ELSEVIER

Journal of Nuclear Materials 258–263 (1998) 1700–1707

journal of nuclear materials

Long-lived activity of elements: Effect of new activation cross-sections and their uncertainties on the selection of materials for IFE reactors

J. Sanz [a,*], C. González [b], J. Juan [b]

[a] *Instituto de Fusión Nuclear (UPM), Ciudad Universitaria s/n, 28040 Madrid, Spain*
[b] *Laboratorio de Estadística, ETSII (UPM), Ciudad Universitaria s/n, 28040 Madrid, Spain*

Abstract

Activation calculations considering the neutron environment of the first structural wall (FSW) of the inertial fusion energy (IFE) reactor HYLIFE-II are performed for each of the natural elements from H to Bi. Results are used to rank the elements under waste management considerations. The concentration limits (CL's) corresponding to hands-on recycling, remote recycling and shallow land burial (SLB) are computed by using the recently upgraded IAEA activation data library FENDL/A-2.0. Concentration limits are also computed using earlier activation libraries, such as EAF-3.1 and EAF-4.1, to assess the impact of using FENDL on activation studies for fusion. In addition, the accuracy of activation predictions based on FENDL is assessed by computing the uncertainties on the production of the nuclides dominating the long-lived activity of several important elements.

1. Introduction

In magnetic fusion energy (MFE) numerous efforts [1–4] have addressed the activation of all chemical elements under safety and waste management considerations to define low activation (LA) material specifications for structural components. In IFE, most of the activation studies have been related to specific materials in the frame of particular reactor concepts [5–7], and most of the IFE-intended LA materials were taken from MFE proposals. However, some studies were also performed to compare and quantify the LA acceptability of the different elements. The long-term activation behavior of the natural elements with atomic number $Z=1$ to $Z=83$ and some candidate structural materials was quantified in [8], and the comparison with results from MFE environments was made in [9]. The assessment of the short-term activation acceptability of some elements and materials was addressed in [10], and differences with respect to a MFE environment were highlighted.

The prediction of all those works has shown to be greatly influenced by the decay and activation cross-section data available at the time of calculations. Recently, significant progresses have been achieved in activation cross-section data development, emphasizing those related to the generation of long-lived radionuclides [11]. As a result of these efforts new improved databases, such as EAF-4.1 [12] and FENDL/A-2.0 [13] have been produced. In spite of the significant advances, there is still a significant lack of experimental data, and uncertainties of several cross-sections remain high. The effect of these uncertainties in the activation calculations is an issue that is drawing more and more attention. Cross-section uncertainty files have been made available such as EAF UN-4.1 [12] and FENDL UN/A-2.0 [14], and some calculational procedures [15] have been developed to compute uncertainties on activation calculations.

Here, we analyze the long-lived activity of natural elements under the neutron environment of the HYLIFE-II [16] vessel structure. First, we assess how conclusions of earlier works, particularly those [5–9,17]

* Corresponding author. Permanent address: ETSII (UNED), Ciudad Universitaria s/n, 28040 Madrid, Spain

0022-3115/98/$19.00
PII: S0022-3115(98)00155-X

dealing with the activation of the liquid protected FSW of IFE reactors, are changed when using the new activation libraries. Secondly, using the newest activation library, FENDL/A-2.0, we perform a detailed study, setting the limits on concentration of elements under waste management requirements. Finally, uncertainty of results for some important elements is obtained.

2. Neutron environment and calculational methods

The neutron environment for this paper is taken [17] from the midplane region of the HYLIFE-II reactor vessel. The flux intensity is 1.29×10^{15} cm^{-2} s^{-1}, assuming a continuous irradiation of 30 yr (corresponding to the desirable FSW lifetime) and a 75% capacity factor. The average neutron energy is 0.38 MeV.

The radionuclide inventory, contact γ-dose rate, and waste disposal ratings (WDR) are calculated using ACAB [18], the activation cross-section data library FENDL/A-2.0 and the decay data library FENDL/D-2.0 [19]. Also the cross-section libraries EAF-4.1 and the former version EAF-3.1 [20] are used for comparison purposes.

In defining CL's for recycling, two criteria are considered [1,3]: hands-on recycling is acceptable when the contact dose rate does not exceed 25 μSv/h at 100 yr cooling, and remote recycling when the dose rate is kept below 10 mSv/h within 50 yr cooling. Serious doubts about the feasibility of the attainment of the hands-on limit within an acceptable cooling time (mainly because of impurities) lead to the proposal [1] of the much less restrictive criterion of 10 mSv/h, level at which radioactive steel scrap could be remelted and converted into feedstock using remote handling techniques. Concerning hands-on recycling a limit of 10 μSv/h is now under consideration and could possibly be used in future works. The CL's on each of the elements are calculated by assuming the element to be placed in a non-active matrix of iron.

In ranking the acceptability of elements for SLB we have adopted the US class C waste criteria (regulatory guide 10CFR61) using as specific activity limits (SAL's in Ci/m^3) those calculated by Fetter et al. [2]. The waste disposal rating (WDR) is defined as the sum of the ratios between the specific activity of all radionuclides and the corresponding SAL's, and the acceptance rule for SLB is $\mathrm{WDR} \leqslant 1$. The concentration limit for SLB, i.e., that for which $\mathrm{WDR} = 1$, is computed here in wt fraction by assuming the element to be present in a non-active matrix of a material with density that of iron (7.87 g cm^{-3}). Limits (in wt fraction) on elements placed in a matrix of different density, D_{ma}, can be obtained by multiplying the limits computed in this paper by the factor $7.87/D_{\mathrm{ma}}$. The SLB-concentration limits are calculated for shutdown after 30 yr operation.

The uncertainty analysis is performed using the method detailed in [15]. The goal is to analyze how cross-section uncertainty is transmitted to $X_i, i = 1, \ldots, n$, the nuclide composition of the irradiated material at time t (fixed). The amount of nuclide i can be considered as a function of $(\sigma_1, \sigma_2, \ldots, \sigma_m)$, the activation cross-sections (or a chosen subset) involved in the problem, that is, $X_i = X_i(\sigma_1, \sigma_2, \ldots, \sigma_m)$. The rest of the parameters affecting X_i (decay constants, time,...) is considered fixed and they will not be included for simplicity of notation. Let $\sigma_0 = (\sigma_{10}, \sigma_{20}, \ldots, \sigma_{m0})$ be the estimated cross-sections, that is, the usual values used when uncertainties are not considered, and $\mu_i = X_i(\sigma_{10}, \sigma_{20}, \ldots, \sigma_{m0})$. The first order Taylor series provides an approximation of X_i

$$X_i \approx \mu_i + \sum_{j=1}^{m} \left[\frac{\partial X_i}{\partial \sigma_j}\right]_{\sigma_0} (\sigma_j - \sigma_{j0}), \tag{1}$$

which can be written as

$$\frac{X_i - \mu_i}{\mu_i} \approx \sum_{j=1}^{m} \rho_{ij} \frac{(\sigma_j - \sigma_{j_0})}{\sigma_{j0}},$$

where $\rho_{ij} = (\sigma_{j0}/\mu_i)[\partial X_i/\partial \sigma_j]_{\sigma_0}$, is known as the sensitivity coefficient for the production of nuclide i due to uncertainty in cross-section j. This quantity is used in conjuction with the cross-section uncertainties to perform the uncertainty analysis of Section 5.

The cross-section uncertainties are taken from FENDL UN/A-2.0. The uncertainty data of the library are adopted considering that [12] $\log(\sigma_j/\sigma_{j0})$ approximately follows the normal distribution with mean 0 and variance Δ_j^2. The value σ_{j0} is that given in the cross-section file, and Δ_j^2 is given in the uncertainty file.

Uncertainties are provided in one-energy group for threshold reactions and in a three-energy group structure for (n,γ) reactions. Assuming that errors in cross-sections included in an energy group are 100% correlated, and that the errors in the different energy groups are uncorrelated, then the variance corresponding to the spectrum-averaged or "effective" cross-section of a reaction can be obtained as a linear combination of the variance given for each energy group [15]. This quantity is the variance, Δ^2, used in Section 5 (Table 3).

3. Comparison between results based on different cross-section data libraries

Concentration limits for SLB and recycling have been computed for all the elements using FENDL/A-2.0, EAF-4.1 and EAF-3.1, and the values of those elements limited for any of the waste management criteria have been compared [21]. The results based on EAF-3.1 are a good indication of the state-of-art on activation studies before 1996, since it was one of the most complete data

library before the appearing of the new ones EAF-4.1 and FENDL-2. The EAF-4.1 library is the basic one for FENDL/A-2.0, and there are differences between both for cross-sections of about 235 reactions out of 13 006. Here, the comparison for SLB concentration limits is shown in Table 1. Elements are listed in decreasing order of absolute Relative Differences (the definition of the RD index is given in Table 1) between EAF-3.1 and FENDL/A-2.0, and all those with a $|RD| > 0.6$ are provided. The last three elements in the table (with $|RD| < 0.6$) are provided for comments when comparing EAF-4.1 and FENDL/A-2.0.

When comparing EAF-3.1 versus FENDL/A-2.0 we find that most of the elements present negative RD. These differences are very significant for a great number of elements, and so their radiological impact is very conservatively assessed if EAF-3.1 is used. This explains that in earlier works, proposed LA elements such as Ta, or W, were assessed as undesirable even as minor constituent elements in IFE environments; and impurities such as Ag were considered very critical.

Only a few elements present positive relative differences. These differences for SLB concentration limits, except for Co (RD = 0.65), are never higher than 0.3. For recycling, the highest RD is around 0.9 for Rh, Se, Ni and Zn.

When comparing EAF-4.1 with FENDL/A-2.0, we find that for most of the elements the differences are negligible. When existing, the relative differences are in most cases negative. The most important occur for O and N (not limited with FENDL). These elements, when comparing SLB concentration limits, exhibit an RD = −0.9. For Ir the difference is also significant (RD = −0.6). For recycling the highest difference appears for Ir, with an RD around −0.6. For positive RD, and SLB-CL's, the highest differences are for Al (RD = 0.65) and Co (RD = 0.38), for remote recycling there is only one significant difference, Zn (RD = 1.3), and for hands-on recycling there are two, Tl (RD = 0.95) and Al (RD = 0.65).

4. Induced long-term activity in elements

Table 2 gives the concentration limits for SLB, as well as hands-on and remote recycling. Elements are listed in order of increasing CL for hands-on recycling. The dominant radionuclides with a contribution (in brackets) higher than 5% to the radiological quantity associated to each CL criteria are also listed.

It can be seen that elements such as C, Si, V, Ti, Cr, which are major constituents of some proposed LA

Table 1
Comparison of SLB-concentration limits (in wt fraction) obtained from EAF-3.1, EAF-4.1, and FENDL/A-2.0

ELEMENT	EAF-3.1		EAF-4.1		FENDL/A-2.0
	CL	RD [a]	CL	RD [a]	CL
Ta	5.55×10^{-5}	−0.991	5.16×10^{-3}	−0.148	6.06×10^{-3}
W	3.02×10^{-5}	−0.990	2.58×10^{-3}	−0.187	3.18×10^{-3}
Re	2.33×10^{-5}	−0.990	1.87×10^{-3}	−0.218	2.39×10^{-3}
Os	5.70×10^{-5}	−0.988	3.14×10^{-3}	−0.358	4.90×10^{-3}
Rh	1.44×10^{-2}	0.971	5.14×10^{-3}	−0.296	7.30×10^{-3}
Hf	2.65×10^{-4}	−0.970	8.66×10^{-3}	−0.022	8.86×10^{-3}
Pt	6.00×10^{-1}	−0.957	7.61	−0.450	1.38×10
Ir	3.14×10^{-2}	−0.940	2.00×10^{-1}	−0.619	5.24×10^{-1}
Cd	8.04×10^{-4}	−0.933	1.15×10^{-2}	−0.041	1.20×10^{-2}
Lu	1.13×10^{-3}	−0.908	1.24×10^{-2}	0.006	1.23×10^{-2}
Ag	8.58×10^{-5}	−0.885	6.65×10^{-4}	−0.107	7.44×10^{-4}
Yb	1.96×10^{-2}	−0.774	8.75×10^{-2}	0.008	8.68×10^{-2}
Co	1.61×10^{-1}	0.649	1.35×10^{-1}	0.379	9.78×10^{-2}
Tb	1.84×10^{-6}	−0.619	4.82×10^{-6}	0.000	4.82×10^{-6}
Dy	2.95×10^{-6}	−0.619	7.73×10^{-6}	0.000	7.73×10^{-6}
Eu	2.73×10^{-6}	−0.618	7.11×10^{-6}	−0.004	7.14×10^{-6}
Gd	2.08×10^{-6}	−0.617	5.42×10^{-6}	−0.002	5.42×10^{-6}
Er	1.03×10^{-3}	−0.615	2.68×10^{-3}	0.001	2.68×10^{-3}
Sm	5.53×10^{-6}	−0.614	1.42×10^{-5}	−0.007	1.43×10^{-5}
Nd	1.80×10^{-4}	−0.605	4.47×10^{-4}	−0.019	4.56×10^{-4}
Ho	1.37×10^{-3}	−0.601	3.31×10^{-3}	−0.037	3.44×10^{-3}
O	2.22	−0.319	4.37×10^{-1}	−0.866	3.26
Ne	1.32	0.280	1.05×10^{-1}	−0.898	1.03
Al	2.10×10^{-2}	0.114	3.11×10^{-2}	0.648	1.89×10^{-2}

[a] RD: Relative difference $= \frac{\text{Results for a particular activation library} - \text{Results for a reference library}}{\text{Reference library results}}$, where, Reference library: FENDL/A-2.0.

structural materials (SiC/SiC composites, V-alloys) exhibit an excellent performance. Other elements used as minor constituents in those materials, such as Y or Tl present also a very low long-term radiological impact.

Among the metallurgically valuable elements that are very limited for SLB requirements, it is worth mentioning Mo and Nb. Consequently, the austenitic steels (such as PCA, manganese based SS316) containing these elements cannot be considered for SLB. For W, the SLB concentration limit is much higher (0.3%), but comparing with the content required for Cr–W based steels, such as the martensitics HT-9, and the intended LA modified HT-9, it can be concluded that those steels are not likely to be suitable for SLB.

One of the steel specifications that seems to be promising for SLB is that of SS304, as it can be seen when comparing its composition [5] with CL's of Table 1. However more careful study is required.

For recycling, some of the important metallurgical elements significantly limited are Ni and specially Fe. This seriously questions the possibility of considering steels for recycling under the IFE neutron environment considered.

The limits for potential impurity elements are very restricted. The hands-on criterium set the lowest limits on impurity levels: there are seven elements with CL in the region between 0.01 and 1 ppm, and five in that between 1 and 10 ppm. For SLB, Nb exhibits the lowest limit (below 1 ppm) and there are four elements with CL in the region of 1–10 ppm. Remote recycling is the waste management option requiring the lowest degree of purity for materials. The lower limit is 3 ppm for Co, and there are three elements with CL between 10 and 100 ppm.

It is worth pointing out that although the critical radionuclides for waste management concerns are long-lived, their production in several elements (such as Ag, Cd, Tb, Dy) reaches its peak before the 30 yr irradiation time (supposed life time of the HYLIFE-II reactor) [21].

5. Uncertainties in the SLB performance

The effect of uncertainties in FENDL cross-section data on the assessment of the SLB performance of some elements is summarized in Table 3. The elements included are of interest in activation studies as worrisome potential impurities (Nb, Ag, Cd, Eu, Gd, Tb, Dy, Bi), as "proposed" LA alloying elements (W, Ta), and as troublesome constituents in some conventional steels (Mo, Nb). For each of them, the WDR-dominant nuclides and the reactions with the cross-sections introducing the largest uncertainties in their production are shown. In addition to the index $\rho\Delta$ (which for small Δ values, less than 0.3, is the standard deviation for the normal distribution describing the relative change in the amount of a nuclide) used earlier [15], a new one, the 95-confidence concentration limit (CL95), is also used to rank cross-sections inducing higher uncertainties in the WDR calculations.

The CL95 is defined as the concentration for which the WDR is $\leqslant 1$ with a probability of 0.95. For each of the reaction cross-sections σ_j of Table 3, the corresponding $CL95_j$ is given in the last column. In the derivation [15] of $CL95_j$, the points to consider are the following: (i) the WDR is a linear function of the inventory, (ii) the inventory is assumed to follow the linear approach of Eq. (1), and (iii) for the random variable σ_j, it is assumed that $\log(\sigma_j/\sigma_{j0})$ is $N(0, \Delta_j^2)$. The expression for $CL95_j$ is

$$\mathrm{CLP5}_j = \frac{\mathrm{CL}}{F_j},$$

where

$$F_j = 1 + P_j(\mathrm{e}^{aj} - 1), \qquad P_j = \sum_{i=1}^{q} b_i \rho_{ij}$$

and b_i is the fractional contribution of the radionuclide i to the WDR (the sum is over all dominant nuclides) and $a_j = -1.64\Delta_j$ if $P_j < 0$; $a_j = 1.64\Delta_j$ if $P_j > 0$

For each of the elements analysed in Table 3, there is a single radionuclide contributing to the WDR (see Table 2), therefore only one term is taken in the calculation of P_j.

In Table 3, it can be seen that uncertainties in some of the cross-sections of interest are important. For each element, the cross-section σ_j inducing the higher WDR uncertainty leads to the lower $CL95_j$, and the relative error of CL with respect to this lower $CL95_j$, $\mathrm{RE} = (CL95_j - CL)|CL$, is for Nb, 0.346; Mo, 0.088; Ag, 0.410; Cd, 0.433; Eu, 0.535; Gd, 0.533; Tb, 0.519; Dy, 0.530; Ta, 0.604; W, 0.560, and Bi, 0.645. These results suggest that some cross-sections need further improvement. However, if the new values of the cross-sections fall within the current 95% confidence intervals, they are not expected to have a very important impact.

If comparison is made with earlier work on WDR-uncertainties [15,22] for some constituents of steels, then there are huge differences for some elements (W, Ta, Bi). This is due to the overconservative cross-section uncertainties of EAF 4.1, that were used in those calculations.

6. Conclusions

Large differences are observed between some results obtained using new data libraries, EAF-4.1, FENDL/A-2.0, and a former one, EAF-3.1, that can be considered as one of the most complete up to 1996. In general EAF-4.1 and FENDL/A-2.0 provide similar results, but for a few elements, significant differences are found.

Table 2
Limits on element concentrations (in wt fraction), and contribution of dominant radionuclides

Element	Dominant nuclides			Concentration limits		
		Recycling			Recycling	
	SLB	Remote	Hands-on	SLB	Remote	Hands-on
Nb	NB 94 (100.)	NB 94 (100.)	NB 94 (100.)	6.93×10^{-7}	1.91×10^{-5}	4.78×10^{-8}
Tb	H0166M (100.)	H0166M (100.)	H0166M (100.)	4.82×10^{-6}	1.43×10^{-4}	3.67×10^{-7}
Gd	H0166M (99.)	H0166M (96.)	H0166M (96.)	5.42×10^{-6}	1.55×10^{-4}	4.00×10^{-7}
Eu	H0166M (99.)	TB158 (12.) H0166M (88.)	TB158 (10.) H0166M (90.)	7.14×10^{-6}	1.90×10^{-4}	4.97×10^{-7}
Dy	H0166M (100.)	H0166M (100.)	H0166M (100.)	7.73×10^{-6}	2.29×10^{-4}	5.89×10^{-7}
Sm	H0166M (97.)	EU154 (91.) H0166M (6.)	EU154 (19.) TB158 (13.) H0166M (66.)	1.43×10^{-5}	2.50×10^{-5}	7.46×10^{-7}
Cs	CS137 (100.)	BA133 (16.) BA137M (84.)	BA137M (98.)	1.15×10^{-1}	9.89×10^{-5}	9.05×10^{-7}
Xe	CS137 (100.)	BA137M (99.)	BA137M (100.)	1.48×10^{-1}	1.49×10^{-4}	1.19×10^{-6}
Bi	BI208 (100.)	BI207 (100.)	BI207 (100.)	1.09×10^{-4}	1.80×10^{-4}	1.34×10^{-6}
Ag	AG108M (100.)	AG108M (99.)	AG108M (100.)	7.44×10^{-4}	1.56×10^{-3}	4.27×10^{-6}
Nd	TB158 (7.)H0166M (93.)	EU154 (99.)	EU154(76.) TB158(7.) H0166M(14.)	4.56×10^{-4}	4.79×10^{-5}	5.18×10^{-6}
Co	FE 60 (77.)CO 60 (21.)	CO 60 (100.)	CO 60 (100.)	9.78×10^{-2}	3.28×10^{-6}	5.84×10^{-6}
Pd	AG108M (100.)	AG108M (99.)	AG108M (100.)	2.93×10^{-3}	6.14×10^{-3}	1.68×10^{-5}
Kr	KR 81 (100.)	KR 85 (100.)	KR 85 (100.)	5.76×10^{-2}	6.07×10^{-4}	3.83×10^{-5}
Rh	AG108M (97.)	AG108M (99.)	AG108M (100.)	7.30×10^{-3}	1.58×10^{-2}	4.33×10^{-5}
Br	KR 81 (99.)	KR 85 (100.)	KR 81 (10.) KR 85 (90.)	2.23×10^{-3}	1.06×10^{-3}	6.05×10^{-5}
Cd	AG108M (100.)	AG108M (91.) CD113M (9.)	AG108M (99.)	1.20×10^{-2}	2.31×10^{-2}	6.82×10^{-5}
Ba	–	BA133 (77.) BA137M (23.)	BA133 (29.) BA137M (71.)	NL	4.64×10^{-3}	1.14×10^{-4}
Re	IR192s (100.)	IR192 (100.)	IR192 (100.)	2.39×10^{-3}	4.04×10^{-2}	1.17×10^{-4}
Mo	TC 99 (99.)	NB 91 (24.) NB 94 (75.)	NB 91 (24.) NB 94 (76.)	1.14×10^{-5}	5.75×10^{-2}	1.46×10^{-4}
W	IR192s (100.)	IR192 (100.)	IR192 (100.)	3.18×10^{-3}	5.38×10^{-2}	1.55×10^{-4}
Ru	TC 98 (10.)TC 99 (89.)	TC 98 (24.) AG108M (74.)	TC 98 (26.) AG108M (74.)	4.81×10^{-5}	7.22×10^{-2}	1.96×10^{-4}
Er	H0166M (100.)	H0166M (100.)	H0166M (100.)	2.68×10^{-3}	7.93×10^{-2}	2.04×10^{-4}
Os	IR192s (100.)	IR192 (97.)	IR192 (100.)	4.90×10^{-3}	8.06×10^{-2}	2.39×10^{-4}
Ho	H0166M (100.)	H0166M (100.)	H0166M (100.)	3.44×10^{-3}	1.02×10^{-1}	2.62×10^{-4}
Ta	IR192s (100.)	IR192 (100.)	IR192 (100.)	6.06×10^{-3}	1.03×10^{-1}	2.96×10^{-4}
Ni	NI 59 (54.) NI 63 (44.)	CO 60 (100.)	CO 60 (100.)	3.40×10^{-1}	2.76×10^{-4}	4.91×10^{-4}
Hf	HF182 (72.) IR192s (27.)	TA182 (55.) IR192 (40.)	TA182 (58.) IR192 (37.)	8.86×10^{-3}	2.18×10^{-1}	5.75×10^{-4}
Lu	HF182 (93.) IR192s (7.)	HF182 (7.) TA182 (81.) IR192 (12.)	HF182 (7.) TA182 (82.)IR192(11.)	1.23×10^{-2}	3.45×10^{-1}	8.77×10^{-4}
Al	AL 26 (100.)	AL 26 (100.)	AL 26 (100.)	1.89×10^{-2}	7.84×10^{-1}	1.96×10^{-3}
Se	SE 79 (100.)	KR 85 (100.)	KR 85 (100.)	1.57×10^{-3}	4.50×10^{-2}	2.84×10^{-3}
I	I129 (100.)	BA133 (25.) BA137M (75.)	BA137M (96.)	3.48×10^{-1}	3.50×10^{-1}	3.55×10^{-3}
Te	I129 (100.)	BA133 (23.) BA137M (77.)	BA137M (96.)	5.55×10^{-2}	3.99×10^{-1}	3.95×10^{-3}
Fe	–	CO 60 (100.)	CO 60 (100.)	NL	2.85×10^{-3}	5.07×10^{-3}
Cu	NI 63 (99.)	CO 60 (100.)	CO 60 (100.)	7.62×10^{-1}	3.19×10^{-3}	5.68×10^{-3}
Yb	HF182 (98.)	–	HF182 (8.) TA182 (89.)	8.68×10^{-2}	NL	6.37×10^{-3}
Rb	–	KR 85 (100.)	KR 85 (100.)	NL	1.02×10^{-1}	6.47×10^{-3}
Sn	SN121M (5.)SN126 (95.)	SN121M (8.) SB125 (89.)	SN121M (65.) SB126 (7.) SB126M(28.)	3.51×10^{-1}	4.31×10^{-1}	1.55×10^{-2}
La	–	–	BA137M (100.)	NL	NL	1.63×10^{-2}

Table 2 (continued)

Element	Dominant nuclides			Concentration limits		
		Recycling			Recycling	
	SLB	Remote	Hands-on	SLB	Remote	Hands-on
Ir	IR192s (100.)	–	IR192 (100.)	5.24×10^{-1}	NL	2.56×10^{-2}
Pb	–	–	BI207 (100.)	NL	NL	3.06×10^{-2}
Zr	TC 99 (100.)	NB 94 (95.)	NB 94 (98.)	8.56×10^{-4}	1.62×10	4.17×10^{-2}
Tm	HF182 (99.)	–	HF182 (8.) TA182 (91.)	6.71×10^{-1}	NL	4.98×10^{-2}
Sc	–	–	K 42 (100.)	NL	NL	6.02×10^{-2}
Pr	–	EU154 (98.)	EU152 (6.) EU154 (94.)	NL	4.66×10^{-1}	6.24×10^{-2}
Ce	–	EU154 (98.)	BA137M(11.) EU152(5.) EU154(84.)	NL	6.12×10^{-1}	7.36×10^{-2}
K	CL 36 (61.)AR 39 (38.)	–	K 40 (91.)K 42 (9.)	8.91×10^{-3}	NL	8.73×10^{-2}
Ca	CL 36(22.) AR39(45.) K 40(18.)CA 41(15.)	–	K 40 (86.)K 42 (14.)	5.02×10^{-1}	NL	1.36×10^{-1}
Sb	–	–	SN121M (99.)	NL	NL	1.54×10^{-1}
Sr	–	–	KR 85 (87.)Y 90 (13.)	NL	NL	1.99×10^{-1}
Mn	–	CO 60 (100.)	CO 60 (100.)	NL	1.83×10^{-1}	3.26×10^{-1}
Pt	–	–	IR192 (100.)	NL	NL	6.81×10^{-1}
Ti	–	–	K 42 (100.)	NL	NL	7.87×10^{-1}
Cl	CL 36 (100.)	–	–	3.54×10^{-4}	NL	NL
N	C 14 (100.)	–	–	1.35×10^{-3}	NL	NL
As	SE 79 (100.)	–	–	3.45×10^{-3}	NL	NL
Ar	AR 39 (95.)	–	–	3.69×10^{-2}	NL	NL
Ge	SE 79 (100.)	–	–	1.20×10^{-1}	NL	NL
Zn	–	CO 60 (100.)	–	NL	7.59×10^{-1}	NL

Elements not restricted for SLB and Recycling criteria: H, He Li, Be, B, C, O, F, Ne, Na, Mg, Si, P, S, Ti, V, Cr, Ga, Y, Yb, Au, Hg.

Table 3
Uncertainty and sensitivity information for cross sections that contribute most to the uncertainty in the WDR of some important elements

	Reactions			$\hat{\sigma}$	Δ	ρ	$\lvert\rho\Delta\rvert$	CL95
Nb → ^{99}NB	^{93}Nb	(n,γ)	^{94m}Nb	0.67254	0.5523	0.3068	0.1694	4.77×10^{-5}
	^{94}Nb	(n,γ)	^{95}Nb	2.46400	0.5782	−0.8621	0.4985	4.53×10^{-5}
Mo → ^{99}Tc	^{97}Mo	(n,γ)	^{98}Mo	1.54020	0.2129	0.2435	0.0518	1.04×10^{-3}
	^{98}Mo	(n,γ)	^{99}Mo	0.60767	0.0570	0.6719	0.0383	1.07×10^{-3}
Ag → ^{108m}Ag	^{107}Ag	(n,γ)	^{108}Ag	4.06370	0.2112	−2.3689	0.5003	4.39×10^{-2}
	^{109}Ag	(n,2n)	^{108m}Ag	0.00659	0.6848	0.2762	0.1891	4.73×10^{-2}
	^{108m}Ag	(n,γ)	^{109}Ag	7.13070	0.7754	−0.6706	0.5200	5.02×10^{-2}
	^{108m}Ag	(n,γ)	^{109m}Ag	6.85180	0.7754	−0.6444	0.4996	5.08×10^{-2}
Cd → ^{108m}Ag	^{107}Ag	(n,γ)	^{108}Ag	4.06370	0.2112	−0.8773	0.1853	9.50×10^{-1}
	^{107}Ag	(n,γ)	^{108m}Ag	0.03777	0.2780	0.8894	0.2472	7.90×10^{-1}
	^{106}Cd	(n,γ)	^{107}Cd	0.76121	0.5469	0.5284	0.2890	6.80×10^{-1}
Eu → ^{166m}Ho	^{164}Dy	(n,γ)	^{165m}Dy	1.41620	0.5000	0.4020	0.2010	4.73×10^{-4}
	^{165}Ho	(n,γ)	^{166}Ho	17.61200	0.4408	−0.8072	0.3558	5.05×10^{-4}
	^{165}Ho	(n,γ)	^{166m}Ho	1.00760	0.4823	0.9562	0.4612	3.32×10^{-4}
Gd → ^{166m}Ho	^{165}Ho	(n,γ)	^{166}Ho	17.61200	0.4408	−0.9039	0.3984	3.70×10^{-4}
	^{165}Ho	(n,γ)	^{166m}Ho	1.00760	0.4823	0.9487	0.4576	2.53×10^{-4}
Tb → ^{166m}Ho	^{165}Ho	(n,γ)	^{166}Ho	17.61200	0.4408	−1.0065	0.4437	3.17×10^{-4}
	^{165}Ho	(n,γ)	^{166m}Ho	1.00760	0.4823	0.8951	0.4317	2.32×10^{-4}
Dy → ^{166m}Ho	^{164}Dy	(n,γ)	^{165m}Dy	1.41620	0.5000	−0.3022	0.1511	6.61×10^{-4}
	^{165}Ho	(n,γ)	^{166}Ho	17.61200	0.4408	−1.0749	0.47398	4.97×10^{-4}
	^{165}Ho	(n,γ)	^{166m}Ho	1.00760	0.4823	0.9361	0.4515	3.63×10^{-4}
Ta → ^{192n}Ir	^{182}W	(n,γ)	^{183}W	5.61300	1.1339	0.2808	0.3184	2.40×10^{-1}
	^{183}W	(n,γ)	^{184}W	11.24000	0.8691	0.2512	0.2183	3.40×10^{-1}
	^{184}W	(n,γ)	^{185}W	1.65310	0.5556	0.7425	0.4125	2.90×10^{-1}
	^{190}Os	(n,γ)	^{191}Os	0.49163	0.8133	0.2216	0.1803	3.70×10^{-1}
	^{192}Ir	(n,n′)	^{192n}Ir	0.03747	0.7810	0.5102	0.3985	2.60×10^{-1}
	^{192n}Ir	(n,γ)	^{193}Ir	43.27500	0.7744	−0.8180	0.6334	3.80×10^{-1}
W → ^{192n}Ir	^{184}W	(n,γ)	^{185}W	1.65310	0.5556	0.3835	0.2131	2.00×10^{-1}
	^{190}Os	(n,γ)	^{191}Os	0.49163	0.8133	0.1503	0.1222	2.20×10^{-1}
	^{191}Ir	(n,γ)	^{192n}Ir	0.00312	0.4821	0.3744	0.1805	2.20×10^{-1}
	^{192}Ir	(n,n′)	^{192n}Ir	0.03747	0.7810	0.4952	0.3867	1.40×10^{-1}
	^{192n}Ir	(n,γ)	^{193}Ir	43.27500	0.7744	−0.8606	0.6664	2.00×10^{-1}
Bi → ^{208}Bi	^{209}Bi	(n,2n)	^{208}Bi	0.02422	0.6848	0.8793	0.6021	3.87×10^{-3}
	^{209}Bi	(n,2n)	^{208m}Bi	0.00302	0.6848	0.1095	0.0750	8.91×10^{-3}
	^{208}Bi	(n,γ)	^{209}Bi	0.42540	1.0083	−0.1816	0.1831	9.53×10^{-3}

Note: $\hat{\sigma}$ is the average cross-section (in barns), Δ is the corresponding standard deviation, ρ is the sensitivity coefficient for the production of a nuclide from the activation of an element after 30 yr of irradiation. CL95 is given in wt %.

FENDL/A-2.0 is used to compute the concentration limits on natural elements for different low activation waste management options. From the results it can be concluded that: (i) C, Si and V exhibit an optimum performance and therefore, SiC/SiC composites and V-alloys are very promising LA options. Impurity control in these materials is particularly important; (ii) steels containing Mo or Nb are clearly rejected, those based on Cr–W (martensitics) are not likely to be suitable, and the type 304 SS seems to be a promising option for SLB. For recycling, the only presence of iron in steels is sufficient to prevent from meeting the corresponding criteria; (iii) the limits on impurities for hands-on recycling and SLB are very stringent. For remote recycling, the permitted levels are less restrictive and can probably be reached with current purification techniques.

Uncertainty analyses have shown that some cross-sections of FENDL/A-2.0 need further improvement for the assessment of the long-lived activity of some elements. However, this improvement is not expected to qualitatively change the ranking of the elements for waste management-LA acceptability, and its impact on activation studies will be much more reduced than the consequences of going from EAF-3.1 to FENDL/A-2.0.

Acknowledgements

This work has been performed under Project DGCIT PB95-0230 of the Ministerio de Educación y Ciencia, Spain, and IAEA Contract 7910/R2/RB.

References

[1] G.J. Butterworth, L. Giancarli, J. Nucl. Mater. 155–157 (1988) 575.
[2] S. Fetter, E.T. Cheng, F.M. Mann, Fusion Eng. Des. 13 (1990) 239.
[3] S.J. Piet et al., Fusion Technol. 19 (1991) 146.
[4] P. Rocco, M. Zucchetti, Fusion Eng. Des. 15 (1992) 235.
[5] J.D. Lee, Fusion Technol. 26 (1994) 74.
[6] J.M. Perlado et al., J. Nucl. Mater. 233–237 (1996) 1523.
[7] H.Y. Khater, L.J. Wittenberg, Fusion Technol. 30 (1996) 1584.
[8] J. Sanz et al., Fusion Technol. 21 (1992) 2009.
[9] J. Sanz et al., J. Nucl. Mater. 191–194 (1992) 1450.
[10] J. Sanz et al., J. Nucl. Mater. 212–215 (1994) 673.
[11] A.B. Pashchenko (Ed.), Activation cross-sections for the generation of long-lived radionuclides of importance in fusion reactor technology, IAEA Report, INDC(NDS)-342, 1996.
[12] J. Kopecky, D. Nierop, The European Activation File EAF-4, Summary Documentation, ECN-C-95-072, December 1995.
[13] A.B. Pashchenko et al., FENDL/A-2.0. Neutron activation cross-section data library for fusion applications (version 1 of March 1996), International Atomic Energy Agency, IAEA-NDS-173, March 1997.
[14] Generated at UKAEA Culham during the processing of FENDL/A-2.0, and made available to us by R.A. Forrest.
[15] J. Sanz, J. Juan, J.F. Latkowski, Fusion Technol. 30 (1996) 1557.
[16] R.W. Moir et al., Fusion Technol. 25 (1994) 5.
[17] J.F. Latkowski, Inertial Fusion Energy: A Clearer View of the Safety and Environmental Perspectives, Ph.D. Dissertation, University of California at Berkeley, May 1996; UCRL-LR-125741, November 1996.
[18] J. Sanz et al., ACAB, Activation Code for Fusion Applications: User's Manual V2.0, UCRL-MA-122002, 1995.
[19] R.A. Forrest, FENDL/D-2.0 and testing of FENDL/A-2.0, Presented at the IAEA Advisory Group Meeting, FENDL-2, Viena, March 1997.
[20] J. Kopecky et al., The European file EAF-3 with neutron activation and trasmutation cross-sections, Netherlands Energy Research Foundation Report ECN-C-92-058, 1992.
[21] J. Sanz, C. González, J. Juan, Long-lived activity of elements: Effect of new activation cross-sections and their uncertainties on the selection of materials for IFE reactors, Instituto de Fusión Nuclear, DENIM-418, September 1997, presented in poster session ICFRM-8.
[22] J. Sanz, C. González, J. Juan, Long-term activation of elements important to IFE materials: Effect of recent cross-sections developments and uncertainty analysis, preliminary results, Presented at the IAEA Advisory Group Meeting, FENDL-2, Vienna, March 1997; DENIM-409, March 1997.