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Calculated Irradiation Response of Materials Using a Fusion-Reactor First-Wall Neutron Spectrum

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CALCULATED IRRADIATION RESPONSE OF MATERIALS USING
A FUSION-REACTOR FIRST-WALL NEUTRON SPECTRUM

T. A. Gabriel, B. L. Bishop, and F. W. Wiffen

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CALCULATED IRRADIATION RESPONSE OF MATERIALS USING
A FUSION-REACTOR FIRST-WALL NEUTRON SPECTRUM

T. A. Gabriel*, B. L. Bishop**, and F. W. Wiffen

ABSTRACT

This paper presents the calculated irradiation response in displacements per atom and gas production values of a number of elements and metal alloys in a fusion reactor first-wall neutron spectrum. The gas production rates for new alloy compositions can be synthesized from these results, and all comparisons are thus kept on a consistent basis. The sensitivity to the nuclear data base used and to the exact neutron spectrum is found to be greatest in the helium production rates. This helium production value in some alloys may also be sensitive to composition. In type 316 stainless steel variations of $\pm 9\%$ are possible for compositions within the specification range.

INTRODUCTION

Predictions of the property changes that will result from metallic component service in a previously untested neutron spectrum are made by interpolation or extrapolation of the available understanding of irradiation effects. The best available basis for comparing neutron irradiation effects for exposures in different spectra is in terms of the calculated materials response, given in terms of displacements per atom (dpa), helium from α -producing transmutations, and hydrogen from (n,p) and other hydrogen isotope production reactions.

The existing neutronics calculations available for fusion reactor spectra have been performed mainly for the materials used in conceptual

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designs. Results from different designs are not directly comparable owing to different approaches used in performing the calculations. One set of calculations is available¹ comparing the response of several alloys of potential interest in a single fusion reactor spectrum. However, the results are not presented in a form to allow evaluation of the effect of alloy modification, and they are not based on the latest available neutron cross-section data.

This paper presents a self-consistent set of calculations of the neutronic response of a number of elements and alloys to a projected fusion reactor first wall neutron spectrum.

CALCULATION MODEL

The materials chosen for analysis include several alloys that are of potential use as structural materials in fusion reactors, namely type 316 stainless steel (taken to be of atomic composition Fe-19.4% Cr-12.4% Ni-1.4% Mo), Nimonic PE-16 (taken as Ni-35.3% Fe-18.1% Cr-2.0% Mo), V-20% Ti, aluminum, niobium, and molybdenum. Also included are the elemental constituents of these alloys and other elements that are either common impurities or common alloy constituents.

All calculations have been performed for a single neutron spectrum. The spectrum used is the first wall spectrum calculated by Santoro et al.² for the stainless steel - lithium - graphite blanket shown schematically in one dimension in Fig. 1. The major difference between this blanket and most blankets previously analyzed is in the depth of the lithium zone; viz. 25 cm lithium zone in this blanket compared to 51 cm of lithium in the UWMAK-I design.³ The blanket indicated in Fig. 1 gives a calculated

Fig. 1. Schematic One-Dimensional View of the Blanket and Shield Region of the Fusion Reactor Used for Analysis (From Reference 2).

tritium breeding ratio of 1.15,² probably adequate for a fusion power reactor. The neutron spectrum in 20-group format is given in Table 1.

Table 1. Neutron Energy Spectrum at the First Wall of the Fusion Reactor Shown in Fig. 1. This 20-group spectrum has been collapsed from the 100-group spectrum used in calculations.^a

Energy Group Number	Lower Energy of Group (MeV)	Fraction of Neutrons in Group	Fraction of Neutrons with Energy Above Group Lower Bound
1	14.92	0	0
2	13.50	0.1893	0.1893
3	10.00	0.0280	0.2173
4	6.07	0.0368	0.2541
5	3.01	0.0396	0.2937
6	2.02	0.0365	0.3302
7	1.50	0.0344	0.3646
8	1.00	0.0521	0.4167
9	.672	0.0592	0.4759
10	.451	0.0629	0.5388
11	.247	0.0619	0.6007
12	.150	0.0542	0.6549
13	.111	0.0439	0.6988
14	.0865	0.0310	0.7298
15	.0525	0.0539	0.7837
16	.0318	0.0413	0.8250
17	.0117	0.0671	0.8921
18	.00123	0.0832	0.9753
19	.0001	0.0231	0.9984
20	10 ⁻¹⁰	0.0016	1.0000

^aThe full 100-group spectrum is available from the authors.

This spectrum has been collapsed from the full 100-group spectrum used in the calculations. The slight changes in the neutron spectrum that would result from the replacement of stainless steel by other structural materials have not been taken into account.

The methods used to calculate the irradiation response of elements of interest have been described in detail elsewhere.⁴ All elastic, inelastic, charged particle, and capture reactions which are considered in ENDF/B-IV have been included in this analysis. Nuclear data are taken from the ENDF/B-IV file, and displacement damage calculations follow the recommendations of the IAEA working group.⁵ For elements other than iron, effective displacement energies recommended by Doran and Graves⁶ were used.

RESULTS OF CALCULATIONS

The calculated data are given in Tables 2, 3, and 4. In Table 2 the dpa and gas-production rates are given for a neutron wall loading of

Table 2. DPA and Gas-Production Rates in Typical Candidate Alloys at the First Wall of a Fusion Reactor^a

Alloy	Effective Displacement Threshold Energy (eV)	Displacement Damage (dpa/sec)	Helium (appm/sec)	Hydrogen (appm/sec)
		$\times 10^{-7}$	$\times 10^{-7}$	$\times 10^{-7}$
316 SS	40	3.64	45.6	169.
PE-16	40	3.72	76.1	248.
Al	25	4.63	101.	94.5
V - 20 Ti	40	3.65	18.7	72.5
Nb	60	2.31	9.18	33.3
Mo	60	2.38	[15.] ^b	[30.] ^b

^aNeutron wall loading = 1 MW/m².

^bThere is no ENDF/B-IV data on gas production in molybdenum. These numbers are taken from Kulcinski, Doran, and Abdou, Reference (1), and are based on calculated cross-sections and on a slightly different first-wall neutron spectrum.

1 MW/m². The accumulated damage responses for the alloys are given in Table 3 for a "lifetime" loading of 40 MW-yr/m². In addition, gas-production and dpa calculations have been performed for some pure elements. These results, given in Table 4, can be used to synthesize gas production in most alloys being considered for fusion reactor application. The effective displacement thresholds are also given. The dpa results for other thresholds can be obtained by multiplying by the ratio of the threshold value in Table 4 to the required threshold value.

Table 3. Total dpa and Gas Production in Typical Candidate First Wall Alloys for a Fusion Reactor Operation of 40 MW year/m²

Alloy	Effective Displacement Threshold Energy (eV)	Displacement Damage (dpa)	Helium (appm)	Hydrogen (appm)
316 SS	40	460	5750	21,300
PE-16	40	470	9590	31,200
Al	25	580	12,700	11,900
V-20 Ti	40	460	2360	9,140
Nb	60	290	1160	4200
Mo	60	300	(1890) ^a	(3780) ^a

^aThere is no ENDF/B-IV data on gas production in molybdenum. These numbers are taken from Kulcinski, Doran, and Abdou, Reference (1), and are based on calculated cross-sections and on a slightly different first-wall neutron spectrum.

Table 4. DPA and Gas-Production Rates in the Elemental Constituents of Candidate Alloys in a Fusion Reactor First Wall Neutron Spectrum^a

Element	Effective Displacement Threshold Energy (eV)	Displacement Damage (dpa/sec)	Helium (appm/sec)	Hydrogen (appm/sec)
		$\times 10^{-7}$	$\times 10^{-7}$	$\times 10^{-7}$
Fe	40	3.62	34.9	151.
Ni	40	3.87	130.	397.
Cr	40	3.58	32.6	100.
Mn	40	3.58	26.7	100.
V	40	3.63	15.0	78.2
Nb	60	2.31	9.18	33.3
Mo	60	2.38	b	b
Ti	30	5.03	33.5	49.7
Zr	50	2.54	2.93	25.2
Al	25	4.63	101.	94.5
Mg	40	2.80	147.	148.
Cu	30	4.88	31.8	173.
Co	40	3.60	23.1	73.7
C		c	604.	b
N		c	205.	144.
O		c	118.	41.0
Si	25	4.61	159.	298.
¹⁰ B		c	8980.	28.7
¹¹ B		c	23.6	12.5
⁶ Li		c	3081.	3071.
⁷ Li		c	360.	367.

^aNeutron wall loading = 1 MW/m².

^bNo ENDF/B-IV data on gas production.

^cCalculational model used for dpa does not apply to light elements.

DISCUSSION

With the current interest in fusion reactor designs based on the "conventional" alloys of the Fe-Cr-Ni system, it is important to have an understanding of the difference in irradiation response between the many candidate alloys in this system. Tables 2 and 3 show that there is a significant difference in the gas production rates in type 316 stainless steel and Nimonic alloy PE-16, although displacement rates are nearly identical. Table 4 shows that the differences in gas production rates between these two alloys are almost entirely caused by the differences in nickel content. This conclusion also applies to the other stainless steels, superalloys, and other conventional alloys that could be chosen from the Fe-Cr-Ni system. Changes in iron or chromium content or in any of the many minor alloying additives will have little influence on the gas production rate; that rate will be dominated⁷ by the nickel content. The helium production rate throughout the entire class of Fe-Cr-Ni alloys will range from the value for pure iron to the value for pure nickel. That is, the range of helium production in these alloys will be 110 to 410 appm per MW-yr/m² of fusion reactor operation.

It has been shown earlier⁴ that improvements in nuclear data in ENDF/B-IV compared to the earlier ENDF/B-III resulted in some changes in the calculated fusion reactor irradiation response. In the cases examined, the most important change was a decrease in the calculated helium production rate in type 316 stainless steel, reflecting a decrease in the (n, α) cross section for iron.

The calculations in this paper were based on the first-wall neutron spectrum of a Tokamak designed to provide adequate tritium breeding without

excessive tritium inventory. These boundary conditions give a narrower lithium zone and a softer neutron spectrum than in several earlier studies. The major effect on the materials response is again a decrease in the helium production rate in stainless steel.* Other changes produced by the spectrum change are much less important. This series of changes in the helium production rate in type 316 stainless steel is shown in Table 5. Hydrogen production rates from the same studies show both the small change in nuclear data for hydrogen production reactions and the relative insensitivity of hydrogen production to small changes in the first wall neutron spectrum.

A range of composition is always allowed in the specification of an alloy. The data in Table 4 have been used to evaluate the effect of such variation on the rate of helium production in a type 316 stainless steel first wall. Two specifications were used, the "standard" AISI specification for 316 and the more restrictive AEC-RDT specification. The results of this sensitivity analysis are shown in Table 6, where compositions within specifications were adjusted first to minimize and then to maximize the helium production. Average helium production for the AISI specification range was 47.4×10^{-7} appm/sec, with extremes for the composition range $\pm 9.0\%$ of the average. Within the more closely controlled AEC-RDT specification, the average production rate was higher, 49.3×10^{-7} appm/sec, with the rate extremes for the composition range only $\pm 2.4\%$ of the average.

*Slight differences in the composition assumed for 316 stainless steel in the three cases treated in Table 5 have probably also affected the calculated helium production rates.

Table 5. Gas Production in Type 316 Stainless Steel for Several Calculational Cases.

Nuclear Data Base	Neutron Spectrum	Reference	Helium Production Rate ^a	Hydrogen Production Rate ^a
			appm/sec	appm/sec
			($\times 10^{-7}$)	($\times 10^{-7}$)
ENDF/B-III	UWMAK-I	(1)	64	170
ENDF/B-IV	Early EPR	(4)	56	179
ENDF/B-IV	EPR, 25 cm Li	(b)	45.6	169

^aDifferences in the assumed composition of type 316 stainless steel could account for part of the calculated differences in the gas production rates.

^bThis work. Blanket design from Reference (2).

SUMMARY

This paper provides a set of self-consistent calculations of the irradiation response of candidate structural alloys to the neutron spectrum at the first-wall of a fusion reactor. Results are also included for the elements that are constituents of the common alloy systems. These results can be used to synthesize the response of alloys of interest that have not been included explicitly, and thus make possible the comparison of any set of alloys on a consistent basis.

Comparison of results for stainless steel with previous calculations show that dpa and hydrogen production rates are relatively insensitive to differences in nuclear data between ENDF/B-III and ENDF/B-IV and to slight neutron spectrum changes between different Tokamak designs. Helium production in alloys based on the Fe-Cr-Ni system are sensitive to these changes and to changes in composition within the specification range for

Table 6. Variation in Helium Production Rate in Type 316 Stainless Steel for Compositional Variations Within Specification Range.

Element	VARIATION WITHIN AISI SPECIFICATION				VARIATION WITHIN RDT M3-28T SPECIFICATION			
	Adjusted for Minimum He Production		Adjusted for Maximum He Production		Adjusted for Minimum He Production		Adjusted for Maximum He Production	
	Composition (at.%)	He Production Rate (appm/sec)	Composition (at.%)	He Production Rate (appm/sec)	Composition (at.%)	He Production Rate (appm/sec)	Composition (at.%)	He Production Rate (appm/sec)
		$\times 10^{-7}$		$\times 10^{-7}$		$\times 10^{-7}$		$\times 10^{-7}$
Cr	17.4	5.67	19.6	6.39	18.5	6.03	19.6	6.39
Ni	9.63	12.52	13.5	17.55	12.5	16.25	13.5	17.55
C	0	0	0.38	2.28	0.19	1.14	0.29	1.74
Mo	1.77	0.27	1.18	0.18	1.77	0.27	1.18	0.18
Mn	2.06	0.55	0	0	2.06	0.55	1.54	0.41
N	0	0	0	0	0	0	0.04	0.08
Si	0	0	2.01	3.20	1.00	1.59	1.51	2.40
Fe	69.14	24.13	63.33	22.10	63.98	22.33	62.34	21.76
Total He Production Rate for this composition		43.14		51.7		48.16		50.51

the given alloy. Coupled with the well-established effect of helium on the engineering properties of metals, this mandates careful attention to reactor design changes that change the neutron spectrum. The dominant effect of nickel content on the helium production also requires that the exact alloy composition (or at least the specific nickel content) be treated, rather than assuming similar behavior for all alloys of a single class.

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