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Designation: E 693 – 94

Standard Practice for Characterizing Neutron Exposures in Iron and Low Alloy Steels in Terms of Displacements Per Atom (DPA), E706(ID)[1]

This standard is issued under the fixed designation E 693; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ϵ) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This practice describes a standard procedure for characterizing neutron irradiations of iron (and low alloy steels) in terms of the exposure index displacements per atom (dpa) for iron.

1.2 Although the general procedures of this practice apply to any material for which a displacement cross section $\sigma_d(E)$ is known (see Practice E 521), this practice is written specifically for iron.

1.3 It is assumed that the displacement cross section for iron is an adequate approximation for calculating displacements in steels that are mostly iron (95 to 100 %) in radiation fields for which secondary damage processes are not important.

1.4 Procedures analogous to this one can be formulated for calculating dpa in charged particle irradiations. (See Practice E 521.)

1.5 The application of this practice requires knowledge of the total fluence and the neutron-flux spectrum. Refer to Practice E 521 for determining these quantities.

1.6 The correlation of radiation effects data is beyond the scope of this practice.

1.7 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

2. Referenced Documents

2.1 *ASTM Standards:*

E 170 Terminology Relating to Radiation Measurements and Dosimetry[2]

E 521 Practice for Neutron Radiation Damage Simulation by Charged-Particle Irradiation[2]

E 560 Practice for Extrapolating Reactor Vessel Surveillance Dosimetry Results, E706 (IC)[2]

E 853 Practice for Analysis and Interpretation of Light-Water Reactor Surveillance Results, E706 (IA)[2]

3. Terminology

3.1 Definitions for terms used in this practice can be found in Terminology E 170.

4. Significance and Use

4.1 A pressure vessel surveillance program requires a methodology for relating radiation-induced changes in materials exposed in accelerated surveillance locations to the condition of the pressure vessel (see Practices E 560 and E 853). An important consideration is that the irradiation exposures be expressed in a unit that is physically related to the damage mechanisms.

4.2 A major source of neutron radiation damage in metals is the displacement of atoms from their normal lattice sites. Hence, an appropriate damage exposure index is the number of times, on the average, that an atom has been displaced during an irradiation. This can be expressed as the total number of displaced atoms per unit volume, per unit mass, or per atom of the material. Displacements per atom is the most common. The number of dpa associated with a particular irradiation depends on the amount of energy deposited in the material by the neutrons, hence, depends on the neutron spectrum. (For a more extended discussion, see Practice E 521.)

4.3 No simple correspondence exists in general between dpa and a particular change in a material property. A reasonable starting point, however, for relative correlations of property changes produced in different neutron spectra is the dpa value associated with each environment. That is, the dpa values themselves provide a spectrum-sensitive index that may be a useful correlation parameter, or some function of the dpa values may affect correlation.

4.4 Since dpa is a construct that depends on a model of the neutron interaction processes in the material lattice, as well as the cross section (probability) for each of these processes, the value of dpa would be different if improved models or cross sections are used. The calculated dpa cross section for ferritic iron, as given in this practice, is determined by the procedure given in 6.3. This dpa cross section has been used as a neutron exposure parameter for reporting a considerable body of irradiated materials data. Therefore, the cross section has not been updated to reflect model or cross section improvements.

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[1] This practice is under the jurisdiction of ASTM Committee E-10 on Nuclear Technology and Applications and is the direct responsibility of Subcommittee E10.05 on Nuclear Radiation Metrology.

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[2] *Annual Book of ASTM Standards*, Vol 12.02.

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The continued used of the same cross section is justified pending improved damage theories that can determine exposure parameters that do correspond to materials property changes.

5. Procedure

5.1 The displacement rate at time t is calculated as follows:

$$\text{dpa/s} = \int_0^\infty \sigma_d(E)\phi(E,t)\,dE \tag{1}$$

where:

$\sigma_d(E)$ = the displacement cross section for a particular material, and

$\phi(E,t)\,dE$ = the fluence rate of neutrons in the energy interval E to $E + dE$.

5.2 The exposure index, dpa, is then the time integrated value of the displacement rate, calculated as follows:

$$\text{dpa} = \int_0^{t_r} \phi_{\text{tot}}(t) \int_0^\infty \sigma_d(E)\psi(E,t)\,dE\,dt \tag{2}$$

where:

$\phi_{\text{tot}}(t)$ = the time dependent fluence rate intensity, and

$\psi(E,t)$ = the fluence rate spectrum normalized to give unit integral fluence rate when integrated over energy.

5.2.1 If the fluence rate spectrum is constant over the duration, t_r, of the irradiation, then:

$$\text{dpa} = \phi_{\text{tot}} t_r \int_0^\infty \sigma_d(E)\psi(E)\,dE = \phi_{\text{tot}} t_r \bar{\sigma}_d \tag{3}$$

where $\bar{\sigma}_d$ = the spectrum-average displacement cross section.

5.3 It is assumed for purposes of this practice that the fluence $\phi_{\text{tot}} t_r$ and the spectrum (E) are known.

6. Calculation

6.1 The integral can be evaluated by a simple numerical integration as follows:

$$\int_0^\infty \sigma_d(E)\phi(E)\,dE = \sum_{i=1}^{N} (\sigma_d)_i \phi_i \Delta E_i \tag{4}$$

where $(\sigma_d)_i$ and ϕ_i are grouped-averaged values over the interval $E_i < E < E_{i+1}$, and ΔE_i is the width of the interval and is given by $E_{i+1} - E_i$.

6.2 The only computational problem, then, is to obtain $\sigma_d(E)$ and $\phi(E)$ in the same group structure. $\sigma_d(E)$ is available **(1)**[3] in the SAND-II group structure (included here as Table 1), which is as fine or finer than the group structure in which $\phi(E)$ is generally available. Hence the problem is to collapse $\sigma_d(E)$ to match the $\phi(E)$ group structure.

6.2.1 If the $\phi(E)$ group structure is sufficiently fine, for example, one-quarter lethargy or less, a simple group averaging is sufficient:

$$(\sigma_d)_i = \frac{1}{\Delta E_i} \sum_{k=1}^{M_i} (\sigma_d)_{ik} \Delta E_{ik} \tag{5}$$

where M_i is the number of groups in $\sigma_d E$ between E_i and E_{i+1}, and the $\Delta E_{ik} \equiv E_{ik+1} - E_{ik}$ are the group widths.

6.2.1.1 If the ΔE_{ik} are constant (as above 1 MeV in Table 1), this becomes a simple average of the M_i groups in ΔE_i as follows:

$$(\sigma_d)_i = \frac{1}{M_i} \sum_{k=1}^{M_i} (\sigma_d)_{ik} \tag{6}$$

6.2.2 For a coarse group representation of $\phi(E)$, the group averages of $\sigma_d(E)$ should be weighted averages, unless such weighting has been shown to have negligible effects. The ideal weighting function is, of course, the actual spectrum $\phi(E)$. For light-water reactor applications, a generalized spectrum is often used consisting of a fission spectrum plus a low energy $1/E$ tail. Let the weighting spectrum be designated by $W(E)$. Then the recommended form and energy regimes are as follows:

$$W(E) = C_1/E \qquad E < 0.82 \text{ MeV}$$
$$= C_2 E^{1/2} e^{-E/1.4} \qquad E \geq 0.82 \text{ MeV}$$

The constants C_1 and C_2 are arbitrary.

The group averages are then computed from the following equation:

$$(\sigma_d)_i = \frac{\sum_{k=1}^{M_i} (\sigma_d)_{ik} W(E_{ik}) \Delta E_{ik}}{\sum_{k=1}^{M_i} W(E_{ik}) \Delta E_{ik}} \tag{7}$$

where $\hat{E}_{ik}$ = the average energy of the *kth* group, or

$$E_{ik} \equiv (E_{ik+1} + E_{ik})/2 \tag{8}$$

6.2.3 It may be that the group structure of $\phi_d(E)$ is not a subset of the group structure of $\sigma_d(E)$; that is, none of the values of E_{ik} coincide with E_i or E_{i+1}, or both. This should pose no problem because the $\sigma_d(E)$ group structure is sufficiently fine that accurate interpolation is easily accomplished.

6.3 The recommended displacement cross section for iron $\sigma_d(E)$, is given as a function of energy in Table 1. The energy values chosen for the table entries are those of the SAND-II energy group structure **(2)**. The table is a listing of energies and corresponding displacement cross sections. A graphical display of the displacement cross sections as a function of energy appears in Fig. 1. The values of the displacement cross section are based on ENDF/B IV cross sections **(3)**, the Robinson analytical function **(4)** of the Lindhard model of energy partition between atoms and electrons **(5)**, and the IAEA recommended conversion of damage energy to displacements **(6)**, as calulated in Ref **(7)**.

6.4 A single calculation suffices, of course, to characterize a given spectrum in terms of the spectrum-averaged displacement cross section $\bar{\sigma}_d$.

6.4.1 The quantity $\bar{\sigma}_d$ is a good measure of spectrum hardness if the thermal-to-fast ratio is not large. However, a modified σ_d can be used with any thermal-to-fast ratio, if it is assumed that displacements are caused predominantly by neutrons of energies greater than E_o. Then one can define $\bar{\sigma}_d(E > E_o)$ by the following equation:

$$\sigma_d(E > E_0) = \frac{\int_{E_o}^\infty \sigma_d(E)\phi(E)dE}{\int_{E_o}^\infty \phi(E)\,dE} \tag{9}$$

and

[3] The boldface numbers in parentheses refer to the list of references appended to this practice.

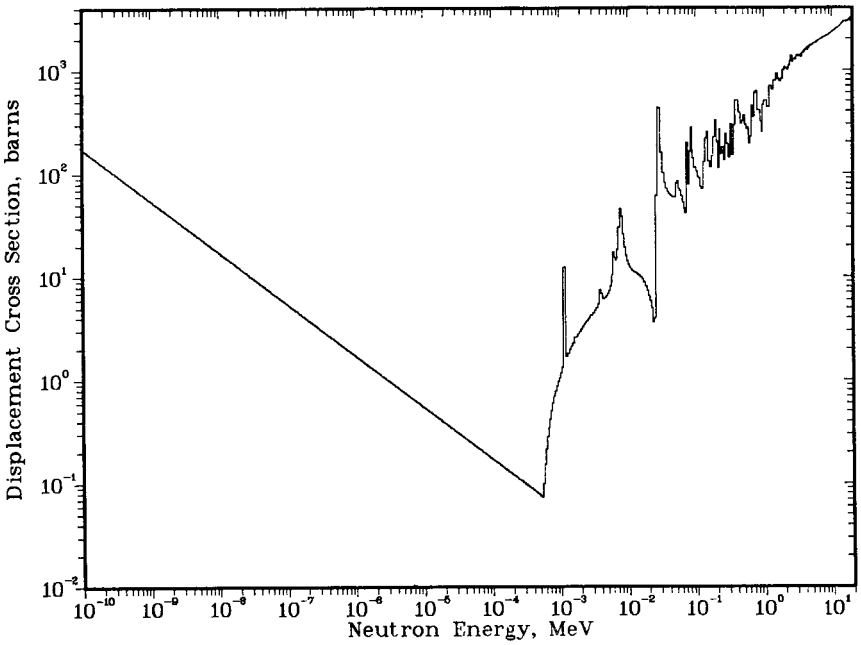

FIG. 1 Displacement Cross Section for Iron, Plotted as a Function of Neutron Energy

$$\text{dpa/s} \cong \bar{\sigma}_d (E > E_o) \times \phi(E > E_o) \quad (10)$$

A reasonable value for E_o is 0.01 MeV. The quantity $\bar{\sigma}_d$ ($E >$ 0.01 MeV) is then a good index of spectrum hardness irrespective of the thermal-to-fast ratio.

7. Precision and Accuracy

7.1 *Precision*—For a neutron fluence spectrum in a fine-group structure, the precision of the dpa calculation is estimated to be better than 1 %. For typical coarse group structures, the need for more group averaging of $\sigma_d(E)$ will lead to some loss of precision.

7.2 *Accuracy*:

7.2.1 *Absolute Accuracy*—The absolute accuracy of the dpa calculation is not important when dpa is used as an exposure unit or correlation parameter for neutron irradiations, so long as a standard practice is used by all laboratories in calculating dpa. The absolute uncertainty is estimated to be 40 % or more when applied to a light water reactor spectrum (less in a softer spectrum). The major sources of error are the fluence spectrum, the reaction cross sections used in calculating $\sigma_d(E)$, the Lindhard model for the partition of energy between atoms and electrons, and the conversion of deposited energy to displacements.

7.2.2 *Relative Accuracy*—The relative accuracy of dpa calculations for different environments depends on the energy dependence of $\sigma_d(E)$ and on the relative accuracy of fluence-spectrum determinations. For a discussion of the effect of the energy dependence of $\sigma_d(E)$ on the relative accuracy of the dpa calculation see Ref **7** and Practice E 521. Losses in the relative accuracy of the dpa calculation due to this effect are estimated to be less than 10 % for most reactor spectra **(7)**. The relative accuracy of the fluence-spectrum determination depends on the method of determination. (For recommended methods see E 10.05 Matrix Standard, E 706.) Any uncertainty in the total fluence is, of course, reflected directly in the dpa calculation (see 5.2.1).

8. Damage Correlation

8.1 This practice is concerned with standardizing a radiation exposure unit. It is concerned only secondarily with the correlation of damage produced in different environments. As stated in 4.1, the dpa is a logical first step in attempting to correlate displacement damage. Active research programs on improving correlation methodology are in progress. Because many past data correlations have been based on "fast fluence" ($E > 1$ MeV), this quantity should also be given, along with the dpa value, when expressing irradiation exposures. (For a general discussion of the damage correlation problem, see Ref **8**.)

9. Keywords

9.1 atomic displacements; cross section; irradiation; materials damage; neutron; steel

TABLE 1 Displacement Cross Section for Iron

Energy,[A] MeV	Sigma,[A] barns	Energy, MeV	Sigma, barns	Energy, MeV	Sigma, barns	Energy, MeV	Sigma, barns	Energy, MeV	Sigma, barns	Energy, MeV	Sigma, barns
1.000E − 10	1.710E + 02	1.050E − 10	1.669E + 02	1.100E − 10	1.632E + 02	1.150E − 10	1.597E + 02	1.200E − 10	1.556E + 02	1.275E − 10	1.511E + 02
1.350E − 10	1.470E + 02	1.425E − 10	1.431E + 02	1.500E − 10	1.391E + 02	1.600E − 10	1.348E + 02	1.700E − 10	1.309E + 02	1.800E − 10	1.273E + 02
1.900E − 10	1.240E + 02	2.000E − 10	1.209E + 02	2.100E − 10	1.180E + 02	2.200E − 10	1.154E + 02	2.300E − 10	1.129E + 02	2.400E − 10	1.100E + 02
2.550E − 10	1.068E + 02	2.700E − 10	1.044E + 02	2.800E − 10	1.017E + 02	3.000E − 10	9.833E + 01	3.200E − 10	9.530E + 01	3.400E − 10	9.253E + 01
3.600E − 10	8.999E + 01	3.800E − 10	8.765E + 01	4.000E − 10	8.524E + 01	4.250E − 10	8.276E + 01	4.500E − 10	8.049E + 01	4.750E − 10	7.840E + 01
5.000E − 10	7.646E + 01	5.250E − 10	7.466E + 01	5.500E − 10	7.298E + 01	5.750E − 10	7.141E + 01	6.000E − 10	6.980E + 01	6.300E − 10	6.816E + 01
6.600E − 10	6.662E + 01	6.900E − 10	6.519E + 01	7.200E − 10	6.364E + 01	7.600E − 10	6.198E + 01	8.000E − 10	6.045E + 01	8.400E − 10	5.903E + 01
8.800E − 10	5.770E + 01	9.200E − 10	5.646E + 01	9.600E − 10	5.529E + 01	1.000E − 09	5.407E + 01	1.050E − 09	5.279E + 01	1.100E − 09	5.161E + 01
1.150E − 09	5.050E + 01	1.200E − 09	4.921E + 01	1.275E − 09	4.778E + 01	1.350E − 09	4.647E + 01	1.425E − 09	4.526E + 01	1.500E − 09	4.397E + 01
1.600E − 09	4.262E + 01	1.700E − 09	4.138E + 01	1.800E − 09	4.025E + 01	1.900E − 09	3.920E + 01	2.000E − 09	3.823E + 01	2.100E − 09	3.733E + 01
2.200E − 09	3.649E + 01	2.300E − 09	3.571E + 01	2.400E − 09	3.480E + 01	2.550E − 09	3.379E + 01	2.700E − 09	3.301E + 01	2.800E − 09	3.215E + 01
3.000E − 09	3.109E + 01	3.200E − 09	3.014E + 01	3.400E − 09	2.926E + 01	3.600E − 09	2.846E + 01	3.800E − 09	2.772E + 01	4.000E − 09	2.695E + 01
4.250E − 09	2.617E + 01	4.500E − 09	2.545E + 01	4.750E − 09	2.479E + 01	5.000E − 09	2.418E + 01	5.250E − 09	2.361E + 01	5.500E − 09	2.308E + 01
5.750E − 09	2.258E + 01	6.000E − 09	2.207E + 01	6.300E − 09	2.155E + 01	6.600E − 09	2.107E + 01	6.900E − 09	2.061E + 01	7.200E − 09	2.012E + 01
7.600E − 09	1.960E + 01	8.000E − 09	1.912E + 01	8.400E − 09	1.866E + 01	8.800E − 09	1.825E + 01	9.200E − 09	1.785E + 01	9.600E − 09	1.748E + 01
1.000E − 08	1.710E + 01	1.050E − 08	1.669E + 01	1.100E − 08	1.632E + 01	1.150E − 08	1.597E + 01	1.200E − 08	1.556E + 01	1.275E − 08	1.511E + 01
1.350E − 08	1.470E + 01	1.425E − 08	1.431E + 01	1.500E − 08	1.391E + 01	1.600E − 08	1.348E + 01	1.700E − 08	1.309E + 01	1.800E − 08	1.273E + 01
1.900E − 08	1.240E + 01	2.000E − 08	1.209E + 01	2.100E − 08	1.180E + 01	2.200E − 08	1.154E + 01	2.300E − 08	1.129E + 01	2.400E − 08	1.100E + 01
2.550E − 08	1.068E + 01	2.700E − 08	1.044E + 01	2.800E − 08	1.017E + 01	3.000E − 08	9.833E + 00	3.200E − 08	9.530E + 00	3.400E − 08	9.253E + 00
3.600E − 08	8.999E + 00	3.800E − 08	8.765E + 00	4.000E − 08	8.524E + 00	4.250E − 08	8.276E + 00	4.500E − 08	8.049E + 00	4.750E − 08	7.840E + 00
5.000E − 08	7.646E + 00	5.250E − 08	7.466E + 00	5.500E − 08	7.298E + 00	5.750E − 08	7.141E + 00	6.000E − 08	6.980E + 00	6.300E − 08	6.816E + 00
6.600E − 08	6.662E + 00	6.900E − 08	6.519E + 00	7.200E − 08	6.364E + 00	7.600E − 08	6.198E + 00	8.000E − 08	6.045E + 00	8.400E − 08	5.903E + 00
8.800E − 08	5.770E + 00	9.200E − 08	5.646E + 00	9.600E − 08	5.529E + 00	1.000E − 07	5.407E + 00	1.050E − 07	5.279E + 00	1.100E − 07	5.161E + 00
1.150E − 07	5.050E + 00	1.200E − 07	4.921E + 00	1.275E − 07	4.778E + 00	1.350E − 07	4.647E + 00	1.425E − 07	4.526E + 00	1.500E − 07	4.397E + 00
1.600E − 07	4.262E + 00	1.700E − 07	4.138E + 00	1.800E − 07	4.025E + 00	1.900E − 07	3.920E + 00	2.000E − 07	3.823E + 00	2.100E − 07	3.733E + 00
2.200E − 07	3.649E + 00	2.300E − 07	3.571E + 00	2.400E − 07	3.480E + 00	2.550E − 07	3.379E + 00	2.700E − 07	3.301E + 00	2.800E − 07	3.215E + 00
3.000E − 07	3.109E + 00	3.200E − 07	3.014E + 00	3.400E − 07	2.926E + 00	3.600E − 07	2.846E + 00	3.800E − 07	2.772E + 00	4.000E − 07	2.695E + 00
4.250E − 07	2.617E + 00	4.500E − 07	2.545E + 00	4.750E − 07	2.479E + 00	5.000E − 07	2.418E + 00	5.250E − 07	2.361E + 00	5.500E − 07	2.308E + 00
5.750E − 07	2.258E + 00	6.000E − 07	2.207E + 00	6.300E − 07	2.155E + 00	6.600E − 07	2.107E + 00	6.900E − 07	2.061E + 00	7.200E − 07	2.012E + 00
7.600E − 07	1.960E + 00	8.000E − 07	1.912E + 00	8.400E − 07	1.866E + 00	8.800E − 07	1.825E + 00	9.200E − 07	1.785E + 00	9.600E − 07	1.748E + 00
1.000E − 06	1.710E + 00	1.050E − 06	1.669E + 00	1.100E − 06	1.632E + 00	1.150E − 06	1.597E + 00	1.200E − 06	1.556E + 00	1.275E − 06	1.511E + 00
1.350E − 06	1.470E + 00	1.425E − 06	1.431E + 00	1.500E − 06	1.391E + 00	1.600E − 06	1.348E + 00	1.700E − 06	1.309E + 00	1.800E − 06	1.273E + 00
1.900E − 06	1.240E + 00	2.000E − 06	1.209E + 00	2.100E − 06	1.180E + 00	2.200E − 06	1.154E + 00	2.300E − 06	1.129E + 00	2.400E − 06	1.100E + 00
2.550E − 06	1.068E + 00	2.700E − 06	1.044E + 00	2.800E − 06	1.017E + 00	3.000E − 06	9.833E − 01	3.200E − 06	9.530E − 01	3.400E − 06	9.253E − 01
3.600E − 06	8.999E − 01	3.800E − 06	8.765E − 01	4.000E − 06	8.524E − 01	4.250E − 06	8.276E − 01	4.500E − 06	8.049E − 01	4.750E − 06	7.840E − 01
5.000E − 06	7.646E − 01	5.250E − 06	7.466E − 01	5.500E − 06	7.298E − 01	5.750E − 06	7.141E − 01	6.000E − 06	6.980E − 01	6.300E − 06	6.816E − 01
6.600E − 06	6.662E − 01	6.900E − 06	6.519E − 01	7.200E − 06	6.364E − 01	7.600E − 06	6.198E − 01	8.000E − 06	6.045E − 01	8.400E − 06	5.903E − 01
8.800E − 06	5.770E − 01	9.200E − 06	5.646E − 01	9.600E − 06	5.529E − 01	1.000E − 05	5.407E − 01	1.050E − 05	5.279E − 01	1.100E − 05	5.161E − 01
1.150E − 05	5.050E − 01	1.200E − 05	4.921E − 01	1.275E − 05	4.778E − 01	1.350E − 05	4.647E − 01	1.425E − 05	4.526E − 01	1.500E − 05	4.397E − 01
1.600E − 05	4.262E − 01	1.700E − 05	4.138E − 01	1.800E − 05	4.025E − 01	1.900E − 05	3.920E − 01	2.000E − 05	3.823E − 01	2.100E − 05	3.733E − 01
2.200E − 05	3.649E − 01	2.300E − 05	3.571E − 01	2.400E − 05	3.480E − 01	2.550E − 05	3.379E − 01	2.700E − 05	3.301E − 01	2.800E − 05	3.215E − 01
3.000E − 05	3.109E − 01	3.200E − 05	3.014E − 01	3.400E − 05	2.926E − 01	3.600E − 05	2.846E − 01	3.800E − 05	2.772E − 01	4.000E − 05	2.695E − 01
4.250E − 05	2.617E − 01	4.500E − 05	2.545E − 01	4.750E − 05	2.479E − 01	5.000E − 05	2.418E − 01	5.250E − 05	2.361E − 01	5.500E − 05	2.308E − 01
5.750E − 05	2.258E − 01	6.000E − 05	2.207E − 01	6.300E − 05	2.155E − 01	6.600E − 05	2.107E − 01	6.900E − 05	2.061E − 01	7.200E − 05	2.012E − 01
7.600E − 05	1.960E − 01	8.000E − 05	1.912E − 01	8.400E − 05	1.866E − 01	8.800E − 05	1.825E − 01	9.200E − 05	1.785E − 01	9.600E − 05	1.748E − 01
1.000E − 04	1.710E − 01	1.050E − 04	1.669E − 01	1.100E − 04	1.632E − 01	1.150E − 04	1.597E − 01	1.200E − 04	1.556E − 01	1.275E − 04	1.511E − 01
1.350E − 04	1.470E − 01	1.425E − 04	1.431E − 01	1.500E − 04	1.391E − 01	1.600E − 04	1.348E − 01	1.700E − 04	1.309E − 01	1.800E − 04	1.273E − 01
1.900E − 04	1.240E − 01	2.000E − 04	1.209E − 01	2.100E − 04	1.180E − 01	2.200E − 04	1.154E − 01	2.300E − 04	1.129E − 01	2.400E − 04	1.100E − 01
2.550E − 04	1.068E − 01	2.700E − 04	1.044E − 01	2.800E − 04	1.017E − 01	3.000E − 04	9.833E − 02	3.200E − 04	9.530E − 02	3.400E − 04	9.253E − 02
3.600E − 04	8.999E − 02	3.800E − 04	8.765E − 02	4.000E − 04	8.524E − 02	4.250E − 04	8.276E − 02	4.500E − 04	8.049E − 02	4.750E − 04	7.840E − 02
5.000E − 04	7.608E − 02	5.250E − 04	7.354E − 02	5.500E − 04	9.936E − 02	5.750E − 04	1.535E − 01	6.000E − 04	2.144E − 01	6.300E − 04	2.818E − 01
6.600E − 04	3.473E − 01	6.900E − 04	4.149E − 01	7.200E − 04	5.030E − 01	7.600E − 04	5.989E − 01	8.000E − 04	6.942E − 01	8.400E − 04	7.884E − 01
8.800E − 04	8.768E − 01	9.200E − 04	9.694E − 01	9.600E − 04	1.050E + 00	1.000E − 03	1.168E + 00	1.050E − 03	1.334E + 00	1.100E − 03	1.299E + 01
1.150E − 03	1.238E + 01	1.200E − 03	1.686E + 00	1.275E − 03	1.821E + 00	1.350E − 03	1.967E + 00	1.425E − 03	2.110E + 00	1.500E − 03	2.274E + 00
1.600E − 03	2.585E + 00	1.700E − 03	2.626E + 00	1.800E − 03	2.792E + 00	1.900E − 03	2.952E + 00	2.000E − 03	3.107E + 00	2.100E − 03	3.258E + 00
2.200E − 03	3.405E + 00	2.300E − 03	3.575E + 00	2.400E − 03	3.715E + 00	2.550E − 03	3.910E + 00	2.700E − 03	4.068E + 00	2.800E − 03	4.248E + 00
3.000E − 03	4.487E + 00	3.200E − 03	4.734E + 00	3.400E − 03	4.986E + 00	3.600E − 03	5.414E + 00	3.800E − 03	7.472E + 00	4.000E − 03	6.842E + 00
4.250E − 03	6.121E + 00	4.500E − 03	6.251E + 00	4.750E − 03	6.502E + 00	5.000E − 03	6.849E + 00	5.250E − 03	7.359E + 00	5.500E − 03	8.188E + 00
5.750E − 03	1.039E + 01	6.000E − 03	1.731E + 01	6.300E − 03	1.548E + 01	6.600E − 03	1.438E + 01	6.900E − 03	1.826E + 01	7.200E − 03	2.993E + 01
7.600E − 03	4.576E + 01	8.000E − 03	3.840E + 01	8.400E − 03	2.580E + 01	8.800E − 03	1.924E + 01	9.200E − 03	1.614E + 01	9.600E − 03	1.422E + 01
1.000E − 02	1.308E + 01	1.050E − 02	1.230E + 01	1.100E − 02	1.191E + 01	1.150E − 02	1.145E + 01	1.200E − 02	1.114E + 01	1.275E − 02	1.086E + 01
1.350E − 02	1.061E + 01	1.425E − 02	1.038E + 01	1.500E − 02	9.947E + 00	1.600E − 02	9.448E + 00	1.700E − 02	8.834E + 00	1.800E − 02	8.124E + 00
1.900E − 02	7.339E + 00	2.000E − 02	6.538E + 00	2.100E − 02	5.863E + 00	2.200E − 02	5.008E + 00	2.300E − 02	3.605E + 00	2.400E − 02	3.919E + 00
2.550E − 02	6.076E + 01	2.700E − 02	4.356E + 02	2.800E − 02	4.289E + 02	3.000E − 02	1.579E + 02	3.200E − 02	1.011E + 02	3.400E − 02	8.107E + 01
3.600E − 02	7.140E + 01	3.800E − 02	6.620E + 01	4.000E − 02	6.275E + 01	4.250E − 02	6.052E + 01	4.500E − 02	5.931E + 01	4.750E − 02	5.932E + 01
5.000E − 02	8.029E + 01	5.250E − 02	8.424E + 01	5.500E − 02	7.094E + 01	5.750E − 02	6.825E + 01	6.000E − 02	6.025E + 01	6.300E − 02	5.230E + 01
6.600E − 02	4.575E + 01	6.900E − 02	4.135E + 01	7.200E − 02	1.999E + 02	7.600E − 02	7.815E + 01	8.000E − 02	1.617E + 02	8.400E − 02	2.784E + 02
8.800E − 02	1.407E + 02	9.200E − 02	1.141E + 02	9.600E − 02	1.146E + 02	1.000E − 01	1.052E + 02	1.050E − 01	9.306E + 01	1.100E − 01	9.024E + 01
1.150E − 01	7.400E + 01	1.200E − 01	7.067E + 01	1.275E − 01	1.295E + 02	1.350E − 01	2.200E + 02	1.425E − 01	2.531E + 02	1.500E − 01	1.306E + 02

TABLE 1 *Continued*

Energy,[A] MeV	Sigma,[A] barns	Energy, MeV	Sigma, barns	Energy, MeV	Sigma, barns	Energy, MeV	Sigma, barns	Energy, MeV	Sigma, barns	Energy, MeV	Sigma, barns
1.600E − 01	1.148E + 02	1.700E − 01	1.475E + 02	1.800E − 01	2.230E + 02	1.900E − 01	3.249E + 02	2.000E − 01	2.014E + 02	2.100E − 01	1.124E + 02
2.200E − 01	2.675E + 02	2.300E − 01	1.540E + 02	2.400E − 01	1.783E + 02	2.550E − 01	1.339E + 02	2.700E − 01	2.411E + 02	2.800E − 01	1.921E + 02
3.000E − 01	1.422E + 02	3.200E − 01	2.977E + 02	3.400E − 01	1.503E + 02	3.600E − 01	2.917E + 02	3.800E − 01	5.052E + 02	4.000E − 01	5.088E + 02
4.250E − 01	3.876E + 02	4.500E − 01	3.023E + 02	4.750E − 01	3.189E + 02	5.000E − 01	3.643E + 02	5.250E − 01	2.972E + 02	5.500E − 01	2.686E + 02
5.750E − 01	2.789E + 02	6.000E − 01	1.931E + 02	6.300E − 01	2.257E + 02	6.600E − 01	4.492E + 02	6.900E − 01	3.499E + 02	7.200E − 01	6.007E + 02
7.600E − 01	6.220E + 02	8.000E − 01	4.099E + 02	8.400E − 01	4.068E + 02	8.800E − 01	3.191E + 02	9.200E − 01	2.486E + 02	9.600E − 01	4.607E + 02
1.000E + 00	5.042E + 02	1.100E + 00	4.377E + 02	1.200E + 00	6.974E + 02	1.300E + 00	6.512E + 02	1.400E + 00	7.855E + 02	1.500E + 00	9.153E + 02
1.600E + 00	8.127E + 02	1.700E + 00	7.757E + 02	1.800E + 00	8.195E + 02	1.900E + 00	9.886E + 02	2.000E + 00	1.068E + 03	2.100E + 00	1.028E + 03
2.200E + 00	1.006E + 03	2.300E + 00	1.096E + 03	2.400E + 00	1.214E + 03	2.500E + 00	1.373E + 03	2.600E + 00	1.198E + 03	2.700E + 00	1.259E + 03
2.800E + 00	1.275E + 03	2.900E + 00	1.265E + 03	3.000E + 00	1.365E + 03	3.100E + 00	1.389E + 03	3.200E + 00	1.352E + 03	3.300E + 00	1.342E + 03
3.400E + 00	1.395E + 03	3.500E + 00	1.330E + 03	3.600E + 00	1.434E + 03	3.700E + 00	1.457E + 03	3.800E + 00	1.508E + 03	3.900E + 00	1.490E + 03
4.000E + 00	1.556E + 03	4.100E + 00	1.595E + 03	4.200E + 00	1.562E + 03	4.300E + 00	1.615E + 03	4.400E + 00	1.555E + 03	4.500E + 00	1.663E + 03
4.600E + 00	1.643E + 03	4.700E + 00	1.676E + 03	4.800E + 00	1.719E + 03	4.900E + 00	1.705E + 03	5.000E + 00	1.718E + 03	5.100E + 00	1.747E + 03
5.200E + 00	1.752E + 03	5.300E + 00	1.785E + 03	5.400E + 00	1.793E + 03	5.500E + 00	1.792E + 03	5.600E + 00	1.826E + 03	5.700E + 00	1.825E + 03
5.800E + 00	1.830E + 03	5.900E + 00	1.851E + 03	6.000E + 00	1.872E + 03	6.100E + 00	1.862E + 03	6.200E + 00	1.873E + 03	6.300E + 00	1.928E + 03
6.400E + 00	1.927E + 03	6.500E + 00	1.948E + 03	6.600E + 00	1.958E + 03	6.700E + 00	1.964E + 03	6.800E + 00	1.982E + 03	6.900E + 00	1.980E + 03
7.000E + 00	1.987E + 03	7.100E + 00	2.010E + 03	7.200E + 00	2.010E + 03	7.300E + 00	2.040E + 03	7.400E + 00	2.038E + 03	7.500E + 00	2.062E + 03
7.600E + 00	2.052E + 03	7.700E + 00	2.068E + 03	7.800E + 00	2.085E + 03	7.900E + 00	2.089E + 03	8.000E + 00	2.092E + 03	8.100E + 00	2.095E + 03
8.200E + 00	2.117E + 03	8.300E + 00	2.150E + 03	8.400E + 00	2.150E + 03	8.500E + 00	2.146E + 03	8.600E + 00	2.143E + 03	8.700E + 00	2.163E + 03
8.800E + 00	2.181E + 03	8.900E + 00	2.194E + 03	9.000E + 00	2.207E + 03	9.100E + 00	2.220E + 03	9.200E + 00	2.232E + 03	9.300E + 00	2.245E + 03
9.400E + 00	2.258E + 03	9.500E + 00	2.269E + 03	9.600E + 00	2.279E + 03	9.700E + 00	2.289E + 03	9.800E + 00	2.299E + 03	9.900E + 00	2.308E + 03
1.000E + 01	2.320E + 03	1.010E + 01	2.332E + 03	1.020E + 01	2.344E + 03	1.030E + 01	2.356E + 03	1.040E + 01	2.369E + 03	1.050E + 01	2.381E + 03
1.060E + 01	2.394E + 03	1.070E + 01	2.407E + 03	1.080E + 01	2.419E + 03	1.090E + 01	2.432E + 03	1.100E + 01	2.444E + 03	1.110E + 01	2.455E + 03
1.120E + 01	2.466E + 03	1.130E + 01	2.479E + 03	1.140E + 01	2.490E + 03	1.150E + 01	2.503E + 03	1.160E + 01	2.514E + 03	1.170E + 01	2.524E + 03
1.180E + 01	2.532E + 03	1.190E + 01	2.540E + 03	1.200E + 01	2.546E + 03	1.210E + 01	2.551E + 03	1.220E + 01	2.556E + 03	1.230E + 01	2.567E + 03
1.240E + 01	2.582E + 03	1.250E + 01	2.592E + 03	1.260E + 01	2.601E + 03	1.270E + 01	2.615E + 03	1.280E + 01	2.629E + 03	1.290E + 01	2.642E + 03
1.300E + 01	2.655E + 03	1.310E + 01	2.668E + 03	1.320E + 01	2.683E + 03	1.330E + 01	2.697E + 03	1.340E + 01	2.713E + 03	1.350E + 01	2.730E + 03
1.360E + 01	2.747E + 03	1.370E + 01	2.767E + 03	1.380E + 01	2.786E + 03	1.390E + 01	2.806E + 03	1.400E + 01	2.824E + 03	1.410E + 01	2.840E + 03
1.420E + 01	2.857E + 03	1.430E + 01	2.874E + 03	1.440E + 01	2.890E + 03	1.450E + 01	2.905E + 03	1.460E + 01	2.917E + 03	1.470E + 01	2.929E + 03
1.480E + 01	2.941E + 03	1.490E + 01	2.954E + 03	1.500E + 01	2.958E + 03	1.510E + 01	2.955E + 03	1.520E + 01	2.952E + 03	1.530E + 01	2.948E + 03
1.540E + 01	2.942E + 03	1.550E + 01	2.938E + 03	1.560E + 01	2.936E + 03	1.570E + 01	2.932E + 03	1.580E + 01	2.928E + 03	1.590E + 01	2.924E + 03
1.600E + 01	2.924E + 03	1.610E + 01	2.928E + 03	1.620E + 01	2.932E + 03	1.630E + 01	2.936E + 03	1.640E + 01	2.940E + 03	1.650E + 01	2.944E + 03
1.660E + 01	2.948E + 03	1.670E + 01	2.951E + 03	1.680E + 01	2.955E + 03	1.690E + 01	2.958E + 03	1.700E + 01	2.966E + 03	1.710E + 01	2.978E + 03
1.720E + 01	2.990E + 03	1.730E + 01	3.003E + 03	1.740E + 01	3.014E + 03	1.750E + 01	3.026E + 03	1.760E + 01	3.037E + 03	1.770E + 01	3.049E + 03
1.780E + 01	3.061E + 03	1.790E + 01	3.073E + 03	1.800E + 01	3.087E + 03	1.810E + 01	3.102E + 03	1.820E + 01	3.118E + 03	1.830E + 01	3.133E + 03
1.840E + 01	3.149E + 03	1.850E + 01	3.164E + 03	1.860E + 01	3.180E + 03	1.870E + 01	3.195E + 03	1.880E + 01	3.211E + 03	1.890E + 01	3.226E + 03
1.900E + 01	3.239E + 03	1.910E + 01	3.249E + 03	1.920E + 01	3.259E + 03	1.930E + 01	3.269E + 03	1.940E + 01	3.279E + 03	1.950E + 01	3.289E + 03
1.960E + 01	3.300E + 03	1.970E + 01	3.310E + 03	1.980E + 01	3.320E + 03	1.990E + 01	3.331E + 03	2.000E + 01	0.00 E + 00		

[A] Energies given are the lower bounds of each group. Cross sections are given in units of 10^{-24}cm^2.

REFERENCES

(**1**) Doran, D. G., and Graves, N. J., "Neutron Displacement Damage Cross Sections for Structural Metals," *Irradiation Effects on the Microstructure and Properties of Metals, ASTM STP 611*, Am. Soc. Testing Mats., 1976, pp. 463–482.

(**2**) McElroy, W. N., Berg, S., and Crockett, T., "A Computer Automated Iterative Method for Neutron Flux Spectra Determined by Foil Activation," AFWL-TR-67-4, Vols 1–4, Air Force Weapons Laboratory, 1967.

(**3**) Evaluated Nuclear Data File/B, National Neutron Cross Section Center, Brookhaven National Laboratory, Upton, NY.

(**4**) Robinson, M. T., "The Energy Dependence of Neutron Radiation Damage in Solids," in *Nuclear Fusion Reactor*, Proceedings of International Conference (British Nuclear Energy Society, London), 1970, pp. 364–377.

(**5**) Lindhard, J., Scharff, M., and Schi;asott, H. E., "Range Concepts and Heavy Ion Ranges," *Matematisk-fysiske Meddelelser-Kongelige Danske Videnskaberns Selskab*, KDVSA, Vol 33, No. 14, 1963.

(**6**) "Recommendations for Displacement Calculations for Reactor/Accelerator Studies in Austenitic Steel," *Nuclear Engineering and Design*, Vol 33, 1975, p. 91.

(**7**) Doran, D. G., Parkin, D. M., and Robinson, M. T., "Damage Energy and Displacement Cross Sections: Survey and Sensitivity," CONF-761146-1, November 1976. Available from National Technical Information Service, U. S. Department of Commerce, Springfield, VA 22161.

(**8**) Doran, D. G., Odette, G. R., Mansur, L. K., and Simons, R. L., "Damage Correlation in Theory and Practice," *Radiation Effects in Breeder Reactor Structural Materials*, M. L. Bleibert and J. W. Bennett, eds., AIME, New York, NY, 1977, p. 591.

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