Production and Behavior of Point Defects in Pulsed Inertial Confinement Fusion Reactors

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

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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 inter-
stititals. Swelling of the protected ferritic steel first wall of HIBALL is found to
be insignificant.

1. INTRODUCTION

Time-dependent neutronics calculations are es-
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sential 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]. Con-

sequently, high instantaneous atom displacement

and gas production rates are obtained. The ma-

terial property changes are, thereby, expected
to be different when compared to the response
under equivalent continuous irradiation condi-
tions [2,3].

The time structure of the dpa and helium pro-
duction rates is dependent on design consider-
ations. Therefore, it is important to study
spectral and time spreading effects in the
blanket structural material. Since the (n, a)
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 pro-
nounced than that on atomic displacements.
Consequently, the helium to dpa ratio, which is
an important parameter in microstructure calcu-
lations, is expected to decrease with neutron
spectrum softening. Cavity nucleation is in-
fluenced mainly by the presence of helium atoms.
Spectrum softening is, therefore, expected to
affect the nucleation phase of gas-filled cav-
ities. 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 anal-
ysis of the primary damage state, in terms of
helium and atomic displacement production, and
the resulting microstructure. The helium pro-
duction 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 micro-
structure 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 uti-
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lizes 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$_2$Pb$_3$ liquid metal eutectic coolant/
breeder flows. This wall protection concept is
based on inhibited flow in porous tubes
(INPORT). The protection region has an effec-
tive 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$_2$Pb$_3$ coolant. Behind
the reflector, a 3.5 m thick concrete shield is
used.

A consistent neutronics analysis of an ICF re-
actor must account for neutron multiplication
and spectrum softening inside the pellet. This
results from neutron interactions with the ex-
tremely 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 re-
sulting 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 ppm/s, the time spread increases from 5 to 26 ns, and the total helium production per FPY decreases from 229 to .364 ppmn.

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.

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
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 de-trapping energy is high (E_{He} = 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 are 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 (t_{on} = 0.327 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 x 10^{-8} dpa/sec/gd and the helium production rate as 1.16 x 10^{-7} at/at/second. The results of these calculations at 450°C are shown in Figure 5, where the average cavity radius R_{av}, the cavity density/cm^{3}, N_{v}, and the percent swelling, ε_{s}/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, ε_{s} = 10%. 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.

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


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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