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AN ESTIMATE OF THE EFFECT OF NEUTRON-ENERGY SPECTRUM ON RADIATION DAMAGE OF STEEL

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Abstract

Data on damage to steel by neutron irradiation, as measured by a shift in the nil ductility transition temperature, is usually correlated with total exposure to neutrons with energies greater than 1 Mev (as measured by a threshold counter). Such results inherently include damage from neutrons of lower energy in the particular energy spectrum at the experimental position in the reactor. Indiscriminate use of such data in the design of another reactor with a different spectrum can therefore lead to significant underestimation of the radiation damage to the pressure vessel.

The effect of the neutron spectrum on radiation damage to steel has been examined and discussed by Rossin.[1] In this report the Rossin postulate that the average number of lattice displacements is directly proportional to the available energy is carried one step further; it is assumed that damage to steel (particularly in regard to brittle fracture) is proportional to the number of lattice vacancies that occur. The model, although crude, permits estimation of the relative damage resulting from differences in neutron spectra. These results can be used as a rough method of correcting damage data for the effect of the neutron-energy spectrum.

Radiation damage calculations for steel, relative to those for a fission spectrum, were made for neutron spectra that result from fission neutrons penetrating water or graphite. The results were plotted as a function of effective distance from the fission source. From this plot it is possible to make a conservative estimate of the correction factor to apply to damage data obtained with different neutron spectra.

AN ESTIMATE OF THE EFFECT OF NEUTRON-ENERGY SPECTRUM ON RADIATION DAMAGE OF STEEL

H. C. Claiborne

Introduction

It is well-known that mild steel under load is subject to brittle fracture at low temperatures under certain conditions of stress application and that one effect of neutron irradiation is to raise the temperature at which fracture can occur. This has particular importance in the design of a reactor pressure vessel whose operating temperature is around 100°F (such as the pressure vessel for the HFIR).

The primary factors that influence brittle fracture in unirradiated steel include average and localized stress levels, temperature, and flaw size. All commercial steel products have microcracks or inclusions that act like cracks from the viewpoint of stress concentration. Since flaw size is somewhat imponderable and stress level can be controlled by design practice, service temperature has become the criterion for avoidance of brittle fracture in reactor pressure vessels.

To provide for almost certain protection against the classical type of brittle fracture, i.e., nearly explosive propagation of a crack across a loaded member, the operating temperature must be above the temperature corresponding to the fracture transition for elastic loading, commonly called FTE, or the fracture arrest temperature referred to by the British. Above this temperature, it has been established experimentally that a brittle fracture cannot propagate across any region that is loaded within the elastic range (below yield point). Since design practice requires that stresses not exceed the yield point in any extensive region, only small localized areas of excessive stress (assuming no long stringers are present) would exist due to some stress raiser, such as a flaw. Under such a condition a fracture might be initiated, but it certainly would not propagate if the region temperature was above the FTE temperature.

In design practice, the reference temperature has become the nil ductility transition temperature (commonly called NDT); it is established by the simple Charpy V-notch test, which must be correlated with the "drop weight test" or "explosion bulge test." The FTE temperature for mild steels may be obtained for practical purposes by adding 60°F to the NDT temperature. The NDT temperature is the temperature below which a minute crack or flaw, irrespective of size, could initiate a fracture (provided the yield point stress was reached at the flaw) that could propagate through the surrounding region even though the general stress level was below the yield point. As the flaw size increases, there is a decrease in the stress required to initiate brittle fracture. Below a nominal stress of about 5000 to 8000 psi, however, brittle fractures probably will not occur, since there is insufficient elastic strain energy available to support propagation of fractures.[2]

It is the effect of radiation on the NDT and FTE temperatures that concerns the designer of pressure vessels for nuclear reactors; fast neutron-bombardment shifts these temperatures upward. The experimental data of Hawthorne and Steele,[3] which were used in the design of the HFIR pressure vessel, are shown in Fig. 1. For a neutron exposure of around 3×10^{18}, which is near the expected neutron dose after 20 years for the beam hole nozzles of the HFIR, the NDT temperature increases about 50°F, which gives an FTE temperature of about 110°F. This means that if the pressure vessel is to operate at 100°F, avoiding the possibility of brittle fracture requires the use of steel with an unirradiated NDT temperature of less than -10°F. A cold startup at full pressure would require an even lower initial NDT temperature.

Aside from the uncertainty indicated by the spread of the data, there is further uncertainty that arises when such data are used to predict damage caused by the same number of neutrons with a different energy spectrum. The method of correlating property change with exposure to neutrons with energies greater than 1 Mev ignores the damage from neutrons with energies less than 1 Mev (although this is inherently included in the experimental results for a particular spectrum). Under certain conditions these neutrons with energies less than 1 Mev may make the larger contribution to radiation damage.

The effect of the neutron spectrum on radiation damage to steel has been examined and discussed by Rossin.[1] An analytical method was developed to compute the relative amounts of neutron energy available for the

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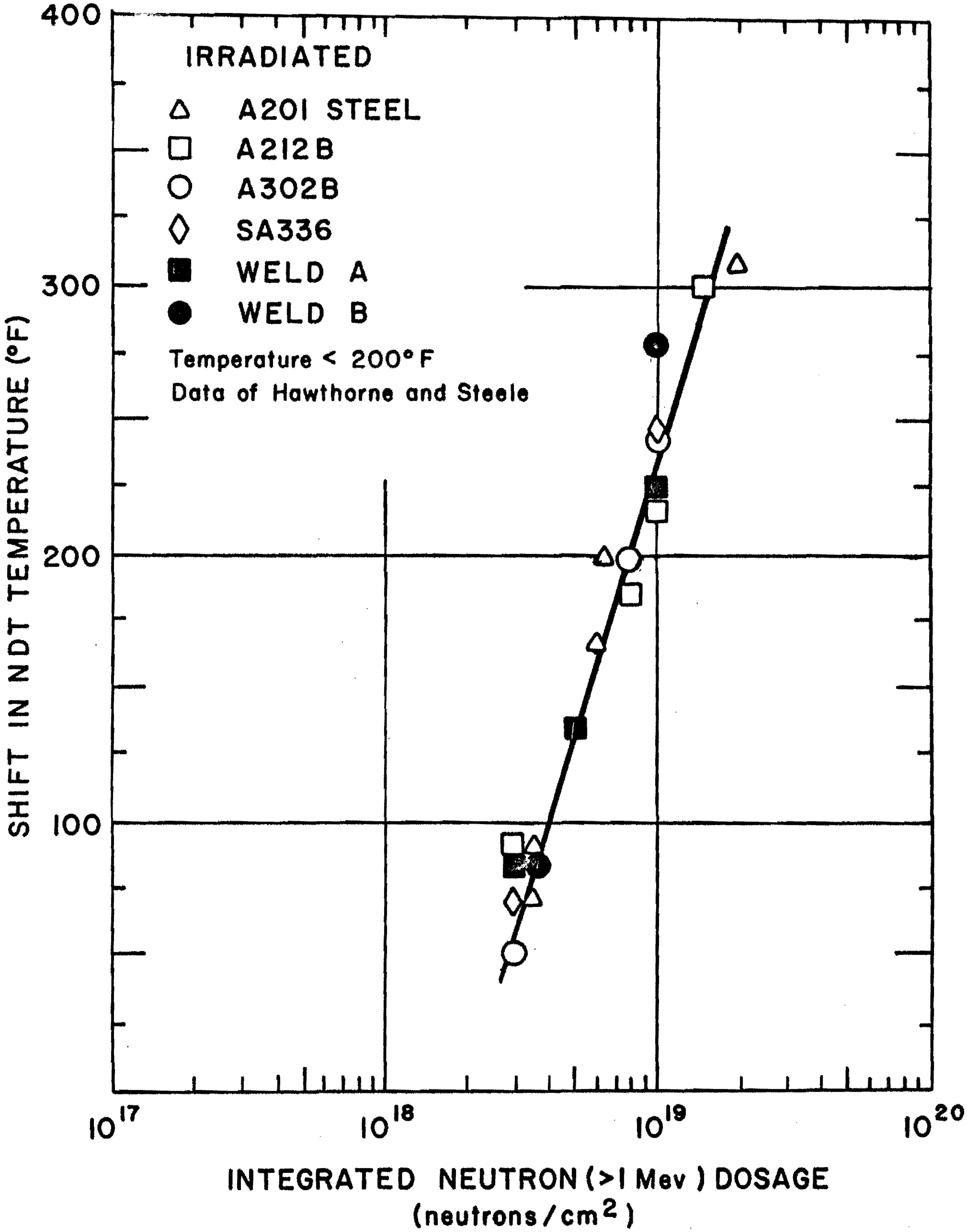

FIG. 1 CORRELATION OF TRANSITION TEMPERATURE SHIFTS WITH TOTAL NEUTRON EXPOSURE (>1.0 Mev) OF STEEL

production of lattice vacancies, which is a large factor in neutron damage of steel. The basic postulate was that the average number of displacements produced following a neutron interaction was directly proportional to the available energy for producing these displacements. The relative importance of the neutron spectrum below 1 Mev was demonstrated for several reactors, and the relative rate of lattice vacancy production was shown to be heavily dependent on the neutron-energy spectrum.

The Rossin[1] postulate is carried one step further here; it is assumed that damage to steel (particularly in regard to brittle fracture) is proportional to the number of lattice vacancies. Actually this is generally implied by Rossin in the discussion of results and he does point out that, to a first approximation, the available energy would be proportional to the damage created. Apparently, there is a reluctance to exploit this point because of the crudeness of the model, which neglects such things as strain aging and the annealing effects of thermal spikes and other rate processes. The net effect of neglecting thermal spikes is to overestimate the number of vacancies and to give greater weight to the higher energy neutrons. The advantage that accrues from full exploitation of Rossin's work is that it permits estimation of the relative damage or property change resulting from differences in neutron spectra; the data thus obtained can be used as a rough method for correcting damage data for the effect of energy spectrum.

In the following sections the necessary equations are developed and the method of calculation described. Relative damage results (using these equations) are obtained and compared for neutron spectra that result from the fission spectrum penetrating several thicknesses of water and graphite.

Basic Equations

The basic postulate is that the rate of change in a physical property or the rate at which damage occurs is proportional to the rate of production of lattice displacements. For a continuous neutron spectrum, this is expressed in equation form by

$$\frac{dD}{dt} = k \int_{E_t}^{\infty} N\,\sigma(E)\,\phi(E)\,dE \quad , \qquad (1)$$

where

D = total damage,

t = time,

k = proportionality constant,

N = number of atoms per unit volume,

$\sigma(E)$ = energy dependent cross section for lattice displacement,

$\phi(E)$ = neutron flux per unit energy,

E_t = threshold energy for lattice displacement.

Assuming no functional dependence on time, Eq. (1) can be integrated to give

$$D = kt \int_{E_t}^{\infty} N\,\sigma(E)\,\phi(E)\,dE \quad . \qquad (2)$$

It follows from Eq. (2) that the ratio of damage resulting from exposure to a neutron flux of one environment to that of another is

$$\frac{D_2}{D_1} = \frac{t_2 \int_{E_t}^{\infty} \sigma(E)\,\phi_2(E)\,dE}{t_1 \int_{E_t}^{\infty} \sigma(E)\,\phi_1(E)\,dE} \quad . \qquad (3)$$

When the neutron exposure (nvt) to each spectrum is set equal; i.e.,

$$t_2 \int_{E_t}^{\infty} \phi_2(E)\,dE = t_1 \int_{E_t}^{\infty} \phi_1(E)\,dE \quad , \qquad (4)$$

then Eq. (3) represents a correction factor, F, that can be applied to experimental damage data to correct only for differences in energy spectrum. Therefore when experimental data are correlated on the basis of exposure to neutrons of an energy greater than some threshold value,

$$D_1 = \Psi_1 \ (nvt, >E_t) \quad , \tag{5}$$

and

$$D_2 = F \ \Psi_1(nvt, >E_t) \quad . \tag{6}$$

Calculations

Using Eq. (3) of the previous section, radiation damage calculations relative to that for the Cranberg fission spectrum[4] were made for steel [assuming $\sigma(E)$ to be the same as that for iron] for the spectra that result from fission neutrons penetrating water or graphite.

The attenuated spectra were calculated by the moments method using RENUPAK,[5] an IBM 7090 code. The water spectra were obtained by Trubey;[6] the graphite results were previously published.[7] A sample of these results is shown in Fig. 2.

The vacancy production cross section calculated by Rossin[1] as a function of neutron energy is shown in Fig. 3.

Calculations were made for threshold displacement energies of 0.0005, 0.1, and 1.0 Mev for comparison purposes. The lowest value represents a reasonable energy threshold for lattice displacement in iron (theoretical minimum, 363 ev neutron for head-on collision) and is the lower level of the energy group assigned a zero cross section by Rossin.

Using the plots shown in Figs. 2 and 3, Eq. (3) was numerically integrated, assuming equal times and

$$\int_{E_t}^{\infty} \phi_1(E) \ dE = \int_{E_t}^{\infty} \phi_2(E) \ dE = 1 \quad . \tag{7}$$

Linear extrapolation on the plots, as shown, was used to extend both ends of the curve in Fig. 3 and the high energy end in Fig. 2. Although not shown, sufficient low-energy points were calculated to define the water-attenuated spectra in the energy range below 0.1 Mev. The graphite spectra data were less complete, however, and a 1/E spectrum (which fit the few points quite well) was used to interpolate the portion of the spectrum below 0.1 Mev.

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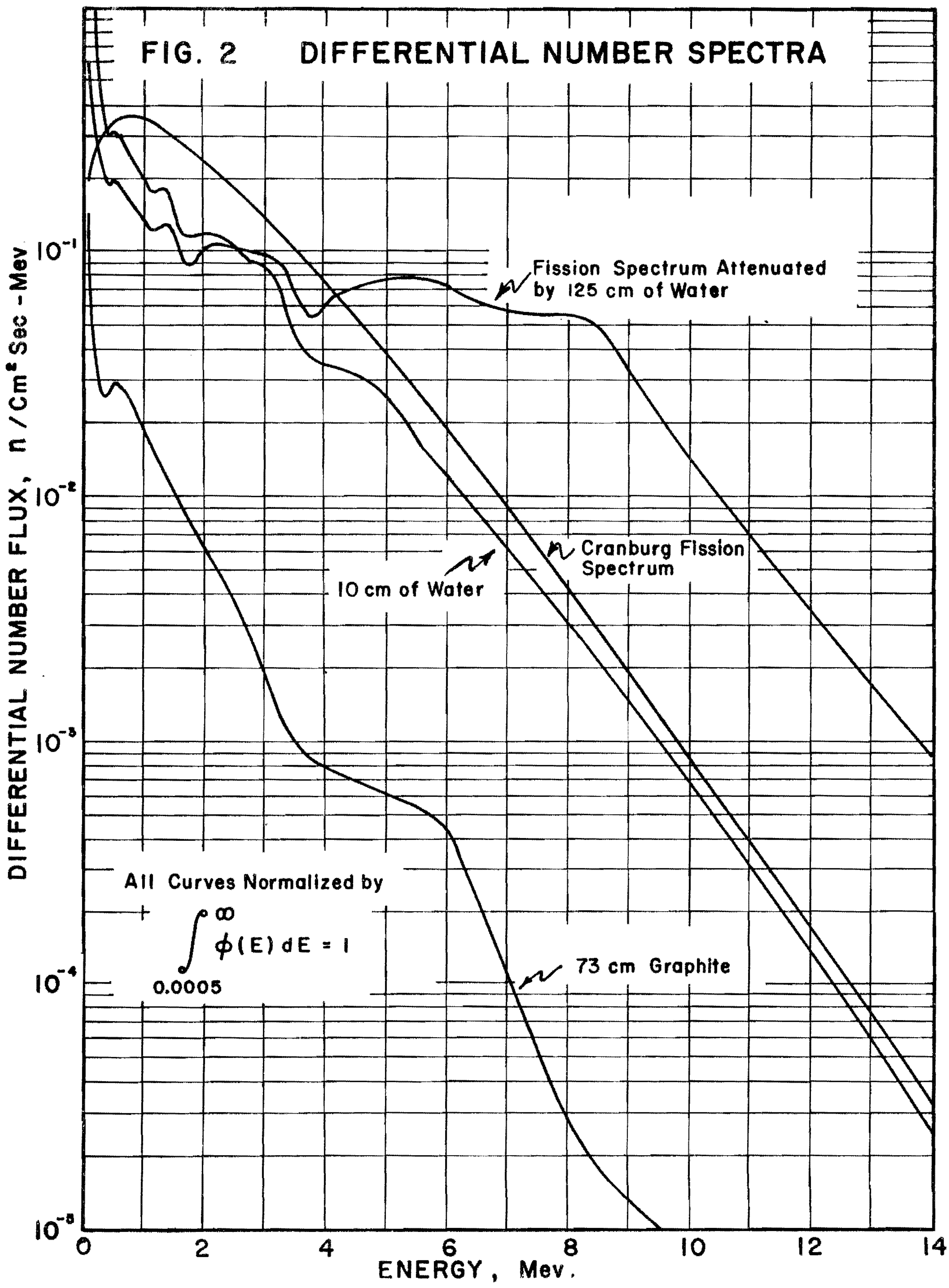

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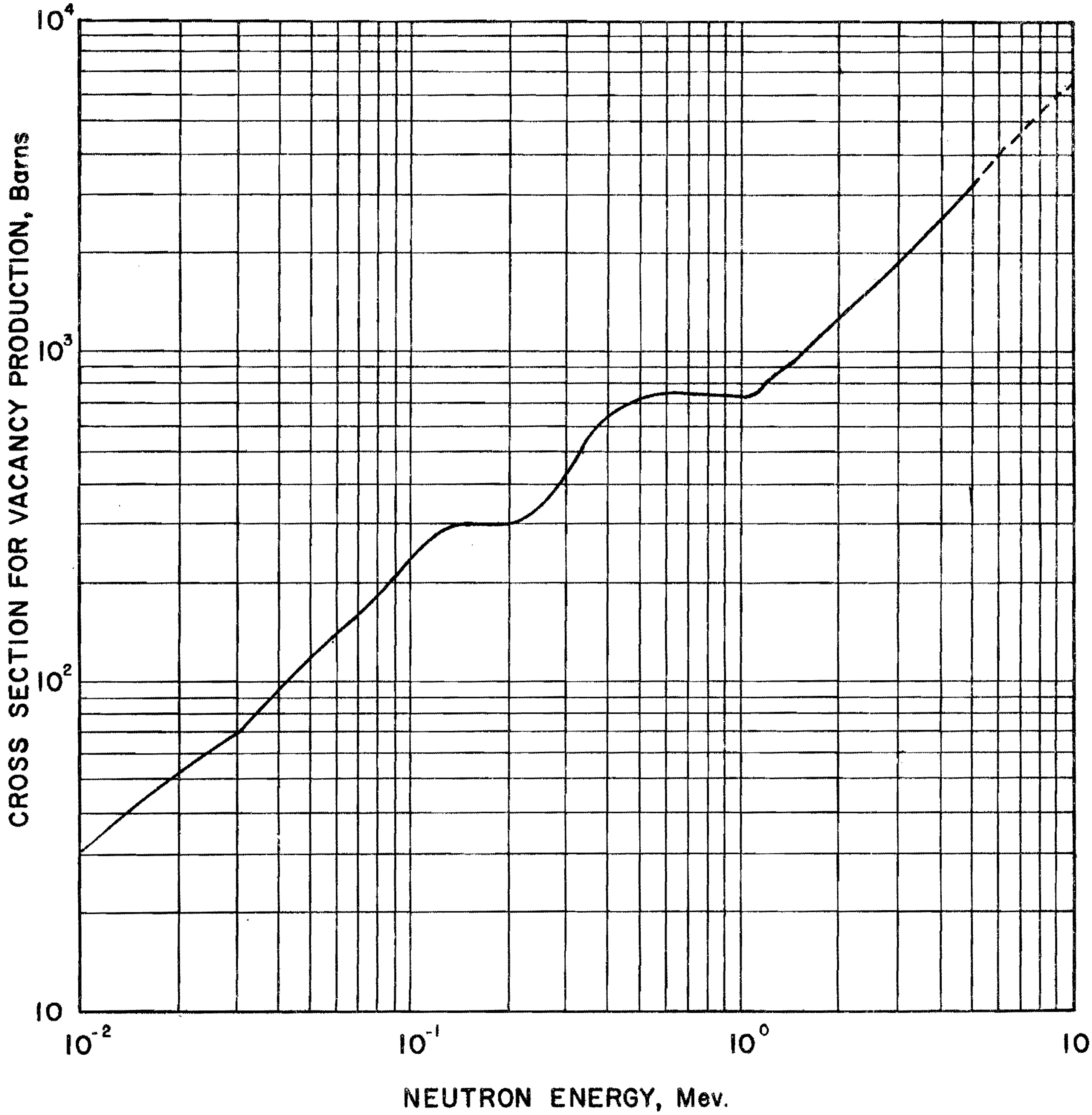
FIGURE 3 CROSS SECTION FOR PRODUCTION OF VACANCIES IN IRON



Results and Discussion

The calculated values of the relative damage (relative to a pure fission spectrum) that result in steel from spectra obtained by attenuating fission neutrons through water and through graphite are shown in Fig. 4 as a function of the effective distance (i.e., density × distance) from the source; this effective distance is a convenient method of classifying the neutron-energy spectrum with respect to an approximate position in a reactor. The spectra that result from the penetration of several thicknesses of these media are given in Table 1 in terms of the fraction that appears within the indicated energy group. Table 2 shows the fraction of damage from each of the neutron energy groups in Table 1.

The difference in the effect of water and graphite on the energy spectrum is strikingly reflected in Fig. 4. After an initial dip (1-Mev threshold case shows no dip; a dip probably occurs at less than 10-cm penetration, the lower limit of the calculation), which is caused by a sudden increase in the number of lower energy neutrons as a result of slowing down by hydrogen, the well-known spectral hardening effect of water (see Table 1) is reflected by the rapid rise in relative damage with depth of penetration. Graphite, however, shows little change in relative damage after the initial drop, but it does exhibit a very slight hardening effect. This seems reasonable, since the scattering cross section of graphite, like that of hydrogen but to a much lesser degree, decreases with energy at neutron energies greater than 1 Mev.

It is evident from Fig. 4 that the choice of the threshold energy for damage can lead to significantly different results. The lowest threshold value, 0.0005 Mev, shows the greatest rate of increase in damage with penetration for distances greater than 10 cm (approximate minimum point) for water attenuated spectra.

The results, as shown, are not directly applicable to the correction of experimental results, since they represent hypothetical cases that do not ordinarily exist in an operating reactor. The curves are very useful, however, to the designer in estimating a conservative correction factor to apply to experimental data obtained for a different energy spectrum. It is obvious from Fig. 4 that damage data obtained for spectra

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FIGURE 4 EFFECT OF NEUTRON ENERGY SPECTRUM ON RADIATION DAMAGE TO STEEL

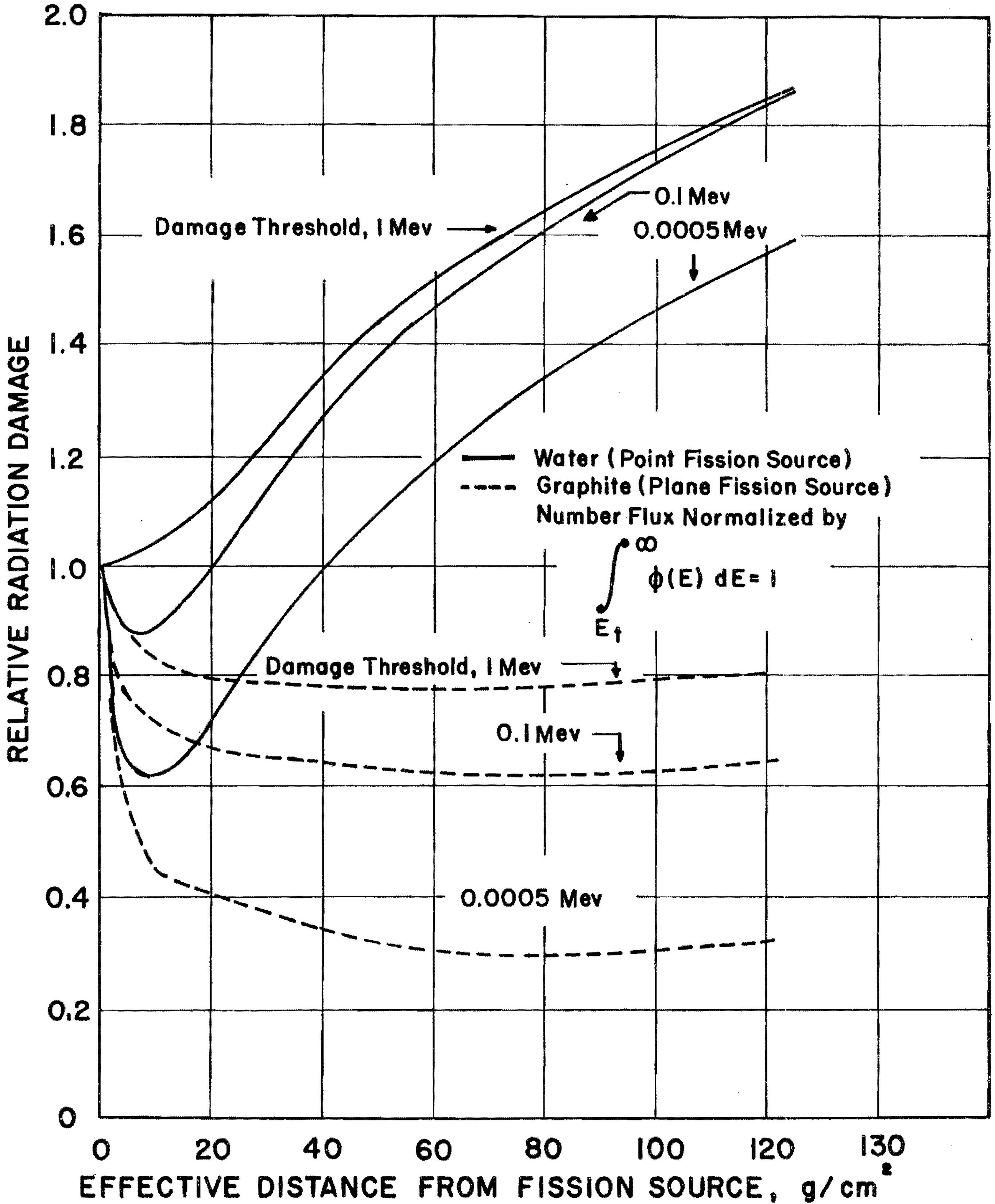

Table 1. Neutron-Energy Spectrum as a Function of Penetration Through Water or Graphite

Energy Range (Mev)	Neutrons in Indicated Energy Range (%)										
	Effective Distance in Water (cm²/g)						Effective Distance in Graphite (cm²/g)				
	0	10	20	30	50	125	10	20	30	60	120
>10	0.08	0.14	0.26	0.55	2.02	0.11	0.02	0.02	0.01	0.01	0.01
10–5	3.42	5.29	7.95	14.46	26.73	5.07	1.13	1.05	0.83	0.77	0.87
5–2	19.11	21.50	7.04	27.05	24.98	34.12	10.98	9.13	7.78	5.30	5.93
2–1	14.80	14.04	15.07	13.53	11.22	29.58	16.68	15.53	14.31	11.89	11.36
1–0.1	30.93	27.14	25.30	22.55	19.19	29.69	32.19	31.70	30.41	28.03	26.85
0.1–0.01	15.20	14.03	11.63	10.47	8.26	1.37	18.18	19.47	20.69	22.87	22.90
0.01–0.0005	16.46	17.86	12.76	11.37	7.60	0.04	20.81	23.11	25.96	31.13	32.08

Table 2. Distribution of Damage by Energy Group for Neutron Spectra Resulting from Penetration of Water or Graphite

Energy Range (Mev)	Damage per Energy Group (%)										
	Effective Distance in Water (cm^2/g)						Effective Distance in Graphite (cm^2/g)				
	0	10	20	30	50	125	10	20	30	60	120
>10	0.57	0.70	1.09	1.62	2.80	7.12	0.26	0.24	0.19	0.12	0.14
10–5	15.43	16.68	23.67	28.50	41.89	57.07	7.43	7.63	6.43	7.18	7.99
5–2	48.25	43.41	43.51	43.97	37.10	25.22	32.28	28.49	27.15	22.11	24.75
2–1	21.24	16.72	14.13	12.58	8.80	5.06	25.90	26.17	26.63	26.48	25.01
1–0.1	14.37	20.51	15.98	12.23	8.64	5.09	30.90	33.64	35.22	38.44	36.50
0.1–0.01	0.14	1.82	1.47	1.00	0.72	0.39	2.90	3.42	3.89	5.01	4.90
0.01–0.0005	<0.01	0.17	0.12	0.09	0.06	0.03	0.33	0.41	0.49	0.66	0.72

predominantly influenced by water (such as that at the experimental face of the Oak Ridge Research Reactor) are conservative when used in the design (in regard to brittle fracture) of pressure vessels for graphite-reflected reactors. Conversely, using uncorrected data from graphite-influenced spectra (such as the Brookhaven pile) in pressure vessel design for reactors that depend on water for neutron attenuation could be dangerous, since damage will be significantly underestimated. A specific case was the use of damage data from water-influenced spectra in the design of the pressure vessel of the High Flux Isotope Reactor. At the point of penetration of the radial beam hole, the average thickness (based on line-of-sight from base) of water protection is about 50 cm. Using the 0.0005-Mev threshold curve (worst case) and assuming that the damage data were obtained for a spectrum equivalent to that for minimum damage (at 10 cm), the spectral correction factor, which was the ratio of damage at 60 cm to that at 10 cm, was ~2.

It is felt that in spite of the crudeness of the model, the spectral correction factors obtained by this method are very useful to the designer, and they help reduce the area of ignorance inherent in brittle fracture considerations.

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