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Low-activation characteristics of V-alloys and SiC composites

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Abstract

Two novel low-activation materials for a fusion reactor first wall and blanket structures are examined: a vanadium-based alloy (V–4Cr–4Ti) and a SiC/SiC composite. The comparison concerns low-activation properties, and stresses the importance of data on the impurity content. In particular, new data about impurity levels in vanadium alloys show that long-term activation of such materials may be strongly reduced if certain impurities are kept under control.

1. Introduction

Due to their neutron-induced radioactivity, first-wall and blanket materials for fusion may be harmful in different situations during the reactor life and decommissioning, such as, for instance: waste management, accidental release to the environment, maintenance and inspection of components.

This paper compares two candidate novel low-activation materials for a fusion reactor first wall: a vanadium-based alloy (V–4Cr–4Ti) and a SiC/SiC composite. The comparison concerns low-activation properties, and stresses the importance of data on the impurity content. In particular, already available data about impurity levels in SiC/SiC have been combined with new data about impurity levels in vanadium alloys.

2. Low activation criteria

Some 'evaluation parameters' to decide whether the material is a 'low-activation' one, or not, have been published in previous works [1–3] and they will be adopted in this paper. They deal with three aspects (waste management, accidental release, maintenance), and can be summarised as follows:

Waste management: Activated waste is defined as low level waste (LLW), if the dose rate after a 50-year decay does not exceed 2 mSv/h. Furthermore, the decay heat must be below any "significant amount", e.g. less than 1 W/m^3. If this limit is not fulfilled, the waste may release significant amounts of decay heat, i.e., more than 10 W/m^3 after 50 yr of cooling. This value, and/or a dose rate higher than 20 mSv/h, rates the waste as HLW. If the material has a dose rate under 20 mSv/h and a decay heat under 10 W/m^3, after 50 yr of cooling, it can be classified as Medium Level Waste (MLW). This classification supports a waste management strategy based on "hands-on" (HOR) and "remote handling" (RHR) recycling scenarios: in particular, the HOR limit is set to 10 μSv/h, while the RHR limit is in the range (10 μSv/h, 10 mSv/h), according to the different grades of adopted shielding. With this classification, all LLW and most MLW may be recycled, while HLW has to be permanently disposed of.

Accidental release: The radiological effect (early dose) on the public (the M.E.I. – Most Exposed Individual) due to the release of a conservative quantity of activated material (1–10 kg) must not exceed 50 mSv. The effect of the concurrent release of tritium is estimated to be 50 mSv as a requirement, so that the total early dose should

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not exceed 100 mSv. This quantity will be called ''Release dose''.

Maintenance: The dose rate produced by a material placed around the plasma chamber (first wall, divertors) should not exceed 10^4 Gy/h, after one day of cooling. This should permit the robotised maintenance of plasma-facing components for about 1000 h, before the electronic apparatuses fail (integral dose of 10^7 Gy).

3. Investigated materials and composition experimental determination

Since the activation data, and then the 'low-activation evaluations' may be greatly influenced by the impurity content (down to ppb's for certain elements) [4], evaluations and comparisons dealing with low-activation properties are significant only if the impurity levels are known in great detail.

This paper compares two candidate novel low-activation materials for a fusion reactor first wall: a vanadium-based alloy (V–4Cr–4Ti) and a SiC/SiC composite. The Institute of Advanced Materials of JRC Ispra has determined a full list of impurities for an industrial 2D SiC/SiC composite, by means of different experimental techniques [5]. Concerning the V–4Cr–4Ti alloy (V-alloy), two compositions have been taken into account. In fact V-alloy is one of the reference structural materials for the Safety and Environmental Assessment of Fusion Power (SEAFP) study [6]: in particular, it is the first-wall and blanket material for the SEAFP2 Plant Model 1 [7], in the frame of the long-term safety and environmental actions of the European Fusion Technology Programme (EFTP).

At present, metallic vanadium is produced in the Russian Federation from vanadium pentoxide by alumothermy followed by purification of the metal to the required condition by electrolytic refining and electron beam remelting. Russian industry produces vanadium of several types, differing in purity: VnM-2, VnM-1, VnM-0 and Vn–M-00. To determine the suitability of the available on the market specimens of vanadium and chromium as a base for manufacturing low-activity alloys, a detailed elemental analysis of the samples by methods of neutron activation (vanadium) and spark mass spectrometry (vanadium and chromium) has been fulfilled. The vanadium specimen of VnM-1 type [8] and chromium sample of ERC-type (electrolytically refined) were used for analysis. The gas forming elements (C, N, O) were determined in vanadium by means of vacuum extraction. It is worth to note, that a suitable method for determination of these three elements is gamma-activation analysis, allowing a sensitivity of 0.1 ppm for each element. The correspondent radiochemical methods of analysis have been developed at the Vernadsky Institute. The composition of the V-alloys is compared in Table 1. For SiC/SiC composition, see Ref. [5].

4. Irradiation simulation of investigated materials

The irradiation of the materials (with the full content of impurities) in the first wall of a fusion power reactor has been simulated, by means of two different inventory codes.

The first one, the FISPACT code [9], is the EFTP reference code. The second one is program ACTIVA [10] connected with multitables relational data base, that permits access of various data sets for their analysis by means of suitable software [11]. Only FISPACT results will be shown in this paper: however, a comparison of the results of the two codes for V-alloy activation will be the subject of future work.

Spectra and fluences determined for the SEAFP-2 Plant Model 1 have been used, since this reactor has a vanadium alloy as first wall material. Variations in the neutronic flux of different V-alloy compositions used as a structure are very small, and their effects on the activation levels may be neglected: therefore, the same flux will be used to assess the activation response of the alloys. The irradiation conditions deal with a continuous exposure for 5 yr at a neutron wall loading of 2 MW/m^2, either as a first wall structure or as a blanket structure.

5. Results and discussion

Results of the irradiation simulation are reported in Table 2, which compares the activation characteristics of the investigated materials with the low activation criteria. For this table, results obtained with the FISPACT code have been used. Activation data for most common fusion structural material (stainless steel SS 316 LN) have been included for reference. Impurity content of the ITER grade reference alloy has been adopted [12]. Activation results shown in Table 2 for the Russian V-alloy do not change if elements below the detection limit are assumed to be present even to a maximum level equal to the detection limit. This is the first important result of our investigation: the application of conventional spark mass spectrometry method for panoramic analysis of materials is a sufficiently informative method to determine trace elements in low activation materials such as V-alloys. The detection limits of the method are acceptable in most cases for trace elements monitoring.

Table 1
Composition of the V–4Cr–4Ti alloy (Reference SEAFP2 and Russian). Negative numbers indicate elements below the detection limits: their content has been assumed equal to the detection limit itself. Numbers are in ppm

Element	SEAFP2	Russian
Al	200	920
Si	500	970
P	30	280
S	30	33
Cl	3	1.6
K	1	2.6
Ca	1	1.6
Sc	n/a	0.02
Ti	4%	4%
V	Balance	Balance
Cr	4%	4%
Fe	300	620
Co	n/a	0.77
Ni	120	22
Cu	50	0.6
Zn	n/a	12
Ga	10	n/a
As	3	n/a
Br	n/a	-4.0×10^{-2}
Rb	n/a	-3.2×10^{-2}
Sr	60	-4.0×10^{-2}
Y	n/a	-2.0×10^{-2}
Zr	65	920
Nb	20	31
Mo	50	180
Ru	7	-2.4×10^{-2}
Rh	n/a	-4.0×10^{-2}
Pd	n/a	-4.0×10^{-2}
Ag	1	-1.6×10^{-2}
Cd	n/a	-1.6×10^{-2}
In	n/a	-4.0×10^{-3}
Sn	n/a	-9.2×10^{-2}
Sb	n/a	-9.2×10^{-2}
Te	n/a	-1.2×10^{-2}
Cs	n/a	-4.0×10^{-3}
Ba	n/a	-1.2×10^{-2}
La	n/a	-1.2×10^{-2}
Ce	n/a	-1.2×10^{-2}
Pr	n/a	-2.8×10^{-1}
Nd	n/a	-4.0×10^{-2}
Sm	n/a	-1.2×10^{-2}
Eu	n/a	-8.0×10^{-3}
Gd	n/a	-8.0×10^{-3}
Tb	n/a	-2.4×10^{-3}
Dy	n/a	-8.0×10^{-3}
Ho	n/a	-2.4×10^{-3}
Er	n/a	-8.0×10^{-3}
Tm	n/a	-2.4×10^{-3}
Yb	n/a	0.14
Lu	n/a	-2.4×10^{-3}
Hf	11	-1.2×10^{-2}
Ta	3	180
W	23	0.028
Re	n/a	-4.0×10^{-3}
Os	n/a	-8.0×10^{-3}

Table 1 (Continued)

Element	SEAFP2	Russian
Ir	n/a	-4.0×10^{-3}
Pt	n/a	-8.0×10^{-3}
Au	n/a	-2.8×10^{-1}
Hg	n/a	-8.0×10^{-3}
Tl	n/a	-4.6×10^{-2}
Pb	n/a	0.12
Bi	500	-4.0×10^{-3}
Th	n/a	-4.0×10^{-3}
U	n/a	-4.0×10^{-3}
B	5	n/a
C	200	100
H	10	n/a
N	200	100
O	40	200

Other important results can be summarised as follows.

- Long-term activation of the V-alloy is different for the two compositions. In particular, SEAFP-2 reference V-alloy suffers for the high content of Bi as an impurity (500 ppm): in fact, about 98% of the 50 yr dose rate is due to activation products of Bi (mostly Bi207). The long-term activation data for the Russian composition are about two orders of magnitude lower (see Fig. 1), in the interval 50–100 yr.
- Long-term activation of V-alloy is almost entirely due to impurities activation, for both compositions (see for instance Fig. 2)
- Short-term activation and 'Release doses' are instead coming from activation of V-alloys main constituents (V,Cr,Ti), while impurities effect is negligible. Then, those data are equal for the two compositions. Short-term dose rate decays below the limit after two days of cooling (first wall), or after less than one day (blanket).
- SiC/SiC confirms its excellent low-activation properties in all situations. V-alloys, however, may almost equal its performance, but only if certain impurities are reduced.
- Recycling with remote-handling techniques is the most convenient solution for irradiated V-alloys, at least from the radioactivity viewpoint. However, this is not possible with the SEAFP-2 composition irradiated in the first wall, due to the Bi activation products. Impurity elimination through refinement should concentrate mainly on Bi for the SEAFP-2 composition. Concerning the Russian V-alloy, long term activation is quite low (less than 2 mSv/h after 50 yrs of cooling), and it is mostly due to Nb94 and Co60. Nb94 is an activation product of Nb (Nb93(n,g)Nb94) and Mo (Mo94(n,p)Nb94). Co60 is an activation product of Ni (Ni60(n,p)Co60, Ni61(n,d)Co60), Co (Co59(n,g)Co60), and Cu (Cu63(n,a)Co60). Then, the attention should be pointed at Nb, Ni, Co, Mo and Cu impurities.
- Recycling of SiC/SiC, however radiologically possible, is not the appropriate solution, since it is a composite material and not an alloy. Disposal as LLW is the suggested strategy for SiC/SiC activated materials.

6. Conclusions and work ahead

The main results of this investigation are the following.

- The application of the conventional spark mass spectrometry method for panoramic analysis of materials is a sufficiently informative method to determine trace elements in V-alloys. The detection limits of the method are acceptable for trace elements monitoring.
- Recycling of V–4Cr–4Ti used in the first wall and blanket of SEAFP2 Plant Model 1 appears radiologically feasible, if remote handling techniques are used. However, the content of certain impurities must be reduced. In particular, the Bi impurity is responsible of most of the long-term radioactivity of the alloy. The comparison of the SEAFP2 reference V-alloy with another composition (experimentally determined) shows that long-term activation may be reduced up to about 100 times, if impurity content changes.

A further step of this research will deal with the problem of tritium contamination of the two alloys when used as fusion structural material. Tritium inventory into reference V-alloy and SiC/SiC first wall/blanket structures has to be computed, in order to assess its safety relevance in such situations as accidental releases of material to the environment, and occupational doses to workers.

Table 2
Low activation properties of candidate fusion structural materials

	Limit	SS 316 LN First wall	SEAFP2 V-alloy First wall	Russian V-alloy First wall	SiC/SiC First wall	SS 316 LN blanket	SEAFP2 V-alloy blanket	Russian V-alloy blanket	SiC/SiC blanket
Early dose (mSv/1 kg) - (mSv/10 kg)	<50	28–280 Co58 28% Co60 24% Mn54 21% Co57 17%	0.69–6.9 Sc46 84% Ca45 7% Cr51 7%	0.70–7.0 Sc46 84% Ca45 7% Cr51 7%	0.020–0.20 Na24 78%	10.5–105 Co58 33% Co60 23% Mn54 21% Co57 14%	0.24–2.4 Sc46 88%	0.24–2.4 Sc46 88%	0.007–0.07
Relative to SS 316 LN		1	0.025	0.025	0.0007	1	0.023	0.023	0.0007
Dose rate inside the plasma chamber after 1 d (3 d) (Gy/h)	10^4	2.6×10^4 (2.5×10^4) Co58 50% Mn54 34%	1.5×10^4 (0.7×10^4) Sc48 93% Sc46 6%	1.5×10^4 (0.7×10^4) Sc48 92% Sc46 6%	2.4×10^2	1.1×10^4 (1.0×10^4) Co58 56% Mn54 32%	5.0×10^3	5.1×10^3	4.4×10^1
Contact dose rate after 50 yrs (mSv/h)	LLW <2 MLW <20	3180	105	1.8	1.5	1160	14.5	0.82	0.62
		Co60 91%	Bi207 97%	Nb94 54%	Ba 137m 31%	Co60 91%	Bi207 91%	Nb94 64%	Ba137m 41%
	RHR <10 HOR <0.01	Ag108m 8.7%	Co60 1%	Co60 32%	Co60 30% Kr85 11%	Ag108m 8.8%	Co60 3% Nb94 2%	Co60 26%	Co60 26% Nb94 12%
Decay heat after 50 yrs (W/m^3)	LLW <1	17	0.47	<0.1	<0.1	6.0	<0.1	<0.1	<0.1
	MLW <10	Co60 80%				Co60 81%			
Contact dose rate after 100 yrs (mSv/h)	RHR <10 HOR <0.01	272	36.2	1.1	0.45	100	5.2	0.56	0.19
		Ag108m 94% Nb94 4%	Bi207 94% Bi208 2%	Nb94 89% Al26 5%	Ba137m 33% Nb94 31% Tb158 15%	Ag108m 94% Nb94 4%	Bi207 84% Nb94 6% Bi208 5%	Nb94 94% Al26 3%	Ba137m 42% Nb 94 40% Ag108m 7%
Proposed waste management strategy		Disposal as HLW	Disposal as HLW	LLW Recycling (RHR)	LLW	Disposal as HLW	MLW Recycling (RHR)	LLW Recycling (RHR)	LLW

Early dose: 50 yr committed EDE due to the first week of exposure. Reference release: 1–10 kg of activated material. Irradiation conditions: SEAFP2 outboard first wall and mean outboard blanket fluxes: 2 MW/m^2 for 5 yrs.

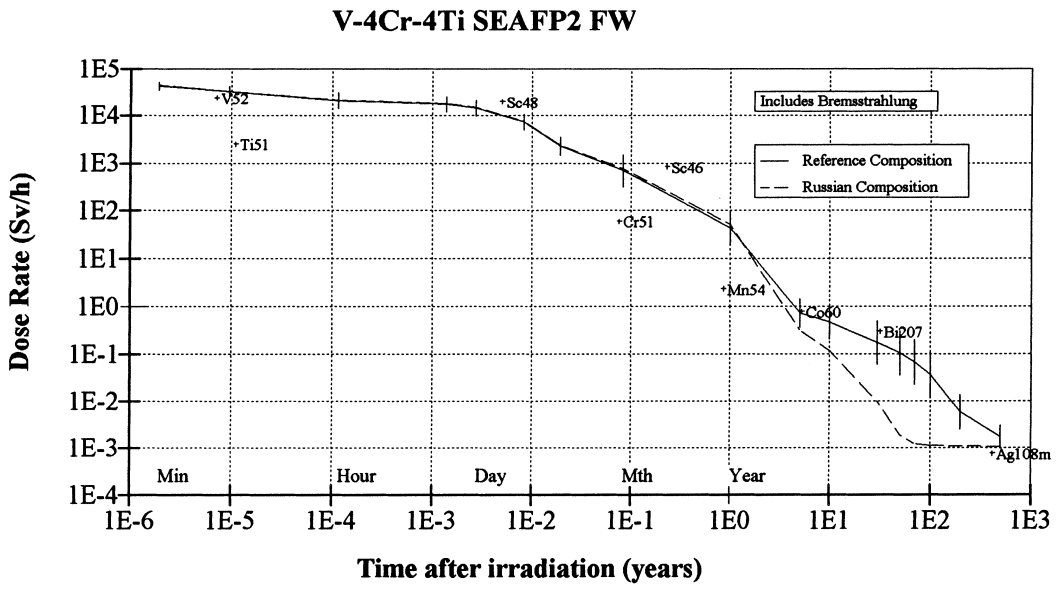

Fig. 1. Comparison of dose rate in V–Cr–Ti alloys: reference SEAFP-2 composition versus Russian composition.

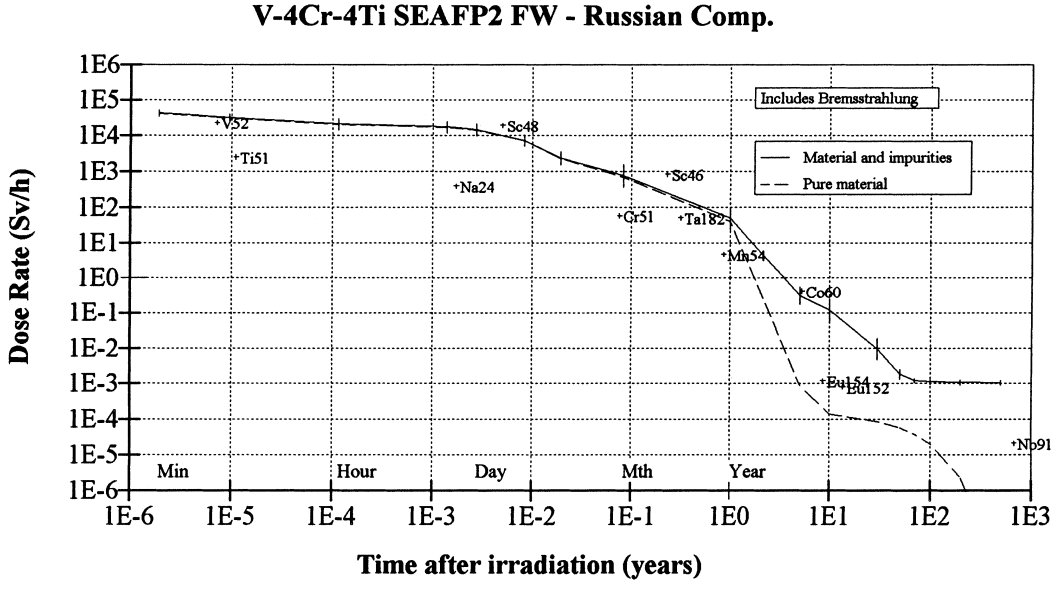

Fig. 2. Effect of impurities activation on long term dose rate of V-alloy.

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