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SPECTER: NEUTRON DAMAGE CALCULATIONS FOR MATERIALS IRRADIATIONS

by

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Abstract

Neutron displacement damage-energy cross sections have been calculated for 41 isotopes in the energy range from 10^{-10} to 20 MeV. Calculations were performed on a 100-point energy grid using nuclear cross sections from ENDF/B-V and the DISCS computer code. Elastic scattering is treated exactly including angular distributions from ENDF/B-V. Inelastic scattering calculations consider both discrete and continuous nuclear level distributions. Multiple (n,xn) reactions use a Monte Carlo technique to derive the recoil distributions. The (n,d) and (n,t) reactions are treated as (n,p) and n,^{3}He) as (n,^{4}He). The (n,γ) reaction and subsequent β-decay are also included, using a new treatment of γ-γ coincidences, angular correlations, β-neutrino correlations, and the incident neutron energy. The Lindhard model was used to compute the energy available for nuclear displacement at each recoil energy. The SPECTER computer code has been developed to simplify damage calculations. The user need only specify a neutron energy spectrum. SPECTER will then calculate spectral-averaged displacements, recoil spectra, gas production, and total damage energy (Kerma). The SPECTER computer code package is readily accessible to the fusion community via the National Magnetic Fusion Energy Computer Center (NMFECC) at Lawrence Livermore National Laboratory.

I. Introduction

Neutron radiation damage in materials results from nuclear collisions and reactions which produce energetic recoil atoms of the host material or reaction products. These recoiling atoms then generate electronic excitations in the host material (electronic energy loss) and elastic and inelastic collision events (nuclear energy loss) that sometimes result in displacing additional host atoms. This report deals with the calculation of the second type of damage (nuclear energy loss) mentioned above which will be referred to in later discussions as displacement damage. In metals this is the only process that leads to permanent damage and the displacements-per-atom (DPA) is routinely used to characterize neutron irradiations. For insulators the electronic interactions also lead to permanent damage so the irradiations are characterized by the total dose in Rads. We use the Lindhard model[1] to calculate the partition of recoil energy between nuclear and electronic effects for the recoiling atoms.

Calculations of displacement cross sections have been done using the DISCS[2] computer code. A complete description of the code is given in Ref. 2 and only a brief summary will be discussed in this report. All nuclear reaction data was obtained from ENDF/B-V[3] distributed by Brookhaven National Laboratory. The most important reactions have been treated exactly; however, simplifying approximations have been made for several of the less important reactions. The list of elements and reactions included is given in Table I. Some approximations are required for all elements since nuclear data is simply not available in some cases, especially between 6-13 MeV and above 15 MeV. Nevertheless, most of these approximations do not significantly contribute to the overall errors of the displacement cross sections. Absolute errors are

Table I: Elements, Reactions, and ENDF/B-V References for SPECTER
All elements have ENDF files for elastic scattering.
Only Be lacks an inelastic scattering file and He lacks a capture gamma file.

			Reactions Included in ENDF/B-V						
Element	ENDF/B-V Tape	Ref. Mat.	16 2n	17 3n	22 n'α	24 2nα	28 n'p	103-105 H	106-107 He
H	511	1301	--	--	--	--	--	--	--
^{3}He	511	1146	--	--	--	--	--	X	--
^{4}He	501	1270	--	--	--	--	--	--	--
^{6}Li	511	1303	--	--	--	X	--	X	--
^{7}Li	505	1272	X	--	--	X	--	X	--
Be	505	1304	X	--	--	--	--	X	X
^{10}B	511	1305	--	--	--	--	--	X	X
^{11}B	501	1160	X	--	--	--	--	X	X
C	511	1306	--	--	--	--	--	X	X
N	505	1275	X	--	--	--	--	X	X
^{16}O	505	1276	--	--	--	--	--	X	X
F	503	1309	X	--	X	--	X	X	X
Na	506	1311	X	--	--	--	--	X	X
Mg	506	1312	X	--	X	--	X	X	X
Al	506	1313	X	--	--	--	--	X	X
Si	507	1314	X	--	X	--	X	X	X
P	503	1315	X	--	--	--	X	X	X
S	503	1316	X	--	--	--	X	X	X
Cl	513	1149	X	--	X	--	X	X	X
K	513	1150	X	--	X	--	X	X	X
Ca	507	1320	X	--	X	--	X	X	X
Ti	508	1322	X	X	X	--	X	X	X
V	508	1323	X	--	X	--	X	X	X
Cr	512	1324	X	X	X	--	X	X	X
Mn	508	1325	X	X	X	--	X	X	X
Fe	513	1326	X	--	X	--	X	X	X
Co	501	1327	X	--	X	--	X	X	X
Ni	512	1328	X	--	X	--	X	X	X
Cu	508	1329	X	X	X	--	X	X	X
Zr	508	1340	X	--	--	--	--	X	X
Nb	510	1189	X	X	X	--	--	X	X
Mo	513	1321	X	X	--	--	--	--	--
^{107}Ag	510	1371	X	--	--	--	--	X	X
^{109}Ag	510	1373	X	--	--	--	--	X	X
Ta	502	1285	X	X	--	--	--	X	--
^{182}W	502	1128	X	X	--	--	X	X	X
^{183}W	502	1129	X	X	--	--	X	X	X
^{184}W	502	1130	X	X	--	--	X	X	X
^{186}W	502	1131	X	X	--	--	X	X	X
Au	511	1379	X	X	--	--		X	X
Pb	508	1382	X	X	--	--	--	--	--

typically estimated at 10-30%, mainly due to errors in the nuclear data for elastic and inelastic scattering and (n,xm) reactions.

It must also be pointed out that the calculated cross sections only describe the initial displacement of atoms from their lattice sites. Naturally, many displaced atoms will recombine with holes in the lattice, especially at elevated temperatures. Hence, some of the displacement damage can always be annealed out of the material. The present cross sections are thus most directly applicable to cryogenic temperatures where defects tend to be "frozen in". On the other hand, the present cross sections are still crucially important in characterizing irradiations since they are a measure of the total damage energy deposited in a material, and changes in physical and mechanical properties are fundamentally related to the available energy. Furthermore, nuclear displacements or damage energy remove the spectral dependence that is inherent in simply quoting neutron fluence. Hence, the DPA unit is now the recommended value to characterize neutron irradiations.[4]

II. Theory

The probability of displacing atoms from their lattice sites depends on the incident neutron energy and cross sections, primary recoil atom energy distributions, and secondary recoil atom probabilities. Mathematically this is expressed as follows:

$$\sigma_{DIS}(E) = \sum_i \sigma_i(E) \int_{T1}^{T2} K(E,T)_i \, \nu(T) \, dT \qquad (1)$$

where E = incident neutron energy (laboratory system), T = recoil nucleus energy (laboratory system), $\sigma_i(E)$ = nulcear cross section for channel i at energy E, $K(E,T)_i$ = neutron-atom energy transfer kernel, and $\nu(T)$ = secondary displacement function.

The kernel K is simply the probability that a neutron of energy E will produce a recoil atom of energy T known as a primary knock-on atom (PKA). The function ν then describes how many additional or secondary atoms will be knocked out due to the stopping of the first recoil atom. The secondary displacement function $\nu(T)$ is the most uncertain term in Eq. (1) since it requires a detailed knowledge of the nuclear stopping cross section for a recoiling atom as well as the energy required to displace an atom from its lattice site. The Lindhard model[1] is used to describe nuclear stopping. Experimental and theoretical studies[5] have been made to determine the effective atomic binding energies or the average recoil-energy loss per displacement.

The evaluation of Eq. (1) for various neutron interactions with materials primarily involves the definition of the energy transfer kernel, K(E,T), for each specific reaction. The relationship between neutron energy and recoil energy can be described by one general equation derived from conservation of energy and momentum in the center of mass system:

$$T(E,E_x,\theta) = U_3E_x + U_1U_4E - 2[EE_xU_1U_3U_4]^{1/2}\cos\theta \qquad (2)$$

where $E_x = U_2E_1 + Q$ = total energy, Q = energy-mass conversion in the nuclear reaction, θ = angle between the indicent neutron direction and the recoil atom direction, $U_i = m_i/(m_1 + m_2)$, m = mass, and i = 1, 2, 3, or 4 for the neutron, target atom, emitted particle, and recoil atom, respectively. Each reaction will now be considered separately.

A. Pre-Processing of Nuclear Data

In order to use DPA as a neutron exposure unit it is necessary to average the energy-dependent displacement cross sections over the neutron energy spectrum. This requires that the displacement cross sections be group-averaged, especially in the resonance energy region where sharp, rapid

fluctuations occur. This is most simply accomplished by group-averaging all nuclear data prior to running the DISCS code. The code INDISC[6] was thus written to read the ENDF/B-V magnetic tapes from BNL and to produce 100-group cross sections and elastic angular distributions. Calculations in the resolved and unresolved resonance regions use the RESCAL[7] subroutine which uses integral approximation formulae to evaluate the group cross sections. The RESCAL results are then collapsed without any spectral weighting to the 100-point grid used in this report. We normally perform flux-spectral dosimetry on the same grid to facilitate spectral averaging: however, this is certainly not required.

B. Elastic Scattering

Elastic scattering cross sections and angular distributions are available for most elements. Hence, this process can be treated exactly. Since there is no conversion of mass into energy (Q = 0) and the initial and final masses are identical, the transfer kernel can be written simply as follows:

$$K(E,T)dt = \sum_{\ell} \frac{(2\ell + 1)}{4\mu_1\mu_2 E} a_\ell(E)\, P_\ell\left(1 - \frac{T}{2\mu_1\mu_2 E}\right) \qquad (3)$$

where the P_ℓ terms are Legendre polynomials and the energy-dependent coefficients, $a_\ell(E)$, are taken from ENDF/B-V. The elastic scattering displacement cross section is usually the dominant process especially at low neutron energies.

C. Inelastic Scattering

Inelastic scattering involves the excitation of the compound nucleus into either a resolved or unresolved level. Resolved levels can be treated exactly· however, angular distributions are not always available. Hence, we

have made the approximation that the reactions are isotopic in the center-of-mass coordinate system. Unresolved levels are treated using the evaporation model, as follows:

$$P(E,E_x) = C\ E_x \exp\ (-E_x/\theta[E]) \qquad (4)$$

where E_x is the excitation energy, θ is the nuclear temperature, defined as $[E/AA]^{1/2}$ where AA is the level density parameter, $(m_2/10)$, and C is a normalization constant. The function P is the probability that an incident neutron of energy E will produce a nuclear de-excitation energy, E_x.

If the nucleus is left with sufficient energy to evaporate a second neutron, then the (n,n') process is treated as an $(n,2n)$ process, as will be discussed later.

D. (n,xn) Reactions

Multiple particle reactions are more difficult to handle since secondary neutron energy distributions are not generally known. We have thus assumed that each neutron emission can be descirbed by the evaporation model, given in Eq. (4) except the E_x is now the energy of the first or second neutron and the temperature is adjusted to fit the available excitation energy for each decay. The energy transfer kernel, K, is now developed by a Monte Carlo simulation procedure. Random numbers are selected sequentially from the neutron probability distributions and random angles are chosen between the directions of emission. Conservation of energy and momentum is then applied in a straightforward manner to determine the recoil atom energy which is collected in a histogram. Several thousand events are usually needed to obtain a smooth energy distribution. At present, only $(n,2n)$ events are treated exactly and multiple decay is treated as if it were an $(n,2n)$ event. This approxi-

mation is not very important in the present case since the data files stop at 20 MeV which is below the threshold energy for most (n,3n) reactions.

E. Charged Particle Reactions

Charged particle reactions are also treated using the evaporation model with the important addition of a coulomb barrier, as follows:

$$P(E,E_x) = \frac{(E_x - E_c)\ \exp(-CE_x - E_c)/\theta[E])}{C_p} \tag{5}$$

where E_x is the particle energy and E_c is the coulomb barrier height, given by:

$$E_c = C_k(1.44 \times 10^{-13}\ Z_3Z_4)/(Ro + Rc) \tag{6}$$

where Z_3 and Z_4 are the atomic numbers of the particle and recoil nucleus, Ro is the radius of the compound nucleus $[1.5 \times 10^{-13}\ (m_1 + m_2)^{1/3}]$ and R_c and C_k are correction terms.[8] The normalization constant "C_p" is given by:

$$C_p = \int_{ECB}^{E(max)} P(E,Ex)\ dEx \tag{7}$$

In the DISCS code we assume that all charged particle angular distributions are isotropic in the center-of-mass system since nuclear data is generally not available. We further approximate the (n,d) and (n,t) reactions by adding their cross sections to the (n,p) cross section and adding (n,^{3}He) reactions cross section to the (n,^{4}He) cross section. None of these approximations are very significant since the charged particle cross sections are generally much less than those for scattering and the (n,2n) processes. Hence, charged particle displacements are usually less than 10% of the total.

F. The (n,γ) Reactions

In previous treatments the recoil energy calculated for the (n,γ) reaction included only the recoil energy associated with the emission of prompt gamma rays.[9] The present program includes the recoil effects associated with

the finite energy of the incoming neutron as well as the additional recoil energy generated by the β-decay process when appropriate (see Section G). The calculation of all three of these effects have been discussed in recent publications.[10,11,12,13] A short summary of each appears below combined with the discussion of how they are used in the program to calculate displacement damage. A typical (n,γ) plus β-decay recoil sequence appears in Fig. 1.

The recoil energy resulting from the emission of an individual gamma-ray is given by Eq. (8).

$$E_r(ev) = \frac{E_\gamma^2}{(A+1)m_o c^2} = \frac{536.7\ E_\gamma^2}{(A+1)} \tag{8}$$

where "E_γ" is the gamma-ray energy in MeV and "A" is the atomic weight of the capturing atom. The recoil energy associated with the finite energy of the incoming neutron is given by Eq. (9).

$$E_r\ (ev) = \frac{E_n\ (ev)}{(A+1)} \tag{9}$$

where E_n is the incident neutron energy in ev. If the capture state is short-lived, then the momentum of the two recoils will add vectorially and the recoil energy will be given by Eq. (10).

$$E_r = \frac{E_\gamma^2}{(A+1)\ m_o c^2} + \frac{E_n}{A+1} + \frac{2}{A+1}\left(\frac{E_\gamma^2 E_n}{m_o c^2}\right)^{1/2} \cos\theta \tag{10}$$

where θ is the angle between the two momentum vectors (see Fig. 1). The recoil energy generated by two successive gamma rays with a short lifetime for the intermediate state is given by Eq. (11)

$$E_r = \frac{1}{(A+1)\ m_o c^2}\left[E^2_{\gamma 1} + E^2_{\gamma 2} + 2E_{\gamma 1}E_{\gamma 2}\cos\theta\right] \tag{11}$$

so the momentum kick received from the incoming neutron acts just like the emission of a gamma ray of the appropriate energy. This means that the neutron

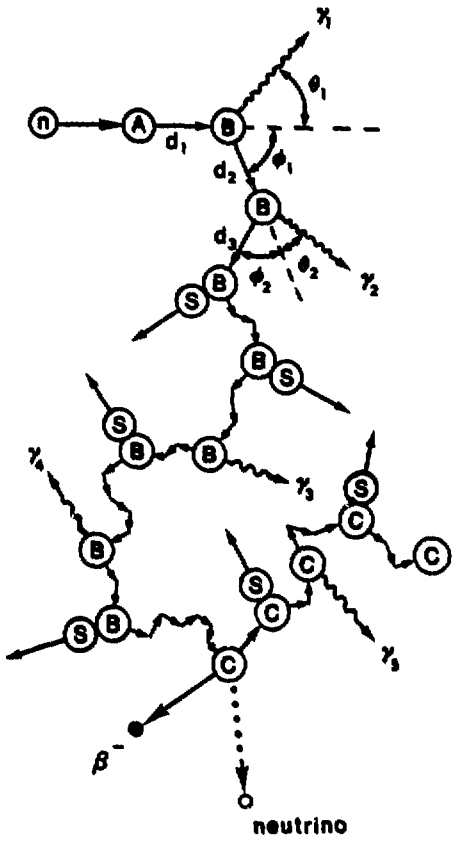

Fig. 1. Typical neutron capture recoil event. The neutron (n) strikes the target nucleus (A) and is captured, producing nucleus (B) which recoils a distance (d_1) before emitting a gamma ray (γ_1). An additional gamma ray is emitted (γ_2) after "B" recoils a distance (d_2) and a number of secondary recoil displacements (S) are produced before the nucleus (B) comes to rest. A third gamma ray (γ_3) is emitted and the recoiling atom (B) produces an additional secondary displacement before coming to rest. A fourth gamma ray is emitted and the recoiling atom (B) produces another secondary displacement (S) before coming to rest. A β and a neutrino are then emitted as nucleus "B" β-decays to form nucleus "C". The recoiling "C" produces a secondary displacement before coming to rest. A gamma ray (γ_5) is then emitted and the recoiling atom (C) produces a secondary displacement before coming to rest.

momentum is treated the same way mathematically as the momentum generated by gamma ray emission. Figure 2 shows the recoil energy spectrum for three gamma rays emmitted sequentially when (a) both intermediate states are slow, (b) the first intermediate state is fast and the second is slow, and (c) when both intermediate states have short lifetimes. The gamma rays are assumed to be emitted isotropically.

The average recoil energy for this three gamma cascade is given by Eq. (12).

$$\bar{E}_v \text{ (triple cascade)(ev)} = \frac{536.7}{A+1} [E^2_{\gamma 1} + E^2_{\gamma 2} + E^2_{\gamma 3}] \qquad (12)$$

The general expression for "i" gamma cascades plus the incoming neutron energy is given by Eq. (13)

$$\bar{E}_v \text{ (i}\gamma\text{'s + n)(ev)} = 536.7 [E^2_{\gamma 1} + E^2_{\gamma 2} \ldots E^2_{\gamma 1}] + \frac{En}{A+1} \qquad (13)$$

where the "$E_{\gamma}$is" are in "MeV" and the "En" is in "ev". Note that this result is independent of the lifetime of the intermediate states and also the angular correlation of the gamma rays. This last fact comes about because the γ-γ angular correlations involve only even powers of cos θ so the effects are symmetric and no shift in the average energy results. This independence of the average recoil energy from both the lifetimes of the intermediate states and the γ-γ angular correlations makes it possible to calculate the average recoil energy per neutron capture without knowing anything about the level scheme or gamma-ray branching ratios of the product nucleus. All that is needed is the relative intensities of the gamma rays produced by the (n,γ) reaction. The tabulation of (n,γ) spectra by V. J. Orphan, et al.[14] were used for most of the cases calculated and the relative intensities were normalized so that

$$I_{\gamma} E_{\gamma} = E_b \qquad (14)$$

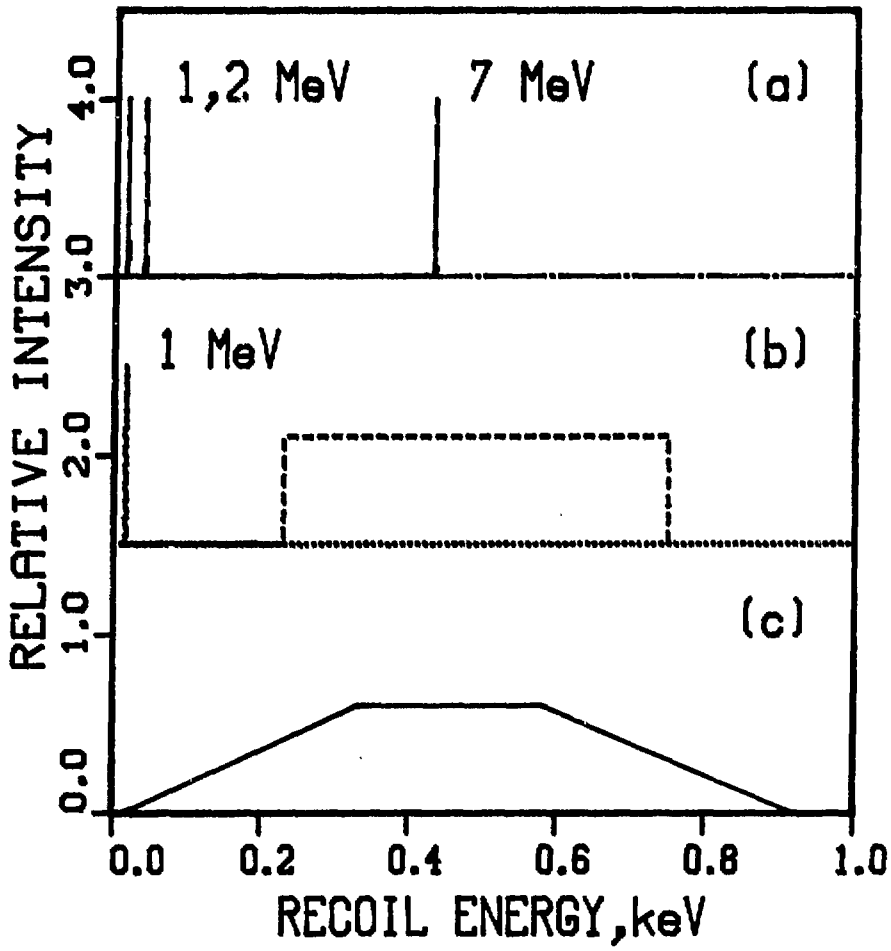

Fig. 2. (a) Recoil energy spectrum for three gamma rays (7 MeV, 2 MeV, and 1 MeV) considered as separate events in the $^{57}Fe(n,\gamma)^{58}Fe$ reaction. (b) The recoil energy spectrum for a two-step cascade (E_γ = 7 MeV and 2 MeV) which has a rectangular shape followed by a one-step cascade (E_γ = 1 MeV) which generated the spike at 9.3 eV. (c) The recoil energy spectrum of a three-step cascade (E_γ = 7 MeV, 2 MeV, and 1 MeV) which results in a near trapezoidal shape distribution.

where E_γ is the gamma-ray energy, I_γ is the gamma-ray intensity in photons per neutron capture and E_b is the neutron binding energy in the final nucleus. The average recoil energy, $\bar{E}r$, is then given by Eq. (15)

$$\bar{E}_v(ev) = \frac{537.7}{A+1} \sum_i I_{\gamma i} E^2_{\gamma i} \text{ (Mev)} \tag{15}$$

where $I_{\gamma i}$ is the intensity and $E_{\gamma i}$ is the energy of the "i^{th}" gamma ray. The values of $\bar{E}r$ listed in Table II are calculated with a low-energy cutoff so that the sum goes from E_γ (max) to E_γ (cutoff) where

$$E_\gamma(\text{cutoff}) = \left[\frac{A+1}{538.7} \cdot E_v(\text{min})\right]^{1/2} \tag{16}$$

where E_v (min) is the minimum energy needed to produce a primary displacement 50% of the time. These minimum recoil energies are listed in Table II. These cutoff energies are the same as those used in calculations of recoils from nuclear scattering and nuclear reactions in Sections B-E. The average recoil energy per neutron capture is multiplied by the Lindhard factor[1] to obtain the fraction of the recoil energy that produces displacement damage thus eliminating the fraction that produces electron damage. The corrected values of $\bar{E}\gamma$ are also listed in Table II.

In the above discussion it is important to remember that one is calculating average recoil energies per neutron capture rather than average recoil energy per emitted gamma ray. These two numbers can be quite different when many gamma-rays are emitted per neutron capture. The use of a cut-off energy in this calculation underestimates the average recoil energy because there will be cases where a low-energy gamma-ray in the cascade with an energy below the cutoff will be emitted soon enough to be part of the former recoil event and should have been added to the sum.

Table II. Cutoff Energies and (n,γ), β-decay Recoil Energies (eV)
E_d = Lindhard cutoff; energy required to displace atom
T_{GAM} = Recoil energy from (n,γ), β-decay

		T_{GAM}				T_{GAM}	
Element	Ed	True[a]	Effective[b]	Element	Ed	True[a]	Effective[b]
H	10	1329	528	Ti	40	367	400
^{3}He	10	56849	3988	V	40	465	447
^{4}He	10	--	--	Cr	40	516	554
^{6}Li	10	3200	1824	Mn	40	363	395
^{7}Li[c]	10	3.0×10^{6}	7555	Fe	40	404	395
Be[d]	31	1230	1307	Co	40	327	360
^{10}B	25	933	711	Ni	40	530	491
^{11}B	25	6427	4013	Cu	40	403	366
C	31	683	671	Zr	40	112	142
N	30	2311	1659	Nb	40	102	111
^{16}O	30	366	292	Mo	60	132	105
F	30	1544	1207	^{107}Ag	60	132	143
Na	25	497	618	^{109}Ag	60	145	166
Mg	25	284	574	Ta	53	107	19
Al	27	696	674	^{182}W	90	114	14
Si	25	335	565	^{183}W	90	118	20
P	30	613	500	^{184}W	90	115	13
S	30	584	473	^{186}W	90	119	15
Cl	40	655	532	Au	30	75	66
K	40	218	349	Pb	25	140	126
Ca	40	210	388				

[a]True average energy of recoil spectra (spike approximation).

[b]Effective damage energy allowing for cutoff, gamma multiplicity, and Lindhard factor.

[c]^{7}Li capture to ^{8}Be results in 2α decay.

[d]Beta-decay not included due to long half-life.

The energy spectra for the primary recoils resulting from the (n,γ) reactions are not available from the present computer program. Detailed knowledge of the level schemes, gamma ray branching ratios and lifetimes of the intermediate states are needed to perform these calculations. Some individual primary recoil spectra for Ni and Fe isotopes were calculated during the analysis and reported in DAFS Reports.[11,12]

G. Beta Decay

The (n,γ) reaction will often produce an unstable product nucleus $(A + 1)$ which then β decays to a new nucleus $(A + 1, Z \pm 1)$. The combined momentum of the beta-ray and the neutrino produces a recoil event that can result in further displacement damage. In some cases this displacement damage is larger than the displacement damage generated by the (n,γ) reaction. This β-decay displacement damage has been calculated for all the elements listed in Table I. As noted above, this β-decay displacement damage energy is corrected for the Lindhard factor and then added to the (n,γ) displacement damage energy so that only one number, the sum, appears in the program.

The average recoil energy for the β-decay process depends not only on the end-point energy but also on the angular correlation between the electron and the neutrons. This correlation is determined by the energy of the electron and by the type of β-decay interaction, i.e., Tensor, axial vector, scaler, etc. In practice the average recoil energy per β decay is usually between 60% and 80% of the maximum recoil energy. A value of 70% is used to calculate the average damage energies where the form of the β decay is unknown. If any gamma rays are emitted following the β decay the average recoil energy per β-decay for these gamma rays is added to the average recoil energy from

the β-decay process. Thus for the case where the character of the β-decay is unknown the average recoil energy per β decay is given by Eq. (17)

$$\bar{E}_r(\beta + \delta's) = 0.7\ E_r(\beta\ max) + \frac{1}{2(A+1)m_oc^2}\ [E^2_{\gamma 1} + E^2_{\gamma 2} + etc.] \qquad (17)$$

where

$$E_r(\beta\ max) = \frac{E^2_\beta(max)}{2(A+1)m_oc^2}\left[1 + \frac{m_oc^2}{E\beta(max)}\right] \qquad (18)$$

The recoil energy generated by an individual β decay is given by Eq. (19)

$$E_v(\beta + V) = \frac{1}{2(A+1)m_oc^2}\ \Big\{E_e(E_e + 2m_oc^2) + E_o - E_e)^2 + 2\ [E_e(E_e + 2m_oc^2)]^{1/2}\ [E_o - E_e]\ \cos\theta\Big\} \qquad (19)$$

where "E_e" is the electron energy, "E_o" is the end point energy, "m_o" is the atomic mass unit, "m_e" is the electron mass and "θ" is the angle between the electron and the neutrino emmission. It is convienent to rewrite Eq. (19) in terms of the normalized energy parameter, $a = E_e/E_o$ and $b = m_ec^2/E_o$. Equation (19) then becomes Eq. (20).

$$E_v(\beta + V) = \frac{E_o^2}{2(A+1)m_oc^2}\ \Big\{[a(a+b)] + (1-a)2 + [a(a+b)]^{1/2}\ (1-a)\ \cos\theta\Big\} \qquad (20)$$

The number of recoils per electron energy increment, dE_e and angular increment $d\theta$ is given by Eq. (21)

$$F(E_e,\theta)\ dE_e d\theta = (a+b)^2(1-a)^2\left(1 + C\,\frac{V_e}{c}\cos\theta\right) F_s\ \frac{V_e}{c}\ d\theta\ dE_e \qquad (21)$$

where "V_e/c" is the velocity of the electron divided by the speed of light and "$F_s(V_e/c)$" is a slowly varying function of V_e/c which remains close to one in most cases. The coefficient "C" depends on the character of the β-decay interaction and reflects the angular correlation between the electron and the neutrino. If the coefficient "C" is known then Eq. (20) and Eq. (21) can be

used to calculate the primary recoil energy spectrum for the β-decay process and also the average recoil energy per β decay. Figure 3 shows the recoil spectrum for the β decay of ^{28}Al (C_o = 2.871, axial vector, C = -1/3). The average value of the recoil energy for this case is 61% of the maximum value of $E_r(\beta+)$ which occurs when $E_e = E_o$.

H. Secondary Displacement Model

As discussed previously in Section II, DISCS uses a secondary displacement function, $\nu(T)$ to describe the production of secondary recoil atoms as the primary recoil atom stops in the material. This function appears explicitly in Eq. (1). We use the Lindhard theory[1] to describe $\nu(T)$, as follows:

$$\nu(T) = \frac{0.8\ T_{DAM}}{2\ E_D},\ T \geq 2\ E_d \tag{22}$$

$$\nu(T) = 1,\ E_d \leq T < 2\ E_d \tag{23}$$

$$\nu(T) = 0,\ T < E_d \tag{24}$$

where T is the recoil energy and E_d is the energy required to remove an atom from its lattice site (see Table II).

The function T_{DAM} in Eq. (22) is defined as the energy available for producing recoils. In the Lindhard model, this is simply the nuclear stopping fraction. If the total recoil energy is T, then:

$$\frac{T_{DAM}}{T} = \frac{1}{[1 + kg(E)]} \tag{25}$$

where

$$E = \frac{T}{(0.0869\ z^{2/3})},\ T \text{ in kev} \tag{26}$$

and

$$K = 0.0876\ Z^{1/6} \tag{27}$$

$$z = \text{atomic number}$$

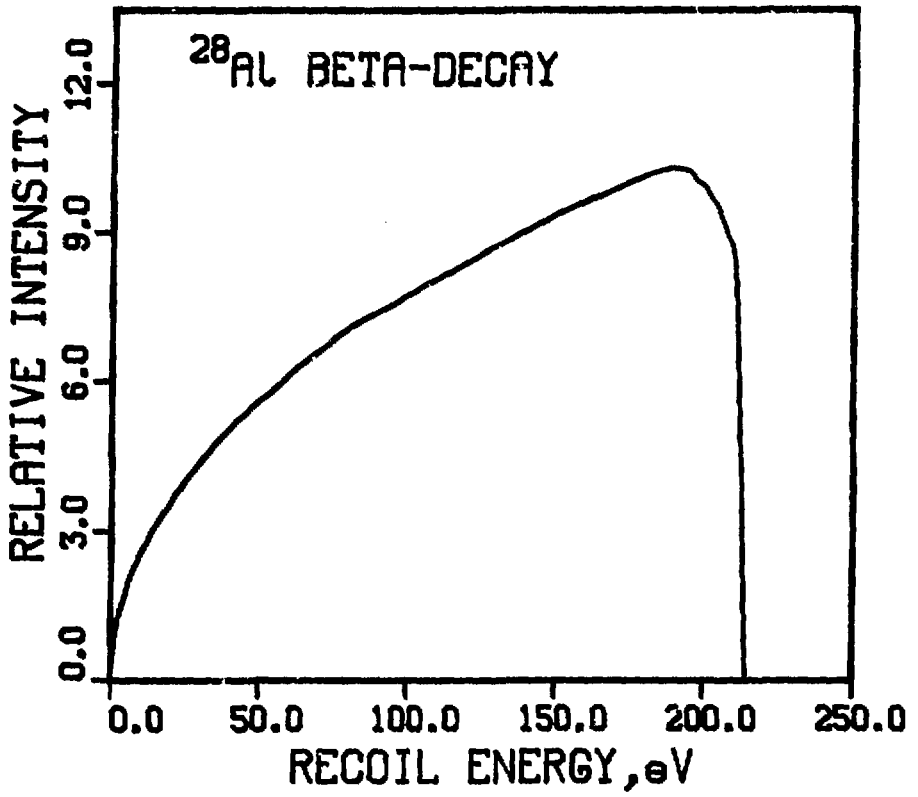

Fig. 3. Recoil atom energy spectrum for the beta-decay of ^{28}Al ($T_{1/2}$ = 2.24 m). Both the beta and neutrino are taken into account, as described in Refs. 10 and 11.

According to Robinson[15], the function g(E) can be described by:

$$g(E) = E + 0.402\ E^{3/4} + 3.40\ E^{1/6} \qquad (28)$$

For simplicity, it should be noted that the equations above assume that the atomic number Z is about half the atomic weight. A more generalized equation is found in Ref. (1).

III. Discussion and Use of Results

The calculated displacement damage-energy cross sections are listed in Appendix A and shown in Appendix B. The relative contributions to the total displacement cross section are shown in Fig. 4 for iron. In order to use this data for a given irradiation, the user must multiply these cross sections times his particular neutron energy spectrum. This yields the damage-energy per atom. To get actual displacements, one must also multiply by a factor of $0.8/2\ E_D$ where E_D is the effective displacement threshold energy listed in Table II. [The value of 0.8 is an empirical efficiency factor and the factor of 2 corrects for the many nuclear collisions which absorb energy but do not produce a displacement.] The advantage of listing cross sections in this fashion is that they are relatively independent of the value chosen for E_D which may be changed at the discretion of the user.

The computer code SPECTER (see Section IV) has been developed to routinely provide users with spectral-averaged cross sections and PKA distributions. Each reaction is listed separately and gas production cross sections can also be obtained. This program, as well as all of our data files, are resident at the Magnetic Fusion Energy Computer Center at Lawrence Livermore Laboratory. Most fusion experimenters thus have easy access to the data. The SPECTER code is also designed to couple with our flux unfolding code STAYSL[16] so that the flux covariance matrix can be used to correctly determine uncertainties in DPA values for a given irradiation.

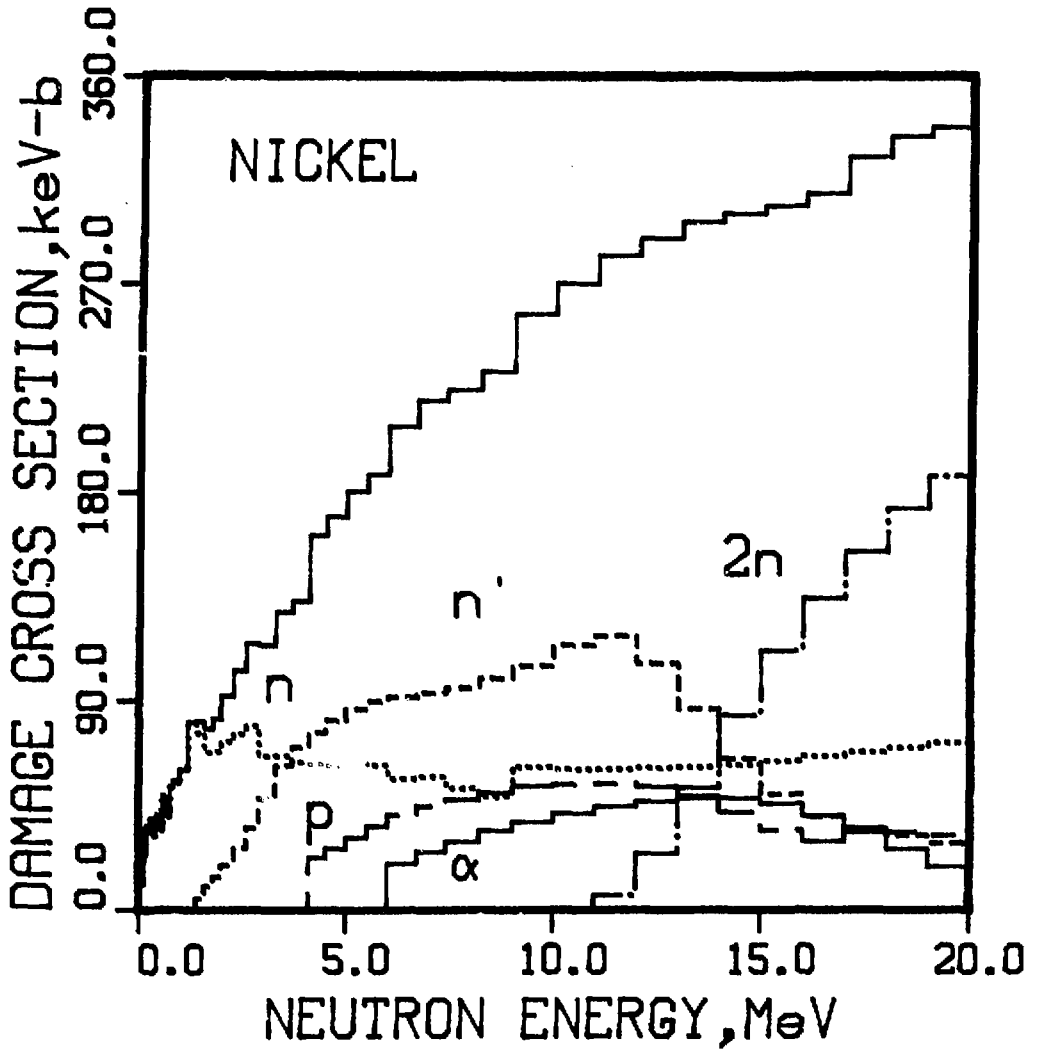

Fig 4. Displacement damage energy cross section for nickel showing contributions from each subreaction. These cross sections were calculated using the DISCS code (Ref. 2) and the values are stored in the SPECTER master libraries.

IV. The SPECTER Computer Code

The SPECTER computer code has been written to facilitate damage calculations for any specified neutron irradiation. Unlike some older codes, SPECTER relies on master libraries of displacement cross sections, recoil distributions, and other nuclear data. Hence, the DISCS code only needs to be used to generate the master libraries. SPECTER itself is thus a relatively short program· however, the library files are rather extensive. In order to run SPECTER, a user need only specify the neutron flux spectrum. The program will then convert the required master library files into the users group structure and proceed to spectral average all quantities. If an irradiation time is specified, then the code will provide absolute displacements, gas production, etc.

In order to provide users with the most complete package of damage information, we have also included the MACKLIB[17] library of total damage from Kerma or Rads and the ENDF/B-V Gas Production File (533)[18] for the latest gas production values. It should be noted that MACKLIB was generated using ENDF/B-IV; however, the differences with Version V are quite small, especially concerning total damage energy. As to gas production, the program will actually list two values for a few elements. We assume that the Gas Production File (listed first) is the most accurate and should always be used in preference to the general ENDF files (listed by element).

The SPECTER computer code has several limitations, which are worth noting. The code was originally written to calculate damage from medium weight elements, such as iron. In these cases only the heavy recoil nuclei need be considered in subsequent damage calculations. Hence, for very light nuclei some error may be introduced when the light charged particle is neglected. In fact, the only significant error occurs for the $^{6}Li(n,\alpha)t$ and $^{10}B(n,\alpha)^{7}Li$ reactions

where the displacements calculated by the code are incorrect. However, this error is not very important due to a second limitation of SPECTER, namely, that displacements are always assumed to occur in a pure metallic lattice. Hence, lithium displacements in lithium would only rarely be of interest. In both cases, true displacements can be easily computed from thermal kinematics and basic Lindhard theory (see Section II-H).

For insulators or other compounds or alloys, we assume that the appropriate displacements or gas production can be determined by simply adding up the individual contributions from each element weighted by the appropriate atomic fraction. In fact, this approximation is only valid when all elements in the mixture have nearly equal atomic weights (e.g., stainless steel). For other cases, a revised secondary displacement formalism is clearly required.[19] At present, no computer codes have been written to do this properly.

It must also be remembered that SPECTER does not account for burnup and neutron self-shielding effects. Both effects are usually only important in regard to the thermal neutron flux. For fast neutrons, both effects are usually quite small for a small sample and, in the case of burnup, it is usually true that the transformed element produces displacements at a rate comparable to the original target element. For thermal neutrons, these effects must be considered since elements with a high thermal cross section can be depleted or produce very nonuniform damage in the sample. For example, if we consider cobalt in a mixed reactor like the High Flux Isotopes Reactor at Oak Ridge National Laboratory, SPECTER predicts that the (n, γ) reaction produces 21% of the displacement damage. However, the large thermal cross section will lead to rapid depletion of the cobalt in thin samples and strongly nonuniform damage gradients in thick samples. In such cases, users must have access to time-dependent neutronics calculations and then use SPECTER to

predict the damage at a given location in the sample at a given time in the irradiation. Burnup effects may be seen in the gas file output, especially for ^{6}Li and ^{10}B. In these cases, a burnup correction can be made by replacing the total helium value ($\sigma\phi t$) by the expression $1 - \exp(-\sigma\phi t)$.

Due to the large size of the PKA recoil files, SPECTER may be run without them (see Section IV-A). If they are needed, then the user must select one of four groupings of elements to be calculated. Concatenation of these files is possible, but not recommended due to disk storage limitations on most computers. In severe cases, users may be forced to run SPECTER with the PKA files on magnetic tape. For such users, a smaller version of SPECTER exists which only retains the total recoil spectra rather than recoils for each type of nuclear reaction. A sample spectral-averaged recoil spectrum is shown in Fig. 5. The contribution from each reaction type is shown on the figure.

SPECTER does not include the two-step thermal reaction, $^{58}Ni(n,\gamma)^{59}Ni$-$(n,\alpha)^{56}Fe$, which is used to simulate fusion-like helium-to-dpa ratios in stainless steel in mixed-spectrum reactors. This reaction has been discussed in recent publications.[20,21] The energetic (340 keV) ^{56}Fe recoils from this reaction produce significant extra displacement damage in the ratio of 1 dpa for every 567 appm He generated.

A. SPECTER Input

Formats listed below are only required by the CRAY version of SPECTER at the NMFECC. Versions written for the IBM and VAX computers have no format restrictions.

Input File (Unit 5):

1. TITLE 40A2 = Title of job (full line).
2. ITYP, ISIG, IGP, IPKA, ACNM, TIME, (4I2, 2F10.4).

   ITYP = 0 if no flux covariances; 2 otherwise

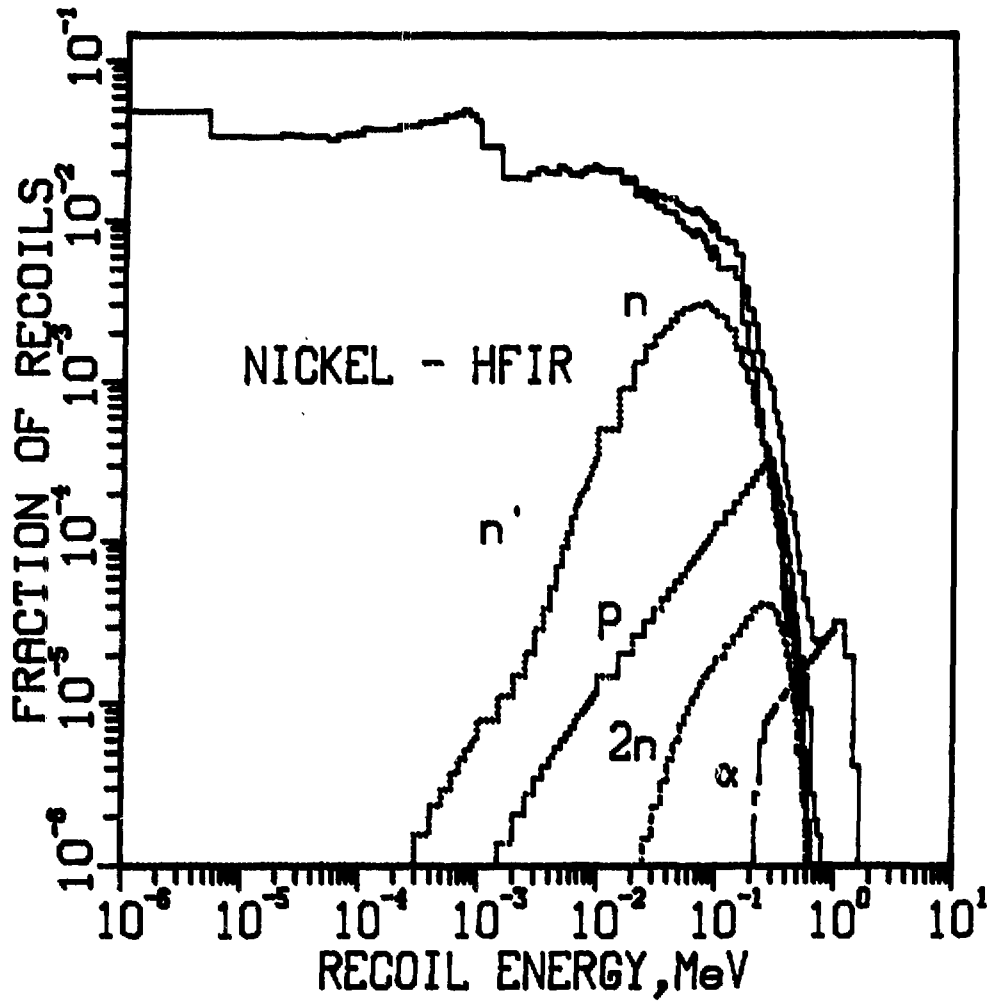

Fig. 5. Recoil atom energy spectrum for nickel averaged over the neutron energy spectrum in the PTP position of HFIR. Each subreaction calculated by SPECTER is shown separately.

ISIG = 1 to print dpa cross sections 0 otherwise

IGP = 0 for group-averaged differential flux

= 1 for point differential flux

= 2 for group flux

IPKA = 0 to calculate PKA distributions

= 1 to calculate only dpa's

ACNM = 1.0 unless file is generated by other codes (STAY'SL)

TIME = Time in seconds (for fluence, dpa, etc.)

3. NPT (I3) = number of flux points or groups.

4. Energies (7E10.3) = energies starting at lowest (MeV).

5. Fluxes (7E10.3) = flux values (note if IGP=2, there should be one extra upper energy listed).

Optional.

6. Flux covariance matrix (7E10.3), only half need be listed since matrix is symmetric. First entry of each line is the diagonal variance. (This file is normally generated by STAY'SL.)

Logical Unit Assignments:

5 Input File

6 Output File

10 PKA File (one of four groups)

15 DPA File (one of four groups)

17 MACKLIB File

18 Gas Production File

23 (n,γ), β-decay File

If IPKA = 1, then file 10 is not needed. If IPKA = 0, then files 10 and 15 must match (i.e., PKA2 with SIGD2, etc.).

Grouping of Elements:

File 1 H to F

File 2 Na to Ca

File 3 Ti to Mo

File 4 Ag to Pb

A sample SPECTER input file is shown in Table III.

B. SPECTER Output

1. List of input spectrum in group-differential form (E in MeV, flux in n/cm^2-s-MeV).
2. List of Kerma factors (MACKLIB), Rads = Kerma x neutron fluence.
3. List of gas production from ENDF File 533, Gas (appm) = cross section x neutron fluence.
4. Detailed output by element:

   dpa, He, H = cross section x neutron fluence

   Displacement cross sections (barns)

   Displacement-damage cross sections (keV-barns)

   Ordinary nuclear cross sections (barns)

   Capture gamma and β-decay damage
5. PKA files (IPKA = 0)

   Differential Recoil Spectra

   Integral Recoil Spectra (Norm = 1.0)

   Average Damage Energy

   Average PKA Energy

A sample output is shown in Tables IV-VI.

C. Specific Instructions for the NMFECC CRAY Computer

Users with access to the National Magnetic Fusion Energy Computer Center can immediately run SPECTER by copying public files from user = 15060

Table III: Sample Specter Input

```
 HIGH FLUX ISOTOPE REACTOR (ORNL)  CTR32  100 MW  MIDPLANE
 0 0 0 1  1.000E+00 9.380E+06
   100     1
1.00E-10 1.00E-09 1.00E-08 2.30E-08 5.00E-08 7.60E-08 1.15E-07 1.70E-07
2.55E-07 3.80E-07 5.50E-07 8.40E-07 1.28E-06 1.90E-06 2.80E-06 4.25E-06
6.30E-06 9.20E-06 1.35E-05 2.10E-05 3.00E-05 4.50E-05 6.90E-05 1.00E-04
1.35E-04 1.70E-04 2.20E-04 2.80E-04 3.60E-04 4.50E-04 5.75E-04 7.60E-04
9.60E-04 1.28E-03 1.60E-03 2.00E-03 2.70E-03 3.40E-03 4.50E-03 5.50E-03
7.20E-03 9.20E-03 1.20E-02 1.50E-02 1.90E-02 2.55E-02 3.20E-02 4.00E-02
5.25E-02 6.60E-02 8.80E-02 1.10E-01 1.35E-01 1.60E-01 1.90E-01 2.20E-01
2.55E-01 2.90E-01 3.20E-01 3.60E-01 4.00E-01 4.50E-01 5.00E-01 5.50E-01
6.00E-01 6.60E-01 7.20E-01 7.80E-01 8.40E-01 9.20E-01 1.00E+00 1.20E+00
1.40E+00 1.60E+00 1.80E+00 2.00E+00 2.30E+00 2.60E+00 2.90E+00 3.30E+00
3.70E+00 4.10E+00 4.50E+00 5.00E+00 5.50E+00 6.00E+00 6.70E+00 7.40E+00
8.20E+00 9.00E+00 1.00E+01 1.10E+01 1.20E+01 1.30E+01 1.40E+01 1.50E+01
1.60E+01 1.70E+01 1.80E+01 1.90E+01 2.00E+01
1.25E+21 9.27E+21 1.99E+22 2.19E+22 1.66E+22 9.22E+21 3.57E+21 1.09E+21
3.99E+20 2.55E+20 1.73E+20 1.22E+20 8.59E+19 5.63E+19 3.71E+19 2.47E+19
1.71E+19 1.18E+19 7.96E+18 5.34E+18 3.68E+18 2.44E+18 1.63E+18 1.16E+18
8.84E+17 6.94E+17 5.40E+17 4.23E+17 3.34E+17 2.65E+17 2.04E+17 1.58E+17
1.22E+17 9.45E+16 7.55E+16 5.84E+16 4.46E+16 3.44E+16 2.65E+16 2.06E+16
1.57E+16 1.23E+16 9.75E+15 7.86E+15 6.15E+15 4.82E+15 3.95E+15 3.23E+15
2.65E+15 2.17E+15 1.80E+15 1.56E+15 1.39E+15 1.25E+15 1.13E+15 1.06E+15
9.99E+14 9.44E+14 8.68E+14 7.83E+14 7.07E+14 6.57E+14 6.42E+14 6.32E+14
6.23E+14 6.02E+14 5.62E+14 5.19E+14 4.76E+14 4.35E+14 3.90E+14 3.44E+14
3.08E+14 2.76E+14 2.48E+14 2.20E+14 1.83E+14 1.47E+14 1.17E+14 9.01E+13
6.82E+13 5.26E+13 3.95E+13 2.83E+13 2.05E+13 1.40E+13 9.14E+12 5.91E+12
3.76E+12 2.32E+12 1.06E+12 3.21E+11 1.36E+11 6.14E+10 2.63E+10 1.09E+10
4.76E+09 2.19E+09 1.22E+09 9.59E+08
```

Table IV: MACKLIB Output From SPECTER
(HFIR-CTR32 Input in Table III)

	SPECTRAL AVERAGED KERMA (MACKLIB)	
	KEV-BARNS	RADS (4.78E+22)*
HYDROGEN	6.1958E+02	2.8602E+14
DEUTERIUM	4.2973E+02	9.9188E+13
HELIUM	3.5032E+02	4.0404E+13
LITHIUM 6	1.5566E+06	1.1977E+17
LITHIUM 7	2.8416E+02	1.8740E+13
BERYLLIUM	1.7247E+02	8.8344E+12
BORON 10	3.1076E+06	1.4345E+17
BORON 11	1.2387E+02	5.1985E+12
CARBON 12	1.1110E+02	4.2741E+12
NITROGEN	5.4035E+02	1.7809E+13
OXYGEN	9.6357E+01	2.7802E+12
FLOURINE	1.1791E+02	2.8651E+12
SODIUM	1.7774E+02	3.5689E+12
MAGNESIUM	6.6489E+01	1.2625E+12
ALUMINUM	1.5652E+02	2.6780E+12
SILICON	6.1526E+01	1.0113E+12
CHLORINE	4.2339E+03	5.5129E+13
POTASSIUM	2.0186E+02	2.3831E+12
CALCIUM	1.5160E+02	1.7461E+12
TITANIUM	1.3873E+02	1.3370E+12
VANADIUM	1.9190E+03	1.7390E+13
CHROMIUM	6.3946E+01	5.6772E+11
MANGANESE	3.6924E+03	3.1026E+13
IRON	3.7253E+01	3.0793E+11
COBALT	3.9908E+01	3.1260E+11
NICKEL	1.1319E+02	8.8997E+11
COPPER	6.9447E+02	5.0455E+12
ZIRCONIUM	2.4555E+01	1.2427E+11
NIOBIUM	2.6752E+01	1.3292E+11
MOLYBDENUM	3.5935E+02	1.7291E+12
TIN	1.9910E+01	7.7439E+10
TANTALUM	1.8129E+01	4.6251E+10
TUNGSTEN 182	1.7285E+01	4.3843E+10
TUNGSTEN 183	1.6182E+01	4.0820E+10
TUNGSTEN 184	1.4677E+02	3.6824E+11
TUNGSTEN 186	9.0611E+03	2.2489E+13
LEAD	2.3218E+01	5.1730E+10
THORIUM 232	4.8211E+03	9.5929E+12
PROTACTINIUM	1.4967E+04	2.9910E+13
URANIUM 233	3.3954E+07	6.7271E+16
URANIUM 234	4.3370E+04	8.5560E+13
URANIUM 235	3.3628E+07	6.6059E+16
URANIUM 236	1.9563E+04	3.8266E+13
URANIUM 238	1.0099E+04	1.9588E+13
NEPTUNIUM	5.2736E+04	1.0272E+14
PLUTONIUM 238	1.1091E+06	2.1513E+15
PLUTONIUM 239	6.5438E+07	1.2639E+17
PLUTONIUM 240	6.5751E+04	1.2647E+14
PLUTONIUM 241	7.1867E+07	1.3766E+17
PLUTONIUM 242	4.6266E+04	8.8255E+13
AMERICIUM 241	3.9403E+05	7.5476E+14
AMERICIUM 243	3.7071E+04	7.0424E+13

* Caution: Burnup effects not included.

Table V. Sample Gas Production Results from SPECTER (HFIR Input in Table III)

SPECTRAL AVERAGED GAS PRODUCTION (ENDF 533)*

	SIGMA(MB)	GAS(APPM) (4.78E+22)
LI6(N,HYDROGEN)	9.7882E-01	4.6824E+01
LI6(N,DEUTERIUM)	2.3394E+01	1.1191E+03
LI6(N,TRITIUM)	3.1126E+05	1.0000E+06
LI6(N,HELIUM)	3.1128E+05	1.0000E+06
LI7(N,DEUTERIUM)	3.4531E-03	1.6519E-01
LI7(N,TRITIUM)	4.5686E+00	2.1855E+02
LI7(N,HELIUM)	2.8447E+01	1.3608E+03
BE9(N,HYDROGEN)	4.6710E-06	2.2345E-04
BE9(N,DEUTERIUM)	5.0308E-06	2.4066E-04
BE9(N,TRITIUM)	6.1720E-04	2.9525E-02
BE9(N,HELIUM)	4.8723E+01	2.3308E+03
B10(N,HYDROGEN)	1.7095E+00	8.1780E+01
B10(N,DEUTERIUM)	2.7667E-01	1.3235E+01
B10(N,HELIUM)	1.2753E+06	1.0000E+06
B11(N,HYDROGEN)	4.7018E-05	2.2492E-03
B11(N,TRITIUM)	4.5617E-04	2.1822E-02
B11(N,X)HELIUM	9.8452E-03	4.7097E-01
C12(N,HYDROGEN)	3.5266E-05	1.6870E-03
C12(N,HELIUM)	4.5151E-01	2.1599E+01
N14(N,HYDROGEN)	6.1271E+02	2.9310E+04
N14(N,HELIUM)	1.5503E+01	7.4162E+02
F19(N,HYDROGEN)	2.2115E-01	1.0579E+01
F19(N,HELIUM)	4.6436E+00	2.2214E+02
AL27(N,HYDROGEN)	8.0259E-01	3.8394E+01
AL27(N,HELIUM)	1.7148E-01	8.2029E+00
SI28(N,HYDROGEN)	1.1873E+00	5.6796E+01
SI28(N,HELIUM)	5.7668E-01	2.7587E+01
TI(N,HYDROGEN)	5.1671E-01	2.4718E+01
TI(N,HELIUM)	1.1246E-01	5.3798E+00
V(N,HYDROGEN)	9.8645E-02	4.7189E+00
V(N,HELIUM)	5.7802E-03	2.7651E-01
CR(N,HYDROGEN)	7.9783E-01	3.8166E+01
CR(N,DEUTERIUM)	1.8507E-05	8.8531E-04
CR(N,TRITIUM)	2.8279E-05	1.3528E-03
CR(N,HELIUM3)	9.0368E-07	4.3230E-05
CR(N,HELIUM4)	3.9193E-02	1.8749E+00
MN55(N,HYDROGEN)	1.4163E-01	6.7752E+00
MN55(N,HELIUM)	3.4704E-02	1.6602E+00
FE(N,HYDROGEN)	1.0707E+00	5.1222E+01
FE(N,HELIUM)	6.9787E-02	3.3384E+00
CO59(N,HYDROGEN)	2.8617E-01	1.3690E+01
CO59(N,HELIUM)	3.4375E-02	1.6444E+00
NI(N,HYDROGEN)	1.2970E+01	6.2044E+02
NI(N,DEUTERIUM)	2.5831E-03	1.2357E-01
NI(N,HELIUM)	9.1864E-01	4.3945E+01
CU(N,HYDROGEN)	2.2322E+00	1.0678E+02
CU(N,HELIUM)	6.2302E-02	2.9804E+00

*Caution: Burnup effects not considered.

Table VI: Displacement Damage Output from SPECTER
(HFIR-CTR32 Input in Table III)

TITANIUM 1322
EDL = 0.40000E-04 MEV TOTAL FLUENCE = 4.78373E+22 +/- 3.70 %

DPA = 1.0464E+01 HELIUM(APPM) = 5.3709E+00 HYDROGEN(APPM) = 2.4627E+01

ELASTIC	INELST	(N,2N)	(N,2N)P	(N,2N)SUM	CH1	CH2	SUM	
1.5176E+02	5.8294E+01	1.6675E-02	5.1851E-02	6.8550E-02	3.5695E-01	4.3025E-02	2.1053E+02	BARNS
1.5176E+01	5.8294E+00	1.6675E-03	5.1851E-03	6.8550E-03	3.5695E-02	4.3025E-03	2.1053E+01	KEV-BARNS
+/- 7.04%	+/- 5.75%	+/- 12.01%	+/- 12.12%	+/- 12.01%	+/- 5.19%	+/- 8.75%	+/- 6.39%	
6.0330E+00	1.1528E-01	1.1761E-05	3.5086E-05		5.1481E-04	1.1227E-04	6.1489E+00	NUCLEAR - BARNS
+/- 5.97%	+/- 7.00%	+/- 12.03%	+/- 12.14%		+/- 4.50%	+/- 4.46%	+/- 5.86%	

CAPTURE GAMMA DAMAGE = 8.2036E-01 KEV-B +/- 4.09% CS = 2.0225E+00 BARNS, TGAM = 400.0 EV

TOTAL DPA CROSS-SECTION = 2.1873E+01 KEV-B; OR 2.1873E+02 BARNS

IRON - 1326
EDL = 0.40000E-04 MEV TOTAL FLUENCE = 4.78373E+22 +/- 3.70 %

DPA = 9.1455E+00 HELIUM(APPM) = 3.1944E+00 HYDROGEN(APPM) = 5.0028E+01

ELASTIC	INELST	(N,2N)	(N,2N)P	(N,2N)SUM	CH1	CH2	SUM	
1.2978E+02	5.7071E+01	1.8712E-02	5.7735E-02	7.6442E-02	6.6229E-01	8.9148E-02	1.8768E+02	BARNS
1.2978E+01	5.7071E+00	1.8712E-03	5.7735E-03	7.6442E-03	6.6229E-02	8.9148E-03	1.8768E+01	KEV-BARNS
+/- 6.99%	+/- 5.64%	+/- 12.08%	+/- 12.15%	+/- 12.00%	+/- 5.91%	+/- 9.66%	+/- 6.23%	
8.6295E+00	1.2214E-01	1.3282E-05	4.0015E-05		1.0458E-03	6.6776E-05	8.7528E+00	NUCLEAR - BARNS
+/- 3.68%	+/- 7.08%	+/- 12.09%	+/- 12.17%		+/- 4.61%	+/- 6.99%	+/- 3.63%	

CAPTURE GAMMA DAMAGE = 3.5033E-01 KEV-B +/- 4.04% CS = 8.5700E-01 BARNS, TGAM = 395.0 EV

TOTAL DPA CROSS-SECTION = 1.9118E+01 KEV-B; OR 1.9118E+02 BARNS

COPPER - 1329
EDL = 0.40000E-04 MEV TOTAL FLUENCE = 4.78373E+22 +/- 3.70 %

DPA = 8.9212E+00 HELIUM(APPM) = 2.8999E+00 HYDROGEN(APPM) = 1.0298E+02

ELASTIC	INELST	(N,2N)	(N,2N)P	(N,2N)SUM	CH1	CH2	SUM	
1.2490E+02	5.4999E+01	9.0949E-02	4.8554E-01	5.7643E-01	7.5308E-01	3.2401E-02	1.8127E+02	BARNS
1.2490E+01	5.4999E+00	9.0949E-03	4.8554E-02	5.7643E-02	7.5308E-02	3.2401E-03	1.8127E+01	KEV-BARNS
+/- 7.07%	+/- 5.72%	+/- 10.75%	+/- 11.01%	+/- 10.89%	+/- 6.26%	+/- 10.95%	+/- 6.20%	
7.6410E+00	1.3669E-01	7.8463E-05	4.0682E-04		2.1526E-03	6.0621E-05	7.7804E+00	NUCLEAR - BARNS
+/- 3.89%	+/- 7.25%	+/- 10.78%	+/- 11.04%		+/- 5.65%	+/- 7.71%	+/- 3.82%	

CAPTURE GAMMA DAMAGE = 5.2225E-01 KEV-B +/- 3.85% CS = 1.3295E+00 BARNS, TGAM = 366.0 EV

TOTAL DPA CROSS-SECTION = 1.8649E+01 KEV-B; OR 1.8649E+02 BARNS

Table VII: Selected Displacement-Damage Cross Sections from SPECTER
To obtain displacement cross sections, multiply by $0.8/2E_d$, where E_d is taken from Table II or a value of your choice. Values below are in keV-b.

	Theoretical			Reactors[d]			
Element	Thermal[a]	Fission[b]	14 MeV[c]	HFIR	EBR-II	FFTF	Fusion
Be	0.010	35.3	23.1	11.1	36.1	28.9	27.5
C	0.002	52.0	39.0	14.6	46.8	34.1	36.1
Na	0.328	97.1	140.	24.1	67.2	42.3	74.1
Mg	0.029	92.8	160.	24.4	73.7	52.3	81.5
Al	0.156	96.3	177.	23.2	65.1	41.5	83.2
Si	0.097	96.0	191.	22.7	64.4	38.8	85.0
K	0.733	89.3	257.	19.2	44.4	24.1	95.1
Ca	0.167	95.4	273.	20.2	47.2	25.5	101.8
Ti	2.44	92.8	244.	21.9	47.8	30.4	93.7
V	2.27	101.	270.	24.5	58.2	37.3	105.5
Cr	1.70	94.8	278.	21.6	52.0	30.6	104.0
Mn	5.25	94.6	260.	23.8	54.2	34.6	101.4
Fe	1.01	84.4	290.	19.1	46.3	27.3	101.8
Co	13.38	81.7	294.	24.1	49.0	30.4	102.9
Ni	2.20	85.0	300.	20.6	51.0	32.2	109.4
Cu	1.38	79.2	296.	18.6	46.6	28.5	103.8
Zr	0.026	86.0	259.	20.1	54.3	32.9	98.3
Nb	0.128	79.5	271.	18.5	49.9	29.8	96.9
Mo	0.268	83.5	259.	20.6	53.6	35.4	100.1
Ag	10.06	71.1	230.	23.0	42.0	24.9	83.0
Ta	0.401	53.5	216.	12.4	29.5	16.9	72.5
W	0.275	50.8	197.	11.6	28.6	16.5	68.0
Au	6.51	50.2	218.	15.8	27.7	16.4	72.5
Pb	0.021	59.6	203.	13.0	31.3	18.1	71.4

[a]Thermal (n,γ). Value equals T_{GAM} (Table 2) x σ_o (2200 m/s).

[b]^{235}U fission spectrum.

[c]Average value of SPECTER energy group from 14-15 MeV.

[d]HFIR = High Flux Isotope Reactor (ORNL) - PTP position.
EBR-II = Experimental Breeder Reactor II (ANL-W) - Row 2.
FFTF = Fast Flux Test Facility (HEDL) - MOTA
Fusion = First Wall Fusion Spectrum (UWMAK design).
All values are averages over the entire spectrum.

(L. Greenwood). The procedure for running SPECTER is contained in a single COSMOS file named COSPECT. This file will automatically do a FILEM to retrieve the necessary files from disk, run SPECTER, and NETOUT the results to your location. The files needed by SPECTER are contained in my directory, .111. Before running, copy both COSPECT and the directory .111 to your space. Add to your FILEM space for a permanent record.

To run SPECTER, create an input file named SPIN (see sample in my directory as well as output SPOUT). Then simply type in:

COSMOS COSPECT SITE = XXX BOX = YYY

SPECTER will create an output file named SPOUT and do a NETOUT to your box.

D. SPECTER Results for Selected Cases

Table VII lists same selected spectral-averaged dpa cross sections for various neutron spectra. Figure 6 shows the calculated range of helium and dpa values for typical irradiations in fusion materials facilities. Detailed examples of SPECTER results have also been published in many recent Damage Analysis and Fundamental Studies and Alloy Development for Irradiation Performance Quarterly Progress Reports published by the U.S. Department of Energy.

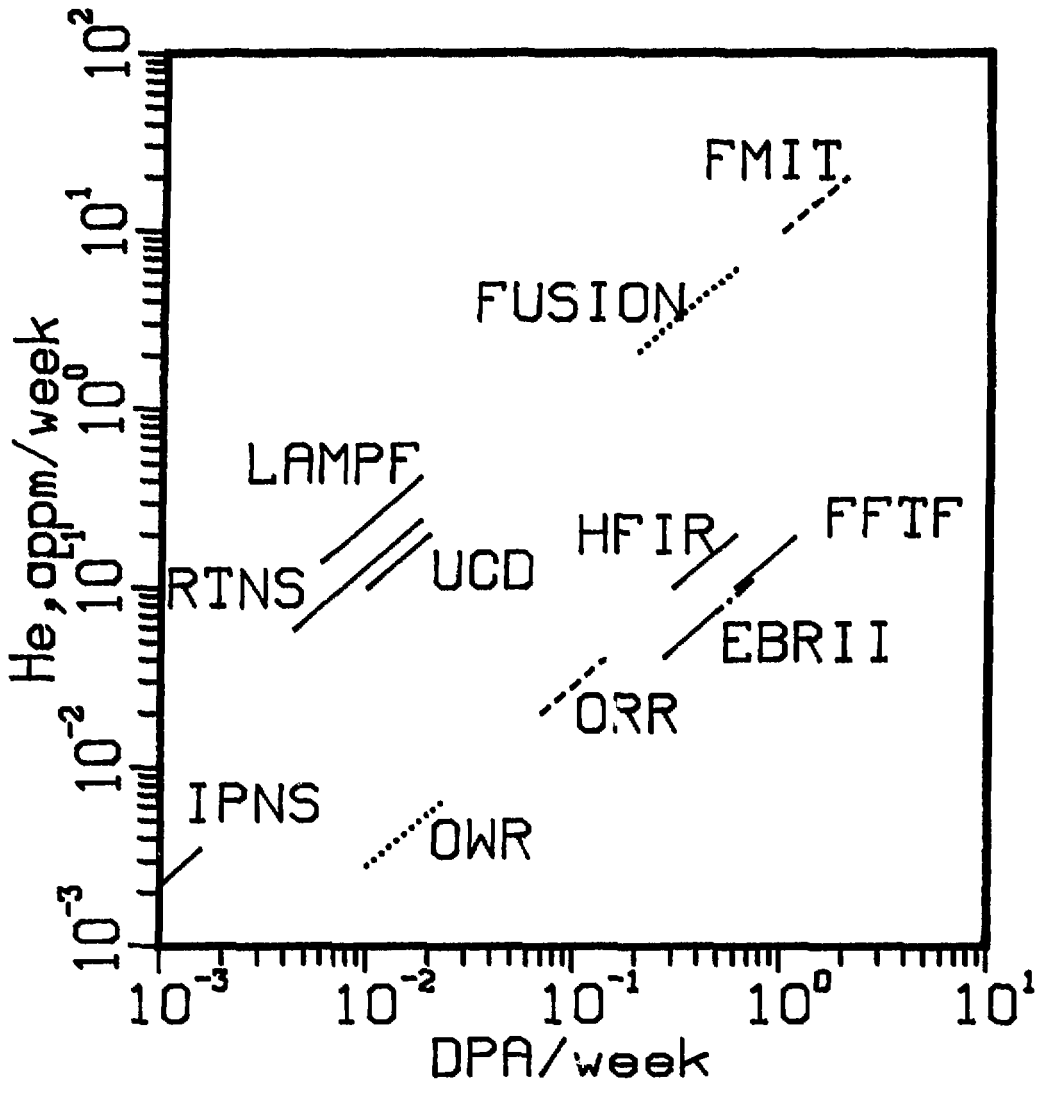

Fig. 6. Helium (appm) and dpa rates per week for iron are shown for most of the fusion materials irradiation facilities. Note that fission reactors produce high dpa but lot helium (relative to fusion) whereas accelerators have a high helium-to-dpa ratio but low flux.

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APPENDIX A

Displacement Damage-Energy Cross Section Tables

Displacement damage-energy cross sections are listed in units of keV-b. The displacement damage cross sections can be obtained by multiplying times the factor $0.8/2E_d$, where E_d is the cutoff energy in Table II (or a value of your choice). The cross sections are listed in order of increasing atomic number (except for Be which is included with H).

DISPLACEMENT DAMAGE-ENERGY CROSS SECTIONS, keV-b

ENERGY	H	Be	ENERGY	H	Be
1.00E-10	1.339	0.09	0.088	6.92	31.02
1.00E-09	0.424	0.03	0.110	6.52	33.67
1.00E-08	0.222	0.02	0.135	6.15	35.69
2.30E-08	0.14[illegible]	0.01	0.160	5.78	37.15
5.00E-08	0.112	0.01	0.190	5.44	38.07
7.60E-08	0.091	0.01	0.220	5.13	38.44
1.15E-07	0.074	0.01	0.255	4.83	38.85
1.70E-07	0.061	0.00	0.290	4.62	39.40
2.55E-07	0.050	0.00	0.320	4.38	39.57
3.80E-07	0.041	0.00	0.360	4.16	39.53
5.50E-07	0.034	0.00	0.400	3.94	39.16
8.40E-07	0.027	0.00	0.450	3.74	38.43
1.28E-06	0.022	0.00	0.500	3.56	38.65
1.90E-06	0.018	0.00	0.550	3.41	43.03
2.80E-06	0.015	0.00	0.600	3.26	65.51
4.25E-06	0.012	0.00	0.660	3.12	42.34
6.30E-06	0.010	0.00	0.720	2.98	41.31
9.20E-06	0.008	0.00	0.780	2.89	46.31
1.35E-05	0.007	0.00	0.840	2.76	42.36
2.10E-05	0.006	0.00	0.920	2.64	41.48
3.00E-05	0.005	0.00	1.000	2.48	39.20
4.50E-05	0.164	0.00	1.200	2.28	34.04
6.90E-05	0.521	0.00	1.400	2.12	28.99
1.00E-04	0.657	0.09	1.600	1.98	25.54
1.35E-04	0.708	0.17	1.800	1.87	23.85
1.70E-04	0.790	0.24	2.000	1.75	26.34
2.20E-04	0.910	0.26	2.300	1.63	35.75
2.80E-04	1.068	0.30	2.600	1.53	49.54
3.60E-04	1.250	0.36	2.900	1.43	40.27
4.50E-04	1.485	0.43	3.300	1.34	33.02
5.75E-04	1.785	0.54	3.700	1.26	28.85
7.60E-04	2.137	0.68	4.100	1.19	28.49
9.60E-04	2.539	0.87	4.500	1.12	28.56
1.28E-03	2.980	1.09	5.000	1.06	28.45
1.60E-03	3.415	1.35	5.500	1.00	28.11
2.00E-03	3.952	1.72	6.000	0.95	27.77
2.70E-03	4.515	2.20	6.700	0.89	27.31
3.40E-03	5.072	2.79	7.400	0.84	26.97
4.50E-03	5.586	3.46	8.200	0.79	26.61
5.50E-03	6.082	4.29	9.000	0.74	26.17
7.20E-03	6.577	5.38	10.000	0.70	25.68
9.20E-03	7.015	6.73	11.000	0.67	25.13
1.20E-02	7.371	8.25	12.000	0.64	24.50
1.50E-02	7.646	9.96	13.000	0.61	23.95
1.90E-02	7.872	12.31	14.000	0.59	23.22
2.55E-02	7.972	14.94	15.000	0.57	22.79
3.20E-02	7.972	17.55	16.000	0.56	21.99
4.00E-02	7.860	20.77	17.000	0.54	21.99
5.25E-02	7.648	24.12	18.000	0.53	21.86
6.60E-02	7.323	27.70	19.000	0.52	21.42

DISPLACEMENT DAMAGE-ENERGY CROSS SECTIONS, keV-b

ENERGY	3-He	4-He	ENERGY	3-He	4-He
1.00E-10	124950.000	0.00	0.088	10.22	2.12
1.00E-09	39425.000	0.00	0.110	9.84	2.26
1.00E-08	20630.000	0.00	0.135	9.55	2.38
2.30E-08	13835.000	0.00	0.160	9.36	2.51
5.00E-08	10397.000	0.00	0.190	9.23	2.64
7.60E-08	8445.000	0.00	0.220	9.08	2.79
1.15E-07	6912.500	0.00	0.255	8.95	2.98
1.70E-07	5662.500	0.00	0.290	8.88	3.16
2.55E-07	4635.000	0.00	0.320	8.81	3.41
3.80E-07	3827.500	0.00	0.360	8.73	3.74
5.50E-07	3137.500	0.00	0.400	8.66	4.20
8.40E-07	2545.000	0.00	0.450	8.61	4.84
1.28E-06	2078.000	0.00	0.500	8.58	5.67
1.90E-06	1709.200	0.00	0.550	8.53	6.72
2.80E-06	1398.700	0.00	0.600	8.52	8.18
4.25E-06	1144.700	0.00	0.660	8.53	10.22
6.30E-06	944.250	0.00	0.720	8.60	12.91
9.20E-06	779.500	0.00	0.780	8.69	15.53
1.35E-05	633.250	0.00	0.840	8.85	19.38
2.10E-05	520.500	0.00	0.920	9.02	23.19
3.00E-05	429.250	0.01	1.000	9.32	26.25
4.50E-05	348.500	0.01	1.200	9.70	24.41
6.90E-05	285.750	0.01	1.400	10.08	20.41
1.00E-04	242.020	0.02	1.600	10.25	17.19
1.35E-04	212.200	0.02	1.800	10.25	14.96
1.70E-04	187.620	0.03	2.000	10.10	13.13
2.20E-04	165.350	0.04	2.300	9.92	11.70
2.80E-04	146.000	0.05	2.600	9.67	10.77
3.60E-04	129.750	0.06	2.900	9.35	10.04
4.50E-04	115.420	0.07	3.300	8.95	9.45
5.75E-04	101.220	0.09	3.700	8.60	9.02
7.60E-04	89.150	0.12	4.100	8.27	8.65
9.60E-04	78.350	0.15	4.500	7.91	8.28
1.28E-03	69.200	0.18	5.000	7.55	7.91
1.60E-03	61.825	0.22	5.500	7.22	7.56
2.00E-03	53.800	0.28	6.000	6.84	7.17
2.70E-03	46.325	0.34	6.700	6.41	6.75
3.40E-03	40.200	0.42	7.400	6.02	6.33
4.50E-03	35.300	0.50	8.200	5.63	5.93
5.50E-03	31.075	0.59	9.000	5.27	5.51
7.20E-03	27.100	0.70	10.000	4.87	5.11
9.20E-03	23.707	0.83	11.000	4.53	4.75
1.20E-02	20.950	0.95	12.000	4.24	4.43
1.50E-02	18.720	1.08	13.000	3.97	4.14
1.90E-02	16.520	1.24	14.000	3.74	3.88
2.55E-02	14.725	1.39	15.000	3.55	3.65
3.20E-02	13.415	1.52	16.000	3.34	3.44
4.00E-02	12.227	1.67	17.000	3.15	3.26
5.25E-02	11.287	1.82	18.000	3.00	3.10
6.60E-02	10.577	1.97	19.000	2.87	2.95

DISPLACEMENT DAMAGE-ENERGY CROSS SECTIONS, keV-b

ENERGY	6-Li	7-Li	ENERGY	6-Li	7-Li
1.00E-10	65176.000	1.96	0.088	9.68	3.91
1.00E-09	20635.000	0.64	0.110	11.14	4.24
1.00E-08	10775.000	0.34	0.135	14.37	4.85
2.30E-08	7230.100	0.23	0.160	22.56	6.11
5.00E-08	5432.500	0.17	0.190	43.47	9.39
7.60E-08	4412.500	0.14	0.220	72.38	35.58
1.15E-07	3610.000	0.12	0.255	59.47	43.85
1.70E-07	2957.500	0.10	0.290	39.97	18.81
2.55E-07	2418.800	0.08	0.320	27.08	11.52
3.80E-07	1997.000	0.06	0.360	20.40	9.29
5.50E-07	1635.800	0.05	0.400	16.71	8.70
8.40E-07	1326.300	0.04	0.450	14.44	8.28
1.28E-06	1082.000	0.03	0.500	13.15	8.10
1.90E-06	889.010	0.03	0.550	12.27	8.18
2.80E-06	726.510	0.02	0.600	11.63	8.49
4.25E-06	593.500	0.02	0.660	11.14	8.99
6.30E-06	489.500	0.02	0.720	10.77	9.62
9.20E-06	404.500	0.01	0.780	10.56	10.21
1.35E-05	328.750	0.01	0.840	10.33	11.22
2.10E-05	269.750	0.01	0.920	10.16	12.53
3.00E-05	222.830	0.02	1.000	10.02	14.16
4.50E-05	180.900	0.02	1.200	9.92	14.92
6.90E-05	148.430	0.02	1.400	10.02	14.77
1.00E-04	125.750	0.03	1.600	10.39	14.88
1.35E-04	110.300	0.03	1.800	11.17	15.23
1.70E-04	97.626	0.04	2.000	12.21	15.94
2.20E-04	86.251	0.04	2.300	13.35	16.97
2.80E-04	76.226	0.06	2.600	14.50	17.75
3.60E-04	67.701	0.07	2.900	16.04	18.33
4.50E-04	60.201	0.08	3.300	17.29	19.08
5.75E-04	52.800	0.11	3.700	18.04	20.79
7.60E-04	46.525	0.14	4.100	18.03	22.35
9.60E-04	40.900	0.17	4.500	17.79	22.09
1.28E-03	36.050	0.22	5.000	17.35	19.70
1.60E-03	32.275	0.27	5.500	17.09	19.01
2.00E-03	28.375	0.34	6.000	16.69	18.42
2.70E-03	24.968	0.43	6.700	16.40	17.20
3.40E-03	22.080	0.54	7.400	15.89	16.34
4.50E-03	19.753	0.66	8.200	15.35	16.10
5.50E-03	17.720	0.82	9.000	14.82	15.61
7.20E-03	15.823	1.01	10.000	14.16	15.04
9.20E-03	14.205	1.24	11.000	13.59	14.63
1.20E-02	12.898	1.48	12.000	13.05	14.25
1.50E-02	11.853	1.74	13.000	12.51	13.75
1.90E-02	10.853	2.07	14.000	12.01	13.25
2.55E-02	10.088	2.41	15.000	11.57	12.86
3.20E-02	9.583	2.72	16.000	11.14	12.54
4.00E-02	9.185	3.06	17.000	10.75	12.21
5.25E-02	8.990	3.38	18.000	10.42	11.86
6.60E-02	9.080	3.67	19.000	10.13	11.58

DISPLACEMENT DAMAGE-ENERGY CROSS SECTIONS, keV-b

ENERGY	10-B	11-B	ENERGY	10-B	11-B
1.00E-10	725630.000	0.15	0.088	66.56	27.71
1.00E-09	231310.000	0.05	0.110	66.00	30.70
1.00E-08	121250.000	0.03	0.135	66.44	33.11
2.30E-08	81188.000	0.02	0.160	67.50	35.26
5.00E-08	61056.000	0.01	0.190	68.82	37.36
7.60E-08	49563.000	0.01	0.220	70.00	39.31
1.15E-07	40544.000	0.01	0.255	70.50	40.02
1.70E-07	33238.000	0.01	0.290	70.82	40.53
2.55E-07	27175.000	0.01	0.320	70.50	41.33
3.80E-07	22444.000	0.00	0.360	70.32	44.90
5.50E-07	18381.000	0.00	0.400	70.25	76.56
8.40E-07	14906.000	0.00	0.450	69.69	59.78
1.28E-06	12156.000	0.00	0.500	67.63	48.72
1.90E-06	9993.800	0.00	0.550	64.50	46.32
2.80E-06	8162.500	0.00	0.600	61.17	45.06
4.25E-06	6668.800	0.00	0.660	58.12	44.05
6.30E-06	5503.100	0.00	0.720	55.42	43.53
9.20E-06	4548.800	0.00	0.780	53.63	43.26
1.35E-05	3695.600	0.00	0.840	51.26	42.42
2.10E-05	3033.800	0.00	0.920	49.31	41.03
3.00E-05	2505.000	0.00	1.000	46.49	41.74
4.50E-05	2034.400	0.00	1.200	42.58	62.42
6.90E-05	1670.000	0.00	1.400	39.63	45.70
1.00E-04	1413.800	0.08	1.600	40.49	43.95
1.35E-04	1236.900	0.13	1.800	44.76	40.50
1.70E-04	1092.500	0.16	2.000	40.53	35.35
2.20E-04	963.750	0.18	2.300	42.64	37.99
2.80E-04	851.250	0.22	2.600	47.97	35.51
3.60E-04	756.250	0.26	2.900	40.36	31.89
4.50E-04	671.250	0.31	3.300	33.92	34.24
5.75E-04	587.750	0.40	3.700	34.45	32.39
7.60E-04	517.060	0.50	4.100	36.47	29.42
9.60E-04	453.310	0.64	4.500	32.31	37.35
1.28E-03	398.440	0.81	5.000	27.83	36.88
1.60E-03	355.690	1.00	5.500	27.19	36.73
2.00E-03	310.940	1.29	6.000	29.35	35.26
2.70E-03	272.310	1.64	6.700	30.98	33.04
3.40E-03	239.190	2.09	7.400	30.78	33.68
4.50E-03	212.190	2.60	8.200	30.09	30.69
5.50E-03	188.500	3.24	9.000	29.94	30.47
7.20E-03	166.000	4.10	10.000	30.59	30.42
9.20E-03	146.440	5.18	11.000	31.06	30.52
1.20E-02	130.380	6.46	12.000	30.98	31.23
1.50E-02	117.060	7.96	13.000	30.86	33.18
1.90E-02	103.880	11.42	14.000	30.86	33.42
2.55E-02	93.126	12.22	15.000	30.90	33.20
3.20E-02	85.314	14.39	16.000	30.84	32.83
4.00E-02	78.251	17.16	17.000	30.83	32.46
5.25E-02	72.814	20.24	18.000	30.81	32.09
6.60E-02	68.814	23.88	19.000	30.77	31.70

DISPLACEMENT DAMAGE-ENERGY CROSS SECTIONS, keV-b

ENERGY	C	N	O	ENERGY	C	N	O
1.00E-10	0.02	0.95	0.00	0.088	28.51	28.47	23.26
1.00E-09	0.01	0.30	0.00	0.110	32.63	31.58	27.87
1.00E-08	0.00	0.16	0.00	0.135	36.37	34.46	32.53
2.30E-08	0.00	0.11	0.00	0.160	39.88	37.16	37.49
5.00E-08	0.00	0.08	0.00	0.190	43.11	39.63	42.70
7.60E-08	0.00	0.06	0.00	0.220	46.03	41.92	48.38
1.15E-07	0.00	0.05	0.00	0.255	48.58	43.67	54.95
1.70E-07	0.00	0.04	0.00	0.290	50.67	45.14	61.90
2.55E-07	0.00	0.04	0.00	0.320	52.40	46.28	73.15
3.80E-07	0.00	0.03	0.00	0.360	54.03	47.75	99.00
5.50E-07	0.00	0.02	0.00	0.400	55.45	62.44	201.30
8.40E-07	0.00	0.02	0.00	0.450	56.61	46.17	110.10
1.28E-06	0.00	0.02	0.00	0.500	57.44	42.42	60.11
1.90E-06	0.00	0.01	0.00	0.550	57.98	38.66	58.64
2.80E-06	0.00	0.01	0.00	0.600	58.33	41.44	61.30
4.25E-06	0.00	0.01	0.00	0.660	58.43	51.74	64.98
6.30E-06	0.00	0.01	0.00	0.720	58.24	46.62	68.39
9.20E-06	0.00	0.01	0.00	0.780	58.20	43.20	73.17
1.35E-05	0.00	0.00	0.00	0.840	57.68	37.29	86.70
2.10E-05	0.00	0.00	0.00	0.920	57.02	32.06	162.90
3.00E-05	0.00	0.00	0.00	1.000	55.62	56.39	133.42
4.50E-05	0.00	0.00	0.00	1.200	53.29	56.05	101.10
6.90E-05	0.00	0.00	0.00	1.400	50.90	61.58	75.15
1.00E-04	0.00	0.00	0.00	1.600	48.63	63.26	75.97
1.35E-04	0.08	0.11	0.02	1.800	46.62	52.72	73.06
1.70E-04	0.15	0.25	0.07	2.000	50.21	52.88	52.54
2.20E-04	0.19	0.34	0.12	2.300	45.62	48.23	29.65
2.80E-04	0.21	0.38	0.15	2.600	55.72	50.57	46.05
3.60E-04	0.25	0.44	0.17	2.900	58.12	64.79	70.21
4.50E-04	0.29	0.51	0.19	3.300	72.73	65.89	117.97
5.75E-04	0.36	0.62	0.24	3.700	61.36	74.38	92.78
7.60E-04	0.45	0.77	0.29	4.100	52.53	73.68	73.87
9.60E-04	0.57	0.95	0.37	4.500	39.43	45.71	53.60
1.28E-03	0.72	1.18	0.47	5.000	36.31	55.62	54.74
1.60E-03	0.89	1.43	0.58	5.500	33.61	54.88	58.51
2.00E-03	1.14	1.81	0.74	6.000	35.15	52.10	48.52
2.70E-03	1.46	2.27	0.95	6.700	30.33	53.28	63.85
3.40E-03	1.86	2.85	1.21	7.400	51.57	60.41	61.20
4.50E-03	2.31	3.50	1.52	8.200	31.47	50.92	67.20
5.50E-03	2.89	4.30	1.91	9.000	30.54	53.40	64.77
7.20E-03	3.66	5.37	2.43	10.000	33.43	58.08	69.82
9.20E-03	4.63	6.68	3.09	11.000	39.79	58.47	86.63
1.20E-02	5.76	8.18	3.88	12.000	39.13	63.72	78.15
1.50E-02	7.07	9.80	4.82	13.000	38.51	63.51	79.95
1.90E-02	8.94	11.97	6.18	14.000	39.11	63.18	83.55
2.55E-02	11.13	14.38	7.82	15.000	43.03	62.94	82.43
3.20E-02	13.41	16.67	9.59	16.000	44.28	62.08	80.70
4.00E-02	16.40	19.37	12.02	17.000	42.79	61.24	82.95
5.25E-02	19.85	22.14	14.95	18.000	45.59	60.54	81.60
6.60E-02	24.02	25.28	18.79	19.000	46.58	59.83	82.35

DISPLACEMENT DAMAGE-ENERGY CROSS SECTIONS, keV-b

ENERGY	F	Na	Mg	ENERGY	F	Na	Mg
1.00E-10	0.09	2.49	0.28	0.088	94.07	18.11	51.94
1.00E-09	0.03	0.79	0.09	0.110	39.31	21.24	27.88
1.00E-08	0.01	0.41	0.05	0.135	31.37	24.25	29.98
2.30E-08	0.01	0.28	0.03	0.160	32.17	28.09	34.36
5.00E-08	0.01	0.21	0.02	0.190	38.66	48.35	51.18
7.60E-08	0.01	0.17	0.02	0.220	62.90	52.96	86.06
1.15E-07	0.00	0.14	0.02	0.255	108.70	33.98	119.06
1.70E-07	0.00	0.11	0.01	0.290	108.01	44.13	99.69
2.55E-07	0.00	0.09	0.01	0.320	109.13	46.28	77.75
3.80E-07	0.00	0.08	0.01	0.360	115.66	63.45	66.25
5.50E-07	0.00	0.06	0.01	0.400	117.60	62.95	132.25
8.40E-07	0.00	0.05	0.01	0.450	85.96	50.69	82.72
1.28E-06	0.00	0.04	0.00	0.500	88.88	50.06	69.22
1.90E-06	0.00	0.03	0.00	0.550	84.99	86.26	69.53
2.80E-06	0.00	0.03	0.00	0.600	80.63	94.63	46.72
4.25E-06	0.00	0.02	0.00	0.660	68.39	143.01	84.78
6.30E-06	0.00	0.02	0.00	0.720	92.40	113.45	69.10
9.20E-06	0.00	0.02	0.00	0.780	96.60	100.76	79.16
1.35E-05	0.00	0.01	0.00	0.840	94.88	105.01	76.97
2.10E-05	0.00	0.01	0.00	0.920	92.63	85.44	60.61
3.00E-05	0.00	0.01	0.00	1.000	99.45	91.88	67.53
4.50E-05	0.00	0.01	0.00	1.200	125.41	101.26	88.97
6.90E-05	0.00	0.01	0.00	1.400	111.76	87.45	72.10
1.00E-04	0.00	0.01	0.00	1.600	119.10	105.07	110.78
1.35E-04	0.00	0.00	0.00	1.800	113.40	98.82	99.72
1.70E-04	0.04	0.04	0.03	2.000	114.98	120.83	105.97
2.20E-04	0.09	0.07	0.07	2.300	123.38	121.02	105.53
2.80E-04	0.13	0.10	0.11	2.600	122.26	110.95	127.16
3.60E-04	0.15	0.11	0.12	2.900	105.91	103.58	103.66
4.50E-04	0.17	0.13	0.14	3.300	98.56	122.83	118.41
5.75E-04	0.21	0.16	0.17	3.700	87.68	117.08	101.54
7.60E-04	0.25	0.21	0.21	4.100	98.86	117.65	134.67
9.60E-04	0.32	0.30	0.25	4.500	93.91	115.15	129.98
1.28E-03	0.40	0.49	0.32	5.000	90.46	120.09	124.61
1.60E-03	0.49	1.05	0.39	5.500	101.03	116.72	124.68
2.00E-03	0.63	10.93	0.51	6.000	93.76	120.04	108.75
2.70E-03	0.81	37.29	0.65	6.700	94.73	114.29	122.44
3.40E-03	1.04	5.71	0.84	7.400	99.53	121.42	121.45
4.50E-03	1.30	3.08	1.05	8.200	102.46	118.55	130.33
5.50E-03	1.63	2.73	1.33	9.000	103.21	120.43	130.22
7.20E-03	2.08	2.83	1.69	10.000	106.13	128.50	137.29
9.20E-03	2.66	3.19	2.18	11.000	106.36	133.82	143.99
1.20E-02	3.36	3.70	2.74	12.000	107.93	136.71	150.93
1.50E-02	4.18	4.35	3.93	13.000	108.76	138.78	153.75
1.90E-02	5.63	5.37	7.04	14.000	110.33	139.98	159.95
2.55E-02	26.46	6.68	6.29	15.000	111.76	140.93	158.59
3.20E-02	9.08	8.17	7.39	16.000	111.61	142.19	158.22
4.00E-02	34.45	11.81	9.21	17.000	110.86	143.95	159.54
5.25E-02	13.12	22.19	12.43	18.000	110.48	145.34	160.18
6.60E-02	21.84	14.99	92.95	19.000	109.82	146.47	160.31

DISPLACEMENT DAMAGE-ENERGY CROSS SECTIONS, keV-b

ENERGY	Al	Si	P	ENERGY	Al	Si	P
1.00E-10	1.20	0.69	0.67	0.088	35.15	5.21	13.90
1.00E-09	0.38	0.22	0.23	0.110	18.19	3.39	10.71
1.00E-08	0.20	0.11	0.12	0.135	61.45	2.55	17.65
2.30E-08	0.13	0.08	0.09	0.160	35.39	62.91	19.64
5.00E-08	0.10	0.06	0.06	0.190	42.91	91.10	22.34
7.60E-08	0.08	0.05	0.05	0.220	31.51	61.52	20.61
1.15E-07	0.07	0.04	0.04	0.255	34.40	51.46	28.01
1.70E-07	0.05	0.03	0.03	0.290	57.59	49.28	23.69
2.55E-07	0.04	0.03	0.03	0.320	36.47	48.04	28.25
3.80E-07	0.04	0.02	0.02	0.360	51.76	49.33	48.71
5.50E-07	0.03	0.02	0.02	0.400	68.19	50.69	46.70
8.40E-07	0.02	0.01	0.02	0.450	63.65	52.81	54.62
1.28E-06	0.02	0.01	0.01	0.500	68.52	63.84	37.14
1.90E-06	0.02	0.01	0.01	0.550	70.95	67.60	57.32
2.80E-06	0.01	0.01	0.01	0.600	74.12	52.20	46.96
4.25E-06	0.01	0.01	0.01	0.660	63.56	56.30	46.94
6.30E-06	0.01	0.01	0.01	0.720	80.87	69.21	46.17
9.20E-06	0.01	0.00	0.01	0.780	99.23	118.80	45.48
1.35E-05	0.01	0.00	0.01	0.840	83.64	81.91	63.79
2.10E-05	0.00	0.00	0.01	0.920	70.27	110.29	87.87
3.00E-05	0.00	0.00	0.00	1.000	87.82	65.23	77.97
4.50E-05	0.00	0.00	0.00	1.200	86.54	87.85	89.60
6.90E-05	0.00	0.00	0.00	1.400	100.11	101.59	96.73
1.00E-04	0.00	0.00	0.00	1.600	103.96	104.84	104.76
1.35E-04	0.00	0.00	0.00	1.800	104.50	145.53	115.33
1.70E-04	0.00	0.00	0.00	2.000	122.32	98.29	120.21
2.20E-04	0.02	0.03	0.00	2.300	114.42	121.04	126.06
2.80E-04	0.03	0.05	0.07	2.600	118.27	123.86	140.98
3.60E-04	0.05	0.07	0.12	2.900	122.86	113.56	151.03
4.50E-04	0.05	0.08	0.16	3.300	125.76	101.87	134.54
5.75E-04	0.06	0.09	0.18	3.700	128.93	121.76	151.27
7.60E-04	0.07	0.11	0.21	4.100	126.71	135.32	162.52
9.60E-04	0.09	0.13	0.26	4.500	129.27	155.64	149.33
1.28E-03	0.11	0.17	0.32	5.000	134.94	138.03	150.08
1.60E-03	0.14	0.21	0.38	5.500	136.77	147.78	141.84
2.00E-03	0.18	0.26	0.49	6.000	139.54	134.67	155.87
2.70E-03	0.23	0.34	0.63	6.700	139.55	131.43	166.22
3.40E-03	0.29	0.43	0.80	7.400	143.34	169.06	165.25
4.50E-03	0.37	0.56	1.00	8.200	144.17	165.45	168.18
5.50E-03	0.88	0.68	1.33	9.000	145.81	168.46	170.36
7.20E-03	0.58	0.86	2.04	10.000	151.97	171.66	169.99
9.20E-03	0.70	1.07	2.46	11.000	160.57	176.48	172.39
1.20E-02	0.84	1.33	3.19	12.000	168.63	181.37	177.64
1.50E-02	0.82	1.64	3.43	13.000	172.71	191.19	186.93
1.90E-02	0.80	2.03	3.84	14.000	177.07	191.57	186.63
2.55E-02	2.26	2.45	5.25	15.000	180.42	194.15	192.86
3.20E-02	32.80	3.00	7.20	16.000	181.77	196.03	192.03
4.00E-02	8.20	2.63	9.43	17.000	182.03	195.91	192.11
5.25E-02	5.27	14.34	11.44	18.000	181.23	199.86	190.76
6.60E-02	24.45	6.31	14.19	19.000	179.89	200.24	192.79

DISPLACEMENT DAMAGE-ENERGY CROSS SECTIONS, keV-b

ENERGY	S	C1	K	ENERGY	S	C1	K
1.00E-10	1.34	133.59	5.60	0.088	31.93	7.33	8.92
1.00E-09	0.50	43.67	1.77	0.110	55.25	8.00	8.36
1.00E-08	0.28	22.74	0.93	0.135	28.31	12.51	11.12
2.30E-08	0.20	14.82	0.62	0.160	21.08	11.93	8.22
5.00E-08	0.16	11.14	0.47	0.190	27.29	14.97	9.31
7.60E-08	0.13	9.05	0.38	0.220	20.60	14.46	11.86
1.15E-07	0.11	7.45	0.31	0.255	28.20	16.55	17.07
1.70E-07	0.09	6.16	0.25	0.290	28.00	19.65	23.45
2.55E-07	0.08	5.08	0.21	0.320	18.66	24.26	19.57
3.80E-07	0.07	4.22	0.17	0.360	34.62	23.54	21.97
5.50E-07	0.06	3.47	0.14	0.400	32.36	27.58	28.43
8.40E-07	0.05	2.84	0.11	0.450	30.17	30.57	26.92
1.28E-06	0.05	2.26	0.09	0.500	30.92	31.95	24.93
1.90E-06	0.05	1.82	0.08	0.550	46.14	29.57	30.25
2.80E-06	0.05	1.45	0.06	0.600	29.19	35.01	31.96
4.25E-06	0.05	1.14	0.05	0.660	35.85	35.34	34.85
6.30E-06	0.04	0.92	0.04	0.720	51.33	38.47	37.76
9.20E-06	0.04	0.74	0.03	0.780	44.50	41.36	40.69
1.35E-05	0.04	0.58	0.03	0.840	36.78	46.79	43.99
2.10E-05	0.04	0.45	0.02	0.920	51.72	47.02	48.31
3.00E-05	0.04	0.34	0.02	1.000	49.17	54.82	58.16
4.50E-05	0.04	0.23	0.02	1.200	67.65	65.31	67.01
6.90E-05	0.04	0.16	0.01	1.400	67.23	75.92	80.31
1.00E-04	0.04	0.11	0.01	1.600	85.73	86.57	88.95
1.35E-04	0.04	0.08	0.01	1.800	81.38	94.82	103.51
1.70E-04	0.04	0.06	0.01	2.000	91.21	108.00	108.81
2.20E-04	0.04	0.04	0.01	2.300	98.93	118.20	121.11
2.80E-04	0.06	0.13	0.01	2.600	123.83	126.80	138.11
3.60E-04	0.07	0.36	0.01	2.900	124.58	134.80	152.31
4.50E-04	0.08	0.22	0.03	3.300	115.28	139.40	157.61
5.75E-04	0.08	0.14	0.05	3.700	161.18	139.10	161.01
7.60E-04	0.09	0.14	0.07	4.100	158.48	141.80	160.41
9.60E-04	0.10	0.14	0.07	4.500	153.01	146.90	156.11
1.28E-03	0.11	0.14	0.08	5.000	146.34	147.80	185.11
1.60E-03	0.13	0.17	0.09	5.500	160.89	153.60	192.01
2.00E-03	0.15	0.17	0.11	6.000	183.91	173.40	211.41
2.70E-03	0.18	0.25	1.26	6.700	178.21	176.70	214.61
3.40E-03	0.21	0.37	1.77	7.400	178.21	188.00	227.61
4.50E-03	0.26	0.31	0.47	8.200	186.46	194.70	233.11
5.50E-03	0.32	0.54	0.35	9.000	189.54	200.70	239.11
7.20E-03	0.42	1.60	1.11	10.000	193.96	208.40	245.51
9.20E-03	0.57	0.91	2.08	11.000	195.84	219.20	248.11
1.20E-02	0.76	2.04	0.66	12.000	194.94	229.20	255.11
1.50E-02	0.79	2.27	1.36	13.000	190.89	237.50	254.51
1.90E-02	0.80	3.53	1.59	14.000	192.99	243.30	256.71
2.55E-02	1.21	5.02	2.90	15.000	191.19	244.70	258.81
3.20E-02	0.97	3.29	2.80	16.000	207.91	244.90	261.61
4.00E-02	1.09	4.86	4.83	17.000	212.11	247.70	266.21
5.25E-02	1.24	6.00	7.16	18.000	216.08	249.80	271.81
6.60E-02	4.50	7.02	7.80	19.000	216.61	258.70	275.51

DISPLACEMENT DAMAGE-ENERGY CROSS SECTIONS, keV-b

ENERGY	Ca	Ti	V	ENERGY	Ca	Ti	V
1.00E-10	1.27	18.70	17.28	0.088	5.78	9.41	8.46
1.00E-09	0.40	5.91	5.47	0.110	5.12	7.82	31.04
1.00E-08	0.21	3.09	2.86	0.135	21.17	7.30	24.22
2.30E-08	0.14	2.07	1.92	0.160	16.68	6.62	40.64
5.00E-08	0.11	1.56	1.44	0.190	12.54	16.07	38.61
7.60E-08	0.09	1.26	1.17	0.220	30.48	13.76	32.90
1.15E-07	0.07	1.03	0.96	0.255	25.69	21.09	31.43
1.70E-07	0.06	0.84	0.78	0.290	10.05	15.16	44.17
2.55E-07	0.05	0.69	0.64	0.320	33.07	19.19	40.01
3.80E-07	0.04	0.57	0.53	0.360	17.43	13.41	31.38
5.50E-07	0.03	0.46	0.43	0.400	19.00	22.22	33.71
8.40E-07	0.03	0.37	0.35	0.450	12.84	35.46	39.40
1.28E-06	0.02	0.30	0.29	0.500	21.38	24.89	30.62
1.90E-06	0.02	0.24	0.24	0.550	28.97	30.71	34.69
2.80E-06	0.01	0.19	0.19	0.600	49.42	34.90	44.01
4.25E-06	0.01	0.15	0.16	0.660	25.13	56.21	50.77
6.30E-06	0.01	0.11	0.13	0.720	30.29	55.28	43.27
9.20E-06	0.01	0.09	0.11	0.780	33.85	41.42	47.97
1.35E-05	0.01	0.06	0.09	0.840	57.39	50.06	67.03
2.10E-05	0.01	0.05	0.07	0.920	47.46	58.55	67.70
3.00E-05	0.00	0.03	0.06	1.000	54.53	48.98	73.96
4.50E-05	0.00	0.02	0.05	1.200	60.40	72.74	87.36
6.90E-05	0.00	0.02	0.04	1.400	83.79	88.17	98.66
1.00E-04	0.00	0.01	0.04	1.600	105.61	89.11	114.54
1.35E-04	0.00	0.01	0.18	1.800	111.61	119.65	117.84
1.70E-04	0.00	0.01	0.05	2.000	131.91	121.76	130.14
2.20E-04	0.00	0.01	0.02	2.300	155.81	139.96	134.04
2.80E-04	0.00	0.01	0.02	2.600	140.21	139.56	145.64
3.60E-04	0.00	0.01	0.02	2.900	155.41	146.57	150.05
4.50E-04	0.05	0.01	0.02	3.300	147.41	157.56	159.25
5.75E-04	0.11	0.12	0.14	3.700	174.91	162.26	161.25
7.60E-04	0.15	0.20	0.26	4.100	172.01	172.26	165.36
9.60E-04	0.17	0.26	0.38	4.500	167.01	171.45	169.76
1.28E-03	0.20	0.31	0.52	5.000	214.61	173.24	171.47
1.60E-03	0.22	0.38	0.57	5.500	217.51	176.34	177.57
2.00E-03	0.27	0.52	0.83	6.000	219.02	181.93	186.57
2.70E-03	0.32	1.55	1.93	6.700	224.22	186.83	192.28
3.40E-03	0.39	1.60	23.35	7.400	228.23	192.13	196.68
4.50E-03	0.46	1.56	15.98	8.200	257.04	197.13	205.98
5.50E-03	0.55	2.48	24.97	9.000	267.65	204.03	216.28
7.20E-03	0.66	5.25	7.43	10.000	272.07	208.63	225.68
9.20E-03	0.85	10.49	25.46	11.000	275.79	209.83	226.99
1.20E-02	1.03	25.90	30.91	12.000	279.41	218.26	247.60
1.50E-02	1.26	56.93	23.62	13.000	278.13	231.22	260.61
1.90E-02	1.61	42.20	13.55	14.000	273.25	244.00	270.02
2.55E-02	1.62	18.66	9.24	15.000	271.96	255.83	276.02
3.20E-02	1.88	19.27	5.76	16.000	260.37	268.37	284.83
4.00E-02	2.33	15.14	6.03	17.000	259.58	279.30	291.44
5.25E-02	2.98	22.54	14.11	18.000	259.29	289.53	297.64
6.60E-02	3.80	11.61	19.72	19.000	258.00	298.68	303.25

DISPLACEMENT DAMAGE-ENERGY CROSS SECTIONS, keV-b

ENERGY	Cr	Mn	Fe	ENERGY	Cr	Mn	Fe
1.00E-10	13.12	40.01	7.73	0.088	32.02	14.00	11.84
1.00E-09	4.15	12.65	2.44	0.110	14.24	42.04	11.27
1.00E-08	2.17	6.62	1.28	0.135	36.22	19.53	21.53
2.30E-08	1.46	4.44	0.86	0.160	24.33	23.52	15.85
5.00E-08	1.09	3.34	0.64	0.190	22.63	32.82	22.01
7.60E-08	0.89	2.71	0.52	0.220	26.77	26.17	18.27
1.15E-07	0.73	2.22	0.43	0.255	20.43	16.95	17.37
1.70E-07	0.60	1.82	0.35	0.290	16.55	27.45	13.51
2.55E-07	0.49	1.49	0.29	0.320	23.69	25.85	25.14
3.80E-07	0.40	1.23	0.24	0.360	20.12	29.69	46.52
5.50E-07	0.33	1.01	0.19	0.400	42.95	36.18	43.04
8.40E-07	0.27	0.82	0.16	0.450	40.60	41.91	36.40
1.28E-06	0.22	0.67	0.13	0.500	36.08	34.97	33.22
1.90E-06	0.18	0.55	0.11	0.550	41.12	40.43	34.18
2.80E-06	0.15	0.45	0.09	0.600	31.32	45.13	19.64
4.25E-06	0.12	0.37	0.07	0.660	29.08	44.78	48.89
6.30E-06	0.10	0.31	0.06	0.720	52.60	45.99	74.22
9.20E-06	0.08	0.26	0.05	0.780	50.69	50.90	44.02
1.35E-05	0.07	0.22	0.04	0.840	64.26	61.33	40.97
2.10E-05	0.05	0.18	0.03	0.920	50.85	61.84	50.95
3.00E-05	0.05	0.16	0.03	1.000	56.33	74.23	50.09
4.50E-05	0.04	0.14	0.02	1.200	82.40	89.66	64.54
6.90E-05	0.03	0.14	0.02	1.400	99.54	95.19	73.58
1.00E-04	0.03	0.15	0.01	1.600	98.66	102.45	76.46
1.35E-04	0.02	0.17	0.01	1.800	93.53	108.95	95.15
1.70E-04	0.02	0.25	0.01	2.000	117.71	114.06	93.75
2.20E-04	0.02	0.60	0.01	2.300	128.52	119.36	112.05
2.80E-04	0.02	9.40	0.01	2.600	143.22	127.87	123.55
3.60E-04	0.01	1.14	0.01	2.900	142.01	138.47	133.45
4.50E-04	0.01	0.12	0.01	3.300	151.20	147.57	135.25
5.75E-04	0.10	0.25	0.13	3.700	161.50	159.97	149.55
7.60E-04	0.19	0.60	0.31	4.100	170.19	154.08	158.25
9.60E-04	0.27	6.67	0.67	4.500	182.78	159.78	168.55
1.28E-03	0.33	0.91	0.48	5.000	187.57	169.08	176.46
1.60E-03	0.66	4.08	0.51	5.500	192.96	175.68	183.06
2.00E-03	0.65	31.24	0.57	6.000	198.15	182.48	189.26
2.70E-03	1.31	7.96	0.63	6.700	204.14	191.48	196.67
3.40E-03	3.34	2.10	0.82	7.400	211.54	199.68	203.37
4.50E-03	4.30	0.99	0.83	8.200	217.14	199.39	214.58
5.50E-03	5.33	5.10	1.67	9.000	223.65	204.60	225.69
7.20E-03	5.55	16.70	3.71	10.000	234.96	218.42	237.60
9.20E-03	2.47	5.29	1.49	11.000	247.08	237.44	247.41
1.20E-02	1.77	1.65	1.16	12.000	264.62	249.56	258.52
1.50E-02	1.61	1.62	0.97	13.000	273.16	257.88	271.35
1.90E-02	1.94	12.08	0.55	14.000	278.61	259.79	290.27
2.55E-02	3.38	7.29	26.76	15.000	290.78	270.59	293.20
3.20E-02	3.05	23.33	8.16	16.000	293.23	279.78	292.73
4.00E-02	11.53	9.90	6.51	17.000	295.73	284.77	297.65
5.25E-02	7.70	15.47	6.58	18.000	296.76	293.95	307.26
6.60E-02	4.46	17.66	13.14	19.000	299.07	304.63	316.36

DISPLACEMENT DAMAGE-ENERGY CROSS SECTIONS, keV-b

ENERGY	Co	Ni	Cu	ENERGY	Co	Ni	Cu
1.00E-10	102.42	17.15	10.59	0.088	21.91	14.01	14.13
1.00E-09	32.39	5.42	3.35	0.110	20.38	11.13	16.02
1.00E-08	16.94	2.84	1.75	0.135	14.89	23.21	20.21
2.30E-08	11.36	1.90	1.18	0.160	16.61	26.95	21.06
5.00E-08	8.54	1.43	0.88	0.190	24.15	36.35	20.34
7.60E-08	6.94	1.16	0.72	0.220	21.13	33.71	23.92
1.15E-07	5.68	0.95	0.59	0.255	24.68	33.61	25.21
1.70E-07	4.66	0.78	0.48	0.290	28.27	37.17	30.31
2.55E-07	3.81	0.64	0.39	0.320	32.95	39.38	29.74
3.80E-07	3.15	0.53	0.32	0.360	34.18	32.00	31.76
5.50E-07	2.59	0.43	0.27	0.400	34.20	35.15	31.85
8.40E-07	2.11	0.35	0.21	0.450	45.18	40.79	39.75
1.28E-06	1.73	0.28	0.17	0.500	40.53	39.84	40.95
1.90E-06	1.43	0.23	0.14	0.550	43.63	34.26	41.35
2.80E-06	1.18	0.19	0.12	0.600	47.50	48.93	44.91
4.25E-06	0.99	0.16	0.09	0.660	55.05	42.08	46.78
6.30E-06	0.84	0.13	0.08	0.720	48.94	40.10	49.16
9.20E-06	0.72	0.11	0.06	0.780	53.23	52.49	51.37
1.35E-05	0.63	0.09	0.05	0.840	59.64	54.98	53.35
2.10E-05	0.58	0.07	0.04	0.920	61.59	54.00	55.43
3.00E-05	0.59	0.06	0.03	1.000	62.67	59.75	58.77
4.50E-05	0.73	0.05	0.03	1.200	73.11	80.38	65.96
6.90E-05	1.52	0.04	0.02	1.400	77.00	80.69	66.37
1.00E-04	58.43	0.03	0.02	1.600	82.11	77.53	72.07
1.35E-04	16.31	0.03	0.02	1.800	86.65	82.03	79.20
1.70E-04	0.63	0.03	0.02	2.000	92.59	91.54	86.43
2.20E-04	0.15	0.02	0.34	2.300	103.13	102.03	95.25
2.80E-04	0.06	0.02	0.01	2.600	100.24	113.83	103.48
3.60E-04	0.03	0.02	0.02	2.900	108.04	113.04	112.88
4.50E-04	0.02	0.02	0.27	3.300	118.35	127.34	122.79
5.75E-04	0.03	0.16	2.00	3.700	124.36	132.14	132.50
7.60E-04	0.08	0.49	0.15	4.100	133.47	160.45	146.71
9.60E-04	0.09	0.76	0.23	4.500	148.67	168.66	157.72
1.28E-03	0.10	0.88	0.25	5.000	162.48	179.88	164.63
1.60E-03	0.08	0.98	0.40	5.500	170.69	186.99	172.04
2.00E-03	0.09	1.21	3.62	6.000	178.00	207.51	180.85
2.70E-03	0.24	1.59	0.63	6.700	186.09	218.93	186.77
3.40E-03	7.53	2.99	0.99	7.400	194.81	223.75	198.38
4.50E-03	23.45	4.09	2.85	8.200	202.88	231.66	209.10
5.50E-03	6.12	2.61	1.60	9.000	208.49	256.66	223.02
7.20E-03	3.33	2.02	4.35	10.000	215.21	269.45	245.64
9.20E-03	3.43	5.49	4.08	11.000	227.22	281.94	260.36
1.20E-02	1.92	17.72	4.72	12.000	244.24	289.52	272.08
1.50E-02	4.68	30.59	6.22	13.000	266.95	296.51	284.80
1.90E-02	12.38	10.23	7.60	14.000	294.26	300.19	296.41
2.55E-02	11.43	10.41	9.96	15.000	313.97	303.49	306.43
3.20E-02	11.30	8.74	8.16	16.000	333.36	309.09	313.75
4.00E-02	11.19	7.02	7.59	17.000	345.34	324.69	321.76
5.25E-02	16.08	14.68	11.88	18.000	351.92	333.60	332.88
6.60E-02	16.00	16.90	14.33	19.000	361.71	337.61	347.39

DISPLACEMENT DAMAGE-ENERGY CROSS SECTIONS, keV-b

ENERGY	Zr	Nb	Mo	ENERGY	Zr	Nb	Mo
1.00E-10	0.20	0.98	2.13	0.088	16.31	12.26	14.30
1.00E-09	0.06	0.31	0.67	0.110	18.66	17.66	17.02
1.00E-08	0.03	0.16	0.35	0.135	22.77	20.78	20.09
2.30E-08	0.02	0.11	0.24	0.160	26.39	24.05	23.20
5.00E-08	0.02	0.08	0.18	0.190	26.40	27.40	26.20
7.60E-08	0.01	0.07	0.14	0.220	32.35	30.80	29.12
1.15E-07	0.01	0.05	0.12	0.255	32.55	34.19	32.33
1.70E-07	0.01	0.04	0.10	0.290	33.55	37.06	35.17
2.55E-07	0.01	0.04	0.08	0.320	38.52	39.72	38.02
3.80E-07	0.01	0.03	0.07	0.360	43.68	42.37	41.03
5.50E-07	0.00	0.02	0.05	0.400	50.61	44.89	44.11
8.40E-07	0.00	0.02	0.04	0.450	50.34	47.13	47.19
1.28E-06	0.00	0.02	0.04	0.500	53.74	49.27	50.67
1.90E-06	0.00	0.01	0.03	0.550	54.54	51.42	53.30
2.80E-06	0.00	0.01	0.02	0.600	57.87	53.56	55.83
4.25E-06	0.00	0.01	0.02	0.660	63.34	55.65	58.18
6.30E-06	0.00	0.01	0.02	0.720	62.03	57.26	60.07
9.20E-06	0.00	0.01	0.25	0.780	61.87	58.65	62.03
1.35E-05	0.00	0.01	0.01	0.840	68.38	59.12	63.61
2.10E-05	0.00	0.00	0.02	0.920	67.80	59.75	65.03
3.00E-05	0.00	0.08	2.69	1.000	71.83	60.85	70.91
4.50E-05	0.00	0.00	1.67	1.200	76.83	64.28	76.96
6.90E-05	0.00	0.03	0.15	1.400	81.41	68.14	83.67
1.00E-04	0.00	0.25	1.75	1.600	87.55	75.30	89.09
1.35E-04	0.00	0.00	0.11	1.800	91.56	82.37	92.19
1.70E-04	0.04	0.71	0.01	2.000	96.00	89.13	95.15
2.20E-04	0.01	0.04	0.03	2.300	101 98	96.56	98.08
2.80E-04	0.22	0.15	0.24	2.600	107.44	101.43	102.73
3.60E-04	0.00	0.50	0.39	2.900	113.82	107.13	108.23
4.50E-04	0.00	0.05	0.37	3.300	119.62	112.42	113.36
5.75E-04	0.04	0.23	0.12	3.700	125.02	120.51	118.40
7.60E-04	0.01	0.22	0.14	4.100	131.52	130.11	124.41
9.60E-04	0.08	0.47	0.84	4.500	139.99	140.50	132.41
1.28E-03	0.31	0.59	0.85	5.000	148.77	149.60	141.95
1.60E-03	0.25	0.50	2.84	5.500	157.66	158.00	150.90
2.00E-03	0.33	0.95	4.64	6.000	167.26	170.31	160.49
2.70E-03	0.98	0.61	5.65	6.700	177.15	181.91	169.34
3.40E-03	1.05	0.72	6.03	7.400	187.04	191.51	183.43
4.50E-03	0.81	0.92	6.65	8.200	198.64	200.11	199.02
5.50E-03	1.58	1.28	7.54	9.000	210.94	207.81	213.40
7.20E-03	1.49	1.11	8.87	10.000	224.15	218.80	224.48
9.20E-03	1.12	1.38	10.51	11.000	235.46	228.70	239.77
1.20E-02	2.64	1.70	12.43	12.000	247.58	237.90	253.55
1.50E-02	4.03	2.09	14.60	13.000	254.20	251.00	257.73
1.90E-02	3.73	2.66	17.54	14.000	259.01	271.00	259.35
2.55E-02	3.67	3.36	20.54	15.000	262.91	295.60	268.93
3.20E-02	4.78	4.13	23.16	16.000	270.72	313.41	276.12
4.00E-02	11.36	5.19	25.47	17.000	288.62	332.31	290.50
5.25E-02	11.11	6.51	25.05	18.000	312.01	350.21	308.80
6.60E-02	15.78	8.24	21.53	19.000	343.61	367.52	321.39

DISPLACEMENT DAMAGE-ENERGY CROSS SECTIONS, keV-b

ENERGY	107Ag	109Ag	Ta	ENERGY	107Ag	109Ag	Ta
1.00E-10	40.27	115.39	3.05	0.088	11.65	11.45	6.93
1.00E-09	12.73	36.54	0.96	0.110	13.95	13.64	7.88
1.00E-08	6.66	19.19	0.51	0.135	16.17	15.80	8.81
2.30E-08	4.47	12.97	0.34	0.160	18.43	17.94	9.87
5.00E-08	3.36	9.84	0.26	0.190	20.66	20.06	11.04
7.60E-08	2.73	8.09	0.21	0.220	23.01	22.29	12.34
1.15E-07	2.23	6.74	0.18	0.255	25.25	24.44	13.59
1.70E-07	1.83	5.67	0.15	0.290	27.08	26.21	14.71
2.55E-07	1.50	4.83	0.12	0.320	28.62	27.60	15.91
3.80E-07	1.24	4.23	0.11	0.360	30.36	29.05	17.16
5.50E-07	1.02	3.82	0.10	0.400	31.85	30.72	18.68
8.40E-07	0.83	3.65	0.09	0.450	33.51	32.50	20.50
1.28E-06	0.68	3.90	0.10	0.500	35.22	34.29	22.16
1.90E-06	0.56	5.18	0.15	0.550	37.23	36.10	23.88
2.80E-06	0.46	14.36	6.22	0.600	39.12	38.17	25.69
4.25E-06	0.39	536.31	13.76	0.660	41.24	40.51	27.73
6.30E-06	0.34	5.26	0.07	0.720	43.13	42.47	29.95
9.20E-06	0.39	0.61	3.31	0.780	45.20	44.57	31.09
1.35E-05	13.11	0.16	0.71	0.840	47.50	46.75	32.75
2.10E-05	0.21	0.75	1.11	0.920	50.08	49.57	35.09
3.00E-05	4.92	11.53	3.31	1.000	55.04	54.40	40.11
4.50E-05	7.62	3.49	0.19	1.200	61.35	60.81	46.90
6.90E-05	0.09	6.39	1.10	1.400	67.86	66.40	53.43
1.00E-04	0.09	5.20	0.69	1.600	73.95	71.85	57.88
1.35E-04	0.61	0.36	0.36	1.800	79.04	76.66	60.82
1.70E-04	2.13	3.02	0.83	2.000	84.20	81.81	64.74
2.20E-04	0.31	0.50	0.55	2.300	90.43	87.17	69.93
2.80E-04	1.19	1.93	0.41	2.600	96.06	91.94	73.43
3.60E-04	0.55	1.32	0.35	2.900	101.81	97.00	76.99
4.50E-04	1.01	1.92	0.32	3.300	107.64	103.53	80.93
5.75E-04	0.76	0.83	0.29	3.700	115.04	111.13	83.84
7.60E-04	0.22	0.39	0.25	4.100	122.92	119.30	89.62
9.60E-04	0.59	0.79	0.22	4.500	131.74	128.81	96.73
1.28E-03	0.59	0.78	0.19	5.000	141.09	138.85	103.44
1.60E-03	0.68	0.81	0.17	5.500	149.90	147.95	108.79
2.00E-03	0.95	1.09	0.15	6.000	159.55	157.44	116.01
2.70E-03	1.12	1.24	0.13	6.700	169.54	166.54	125.27
3.40E-03	1.16	1.30	0.12	7.400	178.82	174.02	134.48
4.50E-03	1.23	1.35	0.59	8.200	186.46	181.36	150.49
5.50E-03	1.35	1.45	1.04	9.000	189.00	182.40	166.57
7.20E-03	1.55	1.64	1.37	10.000	197.55	194.40	178.94
9.20E-03	1.80	1.91	1.53	11.000	207.15	198.45	184.19
1.20E-02	2.13	2.23	1.71	12.000	213.30	206.25	195.73
1.50E-02	2.55	2.66	1.95	13.000	222.45	212.55	205.88
1.90E-02	3.18	3.28	2.29	14.000	236.55	222.00	215.76
2.55E-02	3.96	4.04	2.74	15.000	249.15	230.40	224.99
3.20E-02	4.80	4.88	3.31	16.000	256.65	240.15	232.93
4.00E-02	5.99	6.03	4.10	17.000	263.70	251.55	240.13
5.25E-02	7.46	7.46	4.94	18.000	272.55	261.60	250.48
6.60E-02	9.39	9.31	5.85	19.000	281.40	270.00	259.25

DISPLACEMENT DAMAGE-ENERGY CROSS SECTIONS, keV-b

ENERGY	182W	183W	184W	ENERGY	182W	183W	184W
1.00E-10	2.19	1.53	0.17	0.088	6.62	7.43	4.87
1.00E-09	0.69	0.48	0.06	0.110	8.33	8.41	8.45
1.00E-09	0.36	0.25	0.03	0.135	9.32	9.40	9.34
2.30E-08	0.24	0.17	0.02	0.160	10.39	10.47	10.28
5.00E-08	0.18	0.13	0.01	0.190	11.51	11.53	11.30
7.60E-08	0.15	0.10	0.01	0.220	12.70	12.53	12.42
1.15E-07	0.13	0.08	0.01	0.255	13.87	13.48	13.60
1.70E-07	0.10	0.07	0.01	0.290	14.95	14.44	14.68
2.55E-07	0.09	0.06	0.01	0.320	16.14	15.57	15.94
3.80E-07	0.08	0.05	0.01	0.360	17.54	16.88	17.27
5.50E-07	0.07	0.04	0.00	0.400	19.19	18.38	18.90
8.40E-07	0.06	0.03	0.00	0.450	20.93	19.96	20.72
1.28E-06	0.06	0.03	0.00	0.500	22.72	21.63	22.49
1.90E-06	0.09	0.03	0.00	0.550	24.51	23.30	24.33
2.80E-06	12.48	0.03	0.00	0.600	26.53	25.18	26.39
4.25E-06	0.81	0.05	0.00	0.660	28.57	27.30	28.74
6.30E-06	0.03	4.72	0.00	0.720	30.84	29.22	31.06
9.20E-06	0.02	0.03	0.00	0.780	33.16	31.12	33.62
1.35E-05	1.28	0.03	0.00	0.840	35.67	33.08	36.68
2.10E-05	6.15	6.89	0.00	0.920	38.92	35.19	39.45
3.00E-05	0.01	0.42	0.00	1.000	43.22	38.67	43.07
4.50E-05	0.00	3.55	0.00	1.200	46.69	43.30	46.44
6.90E-05	0.00	0.02	0.00	1.400	47.93	47.09	48.36
1.00E-04	0.74	0.35	0.05	1.600	50.30	50.54	52.10
1.35E-04	0.00	0.98	0.01	1.800	53.51	53.57	55.65
1.70E-04	0.00	0.39	0.36	2.000	57.97	57.30	59.70
2.20E-04	0.24	0.44	0.00	2.300	62.46	61.15	63.46
2.80E-04	0.02	0.39	0.07	2.600	66.61	64.88	66.74
3.60E-04	0.16	0.25	0.05	2.900	71.02	68.99	70.48
4.50E-04	0.06	0.18	0.00	3.300	76.63	74.03	75.81
5.75E-04	0.08	0.27	0.04	3.700	81.39	78.61	81.00
7.60E-04	0.04	0.18	0.06	4.100	86.36	83.63	86.45
9.60E-04	0.06	0.16	0.07	4.500	92.79	89.43	92.80
1.28E-03	0.05	0.14	0.04	5.000	99.72	95.89	99.75
1.60E-03	0.02	0.12	0.03	5.500	106.74	102.07	106.69
2.00E-03	0.04	0.10	0.03	6.000	114.93	103.59	114.77
2.70E-03	0.03	0.09	0.02	6.700	124.24	120.57	123.73
3.40E-03	0.03	0.08	0.02	7.400	132.96	133.05	123.25
4.50E-03	0.74	0.82	0.79	8.200	141.85	143.53	144.02
5.50E-03	1.38	1.46	1.52	9.000	157.93	156.66	157.00
7.20E-03	1.79	1.94	1.99	10.000	168.28	169.50	166.15
9.20E-03	1.93	2.06	2.08	11.000	176.77	177.60	173.74
1.20E-02	2.11	2.29	2.25	12.000	182.41	184.45	182.38
1.50E-02	2.35	2.55	2.45	13.000	190.70	192.57	190.08
1.90E-02	2.75	2.99	2.74	14.000	200.48	200.99	196.83
2.55E-02	3.18	3.49	3.04	15.000	209.73	209.74	205.15
3.20E-02	3.63	4.03	3.28	16.000	222.25	222.39	216.43
4.00E-02	4.20	4.70	3.46	17.000	235.66	234.09	228.93
5.25E-02	4.79	5.46	3.48	18.000	247.17	244.47	243.13
6.60E-02	5.40	6.42	3.21	19.000	256.66	258.46	253.07

DISPLACEMENT DAMAGE-ENERGY CROSS SECTIONS, keV-b

ENERGY	186W	Au	Pb	ENERGY	186W	Au	Pb
1.00E-10	4.28	49.33	0.17	0.088	4.34	8.12	8.18
1.00E-09	1.35	15.62	0.05	0.110	8.41	9.41	10.03
1.00E-08	0.71	8.20	0.03	0.135	9.28	10.62	10.90
2.30E-08	0.48	5.54	0.02	0.160	10.18	11.82	12.09
5.00E-08	0.36	4.21	0.01	0.190	11.13	12.89	13.20
7.60E-08	0.29	3.46	0.01	0.220	12.25	13.93	15.05
1.15E-07	0.24	2.88	0.01	0.255	13.38	14.75	16.67
1.70E-07	0.20	2.43	0.01	0.290	14.40	15.65	16.94
2.55E-07	0.16	2.07	0.01	0.320	15.59	16.55	19.28
3.80E-07	0.14	1.82	0.01	0.360	16.91	17.56	18.41
5.50E-07	0.12	1.64	0.00	0.400	18.49	18.79	16.72
8.40E-07	0.10	1.58	0.00	0.450	20.30	19.90	14.82
1.28E-06	0.08	1.71	0.00	0.500	22.05	20.74	20.14
1.90E-06	0.08	2.38	0.00	0.550	23.83	21.48	22.73
2.80E-06	0.07	8.48	0.00	0.600	25.86	22.13	25.03
4.25E-06	0.08	217.74	0.00	0.660	28.15	23.31	25.74
6.30E-06	0.09	1.44	0.00	0.720	30.29	24.73	28.57
9.20E-06	0.18	0.21	0.00	0.780	32.10	26.17	32.97
1.35E-05	17.83	0.05	0.00	0.840	34.38	27.82	30.58
2.10E-05	0.27	0.02	0.00	0.920	36.33	29.13	31.16
3.00E-05	0.02	0.02	0.00	1.000	39.50	32.37	34.64
4.50E-05	0.00	5.53	0.00	1.200	44.47	37.98	41.37
6.90E-05	0.00	0.63	0.00	1.400	48.97	43.83	45.41
1.00E-04	0.00	0.37	0.00	1.600	53.19	49.03	57.42
1.35E-04	0.01	1.67	0.00	1.800	56.63	53.72	58.45
1.70E-04	0.48	0.37	0.00	2.000	60.34	59.20	72.95
2.20E-04	0.03	0.97	0.00	2.300	63.75	64.84	85.63
2.80E-04	0.06	1.33	0.00	2.600	66.70	71.27	96.38
3.60E-04	0.06	0.80	0.00	2.900	70.16	77.27	107.51
4.50E-04	0.09	0.65	0.00	3.300	75.12	83.10	109.38
5.75E-04	0.10	1.15	0.00	3.700	79.78	86.98	113.26
7.60E-04	0.01	0.66	0.00	4.100	85.03	92.61	114.63
9.60E-04	0.05	0.55	0.00	4.500	91.17	101.39	114.19
1.28E-03	0.03	0.44	0.07	5.000	98.02	107.90	114.07
1.60E-03	0.01	0.63	0.20	5.500	104.86	111.36	115.57
2.00E-03	0.03	0.91	0.32	6.000	112.88	117.67	120.64
2.70E-03	0.02	0.90	0.39	6.700	121.26	125.17	125.40
3.40E-03	0.02	1.09	0.45	7.400	127.14	126.70	137.41
4.50E-03	0.73	0.96	0.53	8.200	139.05	143.64	152.24
5.50E-03	1.43	1.04	0.66	9.000	154.16	168.32	162.51
7.20E-03	1.90	1.24	0.84	10.000	163.88	185.36	172.96
9.20E-03	2.02	1.49	1.04	11.000	170.97	195.44	185.64
1.20E-02	2.14	1.79	1.29	12.000	178.69	202.28	193.26
1.50E-02	2.35	2.15	1.62	13.000	186.73	209.39	197.94
1.90E-02	2.60	2.64	2.00	14.000	194.22	217.78	203.50
2.55E-02	2.85	3.19	2.42	15.000	204.73	220.78	211.43
3.20E-02	3.03	3.79	2.99	16.000	217.09	223.78	226.43
4.00E-02	3.12	4.62	4.96	17.000	228.03	229.33	233.30
5.25E-02	3.01	5.59	5.28	18.000	238.41	236.61	234.80
6.60E-02	2.52	6.80	7.76	19.000	253.53	243.81	244.89

APPENDIX B

Graphs of Displacement Damage-Energy Cross Sections

Displacement damage-energy cross sections are shown for all elements in order of increasing atomic number. The linear plots emphasize the fast neutron region which is usually the most important for fusion materials irradiations.

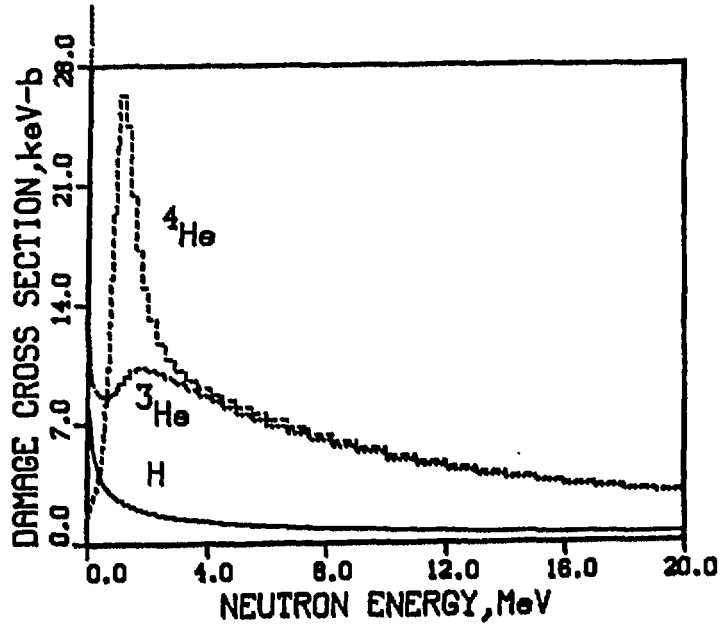

Fig. B-1. Displacement damage-energy cross sections for H, ^{3}He, and ^{4}He.

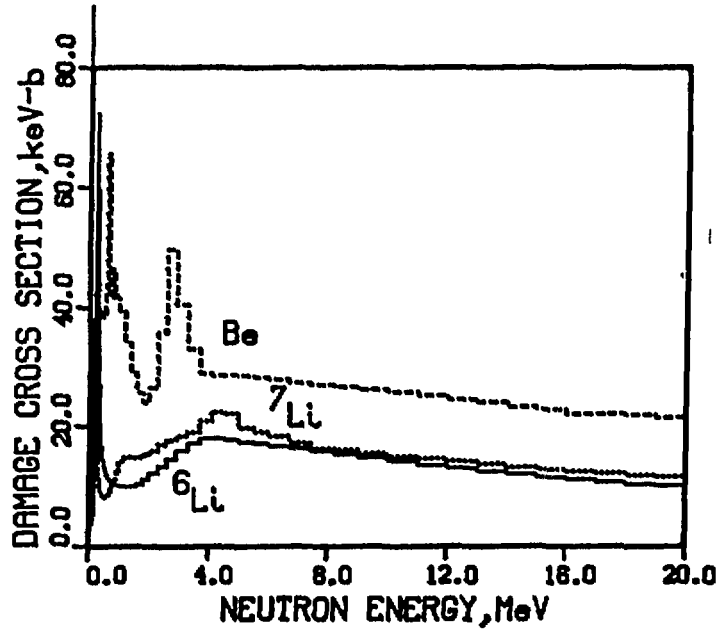

Fig. B-2. Displacement damage-energy cross sections for ^{6}Li, ^{7}Li, and Be.

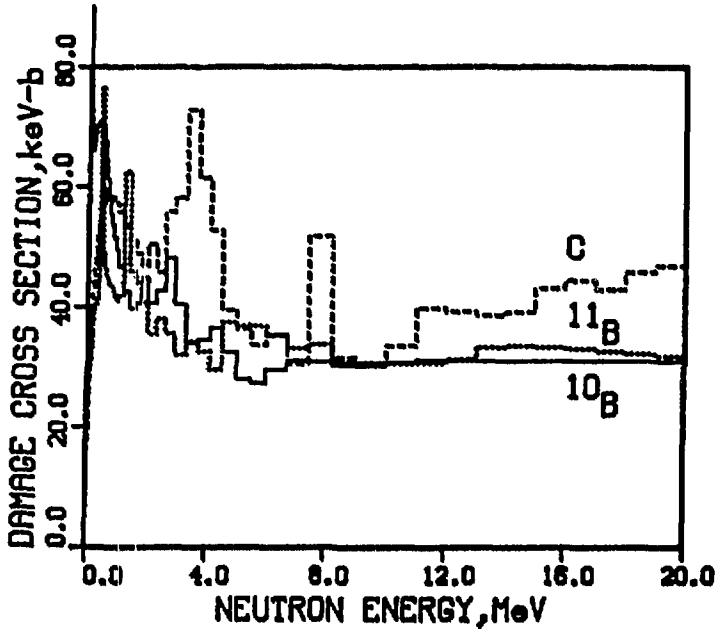

Fig. B-3. Displacement damage-energy cross sections for C, ^{10}B, and ^{11}B.

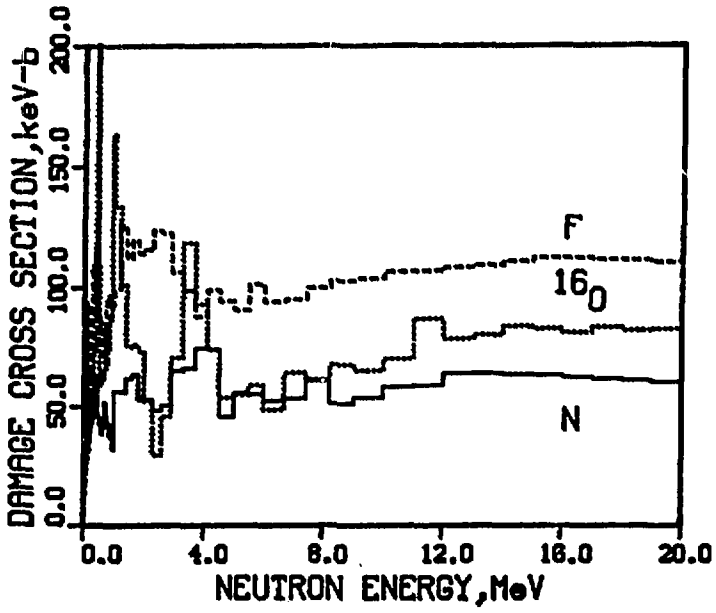

Fig. B-4. Displacement damage-energy cross sections for N, O, and F.

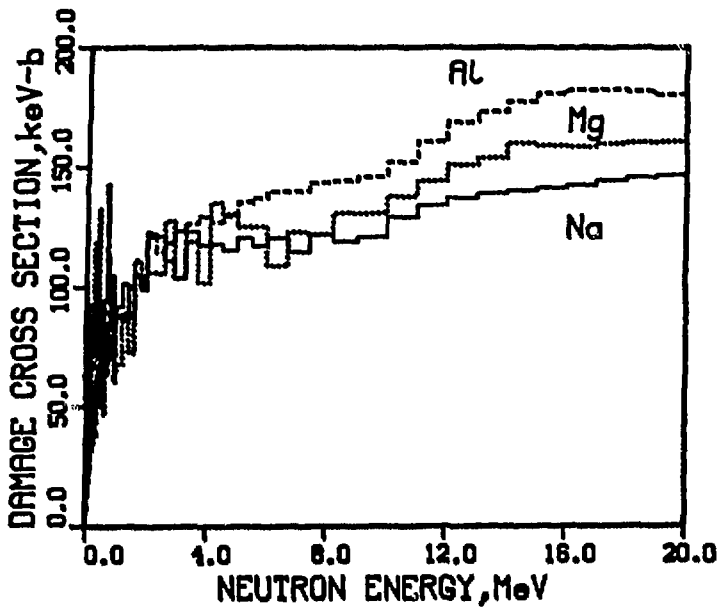

Fig. B-5. Displacement damage-energy cross sections for Na, Mg, and Al.

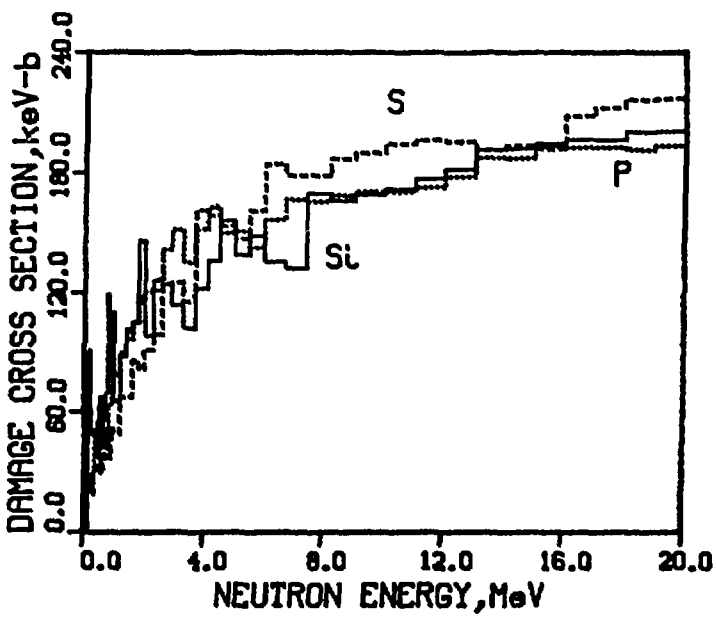

Fig. B-6. Displacement damage-energy cross sections for Si, P, and S.

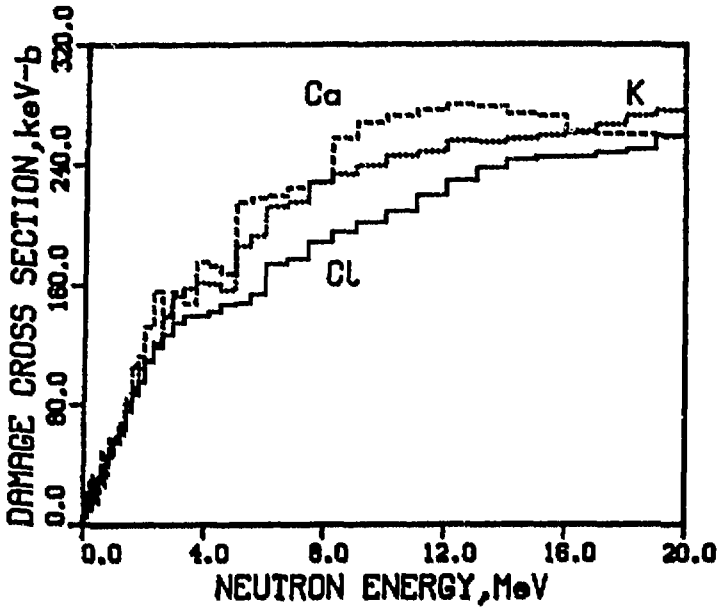

Fig. B-7. Displacement damage-energy cross sections for Cl, K, and Ca.

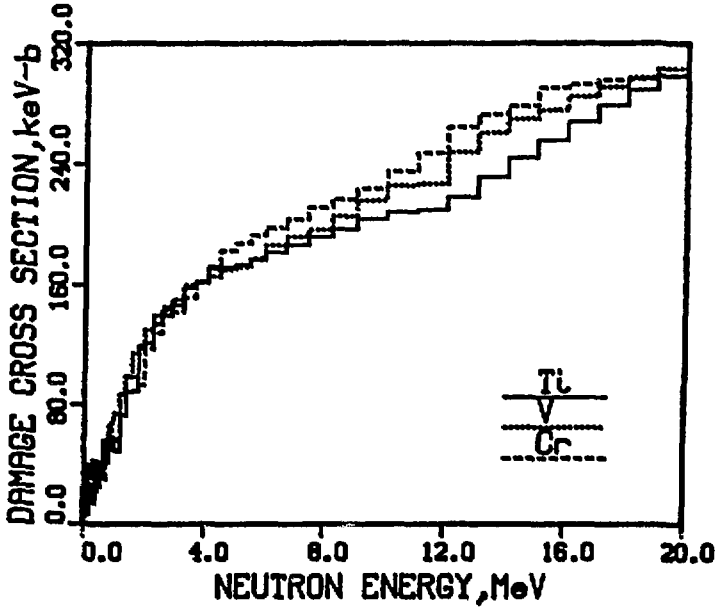

Fig. B-8. Displacement damage-energy cross sections for Ti, V, and Cr.

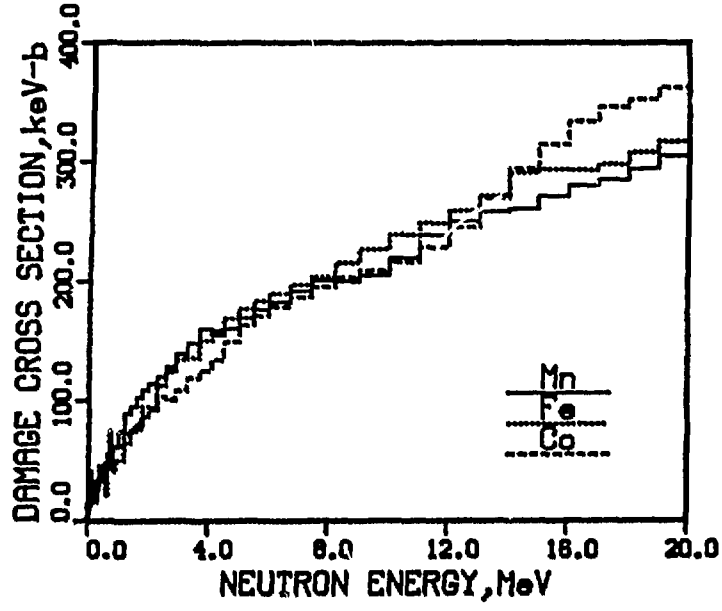

Fig. B-9. Displacement damage-energy cross sections for Mn, Fe, and Co.

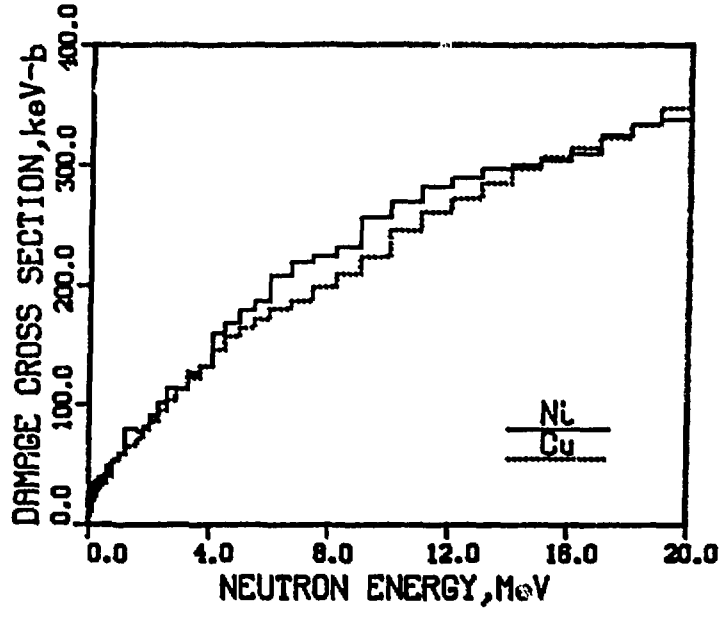

Fig. B-10. Displacement damage-energy cross sections for Ni and Cu.

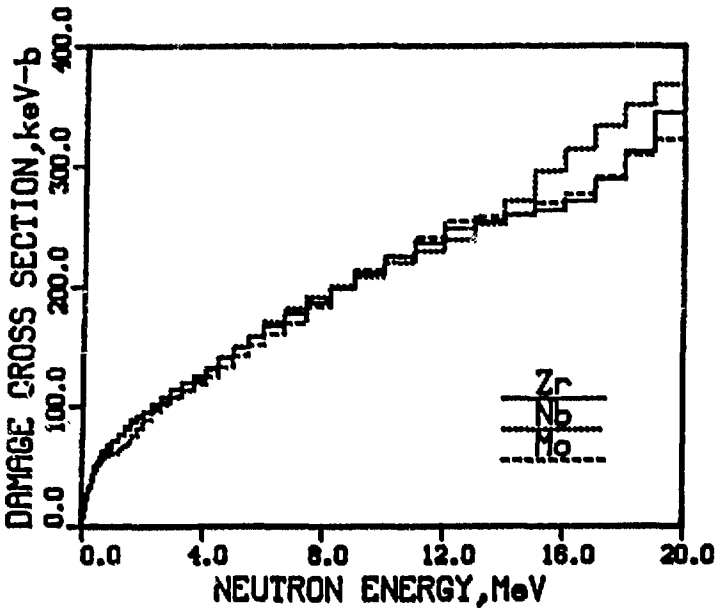

Fig. B-11. Displacement damage-energy cross sections for Zr, Nb, and Mo.

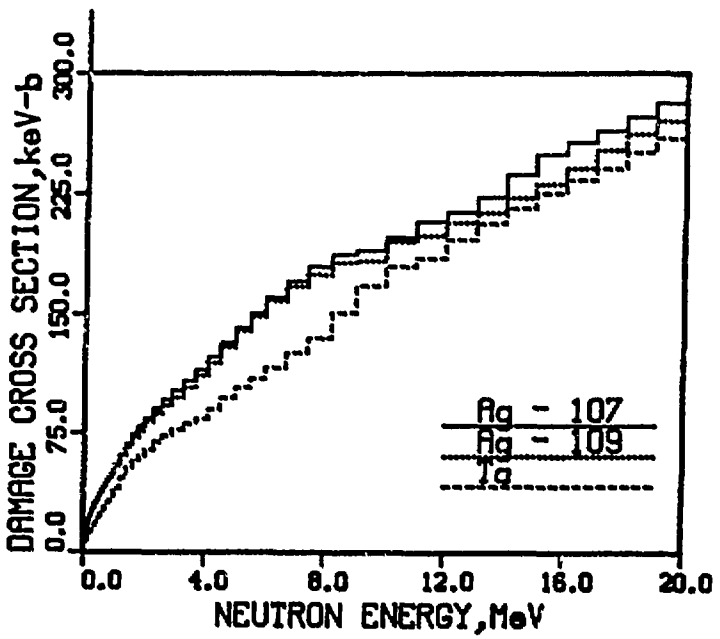

Fig. B-12. Displacement damage-energy cross sections for ^{107}Ag, ^{109}Ag, and Ta.

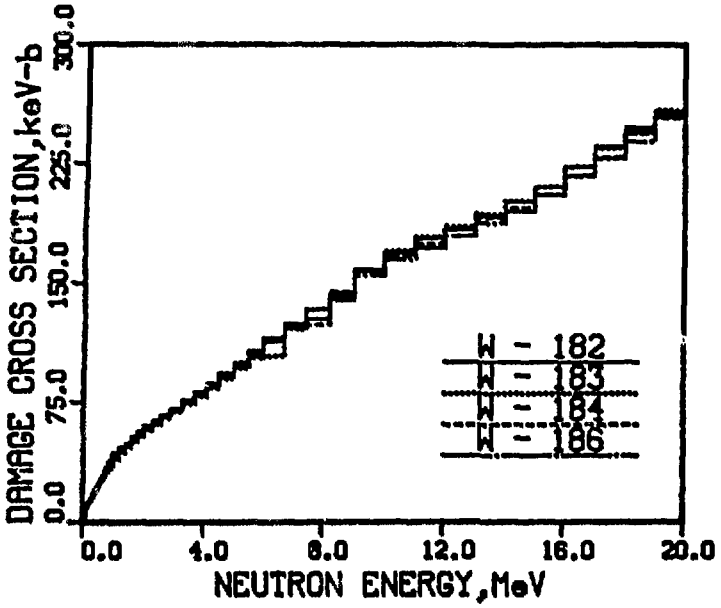

Fig. B-13. Displacement damage-energy cross seccions for W isotopes.

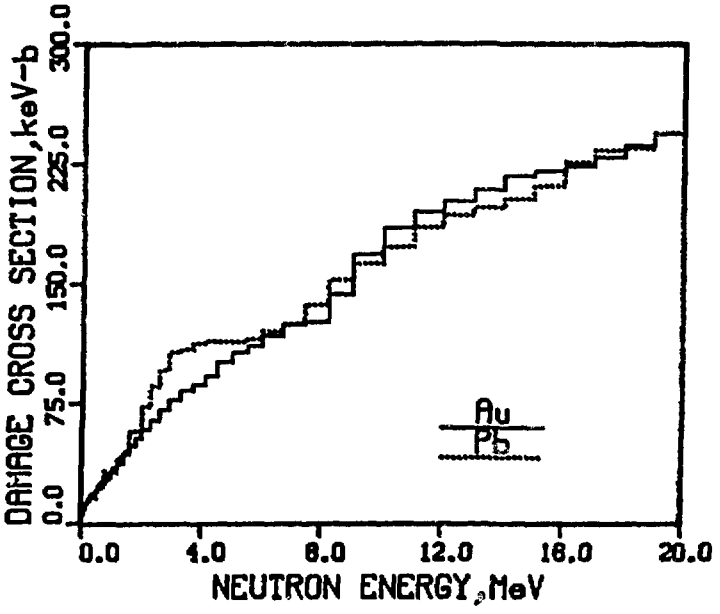

Fig. B-14. Displacement damage-energy cross sections for Au and Pb.

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