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Transmutation behaviour of Eurofer under irradiation in the IFMIF test facility and fusion power reactors

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Abstract

The transmutation behaviour of the low activation steel Eurofer was analysed for irradiation simulations in the high flux test module (HFTM) of the International Fusion Material Irradiation Facility (IFMIF) neutron source and the first wall of a typical fusion power reactor (FPR) employing helium cooled lithium lead (HCLL) and pebble bed (HCPB) blankets. The transmutation calculations were conducted with the analytical and laplacian adaptive radioactivity analysis (ALARA) code and IEAF-2001 data for the IFMIF and the EASY-2003 system for the fusion power reactor (FPR) irradiations. The analyses showed that the transmutation of the main constituents of Eurofer, including iron and chromium, is not significant. Minor constituents such as Ti, V and Mn increase by 5–15% per irradiation year in the FPR and by 10–35% in the IFMIF HFTM. Other minor constituents such as B, Ta, and W show a different transmutation behaviour resulting in different elemental compositions of the Eurofer steel after high fluence irradiations in IFMIF and fusion power reactors.

1. Introduction

The International Fusion Material Irradiation Facility (IFMIF) [1] will provide an accelerator based D–Li neutron source for high fluence test irradiations of fusion reactor candidate materials. Deuterons will be accelerated up to 40 MeV energy resulting in a neutron source spectrum which extends up to ≈55 MeV neutron energy with ≈20% of neutrons above 15 MeV. As a consequence, the IFMIF neutron spectrum will significantly differ from a typical D–T fusion reactor spectrum. By means of calculations it has been shown, however, that IFMIF can meet its design goal as suitable neutron source for fusion-specific simulation irradiations with regard to the displacement damage and gas production in steel [2–4].

Due to the lack of suitable computational tools and data no effort has been spent so far on the assessment of the transmutation behaviour of materials irradiated in the IFMIF neutron spectrum. This, however, may significantly affect the material properties in a different way than in D–T fusion reactors. The recently developed intermediate energy activation file IEAF-2001 [5,6] enables for the first time to perform activation and transmutation calculations for the IFMIF neutron source with the analytical and laplacian adaptive radioactivity analysis (ALARA) activation code [7,8].

In this work, the transmutation behaviour of the low activation steel Eurofer [9] is investigated using neutron flux spectra calculated for the IFMIF high flux test module (HFTM) and the first wall (FW) of a typical fusion power reactor (FPR) employing two types of breeder blankets, the helium cooled pebble bed (HCPB) and the helium cooled lithium lead (HCLL) blanket.

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2. Computational tools and nuclear data for transmutation analyses

The European activation system (EASY-2003), comprising the inventory code FISPACT-2003 [10] and the European activation file EAF-2003 [11], is available for activation and transmutation analyses of fusion energy systems up to 20 MeV neutron energy. It is applied in this work for calculating the transmutation of Eurofer under irradiation in the FPR spectra.

A suitable data library for activation and transmutation calculations of the IFMIF neutron source, the intermediate energy activation file IEAF-2001, has been recently developed by a collaboration of Forschungszentrum Karlsruhe and the Institute of Nuclear Power Engineering, Obninsk [5,6]. The IEAF-2001 data library comprises cross sections up to 150 MeV for target nuclides from hydrogen ($Z = 1$) to polonium ($Z = 84$). IEAF-2001 data can be used with the activation code ALARA, developed at the University of Wisconsin-Madison [7,8]. Application tests demonstrated the suitability of the IEAF-2001 data for IFMIF activation calculations with ALARA [12]. Detailed IEAF-2001 validation analyses conducted recently showed in general satisfactory results with the need to update some specific cross sections [13,14]. It was also shown that ALARA/IEAF-2001 and FISPACT/EAF-2001 activation calculations agree in the energy domain below 20 MeV.

To demonstrate the distinctive features of the IEAF data library, the interaction of fast neutrons with ^{56}Fe is considered. For this case the library contains formation cross sections of 119 product nuclides. The most probable reaction channels lead to the production of iron, manganese and chromium isotopes. Fig. 1 displays the associated production cross sections. The lumped cross section σ(n,Y) denotes the total cross section for the formation of any kind of reaction product that differs from the target nuclide. Below 10 MeV neutron energy ^{56}Fe transmutes to ^{57}Fe by the (n,γ) reaction and above 12 MeV to the unstable ^{55}Fe (which decays to ^{55}Mn) via the (n,2n) reaction. The ^{56}Fe transmutation to manganese starts above 3 MeV neutron energy with the ^{56}Fe(n,p)^{56}Mn reaction. Above 15 MeV the (n,d) and (n,np) reactions create ^{55}Mn. Above 30 MeV, the (n,2np) and (n,nd) reactions yield ^{54}Mn which decays to ^{54}Cr. The next essential transmutation path leads to the formation of chromium starting with the ^{56}Fe(n,α)^{53}Cr reaction at 4 MeV. Above 18 MeV ^{56}Fe is transmuted into ^{52}Cr by the (n,nα) reaction and above 40–50 MeV to ^{50}Cr and ^{51}Cr by the (n,2nα) and (n,3nα) reactions, respectively. Note that many of these reactions produce simultaneously the gaseous transmutation products hydrogen and helium.

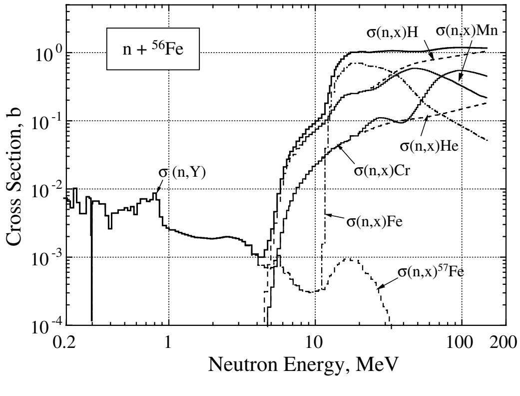

Fig. 1. Total production (n,Y) and transmutation cross sections for ^{56}Fe as available in the IEAF-2001 library.

3. Comparative study of Eurofer steel transmutation in IFMIF and FPR

The reduced activation ferritic–martensitic steel Eurofer is the EU candidate structural material for future fusion power reactors [9,15]. For its qualification, high fluence irradiations will be conducted in the high flux test module (HFTM) of the IFMIF neutron source. Such irradiations should simulate as much as possible the irradiation behaviour of Eurofer in the first wall (FW) structure of typical FPR blankets. The transmutation behaviour of the Eurofer steel, therefore, was investigated for the IFMIF HFTM and two typical variants of a FPR blanket, the helium cooled pebble bed (HCPB) and the helium cooled lithium lead (HCLL) blanket.

The basing neutron flux spectra were provided by means of 3D Monte Carlo calculations using the M^{C}DeLicious code for the IFMIF HFTM [3] and the MCNP code for the FPR models that were developed as part of the European power plant conceptual study (PPCS) [16]. The IFMIF neutron flux spectrum has been averaged over the HFTM volume while the FPR neutron flux spectra were calculated for the FW of the central outboard blanket module which is subjected to the highest neutron wall loading.

Fig. 2 compares the IFMIF HFTM and the FPR neutron flux spectra. It is noted that the HCPB-FPR neutron spectrum shows a comparatively high population of the low-energy region due to the use of the beryllium neutron multiplier in the blanket. The HCLL-FPR neutron spectrum shows a larger fast neutron component due to the absence of any moderating material. This results in higher gas and dpa production rates for the HCLL-FPR (Table 1) since the associated nuclear cross-sections increase with the neutron energy. Table 1 also lists the gas-to-dpa ratio which is another important parameter for the irradiated materials

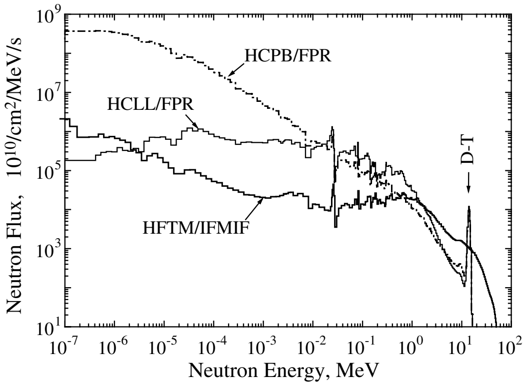

Fig. 2. Comparison of neutron spectra in the HFTM of IFMIF and the first wall of fusion power reactors with HCLL and HCPB blankets.

Table 1
Neutron irradiation parameters and radiation induced effects in Eurofer steel in the centre of the HFTM of IFMIF and the first wall of fusion power reactors with HCLL and HCPB blankets

Facility	IFMIF	FW/FPR	
	HFTM	HCLL	HCPB
Wall loading, MW/m^2	8.1	2.41	2.41
n-flux, 10^{14}/cm^2/s	7.3	15.3	10.6
dpa, 1/fpy	30.0	29.7	20.6
H-production, appm/fpy	1390	1051	951
Ratio H/dpa	46	35	46
He-production, appm/fpy	297	249	230
Ratio He/dpa	10	8	11

behaviour characterization: it is seen that IFMIF will very closely reproduce the gas-to-dpa ratio typical for FPR with HCPB blanket.

3.1. Transmutation of initial elemental composition

The transmutation rates of Eurofer are compared in Fig. 3 in terms of relative changes of the atom numbers for an irradiation of one full power year in IFMIF and the fusion power reactors. Numerical data of the element transmutation rates are given in Table 2 along with the initial Eurofer composition. It is noted that the transmutation of the main constituents of Eurofer, including iron and chromium, is not significant (below 1%). The inventory of other elements such as Ti, V and Mn, however, increases by 5–15% per irradiation year in the FPR/FW and by 10–35% in the IFMIF/HFTM. These elements are minor constituents of Eurofer and are also produced during irradiation by (n,p) and (n,α) reactions on Cr and Fe. The large fraction of high-energy neutrons in the IFMIF spectrum and the high threshold for charge particle production cross sections leads to the higher transmutation rates of these elements in comparison with the FPR spectra. Other elements such as B and Ta show a net generation in the IFMIF/

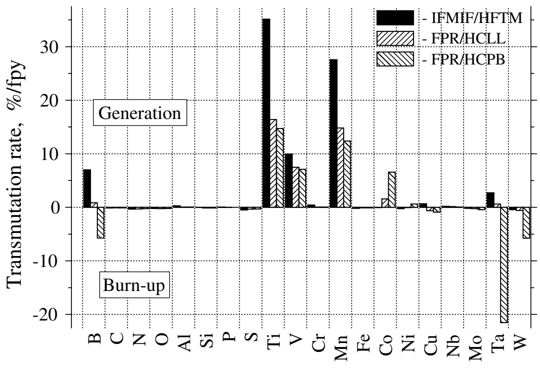

Fig. 3. Transmutation rates of Eurofer constituents under irradiation in the IFMIF high flux test module and the first wall of fusion power reactors with HCLL and HCPB blankets.

Table 2
Elemental composition (appm) of Eurofer steel and transmutation rates (appm/fpy) for the irradiation in the HFTM of IFMIF and the first wall of fusion power reactors with HCLL and HCPB blankets

Element	Content (appm)	HFTM (appm/fpy)	HCLL (appm/fpy)	HCPB (appm/fpy)
H	–	1408	+1051	+951
He	–	+299	+249	+230
Li	–	+0.3	+0.9	+5.3
Be	–	+2.3	+2.3	+2.2
B	*51*	*+3.6*	*+0.5*	*−2.9*
C	*4860*	*−7.2*	*−4.6*	*−4.4*
N	*1191*	*−4.4*	*−3.5*	*−2.9*
O	*347*	*−0.20*	*−0.8*	*−0.7*
Mg	–	+1.6	+1.4	+1.2
Al	*206*	*+0.54*	*+0.2*	*+0.1*
Si	*990*	*−2.3*	*−1.2*	*−1.1*
P	*90*	*−0.01*	*−0.01*	*−0.02*
S	*87*	*−0.42*	*−0.3*	*−0.3*
Ti	*116*	*+32*	*+19*	*+17*
V	*2183*	*+216*	*+164*	*+155*
Cr	*96 240*	*+211*	*+74*	*+55*
Mn	*4048*	*+1111*	*+601*	*+502*
Fe	*885 880*	*−1956*	*−752*	*−738*
Co	*47*	*−0.02*	*−0.02*	*+3.1*
Ni	*47*	*−0.13*	*−0.3*	*+0.3*
Cu	*44*	*+0.02*	*−0.3*	*−0.4*
Nb	*6*	*<0.01*	*<0.01*	*<0.01*
Mo	*29*	*−0.06*	*−0.07*	*−0.1*
Hf	–	+1.5	+1.1	+0.8
Ta	*215*	*+6*	*+1.3*	*−46*
W	*3327*	*−16*	*−19*	*−191*
Re	–	+7.0	+17	+206
Os	–	+0.01	+0.2	+32

The steel alloying elements are italized.

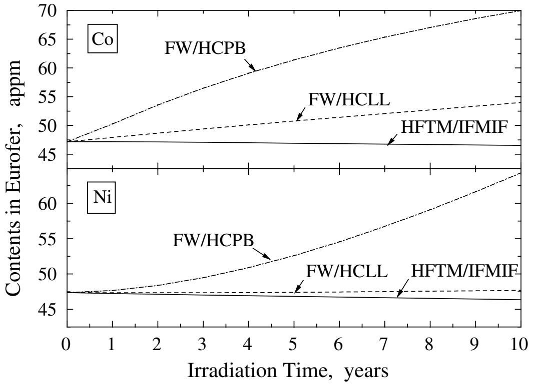

Fig. 4. Co and Ni element inventories in Eurofer steel as function of the irradiation time in HFTM/IFMIF and the first wall of fusion power reactors with HCLL and HCPB blankets.

HFTM irradiation and a net burn-up in the FW/FPR irradiation.

The data given in Table 2 can be used for the assessment of the long-term evolution of the elemental composition during irradiation since most of the elements show a linear dependence on the irradiation time. There are only a few exceptions such as B, Co and Ni. As an example, Fig. 4 shows that the concentration of Co and Ni increases nonlinearly in the case of the HCPB/FPR irradiation. The reaction pathway analysis indicates that the generation of cobalt and nickel atoms in the soft HCPB-FPR spectrum is mainly due to the ^{60}Co and ^{60}Ni isotopes which are generated via the reaction chain ^{59}Co(n,γ)^{60}Co (β^-)^{60}Ni. Since the ^{60}Co half life time is 5.3 years, the formation rate of ^{60}Co during the first irradiation years exceeds its disintegration rate thus resulting in higher formation rates for cobalt than for nickel. At larger irradiation times, the decay of the accumulated ^{60}Co then leads to the production of ^{60}Ni at higher rates.

3.2. Generation of new elements in Eurofer

In addition to the concentration changes of the 20 initial elements constituting the Eurofer steel, new elements will be generated during the intense neutron irradiation in the IFMIF HFTM and the FPR spectra, as shown in Table 2 and Fig. 5. Such new elements are generated in the vicinity of the initial elements by proton and α-particle emitting reactions (lower Z) and by neutron capture reactions followed by β^- decays (higher Z).

In general, the relative atom numbers of newly generated elements are lower by two or more orders of magnitude as compared to the initial element concentrations (see Fig. 5 and Table 2). Hydrogen and helium, however, is generated by the various (n,xp), (n,xd), (n,xt) and (n,x^{3}He), (n,xα) reactions on all nuclei resulting in gas concentrations which are comparable to other Eurofer constituents after one irradiation year. Another exception is the rather high generation of the elements rhenium and osmium. These elements, as shown in Fig. 5, are generated from W via several sequential nuclear reactions and radioactive decays including neutron capture reactions which are sensitive to low-energy neutrons. The soft FPR-HCPB neutron spectrum thus explains the higher generation rate of rhenium and osmium as compared to the HCLL blanket and the IFMIF HFTM (Fig. 5). This effect is also responsible for the higher burn up rate of tantalum and tungsten in the FPR-HCPB irradiation.

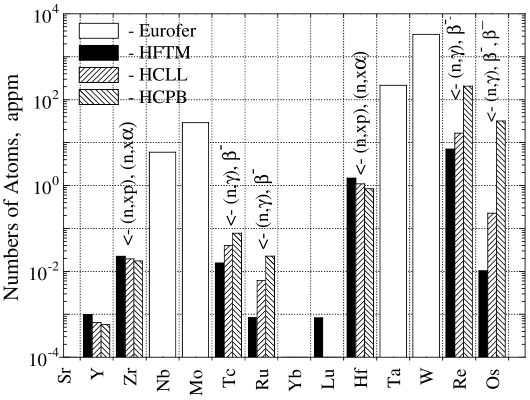

Fig. 5. Heavy element composition of Eurofer before and after a one year irradiation in the HFTM of IFMIF and the first wall of fusion power reactors with HCLL or HCPB blankets.

4. Conclusions

A comparative study has been performed of the transmutation behaviour of the reduced activation ferritic–martensitic steel Eurofer under irradiation in the HFTM of the IFMIF neutron source and the first wall of a typical fusion power reactor FPR employing the HCLL and HCPB blankets. The transmutation calculations for the IFMIF HFTM irradiation have been conducted with the ALARA inventory code and the intermediate energy activation data library IEAF-2001. The transmutation calculations for the fusion power reactor irradiations have been performed with the European activation system EASY-2003.

The analyses showed that the burn-up of the main constituting elements of Eurofer steel including iron and chromium is relatively small for all neutron spectra considered (less than 1% per full power year). The inventory of minor constituting elements such as Ti, V and Mn, however, increases by 5–15% per full power year in the FW/FPR and by 10–35% in the IFMIF/HFTM irradiation. Elements such as B and Ta show a net generation in the IFMIF/HFTM irradiation and a net burn-up in the FW/FPR irradiation. In particular this applies for the soft neutron spectrum of the FPR-HCPB which also leads to high burn-up rates of the Ta and the W Eurofer constituents due to the involved neutron capture reactions.

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