Designation: E 693 – 01

Standard Practice for Characterizing Neutron Exposures in Iron and Low Alloy Steels in Terms of Displacements Per Atom (DPA), E 706(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 neutron fluence and 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, E 706 (IC)[2]

E 821 Practice for Measurement of Mechanical Properties During Charged-Particle Irradiation[2]

E 853 Practice for Analysis and Interpretation of Light-Water Reactor Surveillance Results, E 706 (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 way of expresssing this quantity. The number of dpa associated with a particular irradiation depends on the amount of energy deposited in the material by the neutrons, and 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. A considerable body of irradiated materials data has been reported using dpa cross sections based on the iron

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[1] This practice is under the jurisdiction of ASTM Committee E10 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.

ENDF/B-IV **(1, 2)**[3] cross section. The recent changes in the iron cross section **(3)**, the recommendation to use the updated iron cross sections in radiation transport calculations of pressure vessel spectra **(4)**, and the recent availability of ENDF/B-VI iron dpa cross section calculations **(1, 2, 5)** have resulted in the update of the recommended dpa cross section to reflect the ENDF/B-VI cross sections **(1)**. Although the ENDF/B-VI based dpa cross section differs from the previously recommended ENDF/B-IV dpa cross section **(1)** by about 60 % in the energy region around 10 keV, by about 10 % for energies between 100 keV and 2 MeV, and by a factor of 4 near 1 keV due to the opening of reaction channels in the cross section, the integral iron dpa values are much less sensitive to the change in cross sections. The update from ENDF/B-IV to ENDF/B-VI dpa rates when applied to the H. B. Robinson-2 pressurized water reactor results in "up to ~4 % higher dpa rates in the region close to the pressure vessel outer surface" and in "slightly lower dpa rates ... close to the pressure vessel inner wall" **(6, 7)**. Thus the update of the recommended dpa exposure parameter to reflect an iron cross section consistent with that used in the current radiation transport calculations is "not expected to introduce a bias in embrittlement data bases" **(6)** based on the change in the dpa cross section. Table 1 presents a comparison of the previous edition (Practice E 693-94) and currently recommended dpa estimates for several neutron spectra.

5. Procedure

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

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

where:

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

$\phi(E,t)\,\mathrm{d}E$ = 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:

$$\text{dpa} = \int_0^{t_r} \phi_{\text{tot}}(t) \int_0^\infty \sigma_d(E)\psi(E,t)\,\mathrm{d}E\,\mathrm{d}t \quad (2)$$

where:

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

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

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

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

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

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

6. Calculation

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

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

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 **(16)** in the SAND-II group structure (included here as Table 2), 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.

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

TABLE 1 Changes in Spectrum-Integrated dpa for Benchmark Neutron Spectra

Neutron Spectrum	Spectrum-averaged dpa cross section (barns)[A]		
	"Old" ENDF/B-IV-based E 693 response	"Current" ENDF/B-VI-based E 693 response	Difference ([Current - Old]/ Old) (%)
ENDF/B-VI ^{235}U Thermal Fission **(1, 2)**	875.55	858.54	–1.9
Materials Dosimetry Reference Facility (MDRF) **(8)**	345.03	343.58	–0.42
CFRMF **(9, 10)**	382.94	387.08	1.08
Intermediate-energy Standard Neutron Field (ISNF) **(10, 11)**	483.63	480.00	–0.75
Arkansas Nuclear ONE-1 (ANO) Cavity **(12, 13)**	134.40	139.44	3.75
ORNL Poolside Facility (PSF) T/4 position **(12, 14)**	242.14	238.33	–1.57
Oak Ridge Research Reactor (ORR) **(10)**	291.68	288.86	–0.97
Yayoi **(10)**	613.12	609.03	–0.67
BIGTEN **(10, 15)**	334.98	341.25	1.87
H.B. Robinson-2, in the vessel wall, close to the inner surface **(6, 7)**	219.43	218.81	–0.28
H.B. Robinson-2, ~¼ T vessel wall **(6, 7)**	245.17	249.24	1.66
H.B. Robinson-2, ~¾ T vessel wall **(6, 7)**	203.68	211.23	3.71

[A] The spectrum-average dpa values in this table were computed using Eq 11 in a 640 SAND-II energy group representation and a lower integration bound of $E_o = 10^{-10}$ MeV.

NOTE 1—Table 1 is included to illustrate the effect on the dpa cross sections resulting from the change from the ENDF/B-IV to ENDF/B-VI cross sections. The spectrum-average cross section values given are not recommended for other uses because of their sensitivity to the assumed spectrum representations and the lower energy integration limit.

6.2.1 If the $\phi(E)$ group structure is sufficiently fine, 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 2), 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:

$$W(E) = C_1/E \qquad E < 0.82 \text{ MeV} \tag{7}$$

$$= C_2 E^{1/2} e^{-E/1.4} \qquad E \geq 0.82 \text{ MeV}$$

The constants C_1 and C_2 are arbitrary.

The group averages are then computed from the following equation:

$$(\sigma_d)_i = \frac{\sum_{k=1}^{M_i} (\sigma_d)_{ik} W(\hat{E}_{ik}) \Delta E_{ik}}{\sum_{k=1}^{M_i} W(\hat{E}_{ik}) \Delta E_{ik}} \tag{8}$$

where $\hat{E}_{ik}$ = the average energy of the k^{th} group, or

$$\hat{E}_{ik} \equiv (E_{ik+1} + E_{ik})/2 \tag{9}$$

NOTE 1—This standard does not address the adequacy of the neutron group structure used for the representation and calculation of the energy dependent variations in the neutron spectrum. At positions within thick pressure vessels, Eq 8 may not provide correct results unless the energy groups, indexed by the letter i, are chosen to be adequate for representing the neutron spectrum variations.

6.2.3 It may be that the group structure of $\phi(E)$ 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 2. The energy values chosen for the table entries are those of the SAND-II energy group structure **(17)**. 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. This damage energy to displacement conversion procedure is consistent with Practices E 521 and E 821 recommendations on the treatment of radiation damage by charged particles. The values of the displacement cross section are based on ENDF/B-VI (revision 5) cross sections **(1, 2)** as processed into dpa cross sections with the NJOY-97 code **(18)** using the Robinson analytic representation **(19)** of the Lindhard model of energy partition between atoms and electrons **(20)** and the Norgett-Robinson-Torrens (NRT) recommended conversion of damage energy to displacements **(21)** with an effective displacement threshold energy of E_d=40 eV and an atomic scattering correction factor of β=0.8. The NRT displacement equation defines the number of displacements, N_d, corresponding to a given damage energy, T_d, through the equation

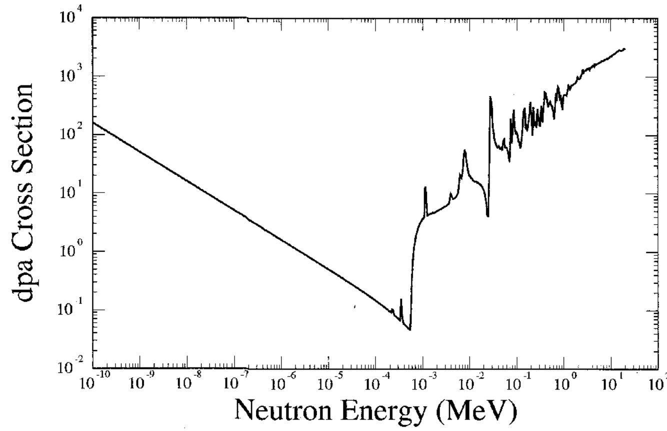

FIG. 1 ENDF/B-VI-based Iron Displacement Cross Section

$$N_d(T_d) = \begin{bmatrix} 0 & T_d < E_d \\ 1 & E_d \leq T_d < 2E_d/\beta \\ \frac{\beta T_d}{2E_d} & 2E_d/\beta \leq T_d < \infty \end{bmatrix} \tag{10}$$

NOTE 2—The iron dpa cross section combines dpa from the individual ENDF/B-VI iron isotopic evaluations using the natural iron isotopic abundance values from Ref. **(22)**. The isotopic cross sections and relative abundances used were:

26-Fe-54, Mat = 2625, Rev. 5, tape 140; rel. abundance = 5.9 %
26-Fe-56, Mat = 2631, Rev. 1, tape 123; rel. abundance = 91.72 %
26-Fe-57, Mat = 2634, Rev. 1, tape 123; rel. abundance = 2.1 %
26-Fe-58, Mat = 2637, Rev. 5, tape 140; rel. abundance = 0.28 %

NOTE 3—Version 97.45 of the NJOY97 code used in this analysis was modified to implement the NRT displacement threshold model.

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 $\bar{\sigma}_d$ 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:

$$\bar{\sigma}_d(E > E_0) = \frac{\int_{E_o}^{\infty} \sigma_d(E)\phi(E)dE}{\int_{E_o}^{\infty} \phi(E)\, dE} \tag{11}$$

and

$$\text{dpa/s} \cong \bar{\sigma}_d(E > E_o) \times \phi(E > E_o) \tag{12}$$

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*—The energy group structure selected to perform the integral in 6.1 should be selected such that the integral of the dpa exposure parameter over the neutron spectrum is within 1 % of that obtained when the complete 640-group SAND-II energy structure is used to represent the energy dependence of the dpa exposure parameter and the energy-dependent structure of the neutron spectrum. The precision in the spectrum-averaged dpa is dominated by the precision in the neutron spectrum characterization, including its representation of the fine energy structure.

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. The covariance matrix for the iron dpa cross section is not available at present, although covariance matrices for the individual File 3 nuclear reaction cross sections which contribute to the dpa can be found in File 33 of the ENDF/B-VI cross section evaluations **(1)**. For a discussion of the effect of the energy dependence of $\sigma_d(E)$ on the relative accuracy of the dpa calculation see Ref **23** 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 **(23)**. The relative accuracy of the fluence-spectrum determination depends on the method of determination. (For recommended methods see E 706, Matrix Standard.) Any uncertainty in the total fluence is, of course, reflected directly in the dpa calculation (see 5.2.1).

NOTE 4—Measurement uncertainty is described by a precision-and-bias statement in this standard. Another acceptable approach is to use Type A and B uncertainty components **(24, 25)**. This Type A/B uncertainty specification is now used in International Organization for Standardization (ISO) standards and this approach can be expected to play a more prominent role in future uncertainty analyses.

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 the damage correlation methodology are in progress, and recent results **(26)** indicate that dpa can, in some cases, produce improved damage correlation when compared to fast neutron fluence. 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 **27**.)

9. Keywords

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

TABLE 2 ENDF/B-VI-based Iron Displacement Cross Section

Bin	Eng[A] (MeV)	σ_d(barns)	Bin	Eng[A] (MeV)	σ_d(barns)	Bin	Eng[A] (MeV)	σ_d(barns)
1	0.100E-09	158.3543	2	0.1050E-09	154.6209	3	0.110E-09	151.1395
4	0.1150E-09	147.8895	5	0.120E-09	144.1054	6	0.1275E-09	139.9202
7	0.1350E-09	136.0860	8	0.1425E-09	132.5445	9	0.150E-09	128.7502
10	0.160E-09	124.7860	11	0.170E-09	121.1728	12	0.180E-09	117.8527
13	0.190E-09	114.8137	14	0.200E-09	111.9561	15	0.210E-09	109.3199
16	0.220E-09	106.8646	17	0.230E-09	104.5694	18	0.240E-09	101.8930
19	0.2550E-09	98.93331	20	0.270E-09	96.65981	21	0.280E-09	94.12717
22	0.300E-09	91.05218	23	0.320E-09	88.24872	24	0.340E-09	85.68787
25	0.360E-09	83.33912	26	0.380E-09	81.17265	27	0.400E-09	78.92472
28	0.4250E-09	76.63646	29	0.450E-09	74.53734	30	0.4750E-09	72.59930
31	0.500E-09	70.81827	32	0.5250E-09	69.14790	33	0.550E-09	67.59222
34	0.5750E-09	66.13822	35	0.600E-09	64.64189	36	0.630E-09	63.12039
37	0.660E-09	61.70157	38	0.690E-09	60.37332	39	0.720E-09	58.92732
40	0.760E-09	57.39681	41	0.800E-09	55.97892	42	0.840E-09	54.65984
43	0.880E-09	53.43220	44	0.920E-09	52.28703	45	0.960E-09	51.21545
46	0.100E-08	50.07727	47	0.1050E-08	48.89598	48	0.110E-08	47.79609
49	0.1150E-08	46.76870	50	0.120E-08	45.57125	51	0.1275E-08	44.25006
52	0.1350E-08	43.03653	53	0.1425E-08	41.91761	54	0.150E-08	40.71708
55	0.160E-08	39.46333	56	0.170E-08	38.32018	57	0.180E-08	37.26968
58	0.190E-08	36.30967	59	0.200E-08	35.40710	60	0.210E-08	34.57391
61	0.220E-08	33.79705	62	0.230E-08	33.06956	63	0.240E-08	32.22424
64	0.2550E-08	31.28942	65	0.270E-08	30.57002	66	0.280E-08	29.76999
67	0.300E-08	28.79791	68	0.320E-08	27.91048	69	0.340E-08	27.10139
70	0.360E-08	26.35879	71	0.380E-08	25.67357	72	0.400E-08	24.96309
73	0.4250E-08	24.23960	74	0.450E-08	23.57548	75	0.4750E-08	22.96268
76	0.500E-08	22.39920	77	0.5250E-08	21.87094	78	0.550E-08	21.37982
79	0.5750E-08	20.91994	80	0.600E-08	20.44705	81	0.630E-08	19.96509
82	0.660E-08	19.51724	83	0.690E-08	19.09670	84	0.720E-08	18.63984
85	0.760E-08	18.15581	86	0.800E-08	17.70708	87	0.840E-08	17.29049

TABLE 2 *Continued*

Bin	Eng[A] (MeV)	σ_d(barns)	Bin	Eng[A] (MeV)	σ_d(barns)	Bin	Eng[A] (MeV)	σ_d(barns)
88	0.880E-08	16.90205	89	0.920E-08	16.54074	90	0.960E-08	16.20166
91	0.100E-07	15.84242	92	0.1050E-07	15.46908	93	0.110E-07	15.12094
94	0.1150E-07	14.79594	95	0.120E-07	14.41855	96	0.1275E-07	14.00095
97	0.13050E-07	13.61661	98	0.1425E-07	13.26338	99	0.150E-07	12.88403
100	0.160E-07	12.48759	101	0.170E-07	12.12633	102	0.180E-07	11.79428
103	0.190E-07	11.49039	104	0.200E-07	11.20760	105	0.210E-07	10.94298
106	0.220E-07	10.69745	107	0.230E-07	10.46804	108	0.240E-07	10.20132
109	0.2550E-07	9.906717	110	0.270E-07	9.679449	111	0.280E-07	9.427035
112	0.300E-07	9.118745	113	0.320E-07	8.838819	114	0.340E-07	8.582926
115	0.360E-07	8.347962	116	0.380E-07	8.131618	117	0.400E-07	7.907534
118	0.4250E-07	7.678809	119	0.450E-07	7.468805	120	0.4750E-07	7.276812
121	0.500E-07	7.097598	122	0.5250E-07	6.930767	123	0.550E-07	6.775607
124	0.5750E-07	6.630701	125	0.600E-07	6.482083	126	0.630E-07	6.330435
127	0.660E-07	6.188963	128	0.690E-07	6.056631	129	0.720E-07	5.913148
130	0.760E-07	5.760298	131	0.800E-07	5.618617	132	0.840E-07	5.486900
133	0.880E-07	5.364337	134	0.920E-07	5.250029	135	0.960E-07	5.143171
136	0.100E-06	5.029254	137	0.1050E-06	4.911427	138	0.110E-06	4.801945
139	0.1150E-06	4.699714	140	0.120E-06	4.581585	141	0.1275E-06	4.450361
142	0.1350E-06	4.329614	143	0.1425E-06	4.218222	144	0.150E-06	4.099185
145	0.160E-06	3.974304	146	0.170E-06	3.860402	147	0.180E-06	3.756055
148	0.190E-06	3.660761	149	0.200E-06	3.571313	150	0.210E-06	3.488699
151	0.220E-06	3.411616	152	0.230E-06	3.339466	153	0.240E-06	3.256051
154	0.2550E-06	3.163276	155	0.270E-06	3.091628	156	0.280E-06	3.013147
157	0.300E-06	2.916945	158	0.320E-06	2.829403	159	0.340E-06	2.749808
160	0.360E-06	2.676750	161	0.380E-06	2.608835	162	0.400E-06	2.527930
163	0.4250E-06	2.440897	164	0.450E-06	2.374384	165	0.4750E-06	2.313606
166	0.500E-06	2.257462	167	0.5250E-06	2.205331	168	0.550E-06	2.154114
169	0.5750E-06	2.108733	170	0.600E-06	2.060134	171	0.630E-06	2.011735
172	0.660E-06	1.966045	173	0.690E-06	1.923586	174	0.720E-06	1.877395
175	0.760E-06	1.828596	176	0.800E-06	1.783008	177	0.840E-06	1.741254
178	0.880E-06	1.703417	179	0.920E-06	1.667792	180	0.960E-06	1.632082
181	0.100E-05	1.595754	182	0.1050E-05	1.558720	183	0.110E-05	1.522295
184	0.1150E-05	1.490200	185	0.120E-05	1.451554	186	0.1275E-05	1.409592
187	0.1350E-05	1.370247	188	0.1425E-05	1.334635	189	0.150E-05	1.296298
190	0.160E-05	1.256143	191	0.170E-05	1.219824	192	0.180E-05	1.187621
193	0.190E-05	1.156028	194	0.200E-05	1.126746	195	0.210E-05	1.099981
196	0.220E-05	1.075226	197	0.230E-05	1.051885	198	0.240E-05	1.026221
199	0.2550E-05	0.9965719	200	0.270E-05	0.9722222	201	0.280E-05	0.9476671
202	0.300E-05	0.9157118	203	0.320E-05	0.8876799	204	0.340E-05	0.8611951
205	0.360E-05	0.8377314	206	0.380E-05	0.8153836	207	0.400E-05	0.7928756
208	0.4250E-05	0.7695923	209	0.450E-05	0.7481711	210	0.4750E-05	0.7286609
211	0.500E-05	0.7107515	212	0.5250E-05	0.6941600	213	0.550E-05	0.6778895
214	0.5750E-05	0.6635014	215	0.600E-05	0.6480775	216	0.630E-05	0.6327240
217	0.660E-05	0.6182052	218	0.690E-05	0.6047435	219	0.720E-05	0.5900444
220	0.760E-05	0.5745604	221	0.800E-05	0.5600318	222	0.840E-05	0.5467011
223	0.880E-05	0.5345984	224	0.920E-05	0.5232391	225	0.960E-05	0.5118709
226	0.100E-04	0.5002917	227	0.1050E-04	0.4884902	228	0.110E-04	0.4769112
229	0.1150E-04	0.4666898	230	0.120E-04	0.4543560	231	0.1275E-04	0.4409762
232	0.1350E-04	0.4284223	233	0.1425E-04	0.4170648	234	0.150E-04	0.4048129
235	0.160E-04	0.3919477	236	0.170E-04	0.3802993	237	0.180E-04	0.3699498
238	0.190E-04	0.3598211	239	0.200E-04	0.3504475	240	0.210E-04	0.3418580
241	0.220E-04	0.3339029	242	0.230E-04	0.3263810	243	0.240E-04	0.3181047
244	0.2550E-04	0.3085413	245	0.270E-04	0.3006880	246	0.280E-04	0.2927655
247	0.300E-04	0.2824593	248	0.320E-04	0.2733916	249	0.340E-04	0.2648267
250	0.360E-04	0.2572175	251	0.380E-04	0.2499703	252	0.400E-04	0.2426542
253	0.4250E-04	0.2350771	254	0.450E-04	0.2280936	255	0.4750E-04	0.2217044
256	0.500E-04	0.2158471	257	0.5250E-04	0.2104036	258	0.550E-04	0.2050605
259	0.5750E-04	0.2003403	260	0.600E-04	0.1952700	261	0.630E-04	0.1902102
262	0.660E-04	0.1854221	263	0.690E-04	0.1809756	264	0.720E-04	0.1761094
265	0.760E-04	0.1709726	266	0.800E-04	0.1661474	267	0.840E-04	0.1616956
268	0.880E-04	0.1576549	269	0.920E-04	0.1538460	270	0.960E-04	0.1500470
271	0.100E-03	0.1461601	272	0.1050E-03	0.1421933	273	0.110E-03	0.1382971
274	0.1150E-03	0.1348528	275	0.120E-03	0.1306799	276	0.1275E-03	0.1261477
277	0.1350E-03	0.1218873	278	0.1425E-03	0.1180186	279	0.150E-03	0.1138330
280	0.160E-03	0.1094287	281	0.170E-03	0.1054279	282	0.180E-03	0.1018602
283	0.190E-03	0.9837523E-01	284	0.200E-03	0.9515446E-01	285	0.210E-03	0.9224781E-01
286	0.220E-03	0.1048459	287	0.230E-03	0.1028288	288	0.240E-03	0.8397242E-01
289	0.2550E-03	0.8057346E-01	290	0.270E-03	0.7782596E-01	291	0.280E-03	0.7506079E-01
292	0.300E-03	0.7147984E-01	293	0.320E-03	0.6842791E-01	294	0.340E-03	0.1581741
295	0.360E-03	0.7452445E-01	296	0.380E-03	0.6020231E-01	297	0.400E-03	0.5752645E-01
298	0.4250E-03	0.5484677E-01	299	0.450E-03	0.5239946E-01	300	0.4750E-03	0.5017326E-01
301	0.500E-03	0.4855164E-01	302	0.5250E-03	0.4750492E-01	303	0.550E-03	0.8634498E-01
304	0.5750E-03	0.3684567	305	0.600E-03	0.7230662	306	0.630E-03	1.085166
307	0.660E-03	1.433057	308	0.690E-03	1.753764	309	0.720E-03	2.100540

TABLE 2 *Continued*

Bin	Eng^A (MeV)	σ_d(barns)	Bin	Eng^A (MeV)	σ_d(barns)	Bin	Eng^A (MeV)	σ_d(barns)
310	0.760E-03	2.428895	311	0.800E-03	2.722788	312	0.840E-03	2.998771
313	0.880E-03	3.258461	314	0.920E-03	3.465372	315	0.960E-03	3.618973
316	0.100E-02	3.787081	317	0.1050E-02	3.964271	318	0.110E-02	13.13789
319	0.1150E-02	10.69382	320	0.120E-02	4.262693	321	0.1275E-02	4.338387
322	0.1350E-02	4.435367	323	0.1425E-02	4.534225	324	0.150E-02	4.592575
325	0.160E-02	4.783180	326	0.170E-02	4.701623	327	0.180E-02	4.841220
328	0.190E-02	4.999009	329	0.200E-02	5.111335	330	0.201E-02	5.183993
331	0.220E-02	5.279069	332	0.230E-02	5.408910	333	0.240E-02	5.523736
334	0.2550E-02	5.695442	335	0.270E-02	5.826853	336	0.280E-02	5.975410
337	0.300E-02	6.173523	338	0.320E-02	6.395415	339	0.340E-02	6.658582
340	0.360E-02	7.183939	341	0.380E-02	10.01168	342	0.400E-02	9.194485
343	0.4250E-02	8.178266	344	0.450E-02	8.229657	345	0.4750E-02	8.508525
346	0.500E-02	8.910876	347	0.5250E-02	9.525395	348	0.550E-02	10.59739
349	0.5750E-02	13.20411	350	0.600E-02	21.17466	351	0.630E-02	19.67340
352	0.660E-02	18.59203	353	0.690E-02	24.36627	354	0.720E-02	39.42936
355	0.760E-02	56.38621	356	0.800E-02	48.66102	357	0.840E-02	35.11790
358	0.880E-02	27.24892	359	0.920E-02	23.52159	360	0.960E-02	20.66808
361	0.100E-01	19.98392	362	0.1050E-01	18.41869	363	0.110E-01	18.51923
364	0.1150E-01	16.80365	365	0.120E-01	16.40945	366	0.1275E-01	16.00651
367	0.1350E-01	16.06792	368	0.1425E-01	15.55876	369	0.150E-01	15.08970
370	0.160E-01	14.61809	371	0.170E-01	13.99511	372	0.180E-01	13.21823
373	0.190E-01	12.01959	374	0.200E-01	10.61530	375	0.210E-01	8.888706
376	0.220E-01	6.857686	377	0.230E-01	4.435299	378	0.240E-01	4.034283
379	0.2550E-01	51.58856	380	0.270E-01	462.4204	381	0.280E-01	374.2036
382	0.300E-01	138.8582	383	0.320E-01	91.99242	384	0.340E-01	75.21491
385	0.360E-01	66.92896	386	0.380E-01	62.40611	387	0.400E-01	65.56062
388	0.4250E-01	59.51893	389	0.450E-01	61.42897	390	0.4750E-01	55.61853
391	0.500E-01	80.54994	392	0.5250E-01	84.93746	393	0.550E-01	61.63473
394	0.5750E-01	61.83547	395	0.600E-01	61.39486	396	0.630E-01	51.44463
397	0.660E-01	41.05520	398	0.690E-01	35.18787	399	0.720E-01	195.2115
400	0.760E-01	72.97270	401	0.800E-01	139.3801	402	0.840E-01	276.0543
403	0.880E-01	138.4568	404	0.920E-01	104.0743	405	0.960E-01	113.7160
406	0.100	105.5489	407	0.1050	78.43095	408	0.110	78.06753
409	0.1150	60.44543	410	0.120	70.47430	411	0.1275	134.1587
412	0.1350	255.3630	413	0.1425	293.0161	414	0.150	133.0900
415	0.160	122.7596	416	0.170	156.0143	417	0.180	244.4100
418	0.190	370.7627	419	0.200	205.3339	420	0.210	101.0349
421	0.220	307.5111	422	0.230	146.9613	423	0.240	171.8077
424	0.2550	135.3387	425	0.270	282.5501	426	0.280	187.6945
427	0.300	142.0391	428	0.320	315.5791	429	0.340	166.5530
430	0.360	302.1184	431	0.380	545.7117	432	0.400	528.4010
433	0.4250	400.4412	434	0.450	309.7825	435	0.4750	351.4453
436	0.500	381.0001	437	0.5250	327.4008	438	0.550	316.9469
439	0.5750	264.2091	440	0.600	190.8042	441	0.630	255.5292
442	0.660	529.8745	443	0.690	389.0167	444	0.720	680.4310
445	0.760	627.3019	446	0.800	427.2328	447	0.840	461.2467
448	0.880	327.1398	449	0.920	278.1719	450	0.960	479.7678
451	1.00	498.4922	452	1.10	477.6893	453	1.20	707.1735
454	1.30	616.4640	455	1.40	716.4101	456	1.50	734.1659
457	1.60	758.8353	458	1.70	784.5580	459	1.80	819.3325
460	1.90	989.3265	461	2.00	928.7681	462	2.10	923.3754
463	2.20	969.4800	464	2.30	1079.716	465	2.40	1143.224
466	2.50	1348.954	467	2.60	1192.105	468	2.70	1263.538
469	2.80	1277.801	470	2.90	1271.578	471	3.00	1364.006
472	3.10	1387.724	473	3.20	1358.466	474	3.30	1346.851
475	3.40	1398.034	476	3.50	1334.743	477	3.60	1424.447
478	3.70	1440.708	479	3.80	1483.880	480	3.90	1464.868
481	4.00	1526.371	482	4.10	1560.443	483	4.20	1530.309
484	4.30	1582.916	485	4.40	1523.340	486	4.50	1626.724
487	4.60	1600.863	488	4.70	1617.455	489	4.80	1653.609
490	4.90	1642.833	491	5.00	1600.075	492	5.10	1682.554
493	5.20	1687.286	494	5.30	1716.469	495	5.40	1731.089
496	5.50	1729.785	497	5.60	1760.852	498	5.70	1760.538
499	5.80	1768.656	500	5.90	1792.105	501	6.00	1811.511
502	6.10	1800.940	503	6.20	1811.547	504	6.30	1859.081
505	6.40	1859.125	506	6.50	1879.237	507	6.60	1890.037
508	6.70	1891.762	509	6.80	1909.485	510	6.90	1909.076
511	7.00	1914.442	512	7.10	1936.414	513	7.20	1941.750
514	7.30	1966.663	515	7.40	1963.306	516	7.50	1986.044
517	7.60	1976.213	518	7.70	1989.243	519	7.80	2003.646
520	7.90	2006.771	521	8.00	2009.093	522	8.10	2013.259
523	8.20	2032.588	524	8.30	2064.755	525	8.40	2063.837
526	8.50	2061.365	527	8.60	2059.507	528	8.70	2072.344
529	8.80	2089.976	530	8.90	2107.525	531	9.00	2122.580

TABLE 2 *Continued*

Bin	Eng[A] (MeV)	σ_d(barns)	Bin	Eng[A] (MeV)	σ_d(barns)	Bin	Eng[A] (MeV)	σ_d(barns)
532	9.10	2135.077	533	9.20	2147.577	534	9.30	2160.074
535	9.40	2172.482	536	9.50	2185.892	537	9.60	2199.950
538	9.70	2213.918	539	9.80	2226.698	540	9.90	2238.281
541	10.0	2250.482	542	10.10	2263.392	543	10.20	2276.220
544	10.30	2288.971	545	10.40	2301.725	546	10.50	2313.910
547	10.60	2325.628	548	10.70	2337.342	549	10.80	2348.869
550	10.90	2360.301	551	11.0	2371.744	552	11.10	2383.112
553	11.20	2395.212	554	11.30	2407.952	555	11.40	2421.344
556	11.50	2434.325	557	11.60	2446.243	558	11.70	2458.956
559	11.80	2471.205	560	11.90	2482.247	561	12.0	2493.659
562	12.10	2506.016	563	12.20	2519.598	564	12.30	2534.971
565	12.40	2549.086	566	12.50	2562.977	567	12.60	2576.115
568	12.70	2586.936	569	12.80	2600.011	570	12.90	2615.468
571	13.0	2630.343	572	13.10	2644.455	573	13.20	2658.475
574	13.30	2672.218	575	13.40	2685.520	576	13.50	2698.683
577	13.60	2711.990	578	13.70	2725.313	579	13.80	2738.112
580	13.90	2750.418	581	14.0	2763.164	582	14.10	2775.980
583	14.20	2788.331	584	14.30	2800.214	585	14.40	2811.915
586	14.50	2824.208	587	14.60	2837.183	588	14.70	2849.781
589	14.80	2862.184	590	14.90	2874.421	591	15.0	2877.552
592	15.10	2871.084	593	15.20	2864.617	594	15.30	2858.147
595	15.40	2851.581	596	15.50	2844.839	597	15.60	2837.641
598	15.70	2830.538	599	15.80	2823.427	600	15.90	2816.329
601	16.0	2813.386	602	16.10	2814.819	603	16.20	2816.344
604	16.30	2817.782	605	16.40	2819.124	606	16.50	2819.920
607	16.60	2819.883	608	16.70	2819.846	609	16.80	2819.725
610	16.90	2819.631	611	17.0	2823.437	612	17.10	2831.455
613	17.20	2839.475	614	17.30	2847.220	615	17.40	2855.056
616	17.50	2862.956	617	17.60	2870.913	618	17.70	2878.960
619	17.80	2886.826	620	17.90	2894.594	621	18.0	2903.983
622	18.10	2914.913	623	18.20	2925.791	624	18.30	2936.340
625	18.40	2946.712	626	18.50	2956.448	627	18.60	2965.448
628	18.70	2974.450	629	18.80	2983.453	630	18.90	2992.455
631	19.0	2999.561	632	19.10	3004.583	633	19.20	3009.698
634	19.30	3014.721	635	19.40	3019.741	636	19.50	3025.406
637	19.60	3031.526	638	19.70	3037.737	639	19.80	3043.950
640	19.90	3050.161	641					

[A]Energies represent the lower bin boundary. The upper bin limit is 20.0 MeV

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