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EXPERIMENTAL STUDIES OF FREE DEFECT GENERATION DURING IRRADIATION- IMPLICATIONS FOR REACTOR ENVIRONMENTS*

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EXPERIMENTAL STUDIES OF FREE DEFECT GENERATION DURING IRRADIATION- IMPLICATIONS FOR REACTOR ENVIRONMENTS.* L. E. Rehn and R. C. Birtcher, Materials Science Division, Argonne National Laboratory, Argonne, IL 60439

Over the past several years, systematic experiments have revealed that irradiations which generate energetically dense cascades are much less effective than light-ion, MeV electron, or thermal neutron irradiations at producing freely-migrating defects. In this paper, the systematic results on freely-migrating defect production from ion-irradiation studies are briefly summarized. Difficulties with applying a simple extrapolation of the ion-irradiation results to neutron environments are discussed. This discussion, coupled with our existing knowledge of neutron-induced property changes, indicates that Compton scattering, and the (n,γ) , (n,He) and (n,p) nuclear reactions, are considerably more important for producing freely-migrating defects than was previously realized.

I. INTRODUCTION

Many technologically critical property changes that occur in reactor environments are driven by freely-migrating defects (FMD's), i.e., those defects which migrate over distances that are large compared to nascent cascade dimensions. The microstructural effects underlying these property changes include, for example, void swelling, radiation-induced segregation, radiation-enhanced diffusion, and radiation embrittlement.

For several decades, attempts to correlate irradiation-induced property changes with different primary recoil spectra, e.g., fission, fusion, and thermal neutrons, as well as high-energy ion and electron sources, have focused on calculations of the number of times an atom is displaced (dpa) from its lattice site. Although normalizing property changes on the basis of dpa generally improves previously recognized trends in measured property changes, the dpa approach falls far short of producing quantitative correlations.¹⁻⁴ The reason for this failure is widely recognized. Since the fraction of freely-migrating defects depends strongly on spatial details of defect generation, and since dpa does not take spatial aspects into account, normalizations performed on the basis of dpa cannot be

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expected to produce quantitative property correlations between irradiation environments with substantially different recoil spectra.

Almost two decades ago, measurements⁵ of defect production at very low temperatures demonstrated that the fraction of defects which actually survived the production event was itself a strong function of primary recoil energy. For recoil energies ≥ 20 keV, only 20 to 30% of the calculated number of defects survived annihilation during the cascade cooling phase.⁶ Such measurements thus provided a first-order correction to dpa normalizations. However, this correction produced only a slight improvement in correlating the types of microstructural changes driven by freely-migrating defects.

About ten years later, evidence began to accrue that irradiations which generate energetically dense cascades are in fact much less than 30% as effective as light-ion, MeV-electron, or thermal-neutron irradiations at producing freely-migrating defects. Systematic studies⁷⁻¹⁰ of radiation-induced segregation rates in three different binary alloys yielded a dependence of freely-migrating defect production on primary recoil energy that was qualitatively similar to the measurements of defect survival at cryogenic temperatures. However, the total fraction of defects found to undergo free migration at elevated temperatures for higher recoil energies was considerably smaller than the fraction found to survive at low temperatures. Subsequent studies¹¹⁻¹³ of radiation-enhanced diffusion rates by the Berlin group confirmed that the fraction of freely-migrating defects becomes $\sim 1\%$ for ion irradiations with high average recoil energies.

Both the radiation-induced segregation and radiation-enhanced diffusion studies employed ion beams. Ion irradiations were successful in providing detailed information on freely-migrating defect production by making it possible to attain, and maintain, steady-state irradiation conditions for times sufficiently long to achieve measurable property changes. Unfortunately, it is not possible to maintain steady-state conditions for similar periods in currently available neutron-irradiation environments. Nevertheless, simple extrapolation of the ion-beam results indicated that the fraction of freely-migrating defects for fission or fusion neutron environments, with typical recoil energies ≥ 20 keV, would be $\leq 1\%$ of the calculated dpa.¹⁴

We have previously discussed in detail the experimental measurements of freely-migrating defect production,⁷ as well as outlined the various factors which make the number of freely-migrating defects so small relative to the total number of defects generated.^{14,15} Therefore, in

this contribution, the systematic results on freely-migrating defect production from the two ion-irradiation studies are summarized only briefly. Instead, we focus on a serious difficulty with the previously employed simple extrapolation of the ion-irradiation results to neutron environments. This discussion, coupled with our existing knowledge of neutron-induced property changes, reveals that Compton scattering events, and the (n,γ) , (n,He) and (n,p) nuclear reactions, are considerably more important in producing freely-migrating defects in reactor environments than previously realized.

II. SUMMARY OF EXPERIMENTAL RESULTS

As pointed out above, two different types of elevated-temperature experiments have been performed systematically to determine the fraction of freely-migrating defects produced during ion irradiation. The results from our own laboratory,⁸⁻¹⁰ based upon ion-beam analysis of radiation-induced segregation in Ni(Si), Cu(Au), and Mo(Re) alloys are summarized in Fig. 1. The "defect-weighted" average recoil energy (the calculated energy above and below which half the defects are produced) is plotted as the abscissa in Fig. 1. The reasons for selecting this quantity, which has also been referred to as the "median recoil energy", have been given elsewhere.¹⁴ A strong decrease in the relative efficiency for producing freely-migrating defects occurs with increasing recoil energy up to a few keV, after which the effect tends toward saturation for values above ~20 keV. Relative to 1-MeV proton irradiation, with an average recoil energy of 730 eV, ion irradiations with recoil-energies of some tens of keV are only a few per cent as efficient at generating freely-migrating defects. A separate in situ study indicated that 1-MeV electrons were approximately twice as efficient as the proton irradiation for generating freely-migrating defects.¹⁶ Interest in these results has focused primarily on the low value, only a few per cent, found at higher recoil energies. It is to be emphasized that these results have been reported as relative efficiencies, which allowed us to extract them without development of a sophisticated model or moot assumptions. However, as has been discussed in more detail by the Berlin group,^{17,18} straightforward assumptions can be employed to convert these data to absolute values. For example, if we assume that half of the defects produced by the proton irradiation become freely-migrating, which is

equivalent to assuming that all (certainly an upper limit) of the defects produced by the 1-MeV electrons do likewise, then only ~1% of the calculated number of defects produced by the heavy-ion irradiations can become freely-migrating. Regardless of any particular assumption, it is clear from the data displayed in Fig. 1 that the resulting fraction of freely-migrating defects at higher recoil energies is at most only a few per cent of the calculated number of generated defects.

The Berlin group has used SIMS to monitor radiation-enhanced diffusion of Ni in Cu, in Ni, and in Fe-Cr-Ni alloys.¹¹⁻¹³ A sample of their results for the tracer diffusion coefficient in Ni for two different calculated displacement rates, 1.3×10^{-2} and 1.3×10^{-4} dpa/s, during irradiation with 300-keV Ni ions is shown in the form of an Arrhenius plot in Fig. 2. The solid lines are fits to the temperature-dependent part of the experimental data using a model that incorporates measured values for the defect-sink concentration as a function of irradiation temperature; dashed lines indicate expected values for recombination-dominated defect annihilation.

From such fits of their data to the model of radiation-enhanced diffusion, these authors obtained an absolute fraction of freely-migrating defects of 1.5% of the calculated displacement rate. Since the average recoil energy for this irradiation is approximately 20 keV, the absolute efficiency of 1.5% is consistent with the small relative efficiency extracted previously from the segregation studies. The Berlin group has presented more direct comparisons of the two different studies elsewhere.¹⁷⁻¹⁹

A consensus of the results from the two studies reveals: (1) For irradiations which generate energetically-dense displacement cascades, only about 1% of the calculated number of displaced atoms actually become free to migrate long distances. (2) The dependence of freely-migrating defect fraction on median recoil energy is similar in all the different alloys which have been investigated to date. (3) There is no indication in any of the experimental studies that the freely-migrating defect fraction is dependent upon temperature, even in the regime where the irradiation-induced defect structure is seen to be undergoing large changes.³ In fact, recombination-limited annihilation, taking into account the "TEM visible" sink structure, fits all the experimental results very well. This latter point is difficult to reconcile within the "production bias"^{20,21} picture, a point to which we will return later.

III. WHY IS THE FRACTION SO SMALL

Three different explanations have been proposed to account for the small fraction of defects that are observed to become freely-migrating at high recoil energies. In one picture,⁸ the small surviving fraction found at elevated temperatures is attributed to additional "intra"cascade defect recombination within energetic displacement cascades. This explanation is the same one used previously to account for the similar, but less drastic reduction observed in defect survival at low temperatures. Alternatively, "inter"cascade defect annihilation due to immobile cascade remnants, e.g., vacancy or interstitial clusters, has also been invoked to account for the strong reduction.²¹ This second picture has led to the concept of a production "bias", in which the generation of one type of freely-migrating defect, for example vacancies, is favored.²⁰ In a third picture, which was proposed recently by the Berlin group, freely-migrating defects result only from "isolated" defect production events, and essentially no mobile defects are assumed to escape from higher-energy recoil events.^{17,18} These three different pictures will be referred to subsequently as the "intracascade annihilation", the "intercascade annihilation" and the "isolated" models of freely-migrating defect production. As we will see below, these models convey quite different implications for our understanding of freely-migrating defect production in neutron irradiation environments.

We suggested the intracascade annihilation (and clustering) mechanism in our initial publication,⁸ and offered two reasons why intracascade effects should be even more effective for reducing the number of freely-migrating defects at elevated temperatures than they are for reducing defect survival at low temperatures: (1) The additional atomic motion which occurs at elevated temperatures will enhance both the annihilation, as well as the clustering, of defects. (2) Although clustering does not significantly alter the low-temperature defect survival results, it will substantially reduce the number of freely-migrating defects. The primary reasons we chose the intracascade interpretation were the relatively broad temperature range over which the fraction of freely-migrating defects was found to remain constant, and the fact that the irradiation-induced sink structure was seen to be important only at the lowest temperatures.

Somewhat later, Wiedersich²¹ suggested that part of the additional loss of freely-migrating defects might be due to intercascade defect

annihilation. He pointed out that computer simulations of the annealing of isolated cascades indicate that although annealing reduces the number of defects, and causes additional clustering of like defects, the calculated reductions are not large enough to account for a saturation fraction as small as one per cent. Instead, Wiedersich proposed that the observed decrease can be better rationalized by the annihilation of freely-migrating interstitial defects at immobile vacancy clusters, which are known to be generated directly within energetic cascades. As a consequence of the stronger clustering of vacancies over interstitials within cascades, an excess of freely migrating interstitials is produced. When these freely-migrating interstitials encounter a vacancy cluster, they annihilate, causing the clusters to shrink even without thermally-activated vacancy emission. Hence the immobile clusters have a finite lifetime, and a quasi-steady-state will develop during irradiation that includes a distribution of cluster sizes, and an excess concentration of freely-migrating interstitials over vacancies. Because of their finite lifetime, no lasting microstructural features such as, for example, radiation-induced precipitation, will persist at any individual cluster site.

Subsequently, other authors²⁰ have proposed that instead of vacancy clusters, interstitial loops, because of their substantially stronger binding energies, are in fact the dominant remnant sink, and an excess of freely-migrating vacancies, rather than interstitials, will result. Clearly, the key to understanding the effect of either remnant vacancy or interstitial loops on intercascade annihilation is knowledge of the immobile cluster lifetimes and number densities as a function of temperature. As argued in Ref. 14, the fact that the irradiation-induced sink density changes dramatically in the same temperature range (500 to 800K) where the fraction of freely-migrating defects remains constant, makes it difficult to accept the intercascade annihilation picture. Equally as difficult to explain in this picture is the observation of a square-root of dose dependence for the diffusion constant, a characteristic which falls naturally out of the intracascade picture.

Naundorf has proposed a third alternative,¹⁸ which assumes that freely-migrating defects are generated only by isolated displacements, i.e., only by displacement events that occur at a sufficiently large distance from any other defect, either directly by the incident ion or by an appropriate

recoil within a collision cascade. All other defects are assumed either to recombine, or agglomerate into immobile clusters. Note that within this third model, as with the first, there is no production bias. Slightly different parameter sets were employed in the two publications related to this issue,^{17,18} but the fundamental conclusion remained unaltered. This "isolated" defect production picture is able to reproduce the experimentally determined freely-migrating fractions found using a wide variety of ion beams. As pointed out by the authors, it also provides a guide for estimating the freely-migrating fraction during neutron irradiation. The first parameter set appears to indicate that the freely migrating defect fraction during fast neutron irradiation is essentially zero, while the second data set permits a finite, but small number.

A discussion of the implications from these ion irradiation studies for neutron environments will be given next. Let us first, however, conclude this section with the following observations. No evidence has appeared which directly contradicts the original interpretation that intracascade annihilation and clustering are responsible for the strong decrease in freely-migrating defect fraction with increasing recoil energy. The strongest counter argument still appears to be the larger number of escaping defects found in the computer simulation studies. The toughest hurdle for the intercascade annihilation picture is the temperature dependent data (c.f. Fig. 2), because these can be accounted for directly in terms of the TEM visible sink densities. Note that this difficulty applies equally to the vacancy and interstitial pictures of "production bias", since as pointed out by Naundorf et al.,¹⁷ the only site for the extra defects generated by the bias to annihilate is at fixed sinks. However no clear indication of annihilation at sinks other than those visible by TEM is seen in either the segregation or the enhanced diffusion studies.

IV. IMPLICATIONS FOR REACTOR (NEUTRON) ENVIRONMENTS

As pointed out in the introduction to this paper, a major motivation for understanding the recoil-energy dependence of freely-migrating defect production is to permit accurate modeling of material property changes in neutron irradiation environments. Hence in this section we consider the implications of the ion-beam results for neutron irradiation.

For purposes of this discussion, it is important to recognize that the choice of median recoil energy for the abscissa in Fig. 1 is not ideal. The rationale for choosing this particular parameter has been given in detail elsewhere¹⁵; essentially no better alternative is currently available. To see the underlying difficulty with the use of this single parameter to characterize the recoil spectra, we first consider Fig. 3, in which calculated recoil spectra for several different ion irradiations of nickel are shown. The computer code PINTO,⁵ written by R. Benedek, was employed for the calculations, along with an average displacement threshold of 29 eV. As the mass (or to a lesser extent the energy) of the bombarding ion increases, the primary recoil spectrum becomes harder. That is, more defects are produced in higher energy recoil events, increasing the spatial correlation among the defects. The long tails extending to low recoil energies for the ions are a consequence of the long-range Coulomb interactions. From the sharp drop in efficiency over the range of recoil energies near 1 keV (Fig. 1), it is clear that these low-energy tails play an important role in enhancing freely-migrating defect production during ion irradiation.

For comparison, calculated recoil spectra for several different neutron irradiations of nickel are shown in Fig. 4.²² Let us consider first the pure fission spectrum, which has a weighted-average recoil energy, i.e., that energy above and below which half of the defects are created, of 70 keV, which is very close to that of the 2-MeV Kr ion irradiation (Fig. 3). However the net fraction of defects produced below 5 keV is almost 15% in the Kr-irradiation, while it is only ~2% for fission neutrons. Hence it is clear that many more freely-migrating defects will be generated by the Kr ions compared to the fission neutrons, despite the similarity of their average recoil energies. Note that the "degraded" fission spectrum found in a reactor environment, e.g., the CP-5 spectrum shown in Fig. 4, has a much more pronounced tail toward lower energies. Hence considerably more freely-migrating defects will be generated in a reactor environment such as CP-5 compared to a pure fission spectrum, but the fraction is still substantially less than that for MeV-Kr irradiation.

The "hardness" of the fission neutron spectrum relative to the ion irradiations becomes even more pronounced when it is realized that knock-on atoms with very high recoil energies ($> \sim 100$ keV) do not generate correspondingly denser cascades. As recoil events increase in energy above

several tens of keV, the increase in spatial correlation among the defects slows because of the increasing probability of subcascade formation. That is, some of the defect production events which appear in Fig. 3 to occur for ions at very high recoil energies actually should be folded back into the lower energy portion of the spectrum. Unfortunately, our current understanding of subcascade formation is insufficient to do this quantitatively. Therefore, both tails in the recoil spectra, the one toward lower energies due to long-range Coulomb interactions as well as the one toward higher energies due to the much larger mass of most ions relative to neutrons, cannot be adequately represented by a simple "average" recoil energy.

It is this fundamental difference in their primary recoil spectra that precludes accurate predictions of freely-migrating defect fractions in reactor environments on the basis of the existing ion data. Although Naundorf et al.¹⁷ have proposed a formalism for such a procedure, the existing uncertainty is clearly substantial. Nevertheless, it is obvious that the low-energy recoil events dominate the production of freely-migrating defects. Combining all the relative information contained in Figs. 1-4 with the 1.5% absolute fraction extracted by the Berlin group from the ion results, it is apparent that $\leq 1\%$ of defects produced by the degraded fission neutron spectrum in a reactor environment can be expected to become freely-migrating.

Despite the simplicity of this reasoning, there are additional factors which, at least at first glance, argue against this conclusion. For example, it is widely recognized that swelling rates on the order of 1% per dpa can be attained in the steady-state swelling regime during neutron irradiation.²³ Also, significant amounts of radiation-induced segregation and creep do occur in reactor environments. If $\leq 1\%$ of the calculated number of defects become freely-migrating, then a bias factor of $\geq 100\%$ (clearly unphysical) is needed to explain a 1% swelling rate in terms of preferential interstitial annihilation at dislocations. Similarly, the observed segregation and creep rates are too high to be explained on the basis of so few defects. Therefore the simple comparison presented above appears to yield too small a fraction of freely-migrating defects to account for known phenomena. This apparent inconsistency would, of course, disappear if other sources of freely-migrating defect production, that is other than energetic

displacement cascades, could be identified for reactor environments. These other sources are the subject of the remainder of this paper.

Recently,²⁴ the important contribution from thermal neutrons to freely-migrating defect production has been recognized, particularly with regard to highly thermalized neutron environments such as at a pressure vessel wall. Indeed, essentially all neutrons eventually become thermalized somewhere in the reactor structure. Unfortunately, the low energy portion of the neutron energy spectrum is typically not well characterized in a reactor environment. Hence, freely-migrating defect production by low energy neutrons provides a strong candidate for explaining heretofore puzzling differences found after irradiation of materials in different neutron environments.^{2,25}

Next, we consider defect production by gamma (γ) rays. There are two major sources of energetic gamma rays in a reactor, prompt fission gammas, and neutron capture gammas. Although the direct displacement of an atom by a gamma ray with energy in the range typical for a reactor environment, 1-10 MeV, is highly unlikely, the indirect process in which the γ generates a Compton electron, causing the material to undergo internal bombardment by MeV electrons, has a significant probability to create defects at low recoil energies of a few hundred eV or less. To see this, we follow an argument given previously by Dienes and Vineyard,²⁶ and in a slightly more correct form by Billington and Crawford.²⁷ Here we follow the formulation provided in the latter reference.

The cross section, σ_c , for Compton scattering is proportional to the number of electrons in the scattering atom, Z . The cross-section per unit energy of the Compton electron from an atom of atomic number Z is given by:

$$\kappa_c^\gamma(E_\gamma; E_c) = \frac{\pi e^4 Z}{m_e c^2} \frac{1}{(E_\gamma - E_c)^2} \left\{ \left[\frac{m_e c^2 E_c}{E_\gamma^2} \right]^2 + 2 \left[\frac{E_\gamma - E_c}{E_\gamma} \right]^2 + \frac{E_\gamma - E_c}{E_\gamma^3} \left[(E_c - m_e c^2)^2 - m_e^2 c^4 \right] \right\}, \quad (1)$$

where E_γ is the incident γ -ray energy and E_c is the energy transferred to the Compton electron. Note that $\kappa_c\gamma$ is weighted heavily toward high values of E_c . For a given E_γ ,

$$E_c(\text{Max}) = 2E_\gamma^2/(m_e c^2 + 2E_\gamma) . \quad (2)$$

For $E_\gamma \gg m_e c^2$, $E_c(\text{Max}) \approx E_\gamma - m_e c^2/2$. This distribution makes the Compton process highly effective for MeV gammas to create electrons with sufficient energy (1-10 MeV) to create displacements at low recoil energies (20 - 100 eV).

In order to calculate the cross-section for generating displacements via the Compton process it is necessary to perform three integrations: (i) one over the distribution of primary energies for an electron of energy E_c , (ii) one over the electron range to obtain the energy distribution of electrons starting with energy E_c , (iii) and a third over $\kappa_c\gamma(E_\gamma; E_c)$ to include the effect of the distribution of Compton electron energies, E_γ .

$$\sigma_{c,d}^\gamma(E_\gamma) = N_A \int_0^{E_c(\text{Max})} \kappa_c^\gamma(E_\gamma; E_c) dE_c \int_0^{E_c} \left(\frac{-dE_e}{dx} \right)^{-1} dE_e \int_{E_d}^{E_p(\text{Max})} \kappa(E_e, E_p) dE_p, \quad (3)$$

where $-dE_e/dx$ is the total electron energy loss per unit path length, N_A is the atomic density, and $\kappa(E_e, E_p)$ is the displacement cross-section per unit energy for producing a Frenkel pair. For this latter cross section we use the following expression, which provides a reasonable fit to the experimental electron cross-section data for copper tabulated by Bailly²⁸ for electron energies of 0.5 to 3 MeV.

$$\kappa(E_e, E_p) = 28 (E - 0.49 \text{ MeV})^{1/2} \quad (4)$$

Here, the cross section is in barns, and the energy is in units of MeV. The results of performing the three integrations for Cu are presented as a function of the gamma energy in Fig. 5.

Most investigations of prompt fission gamma spectra have focused on ^{235}U , for which 7.4 ± 0.8 photons, with energies ranging from 0.3 to 10 MeV, are emitted per fission event.²⁹ Approximately 2 of these fall in the energy range of 1-3 MeV (where $\kappa(E_e, E_p) \sim 0.5$ barns), and about 5 have energies

below 1 MeV (where $\kappa(E_e, E_p) \sim 0$). The effective cross section for Compton production of defects per fission event is therefore about one barn. The collision cross section for fast neutrons to produce a cascade is two to three barns, and each fast neutron collision produces approximately 400 Frenkel pairs. Following this reasoning, we see that for copper in a reactor environment, perhaps (0.1-0.2)% of the displacements are generated by the fission gammas. The Compton mechanism therefore provides a significant, although probably not overwhelming portion of the freely-migrating defects.

Returning to Fig. 5, we see that the cross section for producing displacements via the Compton mechanism increases by about a factor of 100 in going from a photon energy of 1 to 10 MeV. It is interesting to note that while fission photons are prevalent only in the range below 2 MeV, capture gammas extend considerably higher, up to 10 MeV. As presented elsewhere,³⁰ a detailed calculation reveals that defect production via the Compton effect dominates the number of defects generated in medium-Z alloys such as steel, an important finding that has been overlooked for many decades.

Energetic light-ions from nuclear reactions, such as the well known (n,p) and (n,He) reactions, provide yet another source for producing defects in reactor environments. Because of the kinematics of collisions by light particles, as well as the long-range Coulomb interactions, much of the defect production by the emitted ions occurs at low recoil energies.

As pointed out by Greenwood,³¹ who has considered this type of defect generation from the viewpoint of total defect production, the most important He-producing reaction from a technological standpoint is the sequential $^{58}\text{Ni}(n,\gamma)^{59}\text{Ni}(n,\alpha)^{56}\text{Fe}$ reaction. The average ^{56}Fe recoil energy is 340 keV and that of the α particle is 5097 keV. Half of the ^{56}Fe energy and about 0.13% of the alpha energy will be deposited in nuclear collisions. The modified Kinchin-Pease relationship^{32,33} yields approximately 1760 displacements per reaction, i.e. per generated He atom, with approximately 100 of these being generated by the emitted α particle. Consequently, the ratio of displacements from the α particle (100) generated in this reaction to He(appm) is $100/10^6$, or 10^{-4} .

Looking at a previous compilation of data by Doran³⁴ for steels, we see that in a fission reactor environment, approximately 0.5 appm He is

produced per dpa. Hence the additional contribution from the emitted α particle is only $\sim 0.005\%$, too small to be significant even in the case of only 1% freely-migrating defects. In a fusion environment, however, the He generation rate can be much higher, on the order of (50 to 100) appm He per dpa. Hence the same reaction in a fusion environment will produce up to 0.5% of the defects, and therefore can provide a major source of freely-migrating defects.

Although the amount of energy deposited in nuclear collisions is somewhat more than an order of magnitude less for H than for He particles of the same energy, H generation rates in fission and fusion reactor environments by (n, p) reactions are approximately one order of magnitude higher than He generation rates. Hence H producing nuclear reactions also deserve consideration as a source of freely-migrating defects, particularly since the apparent efficiency for producing them is approximately twice (c.f. Fig. 1) as high for protons as for alphas.

V. SUMMARY

Because of long-range Coulomb interactions, which generate low-energy recoils, and higher masses, which increase maximum energy transfers, ions create defects over a much broader range of recoil energies than do neutrons. Hence, although relatively accurate measurements exist of freely-migrating defect production during ion irradiation, it is not possible to extract from this data quantitative information on freely-migrating defect production during neutron irradiation. Nevertheless, the existing measurements clearly indicate that only $\leq 1\%$ of the calculated number of defects can escape from energetic displacement cascades and become freely-migrating.

Simple estimates offered in the present paper indicate that freely-migrating defect production by Compton electrons generated by either prompt fission or thermal neutron capture gamma rays, and light-ions emitted from the (n, γ), (n,p) and (n,He) nuclear reactions, is comparable to or even exceeds that due to energetic displacement cascades generated by fast neutrons. Prompt fission gammas, which fall off rapidly in number for energies above approximately 3 MeV, generate via the Compton process only something like 0.1% of the total number of defects. However, because of the strong increase in the total cross section that occurs for higher

gamma energies, Compton electrons generated by capture gammas, with energies ranging up to approximately 10 MeV, actually dominate total defect production for medium-Z alloys like stainless steels in thermal neutron environments. The light-ion products from the (n,H) and (n,He) nuclear reactions apparently are not important for generating defects in fission environments. However, they can create up to 1% of the total defect production in fusion environments, and therefore may provide the major source of freely-migrating defects in fusion materials.

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FIGURE CAPTIONS

- Fig. 1. Relative efficiencies for producing freely-migrating defects measured in Ni(Si)- filled squares, Cu(Au)- open triangles, and Mo(Re)- open squares alloys during ion irradiation plotted as a function of the weighted-average recoil energy.
- Fig. 2. Arrhenius plot of the self diffusion coefficient (D) in nickel during 300-keV self ion irradiation for calculated displacement rates of 1.3×10^{-2} (solid circles) and for 1.3×10^{-4} dpa/s. The solid lines are theoretical fits to the experimental values based upon measured sink concentrations; the dashed lines show the expected behavior for recombination-dominated defect annihilation.
- Fig. 3. Calculated fraction of defects produced by primary recoil events of energy less than P for different irradiation particles: (1) 1-MeV electrons, (2) 1-MeV ^1H , (3) 2-MeV ^4He , (4) 2-MeV ^7Li , (5) 3-MeV ^{58}Ni , and (6) 3.25-MeV ^{84}Kr .
- Fig. 4. Same as for Fig. 3, only for neutron irradiation. The two curves marked IPNS refer to calculated recoil spectra for the two different irradiation targets initially present at Argonne's Intense Pulsed Neutron Source (IPNS), i. e., the Neutron Scattering Facility (NSF) and the Radiation Effects Facility (REF). Also included are calculations for a pure fission spectrum, for 14-MeV neutrons, and for a reactor (CP-5).
- Fig. 5. The cross section for defect production via the Compton effect plotted as a function of the energy of the gamma ray.

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5

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