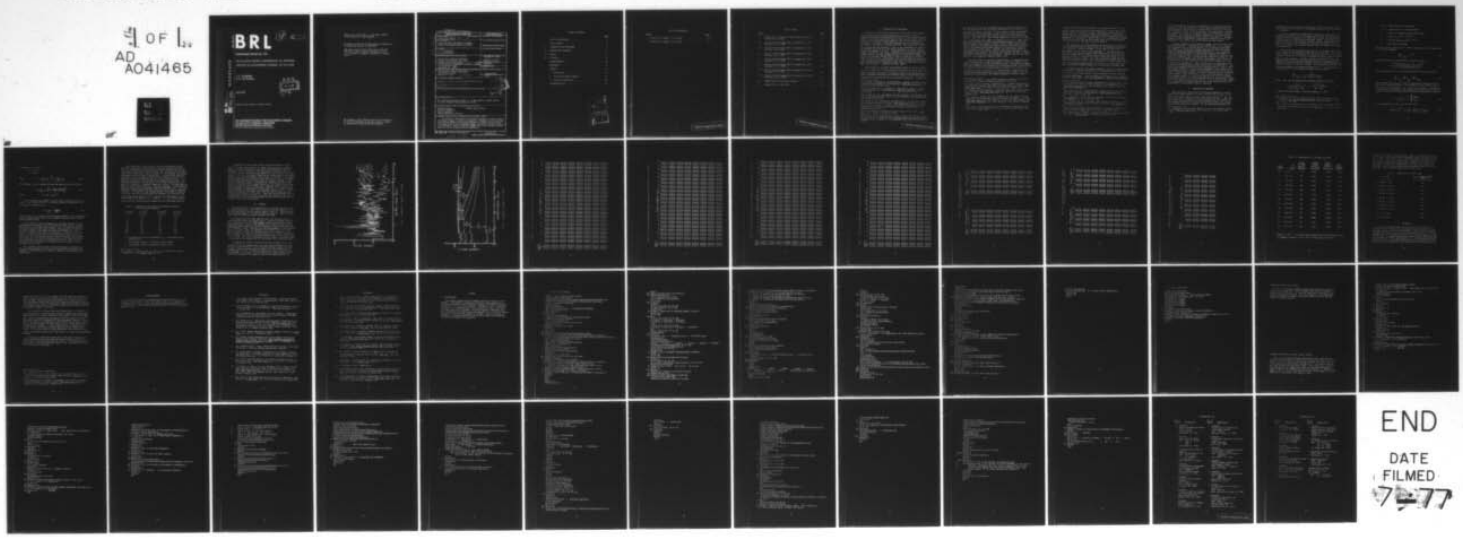
AD-A041 465 BALLISTIC RESEARCH LABS ABERDEEN PROVING GROUND MD F/G 20/8
CALCULATED ENERGY DEPENDENCE OF NEUTRON INDUCED DISPLACEMENT DA--ETC(U)
JUN 77 J E YOUNGBLOOD, W R VAN ANTWERP

UNCLASSIFIED BRL-MR-2759 NL

1 OF 1
AD A041465



END
DATE FILMED
9-77

BRL MR 2759

BRL

12 B.S.

AD

MEMORANDUM REPORT NO. 2759

CALCULATED ENERGY DEPENDENCE OF NEUTRON INDUCED DISPLACEMENT DAMAGE IN SILICON

J. E. Youngblood
W. R. Van Antwerp

June 1977

USA ARMAMENT RESEARCH AND DEVELOPMENT COMMAND
USA BALLISTIC RESEARCH LABORATORY
ABERDEEN PROVING GROUND, MARYLAND

Destroy this report when it is no longer needed.
Do not return it to the originator.

Secondary distribution of this report by originating or sponsoring activity is prohibited.

Additional copies of this report may be obtained from the National Technical Information Service, U.S. Department of Commerce, Springfield, Virginia 22151.

The findings in this report are not to be construed as an official Department of the Army position, unless so designated by other authorized documents.

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER: MEMORANDUM REPORT, NO. 2759
2. GOVT ACCESSION NO.
3. RECIPIENT'S CATALOG NUMBER

4. TITLE (and Subtitle): CALCULATED ENERGY DEPENDENCE OF NEUTRON INDUCED DISPLACEMENT DAMAGE IN SILICON.

5. TYPE OF REPORT & PERIOD COVERED

6. PERFORMING ORG. REPORT NUMBER

7. AUTHOR(s): J. E. Youngblood*, W. R. Van Antwerp

8. CONTRACT OR GRANT NUMBER(s)

9. PERFORMING ORGANIZATION NAME AND ADDRESS: USA Ballistic Research Laboratory, Aberdeen Proving Ground, MD 21005

10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS: RDT&E 1L162118AH75

11. CONTROLLING OFFICE NAME AND ADDRESS: US Army Materiel Development & Readiness Command, 5001 Eisenhower Avenue, Alexandria, VA 22333

12. REPORT DATE: JUNE 1977

13. NUMBER OF PAGES: 56

14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office): US Army Harry Diamond Laboratories, 2800 Powder Mill Road, Adelphi, MD 20783

15. SECURITY CLASS. (of this report): Unclassified

15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

BRL-MR-2759

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

*Mr. Youngblood's present address is: US Army Materiel Systems Analysis Activity, Aberdeen Proving Ground, MD 21005

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Radiation Damage
Neutron Interactions
Energy Dependence
Neutron Reactions in Silicon
Nuclear Weapon Effects

20. ABSTRACT (Continue on reverse side if necessary and identify by block number) (idk)

The results of calculations on the energy-dependence of neutron-induced displacement damage in silicon are presented. A computer code that utilizes all available neutron cross section information has been used to calculate the energy available for displacement damage, according to Lindhard theory, in 5 keV intervals. Tables of results averaged over 25 keV intervals and averaged over 100 keV intervals are also presented.

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

050 750

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF TABLES

I. INTRODUCTION AND BACKGROUND

The need for a definitive formulation of the relationship between neutron energy and displacement damage has been noted by Conrad.[1] A rigorously determined curve based on the physics of the neutron-material interactions and the appropriate neutron cross sections, which can be extended to other materials where adequate cross section information is available, is required. Experimental evaluations of the accuracy and the range of applicability are also required. Some preliminary work on this problem has been reported,[2,3] and, in this memorandum, we present a more detailed calculation of the energy dependence of neutron-induced displacement damage in silicon. A computer code to calculate permanent damage, specifically, the energy available for displacement damage using Lindhard theory, has been prepared and used to calculate the damage in silicon for incident neutrons from 0.1 MeV to 20 MeV using a neutron energy spread of 5 keV. Considerable care has been taken (see Reference 3) to utilize all available neutron cross section information and the results presented here are based on silicon cross sections from a DNA file tape, DNA-4151 MOD. 3 (obtained from RSIC, ORNL).

Early efforts to calculate the permanent damage in silicon include the work of Smith et al.,[4] who carefully considered the nuclear data available at that time, and Stein,[5] who noted a factor of two difference between the damage calculated for a realistic angular distribution (data for aluminum were used) and that for an isotropic distribution. Holmes[6] has

---

[1] *E.E. Conrad, "Consideration in Establishing a Standard for Neutron Displacement Energy Effects in Semiconductors," IEEE Trans. Nucl. Sci., Vol. NS-18, No. 6, pp 200-205, 1971.*

[2] *W.R. Van Antwerp and J.E. Youngblood, "Displacement Damage in Silicon Irradiated with 6- to 10-MeV Neutrons," Bull. Am. Phys. Soc., Vol 17, p 678, 1972.*

[3] *J.E. Youngblood, W.R. Van Antwerp, and R.M. Tapphorn, "Displacement Damage in Silicon Irradiated with 6- to 10-MeV Neutrons," BRL Memorandum Report MR 2738, April 1977.*

[4] *E.C. Smith, et al., "Theoretical and Experimental Determinations of Neutron Energy Deposition in Silicon," IEEE Trans. Nucl. Sci., Vol. NS-13, No. 6, pp 11-17, 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., Vol. 38, No. 1, pp 204-210, 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 67-68, October 1, 1970.*

made detailed calculations of damage using a cylindrical shape of clusters of damage and his data have been considered in the procedures recommended by Thatcher and Green.[7,8] More recently Guenzer and Manning[9] have calculated the displacement damage in InSb for 1 MeV and 14 MeV neutrons, and they compare these results with similar calculations for silicon. InSb shows very little energy dependence and the ratio of damage (14 MeV damage/1 MeV damage) was found to be ca. 1.05. Rogers et al.[10] have calculated both ionization and displacement damage in silicon for neutron energies from thermal to 20 MeV. These authors partition the kinetic energy of the reaction products and use a functional representation of the Lindhard displacement fraction in calculations similar to those presented in this report. However, they use average values of emitted-particle energy and the silicon recoil energy (actually a code-generated average cosine). The results are compared with those of Holmes and found to be about 25% lower in general. Rogers' value for the (14/1) ratio is 1.8 as compared to Holmes' value of 2.0.

The effectiveness of radiation-induced defects in changing the electrical properties of a diode, for example, is certain to depend on the extent of recombination, other forms of annealing, the extent and geometry of cluster formation, the stability of the clusters formed, and the nature (in clusters or not) of the point defects (divacancies, A-centers, etc.). Following the work of Gossick[11] it is expected that a space-charge region and a potential barrier will form at a cluster of defects. The implications of clustering on the energy dependence of neutron damage in

---

[7] *R.K. Thatcher and M.L. Green, "TREE Preferred Procedures," DNA 2028H, Edition No. 2, Battelle Columbus Laboratories, June 1972.*

[8] *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., Vol. NS-19, No. 6, pp 200-208, December 1972.*

[9] *C.S. Guenzer and Irwin Manning, "Calculated Displacement Damage by Neutrons in InSb," IEEE Trans. Nucl. Sci., Vol. NS-21, No. 6, pp 26-29, December 1974.*

[10] *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., Vol. NS-22, No. 6, pp 2326-2329, December 1975. (Also, see erratum, Op. Cit., Vol. NS-23, No. 1, pp 875-876, February 1976.*

[11] *B.R. Gossick, "Disordered Regions in Semiconductors Bombarded by Fast Neutrons," J. Appl. Phys., Vol. 30, No. 8, pp 1214-1218, August 1959.*

silicon have recently been reviewed by van Lint and Leadon.[12] These authors compare earlier work by the same group[13] with available experimental results for electron-, proton-, and neutron-induced radiation damage, and they conclude that, when cluster damage is predominate, carrier removal is a sublinear function of recoil energy while lifetime degradation is superlinear. Specifically, it is concluded that carrier removal scales more like the total energy available for displacements (or, proportional to the number of point defects).

The evaluation of cluster formation and annealing has received continuing interest because of applications to ion implantation and heavy-ion simulation of radiation damage. Current work includes that by Martynenko[14] and by Vinetskii and Kondrachuk.[15] The implications of both these works are that there is much diffusion out of the clusters that are formed, that this results in a limited significance for clustering, and that it is sensible to define a threshold energy for the formation of stable clusters. This last implication results from the fact that stability increases with incident particle energy (defect density). For neutron-induced recoils in silicon it is concluded[15] that the stable-defect threshold energy is a silicon recoil of about 5 keV.

A complete evaluation of radiation effects, based on a dynamic model, can be done by computer simulation, as first demonstrated by Gibson et al.,[16] and an up-to-date review of these techniques has been provided by Jackson and Morgan.[17] This technique can be expensive in an application to a simple cubic structure to determine a single physical parameter

---

[12] *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.*

[13] *V.A.J. van Lint, R.E. Leadon, and J.F. Colwell, "Energy Dependence of Displacement Effects in Semiconductors," IEEE Trans. Nucl. Sci., Vol. NS-19, No. 6, pp 181-185, 1972.*

[14] *Yu. V. Martynenko, "Annealing and Clustering of Defects in Cascades," Rad. Effects, Vol. 29, pp 129-135, 1976.*

[15] *V.L. Vinetskii and A.V. Kondrachuk, "The Kinetics of Formation and the Parameters of Radiation Defect Clusters in Silicon," Rad. Effects, Vol. 30, pp 227-232, 1976.*

[16] *J.B. Gibson, A.N. Goland, M. Milgram, and G.H. Vineyard, "Dynamics of Radiation Damage," Phys. Rev., Vol. 120, pp 1229-1253, 1960.*

[17] *D.P. Jackson and D.V. Morgan "Computer Modelling of Collision Processes in Solids," Contemp. Phys., Vol. 14, No. 1, pp 25-48, 1974.*

such as the threshold energy for displacements. The highly anisotropic structure of silicon, the need to simulate several neutron reactions at several energies, and the need to combine these statistically (the computer simulation itself is not statistical) limit applications. However, the contribution cited, the threshold energy of displacements, would be invaluable. An evaluation by computer simulation of the 'stable-defect threshold energy' suggested above would also seem worthwhile. Although potentially useful refinements, these computer simulation studies are peripheral to the present work and they have not been pursued.

A general statement of the need for a damage curve was given at the start of this report. Some specific applications are: (a) to compare with experiments (as to confirm results); (b) to evaluate experiments (for example, to determine the energy range and the effective average energy for damage experiments using an accelerator); (c) to normalize simulator and threat spectra for evaluating simulator experiments; (d) to evaluate threat spectra in scenarios (for vulnerability analysis, vulnerability reduction, etc.); (e) to provide a base for evaluation of the sensitivity of the damage curve itself to the neutron cross section information used; and (f) to evaluate more approximate damage curves such as those due to Messenger.[18] (For a recent review of approximate functions for calculating neutron-energy equivalence, see Reference 8). The calculations presented here were in part precipitated by a need to evaluate the requirements for cross section measurements (item e above) and a requirement to correct in detail for the spread in neutron energy encountered in "monoenergetic-neutron" accelerator radiation effects experiments (item b above). Even if interest in cross section measurements biased the procedures chosen, it is now clear that the very detailed treatment of available neutron cross section information has produced useful information on the value of cross section details. Also, by modeling the damage only to the extent of determining that part of the energy available for displacements, a most-general result is obtained.

II. COMPUTATIONAL PROCEDURE

Some preliminary calculations on the energy dependence of neutron induced displacement damage in silicon, using our own selection of cross section data from current literature, have been presented.[2,3] The present report covers an extension of those calculations that includes some minor corrections, modification of the program to permit direct use of any evaluated neutron cross section tape in ENDF/B format, and calculations at many more neutron energies. In the following paragraphs the

---

[18] *G.C. Messenger, "Displacement Damage in Silicon and Germanium Transistors," IEEE Trans. Nucl. Sci., Vol. NS-12, No. 2, pp 53-74, April 1965.*

program used for the preliminary calculations will be described and then the changes will be discussed. The program presently in use is included as an appendix.

A computer program was prepared that would accept coefficients for a Legendre polynominal fit to the angular distribution of a particular neutron reaction, determine the silicon recoil energy, and calculate the Lindhard fraction of energy for displacement damage. The program would iterate through 60 equal 3-degree intervals, find the appropriate solid angle in each case, form the product of differential neutron cross section, recoil energy, displacement fraction, and solid angle, and sum the 60 contributions.

The calculations of partial cross section, solid angle, and silicon recoil energy are straightforward and need not be discussed. The silicon recoil energy will be deposited in the silicon crystal in both ionization (inelastic processes, or electronic stopping) and energy lost to displacements (nuclear stopping). Lindhard, Scharff, and Schiott[19] (LSS) have suggested that the ionization scattering process can be represented by a Thomas-Fermi potential and this provides a basis for determining the displacement fraction of the recoil energy. To obtain the displacement fraction an approximation was taken from Bertin et al.[20] This approximation, an empirical fit to the LSS nuclear energy loss, is given by

$$\left.\frac{d\varepsilon}{d\rho}\right|_{nucl} = \frac{\varepsilon^{1/2}}{0.67 + 2.07\varepsilon + 0.03\varepsilon^2} \qquad (1)$$

where ε and ρ are the dimensionless parameters defined by LSS as,

$$\varepsilon = \frac{a\,A_2}{Z_1 Z_2\, e^2 (A_1 + A_2)}\, E \quad , \quad \rho = \frac{4\pi\, a^2\, N\, A_1\, A_2}{(A_1 + A_2)^2}\, X \qquad (2)$$

in terms of particle energy, E and displacement, X. Here,

---

[19] *J. Lindhard, M. Scharff, and H.E. Schiott, "Range Concepts and Heavy Ion Ranges," Kgl. Danske Videnskeb Selskab, Mat. Fys. Medd., Vol. 33, No. 14, pp 1-42, 1963.*

[20] *M.C. Bertin, N. Benczer-Koller, G.G. Seaman, and J.R. MacDonald, "Electromagentic Transisition Rates in ^{58}Ni," Phys. Rev., Vol. 183, pp 964-977, 1969.*

Z_1, A_1 = charge and mass of projectile

Z_2, A_2 = charge and mass of stopping medium

N = number of stopping atoms per unit volume

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

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

e = the electronic charge

The LSS electronic energy loss is taken as proportional to the square root of the energy parameter,

$$\left.\frac{d\varepsilon}{d\rho}\right|_{elec} = k\,\varepsilon^{1/2} \tag{3}$$

where the constant of proportionality as given by LSS is,

$$k = \frac{Z_1^{1/6}(0.0793)(Z_1\ Z_2)^{1/2}\ (A_1 + A_2)^{3/2}}{(Z_1^{2/3} + Z_2^{2/3})^{3/4}\ A_1^{3/2}\ A_2^{1/2}} \tag{4}$$

The total energy loss is the sum of electronic and nuclear fractions,

$$\left.\frac{d\varepsilon}{d\rho}\right|_{tot} = \left.\frac{d\varepsilon}{d\rho}\right|_{nucl} + \left.\frac{d\varepsilon}{d\rho}\right|_{elec} \tag{5}$$

These formulae for energy loss must be combined and integrated to find the nuclear-stopping fraction. If we denote by ε_R the value of the dimensionless energy parameter ε for a given recoil energy E, and denote by ε some smaller (subsequent in the scattering sequence) value of the parameter, the fraction of energy going into nuclear scattering is given by,

$$F = \frac{1}{(\varepsilon_R - \varepsilon)} \int_{\varepsilon}^{\varepsilon_R} \frac{\left.\frac{d\varepsilon}{d\rho}\right|_{nucl}}{\left.\frac{d\varepsilon}{d\rho}\right|_{tot}} d\varepsilon \tag{6}$$

or, by substitution of (1), (3), and (5) in (6)

$$F = \frac{1}{(\varepsilon_R - \varepsilon)} \int_{\varepsilon}^{\varepsilon_R} \frac{d\varepsilon}{1 + 0.67k + 2.07k\varepsilon + 0.03k\varepsilon^2} \tag{7}$$

If we let $A = 1 + 0.67\ k$

$B = 2.07\ k$

$C = 0.03\ k$

Then,
$$F = \frac{1}{(G_R - \varepsilon)} \int_{\varepsilon}^{\varepsilon_R} \frac{d\varepsilon}{A + B\varepsilon + C\varepsilon^2} \tag{8}$$

The integral is now a standard form and the equation has the solution,

$$F = \frac{1}{(\varepsilon_R - \varepsilon)} \left[\frac{1}{D} \ell n \left(\frac{2C\varepsilon + B - D}{2C\varepsilon + B + D}\right)\right]_{\varepsilon}^{\varepsilon_R} \tag{9}$$

where
$$D = (B^2 - 4AC)^{1/2}$$

If we designate the argument of the ℓn term in Equation (9) as Arg R for $\varepsilon = \varepsilon_R$, and Arg 0 for $\varepsilon = 0$, then the fraction of energy for the full range of the particle is

$$F = \frac{1}{\varepsilon_R D} \ell n \frac{\text{Arg R}}{\text{Arg 0}} \tag{10}$$

Equation (10) is in a form, with the constants defined, to be incorporated into a computer program, and F is the Lindhard fraction used in the preliminary calculations.

The treatment of nuclear stopping as a continuous process is only approximate, as the energy lost in a single collision can be a considerable fraction of the total recoil energy. Also, in range calculations the energy losses in individual collisions are spread, and, if they are treated as randomly distributed (not the true distribution), then a Gaussian distribution of ranges is obtained for a single initial recoil energy. A similar spread must occur in the nuclear-stopping fraction. At the same time, LSS has provided 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 sequence, collisions.

This completes the discussion of the preliminary calculations and the following paragraphs will discuss the calculational procedures used currently. The discussion will center on changes in the procedure presented above.

The calculations of partial cross section, solid angle, and primary recoil were done in the same way as the preliminary calculations, but with some added bookkeeping for obtaining the neutron cross sections and angular distributions from a DNA tape. The calculation of the fraction of the primary recoil energy available for displacements was changed substantially for the present calculations. 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. As many as 30 collisions were followed for the higher-energy recoils. The technique was done for silicon recoils (in silicon) for use with (n,n) and (n, n') reactions. Aluminum-, magnesium-, proton-, and alpha-recoils were also done to provide for (n,α) and (n,p) reactions. A more detailed report on calculations is planned by one of the authors (JEY). The significance of the multiple-collision correction can be seen by inspection of Table I. The values of the Lindhard fraction calculated by Equation (10) above, the values obtained with the technique just described, and values tabulated by Mayer et al.[21] are given for a wide range of (silicon) primary recoil energies, E_r, in Table I. It is clear that the multiple collision correction can be substantial for high energy neutrons.

TABLE I. Comparison of Estimates of Displacement Fractions at Several Recoil Energies

E_r (keV)	E_d (keV)[a]	E_d (keV)[b]	E_d (keV)[c]
1	0.91	0.79	0.83
3	2.7	2.3	2.4
10	8.8	7.0	7.3
30	25.	19.	19.
100	68.	50.	51.
300	141.	101.	100.
1000	240.	167.	170.

a. The energy going into displacements, E_d, as calculated using Equation (10).

b. Displacement energy as calculated for this report.

c. Displacement energy as tabulated by Mayer et al.[21]

[21] *J.W. Mayer, L. Eriksson, and J.A. Davies, "Ion Implantation in Semiconductors," p 68, Academic Press, NY, 1970.*

A comparison of the present results with the preliminary calculations[3] and with the calculations of others indicates general agreement; however, at least four factors that affect these comparisons must be mentioned. First, a mistake in the preliminary calculations led to the (n, n) and (n, n') reactions being treated as (n, p) reactions with a recoiling Z = 13 ion. As might be expected, this produced only a very minor change in the calculated damage (3% at 14 MeV, 2% at 4 MeV, 1% at 1 MeV). Second, differences in the neutron cross sections used, and in the methods of utilization, produce variations that can be quite irregular. Third, a quite substantial change is introduced by including a correction for multiple collisions in the Lindhard fraction. This change is quite regular with energy and, when averaged over a complete range of recoil energies produced by a single neutron energy, much less of a change results than the changes for individual recoil energies given in Table I. Finally, fourth, the proton- and alpha-recoil fractions (and energies and cross sections) were tested in a few cases. These few cases confirmed that the charged-particle products of the (n, p) and (n,α) reactions contribute no more than 1 or 2% to the total damage and these contributions were not included in the final calculations.

III. RESULTS

The general nature of the results for 0.1 to 10 MeV can best be seen by inspecting Figure 1. This shows the total calculated damage as well as the contributions from the various neutron reactions. Similar results for the energy range 10 to 20 MeV are shown on Figure 2. Again contributions from the different neutron reactions are shown.

The calculations have been done for each 5 keV interval from 0.1 to 20 MeV and the results are stored on disc. To provide maximum flexibility in obtaining a set of average damage factors for any neutron energy group structure of interest, the complete 5 keV interval results are tabulated and average values for 25 keV intervals and 100 keV intervals are also presented. Table II presents the calculated damage at 5 keV intervals for 0.1 to 4 MeV. Table III continues 5 keV intervals for 4 to 8 MeV. Tables IV and V are the 5 keV calculations for 8 to 12 and for 12 to 16 MeV, respectively. Tables VI and VII provide 25 keV interval averages for 0.1 to 16 MeV. Table VIII has 100 keV average values for the energy range 0.1 to 20. MeV. By using a combination of these tables, an average equal to one based on the complete set of 5 keV results can be obtained rapidly.

To compare these results with the recent work by Rogers et al., as corrected,[10] average damage values were calculated for appropriate parts of the 22-group structure (the first 9 groups include energies less than 0.1 MeV). Both the present work and Rogers' data were normalized to a 14 MeV damage of 1.000. The results are shown in Table IX, and the overall agreement is very good. The substantial (25%) and irregular variations are attributed to the manner in which the Lindhard fraction is

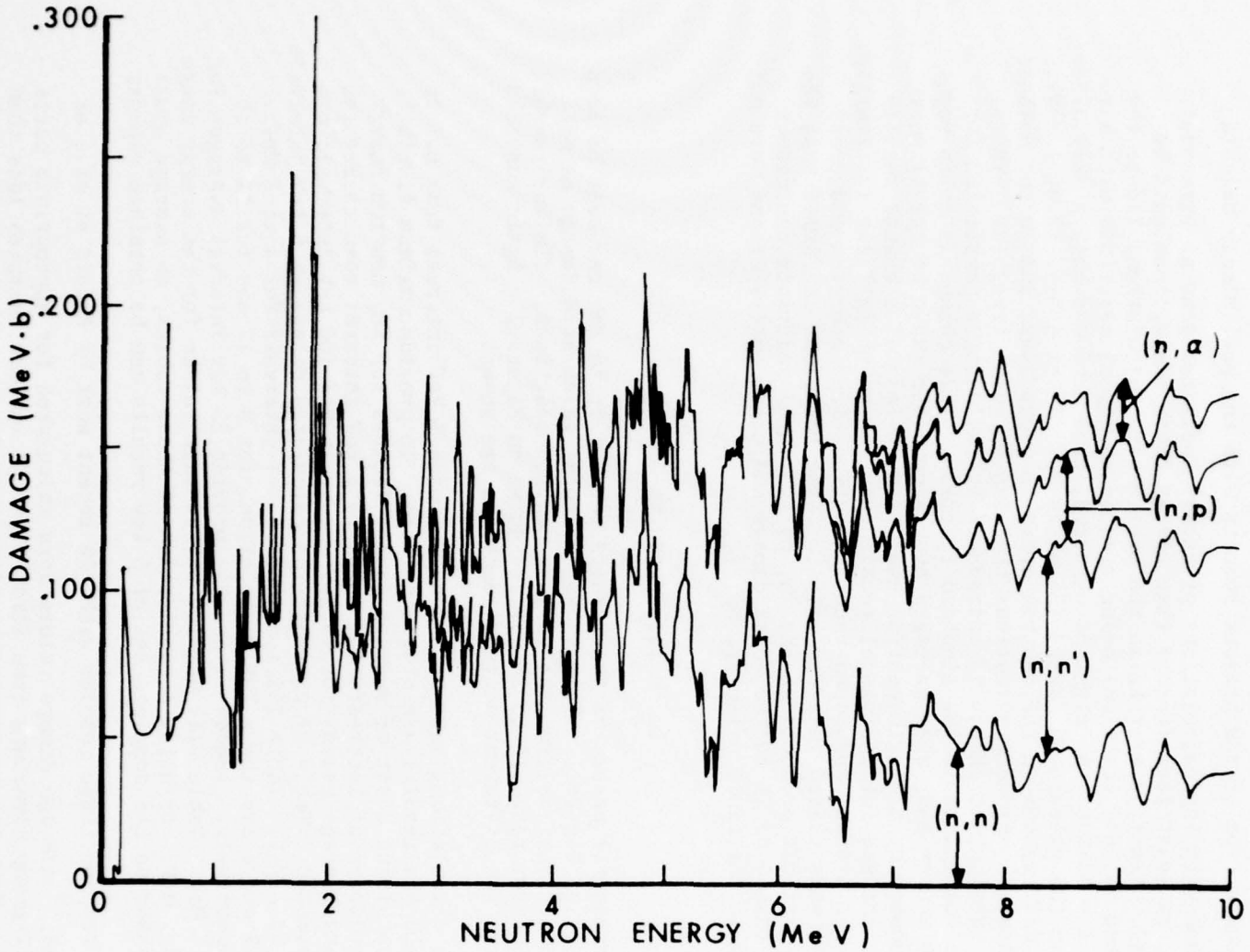


Figure 1. Components of Damage, 0.1 to 10 MeV

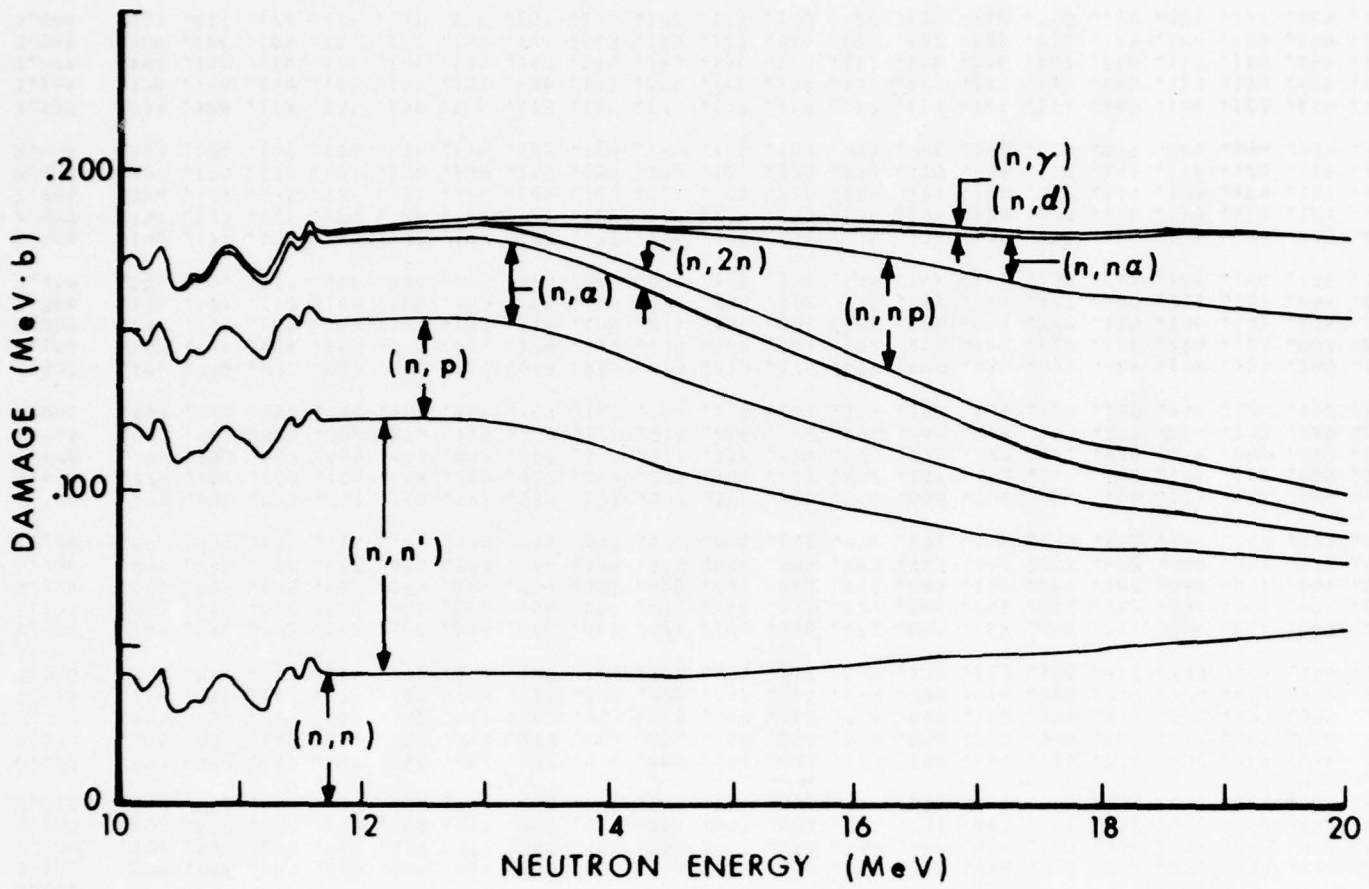


Figure 2. Components of Damage, 10 to 20 MeV

TABLE II. 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	.060	.058	.057	.056	.055	.055	.054	.053	.053	.053	
0.300	.052	.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	.070	.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	.138	.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	.124	.130	.131	

Table III. Relative Neutron Damage (MeV·b) Averaged Over 5 keV Intervals - 4 to 8 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
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	.120	.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	

Table IV. Relative Neutron Damage (MeV·b) Averaged Over 5 keV Intervals - 8 to 12 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
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	.178	.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	

Table V. Relative Neutron Damage (MeV· b) Averaged Over 5 keV Intervals - 12 to 16 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
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	.186	.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	

Table VI. Relative Neutron Damage (MeV·b) Averaged Over 25 keV Intervals - 0.1 to 8 MeV

NEUTRON ENERGY MEV	INTERVAL BOUNDARIES IN KEV 0	25	50	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	.096	.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	.100	.113	.105	
2.400	.093	.090	.139	.163	
2.500	.158	.137	.136	.136	
2.600	.131	.123	.130	.119	
2.700	.117	.105	.109	.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	.129	

NEUTRON ENERGY MEV	INTERVAL BOUNDARIES IN KEV 0	25	50	75	100
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	.158	.160	.131	.123	
4.600	.148	.170	.162	.164	
4.700	.166	.172	.202	.196	
4.800	.170	.155	.175	.155	
4.900	.165	.150	.147	.150	
5.000	.158	.142	.148	.166	
5.100	.163	.178	.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	.138	.142	.148	
6.000	.155	.166	.161	.146	
6.100	.129	.125	.140	.146	
6.200	.162	.183	.193	.184	
6.300	.162	.148	.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	.148	.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 VII. 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	
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 VIII. 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 IX. Damage Results in 22-Group Structure

Group Number	ΔE_N (MeV)	Damage (Present Results) (MeV.mb)	Damage (Present Results) Gr 22=1.00	Damage (Rogers' Results)[a] Gr 22=1.00	Ratio Rogers'/ Present
10	.11-.55	53	0.283	0.255	0.90
11	.55-1.11	84	0.449	0.387	0.86
12	1.11-1.83	97	0.519	0.405	0.78
13	1.83-2.35	125	0.668	0.721	1.08
14	2.35-2.46	103	0.551	0.707	1.28
15	2.46-3.01	127	0.679	0.761	1.12
16	3.01-4.07	120	0.642	0.576	0.90
17	4.07-4.97	151	0.807	0.793	0.98
18	4.97-6.36	153	0.818	0.855	1.05
19	6.36-8.19	158	0.845	0.807	0.96
20	8.19-10.0	166	0.888	0.868	0.98
21	10.0-12.2	176	0.941	0.942	1.00
22	12.2-15.0	187	1.000	1.000	1.00

[a]Rogers, et al.[10] - all these values obtained by dividing published values by damage for Group 22, 7.36×10^{-11} Si Kerma [rad Si/(n/cm^2)].

averaged for different recoil energies. There is a continuing interest in defining a 1-MeV equivalence for different neutron energies and spectra. Several damage ratios, for 14 MeV/1 MeV damage, are shown in Table X. The first four values indicate how a 1-MeV equivalent definition would depend on the energy width chosen at 1 MeV. The second set of four values indicate some extreme ratios, not likely to be physically realized. The last two values are practical energy widths, very near 1 MeV, that differ in damage produced by a factor of two.

TABLE X. Damage Ratios, 14 MeV/1 MeV

E_n (1 MeV ≡)	Ratio, $\frac{\text{Damage, 14 MeV}}{\text{Damage, } E_n}$
1.000 MeV ± 5 keV	1.91
1.000 MeV ± 25 keV	1.55
1.000 MeV ± 100 keV	1.99
1.000 MeV ± 200 keV	2.15
0.813 MeV ± 2.5 keV	1.03
0.913 MeV ± 2.5 keV	1.22
1.157 MeV ± 2.5 keV	4.79
1.247 MeV ± 2.5 keV	4.56
1.1 to 1.2 MeV	3.40
0.9 to 1.0 MeV	1.70

IV. DISCUSSION

Neutron displacement damage in silicon has been calculated, as a function of neutron energy, in a way that utilizes all details of the available neutron cross section information. The results are presented in tabular form for 0.1 to 16 MeV in 5 keV intervals, for 0.1 to 16 MeV averaged over 25 keV intervals, and for 0.1 to 20 MeV averaged over 100 keV intervals. A comparison with other current work has been presented, as has a table of 14 MeV/1 MeV damage ratios. In the detailed treatment of cross sections, the Lindhard fraction, corrected for multiple collisions, has been calculated for each different recoil energy and for the

appropriate recoil ion, Si, Al, or Mg. For those reactions producing a proton or alpha particle, the contribution of the small particle has not been included. These small particles produce only a small fraction of the displacement damage, and, since their ranges often exceed typical device dimensions, it would be necessary to calculate the balance of energy flux of these particles out of silicon and flux into the silicon from its environment (probably not silicon).

The calculation of energy going into displacements is considered to be quite reliable. Approximate calculations[22] suggest that energy dependence (ratios) are not very sensitive to the details of LSS at high energies, while the experimental confirmation of LSS by Sattler and Vook[23] is particularly good at low energies for the displacement fraction. Treatment of the details of damage sites, point defects and clusters, has purposely not been included. If these details do not create differences in the annealing of damage or in the observable effects of damage such as carrier removal and carrier lifetime, then they do not need to be included. To the extent they do create differences, they confirm the conjecture of Lohkamp and McKenzie,[24] that there is no single energy-dependence relation.

The results presented have been used to plan and to evaluate accelerator experiments where the results of neutron exposures with fairly narrow energy-spread have been analyzed. Utility in a wide-range of applications is anticipated and these efforts (e.g., the analysis of simulator spectra) are in progress.

---

[22] *R. Shnidman, private communication.*

[23] *A.R. Sattler and F.L. Vook, "Partition of the Average Energy Deposited in Silicon as a Function of Incident Neutron Energy," Phys. Rev., Vol. 155, No. 2, pp 211-217, March 1967.*

[24] *J.E. Lohkamp and J.M. McKenzie, "Measurement of the Energy Dependence of Neutron Damage in Silicon Devices," IEEE Trans. Nucl. Sci., Vol. NS-22, No. 6, pp 2319-2325, December 1975.*

ACKNOWLEDGEMENTS

The authors would like to acknowledge the participation of Dr. R.M. Tapphorn in early phases of this work, and to thank Dr. R. Shnidman for many helpful discussions. Also, the interest and encouragement of Drs. D. Eccleshall and C.E. Hollandsworth during the course of this investigation are appreciated.

REFERENCES

1. E.E. Conrad, "Considerations in Establishing a Standard for Neutron Displacement Energy Effects in Semiconductors," IEEE Trans. Nucl. Sci., Vol. NS-18, No. 6, pp 200-205, 1971.

2. W.R. Van Antwerp and J.E. Youngblood, "Displacement Damage in Silicon Irradiated with 6- to 10-MeV Neutrons," Bull. Am. Phys. Soc., Vol. 17, p 678, 1972.

3. J.E. Youngblood, W.R. Van Antwerp, and R.M. Tapphorn, "Displacement Damage in Silicon Irradiated with 6- to 10-MeV Neutrons," BRL Memorandum Report BRL MR 2738, April 1977.

4. E.C. Smith, et al., "Theoretical and Experimental Determinations of Neutron Energy Deposition in Silicon," IEEE Trans. Nucl. Sci., Vol. NS-13, No. 6, pp 11-17, 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., Vol. 38, No. 1, pp 204-210, 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. R.K. Thatcher and M.L. Green, "TREE Preferred Procedures," DNA 2028H, Edition No. 2, Battelle Columbus Laboratories, June 1972.

8. 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., Vol. NS-19, No. 6, pp 200-208, December 1972.

9. C.S. Guenzer and Irwin Manning, "Calculated Displacement Damage by Neutrons in InSb," IEEE Trans. Nucl. Sci., Vol. NS-21, No. 6, pp 26-29, December 1974.

10. 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., Vol. NS-22, No. 6, pp 2326-2329, December 1975. (Also, see erratum, Op. Cit., Vol. NS-23, No. 1, pp 875-876, February 1976.

11. B.R. Gossick, "Disordered Regions in Semiconductors Bombarded by Fast Neutrons," J. Appl. Phys., Vol. 30, No. 8, pp 1214-1218, August 1959.

REFERENCES

12. V.A.J. van Lint and R.E. Leadon, "Implications of Cluster Model of Neutron Effects in Silicon," Lattice Deffects in Semiconductors, 1974," Inst. Phys. Conf. Ser., No. 23, The Institute of Physics, London and Bristol, pp 227-232, 1975.

13. V.A.J. van Lint, R.E. Leadon, and J.F. Colwell, "Energy Dependence of Displacement Effects in Semiconductors," IEEE Trans. Nucl. Sci., Vol. NS-19, No. 6, pp 181-185, 1972.

14. Yu. V. Martynenko, "Annealing and Clustering of Defects in Cascades," Rad. Effects, Vol. 29, pp 129-135, 1976.

15. V.L. Vinetskii and A.V. Kondrachuk, "The Kinetics of Formation and the Parameters of Radiation Defect Clusters in Silicon," Rad. Effects, Vol. 30, pp 227-232, 1976.

16. J.B. Gibson, A.N. Goland, M. Milgram, and G.H. Vineyard, "Dynamics of Radiation Damage," Phys. Rev., Vol. 120, pp 1229-1253, 1960.

17. D.P. Jackson and D.V. Morgan, "Computer Modelling of Collision Processes in Solids," Contemp. Phys., Vol. 14, No. 1, pp 25-48, 1974.

18. G.C. Messenger, "Displacement Damage in Silicon and Germanium Transistors," IEEE Trans. Nucl. Sci., Vol. NS-12, No. 2, pp 53-74, April 1965.

19. J. Lindhard, M. Scharff, and H.E. Schiott, "Range Concepts and Heavy Ion Ranges," Kgl. Danske Videnskeb Selskab, Mat. Fys. Medd., Vol. 33, No. 14, pp 1-42, 1963.

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

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

22. R. Shnidman, private communication.

23. A.R. Sattler and F.L. Vook, "Partition of the Average Energy Deposited in Silicon as a Function of Incident Neutron Energy," Phys. Rev., Vol. 155, No. 2, pp 211-217, March 1967.

24. J.E. Lohkamp and J.M. Kenzie, "Measurement of the Energy Dependence of Neutron Damage in Silicon Devices," IEEE Trans. Nucl. Sci., Vol. NS-22, No. 6, pp 2319-2325, December 1975.

APPENDIX

1. Introduction

The computer program used for damage calculations follows in this appendix. The program is presented as presently used, making use of some tabulated material and containing a mixture of FORTRAN and assembly language for use on an SEL-86 computer. Although its use is limited in this form, it is presented here to aid in-house users and to aid others in formulating similar programs. An unusual amount of redundancy and error checking was included because the computer was in a state of dynamic evaluation at the time the program was prepared. The main program is followed by a program preparation routine and a number of sub-routines, and these are largely self-explanatory.

2. Listing of Main Program

```
      COMMON E(200),S(200),F(200),D(200)
      COMMON/ISSWN/ISSW5,ISSW6
      COMMON/REACT/E3,S3,Q,LCT,NN,A0,A(25),M1,M2,M3,M4,FLAG,XMIN
      DIMENSION TITLE(5),AL(25),AH(25),AMAT(25,25),NBT3(10),
     1 INT3(10),NBT4(10),INT4(10)
      INTEGER Z2,Z4
      REAL M1,M2,M3,M4
      DATA FILE5,CR1,TY1/'5    ',Z43523100,Z54593200/
      CALL SETIO(FILE5,TY1)
      CALL POST39
  100 CONTINUE
      CALL SETIO(FILE5,CR1)
       READ(5,1)MT,MTNUM,M1,M2,M3,M4,Z2,Z4,TITLE
    1 FORMAT(2I5,4F10.0,2I5,5A4)
      CALL SETIO(FILE5,TY1)
      IF(MT.GE.2.OR.MT.LE.999) GO TO 105
      WRITE(5,31)MT
   31 FORMAT(' ILLEGAL MT =',I6)
      PAUSE MT
      GO TO 100
  105 CONTINUE
  110 WRITE(6,11)MT,MTNUM,TITLE,M1,M2,M3,M4,Z2,Z4
   11 FORMAT(1H1,'REACTION CODE =',I5,10X,'REVISION',I5,20X,5A4/
     1 ' M1 =',F10.5,10X,'M2 =',F10.5,10X,'M3 =',F10.5,10X,'M4 =',F10.5/
     2 24X,'Z2 =',I5,15X,24X,'Z4 =',I5)
      CALL FRACT(Z4,M4,Z2,M2)
      CALL ENTER(MT,N13TOT,N14TOT,N15TOT)
      REWIND 13  ;  REWIND 14
      CALL SWITCH(MT)
      READ(13,21)N13,ZA,AWR,LIS,LFS
   21 FORMAT(I10,2F11.0,4I11)
      READ(13,21)N13,T,Q,LT,N,NR3,NE3
      Q=Q/1.E6
      IF(NR3.GT.10) PAUSE NR3
  115 READ(13,22)(NBT3(I),INT3(I),I=1,NR3)
   22 FORMAT(10X,6I11)
      WRITE(6,12)ZA,AWR,Q,LIS,LFS,NE3
   12 FORMAT(' ZA =',F8.0,10X,'AWR =',1PE12.5,10X,'Q =',0PF10.5/
     1 ' INITIAL STATE =',I5,10X,'FINAL STATE =',I5/
     2 ' NUMBER OF ENTRIES IN THE CROSS-SECTION TABLE =',I6)
      IF(LT.GT.1.OR.T.NE.0.0) WRITE(6,13)T,LT
   13 FORMAT(' NUCLEAR TEMPERATURE =',1PE12.5,10X,'LT =',I5)
      WRITE(6,14)NR3,(NBT3(I),INT3(I),I=1,NR3)
   14 FORMAT(' THERE ARE',I3,' INTERPOLATION RANGES'/(10X,2I10))
      NTOTAL=0
      NBLK=0
      E=0.
      S=0.
      REWIND 37
      I13=3+(NR3+2)/3
```

```
      N3=-2
  125 READ(13,23)N13,(E(I),S(I),I=1,3)
   23 FORMAT(I10,6F11.0)
      IF(I13.EQ.N13) GO TO 128
      CALL POST13(I13,N13,N13TOT)
      GO TO 125
  128 I13=I13+1
      N3=N3+3
      IF(E(3).GE.1.E5) GO TO 130
      IF(N3+2.LT.NE3) GO TO 125
      WRITE(5,33)
   33 FORMAT(' THERE ARE NO ENERGIES ABOVE 10 KEV.')
      PAUSE EMIN
      GO TO 100
  130 N=3
      IF(E(1).GE.1.E5) GO TO 135
      E(1)=E(2) ; E(2)=E(3) ; E(3)=0.0
      S(1)=S(2) ; S(2)=S(3) ; S(3)=0.0
       N=2
      IF(E(I).GE.1.E5) GO TO 135
      E(1)=E(2) ; E(2)=0.0 ; S(1)=S(2)  ; S(2)=0.0
      N=1
      IF(E(1).GE.1.E5) GO TO 135
      PAUSE ERR135
  135 CONTINUE
      E(1)=E(1)/1.E6  ;  E(2)=E(2)/1.E6  ;  E(3)=E(3)/1.E6
      NSKIP=N3-N+2
      LTOTAL=NE3-NSKIP
      LBLK=(LTOTAL+99)/100
      EL=0.0  ;  EH=100.  ;  NL=NH=1  ;  AL=0.0  ;  AH=0.0  ;  INT4A=2
      IF(ISSW5.EQ.1.OR.ISSW6.EQ.1) GO TO 155
      READ(14,21)N14,ZA4,AWR4,LVT,LTT
      IF(LTT.EQ.1) GO TO 140
      WRITE(5,34)
   34 FORMAT(' ONLY LEGENDRE REPRESENTATION ALLOWED')
      PAUSE LTT
      GO TO 100
  140 READ(14,21)N14,ZA4,AWR4,M,LCT,NK,NM
      AMAT=0.0
      IF(LVT.EQ.0) GO TO 150
      IF(LVT.EQ.1.AND.NK.EQ.((NM+1)*(NM+1))) GO TO 145
      WRITE(5,35)LVT,NK,NM
   35 FORMAT(' LVT =',I3,'   NK =',I4,'   NM =',I3)
      PAUSE LVT
  145 NT=NM+1
      READ(14,25)((AMAT(I,J),I=1,NT),J=1,NT)
   25 FORMAT(10X,6F11.0)
  150 READ(14,21)N14,ZA4,AWR4,M,J,NR4,NE4
      IF(NR4.GT.10) PAUSE NR4
      READ(14,22)(NBT4(I),INT4(I),I=1,NR4)
```

```
      WRITE(6,15)LVT,LTT,LCT,NK,NM,NE4,NR4,(NBT4(I),INT4(I),I=1,NR4)
   15 FORMAT(' LVT =',I5,10X,'LTT =',I5,10X,'LCT =',I5/
     1 ' NUMBER OF ENTRIES IN CONVERSION MATRIX =',I5,15X,
     2 'HIGHEST ORDER POLYNOMIAL USED =',I5/
     3 ' NUMBER OF ENTRIES IN ANGULAR DISTRIBUTION TABLE IS',I5/
     4 ' NUMBER OF INTERPOLATION RANGES IS',I5/(10X,2I10))
      AL=0.0
      AH=0.0
      I14=4+(NR4+2)/3+(NK+5)/6
   24 FORMAT(I10,11X,F11.0,22X,I11/(10X,6F11.0))
  151 READ(14,24)N14,EL,NL,(AL(I),I=1,NL)
      IF(N14.EQ.I14) GO TO 152
      CALL POST14(I14,N14,N14TOT)
      GO TO 151
  152 I14=I14+1+(NL+5)/6
      EL=EL/1.E6
  153 READ(14,24)N14,EH,NH,(AH(I),I=1,NH)
      IF(N14.EQ.I14) GO TO 154
      CALL POST14(I14,N14,N14TOT)
      GO TO 153
  154 I14=I14+1+(NH+5)/6
      EH=EH/1.E6
      N4=2
      NSCH4=1
      INT4A=INT4(1)
      NBT4A=NBT4(1)
  155 IF(N.GE.100) GO TO 160
      IF(N3+2.GE.NE3) GO TO 159
      IF(I13.GT.N13TOT) GO TO 300
      NA=N+1
      N=N+3
  157 READ(13,23)N13,(E(I),S(I),I=NA,N)
      IF(I13.EQ.N13) GO TO 158
      CALL POST13(I13,N13,N13TOT)
      GO TO 157
  158 I13=I13+1
      E(NA)=E(NA)/1.E6  ;  E(NA+1)=E(NA+1)/1.E6  ;  E(N)=E(N)/1.E6
       N3=N3+3
      IF(N3+2.LE.NE3)  GO TO 155
  159 N=N+NE3-N3-2
  160 CONTINUE
      F=0.0
      D=0.0
      WRITE(6,16)
   16 FORMAT(//'     I     ENERGY       SIGMA        DAMAGE      ERROR',
     * '    EFF DAM      EFF E4      EFF F       CHECK',11X,'EL',8X,'EH',
     * '     INT4    N3    N4' / )
      DO 200 II=1,100
      I=II
      IF(I.GT.N) GO TO 201
```

```
      E3=E(I)
      S3=S(I)
  165 IF(E3.LE.EH) GO TO 175
      IF(N4.GE.NE4) GO TO 310
      IF(I14.GT.N14TOT) GO TO 310
      EL=EH  ;  NL=NH  ;  AL=0.0
      DO 170 I=1,NH
  170 AL(I)=AH(I)
  172 AH=0.0
      READ(14,24)N14,EH,NH,(AH(I),I=1,NH)
      EH=EH/1.E6
      IF(N14.EQ.I14) GO TO 174
      CALL POST14(I14,N14,N14TOT)
      GO TO 172
  174 I14=I14+1+(NH+5)/6
      N4=N4+1
       IF(N4.LE.NBT4A) GO TO 165
      IF(NSCH4.LT.NR4) NSCH4=NSCH4+1
      INT4A=INT4(NSCH4)
      NBT4A=NBT4(NSCH4)
      GO TO 165
  175 IF(EL.LE.E3) GO TO 180
      WRITE(5,36)
   36 FORMAT('E3 IS BELOW E4 LOW'/
     * 'C TO TERMINATE,  R TO IMMEDIATELY GET NEXT REACTION CODE.')
      PAUSE E3LOW
  180 CONTINUE
      NN=MAX0(NL,NH)
      DO 185 I=1,NN
      CALL INTERP(E3,EL,EH,AL(I),AH(I),AA,INT4A)
      A(I)=AA*(I+I+1)*0.5
  185 CONTINUE
      A0=0.5
      CALL FSIMP0(X)
      CALL DAMCAL(DAMAGE,ERROR,AVEDAM,AVEE4,FRACTION,TEST)
      I=II
      D(I)=DAMAGE
      F(I)=FRACTION
      NUMBER=NTOTAL+I
      N3A=NUMBER+NSKIP
      CALL SSWTCH(10,ISSW)    ;  IF(ISSW.EQ.1) GO TO 200
      WRITE(6,17)NUMBER,E(I),S(I),D(I),ERROR,AVEDAM,AVEE4,F(I),TEST,
     * EL,EH,INT4A,N3A,N4
   17 FORMAT(1X,I4,2F11.5,1PE14.5,0PF8.3,1P3E11.2,E10.1,5X,0P2F10.4,3I5)
  200 CONTINUE
  201 CONTINUE
      NN=MIN0(N,100)
      IF(NN.LE.0) GO TO 230
      NA=NTOTAL+1
      NAA=NTOTAL+NN
```

```
      NBLK=NBLK+1
      JBLK=NBLK
      WRITE(39)MT,MTNUM,NBLK,LBLK,NN,LTOTAL,NA,NAA,M1,M2,M3,M4,Z2,Z4,Q,
     * TITLE,(E(I),I=1,100),(S(I),I=1,100),(D(I),I=1,100),
     * (F(I),I=1,100),JBLK
      WRITE(6,202)NA,NAA,E(1),S(1),D(1),F(1),E(NN),S(NN),D(NN),F(NN)
  202 FORMAT(///1X,130(1H*)/' TABLE OUTPUT FOR N=',I5,' TO',I5/
     *20X,'FIRST DATA  E=',F10.5,5X,'SIGMA=',F10.5,5X,'DAMAGE=',1PE12.5,
     * 5X,'EFFECTIVE F=',E12.5/20X,' LAST DATA  E=',0PF10.5,5X,
     * 'SIGMA=',F10.5,5X,'DAMAGE=',1PE12.5,5X,'EFFECTIVE F=',E12.5/
     *1X,130(1H*))
      NTOTAL=NTOTAL+NN
      N=N-100
      NA=N+1
      IF(NSKIP+NTOTAL.GE.NE3) GO TO 250
      IF(N)230,220,205
  205 DO 210 I=1,N
      E(I)=E(I+100)
  210 S(I)=S(I+100)
  220 CONTINUE
      DO 215 I=NA,200
      E(I)=0.0
  215 S(I)=0.0
      GO TO 155
  230 NN=NSKIP+NTOTAL
      IF(NN.EQ.NE3) GO TO 250
      WRITE(5,231)NN,NE3
  231 FORMAT('POSSIBLE ERROR IN THE NUMBER OF ENERGIES CALCULATED'/
     * '(NSKIP+NCALC) =',I5,'  WHILE NE3 =',I5/
     * 'C TO ACCEPT AS IS,  R TO RETRY ENTIRE REACTION')
      PAUSE NERR
  250 CONTINUE
      N=1
  260 CONTINUE
      LBLK=LBLK-NBLK
      LTOTAL=LTOTAL-NTOTAL
      NTOTAL=NE3-NTOTAL-NSKIP
      M1=M1+M2-M3-M4
      IZ=Z2-Z4
      WRITE(6,37)MT,MTNUM,LBLK,LTOTAL,NTOTAL,M1,IZ
   37 FORMAT(//' ** TEST **',5I5,F10.3,I5)
      GO TO 100
  300 WRITE(5,301)E(N)
  301 FORMAT('ATTEMPT TO READ MORE THAN N13TOT.'/
     * 'E(N) =',1PE12.5/
     * 'C TO USE AS IS,  R TO RETRY ENTIRE REACTION.')
      PAUSE N13
      GO TO 160
  310 WRITE(311)E(N)
  311 FORMAT('ATTEMPT TO READ MORE THAN N14TOT.'/
```

```
*  'E(N) =',1PE12.5/
*'C TO EXTRAPOLATE,  R TO RETRY ENTIRE REACTION.')
 PAUSE N14
 GO TO 175
 END
```

3. Listing of Subroutines

```
      SUBROUTINE SWITCH(MT)
      COMMON/ISSWN/ISSW5,ISSW6
      CALL SSWTCH(5,ISSW5) ;  CALL SSWTCH(6,ISSW6)
      IF(ISSW5.EQ.1.OR.ISSW6.EQ.1) GO TO 10
      IF(MT.EQ.16) ISSW6=1
      IF(MT.EQ.22) ISSW6=1
      IF(MT.EQ.28) ISSW6=1
      IF(MT.EQ.104)ISSW5=1
      IF(MT.EQ.102)ISSW6=1
   10 CONTINUE
      IF(ISSW5.EQ.1) WRITE(6,1)
    1 FORMAT(/' REACTION IS FORCED TO BE ISOTROPIC'/)
      IF(ISSW6.EQ.1) WRITE(6,2)
    2 FORMAT(/' HEAVY PARTICLE ASSUMED TO REMAIN AT REST IN C.O.M.'/)
      IF(ISSW5.NE.1.AND.ISSW6.NE.1) WRITE(6,3)
    3 FORMAT(/' REACTION TREATED NORMALLY'/)
       RETURN
      END
```

SUBROUTINE SETIO (FILE, DEVICE)

[This is an assembly language routine which dynamically assigns a symbolic unit number (FILE) used in FORTRAN input/output statements to a physical device (DEVICE). It is used to permit use of descriptor 5 for both card reader and teletype. This was a temporary local requirement because the number of symbolic input/output devices was less than the number of hardware devices.]

(SUBROUTINE ENTER (MTT, N13TOT, N14TOT, N15TOT)

[This is an assembly language routine which reads a BCD tape and transfers the card images for the desired reaction code (MTT) to files 13 and 14. File 13 is the cross-section data from DNA file 3 and file 14 is the angular distribution data from DNA file 4. An integer card counter (I10) precedes the card images (20A4). This routine was a local requirement because the computer used could not read BCD coded magnetic tapes by means of its FORTRAN accessible device handlers. N13TOT is the number of cards in file 13 (DNA file 3); N14TOT is the number in file 14 (DNA file 4); and N15TOT is set equal to zero.]

```
      SUBROUTINE POST13(IWANT,NREAD,NTOTAL)
      WRITE(5,2)IWANT,NREAD,NTOTAL
    2 FORMAT(' POST 13  WANT',I5,'   JUST READ',I5,' OF THE',I5,
     * ' RECORDS')
      IF(IWANT.LE.0.OR.IWANT.GT.NTOTAL) GO TO 50
      N=IWANT-NREAD
      IF(N)10,15,20
   10 N=-N
      IF(N.GT.10.OR.IWANT.LT.10) GO TO 30
      N=N+1
      DO 12 I=1,N
   12 BACKSPACE 13
      RETURN
   15 BACKSPACE 13
   20 RETURN
   30 REWIND 13
      IF(IWANT.EQ.1) RETURN
      N=IWANT-1
      DO 35 I=1,N
   35 READ(13,1)J
    1 FORMAT(I10)
      IF(J.EQ.N) RETURN
      WRITE(5,3)
    3 FORMAT(' ERROR POST 13  AUTOMATIC RETRY')
      N=IWANT-J
      IF(N)10,15,20
   50 CONTINUE
      IF(IWANT.LE.0) GO TO 60
      WRITE(5,51)
   51 FORMAT(' REQUESTED RECORD EXCEEDS SIZE OF FILE 13'/
     * ' C TO RETRY  R TO RESTART')
      GO TO 70
   60 WRITE(5,61)
   61 FORMAT(' NON-POSITIVE RECORD NUMBER REQUESTED FOR FILE 13'/
     * ' C TO RETRY  R TO RESTART')
   70 PAUSE N13    ;       RETURN
      END
```

```
      SUBROUTINE POST14(IWANT,NREAD,NTOTAL)
      WRITE(5,2)IWANT,NREAD,NTOTAL
    2 FORMAT(' POST 14  WANT',I5,'   JUST READ',I5,' OF THE',I5,
     * ' RECORDS')
      IF(IWANT.LE.0.OR.IWANT.GT.NTOTAL) GO TO 50
      N=IWANT-NREAD
      IF(N)10,15,20
   10 N=-N
      IF(N.GT.10.OR.IWANT.LT.10) GO TO 30
      N=N+1
      DO 12 I=1,N
   12 BACKSPACE 14
      RETURN
   15 BACKSPACE 14
   20 RETURN
   30 REWIND 14
      IF(IWANT.EQ.1) RETURN
      N=IWANT-1
      DO 35 I=1,N
   35 READ(14,1)J
    1 FORMAT(I10)
      IF(J.EQ.N) RETURN
      WRITE(5,3)
    3 FORMAT(' ERROR POST 14  AUTOMATIC RETRY')
      N=IWANT-J
      IF(N)10,15,20
   50 CONTINUE
      IF(IWANT.LE.0) GO TO 60
      WRITE(5,51)
   51 FORMAT(' REQUESTED RECORD EXCEEDS SIZE OF FILE 14'/
     * ' C TO RETRY  R TO RESTART')
      GO TO 70
   60 WRITE(5,61)
   61 FORMAT(' NON-POSITIVE RECORD NUMBER REQUESTED FOR FILE 14'/
     * ' C TO RETRY  R TO RESTART')
   70 PAUSE N14     !       RETURN
      END
```

```
      SUBROUTINE POST39
      DATA IFLAG/0/
      WRITE(5,1)
    1 FORMAT(' POSITION UNIT 39 FOLLOWING MT,VERSION(2I3)')
      IF(IFLAG.EQ.0) WRITE(5,2)
    2 FORMAT(' USE MT"3C0 TO REWIND UNIT 39'/
     * ' USE MT=0 IF UNIT 39 IS POSITIONED CORRECTLY')
      IFLAG=10
      READ(5,3)MTA,MTNUMA
    3 FORMAT(2I3)
      IF(MTA)5,10,15
    5 REWIND 39
      WRITE(5,6)
    6 FORMAT(' UNIT 39 HAS BEEN REWOUND')
      GO TO 20
   10 WRITE(5,11)
   11 FORMAT(' UNIT 39 HAS NOT BEEN MOVED')
      GO TO 20
   15 REWIND 39
   18 READ(39)MT,MTNUM,IBLK,NBLK
      IF(MT.NE.MTA.OR.MTNUM.NE.MTNUMA.OR.IBLK.NE.NBLK) GO TO 18
      WRITE(5,16)
   16 FORMAT(' UNIT 39 HAS BEEN POSITIONED AS REQUESTED')
   20 CONTINUE
      WRITE(5,21)
   21 FORMAT(' C TO PROCEED    R TO RE-ENTER POST39')
      PAUSE 39
      RETURN
      END
```

```
      SUBROUTINE INTERP(E,EL,EH,SL,SH,S,INT)
C     INT = 1 FOR Y CONSTANT FROM EL TO EH
C     INT=2 FOR Y = A + B * X
C     INT = 3 FOR  Y = A + B * LOG(X)
C     INT = 4  FOR LOG(Y) = A + B * X
C     INT = 5  FOR LOG(Y) = A + B * LOG(X)
      IF(EL.EQ.EH) GO TO 10
      IF(E.EQ.EL.OR.E.EQ.EH) GO TO 10
      IF(INT.LT.1.OR.INT.GT.5) GO TO 11
    5 GO TO (10,11,12,13,14),INT
   10 S=SL
      IF(E.EQ.EH) S=SH
      RETURN
   11 S=SL+(SH-SL)*(E-EL)/(EH-EL)
      RETURN
   12 IF(E.LE.0.0.OR.EL.LE.0.0.OR.EH.LE.0.0) GO TO 11
      S=SL+(SH-SL)*ALOG(E/EL)/ALOG(EH/EL)
      RETURN
   13 IF(SL.LE.0.0.OR.SH.LE.0.0) GO TO 11
      S=ALOG(SH/SL)*(E-EL)/(EH-EL)
      S=EXP(ALOG(SL)+S)
      RETURN
   14 IF(E.LE.0.0.OR.EL.LE.0.0.OR.EH.LE.0.0) GO TO 11
      IF(SL.LE.0.0.OR.SH.LE.0.0) GO TO 11
      S=ALOG(SH/SL)*ALOG(E/EL)/ALOG(EH/EL)
      S=EXP(ALOG(SL)+S)
      RETURN
      END
```

```
      SUBROUTINE FRACT(ZP,AP,ZT,AT)
      COMMON/TABLES/NTAB,AEPS,ETAB(500),FTAB(500)
      INTEGER ZP,ZPA,ZT,ZTA
      DATA ZPA,ZTA/1000,1000/
      ZZ=FLOAT(ZP)**(2./3.)+FLOAT(ZT)**(2./3.)
      AEPS=32517.*AT/((AP+AT)*FLOAT(ZP*ZT)*SQRT(ZZ))
      AK=0.0793*(FLOAT(ZP)**(2./3.))*SQRT(FLOAT(ZT))*(AP+AT)**1.5/
     * (ZZ**0.75*AP**1.5*SQRT(AT))
      WRITE(6,3)ZP,ZT,AP,AT,ZZ,AEPS,AK
    3 FORMAT(2(I8,2X),2F10.5,F10.5,F10.6,F10.7)
       IF(ZP.EQ.ZPA) RETURN
       WRITE(6,1)
    1 FORMAT('           READ NEW DAMAGE FILE')
   15 REWIND 37
   20 READ(37,END=30)ZPA,APA,ZTA,ATA,NTAB,(ETAB(I),I=1,500),
     *(FTAB(I),I=1,500)
      IF(ZP.NE.ZPA) GO TO 20
      RETURN
   30 WRITE(5,31)
   31  FORMAT(' READ EOF'/' C TO REWIND AND RE-READ')
      CALL STATUS(7,ISTAT)
       PAUSE EOF
      GO TO 15
      END
```

```
      SUBROUTINE DAMCAL(DAMAGE,ERROR,AVEDAM,AVEE4,AVEFRACT,TEST)
      COMMON/EXTRA/SUM1,SUM2
      DOUBLE PRECISION SUM1,SUM2
      COMMON/REACT/E,SIGMA,Q,LCT,NL,P0,P(25),M1,M2,M3,M4,FLAG,XLIM
      DAMAGE=ERROR=AVEDAM=AVEE4=AVEFRACT=TEST=0.0
      IF(SIGMA.LE.0.0) RETURN
      IF(FLAG.LT.-0.5) GO TO 10
      IF(FLAG.GT.0.5) GO TO 20
      PCTMIN=0.1  ;  MINPTS=100  ;  MAXPTS=1000
      XLOWER=-1.0  ;  XUPPER=1.0
      CALL SIMP(XLOWER,XUPPER,MINPTS,MAXPTS,PCTMIN,ANS,ERROR)
      AVEDAM=ANS  ;  AVEE4=SUM1  ;  AVEFRACT=ANS/SUM1
      SUM2=SUM2-1.D0  ;  TEST=SUM2
      DAMAGE=SIGMA*ANS
C     THERE ARE TWO FACTORS OF 2(PI) WHICH CANCEL.
C          ONE IS THE INTEGRAL OVER THE POLAR ANGLE,
C          THE OTHER ARISES IN THE DEFINITION OF THE LEGENDRE EXPANSION
C               USED IN THE ENDF/B FILES.
      RETURN
   10 DAMAGE=0.0
C     THE REACTION IS ENERGETICALLY IMPOSSIBLE.
      ERROR=100.
      RETURN
   20 DAMAGE=0.0
C     THE LIGHT PARTICLE IS DOUBLE-VALUED IN ENERGY.
C     CALCULATION NOT SET UP FOR THIS CONDITION
      ERROR=100.
      RETURN
      END
```

```
      SUBROUTINE SIMP(XA,XB,NL,NH,PCTMIN,ANS,ERR)
      DOUBLE PRECISION SUM1,SUM2,S01,S02
      COMMON/EXTRA/SUM1,SUM2
      DOUBLE PRECISION S0,S1,X,DX
      XL=XA
      XH=XB
      NMIN=NL
      NMAX=NH
      IF(NMAX.LE.0) NMAX=999999
      PCT=PCTMIN
      IF(PCT.LE.0.0) PCT=1.
      ANSA=0.
      SUM1=SUM2=0.D0
      S0=FSIMP(XL)+FSIMP(XH)
      S01=SUM1   ;   S02=SUM2;   SUM1=0.D0   ;   SUM2=0.D0
      DX=XH-XL
      N=2
       IF(DX.GT.0.0) GO TO 10
       IF(DX.EQ.0.0) GO TO 200
      ERR=XL
       XL=XH
      XH=ERR
      DX=-DX
   10 CONTINUE
       X=XL+0.5D0*DX
      S1=0.D0
   20 CONTINUE
      XX=X
      S1=S1+FSIMP(XX)
      N=N+1
      X=X+DX
      IF(X.LT.XH) GO TO 20
      ANS=(S0+4.D0*S1)*DX/6.D0
      IF(ANS.EQ.0.) GO TO 150
      ERR=100.*(ANSA/ANS-1.)
      IF(ERR.GT.100.) ERR=100.
      IF(ERR.LT.-100.) ERR=-100.
      IF(N.LT.NMIN) GO TO 50
       IF(N.GT.NMAX) GO TO  100
      IF(ABS(ERR).LT.PCT) GO TO 100
   50 CONTINUE
      ANSA=ANS
      S0=S0+S1+S1
      S01=S01+SUM1+SUM1   ;   S02=S02+SUM2+SUM2
      SUM1=SUM2=0.D0
      DX=0.5D0*DX
      GO TO 10
  100 CONTINUE
      SUM1=(S01+4.D0*SUM1)*DX/6.D0; SUM2=(S02+4.D0*SUM2)*DX/6.D0
      IF(XB.GE.XA) RETURN
```

```
      ANS=-ANS
      SUM1=-SUM1   ;   SUM2=-SUM2
      RETURN
  150 CONTINUE
      IF(N.LT.NMIN) GO TO 50
  200 CONTINUE
      ANS=0.0
      ERR=0.
      SUM1=SUM2=0.D0
      RETURN
       END
```

```
      FUNCTION FSIMP(X)
      COMMON/ISSWN/ISSW5,ISSW6
      COMMON/TABLES/NTAB,AEPS,ETAB(500),FTAB(500)
      COMMON/REACT/E,SIGMA,Q,LCT,NL,P0,P(25),M1,M2,M3,M4,FLAG,XLIM
      COMMON/REACT2/ET,A,B,C,D,AC,DB
      DOUBLE PRECISION SUM1,SUM2
      COMMON/EXTRA/SUM1,SUM2
      DIMENSION POLY(25)
       REAL M1,M2,M3,M4
      E4=M4*M1*E/(M1+M2)**2
      IF(ISSW6.EQ.1) GO TO 17
      IF(LCT.NE.1) GO TO 10
C     LCT = 1    X IS THE COSINE OF THE LABORATORY ANGLE
       CON=DB-(1.-X*X)
      IF(CON.LT.0.0) GO TO 100
      CON=SQRT(CON)
      E3=B*ET*(X+CON)**2
      GO TO 16
   10 CONTINUE
C     LCT = 2    X IS THE COSINE OF THE CENTER OF MASS ANGLE
      E3=ET*(B+D+(AC+AC)*X)
   16 CONTINUE
      IF(E3.LT.0.0) GO TO 100
      E4=ET-E3
      IF(E4.LT.0.0) GO TO 100
   17  SIG=P0
      IF(ISSW5.EQ.1.OR.ISSW6.EQ.1) GO TO 18
      U=X
      CALL LEGPOL(NL,U,POLY)
      DO 15 I=1,NL
   15 SIG=SIG+P(I)*POLY(I)
   18 CONTINUE
      EPS=E4*AEPS
      F=FTAB(1)
      IF(NTAB.LE.1) GO TO 50
      F=1.
      IF(E4.LT.1.E-20) GO TO 50
       V=(ALOG10(EPS)-ALOG10(ETAB(2)))*31.+2.
      N=V
      IF(N.LT.2) N=2
       IF(N.GT.NTAB-1) N=NTAB-1
   20 IF(EPS.GT.ETAB(N+1)) GO TO 25
       IF(EPS.LT.ETAB(N)) GO TO 30
       F=FTAB(N)+(FTAB(N+1)-FTAB(N))*(EPS-ETAB(N))/(ETAB(N+1)-ETAB(N))
      GO TO 50
   25 N=N+1
      IF(N.LT.NTAB-1) GO TO 20
      WRITE(6,26)EPS,ETAB(NTAB)
   26 FORMAT(' REDUCED ENERGY EXCEEDS TABLE.  EPS =',1PE12.5,
     * ' WHILE MAXIMUM VALUE IN TABLE IS',E12.5/)
```

```
      F=FTAB(NTAB)*ETAB(NTAB)/EPS
       GO TO 50
   30 N=N-1
      IF(N.GT.1) GO TO 20
      F=1.-(1.-FTAB(2))*((EPS/ETAB(2))**0.166667)
      GO TO 50
   50 CONTINUE
      SUM1=SUM1+E4*SIG   ;   SUM2=SUM2+SIG
       FSIMP=E4*F*SIG
       RETURN
  100 CONTINUE
      FSIMP=0.0
      RETURN
      END
```

```
      SUBROUTINE FSIMP0(X)
      COMMON/REACT/E,SIGMA,Q,LCT,NL,P0,P(25),M1,M2,M3,M4,FLAG,XLIM
      COMMON/REACT2/ET,A,B,C,D,AC,DB
       REAL M1,M2,M3,M4
      ET=E+Q
      IF(ET.LE.0.0) GO  TO 1000
      U=1./((M1+M2)*(M3+M4))
       A=M1*M4*E*U/ET
       B=M1*M3*E*U/ET
      U=M2*U*(1.+M1*Q/(M2*ET))
      IF(U.LT.0.0) GO TO 1000
       C=M3*U
      D=M4*U
      AC=SQRT(A*C)
      DB=D/B
      XLIM=-1.0
      FLAG=0.0
      IF(D.LT.B.AND.LCT.EQ.1) GO TO 1010
      RETURN
 1000 CONTINUE
C     REACTION BELOW THRESHOLD.
      FLAG=-1.
      RETURN
 1010 CONTINUE
C     THE ENERGY OF THE LIGHT PARTICLE IS DOUBLE-VALUED.
C     THE MINIMUM VALUE OF THE COSINE (XLIM) IS RETURNED TO THE CALLING
C          PROGRAM.  ATTEMPTED USE WILL YIELD A CALCULATION FOR THE
C          HIGHER ENERGY BRANCH FOR THE LIGHTER PARTICLE (THE LOWER
C          ENERGY BRANCH OF THE HEAVY PARTICLE OR INTEREST).
      XLIM=0.0
      FLAG=1.0
      U=1.-DB
      IF(U.GT.0.0) XLIM=SQRT(U)
      RETURN
      END
```

```
      SUBROUTINE LEGPOL(N,X,POLY)
      DIMENSION POLY(1)
        DOUBLE PRECISION  Y,U,V
      Y=X
      IF(N) 10,20,30
   10 WRITE(6,1)
    1 FORMAT(' ERROR IN CALCULATION OF LEGENDRE POLYNOMIALS')
      RETURN
   20 POLY(1)=0.    ;  RETURN
   30 DO 5 I=1,N
    5 POLY(I)=0.
      POLY(1)=Y  ;  IF(N.EQ.1) RETURN  ;  U=1.D0  ;  V=Y  ;  J=N-1
      DO 40 I=1,J
      Y=((I+I+1)*X*V-I*U)/(I+1)        ;   U=V   ;    V=Y
   40 POLY(I+1)=Y
      RETURN
       END
```

DISTRIBUTION LIST

No. of Copies	Organization
12	Commander Defense Documentation Center ATTN: DDC-TCA Cameron Station Alexandria, VA 22314
3	Director Defense Nuclear Agency ATTN: DDST, M. Atkins RARP SPAS Washington, DC 20305
2	DNA Information & Analysis Center TEMPO, General Electric Co. ATTN: Mr. W. Chan Dr. Hendrick 816 State Street Santa Barbara, CA 93102
1	Commander US Army Materiel Development and Readiness Command ATTN: DRCDMA-ST 5001 Eisenhower Avenue Alexandria, VA 22333
1	Commander US Army Aviation Systems Command ATTN: DRSAV-E 12th & Spruce Streets St. Louis, MO 63066
1	Director US Army Air Mobility Research and Development Laboratory Ames Research Center Moffett Field, CA 94035
1	Commander US Army Electronics Command ATTN: DRSEL-RD Fort Monmouth, NJ 07703
1	Commander US Army Missile Research and Development Command ATTN: DRDMI-R Redstone Arsenal, AL 35809
1	Commander US Army Tank Automotive Development Command ATTN: DRDTA-RWL Warren, MI 48090
2	Commander US Army Mobility Equipment Research & Development Command ATTN: Tech Docu Cen, Bldg 315 DRSME-RZT Fort Belvoir, VA 22060
1	Commander US Army Armament Research and Development Command ATTN: DRDAR-LC, J. Gregorits Dover, NJ 07801
2	Commander US Army Harry Diamond Laboratories ATTN: DRXDO-TI DRXDO-NP 2800 Powder Mill Road Adelphi, MD 20783
1	Director US Army TRADOC Systems Analysis Activity ATTN: ATAA-SA White Sands Missile Range, NM 88002
1	Commander US Army Foreign Science and Technology Center ATTN: AMXST-S Federal Office Building 220 7th Street, NW Charlottesville, VA 22091

DISTRIBUTION LIST

No. of Copies	Organization
1	Commander US Army Nuclear Agency Fort Bliss, TX 79916
1	Director US Army Ballistic Missile Defense Program Office ATTN: RDMD, LTC DeBoeser 1300 Wilson Boulevard Arlington, VA 22209
1	Commander US Army Research Office PO Box 12211 Research Triangle Park NC 27709
1	Commander US Naval Surface Weapons Center ATTN: Morton Lutzky Silver Spring, MD 20910
1	Commander US Naval Research Laboratory ATTN: Code 7600, Tech Lib Washington, DC 20375
1	AFWL (SUL) Kirtland AFB, NM 87117
2	Director Argonne National Laboratory Library Services Department Report Section, Bldg 203 RM-CE-125 Argonne, IL 60440
3	Director Los Alamos Scientic Laboratory ATTN: Tech Info Div Dr. P.G. Young Dr. D.G. Foster Los Alamos, NM 87544
1	Oak Ridge National Laboratory ATTN: RSIC Oak Ridge, TN 37830
1	Sandia Laboratories ATTN: Tech Lib PO Box 5800 Albuquerque, NM 87115
	Aberdeen Proving Ground
	Marine Corps Ln Ofc Dir, USAMSAA ATTN: Dr. J. Sperrazza J. E. Youngblood