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Journal of Nuclear Materials 307–311 (2002) 1026–1030

journal of nuclear materials

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Effects of impurities on low activation characteristics of V–4Cr–4Ti alloy

Y. Wu [a,*], T. Muroga [b], Q. Huang [a], Y. Chen [c], T. Nagasaka [b], A. Sagara [b]

[a] *Institute of Plasma Physics, Chinese Academy of Sciences, P.O. Box 1126, Hefei, Anhui 230031, China*
[b] *National Institute of Fusion Science, Oroshi, Toki, Gifu 509-5292, Japan*
[c] *Forschungszentrum Karlsruhe, Institute for Reactor Safety, P.O. Box 3640, 76021 KA, Germany*

Abstract

The required control levels of various impurities such as Co, Nb, Ag, Mo, Al, Na, Ni, Cu, Fe, Si, etc. in vanadium alloy (V–4Cr–4Ti) are given considering the hands-on and remote recycling dose rate limits based on the irradiation neutron spectrum of fusion reactor first wall. The activation level of the vanadium alloy (NIFS-HEAT-2 ingot) currently made by National Institute for Fusion Science (NIFS, Japan) is calculated and compared with the activation levels of previous NIFS-made vanadium alloy (NIFS-HEAT-1) and the USA-made vanadium alloy (US832665).

1. Introduction

Vanadium alloys are considered as a promising candidate structural material for fusion reactor application because of their attractive properties such as superior high temperature thermal and physical properties, good resistance against neutron irradiation and low neutron activation level [1–3]. In addition to the USDOE program efforts to validate the possibility of production of large scale of vanadium alloy heats of high quality [4], The National Institute for Fusion Science (NIFS), Japan, has started a program to produce a high purity large ingot of a V–4Cr–4Ti alloy. One of the main activities is to reduce and to minimize the impurity level of the commercial vanadium and its alloys with a reasonable effort [5,6]. It is well known that increased level of interstitial impurities such as C, N, O would result in loss of workability, weldability and irradiation resistance [7–9]. On the other hand, increased level of undesirable elements such as Co, Nb, Ag, Al, etc. would dominate the activation level of vanadium alloys which would substantially influence not only the recycling aspects of used reactor materials but also the waste management aspects of them. The activation analysis of various fusion reactor structural materials including vanadium alloys were performed by Forty, Taylor, Butterworth, Forrest, et al. [10–12]. A specific research on recycling of the vanadium alloy (V–15Cr–5Ti) was carried out by Dolan and Butterworth [13]. Reuse of the vanadium alloys (V–4Cr–4Ti) for single and multiple recycling and reuse of waste materials was studied based on the ARIES-RS fusion power plant concept and the required impurity levels of several impurity elements (Ag, Al, Mo and Nb) were indicated by Cheng and Muroga [14]. In this contribution, we calculate the activation level of the vanadium alloys currently made by NIFS (NIFS-HEAT-2) [15] and compare it with the activation levels of previous NIFS-made vanadium alloy (NIFS-HEAT-1) and the USA-made vanadium alloy (US832665). In addition, the required control levels of various impurities such as Co, Nb, Ag, Mo, Al, Na, K, Ni, Cu, Fe, etc. in vanadium alloy (V–4Cr–4Ti) are given based on the irradiation neutron spectrum of fusion reactor first wall of the fusion-driven system (FDS) [16,17] considering the hands-on and remote recycling dose rate upper limits (10 μSv/h and 10 mSv/h). The rationale for these values was discussed in Refs. [13,18,19]. Actually the remote recycling limit is in the

* Corresponding author. Tel.: +86-551 5591397; fax: +86-551 5591310.
E-mail address: ycwu@mail.ipp.ac.cn (Y. Wu).

0022-3115/02/$ - see front matter
PII: S0022-3115(02)01167-4

Table 1
The current impurity levels of three vanadium alloys and the required control level for recycling[a]

Impurity	NH1[b]	NH2[b]	US[b]
Co	2	0.7	0.295
Nb	1.4	0.8	60
Ag	<0.05	<0.05	0.0775
Mo	23	24	315
Al	119	59	355
Ni	13	7	9.6
Mn	<1	<1	0.21
Fe	80	49	205
Cu	4	2	0.84
Si	280	270	785
Na	17	<1	0.012
Ta	58	13	19
Sn	<1	<1	0.24
Sb	<1	<1	0.17
W	<1	<1	25
As	1	<1	1.4
N	103	122	100
C	56	69	170
O	181	148	330
Zr	<10	2.5	46
P	16	7	33
S	9	3	16.5
Ca	3	12	0.26
Mg	<1	<1	0.17
B	7	5	3.7

[a] The listed quantities are the measured or possible maximum concentrations in the unit of wppm.

[b] NH1 represents NIFS-HEAT-1; NH2 represents NIFS-HEAT-2; US represents US832665 heat.

range (10 μSv/h to 10 mSv/h) according to the different grades of adopted shielding.

2. Current impurity status and irradiation conditions

For the purpose of comparison, the impurity concentrations of the current NIFS heat (NIFS-HEAT-2), and the previous NIFS heat (NIFS-HEAT-2) and the US heat (US832665) are given in Table 1.

The geometrical and material configuration of the tritium breeding blanket (TBB) conceptual design of the FDS [15,16,20] are selected as the model for neutron transport calculation with the Monte Carlo transport code MCNP and the latest version of the IAEA fusion evaluated nuclear data library (FENDL-2.0) [21]. The tokamak geometrical configuration of the FDS-RT and the arrangement of material zones have been briefly shown in Fig. 1 and Table 2. The design details of FDS-TBB can be seen in Ref. [20]. The neutron spectrum in the outer first wall is used as the input of the activity inventory code FISPACT [22]. The IAEA activation sub-library of FENDL-2.0 is used in the activation

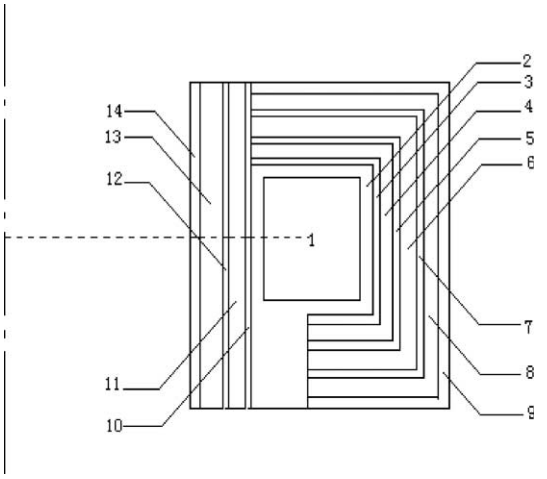

Fig. 1. The geometrical configuration of FDS-TBB tokamak.

calculation. The neutron irradiation fluence is assumed to be 15 MW year/m^2, i.e., a lifetime of 30 years with the average neutron wall loading of 0.5 MW/m^2.

3. Effects of impurities on activation characteristics

The contact dose rates as a function of cooling time for the NIFS-HEAT-2 are given in Fig. 2, where the curves for the theoretically pure V–4Cr–4Ti, NIFS-HEAT-1 and UD83265 heat vanadium alloys based on the same calculation conditions are included for the purpose of comparison. It is clear that about 5 years' and 10 years' cooling times would be enough, respectively, for remote and hands-on recycling of the used perfect V–4Cr–4Ti alloys which was assumed to be perfectly pure without any impurities if we use the 10 mSv/h and 10 μSv/h, respectively as the remote and hands-on recycling dose rate limits. However, it will be impossible to consider a hands-on recycling of the vanadium alloys with current impurity levels of the NIFS heats and the US heat although a remote handling could be considered after a cooling time of 40–50 years after the assumed irradiation. A slight difference can be seen between the activation levels of NIFS-HEAT-1 and NIFS-HEAT-2, i.e., the contact dose rate of NIFS-HEAT-2 is a little lower than that of NIFS-HEAT-1 due to the slightly lower concentration of impurities in NIFS-HEAT-2. The reduction of Co and Na concentrations results in an improvement of the short-term activation levels in the US heat. It is apparently noted that a big improvement of long-term activation characteristic happened to both the NIFS-HEATs as compared to the US heat because of the reduction of the impurities Nb, Mo and Al, etc. in the NIFS-HEATs.

Table 2
The compositions and dimensions of the FDS TBB model

No.	Zone	Compositions	Unit (cm)
1	Neutron source	Void	200
2	Scrape-off layer	Void	15
Outboard blanket			
3	Outer first wall	70%SM[a] + 30%He-gas	1
4	The first tritium breeding-zone	45%Li_2O + 10%Be + 5%SM + 40%He-gas	20
5	Wall-2	70%SM + 30%He-gas	1
6	The second tritium breeding-zone	55%Li_2O + 5%SM + 40%He-gas	30
7	Wall-3	70%SM + 30%He-gas	1
8	Reflector	90%graphite + 10%He-gas	22
9	Structure material	70%SM + 30%He-gas	10
Inboard blanket			
10	Inner first wall	70%SM + 30%He-gas	1
11	Tritium breeding-zone	45%Li_2O + 10%Be + 5%SM + 40%He-gas	30
12	Wall-2	70%SM + 30%He-gas	1
13	Reflector	90%graphite + 10%He-gas	43
14	Structure material	70%SM + 30%He-gas	10

[a] SM represents the structure material, here namely the vanadium alloy.

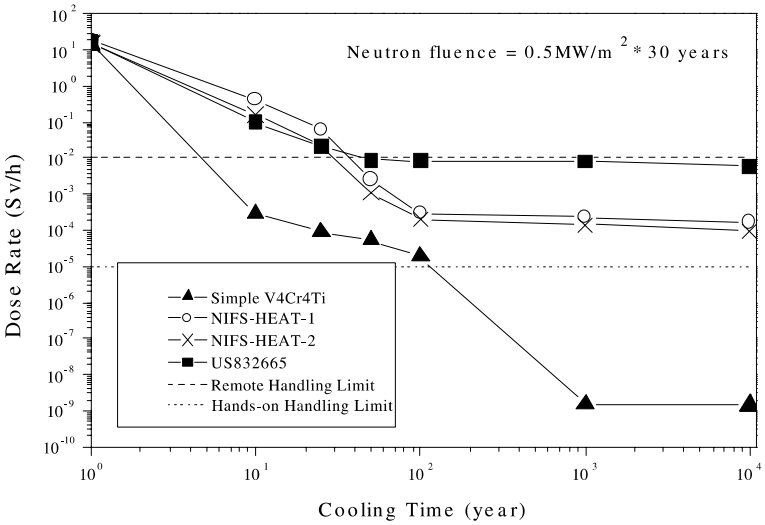

Fig. 2. Dose rate as a function of cooling time for the V-alloys.

Fig. 3 shows the contact dose rates of dominant radioactive nuclides in the irradiated NIFS-HEAT-2 as a function of cooling time. Apparently, the element Co dominates the total dose rate of the alloys at a cooling time of up to about 60 years. After that time, the element Nb dominates the total dose rate. The radioactive nuclide Ag108m had an important contribution to the long-term dose rate, too. Concerning the hands-on handling limit at the cooling time less than 25 years, the reduction of the impurity Na is necessary, too.

4. Requirement of impurity control levels for recycling

To recycle the used vanadium alloy, the impurity level should be controlled by the handling limits. If we consider the remote and hands-on handling limits of dose rates are 10 mSv/h and 10 μSv/h, respectively, the impurity levels of heavier elements in the V–4Cr–4Ti alloys should be controlled as shown in Table 3 where it is assumed that only one specific impurity element would exist in the V–4Cr–4Ti alloys and the activity of ^{42}K

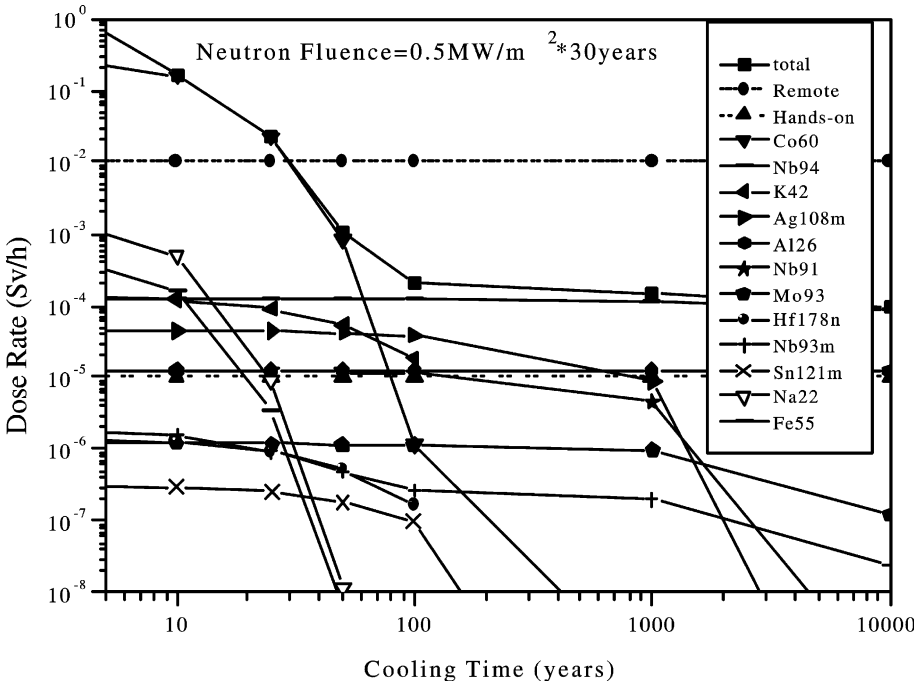

Fig. 3. Contributions of impurities to dose rate of NIFS-HEAT-2.

Table 3
Required impurity level (wppm) for recycle of the first wall materials

Cooling time (yr)	Recycling mechanism	Co	Nb	Ag	Mo	Al	Ni	Fe	Ta	Si	Cu
25	Remote	0.4	74	11	7.9E3	2.7E4	21	2.1E4	5.9E4	1.4E5	38
	Hands-on	3.8E−4	0.07	0.01	7.8	27	0.02	21	58	140	0.04
50	Remote	10	74	12	8.5E3	3.6E4	570	1.3E5	1.3E5	1.3E5	1000
	Hands-on	0.01	0.07	0.01	8.4	35	0.56	120	120	120	1
100	Remote	7.4E3	75	13	8.6E3	3.8E4	1.7E5	1.7E5	1.7E5	1.7E5	1.7E5
	Hands-on	7.3	0.07	0.01	8.6	38	170	170	170	170	170

(with a half-life of about 12 h), which is the nuclide dominating the gamma dose rate of the pure vanadium alloy, could be eliminated from the total dose rate with removal of its precursor ^{42}Ar (with a half-life of about 33 years) by remelting the used vanadium alloy. On the other hand, it is found from the calculated results that it is impossible to meet the requirement for hands-on handling limit if the volatile radioactive nuclide ^{42}Ar would not be removed by remelting the irradiated vanadium alloy as shown in Fig. 2.

Compared to the results with the current impurity level of NIFS-HEAT-2 in Table 2, the levels of impurities Co, Nb, Ag, Mo, Cu, Ni and Al should be further reduced to meet the requirement of handson recycling limit. However, the level of Co, Cu and Ni would not have to be reduced further if the cooling time of 100 years is allowed before the recycling.

5. Conclusions

The gamma dose rate of the vanadium alloys NIFS-HEAT-1, NIFS-HEAT-2, US832665 heat and theoretically pure V–4Cr–4Ti were calculated with the FISPACT code and the IAEA data library FENDL-2.0. The results showed that currently fabricated and postulated vanadium alloy NIFS-HEAT-2 in Japan will not allow hands-on recycle although the impurities were reduced much more than in the previously made NIFS-HEAT-1 in Japan and US832665 heat in USA. The

element Co is the most dominant impurity at the cooling time up to 60 years. To meet the requirement for hands-on handling after cooling for 50 years, the levels of impurities Co, Nb, Ag, Mo, Cu, Ni and Al should be further reduced. The required impurity levels for hands-on recycling are around the magnitude concentrations of 0.01, 0.1, 0.01, 10, 1, 0.5 and 30 wppm, respectively, for the elements Co, Nb, Ag, Mo, Cu, Ni and Al based on the neutron irradiation fluence of 15 MW year/m^2.

Acknowledgements

This work has been performed as part of the Core-University Program of the Japanese Science Promotion Society. Work at Hefei was supported by the National Natural Science Foundation of China under the contracts (no. 10175067 & 10175068) and the Chinese Academy of Sciences.

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