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NUCLEAR RESPONSES IN INTOR PLASMA STABILIZATION ELEMENTS*

Y. Gohar, R. F. Mattas, and S. Yang
Fusion Power Program
Argonne National Laboratory
Argonne, IL 60439

F. W. Wiffen
Oak Ridge National Laboratory, FEDC
P.O. Box Y
Oak Ridge, TN 37830

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Y. Cohar, R. F. Mattas, and S. Yang
Fusion Power Program, Argonne National Laboratory
9700 South Cass Avenue
Argonne, IL 60439
(312) 972-4816

F. W. Wiffen
Oak Ridge National Laboratory, FEDC
P.O. Box Y
Oak Ridge, TN 37830
(615) 574-5064

ABSTRACT

Nuclear responses in the plasma stabilization elements were studied in a parametric fashion as a part of the transient electromagnetics critical issue C of ETR/INTOR activity. The main responses are neutron fluence and radiation dose in the insulator material, induced resistivity and atomic displacement in the conductor material, nuclear heating and life analysis for the elements. Copper and aluminum conductors with either MgAl_2O_4 or MgO insulating material were investigated. Radiation damage and life analysis for these elements were also discussed.

I. INTRODUCTION

A study was carried out to determine the nuclear responses in the plasma stabilization elements as a part of the transient electromagnetics critical issue C of ETR/INTOR activity. The main goal of these stabilization elements¹ is to improve the plasma stabilization and the ability of the reactor chamber (first wall, blanket and shield) to withstand the forces and voltages induced during plasma disruption. The development of a configuration for the INTOR stabilization system from the nuclear design point of view were performed in a parametric fashion with respect to the element location relative to the first wall and material choices, to define and compare the nuclear performance of these elements. The main nuclear responses are neutron fluence and radiation dose in the insulator material, induced resistivity and atomic displacement in the conductor material, nuclear heating and life analysis for the elements. These elements consist of normal conductor where both copper and aluminum materials with either MgAl_2O_4 or MgO insulating material were investigated for INTOR reactor conditions.

This paper describes the radiation damage and lifetime considerations for ceramic insulators, change in the conductor resistivity due to transmutations and the nucleonics analyses for INTOR conditions. In addition, de-

sign recommendations about the element position relative to the first wall and the material choice are discussed.

II. RADIATION DAMAGE AND LIFETIME CONSIDERATIONS

A major limitation for the operation and placement of normal conductors within the blanket is the effect of neutron radiation damage which can degrade both the electrical and mechanical properties of the copper conductor and the insulating material.

The resistivity of the copper will increase as a result of the formation of displacement damage defects and transmutation products. Tests of pure copper, irradiated at 60°C, indicate that the influence of displacement defects saturates at relatively low fluences ($< 10^{20}$ n/cm², $E > 0.1$ MeV), whereas the influence of transmutations continues to increase.² Therefore, transmutations are believed to be the primary cause of resistivity increases at high fluences. The increase in resistivity was determined to be 0.35 $\mu\Omega\cdot\text{m}$ for Ni and Zn concentrations of 240 ppm each. This figure translates into a rate of increase of 7.3 $\mu\Omega\cdot\text{m}$ per atomic percent of transmutation products (Ni + Zn).

Measurements of electrical resistivity changes in copper indicate that at the concentrations of interest, the resistivity increases linearly with concentration. At room temperature the rate of increase for nickel is 11 $\mu\Omega\cdot\text{m}$ per atomic percent, and the rate of increase for Zn is 2 $\mu\Omega\cdot\text{m}$ per atomic percent.³ The predicted increase in transmutation products in INTOR just behind the first wall after total fluence of 6.5 $\text{MW}\cdot\text{y}/\text{m}^2$ is ~.35 at% Zn and ~.65 at% Ni. The projected resistivity increase is ~7.9 $\mu\Omega\cdot\text{m}$ or 46% of the resistivity of OFHC copper.

The influence of radiation on other properties of copper and copper alloys has not been determined at the temperatures and fluences of interest. Radiation damage is expected to result in modified tensile strength

and reduced ductility, but additional experimental effort is needed to determine the degree of change in the properties. Recent reviews of irradiation effects in copper are given in Refs. 4 and 5.

The neutron irradiation will change the strength properties. If annealed material is used the strength will be increased, but if cold-worked copper is used the direction of the strength change is less certain. At temperatures below 400 K, strength will probably be increased; at higher temperatures radiation-induced recovery could decrease the strength. Irradiation is also expected to reduce the ductility of copper, but adequate ductility for service should be maintained. Swelling due to void formation is also probable with swelling of a few percent possible. However, the temperature for maximum swelling is ~600 K and the stabilizing elements will probably operate at temperatures well below this value.

Estimates indicate that the total elongation, i.e. total fracture strain, of copper irradiated up to fluence of $6 \text{ MW}\cdot\text{y}/\text{m}^2$ at 200°C remains larger than 5%.⁵ The swelling of copper for a fluence of $6 \text{ MW}\cdot\text{y}/\text{m}^2$ may be larger than 10% which can be a serious problem.⁵ The swelling can be suppressed by alloying with appropriate elements, but the electrical resistivity may increase due to alloying.

Aluminum conductor is a less attractive candidate primarily because of higher resistivity and lower operating limits on temperature. For example, the electrical resistivity of pure aluminum is 1.7 times as large as that of pure copper at 150°C . The electrical resistivity increase due to neutron irradiation is anticipated to be small, however. The resistivity increment due to displacement damage should be low, relative to copper, because the defect clusters formed in aluminum above room temperature are much coarser than in copper. The contribution due to transmutation products is also low, due to reduced transmutation rates in aluminum. The total elongation of aluminum is expected to remain greater than 5% at least up to a fluence of $6 \text{ MW}\cdot\text{y}/\text{m}^2$.⁵ The swelling of aluminum to a fluence of $6 \text{ MW}\cdot\text{y}/\text{m}^2$ is estimated to be about 1 ~ 5%.⁵ The neutron absorption of aluminum is smaller than that of copper and it has an advantage over copper from this point of view.

Inorganic insulators exhibit an instantaneous decrease in the DC resistivity during neutron and gamma ray irradiation. At lower temperatures ($\leq 400^\circ\text{C}$), the resistivity decreases up to three orders of magnitude in several ceramics for a gamma ray dose rate of $\sim 15 \text{ Gy/s}$.⁶ The original resistivity is recovered when the irradiation is stopped. At elevated temperatures, the resistivity changes

are largely driven by thermal effects and radiation effects are minor. Since the resistivity of most ceramic insulators is very high, however, the decreases associated with irradiation should not present significant problems for element operation.

The major concern with the structural properties of ceramics is the loss of physical integrity due to radiation induced swelling. Ceramics whose crystal structures are non-cubic tend to swell anisotropically, resulting in extensive microcracking and loss of integrity. It is for this reason that cubic ceramics such as MgO and MgAl_2O_4 (Spinel) are preferred. Spinel also exhibits low swelling rates with neutron fluence and is therefore the first choice as an insulator material. Recent experiments indicate that the swelling in Spinel remains below 1% at neutron fluences of $\sim 2 \times 10^{22} \text{ n/cm}^2$ ($E > 0.1 \text{ MeV}$) for temperatures up to 925 K .⁷ The Spinel fluence limit for this study is estimated to be $\sim 4 \times 10^{22} \text{ n/cm}^2$ ($E > 0.1 \text{ MeV}$) based on 3% volume swelling to minimize deformation in the elements.⁶

III. GEOMETRICAL MODEL AND CALCULATIONAL PROCEDURE

In this study, the stabilization elements were located in the outboard blanket as defined from the transient electromagnetics analyses.¹ The outboard blanket⁸ has a tritium breeding capability to supply a fraction of the required tritium for the reactor fueling. The blanket utilizes the Li_4SiO_4 tritium breeder with lead as a neutron multiplier. Low temperature water coolant is used for the different blanket regions. The inboard blanket is used for the protection of the inboard section of the toroidal field coils.⁹ A steel-water mixture is employed for the inboard section with a steel armor for the first wall protection. Table 1 gives the geometrical buildup in the radial direction at the midplane and the composition of the individual regions. The position of the plasma stabilization element relative to the first wall was varied from 0 (at the back of the first wall) to 48 cm (at the outer surface of the blanket). The radial width of the element is 5 cm including coolant and structure materials. Both copper and aluminum conductor materials with either MgAl_2O_4 or MgO insulating material are included in this study. These insulators are the preferred ceramics^{10,11} for the high irradiation environment as discussed in the previous section. The element composition used in this study is 80% conductor material (Cu or Al), 5% water coolant, 10% type 316 steel, and 5% insulating material (MgAl_2O_4 or MgO) by volume.

The transport calculations were performed in one dimension using the geometrical model defined in Table 1. The discrete ordinates

TABLE 1. INTOR GEOMETRY AND COMPOSITIONS USED IN THE ANALYSIS

Zone	Description	Radius (cm)		Thickness (cm)	Compositions (% by Volume)
		From	To		
1	Inboard shield	340	374	34	80% Type 316 steel, 20% H ₂ O
2	First wall	374	375	1	50% Type 316 steel, 50% H ₂ O
3	Inboard armor	375	380	5	100% Type 316 steel
4	Scrape-off	380	410	30	Vacuum
	Plasma	410	650	240	
5	Scrape-off	650	660	10	100% Type 316 steel
	Outboard armor	660	661	1	
6	First wall	661	662	1	50% Type 316 steel, 50% H ₂ O
7	Plasma stabilization element ^a	662	667	5	80% Cu or Al, 5% H ₂ O, 5% MgAl ₂ O ₄ or MgO, 10% Type 316 steel
8	Neutron multiplier	667	674	7	100% Pb
9	Second wall	674	675	1	50% Type 316 steel, 50% H ₂ O
10	Tritium breeder	675	715	40	45% Li ₄ SiO ₄ , 10% H ₂ O, 10% Type 316 steel, 35% He
11	Vacuum gap	715	720	5	Vacuum
12	Shield jacket	720	721.5	1.5	100% Fe1422
13	Steel shield	721.5	756.5	35	90% Fe1422, 10% H ₂ O

^a In this case, the plasma stabilization element is located behind the first wall.

code ANISN¹² with S₈ symmetric angular quadrature set and P₃ legendre expansion for the scattering cross sections. A 67-multigroup cross section set (46-neutrons and 21-photons) collapsed from the CTR library¹³ was used for ANISN calculations. The MACKLIB¹⁴ was employed to calculate the nuclear responses (nuclear heating, radiation damage, etc.).

IV. RESULTS AND DISCUSSIONS

The calculations were performed for four element designs corresponding to the following combinations of conductor and insulator: Cu-MgAl₂O₄, Cu-MgO, Al-MgAl₂O₄, and Al-MgO. Water and type 316 steel are the coolant and the structure materials for all designs, respectively. The element position relative to the back surface of the first wall was varied in steps as follows: 0, 8, 18, 28, 38, and 48 cm. The nuclear responses in the Cu-MgAl₂O₄ elements are shown in Fig. 1 through 3. All the results given in this paper are normalized to the INTOR operating conditions at the first wall, a 1.3 MW/m² neutron wall loading or 6.5 MW·y/m² DT neutron exposure at the end of life (10 years of operation with 50% availability factor).

Figure 1 shows the neutron fluence in the Cu-MgAl₂O₄ element as a function of the distance measured from the back of the first wall. The use of lead in front of the Li₄SiO₄ tritium breeder increases the neutron fluence in the element located near the first wall as shown in Fig. 1. The maximum fast neutron fluence (E > 0.1 MeV) is 6 x 10²² n/cm² at the end of life. The corresponding total neutron

fluence is about 10²³ n/cm². Figure 2 shows the dose in the MgAl₂O₄ insulator material at the end of life. At the first wall, the neutron dose is 1.4 times the gamma dose. However, the neutron dose drops faster than the gamma dose as shown in Fig. 2. At about 18 cm from the first wall, the dose and the fast neutron fluence are 10¹³ rads and 2 x 10²² n/cm², respectively. However, the property changes in ceramic insulators are a function only of the fast neutron fluence. At such nuclear responses, the experimental data^{11,12} show that the swelling is less than -0.4% and the strength shows an increase of 22 to 92%. The other changes in the performance of the MgAl₂O₄ insulator material can be accommodated in the design without difficulty. The nuclear heating in the Cu-MgAl₂O₄ stabilization element is shown in Fig. 3 where the gamma heating contributes more than 75% of the total heating.

The results from the calculations of the other cases are given in Table 2 including the Cu-Mg Al₂O₄ case. The examination of the nuclear responses from these cases leads to the following main observations:

a) There is essentially no changes in the calculated nuclear responses when MgO is substituted for MgAl₂O₄ as an insulating material for the same conductor material. However the experimental data base on swelling for both materials shows that MgAl₂O₄ exhibits less swelling for the same conditions as discussed in the previous sections.

b) The maximum insulator dose in the stabilization elements with aluminum conductor is 1

TABLE 2. NUCLEAR RESPONSES IN THE COPPER STABILIZATION ELEMENT NORMALIZED TO 1.1 MW/m² NEUTRON WALL LOADING AND 6.5 MW.y/m² DT NEUTRON EXPOSURE AT THE FIRST WALL.

Cu-MgAl ₂ O ₄				Cu-MgO				Al-MgAl ₂ O ₄				Al-MgO			
A. Maximum neutron fluence															
Distance From First Wall (cm)	Fluence (E > 0.1 MeV) (n/cm ²)	Fluence (E > 0.0 MeV) (n/cm ²)		Fluence (E > 0.1 MeV) (n/cm ²)	Fluence (E > 0.0 MeV) (n/cm ²)			Fluence (E > 0.1 MeV) (n/cm ²)	Fluence (E > 0.0 MeV) (n/cm ²)			Fluence (E > 0.1 MeV) (n/cm ²)	Fluence (E > 0.0 MeV) (n/cm ²)		
0	6.01+22 ^a	9.66+22		6.00+22	9.65+22			5.61+22	9.62+22			5.60+22	9.61+22		
8	4.03+22	7.78+22		4.03+22	7.79+22			3.74+22	7.36+22			3.73+22	7.36+22		
18	1.63+22	3.24+22		1.63+22	3.24+22			1.52+22	3.06+22			1.52+22	3.06+22		
28	6.99+21	1.47+22		6.99+21	1.47+22			6.51+21	1.39+22			6.51+21	1.39+22		
38	3.14+21	6.64+21		3.14+21	6.64+21			2.94+21	6.31+21			2.94+21	6.31+21		
48	1.52+21	3.14+21		1.52+21	3.14+21			1.45+21	3.17+21			1.45+21	3.17+21		
B. Maximum Insulator Dose															
Distance From First Wall (cm)	n (rads)	y (rads)	Total (rads)	n (rads)	y (rads)	Total (rads)		n (rads)	y (rads)	Total (rads)		n (rads)	y (rads)	Total (rads)	
0	3.57+13	2.55+13	6.12+13	3.70+13	2.56+13	6.26+13		3.76+13	2.33+13	6.09+13		3.90+13	2.34+13	6.24+13	
8	1.12+13	1.13+13	2.25+13	1.15+13	1.13+13	2.28+13		1.15+13	7.51+12	1.91+13		1.18+13	7.56+13	1.93+13	
18	4.55+12	5.15+12	9.70+12	4.73+12	5.18+12	9.91+12		4.66+12	3.86+12	8.52+12		4.86+12	3.88+12	8.74+12	
28	2.01+12	2.82+12	4.83+12	2.10+12	2.84+12	4.94+12		2.06+12	2.26+12	4.32+12		2.16+12	2.27+12	4.43+12	
38	9.15+11	1.50+12	2.41+12	9.59+11	1.51+12	2.47+12		9.41+11	1.28+12	2.22+12		9.88+11	1.28+12	2.27+12	
48	4.25+11	8.07+11	1.23+12	4.47+11	8.12+11	1.26+12		4.39+11	7.74+11	1.21+12		4.61+11	7.79+11	1.24+12	
C. Maximum Nuclear Heating															
Distance From First Wall (cm)	n (W/cm ³)	y (W/cm ³)	Total (W/cm ³)	n (W/cm ³)	y (W/cm ³)	Total (W/cm ³)		n (W/cm ³)	y (W/cm ³)	Total (W/cm ³)		n (W/cm ³)	y (W/cm ³)	Total (W/cm ³)	
0	5.13+0	1.53+1	2.04+1	5.14+0	1.53+1	2.05+1		5.75+0	4.90+0	1.06+1		5.76+0	4.89+0	1.07+1	
8	2.06+0	6.96+0	9.02+0	2.06+0	6.96+0	9.02+0		1.80+0	1.59+0	3.38+0		1.80+0	1.59+0	3.39+0	
18	7.74-1	3.16+0	3.93+0	7.76-1	3.16+0	3.94+0		7.21-1	8.14-0	1.54+0		7.23-1	8.14-1	1.54+0	
28	3.53-1	1.73+0	2.08+0	3.54-1	1.73+0	2.08+0		3.21-1	4.77-0	7.98-1		3.22-1	4.77-1	7.98-1	
38	1.62-1	9.17-1	1.08+0	1.62-1	9.16-1	1.08+0		1.46-1	2.70-1	4.16-1		1.47-1	2.70-1	4.17-1	
48	7.60-2	4.94-1	5.70-1	7.62-2	4.93-1	5.70-1		6.85-2	1.64-1	2.33-1		6.88-2	1.64-1	2.33-1	
D. Maximum Atomic Displacement															
Distance From First Wall (cm)	Displacement (dpa)			Displacement (dpa)				Displacement (dpa)				Displacement (dpa)			
0	7.86+1			7.85+1				8.68+1				8.67+1			
8	3.51+1			3.50+1				4.63+1				4.63+1			
18	1.46+1			1.46+1				1.89+1				1.89+1			
28	6.54+0			6.54+0				8.36+0				8.36+0			
38	3.03+0			3.03+0				3.86+0				3.86+0			
48	1.46+0			1.46+0				1.89+0				1.89+0			

^a 6.01 + 22 reads 6.01 × 10²².

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Fig. 1. Neutron fluence in the plasma stabilization element as a function of the element position relative to the first wall normalized to $6.5 \text{ MW}\cdot\text{y}/\text{m}^2$ DT neutron exposure at the first wall.

to 10% smaller than the copper case for both insulator materials.

c) The maximum fast fluence in the aluminum conductor is 6 to 7% less than the copper conductor due to the difference in the scattering cross section of both materials for both insulators.

d) The nuclear heating in the aluminum element is 50 to 60% smaller than the copper case due to the difference in the gamma heating. This difference is reflecting the difference between the gamma kerma factors of aluminum and copper.

e) The atomic displacement rate in the aluminum material is 10 to 30% higher than the copper material.

In addition, the electrical resistivity of the conductor material will change due to atomic displacement and transmutations^{2,15,16} as discussed before. The displacement damage saturates at low fluences and it results in an insignificant effect on the resistivity. The

Fig. 2. Dose in the MgAl_2O_4 ceramic insulator as a function of the element position relative to the first wall normalized to $6.5 \text{ MW}\cdot\text{y}/\text{m}^2$ DT neutron exposure at the first wall.

neutron interactions with the natural copper material give several isotopes through the following reactions.

The (n,γ) reaction represents about 98% of the total reaction rate which leads to Zn and Ni isotopes. At the end of life for INTOR, the total concentration of the transmutations is 0.93% of the copper. At this level of impurity the electrical resistivity increase is 46% based on the data presented in the previous section. This increase decreases by order of magnitude if the element is located 28 cm from the first wall. For the aluminum conductor, the transmutation production rate is an order of magnitude lower than that of copper which results in an insignificant increase in the electrical resistivity.

Fig. 3. Nuclear heating in the plasma stabilization element as a function of the element position relative to the first wall normalized to 1.3 MW/m^2 neutron wall loading.

V. CONCLUSIONS

The nuclear responses in the plasma stabilization elements of INTOR conceptual design at the first wall are outside the range of existing data base on radiation effects in ceramic insulators and conductor materials. The insulator dose and the fast neutron fluence are about 6×10^{13} rads and $6 \times 10^{22} \text{ n/cm}^2$, respectively behind the first wall. Therefore high fluence irradiation data on the behavior of these ceramic insulators and the conductor materials are required to qualify the materials for INTOR design. Also, the results show that radiation effects on these elements can be accommodated based on the limited experimental data if they are located at least 18 cm behind the first wall.

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