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PRODUCTION AND BEHAVIOR OF POINT DEFECTS IN PULSED INERTIAL CONFINEMENT FUSION REACTORS

M.E. Sawan, G.L. Kulcinski

Nuclear Engineering Department
University of Wisconsin, Madison, Wisconsin 53706

and

N.M. Ghoniem

School of Engineering and Applied Physics
University of California - Los Angeles, Los Angeles, California 90024

A time-dependent neutronics analysis for the HIBALL reactor is presented. The helium to dpa ratio in the ferritic steel structure is found to be sensitive to neutron spectrum softening. The microstructure calculations show that helium diffusivity is a sensitive function of vacancy accumulation from one pulse to the next. A strong coupling exists between the three components of damage: helium, vacancies, and interstitials. Swelling of the protected ferritic steel first wall of HIBALL is found to be insignificant.

1. INTRODUCTION

Time-dependent neutronics calculations are essential in radiation damage analysis of inertial confinement fusion (ICF) reactors. The neutron source has a pulsed nature because the burn time is very small compared to the time of flight and the slowing down time in the blanket [1]. Consequently, high instantaneous atom displacement and gas production rates are obtained. The material property changes are, thereby, expected to be different when compared to the response under equivalent continuous irradiation conditions [2,3].

The time structure of the dpa and helium production rates is dependent on design considerations. Therefore, it is important to study spectral and time spreading effects in the blanket structural material. Since the (n,α) reaction has a threshold energy which is much larger than that for the production of atomic displacements, the effect of neutron spectrum softening on helium production is more pronounced than that on atomic displacements. Consequently, the helium to dpa ratio, which is an important parameter in microstructure calculations, is expected to decrease with neutron spectrum softening. Cavity nucleation is influenced mainly by the presence of helium atoms. Spectrum softening is, therefore, expected to affect the nucleation phase of gas-filled cavities. The time spread of the displacement damage production is longer than the self-interstitial mean lifetime. Blanket time-dependent analysis is, therefore, necessary for microstructure evolution calculations.

In this paper, we develop a comprehensive analysis of the primary damage state, in terms of helium and atomic displacement production, and the resulting microstructure. The helium production rate and the rate of displacements per atom (dpa) obtained from the time-dependent neutronics calculations are approximated as square pulses and used as an input to microstructure evolution calculations. This will be demonstrated for a particular ICF design based on heavy ion beam fusion. The HIBALL reactor, being designed by the University of Wisconsin and the Kernforschungszentrum Karlsruhe (KfK) is considered in this work.

2. NEUTRONICS ANALYSIS

The HIBALL reactor considered in this work utilizes a spherical pellet which ignites at the center of a reactor cavity that is 7 m in radius. The reactor cavity wall is 1 cm thick and is made of the ferritic steel alloy HT-9. The wall is protected by an array of porous tubes made of braided silicon carbide through which a $Li_{17}Pb_{83}$ liquid metal eutectic coolant/breeder flows. This wall protection concept is based on inhibited flow in porous tubes (INPORT). The protection region has an effective thickness of 66 cm. The vacuum wall is followed by a 40 cm thick reflector made of 90 v/o HT-9 and 10 v/o $Li_{17}Pb_{83}$ coolant. Behind the reflector, a 3.5 m thick concrete shield is used.

A consistent neutronics analysis of an ICF reactor must account for neutron multiplication and spectrum softening inside the pellet. This results from neutron interactions with the extremely dense pellet materials. Detailed pellet neutronics calculations have been performed for the HIBALL pellet to yield the spectrum of neutrons escaping from the pellet [4]. The resulting spectrum is used as a source for the subsequent blanket time-dependent calculations. The multigroup discrete ordinates code TDA [5] was used to perform the time-dependent blanket calculations. In order to obtain an accurate estimate for the accumulated damage and helium in each pulse, the steady-state code ANISN [6] was used. Such information can also be obtained through time-dependent analysis by integrating the displacement damage and helium production rates during the pulse. However, this can be computationally prohibitive, since the die-away time for damage is very long.

Significant softening of the energy spectrum of neutrons leaving the pellet leads to a considerable time-of-flight spread as neutrons arrive at the blanket surface. Further time spread occurs as the neutrons arrive at the first wall because of neutron slowing down in the INPORT tubes. Our results show that the time spread of the neutron flux at the first wall is determined primarily by the slowing down time in the inner blanket. The pulsed dpa and helium production rates in the first wall and reflector structural material are calculated using the time-dependent neutron spectrum and the appropriate reaction cross sections.

The effect of the protection region thickness on the pulsed radiation damage to the vacuum wall was investigated. The time spread of the damage was found to increase as the thickness increases because of the spread due to neutron slowing down in the INPORT tubes. Figure 1 shows the time-dependent dpa and helium production rates in the HIBALL first metallic wall for an effective protection region thickness of 66 cm. The results are based on a fusion yield of 400 MJ and a repetition rate of 5 Hz. It is clear that the damage occurs over a relatively long time. The dpa peak at 140 ns after the burn corresponds to the 14 MeV source neutrons arriving at the wall without any collisions. A broad peak at ~ 270 ns corresponds to (n,2n) neutrons resulting from interactions with lead in the INPORT tubes. It is clear that the time spread for He production is much shorter than that for displacements. The reason is that the (n,α) reaction in iron has a threshold energy of ~ 2.7 MeV and, hence, most of the slowed down neutrons do not contribute to helium production.

The effects of protecting the ferritic steel first wall were investigated by comparing the results of an unprotected first wall to those with a 66 cm LiPb protection zone. It was found that the INPORT tubes reduce the peak instantaneous dpa rate from 10.7 to .009 dpa/s, increase the time spread from 5 to 1500 ns, and decrease the total dpa per full power year (FPY) from 25.4 to 2.7 dpa. On the other hand, the peak instantaneous helium production rate decreases from 179 to .11 appm/s, the time spread increases from 5 to 26 ns, and the total helium production per FPY decreases from 229 to .364 appm.

The spatial variation of damage in the HIBALL ferritic steel structure was also investigated. The results given in Table 1 indicate that as one moves from the vacuum wall towards the back of the reflector, the peak instantaneous dpa and helium production rates decrease. On the other hand, the time spread gets longer, and the total dpa and helium production per full power year decrease. The effect on helium production is more pronounced because of the increased neutron spectrum softening.

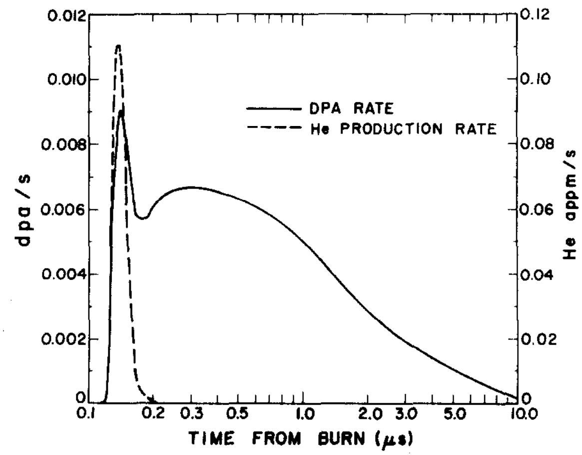

Figure 1. Pulsed radiation damage in HIBALL first wall.

Because of the large difference between the threshold energies for helium production and dpa reactions, the helium to dpa ratio is sensitive to both the thickness of the protection zone and the depth inside the reflector. Figure 2 shows the effect of INPORT tube zone thickness on dpa, helium production and helium to dpa ratio in the first wall. It is clear that the wall protection has a more pronounced effect on helium production. Consequently, the helium to dpa ratio declines from a value of 9 for the unprotected wall to a value of .135 when a thickness of 66 cm is used. The helium to dpa ratio was found also to decrease as one moves inside the reflector. The helium to dpa ratio decreases from .135 at the first wall to .019 at the back of the reflector. These different helium to dpa ratios have an important effect on the microstructural changes.

3. DAMAGE ANALYSIS

The behavior of helium produced by transmutation reactions is now recognized to have a prominent role on the development of the microstructure [7]. Of particular significance is the method by which helium affects swelling in ICF reactors where the helium and displacement damage production rates are strong functions of time. Pulsed damage studies [2,3,8] have considered only void growth under pulsed irradiations. The basic conclusion of such studies was that high frequency pulsing reduces void growth in metals, especially at high temperatures. It is of interest, therefore, to assess the role of

Table 1

Pulsed Damage to Ferritic Steel Structure in HIBALL

		First Wall	Center of Reflector	Back of Reflector
DPA	Total dpa (dpa/FPY)	2.7	0.321	0.028
	Peak dpa rate (dpa/s)	0.009	9×10^{-4}	7.9×10^{-5}
	Time spread (ns)	1500	2000	2400
He Production	Total He production (appm/FPY)	0.364	0.0112	5.43×10^{-4}
	Peak He production rate (appm/s)	0.11	3.33×10^{-3}	1.12×10^{-4}
	Time spread (ns)	26	30	38

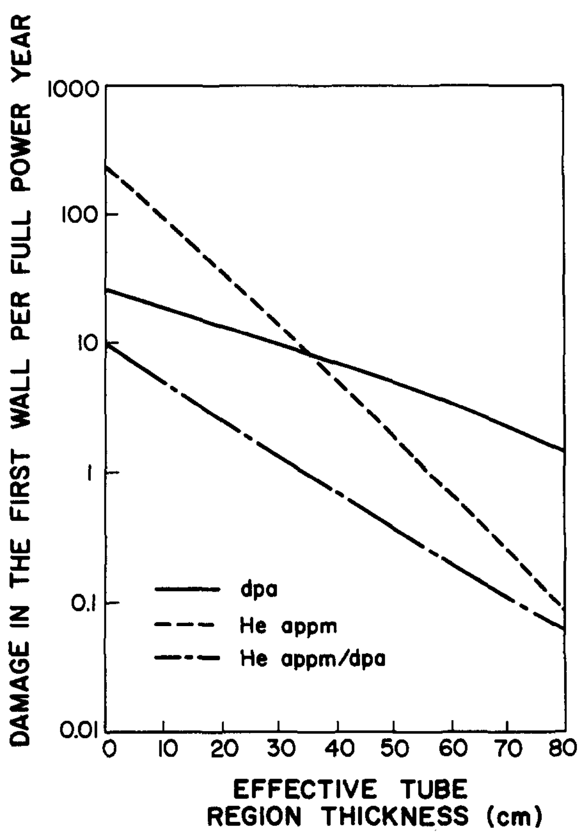

Figure 2. Effect of INPORT tubes on damage in HT-9 first wall.

helium on both the nucleation and growth of cavities in ICF reactors.

Recently, a theory for the interaction of helium and displacement damage in fusion reactor structural materials was developed [9]. A new computational method was also developed for the application of this theory to the specialized ICF pulsed irradiation conditions, and some results are presented in this conference [10]. Modelling helium behavior is based upon the homogeneous, time-dependent rate theory where conservation equations are used to describe the helium-vacancy clusters. Separate rate equations are used to describe the helium clustering, cavity resolution, thermal dissociation, and migration of helium to cavities, dislocations and grain boundaries.

Helium was speculated to migrate by a variety of mechanisms. These include momentum transfer, helium migrating as a substitutional atom (pop-out mechanism), helium migrating as an interstitial atom in between vacancy traps, and migration in mobile divacancies [9]. Recent calculations indicate, however, that helium transport in fusion materials will be mainly due to a trapping/detrapping mechanism, with very little contribution from migration in mobile divacancies [11]. Reed [12] proposed a simplified diffusion coefficient for helium in the presence of vacancies:

$$D_{He} = \nu_0 \frac{\lambda^2}{6} C_v^{-2/3} \exp\{-E_{He}^D/kT\} \quad (1)$$

where ν_0 is the frequency factor for detrapping helium, λ is the jump distance, and E_{He}^D is approximately the detrapping energy of helium. The EXPRESS computer code [10] for the integration of rate equations with a pulsed source term was used to calculate helium diffusivity in the ferritic steel first wall of the HIBALL design. The results of the calculations for the unprotected wall at 500°C are shown in Figure

3. As the displacement damage builds up with the accumulation of vacancies at each added pulse, the helium diffusion coefficient continues to decrease. The relaxation time for this process is evidently dictated by the vacancy mean lifetime (~ 5 seconds), since the detrapping energy is high ($E^D_{He} \approx 3.16$ eV).

While the computational method and multi-pulse results are presented in a separate paper [10], we will discuss here some aspects of single pulse damage analysis for the protected ferritic steel structure. It is also interesting to analyze the expected swelling of the protected structure using the steady-state version of the EXPRESS code.

Figure 4 shows the vacancy, self-interstitial, and helium behavior during two representative pulses, the first and pulse number 615 of the HIBALL design. Both the helium and displacement damage pulses were approximated as square-wave functions of duration 1.5 microseconds at the first wall. The instantaneous dpa and helium production rates were adjusted to conserve the total amounts as shown in Table 1. It is shown in the figure that self-interstitials diffuse significantly during the on-time of each pulse ($\tau_i \approx .327$ microseconds). Self-interstitials immediately decay after the end of each pulse, while both helium and vacancies accumulate from one pulse to the next.

Steady-state calculations of the swelling of the ferritic steel first wall were performed. The average displacement damage rate was taken as 8.6×10^{-8} dpa/second and the helium production rate as 1.16×10^{-14} at/at/second. The results of these calculations at 450°C are shown in Figure 5, where the average cavity radius $\bar{R}_c$, the cavity density/cm^3, N_c, and the percent swelling, $\Delta v/v$, are all plotted as functions of irradiation time. The strong coupling between the nucleation and growth aspects of helium-filled cavities is clearly indicated. The cavity density starts to reach saturation after a few years of irradiation. The total calculated swelling accumulated by the end of 30 years is extremely small, $\approx 10^{-3}$%. This is consistent with the latest experimental findings on the swelling resistance of ferritic steels [13]. Pulsing the radiation source will further reduce swelling as was demonstrated by the previous void growth studies [2,8], and the recent work on the nucleation and growth of gas-filled cavities [10].

4. CONCLUSIONS

In this paper, we have focussed on the time-dependent damage analysis in ICF reactors, and its impact on the swelling due to helium-filled cavities. The main conclusions of this work are summarized in the following:

1. Time-dependent neutronics analysis is necessary for subsequent microstructure evolution calculations.

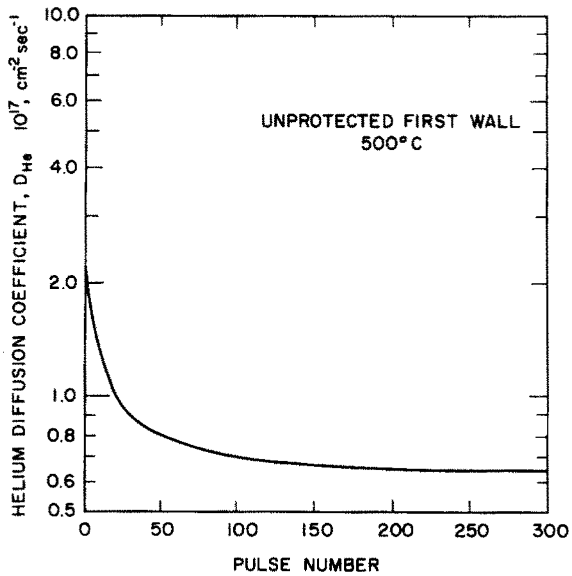

Figure 3. Helium diffusivity in the unprotected first wall.

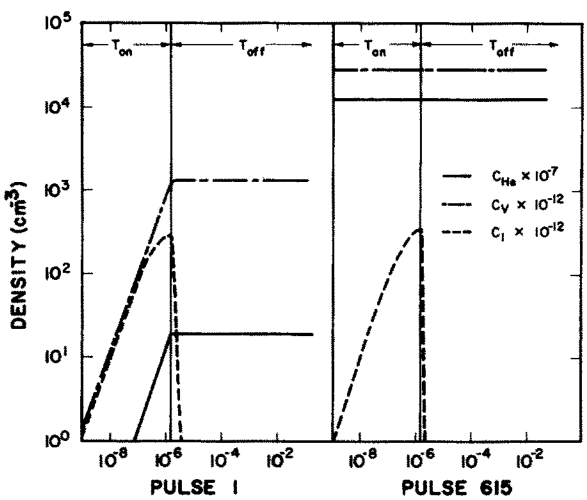

Figure 4. The behavior of vacancy, interstitial and helium in the protected first wall structure at 450°C for pulses #1 and 615.

2. The ratio of the helium/dpa production rates is a very sensitive function of neutron spectrum softening.

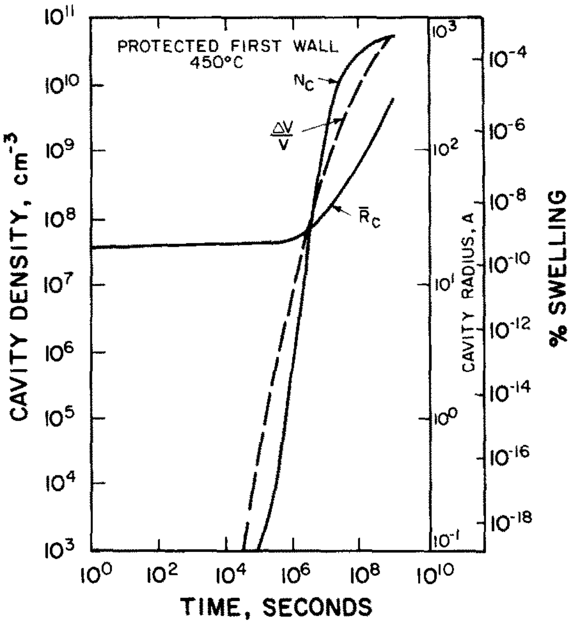

Figure 5. Swelling parameters for the protected first wall at 450°C.

3. Both the protection and reflector zones result in drastic decreases of the helium/dpa ratio. This is attributed to the sensitivity of the (n,α) cross-section to neutron moderation.

4. The helium/dpa ratio affects mainly the nucleation of cavities.

5. Helium diffusivity is a sensitive function of vacancy accumulation from one pulse to the next. Helium is gradually immobilized by vacancies.

6. There is a strong coupling between the three components of damage: helium, vacancies, and interstitials.

7. The swelling of the protected ferritic steel structure in the HIBALL design is insignificant.

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