LA-UR--86-1005

DE86 008750

Received by OSTI

APR 07 1986

CONF-860421--9

Los Alamos National Laboratory is operated by the University of California for the United States Department of Energy under contract W-7405-ENG-36

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AND GROWTH UNDER NEUTRON AND PROTON IRRADIATION

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SUBMITTED TO: Second International Conference on Fusion Reactor Materials,
Chicago, IL, April 13-17, 1986

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NONEQUILIBRIUM STATISTICAL THEORY OF BUBBLE NUCLEATION
AND GROWTH UNDER NEUTRON AND PROTON IRRADIATION

Jinnan Yu,* Walter F. Sommer,** James N. Bradbury**

ABSTRACT

Microstructural evolution in metals under particle irradiation is described by a non-equilibrium statistics method. This method gives a set of equations for the evolution of bubbles and an approximate solution for a distribution function of bubble size as a function of fluence and temperature. The distribution function gives the number of bubbles of radius r at time t , $N(r,t)dr$, as a function of size, r/r_0 (r_0 is the radius of a bubble nucleus). It is found that $N(r,t)dr$ increases with fluence. Also, the peak value of $N(r,t)dt$ shifts to higher r/r_0 with increasing fluence. Nucleation depends mainly on helium concentration and defect cluster concentration while bubble growth is controlled mainly by the vacancy concentration and a fluctuation coefficient. If suitable material parameters are chosen, a reasonable distribution function for bubble size is obtained. The helium diffusion coefficient is found to be less than that for vacancies by five orders of magnitude. The fraction of helium remaining in matrix is less than 10^{-2} ; the majority of the helium is associated with the bubbles.

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1. Introduction

Radiation damage to structural material in a fusion reactor environment is often characterized by high-energy cascades and the production of helium as a transmutation product. Since there are no large scale irradiation facilities that can produce a fusion environment various techniques of simulation have been considered.[1]

Recent computer calculations[2] and microscopic observations on specimens irradiated by the products of the deuterium-tritium (D-T) reaction[3] provide new information about the defect structures associated with high-energy cascades. It is important, at present, to develop effective models which take these new findings into account and, if possible, tie together results from irradiation conditions that vary in PKA spectra, dose, dose rate and transmutation product formation.

The theoretical framework described below forms the basis of a future experiment at the Los Alamos Spallation Radiation Effects Facility (LASREF). The initial work will expose pure metal single-crystal material (then pure polycrystalline material and type 316 stainless steel) to the direct proton beam of energy = 760 MeV, and to the neutron flux that results from spallation events as the protons interact with targets at the Los Alamos Meson Physics Facility (LAMPF) beam stop. This facility provides helium production to atomic displacement ratios that vary by more than a factor of 10 (direct proton beam vs the spallation neutron flux) and, in fact, bracket the fusion case.[4] The primary goal is to predict microstructural evolution under our two different irradiation conditions and then determine to what extent it may be possible to extrapolate these data to conditions inherent in fusion reactors. The development which follows is a summary of a more extensive document[6] in which the details are

described. This document is available from the library at Los Alamos National Laboratory or from one of the authors.

2. Physical model and the bubble evolution equation

We base our model on the fusion environment conditions in which high-energy cascades and transmutational helium are produced. Helium atoms are considered to stabilize defect clusters formed by the cascades, which then can become a bubble nucleus. A flow diagram outlining the entire process is shown in Fig. 1.

The cascade process consists of the two steps. First is the collisional process, the formation of primary knock-on atoms (PKA) by the interaction of injected particles with matrix atoms and the formation of a number of point defects and defect clusters by cascade collisions. This process ceases in a very short time, $\tau \sim 10^{-13}$ s. The second is the diffusional process; the spreading of point defects (vacancies, V, and interstitials, I), the migration of helium (He) atoms, the clustering of V, I, He and the absorption of these point defects at various sinks. We divide this second process into the two parts; a strongly correlated region of dimension R (R is the PKA range), during the time, $t < \tau$, where the concentration of point defects produced by the PKA is large. This area is called a displacement cascade. The second is the region outside R where the density of point defects has decreased by diffusion to nearly the same magnitude as the mean field throughout the material.

Considering first the nucleation process, since the intensity of bombarding particles and the concentration of lattice atoms are both very large, the collision process is assumed to be a series of random events. Accordingly, the formation of a PKA and a cascade and the production of transmutation helium atoms are also assumed to be random events. We assume that the production of cascades and helium atoms is uniform in space and time and independent of any other space

and time region.[9] Since helium atoms are able to stabilize defect clusters[5] which then become bubble nuclei, bubble nucleation probability must be considered to consist of three parts: the first is the cascade nucleation probability where the cascade regions have associated helium atoms, the second is the probability that a helium atom diffuses to a defect cluster, and the third is the probability of helium-helium interactions which form bubble nuclei by homogeneous nucleation. These bubble-nucleation probabilities are independent, thus the nucleation rate, $q(t)$, consists of three terms,

$$q(t) = q_1(t) + q_2(t) + q_3(t) \quad (1)$$

where $q_1(t)$ is the cascade (which has associated helium atoms) nucleation rate, the nucleation rate, $q_2(t)$, is determined by the rate of helium diffusion to defect clusters and $q_3(t)$ is the homogeneous nucleation rate.

The bubble growth process is assumed to satisfy a Langevin equation of the form:

$$\dot{r} = K(r,t) + f(r,t) \quad (2)$$

where r is the bubble radius, $\dot{r}$ is the bubble growth rate, $K(r,t)$ is a bubble growth function and $f(r,t)$ is a fluctuating function. The bubble growth at time t depends only upon the instantaneous helium and point defect concentration and instantaneous state of the microstructure (dislocation density, bubble distribution, grain boundary morphology) at time t and is independent of previous history. Thus the bubble growth can be considered as a Markov process. For stochastic processes characterized by a Markov process, an equivalent Fokker-Planck equation is[9,10]

$$\frac{\partial W(r,t;r_0)}{\partial t} = - \frac{\partial K(r,t)W(r,t;r_0)}{\partial r} + \frac{D\partial^2 W(r,t;r_0)}{2\partial r^2}, \quad (3)$$

where $W(r,t;r_0)$ is a probability density function, $W(r,t;r_0)dr$ is the probability density of bubbles with a radius in the range $[r, r+dr]$ at time t , given that $r = r_0$ at $t = 0$. D is the fluctuation coefficient. When $W(r,t;r_0)dr$ is multiplied by the number of nuclei, we obtain $N(r,t)dr$; the bubble concentration with radius in the range $[r, r+dr]$ at time t . Because the bubble growth can be described as a Markov process, we can also add two terms to equation (3); one to represent the nucleation rate of bubbles, and one to represent the re-resolution of helium atoms from bubbles.[11] The bubble evolution equation is then written as.

$$\frac{\partial N(r,t)}{\partial t} = - \frac{\partial (K(r,t)N(r,t))}{\partial r} + \frac{D\partial^2 N(r,t)}{2\partial r^2} + q(t)\delta(r-r_0) - \eta bN(r,t). \quad (4)$$

The re-resolution parameter[11] is denoted as b . η is the re-resolution efficiency. r_0 is the minimum radius of a bubble nucleus. The nucleation rate, $q(t)$, is

$$q(t) = (1 - \int_{r_0}^{\infty} N(r,t) \frac{4}{3}\pi(r + l_f)^3 dr)(1 - \beta)\dot{N}_d \frac{4}{3}\pi R^3 (\dot{N}_{He}t - \int_{r_0}^{\infty} N(r,t)n(r)dr) \\ + N_c(\dot{N}_{He}t - \int_{r_0}^{\infty} N(r,t)n(r)dr) \frac{4\pi R_1 D_g}{1 + \frac{R_1}{a_0}} + \frac{Z_0 l_1 Q D_g}{a_0^2} (\dot{N}_{He}t - \int_{r_0}^{\infty} N(r,t)n(r)dr)^2. \quad (5)$$

Here, $\dot{N}_{He}$ is the helium production rate, $\dot{N}_d$ is the displacement cascade production rate and l_f is a distance from the bubble surface, in which the bubble can influence diffusion. β is the probability that a helium atom in the cascade region can receive sufficient kinetic energy to be removed from the region and not

be available to stabilize a new bubble nucleus. $n(r)$ can be described as $n(r) = \frac{p(r)(4/3)\pi r^3}{kT + p(r)B}$, ($r \leq 500\text{\AA}$); $n(r) = \frac{p(r)(4/3)\pi r^3}{kT}$, ($r \geq 500\text{\AA}$). $p(r)$ is the bubble gas pressure. k is Boltzmann's constant and T is the solid's absolute temperature(K). $\beta = \frac{3l}{4R} - \frac{l^3}{16R^3}$, ($l \leq R$), where $l(\bar{T})$ is the mean flight length of a helium atom with average kinetic energy $\bar{T}$ in the cascade process. Where N_c is the concentration of defect clusters, $[6]$ R_1 is the radius of the defect cluster plus its region of influence, a_0 is the lattice constant and D_g is the diffusion coefficient for helium. Where Z_{q1} is the combinational number for a helium-helium pair and Ω is matrix atomic volume.

The growth function, $K(r, t)$, is

$$K(r, t) = \frac{D_v \Omega C_v^{eq}}{r} \left[\left(1 - \frac{Z_v}{Z_1}\right) \left(\frac{C_v}{C_v^{eq}} - 1\right) + \frac{\Omega}{kT} \left(p - \frac{2\gamma}{r}\right) \right] + \frac{D_g C_g v \Omega}{r + a_0} \quad (6)$$

D_v , C_v and C_v^{eq} are the diffusion coefficient of vacancies, vacancy concentration at the bubble surface and thermodynamic equilibrium vacancy concentration for a stress-free solid, respectively. $\frac{Z_v}{Z_1}$ is the ratio of the vacancy to interstitial capture coefficient by dislocations. γ is the surface energy. v is the number of atomic volumes associated with each helium atom. C_g is the concentration of helium atoms in the matrix,

$$C_g = \dot{N}_{He} t - \int_{r_0}^{\infty} N(r, t) n(r) dr. \quad (7)$$

The equation (4) may be solved, subject to the following boundary conditions:

$$N(r, t=0) = 0 \quad (8)$$

$$N(r=\infty, t) = 0,$$

Bubble coarsening is considered in detail in the extended document.[6]

3. Approximate solution and results

If the system is in a quasi-equilibrium state and the bubble pressure is in a quasi-equilibrium state ($p \sim \frac{2\gamma}{r}$), and in the incubation period for swelling, $\int_{r_0}^{\infty} N(r,t) \frac{4\pi}{3} (r + r_f)^3 dr \ll 1$ and $(\dot{N}_{He} t - \int_{r_0}^{\infty} N(r,t) n(r) dr) = \epsilon \dot{N}_{He} t$ where ϵ is the fraction of helium in the matrix, the approximate solution in which the nb term is considered alone, is

$$\begin{aligned}
 N(r,t) = & \frac{4E_1 E_3 t^{3/2}}{3\sqrt{2\pi D}} \exp\left[-\frac{(r-r_0)^2}{2Dt} + \frac{A_1}{D} \ln \frac{r}{r_0} + \frac{A_2}{D} C_g \frac{r + a_0}{r_0 + a_0}\right] \left\{ \left[\left(\frac{E_2}{E_3 t} + \frac{4}{5} \right) \right. \right. \\
 & + \left. \left(\frac{E_2}{E_3 t} + \frac{9}{5} \right) \mu + 0.4\mu^2 - \sqrt{\mu} e^{\mu} (1 - \Phi(\sqrt{\mu})) \left(\frac{3}{2} \left(\frac{E_2}{E_3 t} + 1 \right) + \left(\frac{E_2}{E_3 t} + 2 \right) \mu + 0.4\mu^2 \right) \right] \\
 & - \eta b t \left[\left(\frac{2}{5} J_4 + \frac{9}{20} J_7 + \frac{3}{20} J_{10} \right) + \frac{E_2}{2E_3 t} \left(J_3 + \frac{J_5}{2} \right) + 21\sqrt{\mu} \left(\frac{27}{32} \Psi\left(\frac{9}{2}, -\frac{1}{2}; \mu\right) + \frac{11}{32} \Psi\left(\frac{9}{2}, -\frac{3}{2}; \mu\right) \right. \right. \\
 & + \left. \left. \frac{3E_2}{7E_3 t} \Psi\left(\frac{3}{2}, -\frac{5}{2}; \mu\right) \right) + \mu(0.9J_6 + 0.6J_9 + \frac{E_2}{2E_3 t} J_4) + 45\mu^{3/2} \frac{63}{32} \Psi\left(-\frac{1}{2}, -\frac{1}{2}; \mu\right) + \frac{\mu^2}{5} J_8 \right. \\
 & - \left. \frac{9}{16} \exp\left[-\frac{(r-r)^2}{2Dt} + \frac{(r-r_0)^2}{2Dt}\right] \left[\left(\frac{E_2}{E_3 t} + \frac{14}{9} \right) \Psi\left(1, \frac{1}{2}; \bar{\mu}\right) - \left(\frac{2E_2}{E_3 t} + \frac{14}{3} \right) \Psi\left(1, -\frac{1}{2}; \bar{\mu}\right) \right. \right. \\
 & + \left. \left. \left(\frac{E_2}{E_3 t} + \frac{14}{3} \right) \Psi\left(1, -\frac{3}{2}; \bar{\mu}\right) - \frac{14}{9} \Psi\left(1, -\frac{5}{2}; \bar{\mu}\right) \right] \right\}, \quad (9)
 \end{aligned}$$

where μ is $\frac{(r - r_0)^2}{2Dt}$ and E_1 , E_2 and E_3 are $\epsilon \dot{N}_d$, $\dot{N}_{He}$, $\frac{4\pi R^3}{3}(1 - \beta)$ and $D_g \left(\frac{4\pi R_1 \alpha \zeta}{1 + a_0/R_1} \right.$

$\left. + \frac{Z_{01} \dot{N}_{He} \epsilon \Omega}{2 \dot{N}_d} \right)$ respectively. $A_1 = D_v \Omega C_v^{eq} (1 - \frac{Z_v}{Z_1}) (\frac{C_v}{C_v^{eq}} - 1)$, $A_2 = D_g v \Omega$ and $\mu' = \frac{(\xi - r_0)^2}{2D_g t}$. α is the average number of defect clusters produced by every cascade. ζ is $\frac{1}{\alpha \dot{N}_d t}$.

where Ψ is the degenerate hypergeometric function, whose integral representations (J_4 , J_6 , J_7 , J_8 , J_9 , and J_{10}) are given in our paper[6] $\bar{\mu}$ is equal to $\frac{(r-\bar{r})^2}{2Dt}$, where $\bar{r}$ is the median radius of the bubbles.

The formula (9) for the distribution function satisfies the bubble evolution equation (4) and condition (8), representing the early period bubble evolution distribution function under particle radiation. The exponential term in the formula (9) ($\frac{t}{\sqrt{2\pi Dt}} \exp[-\frac{(r-r_0)^2}{2Dt} + \frac{A_1}{D} \ln \frac{r}{r_0} + \frac{A_2}{D} C_g \frac{r+a_0}{r_0+a_0}]$) represents mainly bubble growth and fluctuation effects. The first part of equation (9) ($\frac{4}{3} E_1 E_3 t^2$) represents the nucleation rates. The first term in the large parentheses ($\bar{E}_1(\frac{E_2}{E_3 t}, \mu)$) represents the influence of nucleation and fluctuations on bubble evolution. The second term in the large parentheses represents the effect of radiation re-solution.

If the helium production rate is high enough, $\frac{Z_{01} \dot{N}_{He} \Omega}{a_0 \dot{N}_d} \epsilon \gg \frac{4\pi R_1 \alpha \zeta}{1 + a_0/R_1}$ and $D_g t \frac{Z_{01} \dot{N}_{He} \Omega}{a_0 \dot{N}_d} \epsilon \gg \frac{4}{3} \pi R^3 (1 - \beta)$, the equation becomes,

$$N(r, t) = \frac{4D_g Z_{01} \Omega}{3a_0} C_g^2 \exp[-\frac{(r-r_0)^2}{2Dt} + \frac{A_1}{D} \ln \frac{r}{r_0} + \frac{A_2}{D} C_g \frac{r+a_0}{r_0+a_0}] \left\{ \left[0.8 + 1.8\mu + 0.4\mu^2 - \sqrt{\mu} e^{\mu} (1 - \Phi(\sqrt{\mu})) (\frac{3}{2} + 2\mu + 0.4\mu^2) \right] - \eta b t \left[(\frac{2}{5} J_4 + \frac{9}{20} J_7 + \frac{3}{20} J_{10}) + 21\sqrt{\mu} (\frac{27}{32} \Psi(\frac{9}{2}, -\frac{1}{2}; \mu) + \frac{11}{32} \Psi(\frac{9}{2}, -\frac{3}{2}; \mu)) + \mu (\frac{9}{10} J_6 + \frac{3}{5} J_9) + 45\mu^{3/2} \cdot \frac{63}{32} \Psi(\frac{11}{2}, -\frac{1}{2}; \mu) + \frac{J_8}{5} \mu^2 - \exp[-\frac{(r-\bar{r})^2}{2Dt} + \frac{(r-r_0)^2}{2Dt}] \left(\frac{7}{8} \Psi(1, \frac{1}{2}; \bar{\mu}) - \frac{21}{8} \Psi(1, -\frac{1}{2}; \bar{\mu}) + \frac{21}{8} \Psi(1, -\frac{3}{2}; \bar{\mu}) - \frac{7}{8} \Psi(1, -\frac{5}{2}; \bar{\mu}) \right) \right] \right\}. (9')$$

This formula describes homogeneous nucleation, growth and fluctuation effects, and thus describes bubble evolution in a region containing a large amount of helium.

Substituting equation (9') to (7), the fraction of helium in the matrix (ϵ) is described by

$$\epsilon = \{ \dot{N}_{He} t a_1' \int_{r_0}^{\infty} \left(\frac{r}{r_0} \right)^{\frac{A_1}{D}} \left(\frac{r + a_0}{r_0 + a_0} \right)^{\frac{A_2 C_g}{D}} [f_1'(\mu) - \eta b t f_2'(\mu, \bar{\mu})] e^{-\mu \frac{dr}{r_0}} \}^{-1/2}, \quad (10)$$

$$\text{where } a_1' = \frac{3\pi\gamma r_0^3}{3kT} \cdot \frac{4D_g Z_{01} Q}{3a_0^2} \cdot \frac{t}{\sqrt{2\pi D t}},$$

$$f_1'(\mu) = \left[\frac{4}{5} + \frac{9}{5}\mu + \frac{4}{10}\mu^2 - \sqrt{\mu} e^{\mu} (1 - \Phi(\sqrt{\mu})) \left(\frac{3}{2} + 2\mu + 0.4\mu^2 \right) \right],$$

and

$$\begin{aligned} f_2'(\mu, \bar{\mu}) = & \left[\left(\frac{2}{5}J_4 + \frac{9}{20}J_7 + \frac{3}{20}J_{10} \right) + 21\sqrt{\mu} \left(\frac{37}{32}\Psi\left(\frac{9}{2}, -\frac{1}{2}; \mu\right) + \frac{11}{32}\Psi\left(\frac{9}{2}, -\frac{3}{2}; \mu\right) \right) \right. \\ & + \mu \left(\frac{9}{10}J_6 + \frac{3}{5}J_9 \right) + 45\mu^{3/2} \cdot \frac{63}{32}\Psi\left(\frac{11}{2}, -\frac{1}{2}; \mu\right) + \frac{\mu^2}{5}J_8 - \exp\left[-\frac{(r-\bar{r})^2}{2Dt} + \frac{(r-r_0)^2}{2Dt}\right] \\ & \left. \times \left[\frac{7}{8}\Psi\left(1, \frac{1}{2}; \bar{\mu}\right) - \frac{21}{8}\Psi\left(1, -\frac{1}{2}; \bar{\mu}\right) + \frac{21}{8}\Psi\left(1, -\frac{3}{2}; \bar{\mu}\right) - \frac{7}{8}\Psi\left(1, -\frac{5}{2}; \bar{\mu}\right) \right] \right] \end{aligned}$$

If we select suitable parameters and calculate a bubble distribution function, $\frac{A_2 C_g}{D}$ is found to be much less than unity. Equation (10) is self-consistent and ϵ is calculated to be the order of 10^{-3} .

If the cascade production rate is high enough and the helium production rate is low, $\frac{4\pi R_1 \alpha \zeta}{1 + a_0/R_1} \gg \frac{Z_{01} \dot{N}_{He} Q}{a_0 \dot{N}_d} \epsilon$, then equation (9) becomes

$$\begin{aligned} N(r, t) = & \frac{4\dot{N}_d t}{3} \cdot \frac{4\pi R_1 \alpha \zeta D_g}{1 + a_0/R_1} \cdot \frac{C_g t}{\sqrt{2\pi D t}} \exp\left[-\frac{(r-r_0)^2}{2Dt} + \frac{A_1}{D} \ln \frac{r}{r_0} + \frac{A_1}{D} C_g \frac{r + a_0}{r_0 + a_0}\right] \\ & \times \left\{ f_1\left(\frac{E_1}{E_3 t}, \mu\right) - \eta b t f_2\left(\frac{E_2}{E_3 t}, \mu, \bar{\mu}\right) \right\} \end{aligned} \quad (9'')$$

This formula represents the bubble evolution for inhomogeneous nucleation, and bubble growth with fluctuation effects. This describes the bubble evolution for fission neutron (EBR-II) irradiation conditions. Substituting equation (9") to (7), the fraction of helium concentration in matrix is described by

$$\epsilon = \left\{ 1 + a_1 \int_{r_0}^{\infty} \left(\frac{r}{r_0} \right)^{\frac{A_1}{D}} \left(\frac{r + a_0}{r_0 + a_0} \right)^{\frac{A_2 C_g}{D}} [f_1(u) - \eta b t f_2(u, \bar{u})] e^{-u} \frac{dr}{r_0} \right\}^{-1} \quad (11)$$

where a_1 is $\frac{8\pi\gamma r_0^3}{3kT} \cdot \frac{4\dot{N}_d t}{3} \cdot \frac{4\pi R_1 \alpha \zeta}{1 + a/R_1} \cdot \frac{D_g t}{\sqrt{2\pi D t}}$. If we again select suitable parameters to calculate a bubble distribution function, $\frac{A_2 C_g}{D}$ is still much less than one. Equation (11) is self-consistent and ϵ is found to be on the order of 10^{-2} .

If radiation re-solution is ignored and the parameters of Table I are adopted, the bubble distribution function in aluminum under three different kinds of irradiation are calculated to be as shown in Figures 2 through 5. Note that the displacement rates are specific; those achievable in each of the different irradiation facilities. The bubble distribution under 760-MeV proton irradiation is different than that for spallation neutron irradiation when we consider the sources available at LAMPF. There are two different characteristics. First, the value for the inhomogeneous nucleation terms under proton irradiation are much larger than for the homogeneous nucleation term. But under spallation neutron irradiation the results are reversed, with homogeneous nucleation being dominant. Second, the Frenkel defect production rate under proton irradiation is much higher than for spallation neutron irradiation. The vacancy concentration is high enough to prompt bubble growth under proton irradiation. Under spallation neutron irradiation, the vacancy concentration is not enough to prompt bubble growth, although the helium production rate is moderate. These results can be examined by TEM observation. The bubble number distribution as a function of bubble size

under spallation neutron bombardment decreases exponentially. The bubble number distribution as a function of bubble size under proton irradiation first increases, approaches a maximum value, and then decreases.

The bubble number distribution as a function of bubble size under EBR-II neutron irradiation is similar to that for proton irradiation. But since the helium production rate is much less than that for proton irradiation, the total bubble quantity is, accordingly, less. Because there is a high production rate of single defects and inhomogeneous nucleation in both situations, the bubble number distribution as a function of size is similar. Therefore, bubble nucleation mainly depends on the helium concentration (including other gases) and bubble growth is controlled primarily by the vacancy concentration. If the flux of spallation neutrons in LAMPF were increased by one order of magnitude, the bubble evolution would be similar to that for the protons and for EBR-II neutron irradiation.

Figures 2 through 4 show that as the value of the fluctuation coefficient, D , increases, the bubble size tends to enlarge and the number of bubbles decreases. As expected, as the temperature increases, the fluctuations become larger. Accordingly, the increase in fluctuations results in an enlargement of the bubble size with a decrease in the bubble quantity. This agrees with experimental observations.

Equations (10) and (11) give a relationship for helium concentration in the matrix. An increase in $\dot{N}_d$ enhances the trapping of helium, and the helium concentration in the matrix decreases. An increase in $\dot{N}_{He}$ enhances the homogeneous nucleation rate, and the fraction of helium concentration in matrix also decreases. If the diffusion coefficient of the helium were to increase by one order of magnitude, the fraction of helium in the matrix and the number of bubbles would decrease by one order of magnitude, according to equation (11). If

the vacancy diffusion coefficient (D_v) is taken as that of the diffusion coefficient of helium in aluminum, the fraction of helium concentration becomes 10^{-8} - 10^{-9} and the number of bubbles becomes 10^4 - 10^6 /cm³ under EBR-II neutron irradiation. This is not in agreement with the experimental observations. If the diffusion coefficient of helium is 1.2135×10^{-13} cm²/sec in aluminum, then reasonable results are obtained that agree with the experiment results.[12,7]

TABLE I

THE PARAMETERS USED IN THE CALCULATION OF THE BUBBLE DISTRIBUTION FUNCTION
IN ALUMINIUM AT 120°C.

Parameters	750-MeV proton	spallation neutron	EBR-II
$\dot{N}_{He} (cm^{-3} sec^{-1})$	$.4934 \cdot 10^{13}$	$.5145 \cdot 10^{11}$	$.0489 \cdot 10^{11}$
$\dot{N}_d (cm^{-3} sec^{-1})$	$.3168 \cdot 10^{12}$	$.0201 \cdot 10^{12}$	$.1850 \cdot 10^{12}$
$\dot{N}_p (cm^{-3} sec^{-1})$	$1.0150 \cdot 10^{16}$	$.0643 \cdot 10^{16}$	$1.4797 \cdot 10^{16}$
$R (\text{\AA})^2$	68.08(E=20keV)	54.40(E=15keV)	33.31(E=8keV)
$R_1 (\text{\AA})$	4.049	4.049	4.049
$D (cm^2 sec^{-1})$	$.7264 \cdot 10^{-18}$	$.7264 \cdot 10^{-18}$	$.7264 \cdot 10^{-18}$
	$1.4527 \cdot 10^{-18}$	$1.4527 \cdot 10^{-18}$	$1.4527 \cdot 10^{-18}$
β	.9	.882	.7
α	.1*	.05*	.01*
$D_g[12,7] (cm^2 sec^{-1})$	$1.2135 \cdot 10^{-13}$	$1.2135 \cdot 10^{-13}$	$1.2135 \cdot 10^{-13}$
$r_o (\text{\AA})$	2.512**	2.512	2.512
$Z_v[23]$	1	1	1
$Z_i[23]$	1.08	1.08	1.08
ν	2	2	2
Z_{Q1}	42	42	42
$\gamma[23] (J/m^2)$	1***	1	1

*The average number of defect clusters produced by every cascade is relative to the PKA energy and irradiation temperature. If the irradiation temperature is high, the recombination of vacancy-interstitial pairs in the cascade region is very quick and effective. Thus, the formation probability of defect cluster is low and the value of α is smaller than 1.

**The defect cluster requires vacancies to keep cluster stable. A di-vacancy is able to migrate, but above a tri-vacancy, the cluster is immobile. It is possible that the combination of a di-vacancy with helium plays a role in helium diffusion.[12] Two helium atoms that meet to form a bubble nucleus are thought to be accompanied by four vacancies. Therefore, it is assumed that a tetravacancy including helium can be defined as a bubble nucleus. According to this assumption, the value of r_0 is calculated.

***The surface energy of a bubble under proton irradiation is lower than that of material itself, because a large amount of hydrogen and deuterium are produced. These gases diffuse into the bubble; the surface energy may be decreased by a factor of 2-5. This is important in calculating the fraction of helium in the matrix.

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CAPTIONS

Figure 1: Flow diagram showing the inter-relationship of microstructural evolution under irradiation.

Figure 2: Bubble-size distribution for irradiation of aluminum by spallation neutrons as available at LAMPF.

Figure 3: Bubble-size distribution for irradiation of aluminum by 760-MeV protons as available at LAMPF. Fluctuation coefficient, D , is 0.73×10^{-18} .

Figure 4: Bubble-size distribution for irradiation of aluminum by 760-MeV protons as available at LAMPF. Fluctuation coefficient, D , is 1.46×10^{-18} .

Figure 5: Bubble-size distribution for irradiation of aluminum by fission neutrons as available at EBR-II.

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