BNL-20531

CONF-751026--21

ANALYSIS OF RADIATION DAMAGE IN FUSION-SIMULATION NEUTRON SPECTRA*

Don M. Parkin
Los Alamos Scientific Laboratory
Los Alamos, New Mexico 87545

and

Allen N. Goland
Brookhaven National Laboratory
Upton, New York 11973

ABSTRACT

During the next decade experiments will be performed at a number of neutron sources in an effort to discover and alleviate radiation effects in fusion reactors. Comparison of experimental results obtained after irradiations in diverse neutron spectra will require a versatile analysis method such as the one we have developed. Various parameters which are relevant to an understanding of radiation effects in metals have been evaluated utilizing available neutron spectrum information for several existing sources, e.g. EBRII, HFIR, and LAMPF, as well as the hypothetical spectrum at a fusion reactor first wall, and measured Li(d,n) spectra. Recoil energy distributions were calculated for several metals including Al, Cu, and Nb. The recoil energy range was divided into groups, and the fraction of recoils occurring in each energy group was compared with the fraction of the damage energy contributed by that group. From this comparison it was possible to conclude that the significant recoil range differs by about an order of magnitude between fission and fusion sources. The analysis further confirms that basic defect production characteristics depend upon the neutron spectrum, and that integral calculations of radiation-effect parameters do not provide a complete description of the dependence. This is equally true for comparisons between fusion-related spectra or fission-reactor spectra independently. Four recoil-dependent parameter functions which describe different aspects of radiation damage were used in the calculations. The relative effectiveness of neutron sources was found to depend upon the choice of parameter function. Fission-reactor spectra comparisons are relatively insensitive to the parameter functions used whereas spectra with an appreciable component of high-energy neutrons are much more sensitive.

EB

INTRODUCTION

The potential materials problems caused by the extreme radiation environment in future fusion reactors have been outlined in many publications.[1] The new ingredient arising from the use of the D-T fusion reaction is the presence of high-energy neutrons with energies up to $\sim$ 15 MeV. These neutrons are responsible for generating high-energy recoil atoms and for inducing nonelastic reactions which lead to the production of impurity atoms in the materials surrounding the reaction chamber. The simultaneous generation of high-energy recoil cascades, transmutation products and gaseous impurities at high rates will have important implications for the structural integrity of a fusion reactor. Therefore, because of the accelerated schedule which has been adopted for the construction and operation of fusion-test reactors[2] even more rapid development of neutron sources for materials research and testing is warranted. In all likelihood, a variety of sources will be employed, each characterized by its own neutron-energy spectrum. It is, therefore, imperative that methods be developed for comparing the radiation effects induced by these sources on the basis of relevant parameters. In this paper one particular approach[3,4] which has so far proved useful is outlined.

There are three kinds of input required for calculations of the type to be described: first, nuclear data consisting of accurate flux spectra, detailed cross section information and models for nuclear-reaction kinematics; second, solid-state information in the form of a theory of the stopping power of solids for energetic-recoil atoms with energies up to a few hundred keV; and third, models which relate the production of energetic-recoil atoms to observed changes in measured physical properties or other characteristics of solids.

In previous papers[3-7] we have dealt mainly with the first two kinds of information. This paper is intended to emphasize the latitude available in the choice of models for comparing predictions with experimental results. The central idea is that a different model may be best suited for comparison with each kind of experimental result. The choice of a particular model requires some insight into the nature of the damage process in each case, and as experience is gained, a library of useful models will be accumulated.

In the next section a brief review of the computational method is given in order to make clear what approximations have been made. The third section describes the results of recoil-energy-spectrum calculations for various metals. Section four deals with the interpretation of radiation-effects experiments in terms of several models[8] relating energy deposition to such factors as defect-cluster formation, and Frenkel pair production per recoil atom. The final section summarizes the status of this type of analysis, as well as the future directions of the research.

REVIEW OF COMPUTATIONAL METHOD

Neutron Spectra

A neutron-energy grid corresponding to the input neutron spectrum is used in generating the necessary data for subsequent calculations. Between group boundaries for multigroup neutron data, the calculations do not utilize an energy-weight function because its application to all spectra of interest may not be justified. Hence for both histogram and pointwise data linear interpolation is used between energy-grid points.

It should be noted that the calculational accuracy of all quantities derived from the neutron spectrum is determined in part by the energy-grid mesh and in part by the accuracy of the neutron spectrum data. The finer the energy grid, the more accurate the results; however, using an energy grid finer than that on which the neutron spectrum is specified would be unwarranted. It is in this manner that neutron dosimetry ultimately affects the validity of radiation-effects calculations.

Nuclear Models

Neutron-scattering models[3,9,10] are used to calculate the probability, $K_i(E,T)$, that a neutron with lab energy, E, will produce a primary atom recoil with lab energy between T and T + dT via the i^{th} scattering process. This probability function, when multiplied by the corresponding scattering cross section, is the recoil probability cross section,

$$\sigma_i(E)K_i(E,T)dT$$

for the i^{th} scattering process. This cross section forms the basis for all calculations in DON.[3] Except where noted, all nuclear data required to calculate the recoil probability cross section are obtained from the ENDF/B library.[11] For materials with resonance-elastic-scattering data, a smooth elastic-scattering cross section was generated external to DON.[12]

The total recoil probability cross section is the sum of the partial cross sections for each of the scattering processes and can be written as

$$\begin{aligned}\sigma(E)K(E,T)dT = \sum_i \sigma_i(E)K_i(E,T)dT = \{&\sigma_{el}(E)K_{el}(E,T)\\ &+ \sum_r \sigma_r(E)K_r(E,T) + \sigma_{n,2n}(E)K_{n,2n}(E,T) \qquad (1)\\ &+ \sum_n \sigma_n(E)K_n(E,T) + \sigma_x K_x(E,T)\}dT \quad ,\end{aligned}$$

where the subscripts have the following meaning:

el ≡ elastic scattering

$\sum_r$ ≡ inelastic resolved level scattering

(n,2n) ≡ (n,2n) scattering

$\sum_n$ ≡ other remaining nonelastic scattering processes included (see Table 1)

x ≡ high-energy model scattering.

Table 1. Nonelastic Cross Sections Used in Calculations

n	Cross Section
1	Inelastic Continuum
2	(n,p)
3	(n,d)
4	(n,t)
5	(n,^{3}He)
6	(n,α)

The functional forms of $\sigma_i(E)K_i(E,T)dT$ in Eq. (1) are given in Ref. 3.

Cross section data and the recoil probability cross section are used to compute the following integrals:

1. Generalized Parameter Cross Section.

$$G(E) = \int \sigma(E)K(E,T)g(T)dT \quad , \tag{2}$$

where g(T) is the recoil-dependent parameter function that can be used to relate recoil energy to observable radiation effects. For example, in part of the following discussion we have used the damage energy form of the recoil-dependent parameter function

$$g(T) \equiv e(T) = \begin{cases} 0, \ T < T_o \\ TL(T), \ T_o \leq T \leq T_1 \\ 0, \ T > T_1 \quad . \end{cases} \tag{3}$$

L(T) is the Lindhard efficiency factor[13] as approximated by Robinson[14] in simple analytic form. Thus,

$$\begin{aligned} L(T) &= [1 + K_L f(\omega)]^{-1} \quad , \\ K_L &= 0.133745\ Z^{2/3}\ A^{-1/2} \quad , \\ \omega &= T E_L^{-1} \quad , \\ E_L &= 86.931\ Z^{7/3}\ \mathrm{eV} \quad , \\ f(\omega) &= \omega + 0.40244\ \omega^{3/4} + 3.4008\ \omega^{1/6} \quad . \end{aligned} \tag{4}$$

With this choice of g(T), we obtain the damage energy cross section

$$E_D = \int_{T_o}^{T_1} \sigma(E) K(E,T) e(T) dT \quad , \tag{5}$$

for the recoil-energy interval $T_o \leq T \leq T_1$. If T_o is set equal to the displacement-threshold energy, say 25 eV, and T_1 is taken as the maximum possible recoil energy for a given incident-neutron energy then Eq. (5) is the expression for the total damage energy cross section.

2. Neutron Energy-Spectrum-Dependent Integrals.

(a) normalized primary recoil energy spectrum,

$$P(T) = \frac{\int \sigma(E) K(E,T) \phi(E) dE}{\int \sigma(E) \phi(E) dE} \tag{6}$$

where $\phi(E)dE$ is the differential neutron spectrum.

(b) spectrum-averaged parameter cross section,

$$\langle G(E) \rangle = \frac{\int G(E) \phi(E) dE}{\int \phi(E) dE} \quad . \tag{7}$$

(c) spectrum-averaged neutron cross section,

$$\langle \sigma(E) \rangle = \frac{\int \sigma(E) \phi(E) dE}{\int \phi(E) dE} \quad . \tag{8}$$

(d) spectrum-averaged parameter

$$\bar{G} = \frac{\int G(E) \phi(E) dE}{\int \sigma(E) \phi(E) dE} = \frac{\langle G(E) \rangle}{\langle \sigma(E) \rangle} \quad . \tag{9}$$

The spectrum-averaged cross section for each of the processes used is calculated using the data available in ENDF/B. However, to calculate probabilities at energies above which detailed data are available from ENDF/B, typically 15-20 MeV, a simple evaporation model was used to represent all scattering. This model was adopted on the basis of nuclear systematics,[15] and the assumption that for most materials of interest the major contribution to the generalized parameter cross section above the ENDF/B energy limit, E^*, comes from nonelastic-scattering events.

In earlier calculations[3,4] the high-energy scattering cross section was assumed to be energy independent, and was defined so that it yielded the correct parameter cross section $G(E^*)$ at the energy limit E^*, i.e.

$$\sigma_x(E) = \frac{G(E^*)}{\int K_x(E^*,T)g(T)dT} \quad , \qquad (10)$$

where

$K_x(E,T) = K_1(E,T)$ (subscript 1 refers to inelastic continuum)

with

$\theta(E) = 3.22 \times 10^3 \sqrt{E(eV)/A}$, the nuclear temperature.

Except near reaction thresholds, the calculations are relatively insensitive to the magnitude of the nuclear excitation, Q. Therefore, the value of Q_x was arbitrarily chosen to be 1 MeV.

The results reported in subsequent sections have been obtained with a new high-energy model in which the nuclear-cross sections are individually extended to higher energies by assigning to each cross section its value at the ENDF/B energy limit. This has the effect of removing any discontinuity in the recoil probability distribution at the ENDF/B limit. A comparison of numerical results obtained with both high-energy models reveals that they differ by at most a few percent from one another. Thus, our previously published values for radiation-damage parameters are still reliable.[3-7] Nevertheless, the new model should yield the more accurate values for the recoil probability distributions, P(T), and they are quoted in the next section.

CALCULATED RECOIL SPECTRA

One way of comparing neutron sources is an integral method in which spectral averages are calculated over the full range of neutron energies, E, and allowed recoil energies, T.[3,4] A more detailed method involves restricting the limits of integration on T to intervals small enough that it becomes effectively a differential calculation. When this approach is applied to the general parameter average, $\bar{G}(E)$, it is possible to determine what fraction of $\bar{G}(E)$ is associated with each member of a set of specified recoil energy groups. For example, if $\bar{G}(E)$ is taken to be $\bar{E}_D$, the spectrum-averaged damage energy, then the fractional damage energy in each recoil-energy group can be obtained. The distribution of recoil atoms among the same energy groups is directly given by the normalized primary recoil-energy spectrum, P(T), which is always computed. It is instructive to compare the fraction of primary recoils with the fraction of damage energy in each energy group.

This comparison has been made for Al (ENDF/B Material 1193), Cu (1087) and Nb (1164) in five different neutron spectra corresponding to existing or hypothetical sources: EBRII - midplane, row 7,[16] HFIR,[17] "14-MeV" (13.5 - 14.9 MeV), BENCH (a hypothetical fusion-reactor first-wall spectrum),[18] and Li(d,n) (30-MeV deuteron).[19] The numerical results are given in Tables 2-4.

The first point which is immediately apparent is the importance of recoils in the last energy group, i.e. above 100 keV in the three fusion-related spectra (last three columns). Better than 60 percent of the damage energy is contributed by these primary recoils. Moreover, the results are strikingly similar for the three metals. The Li(d,n) neutron spectrum produces recoil and damage energy fractions in good correspondence to those produced in the "14-MeV" neutron spectrum, and is thus a good simulation source. The fission-reactor spectra, on the other hand, emphasize lower energy recoils and the distributions are somewhat different in EBRII and in HFIR. In the former, about 50 percent of the damage energy is attributable to recoils in the 10–50 keV energy group with other major fractions at lower energies. In the latter, the 10–50 keV range is also important, but damage-energy fractions associated with recoils above 50 keV are considerably larger. Neither source is especially suited to simulation of a fusion-source spectrum from this point of view.

In HFIR from 30 to ∿ 60 percent of the recoils have energies below 100 eV and contribute a negligible fraction to the total damage energy. However, in EBRII-7 less than 4 percent of the recoils are in this lowest energy group. At the high-energy end of the recoil spectrum the opposite situation arises. There are twice as many recoils above 50 keV in HFIR as in EBRII-7. It is interesting to note that the recoil-energy spectrum produced by the BENCH fusion-reactor spectrum is similar to that produced in EBRII-7 below 50 keV in all three metals. The recoil spectrum in this energy range in the BENCH spectrum is determined mainly by the neutrons returning from the blanket. The 14-MeV source current is represented by the recoil component above 50 keV. It is this component, however, that imparts more than 70 percent of the damage energy to each material.

The reason for the good simulation of 14-MeV recoil and damage energy spectra by Li(d,n) neutrons is that for 30-MeV deuterons the most probable neutron energy is about 13 MeV. Therefore, the majority of the neutrons have energies close to the desired value for fusion-related damage studies.

The character of the initial damage production processes plays a role in determining important parameters such as interstitial and vacancy survival rates and cluster formation. The defect density per cascade and the spatial distribution of the cascades depend upon the recoil-energy ranges which contribute the majority of the damage energy. The observations made in this section clearly demonstrate that

(1) basic defect production characteristics can be strongly spectrum dependent, and

(2) integral results previously published do not provide an adequate description of this energy dependence.

PARAMETER FUNCTION COMPARISON

To estimate the effects of radiation on a material in one neutron spectrum relative to those in another, it is necessary to select a particular form of the recoil-dependent parameter function, g(T), to use in the calculation. In principle one would like to have an appropriate g(T) to represent or describe the particular form of damage of interest. The damage energy form of g(T) was used in the above discussion of recoil-energy spectra because of its wide acceptance as a relevant damage parameter although it does not represent all forms of damage. Neutron spectral data help to identify the recoil-energy ranges in which it is most important to have detailed knowledge of a parameter function. Therefore, it is important in using or developing parameter functions to know what recoil-energy range or parameter function is valid or has been tested.

Two approaches to the development of parameter functions that have been utilized are theoretical calculations, including computer simulation,[20,21] and empirical damage function unfolding.[22-24] The computer calculations have generally concentrated on estimating the number of Frenkel pairs, excluding temperature effects, produced by primary recoils. Some attempts, however, have been made to include irradiation temperature and defect clustering.[25-27] At present, the results of theoretical calculations form the basis of most of the irradiation simulation studies.

The damage-function-unfolding technique[22-24] utilizes measured physical property changes in samples irradiated under known conditions as a basis for deriving parameter cross sections representative of the type of damage causing the property change measured. Property-change measurements are made on samples irradiated in several known neutron spectra. The measurements and the neutron spectra in conjunction with a trial solution typically based on a theoretical calculation are used as input in an unfolding computer code which produces a parameter cross section.

The damage-function-derived parameter cross sections have two general characteristics of importance to the present discussion. First, over the neutron-energy range $\sim 10^{-2}$ -5 MeV which is responsible for about 90 percent of the damage in a typical fission reactor the derived parameter cross sections have neutron-energy dependencies very similar to recoil energy or damage-energy trial functions. Second, outside this energy range large differences between trial functions and derived solutions are seen. This fact is due in part to the lack of solution sensitivity outside the range of significant damage. These differences, however, are very important in estimating damage effects for fusion applications. The difference between trial functions based on theoretical calculations and derived parameter cross section above ~5 MeV indicates the range of uncertainty in using these functions in calculations of damage effects in fusion spectra.

In neither case, theoretical calculations nor damage function unfolding do we have an adequate basis for extrapolating damage parameters into the recoil-energy or neutron-energy range most important for fusion spectra damage. One method of illustrating the magnitude of extrapolation uncertainties as well as indicating the types of simulation experiments that may be the most effective in developing new damage parameters is to compare several spectrum-averaged parameter cross sections representative of different forms of damage in a number of diverse neutron spectra.

Spectrum-averaged parameter cross sections using four parameter functions were calculated for Al, Cu and Nb. In addition to the damage-energy function, e(T), (see Eqs. (3) and (5)), the following parameter functions were used:

(a) Total recoil energy

$$t(T) = T \quad , \tag{11}$$

(b) radiation-hardening parameter

$$h(T) = \begin{cases} 0 & T \leq T_\ell \\ T-T_\ell & T_\ell \leq T \end{cases} \quad , \tag{12}$$

(c) Robinson-Torrens model 3[20]

$$r(T) = e(T)/(58 + 1.22 \times 10^{-3} e(T)) \quad . \qquad (13)$$

Equation (12) for h(T) is based on the computer calculations of Beeler,[21] and on the damage function results of Odette and Ziebold[23] for changes in yield stress in Fe. The function h(T) represents the relative probability of producing a defect cluster of sufficient size during the displacement cascade to act as an obstacle to dislocation motion. It has been found by Mitchell et al.[28] to compare favorably with the measured relative hardening rate for reactor neutrons and 14-MeV neutrons incident on Cu.

The Robinson and Torrens model-3 formula, r(T), (Eq. (13)), is derived from the results of computer simulation of displacement cascades in Cu. Their expression indicates that the number of Frenkel pairs produced is not directly proportional to damage energy. The calculations upon which r(T) is based covered a damage-energy range up to 10 keV whereas in the calculations of Parkin and Green[8] and the present calculations, r(T) has been extended to damage energies in the MeV range. Although this may be a "foolhardy" extrapolation into an untested recoil-energy region, for the present interests r(T) has been used since it provides a parameter function similar to damage energy for low recoil energy and extrapolates to values less than the damage energy at high recoil energies.

We can compare t(T), h(T) and r(T) using the damage-energy-parameter function as a reference. t(T) and r(T) are similar to damage energy at low-recoil energy whereas at high-recoil energy they diverge, t(T) becoming greater than and r(T) less than the damage energy. h(T) is less than the damage energy at low-recoil energy and greater than the damage energy at high-recoil energy.

For 9 neutron spectra the spectrum-averaged parameter cross sections for the four parameter functions normalized to their respective values in the EBRII-7 spectra are given in Table 5. The first five spectra are fission-type spectra whereas the last four have significant high-energy-neutron components. The first, third and seventh thru ninth spectra were described in Section III. The remaining four spectra are: LPTR-E-1, irradiation position E-1 in the Livermore Pool Type Reactor;[29] EBRII-2, row 2 midplane in the EBRII;[16] U235, ^{235}U fission spectrum;[30] and M-LAMPF, calculated spectrum for the Los Alamos Meson Physics Facility irradiation effects facility.[31]

One general observation based upon the data in Table 5 is that in the four reactor spectra, the results are essentially independent of the parameter function used, and further that the relative cross sections are similar for all three materials. These similarities point out a difficulty in using only reactor irradiations to study material and spectral-dependent radiation damage. The differences between the form of damage production in EBRII-7 and HFIR are illustrated by using parameter functions t(T) and r(T) which respectively emphasize or deemphasize high-energy recoils. The results are consistent with the discussion in the preceding section regarding the fractional damage energy associated with various recoil-energy groups in different neutron source spectra.

Results for the remaining five spectra on the other hand are sensitive not only to the choice of parameter function, but to material as well. The sensitivity to parameter function increases as the high-energy component in the neutron spectrum increases, the maximum variations occurring at "14 MeV".

The largest variations as a function of material are seen in the two damage-energy-dependent models, e(T) and r(T) whereas the recoil-energy models t(T) and h(T) give more similar results. This difference is due to the inclusion of electronic losses in the damage energy function. The most striking example of this effect is found in Al. Using r(T) we find almost no spectral dependence in the damage.

For a given material the largest difference (2-10) occurs between h(T) and r(T) or e(T). The last two represent simple Frenkel-pair production, while h(T) is used here to represent radiation hardening. Both e(T) and h(T) have been used in comparative analyses of irradiation experiments performed in reactor-neutron spectra and in a 14-MeV neutron flux. Parkin and Snead[32] have used damage energy in comparing neutron and charged-particle induced changes in critical current in Nb_3Sn. They find that for 14-MeV neutrons compared to reactor neutrons the experimental damage effectiveness is less than or equal to the ratio of the damage-energy cross sections calculated using e(T). The radiation-hardening data of Mitchell et al.[23] for copper give relative hardening rate ratios about the same as shown in Table 5 for copper using h(T).

SUMMARY AND CONCLUSIONS

In this paper we have tried to show, by means of some simple examples, that radiation-damage parameters are sensitive to the shape of the incident-neutron spectrum. A good way to exhibit the differences between spectra is to calculate the magnitude of the contribution to a given damage parameter that is to be associated with primary recoil atoms in each one of a set of energy groups. The damage energy is one such parameter, and the results shown in Tables 2-4 exhibit the essential differences between a first-wall-fusion spectrum and a nearly pure "14-MeV" spectrum (13.5 - 14.9 MeV).

The ultimate goal of these studies is to discover models which relate recoil-damage production to changes in the physical properties of solids. In the preceding section we reported the results of using different recoil-dependent parameter functions to compare various neutron sources. The entries in Table 5 lead us to draw two conclusions:

(1) The relative effectiveness of the sources depends upon the choice of parameter function. Different choices undoubtedly will be appropriate for different kinds of experiments.

(2) Fission-reactor spectra comparisons are relatively insensitive to the models used here. However, spectra with an appreciable component of high-energy neutrons are much more sensitive.

The models we have used are extremely rudimentary. Appreciable additional understanding of radiation damage will be forthcoming after theorists have developed more sophisticated parameter functions which can be introduced into the calculations. Even then, we will continue to rely upon semiempirical methods to establish functional forms which are physically meaningful.

ACKNOWLEDGEMENTS

The authors wish to gratefully acknowledge the invaluable programming assistance of H. C. Berry (BNL) and M. L. Simmons (LASL) throughout the course of their work.

REFERENCES

1. See for example, "Proc. 1st Topical Meeting on the Technology of Controlled Thermonuclear Reactors", 16-18 April 1974, San Diego, Cal.
2. See for example, K. M. Zwilsky, in Surface Effects in Controlled Fusion, Eds. H. Wiedersich, M. S. Kaminsky and K. M. Zwilsky, North-Holland Publ. Co., Amsterdam, 1974, p. viii.
3. D. M. Parkin and Allen N. Goland, Brookhaven National Laboratory Report BNL-50434 (1974).
4. D. M. Parkin, A. N. Goland, and H. C. Berry, in "Proc. 1st Topical Meeting on the Technology of Controlled Thermonuclear Reactors", 16-18 April 1974, San Diego, Calif., CONF-75-502, p. 339.
5. D. M. Parkin and A. N. Goland, Trans. Am. Nucl. Soc. 19, 23 (1974).
6. A. N. Goland and D. M. Parkin, Bull. Am. Phys. Soc. 20, 351 (1975).
7. D. M. Parkin and A. N. Goland, Rad. Effects (to be published).
8. D. M. Parkin and W. V. Green, Bull. Am. Phys. Soc. 20, 351 (1975).
9. J. D. Jenkins, Nucl. Sci. Eng. 41, 155 (1970); see also Oak Ridge National Laboratory Report ORNL-TM-2706 (1970).
10. D. G. Doran, Nucl. Sci. Eng. 49, 130 (1972).
11. O. Ozer and D. Garber, ENDF/B Summary Documentation, Brookhaven National Laboratory Report BNL-17541 (ENDF-201) (1973).
12. O. Ozer, INTEND, a computer program for generating group-averaged cross sections from pointwise data, Brookhaven National Laboratory, private communication.

13. J. Lindhard, V. Nielsen, M. Scharff and P. V. Thomsen, Kgl. Dansk, Vidensk. Selsk., Mat-Fys Medd. 33, No. 10 (1963).

14. M. T. Robinson, in Nuclear Fusion Reactors, British Nuclear Energy Soc., London, 1970, p. 364.

15. S. Pearlstein, Nucl. Sci. Eng. 23, 238 (1965).

16. N. D. Dudey and R. R. Heinrich, EBRII data, Argonne National Laboratory, private communication.

17. F.B.K. Kam and J. H. Swands, HFIR PTP location data, Oak Ridge National Laboratory Report, ORNL-TM-3322.

18. A. Aronson, First-wall Spectra Using ORNL Benchmark Design, Brookhaven National Laboratory, private communication.

19. A. N. Goland, C. L. Snead, Jr., D. M. Parkin, and R. B. Theus, IEEE Trans. Nucl. Sci. 22, 1776 (1975).

20. M. T. Robinson and I. M. Torrens, Phys. Rev. B9, 5008 (1974).

21. J. R. Beeler, Jr., J. Appl. Phys 37, 3000 (1966).

22. W. N. McElroy, R. E. Dahl, Jr., and C. Z. Serpan, Jr., Nucl Appl. Technol. 7, 561 (1969).

23. G. R. Odette and T. O. Ziebold, Nucl. Sci. Eng. 49, 72 (1972).

24. R. L. Simons, W. N. McElroy, and L. D. Blackburn, Hanford Engineering and Development Laboratory Report HEDL-TME 73-85 (1973.

25. D. G. Doran, Rad. Effects 2, 249 (1970).

26. J. R. Beeler and M. F. Beeler, Nucl Metallurgy 18, 581 (1973).

27. I. M. Torrens and M. T. Robinson in "Radiation-Induced Voids in Metals" USAEC Conf. 710601, p. 739.

28. J. B. Mitchell, R. A. van Konynenburg and D. M. Parkin, this conference.

29. R. A. van Konynenburg, Lawrence Livermore Laboratory, private communication.

30. Obtained from Radiation Shielding Information Center, Oak Ridge National Laboratory.

31. D. J. Dudziak, M. L. Simmons and G. J. Russell, Trans. Am. Nucl. Soc. 19, 465 (1974).

32. D. M. Parkin and C. L. Snead, Jr., (to be published).

* Research supported by the Energy Research and Development Administration.

Table 2. Al (1193) - Recoil-Energy and Damage-Energy Spectra

Recoil Energy	EBRII-7		HFIR		BENCH		"14 MeV"		Li(d,n) 30 MeV	
(keV)	P(T)	$\%E_D$	P(T)	$\%E_D$	P(T)	$\%E_D$	P(T)	$\%E_D$	P(T)	$\%E_D$
0 - 0.1	0.7%	0.	30.4%	0.	0.8%	0.	0. %	0.	0. %	0.
0.1 - 1.0	6.1	0.2	7.4	0.2	6.0	0.1	0.4	0.	0.4	0.
1.0 - 5.0	24.1	4.7	13.7	2.3	22.2	2.0	1.6	0.	1.9	0.1
5.0 - 10.0	18.1	8.3	8.4	3.4	14.7	3.1	1.8	0.	2.2	0.1
10.0 - 50.0	41.6	51.0	24.3	29.0	32.9	19.1	11.2	1.9	13.8	2.6
50.0 - 100.0	6.9	21.5	8.3	23.6	8.7	12.7	7.9	2.9	10.3	4.3
100.0 - T_{max}	2.5	14.3	7.5	41.5	14.7	63.0	77.1	95.0	71.4	92.9

Table 3. Cu (1087) - Recoil Energy and Damage-Energy Spectra

Recoil Energy	EBRII-7		HFIR		BENCH		"14 MeV"		Li(d,n) 30 MeV	
(keV)	P(T)	%E_D	P(T)	%E_D	P(T)	%E_D	P(T)	%E_D	P(T)	%E_D
0. 0.1	3.8%	0.	63.4%	0.1	5.5%	0.	0.2%	0.	0.2%	0.
0.1 - 1.0	23.2	1.7	15.0	1.3	25.2	0.5	1.5	0.	1.6	0.
1.0 - 5.0	35.0	12.1	7.7	4.5	26.5	2.7	6.1	0.2	6.3	0.2
5.0 - 10.0	15.3	14.5	3.4	5.5	10.3	2.9	6.3	0.4	6.8	0.5
10.0 - 50.0	20.5	51.4	7.6	38.1	19.5	16.7	24.3	4.7	28.5	6.6
50.0 - 100.0	1.7	13.2	2.0	27.3	3.6	9.2	6.9	3.4	11.1	6.6
100.0 - T_{max}	0.5	7.1	0.9	23.2	9.4	68.0	54.7	91.3	45.5	86.1

Table 4. Nb (1164) - Recoil-Energy and Damage-Energy Spectra

Recoil Energy	EBRII-7		HFIR		BENCH		"14 MeV"		Li(d,n) 30 MeV	
(keV)	P(T)	%E_D	P(T)	%E_D	P(T)	%E_D	P(T)	%E_D	P(T)	%E_D
0 - 0.1	3.8%	0.	57.2%	0.1	4.4%	0.	0.3%	0.	0.3%	0.
0.1 - 1.0	22.8	2.2	11.4	1.1	20.6	0.5	2.9	0.2	3.1	0.
1.0 - 5.0	40.3	18.7	12.1	7.3	30.3	3.7	11.0	0.4	11.4	0.4
5.0 - 10.0	16.4	20.4	6.4	10.3	13.2	4.4	10.1	0.8	10.2	1.0
10.0 - 50.0	15.9	48.8	11.0	51.0	19.8	18.0	21.4	4.8	23.6	6.5
50.0 - 100.0	0.7	7.4	1.6	21.6	2.9	8.9	6.2	4.9	12.2	11.0
100.0 - T_{max}	0.1	2.5	0.3	8.6	8.8	64.5	48.1	88.9	38.7	81.1

Table 5. Normalized Parameter Cross Sections

	Damage Energy	Recoil Energy	Radiation Hardening	Modified Damage Energy
Nb (1164)				
HFIR	0.8	0.8	1.0	0.6
LPTRE-1	1.0	1.0	1.1	0.9
EBRII-7	1.0	1.0	1.0	1.0
EBRII-2	1.4	1.5	1.6	1.3
U235	2.6	2.7	3.6	2.1
M-LAMPF	2.0	2.3	3.0	1.3
BENCH	3.4	3.9	5.3	1.8
30 MeV	8.6	10.3	15.1	3.5
"14 MeV"	9.7	11.5	16.9	3.7
CU (1087)				
HFIR	0.8	0.8	0.9	0.6
LPTRE-1	1.0	1.0	1.1	0.8
EBRII-7	1.0	1.0	1.0	1.0
EBRII-2	1.4	1.4	1.6	1.3
U235	2.6	2.8	3.4	1.9
M-LAMPF	1.8	2.2	2.7	1.2
BENCH	3.1	3.80	4.7	1.6
30 MeV	8.0	10.5	13.8	3.1
"14 MeV"	8.4	11.2	14.5	3.0
Al (1193)				
HFIR	0.6	0.7	0.8	0.5
LPTRE-1	0.9	1.0	1.0	0.8
EBRII-7	1.0	1.0	1.0	1.0
EBRII-2	1.3	1.4	1.5	1.2
U235	1.9	2.5	2.8	1.5
M-LAMPF	1.2	2.0	2.2	1.0
BENCH	1.7	3.5	3.9	1.1
30 MeV	3.2	8.9	10.2	1.4
"14 MeV"	3.4	10.5	12.0	1.5