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DISPLACEMENT DAMAGE IN THE FIRST STRUCTURAL WALL OF AN INERTIAL CONFINEMENT FUSION REACTOR: DEPENDENCE ON BLANKET DESIGN

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July 13, 1984

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Work performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore National Laboratory under Contract W-7405-Eng-48.

DISPLACEMENT DAMAGE IN THE FIRST STRUCTURAL WALL OF AN INERTIAL CONFINEMENT FUSION REACTOR: DEPENDENCE ON BLANKET DESIGN*

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Introduction

Future fusion reactors will have to cope with the damaging effects of high energy neutrons. One of the primary radiation damage mechanisms in structural steels is the displacement of atoms from their lattice positions.[1] Displaced atoms leave vacancies which can conglomerate to form voids within the steel, and this leads to a phenomena known as void swelling. After some total amount of damage, expressed in terms of displacements-per-atom or dpa, the structural material is deformed, and/or its properties are degraded to the point where it loses its integrity. Currently there is insufficient data to set absolute damage limits for structures in fusion reactors. It is known, however, that ferritic steels are less susceptible to the effects of displacement damage than austenitic steels,[2] and a damage limit of ~200 dpa was recently suggested as a reasonable estimate for high Cr ferritic steels.[3] A low-alloy, ferritic steel, 2.25 Cr-1 Mo, has been specified in several ICF reactor conceptual designs[4] due to its low cost, resistance to liquid-metal corrosion and resistance to the effects of radiation damage.

In this study we investigate how the design of the neutron blanket effects the displacement damage rate in the first structural wall (FSW) of an Inertial Confinement Fusion (ICF) reactor. Two generic configurations are examined; in the first, the steel wall is directly exposed to the fusion neutrons, whereas in the second, the steel wall is protected by inner blanket of lithium with an effective thickness of 1-m. The latter represents a HYLIFE-type design, which has been shown to have displacement damage rates an order of magnitude lower than unprotected wall designs.[4-6] The two basic configurations were varied to show how the dpa rate changes as the result of

1) adding a Li blanket outside the FSW,
2) adding a neutron reflector (graphite) outside the FSW,
3) changing the position of the inner lithium blanket relative to the FSW.

The effects of neutron moderation in the compressed DT-target are also shown, and the unprotected and protected configurations compared.

Calculations

The displacement damage rate is calculated as follows:

$$R = S \sum_i \sigma_i \Phi_i, \text{ dpa/yr},$$

where S = neutron source, n/yr,

σ_i = energy dependent displacement cross section, b,

Φ_i = energy dependent neutron fluence, n/cm^2 per source neutron, and

i = energy group index for the multigroup calculation.

The source of DT neutrons is related to the fusion power, P_f by

$$S = 11.2 \times 10^{24} P_f,$$

where P_f is in MW.

We used the displacement damage cross section for iron shown in Fig. 1. This cross section was calculated by Doran and Graves[7] and is somewhat higher than a previously published version.[8,9] It is based on an effective displacement energy of 40 eV, which is recommended for iron. For low energy neutrons, the displacement cross section varies as $E^{-0.5}$ from a value of 17b at 0.025 eV.[8]

The 50-energy-group structure shown in Fig. 1 is compatible with the output from TART, the multigroup neutron transport code used to calculate the neutron fluence.[10] All of the neutronics calculations were carried out in one-dimensional spherical geomtery. In all c..es the first structural wall was a 2-cm-thick shell of iron (ρ = 7.86 g/cm^3) located 5.0 m from the neutron source.

Figure 2 illustrates and describes the various cases for the unprotected wall configuration. Case-1 is simply a 14.1 MeV point source without a tritium breeding blanket or neutron reflector. In Case-2, the 14.1 MeV neutron source is uniformly distributed throughout a region of compressed DT, which has a density-radius product, ρR, of 3.0 g/cm^2. Case-3 adds a 1.0-m-thick lithium blanket (ρ = 0.49 g/cm^3) outside the FSW. Natural lithium, 7.42% ^{6}Li and 92.58% ^{7}Li, is used. In Case-4 the 1-m-thick Li blanket is replaced by a 30-cm-thick graphite (ρ = 1.7 g/cm^3) reflector.

Figure 3 illustrates and describes the cases run for the protected wall configuration. Case-5 has a 2-m-thick lithium blanket between the ρR = 3 target and the FSW. This region is at one-half normal density (0.245 g/cm^3) to represent the 50% packing fraction of lithium jets within the HYLIFE chamber. This gives an effective thickness of 1.0 m of lithium protection. The inner radius of the lithium region is 0.5 m. Case-6 adds a 1.0-m-thick lithium blanket (at full density, ρ = 0.49 g/cm^3) outside the FSW. Case-7 replaces the outer lithium blanket with a 30-cm-thick graphite reflector. In case-8, the protective, inner lithium blanket is moved outward so that its inner radius is 2.5 m and its outer radius is 4.5 m.

Results

Figure 4 compares the displacement damage rates for the four unprotected wall cases. These results are based on a fusion power of 3000 MW, a 5-m radius FSW and 100% capacity factor (i.e., the results are per

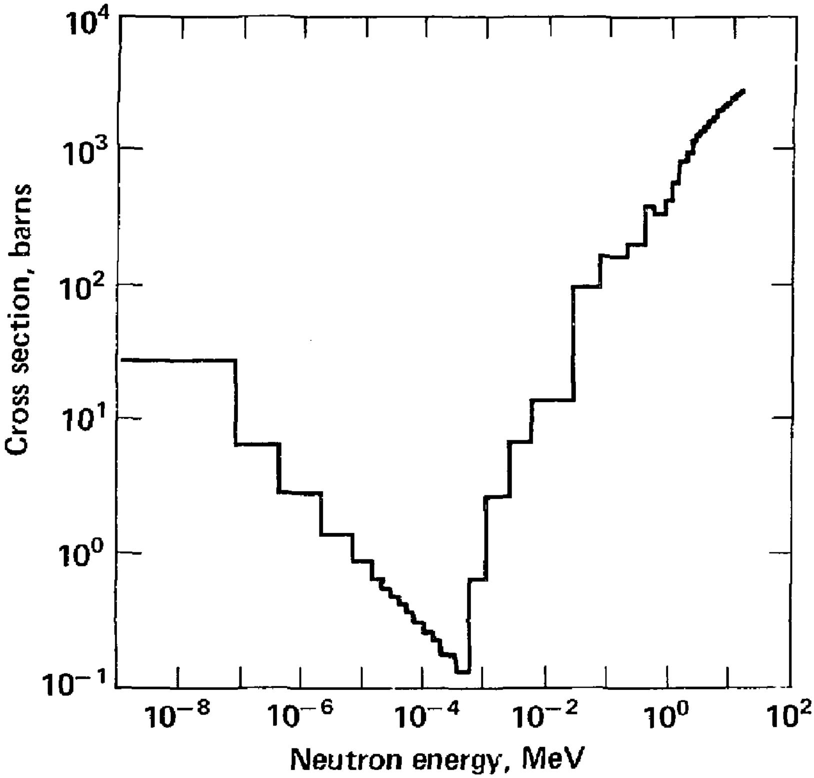

Figure 1. Displacement Damage Cross Section for Iron

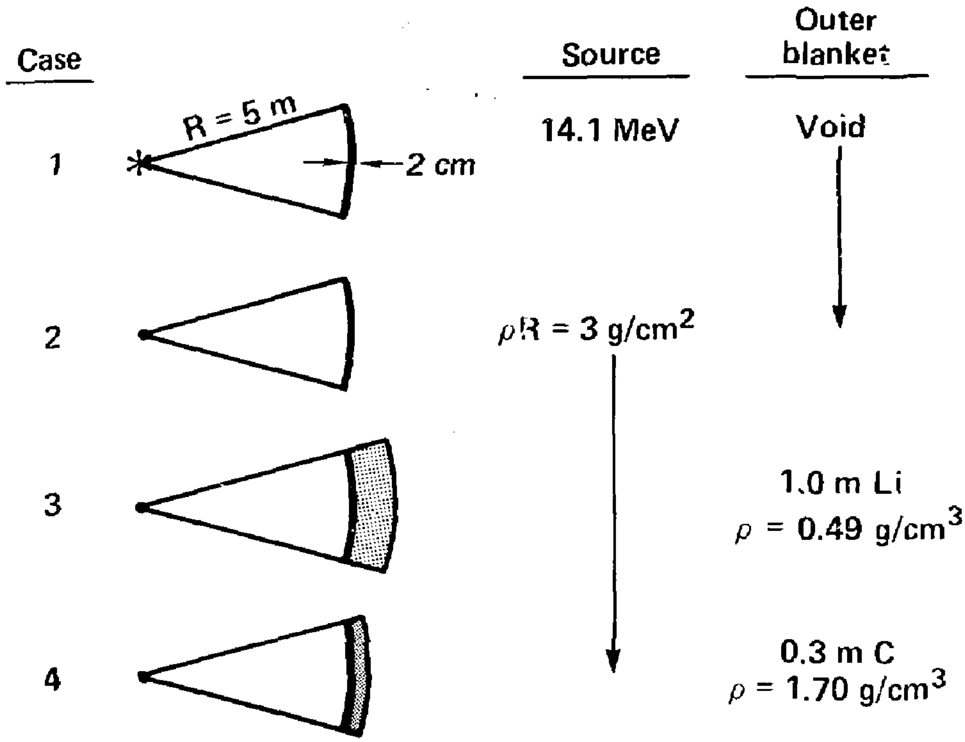

Figure 2. The Four Unprotected Wall Cases

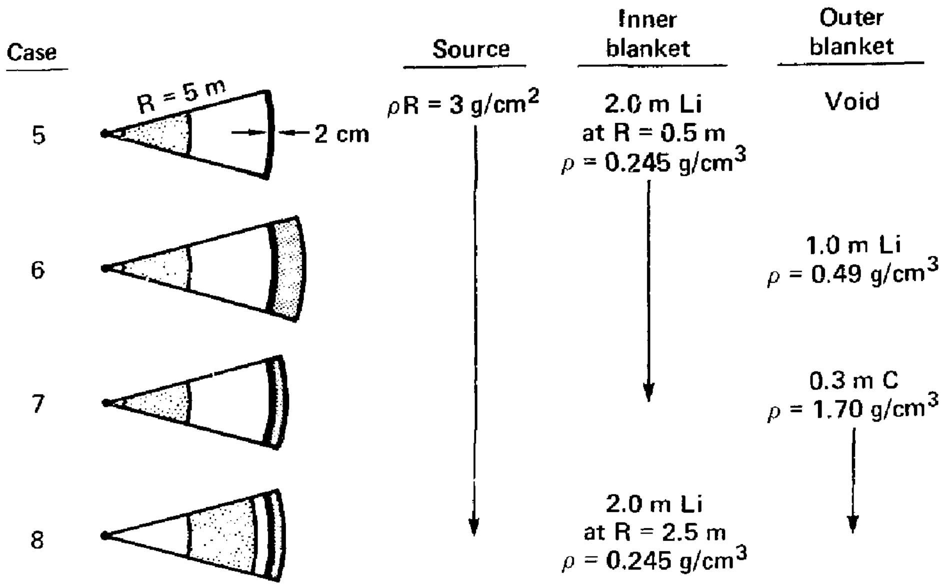

Figure 3. The Four Protected Wall Cases

full-power-year).

For a 14.1 MeV source incident on an unprotected, unreflected FSW (case-1) the displacement damage rate is 35.6 dpa/yr. The moderating effects of the compressed DT in the fusion target (case-2) reduce the damage rate only slightly. Adding a lithium blanket outside the FSW raises the dpa rate by 50%. This increase is the result of two factors; one is that fusion neutrons are scattered back into the wall from the lithium region, and secondly, neutrons emitted by $^7Li(n,n'T)\alpha$ reactions can also impinge on the FSW. Comparing case-4 to case-3 we see that the graphite reflector results in a slightly higher damage rate indicating that more neutrons are directed back at the FSW.

Figure 5 compares the damage rates for four cases in the protected wall configuration. Note that in all cases there is nearly an order of magnitude reduction from the unprotected wall configuration. Cases-5, 6 and 7 show the same trends as cases-2, 3 and 4. In particular adding a lithium blanket outside the FSW increases the damage rate by 45%. Substituting a graphite reflector for the outer lithium blanket (case-7) gives an even higher dpa rate.

Case-8 demonstrates an interesting effect. By moving the inner lithium blanket closer to the FSW, the damage rate is reduced by nearly 30% (from 6.45 to 4.59 dpa/yr). One reason for this is that the blanket closer to the wall results in a larger effective thickness for neutrons which are scattered at least once. This was discussed and illustrated in Ref. 11. Another reason is that neutrons which are reflected back through the FSW are more likely to be absorbed or further moderated by the lithium blanket within the chamber. In other words, a neutron reentering the fusion chamber is more likely to hit lithium than to tranverse the vacuum chamber and strike the wall again. In particular, for a neutron reentering the chamber the solid angle fraction eclipsed by the 2.5-m radius lithium blanket (case-7) is only 13% whereas the 4.5-m radius blanket (case-8) eclipses .56%.

While moving the blanket outward has advantages in terms of reducing displacement damage, in a chamber such as HYLIFE, a significant increase in the Li flow rate would result. In the Cascade chamber, a solid-particle breeding blanket is held against the inside of the FSW by

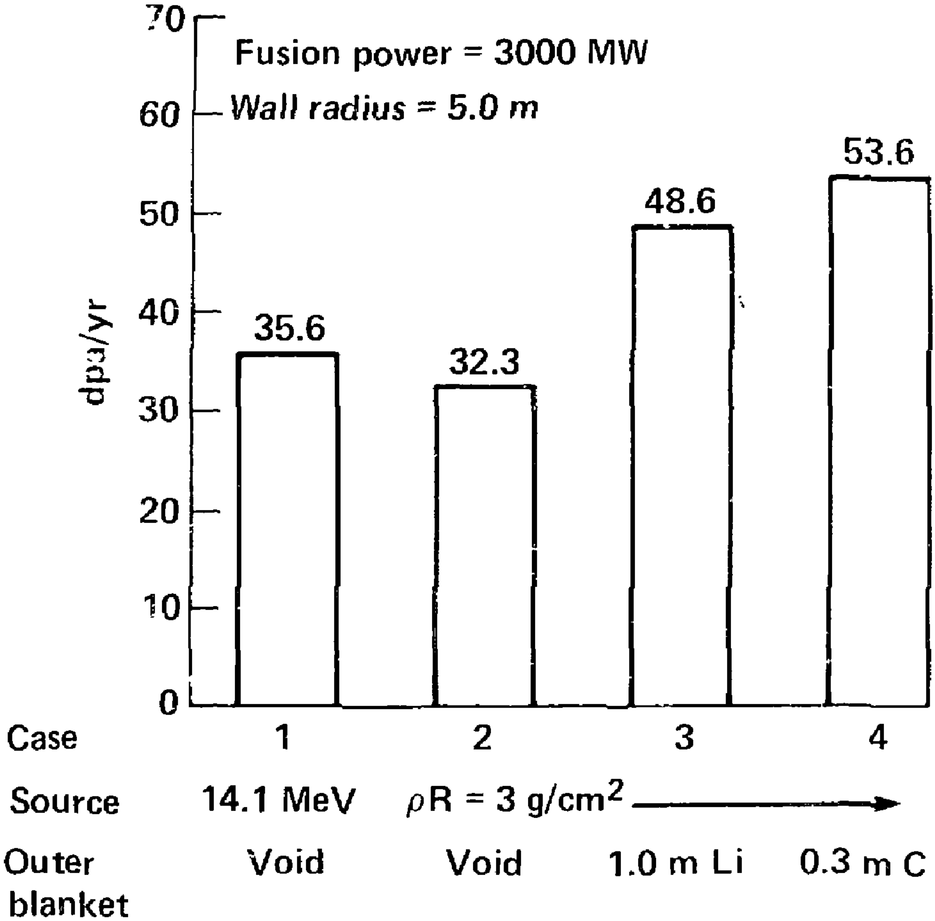

Figure 4. Displacement Damage Rates in an Unprotected Fe Wall

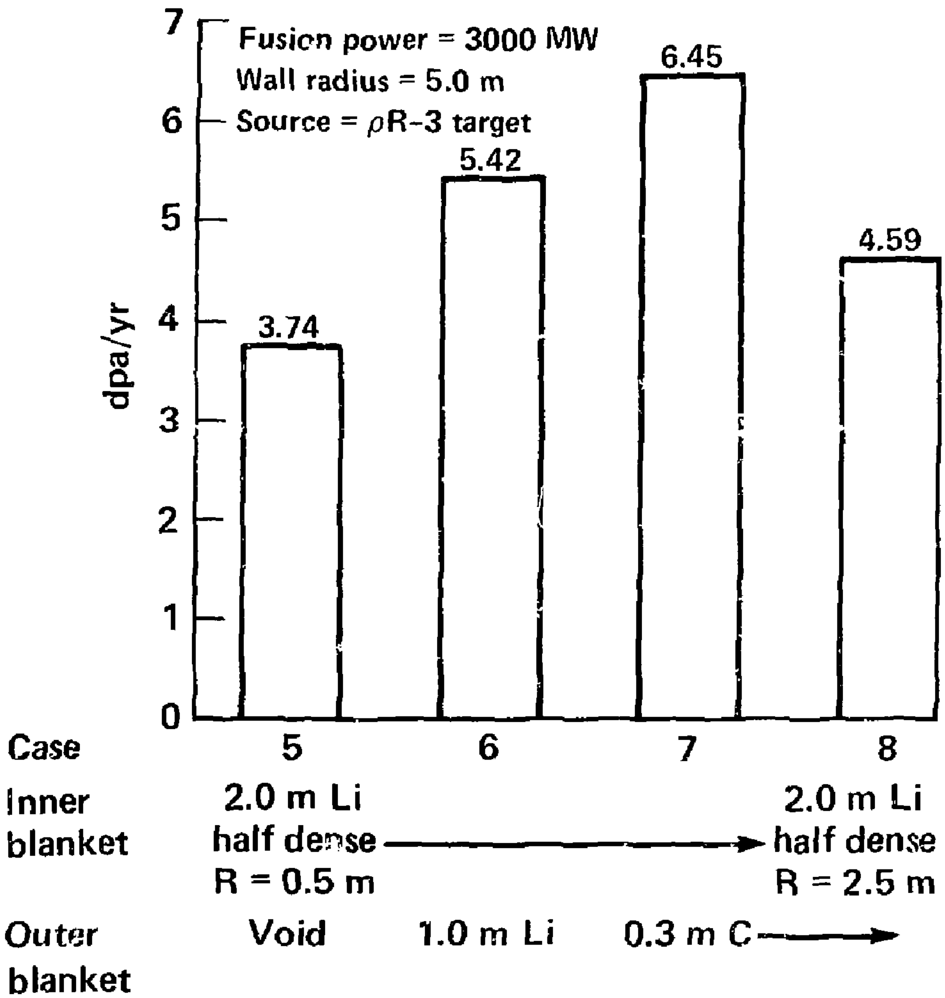

Figure 5. Displacement Damage Rates in a Protected Fe Wall

centrifugal action.[12] Assuming the trends observed for lithium hold for breeding blanket materials such as Li_2O and $LiAlO_2$, the Cascade blanket will be effective in minimizing the displacement damage rate in the rotating chamber wall.

Some additional information, unrelated to the topic of displacement damage but made available by the neutronics calculations, is given in the Appendix for reference.

Summary

We have examined the dependence of displacement damage on the configuration of the fusion chamber blanket. We find that:

1) The compressed DT in the ICF target reduces the dpa rate only slightly(<10%).

2) Adding a lithium blanket outside the FSW increases the displacement damage rate by ~50%. This is true for both the unprotected and protected FSW configurations.

3) Adding a graphite reflector outside the first structural wall increases the dpa rate by 66% for the unprotected case and 73% for the protected configuration.

4) Placing the equivalent of a meter of Li between the fusion target and the FSW decreases the damage rate by nearly an order of magnitude

5) Moving the protective, inner blanket closer to the FSW reduces the damage rate significantly.

Appendix

Some of the results of the neutronics calculations are given here for reference. Table A-1 gives the neutron energy deposition by zone and neutron energy leakage. Table A-2 gives the tritium breeding ratio by isotope and the number of neutrons leaking from the system.

Table A1
Neutron Energy Deposition
(MeV per DT-neutron)

Case	Target	Inner Blanket	FSW	Outer Blanket	Leakage
1	-	-	2.04	-	11.41
2	1.85	-	1.78	-	9.61
3	1.87	-	2.19	11.17	0.39
4	1.83	-	4.42	5.82	1.73
5	1.83	12.08	0.13	-	0.60
6	1.81	12.18	0.19	2.35	0.01
7	1.81	12.88	1.20	0.42	0.08
8	1.85	14.10	0.48	0.31	0.05

Table A2

Tritium Breeding and Neutron Leakage

Case	T6	T7	T	L
1	-	-	-	0.99
2	-	-	-	1.05
3	0.79	0.49	1.28	0.29
4	-	-	-	0.64
5	0.58	0.65	1.23	0.51
6*	0.63/0.39	0.63/0.02	1.26/0.41	0.07
7	0.76	0.64	1.40	0.19
8	0.97	0.65	1.62	0.09

T6 = $^{6}Li(n,T)\alpha$ reactions per DT-neutron

T7 = $^{7}Li(n,n'T)\alpha$ reactions per DT-neutron

T = T6 + T7

L = neutron leakage per DT-neutron

*Numbers given are (inner blanket)/(outer blanket)

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0089Y/3022P