3.68 - 2.23	119
6	2.23 - 1.35	121
7	1.35 - 0.82	82
8	0.82 - 0.50	76
9	0.50 - 0.18	60
10	0.18 - 0.07	10
11-24	$E_n < .1$	-