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Neutron and deuteron activation calculations for IFMIF

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Abstract

The materials for future fusion devices such as DEMO require testing to high neutron fluence. Such testing is planned to be carried out in IFMIF, an accelerator based facility where the neutrons will have maximum energy of about 55 MeV, but with a broad peak near 14 MeV. In order that activation calculations for IFMIF can be carried out, the nuclear data must contain cross sections covering a similar energy range. A description of the EASY-2005 system is given and it is noted that a new library has been added to EASY to cover another significant source of activation from deuteron-induced reactions. Calculations of the neutron activation of materials in many regions of IFMIF have been carried out. These calculations are reported, and the contribution of neutrons above 20 MeV to the activation is discussed. Preliminary calculations using the deuteron library have been made and the activation from deuterons is discussed.

1. Introduction

The materials for future fusion devices such as DEMO require testing to high fluence so as to accumulate significant amounts of damage. Such testing is planned to be carried out in IFMIF [1], a proposed facility where beams of accelerated deuterons impinge on a flowing lithium target producing neutrons. These neutrons will have a maximum energy of about 55 MeV, with a broad peak near 14 MeV, and in order that activation calculations can be carried out, the nuclear data libraries must contain cross sections covering a similar energy range. Conventional activation code packages such as the European Activation System (EASY), designed for the activation of fusion devices, contain data up to only 20 MeV. To overcome this limitation EASY has recently been extended so that the current version EASY-2005 can be used with a neutron spectrum extending to 55 MeV.

EASY is the complete package of data and codes developed as part of the European Fusion Technology Programme to enable detailed and accurate neutron activation calculations to be carried out for fusion applications. The most recent version to be released, EASY-2005 [2] is available. There are many parts of EASY: the developer tool SAFEPAQ-II [3] that is used in the production of all the European Activation File (EAF) libraries, the FISPACT inventory code [4] and the EAF-2005 libraries [5,6]. A total of 62637 neutron-induced reactions have cross section data, while decay data is included for 2192 nuclides.

The potential importance of deuteron interactions with materials in IFMIF has led to work on a deuteron-induced library, and an initial version

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Table 1
Summary of materials, contribution of neutrons above 20 MeV, some dominant nuclides and their pathways (contribution of the pathway) for neutron activation calculations in IFMIF

Material	Cell	Neutrons with energy >20 MeV (%)	Dominant nuclides	Pathways
Eurofer	4499	3.051	Cr-51	Cr-52(n, 2n)Cr-51 (62.9%) Cr-50(n, γ)Cr-51 (26.1%)
			Mn-54	Fe-54(n, p)Mn-54 (65.7%) Fe-56(n, t)Mn-54 (28.6%)
			Fe-55	Fe-56(n, 2n)Fe-55 (92.3%)
			H-3	Fe-56(n, X)H-3 (50.3%) + $\cdots$
			Nb-91	Nb-93(n, 3n)Nb-91 (44.8%) Mo-92(n, d)Nb-91 (26.6%)
			C-14	N-14(n, p)C-14 (99.8%)
Tungsten	5200	4.120	Re-188	W-186(n, γ)W-187(β^-)Re-187(n, γ)Re-188 (95.0%)
			W-187	W-186(n, γ)W-187 (97.9%)
			Ta-183	W-182(n, 2n)W-181(β^+)Ta-181(n, γ)Ta-182(n, γ) Ta-183 (45.2%)
			Re-183	W-184(n, γ)W-185(β^-)Re-185(n, 3n)Re-183 (37.6%)
Lithium	2001	7.539	H-3	Li-7(n, nα)H-3 (46.5%) + $\cdots$
Carbon	5008	2.533	C-11	C-12(n, 2n)C-11 (99.7%)
			Be-7	C-12(n, 2nα)Be-7 (100.0%)
			H-3	C-12(n, d2α)H-3 (37.4%)
			C-14	C-13(n, γ)C-14 (99.7%)
Concrete	8002	0.025	Ar-37	Ca-40(n, α)Ar-37 (100.0%)
			H-3	O-16(n, X)H-3 (24.6%) + $\cdots$
			Ca-41	Ca-40(n, γ)Ca-41 (100.0%)

will be release at the beginning of 2006 as part of the maintenance release EASY-2005.1. The novel nature of the d-induced library means that it is appropriate to give some details here. The library is based entirely on model calculations carried out using the TALYS [7] code with global parameters. The same target and daughter nuclides as for the neutron-induced library were used resulting in a library with 60688 reactions. At this stage very few modifications to the basic data have been carried out, and these are mostly restricted to splitting reactions where necessary into ground (g) and isomeric (m) components (the total is split equally between g and m, where data exist this could be improved in a future version), and to correcting *Q* values and interpolation laws. This library is very preliminary, but can be used to give some useful indicative results, although considerable effort will be required in the next few years if the quality is to approach that of the neutron-induced library.

2. Calculations for IFMIF

Using EASY-2005 and the preliminary deuteron-induced library, activation calculations have been carried out for IFMIF.

2.1. Neutron activation

An MCNP model of the IFMIF test cell and the concrete shielding was used to calculate neutron spectra in 2061 regions. The materials in these regions were Eurofer (a reduced activation ferritic steel[1]), lithium, heavy concrete, carbon and tungsten. For each region activation calculations were made based on the anticipated irradiation history of IFMIF. Further discussion of the amounts of waste is given in the paper by Loughlin and Forrest [8].

It is interesting to consider here the contribution that the neutrons above 20 MeV make in the various materials. The full calculations were made using neutrons in 211 groups. If neutrons above 20 MeV are ignored then the resulting spectrum has 175 groups. Table 1 shows the contribution of neutrons above 20 MeV for the specified cells containing a single material (details of the cells are given in Ref. [8]). The 175 group calculations were made using the same irradiation history but with the

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[1] Eurofer composition: Fe 88.9%, Cr 9.0%, W 1.10%, Mn 0.40%, V 0.20%, C 0.11% plus 25 other elements.

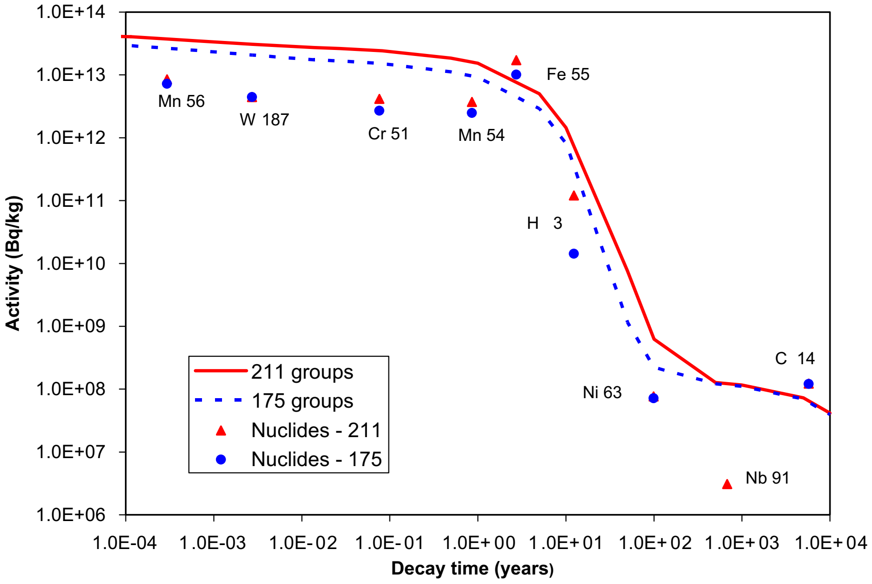

Fig. 1. Activity decay curve for Eurofer following irradiation in the IFMIF vertical test assembly. Symbols show dominant nuclides plotted at nuclide half-life and activity at shutdown.

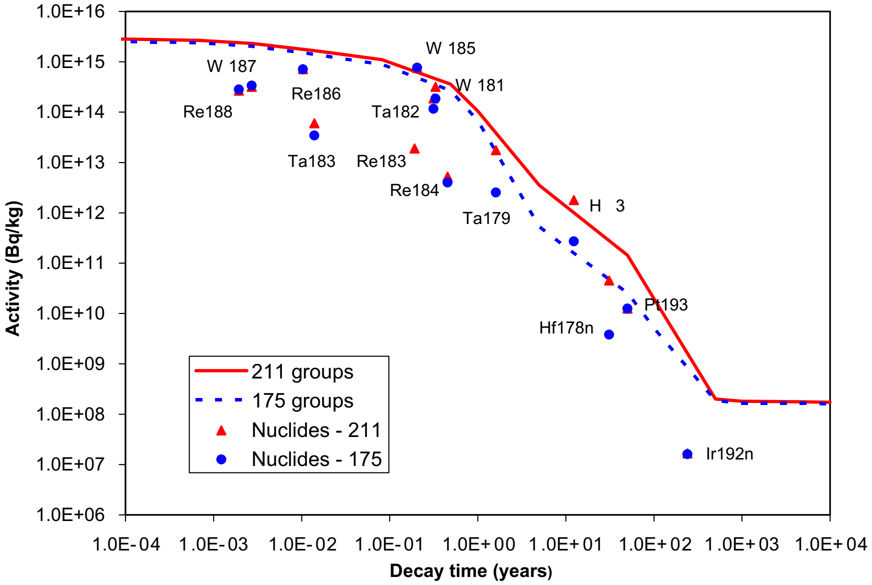

Fig. 2. Activity decay curve for tungsten following irradiation in the IFMIF spectral shifter. Symbols show dominant nuclides plotted at nuclide half-life and activity at shutdown.

fluxes scaled by a factor determined by column 3 of Table 1. Some dominant nuclides and the pathways responsible for their formation are also shown. Figs. 1–3 show activity as a function of decay time for Eurofer, tungsten and carbon following an irradiation time of 33 years. Most of the dominant nuclides are the same whether the high energy neutrons are present or not, and in Eurofer and tungsten the two decay curves follow similar trends with decay time. However, in carbon the dominant nuclides ^{11}C and ^{7}Be are formed only by the high-energy neutrons and thus the two decay curves are more distinct. As shown in Table 1, ^{11}C is formed by the reaction C-12(n, 2n)C-11 while ^{7}Be is formed by the reaction C-12(n, 2nα)Be-7, the thresholds for these reactions are 20.29 and 28.47 MeV, respec-

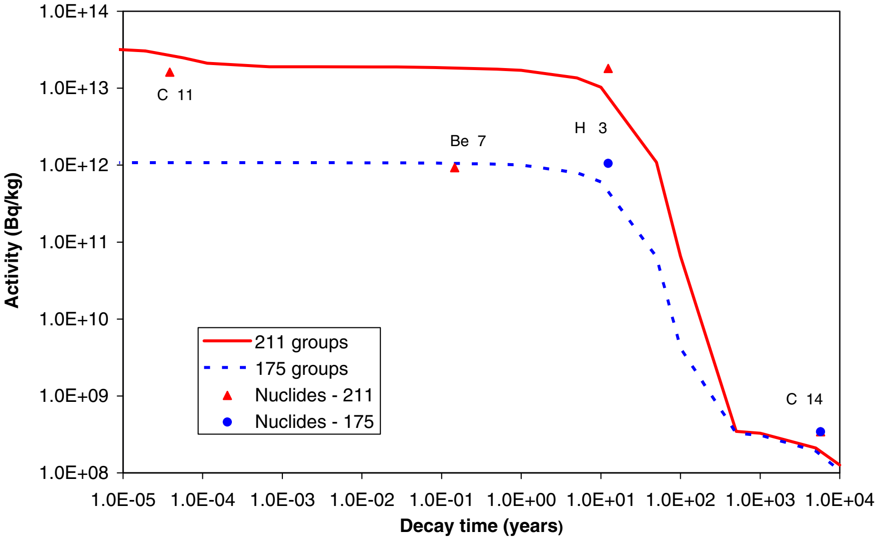

Fig. 3. Activity decay curve for carbon following irradiation in the IFMIF medium flux region. Symbols show dominant nuclides plotted at nuclide half-life and activity at shutdown.

tively, explaining why they do not contribute in the 175 group case.

The broad conclusions that can be drawn about the impact of the neutrons above 20 MeV is that generally the activation properties are dominated by interactions with neutrons below 20 MeV. The same set of dominant nuclides are typically responsible (^{91}Nb in Eurofer and ^{183}Re in tungsten are further examples of dominant nuclides only formed by high-energy neutrons) indicating that while additional nuclides can be formed by high threshold reactions they are typically rather unimportant. Exceptions will be found for low mass materials (such as carbon) where the number of dominant nuclides is small. Typically the same reactions are responsible for the dominant nuclides; an example of a significant difference is the production of ^{54}Mn in Eurofer. Table 1 shows the pathways when high energy neutrons are present, in the 175 group calculation the Fe-56(n, t)Mn-54 reaction does not contribute.

2.2. Deuteron activation

A very important consideration for designing IFMIF is to understand the importance of activation of the corrosion products in the lithium loop that is the target for the deuteron beams. It is estimated that a wide range of elements will be present in the lithium loop due to corrosion of the SS316 steel making up the loop. Two activation effects are of importance: the neutron field produced by the interaction of the deuterons on lithium will cause activation of the corrosion products and impurities in the lithium. This effect has already been estimated [9] using existing neutron libraries. The second effect is due to direct interactions of the deuterons with the impurities in the lithium. Results obtained using the EAF-2005.1 deuteron-induced library are reported here. The composition

Table 2
Elemental composition of the lithium and impurities in the IFMIF lithium loop

Element	Composition (wt%)
H	2.0000E−03
Li	9.9985E+01
C	1.0000E−03
N	1.0000E−03
O	1.0000E−03
Al	5.0000E−07
Si	1.0000E−04
Ti	5.0000E−07
Cr	1.7000E−03
Mn	2.0000E−04
Fe	6.5038E−03
Co	9.0000E−06
Ni	1.2000E−03
Cu	2.0000E−05
Nb	1.0000E−06
Mo	2.5000E−04
Ag	4.0000E−06
Sn	1.0000E−07
Sb	1.0000E−07
Ta	5.0000E−06

of the impure lithium is shown in Table 2. The deuterons will slow down from the initial energy of 40 MeV and stop in a distance of about 1.9 cm. The distance travelled for each 1 MeV loss is known from the stopping power, and a series of forty spectra, in 211 groups with the average energy for each 1 MeV loss were created. It was further assumed that the flux varied linearly from the value at the surface of the lithium to 90% of that value at a distance of 1.9 cm. Forty FISPACT runs were carried out using an initial integrated deuteron flux of 4.3348×10^{11} cm^{-2} s^{-1} for a period of 5 y followed by 10 pulses (90 s off, 2.5×10^{-3} s with flux of 1.5604×10^{16}). This is estimated based on the volume of irradiated lithium ($0.2 \times 0.05 \times 0.025$ m^3), the total lithium volume (9 m^3), a beam current of 250 mA and a lithium flow rate through the target of 20 ms^{-1}. The total activity and activity excluding tritium for each of the forty cases were used to form the weighted average using the distance travelled.

The activity of the lithium following a decay time of 1 min–1 y is almost constant with a value of $\sim 2.2 \times 10^{11}$ Bq kg^{-1}. The dominant nuclides are shown in Table 3, while the pathways responsible for their production are shown in Table 4. The tritium is formed by reactions on the lithium; if this is excluded then the majority of the activity is due to reactions on Fe, Cr, Ni and C and amounts to $\sim 2.0 \times 10^{8}$ Bq kg^{-1}. Allowing for the deuteron slowing down gives activities which are about 80% of the values assuming that the activity is only due to 40 MeV deuterons. The neutron calculations in [9] were repeated using EAF-2005 and it was found that the contribution from deuteron activation of the corrosion products is about 70 times larger than from neutron activation. Ensuring that the filtering for Fe, Cr, Ni and C is efficient may be necessary to prevent a large build up of activity in the lithium loop and consequent occupational radiation exposure potential.

Table 3
Summary of dominant nuclides for activity in the IFMIF lithium following irradiation by deuterons at various times after shutdown

Nuclide	Time after shutdown				
	0	10 s	10 m	1 d	1 y
Li-8	99.009	5.52			
H-3	0.988	94.158	99.697	99.752	99.893
Fe-55	0.001	0.089	0.094	0.094	0.077
Cr-51		0.040	0.043	0.042	
Mn-54		0.037	0.039	0.039	0.018
C-11		0.021	0.016		
Co-57		0.019	0.021	0.020	0.009
Co-56		0.018	0.020	0.019	0.001
Mn-52		0.013	0.014	0.012	
O-15		0.015			

Table 4
Pathways for the dominant nuclides in the impure IFMIF lithium following deuteron irradiation

Nuclide	Pathways	Contribution (%)
Li-8	Li-7(d, p)Li-8	100.0
H-3	Li-7(d, dα)H-3	92.6
	Li-6(d, pα)H-3	7.4
Fe-55	Fe-56(d, t)Fe-55	90.6
	Fe-56(d, 3n)Co-55(β^+)Fe-55	5.1
Cr-51	Cr-52(d, t)Cr-51	73.1
	Fe-56(d, tα)Cr-51	10.8
Mn-54	Fe-56(d, α)Mn-54	89.7
	Mn-55(d, t)Mn-54	7.5
C-11	C-12(d, t)C-11	97.1
	O-16(d, tα)C-11	2.6
Co-57	Ni-58(d, h)Co-57	77.9
	Ni-58(d, t)Ni-57(β^+)Co-57	15.1
Co-56	Fe-56(d, 2n)Co-56	63.5
	Ni-58(d, α)Co-56	31.6
Mn-52	Fe-56(d, 2nα)Mn-52	59.3
	Cr-52(d, 2n)Mn-52	18.6
	Fe-54(d, α)Mn-52	15.3
O-15	O-16(d, t)O-15	100.0

3. Conclusions

Activation calculations for IFMIF are important for determining the detailed design. In order to use the tools produced for the European Fusion Technology Programme (EASY), both the energy range and the projectile in the library needed to be extended. EASY-2005 extends the neutron energy to 60 MeV (group libraries extend to 55 MeV), while the planned maintenance release (EASY-2005.1) in early 2006 will contain a preliminary deuteron-induced library. Using these new tools, calculations of the activation of IFMIF have been carried out to enable categorisation of the waste. Examples of activation are discussed to show the effects of neutrons above 20 MeV. Deuteron activation of the impurity elements in the lithium loop has been calculated and the most important elements identified; deuteron activation is about 70 times more important than that caused by neutrons.

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