The Sensitivity of the First-Wall Radiation Damage to Fusion Reactor Blanket Composition

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Neutron Physics Division

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Journal publication

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Abstract

The atomic displacement and hydrogen and helium gas production rates in a 1-cm-thick type-316 stainless steel first wall have been calculated as a function of blanket composition in a typical one-dimensional fusion reactor model. For a 50-cm-thick blanket, variations in the rates of atomic displacement and hydrogen and helium gas production of factors of 2.7, 1.3, and 1.2, respectively, were obtained. The dependence of the radiation damage responses on the thickness of the first wall and blanket are also given.

INTRODUCTION

The radiation damage to structural components, particularly the first wall, in magnetic fusion reactors is of considerable concern to reactor designers. The radiation environment at the first wall will be extremely severe and changes in the mechanical properties of the first wall material will occur. The operating lifetime of the reactor will be governed by the allowable changes in the dimensions, strength, ductility, etc., of the first wall that govern the safe operation of the reactor. Replacement of the first wall and other structural components will require disassembly of the reactor resulting in long shutdown times, and, in the case of power producing reactors, economic penalties.

This paper examines the sensitivity of the radiation damage rates in a 1-cm-thick type-316 stainless steel wall as a function of blanket composition in a typical one-dimensional fusion reactor model. The radiation response of the stainless steel is calculated in terms of the neutron-induced atomic displacement rate and the hydrogen and helium gas production rates. These rates are compared as a function of the composition of a 50-cm-thick blanket. While some of the materials considered may not be of practical application in actual reactor blanket designs, the results are of interest in defining the sensitivity of these irradiation response parameters.

The dimensions of the reactor model and the materials used in the blanket module are given in Table 1. Stainless steel was selected for the first structural wall mainly on the premise that its availability and known metallurgical properties will probably dictate its use in early fusion reactor designs. For these calculations, the shield and toroidal field coil assemblies have not been included in the calculational model.

Except for the case where the blanket is treated as a void, the effect on the radiation damage responses in the first wall due to backscattering of neutrons from these components is not expected to significantly influence the results.

Table 1. Dimensions of the Reactor Model and Composition of the Blanket Materials

Zone	Outer Radius (cm)	Composition
1	100	Plasma
2	120	Cold Zone
3	121	SS-316 Wall ^a
4	171	Blanket

^aSS-316 - 63% Fe, 18% Cr, 13% Ni, 2.6% Mo, 1.9% Mn, 0.9% Si, C, Ti.

Composition of Blanket Materials

Material	Density (g/cm ³)
Void	0.0
Lithium	0.53
Carbon	2.25
Sodium	0.97
Aluminum	2.70
Potassium	0.87
Iron	7.87
Copper	8.95
Lead	11.5
Water	1.0
SS-316	7.87
SS + H ₂ O	(65% SS; 35% H ₂ O)
SS + K	(65% SS; 35% H ₂ O)
NaOH	2.13

The radiation transport calculations were performed in a one-dimensional cylindrical geometry using the discrete ordinates code ANISN¹ using a P_3 - S_{12} approximation. The neutron and gamma-ray cross section data were taken from the DLC-37² library (ENDF/B-IV) and collapsed to a 35-neutron and 21-gamma-ray energy group subset. The radiation damage response functions for atomic displacement and gas production rates were obtained from the data base RECOIL.³

DISCUSSION

The atomic displacement and gas production rates in the 1-cm-thick stainless steel first wall are compared as a function of blanket composition in Table 2. Also given in the table are the ratios of the hydrogen and helium gas production to the atomic displacement. All of the data are normalized to a neutron wall loading of 1 MW/m². To have a basis for comparison with a realistic reactor model, the radiation damage responses in the 0.14-cm-thick first wall of the ELMO Bumpy Torus Reactor⁴ are also included in the table. The blanket in this reactor is comprised of natural lithium and SS-316.

The atomic displacement rates range from a low value of 8.4 dpa/year for an empty blanket to a high value of 22.6 dpa/year for a lead-filled blanket. The hydrogen gas production rates vary from 423 to 536 appm/year and the helium gas production rates vary from 134 to 159 dpa/year for the empty and carbon-filled blankets, respectively. The case where the blanket zone is treated as a void is included for reference since, in this case, the radiation damage in the stainless steel wall is not sensitive to the neutrons that are backscattered by the blanket material. However, the inclusion of a shield or toroidal field coils would influence the results for this case.

Table 2. Atomic Displacement and Gas Production Rates
in the SS-316 First Structural Wall as a
Function of Blanket Composition

Neutron Wall Loading = 1 MW/m ²					
Blanket Composition	Atomic Displace- ment Rate ^a	Hydrogen Gas Pro- duction Rate	Hydrogen/ DPA Ratio	Helium Gas Production Rate	Helium/ DPA Ratio
	(dpa/yr)	(appm/yr)		(appm/yr)	
Void	8.4	423.	50.4	134.	16.0
Lithium	12.6	532.	42.2	159.	12.6
Carbon	13.1	536.	40.9	159.	12.2
Sodium	11.9	481.	40.4	147.	12.4
Aluminum	12.9	474.	36.8	149.	11.5
Potassium	10.7	472.	44.1	147.	13.8
Iron	14.9	484.	45.2	148.	10.0
Copper	14.6	468.	32.1	145.	9.9
Lead	22.6	488.	21.6	148.	6.6
Water	9.8	463.	47.3	143.	14.6
SS-316	14.5	489.	33.7	149.	10.3
SS+H ₂ O	11.2	484.	43.2	148.	13.2
K+SS	14.2	487.	34.3	149.	10.5
NaOH	10.6	478.	45.1	146.	13.8
EBTR ^b	14.2	621.	43.7	188.	13.2

^aBased on an effective displacement energy for SS-316 of 40 eV.

^bThese data are based on a different reactor model. See Ref. 4.

Analyses based on somewhat arbitrary assumptions suggest that the lifetime of a stainless steel wall in a fusion neutron environment will be of the order of 100 displacements per atom.⁵ Based on this criteria, the lifetime of the first wall would vary from 4.4 to 11.9 years depending on the blanket composition. However, it is reasonable to assume that several of the blanket materials considered in this study have no practical application in a fusion reactor blanket (e.g., void, sodium, potassium, iron, lead, K+SS, and NaOH). When these materials are eliminated, the life span of the first wall changes from 6.8 to 10.2 years for the remaining materials.

The results given in Table 2 were obtained for a homogeneous blanket having a thickness of 50 cm and with no consideration given to the practicality of constructing such a blanket. In actual practice, the blanket will be designed using a combination of materials. The radiation damage in the first wall will depend on the selection and the thickness of the material immediately behind the wall. The radiation damage as a function of blanket thickness when lithium, stainless steel, and stainless steel plus water are used are given in Table 3. For thicknesses ≥ 10 cm, the radiation damage functions are insensitive to the blanket thickness when stainless steel plus water is used. When lithium or stainless steel only is used, the atomic displacement rates vary by factors of 1.2 and 1.1, respectively. The hydrogen and helium gas production rates for the stainless steel configuration are constant for blanket thicknesses ≥ 10 cm, and they exhibit less rapid saturation with thickness when the blanket contains lithium. It should be noted that the radiation damage may also depend on the order of materials in the blanket, but this dependence was not considered in this study.

Table 3. Atomic Displacement and Gas Production Rates
in the SS-316 First Structural Wall as a
Function of Blanket Material and Thickness

Neutron Wall Loading = 1.0 MW/m ²				
Blanket Composition	Blanket Thickness	Atomic Displacement Rate ^a	Hydrogen Gas Production Rate	Helium Gas Production Rate
	(cm)	(dpa/year)	(appm/year)	(appm/year)
Li	0 ^b	8.4	423.	134.
	10	10.7	494.	151.
	25	12.2	528.	159.
	50	12.6	532.	159.
SS	0 ^b	8.4	423.	134.
	10	13.1	488.	150.
	25	14.4	488.	150.
	50	14.5	488.	149.
SS+H ₂ O	0 ^b	8.4	423.	134.
	10	11.1	482.	149.
	25	11.2	484.	149.
	50	11.2	484.	148.

^aBased on an effective displacement energy for SS-316 of 40 eV.

^bThe blanket is treated as a 50-cm-thick void region.

The radiation damage responses calculated for the first wall in the EBTR, and shown in Table 2, are larger than those obtained for the homogeneous blanket compositions considered in this study. In the EBTR, the thickness of the first wall is 0.14 cm compared to 1 cm for the configuration used here. To assess this difference, calculations were performed wherein the thickness of the first wall was varied while holding the blanket thickness at 50 cm. The blanket composition was taken to be natural lithium. The dependence of the radiation damage responses as a function of the thickness of the first wall are given in Table 4a. The atomic displacement rate is $\sim 10\%$ larger in the 0.1-cm-thick wall than in the 1.0-cm-thick wall. Correspondingly, the hydrogen and helium gas production rates vary by factors of 1.13 and 1.20, respectively, for the same wall thickness. The variation in the responses with thickness is due, in part, to the self-shielding of the 14-MeV D-T neutrons in the thicker wall. This phenomena may be observed in Table 4b where the spatial variations in the responses through the 1-cm-thick wall are given. The atomic displacement rate in the spatial interval from 0 to 0.2 cm is a factor of 1.21 larger than the atomic displacement rate in the spatial interval from 0.8 to 1.0 cm. The hydrogen and helium gas production rates vary by factors of 1.27 and 1.29, respectively, in the same intervals. The gas production cross sections in SS-316 are threshold reactions so the attenuation of the neutrons by the stainless steel leads to a reduction in the gas production.

The atomic displacement rates are, in part, a function of the effective thickness of the blanket. For example, for stainless steel, the blanket is 394 g/cm² thick compared to 27 g/cm² for the lithium blanket.

Table 4a. Atomic Displacement and Gas Production Rates
as a Function of Thickness of a SS-316 First Wall

Neutron Wall Loading = 1.0 MW/m ²			
Blanket = Lithium, 50-cm-thick			
Wall Thickness	Atomic Displacement Rate	Hydrogen Gas Production Rate	Helium Gas Production Rate
(cm)	(dpa/year)	(appm/year)	(appm/year)
.1	14.1	602.	189.
.5	13.3	580.	177.
1.0	12.6	532.	158.

Table 4b. Spatial Variations of the Atomic Displacement Gas
Production Rates in a 1-cm-thick SS-316 First Wall

Neutron Wall Loading = 1 MW/m ²			
Blanket = Lithium, 50-cm-thick			
Interval	Atomic Displacement Rate	Hydrogen Gas Production Rate	Helium Gas Production Rate
(cm)	(dpa/year)	(appm/year)	(appm/year)
0. -0.2	13.8	594.	180.
0.2-0.4	13.1	555.	168.
0.4-0.6	12.5	522.	157.
0.6-0.8	11.9	493.	147.
0.8-1.0	11.4	469.	139.
Average	12.6	527.	158.

The atomic displacement rates as a function of the effective blanket thickness for several of the materials are shown in Fig. 1. The open circles, connected by the handfitted dashed line, show the dependence of the atomic displacement as a function of stainless steel blanket thickness. The labeled, solid circles show the atomic displacement rate given in Table 2 for the various materials, but scaled to the effective blanket thickness relative to stainless steel using $[(\rho_{\text{mat}}/\rho_{\text{SS}})50 \text{ cm}]$ where ρ_{mat} and ρ_{SS} are the volume densities for the material being scaled and stainless steel, respectively.

It has been demonstrated that the induced damage (DPA and gas production) in the first wall of a fusion reactor is sensitive to the blanket composition and to the thickness of the first wall primarily due to self shielding characteristics. Variations in the damage of ~ 10 to 20% are possible and therefore depending upon the reactor configuration the operating lifetime of the first wall could be reduced.

Fig. 1. Atomic Displacement Rate versus Effective Blanket Thickness in Density Equivalent Stainless Steel.

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