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THE INTERACTION OF HELIUM AND DISPLACEMENT DAMAGE IN INERTIAL CONFINEMENT FUSION REACTORS

R. F. Schafer, Jr. and N. M. Ghoniem

School of Engineering and Applied Science
University of California, Los Angeles
Los Angeles, CA 90024, U.S.A.

Helium is thermodynamically insoluble in metals and tends to form cavities if the conditions are appropriate for its migration. The processes of helium migration and interaction with point defects are strongly influenced by the level and the mode of displacement damage production. In this paper, we present an application of the rate theory for helium cavity formation in Inertial Confinement Fusion Reactors (ICFR's). A new computer code "EXPRESS" has been developed for the solution of the time-dependent rate equations describing the evolution of the space-averaged damage state of an ICFR first wall. An optimal algorithm was developed for the long-term solution of the rate equations (10^5 pulses) with modest computational requirements. It is shown that the time-fluctuations in point defect and helium concentrations due to ICF-type pulsing lead to an overall reduction in the swelling of ICF materials.

1. INTRODUCTION

Previous studies of the effects of ICF pulsed irradiation on void behavior have indicated that void growth will generally be smaller due to radiation pulsing [1,2]. In order to generalize this statement, however, one would like to examine the effects of pulsing on both the nucleation and growth of voids. Previous nucleation studies [3] are based on concepts that are more relevant to classical nucleation, and are perhaps not applicable to pulsed irradiations. Moreover, helium effects have been neglected in all of the previous studies [1-3].

The helium content and the high ratio of helium concentration to displacement damage for fusion reactors have given rise to expectations of drastic microstructural changes as compared to fast breeder reactors [4]. The present work is devoted to the following area:

i) The formation of a time-dependent rate theory for the continuous evolution of helium-filled cavities (nucleation and growth).

ii) The development of a computational method for the long-term solution of these equations ($\sim > 10^5$ pulses) with modest computational requirements.

iii) The analysis of the swelling in a particular ICFR.

2. THEORY

Many migration mechanisms of helium have been proposed in the literature [5]. Speculations for these mechanisms include substitutional, interstitial, mutual (interstitial + substitutional) diffusion, momentum transfer, diffusion by divacancies and various combinations of these mechanisms. We have recently shown that the transport of helium is mostly dominated by helium interstitials migrating between vacancy traps [6]. Contribution of the other suggested mechanisms of helium transport were shown to be small. In the present study, helium is considered to form in an interstitial position and moves rapidly as an interstitial until it encounters a helium trap (vacancy, void, etc.) or is lost to sinks. Since vacancies are the most abundant helium traps, the helium atom jump distance can be approximated as the distance between available vacancies. The time spent in a vacancy or another trap is long compared with the time the gas atoms spend in an interstitial position. Following this model, Reed [5] gave the following diffusion coefficient

$$D^{He} = \nu_o \frac{\lambda^2}{6} C_v^{-2/3} \exp\left(-E^D_{He}/kT\right) \qquad (1)$$

where ν_o is the helium detrapping frequency, λ is the jump distance, and E^D_{He} is approximately the detrapping energy of helium. Once two helium atoms collide, they are assumed to form a di-helium gas atom cluster for which vacancies are readily available. Because of the possibilities of thermal dissociation and radiation resolutioning, this cluster is unstable. Once a tri-helium gas atom cluster is formed, it can attract a few more vacancies and form the critical nucleus size for small gas-filled cavities. Nucleation is therefore dictated by the behavior of gas atoms rather than by vacancies. It has been recently discussed by Mayer et al. [7], that experimental evidence supports this assumption. The nucleation rate of cavities is the rate at which they cross this boundary in size space. The density of cavities will therefore increase as the density of a single and di-helium species increase. After a certain irradiation time, it becomes more probable for single helium

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to collide with larger size cavities than with the small nuclei. Thus a gradual shift from the nucleation stage to the growth stage is achieved. The large size cavities are assumed to start growing from the nucleus size at only one average speed. The size distribution is therefore approximated by a delta function. Keeping track of vacancy, interstitial and helium atom flows in and out of the average cavity determines its size and nature (void or bubble) at any time. Since interstitial loops nucleate rapidly during irradiation [8,9], their number density is assumed to be constant and is included in the total network dislocation density.

The physics covered by such a simplified description is obviously not exhaustive. However, reasonable agreement with HIFR experiments was achieved using the steady state version of the model. The roles of vacancy loops, divacancies, cavity coalescence, and matrix chemical changes in complex alloys are all neglected. For a detailed description of the rate theory model and the numerical values for input parameters, the reader is referred to reference [10]. In this approach, eight tightly coupled, non-linear ordinary differential equations are numerically solved. The equations represent the concentrations of single helium, di-helium clusters, tri-helium clusters, average-size cavities, single vacancies, and single interstitials. The last two equations represent the average number of helium atoms in a cavity and the rate of growth of the average cavity radius.

3. THE "EXPRESS" COMPUTER CODE

In order to solve a system of rate equations for Inertial Confinement Fusion Conditions, a special computational technique was developed. The EXPRESS computer code (Integration/EXtrapolation Method for Pulsed Rate Equations of Stiff Systems) solves time dependent rate equations describing the evolution of the space-averaged damage state of an ICFR first wall. As such, it represents an extension of the HEGBUF code [10], developed by Ghoniem and Takata to describe the damage-state evolution in steady-state and slowly pulsed fusion machines.

The equations describing this system possess the property of stiffness; that is, the time scales characterizing the various elements of the system span a large range of values. The integration of such a system requires the use of specialized numerical techniques. Many of these techniques have been incorporated into a set of subroutines called the GEAR package [11]. When the pulse frequency is high, as in the case of ICFR's, even the methods of GEAR become prohibitively expensive.

To alleviate this difficulty, we have developed an integration/extrapolation method which allows us to obtain the solution of the equations without integrating each pulse. The solution is started by integrating over a few pulses using the GEAR package. EXPRESS then enters a cyclic integration/extrapolation routine, with each cycle consisting of an integration step followed by an extrapolation step. The integration step uses the GEAR package to integrate a few pulses and determine the local behavior of the solution. The extrapolation step then uses a second degree least squares polynomial fit to extrapolate this behavior over a suitable interval. The initial size of the extrapolation interval is determined by the local agreement between the approximating polynomial and the true solution. A series of error estimations and subsequent extrapolation interval reductions are then performed until an accuracy criterion is satisfied. A more detailed description of this method is contained in a UCLA report [12].

4. RESULTS AND APPLICATION TO THE "HIBALL" ICFR DESIGN

In all of our calculations, the displacement and helium production rates were idealized by square waves of a definite pulse length, T_{on}. The peak displacement damage and helium production rates are determined by conserving the total number of displacements and helium within the on-time. The magnitude of the on-time is determined as the "full width at half maximum (FWHM)" from the nuclear analysis of the wall response. It was also found that under our specific conditions the helium mean-lifetime is much longer than the on-time. No appreciable helium diffusion is therefore expected during the short on-time, and the helium on-time can be approximated by the displacement damage on-time.

The following conditions apply:

$$\left.\begin{array}{ll} \tau_i < T_{on} < \tau_v < \tau_{He}, & \text{(protected FW)} \\ T_{on} < \tau_i < \tau_v < \tau_{He}, & \text{(unprotected FW)} \end{array}\right\} \qquad (2)$$

and

$$T_{on}(\mathrm{He}) = T_{on}(\mathrm{dpa}) \qquad (3)$$

In the following, we will analyze the two cases:

4.1 Unprotected Ferritic Steel First Wall

We first take an example here of a "HIBALL" reactor design with no "inport" protection of the first metallic wall. This will represent the severest case for neutron damage, and will serve to illustrate a few concepts about pulsed neutron damage. The following input was used for the "EXPRESS" computer code:

T_{on} = 5 ns
T_{cycle} = 0.2 s
instantaneous displacement rate = 32.12 dpa/s
instantaneous helium production rate = 2.89×10^{-4} at/at/s
average displacement rate = 25.36 dpa/yr
average helium production rate = 227.6 appm/yr
He/dpa ratio = 9 appm/dpa

With these input parameters, the behavior of helium in the presence of simultaneous displacement damage is analyzed. Figure 1 shows the cavity concentrations for the first 80,000 pulses. The solid line represents the equivalent continuous irradiation case where the average values of helium production and displacement damage are used, while the dotted line is for the actual pulsed case. Pulsed irradiation results in an early and rapid nucleation of cavities. This will in turn tend to saturate the cavity density at a lower level as is observed in Figure 1. The increase in the vacancy concentration is shown in Figure 2, where the solid line is for continuous irradiation and the dashed lines are for the envelope of pulsed vacancy profiles. Details of the vacancy concentration are shown for the first few pulses where the vacancy population undergoes a sharp decline during each pulse due to immediate recombination with self-interstitials. The net effect is an overall enhancement of recombination and a reduction of point defect populations that are able to migrate to sinks.

Figure 3 shows the change in the average cavity radius during pulsed and equivalent continuous irradiations at 500°C. The enhancement of mutual recombination due to radiation pulsing results in a slower growth rate for cavities. We conclude therefore that pulsed irradiation of the "ICF-type" will generally result in a lower amount of swelling as compared to continuous irradiation. Existing swelling data will therefore be an upper bound on what one might expect in ICF reactor environments. The effects of helium and continuous cavity nucleation are factored into this conclusion. It is to be remembered, however, that this conclusion may not be applicable for pulsed systems other than ICFR's. The wide range of pulsing conditions makes it

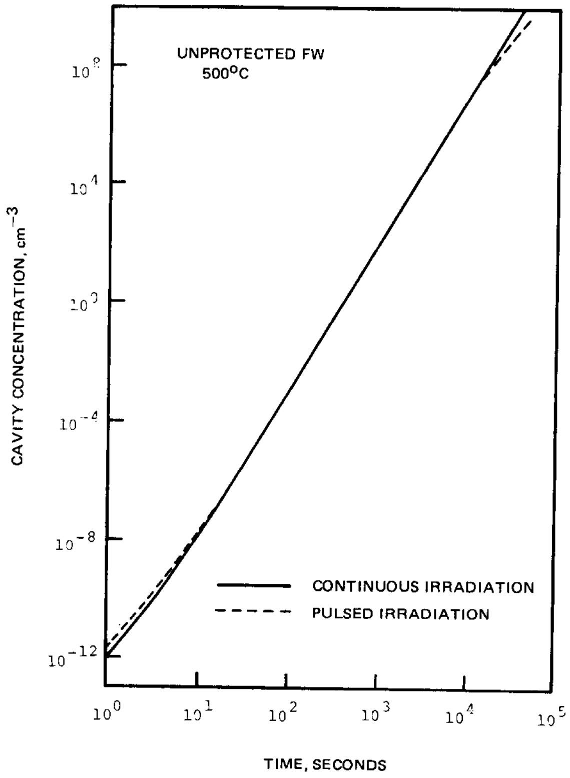

Figure 1 : Cavity concentration for both pulsed and equivalent continuous irradiation of the unprotected first wall at 500°C

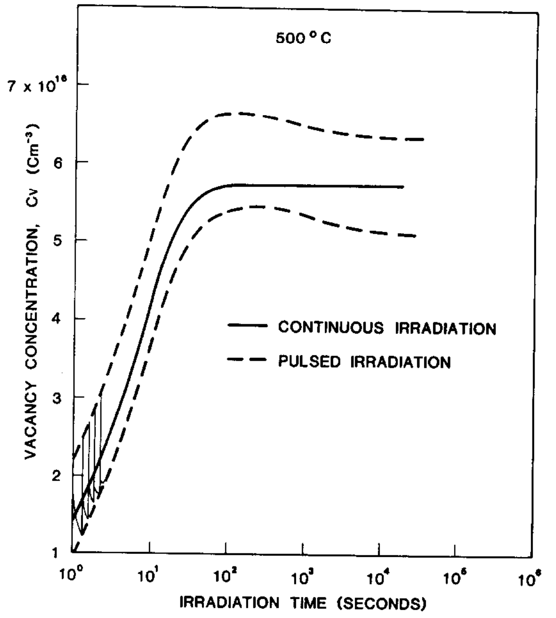

Figure 2 : Vacancy concentration for pulsed and equivalent continuous irradiation of the unprotected first wall at 500°C.

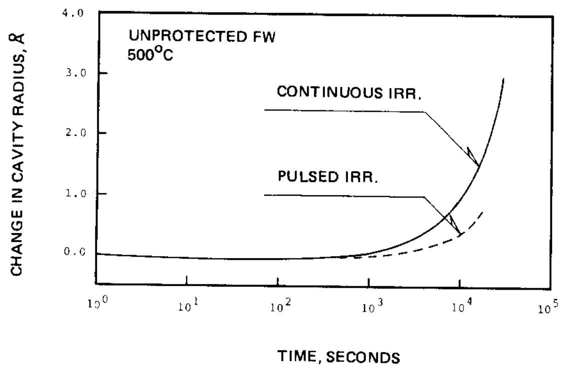

Figure 3 : The change in the average cavity radius during pulsed and equivalent continuous irradiation of the unprotected first wall at 500°C.

difficult to generalize this statement. In fact, slow pulsing may lead to the opposite effect [13].

One important aspect of the present work is the development of a specialized numerical technique for the integration of stiff equations with a pulsed source of irradiation for the study of the long-term behavior. A comparison of the computational requirements of the new integration/extrapolation method, and the standard numerical integration of the system of equations by the GEAR package is shown in Figure 4. Due to the fact that the solution vector tends to a more stable behavior as time proceeds, the computational requirements are reduced. A gain of over a factor of 20 in the computational cost is achieved using the new method. The method can be extended to other studies of pulsed effects that include ratcheting phenomena. Figure 5 shows the relative error in the solution vector components that result due to the extrapolation procedure. The magnitude of the error is generally small.

4.2 Protected Ferritic Steel First Metallic Wall

A summary of the radiation damage parameters in the first metallic wall as well as the reflector for the protected ferritic steel structure is given in Table 1. The protection zone consists of a LiPb stream inside SiC tubes of a total thickness of 66 cm.

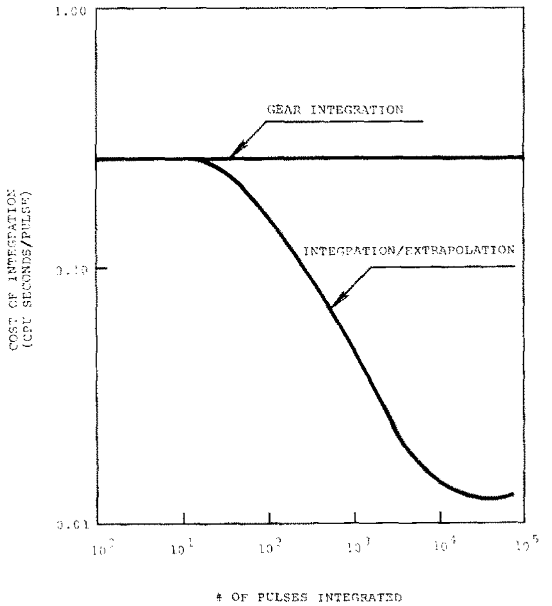

Figure 4 : A comparison of the computational requirements for GEAR integration vs. EXPRESS integration/extrapolation.

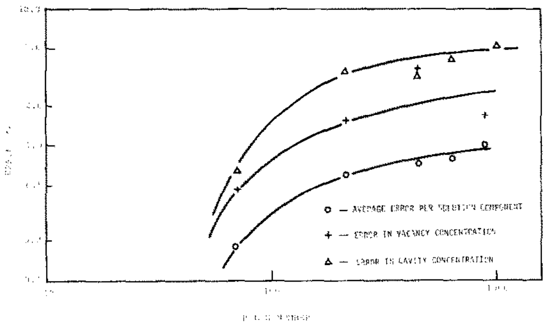

Figure 5 : The error introduced by EXPRESS relative to GEAR integration.

Table 1 : Radiation damage parameters for the protected first metallic wall

	First Wall	Half Reflector Thickness	Full Reflector Thickness
T_{on}, μs	1.5	2.0	2.4
T_{cycle}, s	0.2	0.2	0.2
dpa/yr	2.7	0.32	0.028
appm He/yr	0.364	0.0112	5.4×10^{-4}
He/dpa	0.135	0.035	0.019
dpa/s	1.14×10^{-2}	1.02×10^{-3}	7.4×10^{-5}
at/at He/s	1.54×10^{-9}	3.56×10^{-11}	1.4×10^{-12}

The calculations for these conditions indicate that self-interstitials migrate very quickly to various sinks, and that their lifetime is 3.27×10^{-7} seconds. On the other hand, both vacancies and helium have a much lower diffusion coefficient. For the first metallic wall, the vacancy mean-lifetime is 7.58 seconds at 450°C. The mobility of helium is dependent on the level of displacement damage, since it is assumed to migrate by a trapping-detrapping mechanism. The helium mean-lifetime increases from a value of 2.96×10^4 seconds at the spot of irradiation to a value of 1.96×10^7 seconds after 600 pulses. This is a direct result of vacancy trap accumulation.

An equivalent continuous-irradiation calculation was performed for the peak damage position in the first metallic wall. At 450°C, the percent swelling was found to be very small ($<10^{-3}$ %) over the first wall lifetime (30 years). It is concluded therefore that swelling is not a major design problem, and that the wall lifetime is limited by other considerations. For ferritic steels, low-temperature neutron embrittlement and high temperature creep-rupture are the determining factors [14].

5. CONCLUSIONS

From our study of helium behavior in the "HIBALL" design, we conclude the following:

1. The migration of helium is mainly by a trapping/detrapping mechanism for interstitial helium in between vacancy traps.
2. The He/dpa ratio is a parameter that affects mainly the nucleation of cavities rather than their growth.
3. Maximum nucleation will occur in the first metallic wall.
4. A successful new integration/extrapolation technique has been developed to study the behavior of helium and displacement for pulsed irradiation. The technique results in the reduction of the computational costs by a factor of ∿20 while introducing only small errors (∿1-4%) in the components of the solution vector.
5. Fluctuations in point defect concentrations due to pulsing lead to a *smaller* growth rate of cavities.
6. The overall swelling due to pulsing in ICF reactors will be smaller than corresponding continuous-irradiation.
7. Swelling is not a life-determining factor for the "HIBALL" design.

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