ELSEVIER

Journal of Nuclear Materials 258–263 (1998) 1767–1772

journal of nuclear materials

Section 6.5. Low activation criteria

Concentration limits of natural elements in low activation fusion materials

E.T. Cheng *

TSI Research, Inc., 225 Stevens Avenue, Solana Beach, CA 92075, USA

Abstract

An update on the concentration limits of natural elements in low activation structural alloys was performed using the recently released FENDL/A-2.0 activation cross section and FENDL/D-2.0 decay data libraries.

1. Introduction

Waste management of replaced first wall and blanket materials is one of the important considerations for the development of low activation fusion materials [1]. The issues in handling fusion waste materials include: (1) transportation of discharged components to a permanent storage or recycling site, (2) burial disposal of waste materials, and (3) recycling of decommissioned materials if practical. The transportation stage requires a limiting contact dose rate of 2 mSv/h without a radiation shield. The low level, shallow-land (10CFR61 Class C) waste disposal is a more attractive waste disposal option for fusion. However, the ultimate waste management scenario is the recycling of used materials. For hands-on recycling, the limiting contact dose rate adopted for this study is 25 μSv/h, although a more conservative limit of 10 μSv/h may be more appropriate in future studies. Activation characteristics of the used materials, in general, play the key role in determining the waste management scenario. A detailed study on the waste management aspect of a lithium–vanadium alloy fusion blanket was presented previously [1].

Nuclear data is essential for the assessment of activation characteristics for all natural elements from which the structural alloys and tritium breeding materials are formed. Recently there is an updated activation library, FENDL/A-2.0, developed as part of the Fusion Evaluated Nuclear Data Library (FENDL) under the coordination of the International Atomic Energy Agency [2,3]. It was produced following a very comprehensive selection procedure adopted and executed by an IAEA/NDS Selection Panel [4–6]. FENDL/A-2.0 contains cross sections for 404 important reactions [7]. These cross sections were selected based on the recommendations by the Selection Panel from JENDL-3.2/A, EAF-4.1, ADL-3, IAEA/CRP, and FENDL/A-1.1. The EAF-4.1 library [8], which consists of cross sections for 12,972 reactions, was adopted as the base library. FENDL/A-2.0 was then established by merging the important reaction library and the base library. For the sake of consistent identification of daughter nuclides as in the EAF-4.1 activation library, the EAF-4.1 decay data library was also accepted as the FENDL/D-2.0 decay data library.

In this paper an assessment of concentration limits for natural elements as alloying elements and impurities to qualify as low activation materials is made based on FENDL/A-2.0 and its accompanying decay data library, FENDL/D-2.0.

2. Method of study

The neutron fluxes employed in this study are those from a natural lithium cooled fusion blanket with the vanadium alloy as structure, as described in Ref. [1]. The blanket consists of a 3 mm first wall, a 0.5 m breeding zone (73.7% lithium, 7.1% vanadium alloy, and balance of void), and a 0.5 m reflector/plenum (10% vanadium

* Tel.: +1 619 7933567; fax: +1 619 7930569; e-mail: etcheng@cts.com.

0022-3115/98/$19.00
PII: S0022-3115(98)00134-2

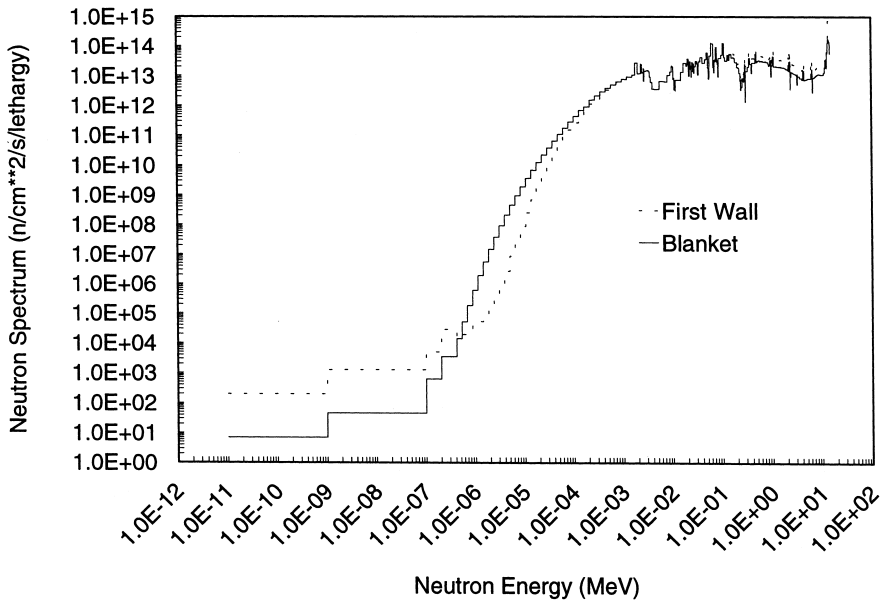

Fig. 1. Neutron spectra at the first wall and blanket of a natural lithium cooled fusion blanket with the vanadium alloy as structure. They are normalized to 1 MW/m^2 neutron wall loading.

alloy, 80% vanadium filler, and 10% lithium). Neutron fluxes were calculated with the ANISN code and FENDL-1 nuclear data library [1]. The neutron spectra at the first wall and breeding blanket are shown in Fig. 1. As assumed in Ref. [1], the irradiation was performed for 4 continuous, full power years at a neutron wall load of 5 MW/m^2. The activation calculation code used, REAC [9], is the same as that employed in the previous study [1]. However, the activation cross section and decay data libraries used in the current study are FENDL/A-2.0 and FENDL/D-2.0.

3. Results and discussion

The results of the activation calculations were analyzed for each element. The concentration limits for the important natural elements are summarized in Tables 1–3. Comparing with the results reported in Ref. [1], the updated results show a factor of 2 or more increase in the allowable concentrations relevant to one aspect or the other of the waste management concerns for the following elements: N, Al, Si, Mn, Ta, W, Cd, Dy, Er, Hf, Ho, Ir, Os, Pd and Pt. This is attributed to the reduction in induced radioactivity due to the updated activation cross sections. The most significant change is with Si, which shows a reduction of almost a factor of 10 in the production of the long-lived radionuclide, Al-26 (half-life 7.2×10^5 y), while all the others show at most a factor of 2 reduction. This has established SiC and its composite as the truly very low activation material. The production of Al-26 in Si is due to a two-step reaction, Si(n,x)Al-27(n,2n)Al-26. Its reduction is primarily because of the low reaction cross sections adopted in the newly updated FENDL/A-2.0 library. Fig. 2 compares the cross sections for the main reaction, Si-28(n,n'p)Al-27, in FENDL/A-2.0 and USACT93, which is the library used for the analysis reported in Ref. [1]. It is noted, however, the cross sections adopted for FENDL/A-2.0, which are taken from ADL-3 evaluation and are consistent with the ENDF/B-VI evaluation, are based on theoretical calculations. Experimental verification of these cross sections is required.

The concentration limits shown in Tables 1–3 may change according to the specified cooling times, irradiation conditions, and half-lives of transmuted radionuclides. In the current assessment, cooling times of 10, 50, and 100 y were adopted, respectively, for the transportation, shallow-land burial disposal, and materials recycling scenarios. These cooling times were selected because they were used in the previous studies and were thought to be reasonable based on the consideration of site operations. However, if further cooling appears to be in favor (e.g., more than a factor of 2 reduction in reasonable additional cooling times) of relaxing the limiting concentration of one or more particular elements, additional cooling times should then be considered. The elements whose concentration limits may increase if the cooling time extends are: (a) transportation scenario only – Ti (due to Sc-46, half-life 83.8 d), Si and Al (Na-22, 2.6 y), and Mn and Fe (Mn-54, 312 d), (b) both transportation and materials recycling scenari-

Table 1
Concentration limits for potential alloying elements to qualify as low activation materials (20 MW-y/m^2 Neutron fluence; Fetter evaluation for class C waste disposal [a])

Element	Transportation-first wall- (10 y; 2 mSv/h)	Waste disposal-blanket- (50 y; fetter evaluation)	Materials recycling-blanket- (100 y; 25 μSv/h)
Vanadium (V)	No limit [No limit] [b]	No limit [No limit]	No limit [No limit]
Chromium (Cr)	No limit [65%, Mn54]	No limit [No limit]	No limit [No limit]
Titanium (Ti)	5.1% (Sc-46) [4.3%, Sc-46]	No limit [No limit]	5.8% (Ar-42) [4.9%,Ar-42]
Silicon (Si)	11% (Na-22)* [1.7%,Na-22]	No limit [No limit]	85% (Al-26)* [9.4%,Al-26]
Calcium (Ca)	No limit [No limit]	36% (K-40) [47%,K-40]	24% (K-40) [25%,K-40]
Nitrogen (N)	No limit [No limit]	3.6% (C-14)* [0.2%,C-14]	No limit [No limit]
Aluminum (Al)	194 ppm (Na-22) [130 ppm,Na-22]	1% (Al-26)* [4.3%,Al-26]	353 ppm (Al-26) [200 ppm,Al-26]
Copper (Cu)	0.2 ppm (Co-60) [0.2ppm,Co-60]	No limit [No limit]	0.1% (Co-60) [830 ppm,Co-60]
Iron (Fe)	160 ppm (Mn-54) [160 ppm,Mn-54]	No limit [No limit]	No limit [No limit]
Manganese (Mn)	9.2 ppm (Mn-54) [8 ppm,Mn-54]	No limit [No limit]	No limit* [670 ppm,Mn-53]
Nickel (Ni)	0.13 ppm (Co-60) [0.1 ppm,Co-60]	69% (Ni-59) [64%,Ni-59]	700 ppm (Co-60)[670 ppm,Co-60]
Zirconium (Zr)	8.6% (Nb-94) [6.7%,Nb-94]	25% (Nb-94) [20%,Nb-94]	1% (Nb-94) [0.8%,Nb-94]
Tantalum (Ta)	0.11% ppm (Hf-178n)* [N/A]	No limit* [N/A]	No limit* [N/A]
Tungsten (W)	0.4% ppm (Hf-178n)* [1.6%,Re186m]	No limit* [13%,Re186m]	No limit* [0.2%,Hf-178n]

[a] See S. Fetter, et al., Fusion Eng. Design 13 (1990) 239.
[b] Information given in the [ ] brackets are those obtained in Ref. [1].
* Indicates significant changes compared to Ref. [1].

Table 2
Concentration limits for critical common impurities to qualify as low activation materials (20 MW-y/m^2 neutron fluence; fetter evaluation for class C waste disposal [a])

Element	Transportation-first wall- (10 y; 2 mSv/h)	Waste disposal-blanket- (50 y; fetter evaluation)	Materials recycling-blanket- (100 y; 25 μSv/h)
Silver (Ag)	0.53 ppm (Ag-108m) [0.3 ppm, \chiAg-108m] [b]	9 ppm (Ag-108m) [4 ppm,Ag-108m]	0.025 ppm (Ag-108m) [0.01 ppm,Ag-108m]
Bismuth (Bi)	0.13 ppm (Bi-207) [0.1 ppm,Bi-207]	25 ppm (Bi-208) [24 ppm,Bi-208]	0.12 ppm (Bi-207) [0.1 ppm,Bi-207]
Niobium (Nb)	9.4 ppm (Nb-94) [8 ppm,Nb-94]	3 ppm (Nb-94) [3 ppm,Nb-94]	0.12 ppm (Nb-94) [0.1 ppm,Nb-94]
Molybdenum (Mo)	380 ppm (Nb-91) [380 ppm,Nb-91]	52 ppm (Tc-99) [42 ppm,Tc-99]	20 ppm (Nb-91) [18 ppm,Nb-94]
Cobalt (Co)	0.02 ppm (Co-60) [0.02 ppm,Co-60]	No limit [No limit]	20 ppm (Co-60) [20 ppm,Co-60]

[a] See S. Fetter, et al., Fusion Eng. Design 13 (1990) 239.
[b] Information given in the [ ] brackets are those obtained in Ref. [1].

os- Cu, Ni, and Co (Co-60, 5.27 y), and Eu, Sm, and Gd (Eu-154, 8.6 y), (c) both waste disposal and materials recycling- Eu (Eu-150, 35.8 y), (d) waste disposal only - Sm (Eu-152, 13.5 y), and (e) materials recycling only-Ti (Ar-42, 32.9 y). To ease the concentration limits for the important alloying elements and common trace elements (impurities), a more reasonable cooling time may be assumed for each waste management stage, such as 30 y for the transportation stage and 200 y for the materials recycling stage.

An assessment of chemistry related to the procurement of vanadium alloys has recently been performed [10]. Ref. [10] lists the concentrations of 17 trace elements in vanadium alloys considered attainable by standard production practice: C (200 appm), N (400), O (600), Al (200), Si (900), P (49), S (16), Cl (0.29), K (0.13), Fe (36), Cu (0.8), As (0.07), Nb (0.55), Mo (2.1), Ta (0.56) and W (0.56). This recent effort has successfully eliminated Nb and Mo as the most offending elements for low activation materials. However, more effort is still needed to address the other trace elements, particularly those shown in Ref. [10] indicating potential concentrations exceeding the limits for shallow-land burial disposal: Ag, Bi, Dy, Er, Ho, Ir, and Tb. Similar assessments may be obtained for structural materials other than the vanadium alloy using the results obtained from this study.

4. Conclusions

Based on the activation analysis (20 MW-y/m2 neutron fluence at the first wall) of a natural lithium cooled

Table 3
Concentration limits for rare but critical impurities to qualify as low activation materials (20 MW-y/m^2 neutron fluence; fetter evaluation for class C waste disposal [a])

Element	Transportation-first wall-(10 y; 2 mSv/h)	Waste disposal-blanket-(50 y; fetter evaluation)	Materials recycling-blanket-(100 y; 25 μSv/h)
Cadmium (Cd)	96 ppm (Ag-108m) [84 ppm,Ag-108m] [b]	0.62% (Ag-108m)* [0.15%,Ag-108m]	19 ppm (Ag-108m)[11 ppm,Ag-108m]
Dysprosium (Dy)	52 ppm (Ho-166m)* [16 ppm,Ho-166m]	64 ppm (Ho-166m)* [0.21%,Ho-166m]	1.7 ppm (Ho-166m)* [0.3 ppm,Ho-166m]
Erbium (Er)	84 ppm (Ho-166m)*[14 ppm,Ho-166m]	82 ppm (Ho-166m)* [14 ppm,Ho-166m]	3.3 ppm (Ho-166m)* [0.6 ppm,Ho-166m]
Europium (Eu)	0.0018 ppm (Eu-154) [0.002 ppm,Eu-154]	0.13% (Eu-150) [750 ppm,Eu-150]	0.0038 ppm (Eu-150) [0.002 ppm,Eu-150]
Gadolinium (Gd)	1.2 ppm (Eu-154) [1 ppm,Eu-154]	140 ppm (Tb-158) [90 ppm,Tb-158]	0.57 ppm (Tb-158) [0.5 ppm,Eu-158]
Hafnium (Hf)	12 ppm (Hf-178n)* [3 ppm,Hf-178n]	No limit* [35%,Hf-178n]	5.7 ppm (Hf-178n)* [0.7 ppm,Hf-178n]
Holmium (Ho)	1.6 ppm (Ho-166m)* [0.2 ppm,Ho-166m]	0.48 ppm (Ho-166m)* [0.08 ppm,Ho-166m]	0.019 ppm (Ho-166m)* [0.003 ppm,Ho-166m]
Iridium (Ir)	2.4 ppm (Ir-192n)* [0.64 ppm,Ir-192n]**	7.5 ppm (Ir-192n)* [0.5 ppm,Ir-192n]	0.13 ppm (Ir-192n)* [0.01 ppm,Ir-192n]
Osmium (Os)	350 ppm (Ir-192n)*[9.8%,Ir194m/Ir-192n]	0.11% (Ir-192n)* [0.4%,Ir-192n]	20 ppm (Ir-192n)* [38 ppm,Ir-192n]***
Palladium (Pd)	2 ppm(Rh-102/Ag-108m)[4 ppm,Rh-102/Ag-108m]	850 ppm (Ag-108m)* [280 ppm,Ag-108m]	2.4 ppm (Ag-108m) [2 ppm,Ag-108m]
Platinum (pt)	0.39% (Ir-192n) [0.32%,Pt193]****	3.5% (Ir-192n)* [560 ppm,Ir-192n]	630 ppm (Ir-192n) [440 ppm,Ir-192n]
Samarium (Sm)	0.062 ppm (Eu-154) [0.06 ppm,Eu-152/Eu-154]	No limit [No limit]	1.2 ppm (Eu-152)[1 ppm,Eu-152]
Terbium (Tb)	0.1 ppm (Tb-158) [0.06 ppm,Tb-158]	1.2 ppm (Tb-158) [1 ppm,Tb-158]	0.0058 ppm (Tb-158) [0.005 ppm,Tb-158]
Thulium (Tm)	588 ppm (Ho-166m) [710 ppm,Ho-166m]	760 ppm (Ho-166m) [890 ppm,Ho-166m]	30 ppm (Ho-166m) [36 ppm,Ho-166m]

[a] See S. Fetter, et al., Fusion Eng. Design 13 (1990) 239.
[b] Information given in the [ ] brackets are those obtained in Ref. [1].
* Indicates significant changes compared to Ref. [1].
** There was an error in Ref. [1] to report this value as 1.6 ppm.
*** There was an error in Ref. [1] to report this value as 3.2%.
**** There was an error in Ref. [1] to report this value as 3.2%.

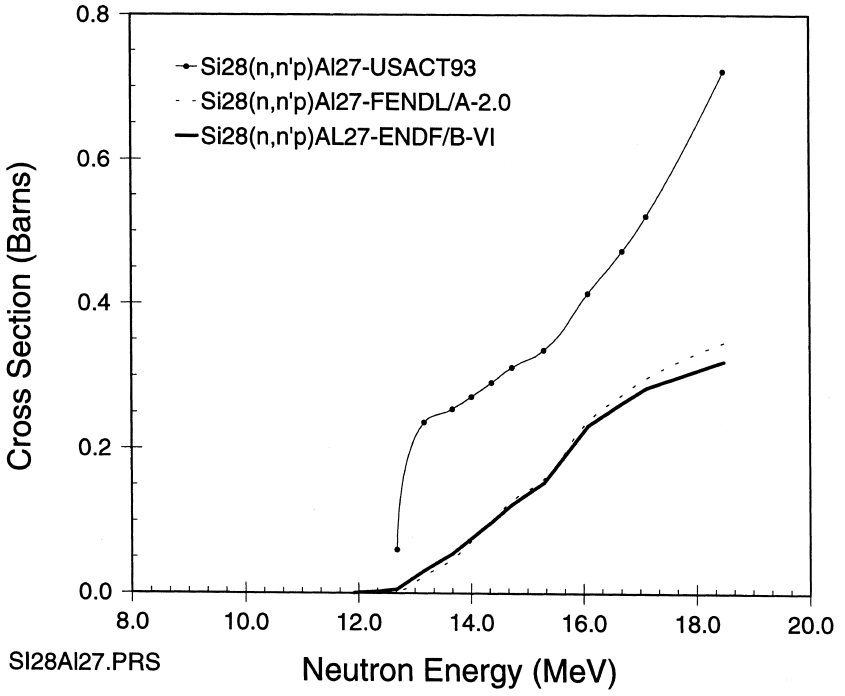

Fig. 2. Comparison of reaction cross sections for Si leading to the production of a stable nuclide Al-27 which can subsequently be transmuted into the long-lived radionuclide, Al-26, by the n,2n reaction.

vanadium fusion blanket using the most up-to-date nuclear data library, the concentration limits of natural elements in the structural alloys have been assessed as follows.

1. Elements considered for shallow-land burial waste disposal after 50 y of cooling: <1 appm – Ho and Tb; <10 appm – Nb, Ir, and Ag; <100 appm – Bi, Mo, Dy, and Er; <1000 appm – Gd, Pd, and Tm; <1 a/o – Al, Os, Eu, and Cd; <10 a/o – N and Pt; <100 a/o – Ca, Ni, and Zr. All other natural elements not listed above are not limited.
2. Elements considered for hands-on materials recycling after 100 y of cooling: <0.01 appm – Eu and Tb; <0.1 appm – Ag and Ho; <1 appm – Bi, Nb, Gd, and Ir; <10 appm – Dy, Er, Pd, Hf, and Sm; <100 appm – Mo, Co, Cd, Os, and Tm; <1000 appm – Al, Cu, Ni, and Pt; <1 a/o – Ta and W; <10 a/o – Ti; <100 a/o – Ca and Si. All other natural elements not listed above have no concentration limits.
3. Elements considered for transportation stage without shielding after 10 y of cooling: <0.01 appm – Eu; <0.1 appm – Co, Ni, Cu, Bi, Sm, and Tb; <1 appm – Ag, Gd, Ho, Ir and Pd; <10 appm – Mn, Nb, and Hf; <100 appm – Al, Fe, Mo, Cd, Dy, Er, Os, and Tm; <1000 appm – Ta, W, and Pt; <10 a/o – Ti, Zr, and Si. All other elements not listed above are not restricted. Although some of the elements may be allowed to increase the concentration limits by extending the cooling times, the general situation shows that radiation shielding may be required to transport the discharged components to the permanent storage site.

Acknowledgements

This work was supported by the US Department of Energy, Office of Fusion Energy Sciences, under Research Grant No.: DE-FG03-92ER54137. The author would like to acknowledge the reviewers whose valuable suggestions have been instrumental in deciding the final form of this paper.

References

[1] E.T. Cheng, J. Nucl. Mater. 233–237 (1996) 1467, and references cited in this paper.
[2] A.B. Pashchenko, H. Wienke, D.W. Muir, FENDL-2: An improved nuclear data library for fusion applications, Proceedings of the International Conference on Nuclear Data for Science and Technology, 1997, Trieste, Italy; E.T. Cheng, A.B. Pashchenko, J. Kopecky, Overview on recent nuclear data development for fusion reactor technology, Fusion Technol. 30 (1996) 1182.
[3] J. Kopecky et al., FENDL/A.2, UKAEA report, 1996.
[4] A.B. Pashchenko, Summary report on the IAEA consultants meeting on selection of evaluations for the FENDL/

A-2 activation cross section library, St. Petersburg, Russia, 1995, IAEA/INDC(NDS)-341, 1996.
[5] S. Ganesan, Summary report on the IAEA advisory group meeting on improved evaluations and integral data testing for FENDL, Garching, Germany, IAEA/INDC(NDS)-341, 1994.
[6] S. Ganesan, Summary report on the IAEA advisory meeting on review of uncertainty files and improved multigroup cross section files for FENDL, Tokai, Japan, 1993, IAEA/INDC(NDS)-297, 1994.
[7] E.T. Cheng, R.A. Forrest, J. Kopecky, F.M. Mann, List of neutron activation reactions important for fusion power plant technology, ECN report, EAF-Doc-004, 1994.
[8] J. Kopecky, D. Nierop, The european activation file EAF-4-summary documentation, ECN report, ECN-C-95-072, The Netherlands, 1995.
[9] F.M. Mann, REAC*2: Users manual and code description, WHC-EP-0282, Westinghouse Hanford Company report, 1989.
[10] D.L. Smith et al., Chemistry related to the procurement of vanadium alloys, Fusion Materials, USDOE/OFES Semi-annual Progress Report for Period Ending June 30, 1997, DOE/ER-0313/22, 1997, p. 3.