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PROPERTIES OF VANADIUM-BASE ALLOYS***

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EFFECT OF DYNAMICALLY CHARGED HELIUM ON MECHANICAL PROPERTIES OF VANADIUM-BASE ALLOYS*

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Abstract: One property of the vanadium-based alloys that is not well understood for the purpose of application as fusion reactor structural material is the effect of simultaneous generation of helium and neutron damage under conditions relevant to fusion-reactor operation. In the present dynamic helium charging experiment (DHCE), helium was produced uniformly in the specimen at linear rates ranging from ≈ 0.4 to 4.2 appm helium/dpa by the decay of tritium during irradiation to 18–31 dpa at 425–600°C in the Li-filled DHCE capsules in the Fast Flux Test Facility. This paper presents results of postirradiation tests of mechanical properties of V-4Cr-4Ti alloy which has been identified as the most promising candidate alloy on the basis of its superior baseline and irradiation properties. Effects of helium on tensile strength and ductility were insignificant for test temperatures $>420^\circ\text{C}$. However, room-temperature ductilities of the DHCE specimens were higher than those of the non-DHCE specimens (negligible helium generation) whereas strengths were lower, indicating that different types of hardening centers are produced during the DHCE and non-DHCE irradiation. Ductile-brittle transition behavior of the DHCE specimens was also determined from bend tests on TEM disks and broken tensile specimens. No brittle behavior was observed at temperatures $>-150^\circ\text{C}$ for DHCE specimens. Predominantly brittle-cleavage fracture morphologies were observed only at -196°C in some specimens that were irradiated to 31 dpa at 425°C during DHCE. In strong contrast to tritium-trick experiments in which large amount of helium is produced in absence of displacement damage, no intergranular fracture was observed in any tensile or bend-tested specimens that were irradiated in the DHCE.

Key words: vanadium-base alloys, helium, displacement damage, tensile properties, ductile-brittle transition

Vanadium-base alloys have significant advantages over other candidate alloys (such as austenitic and ferritic steels) for use as structural materials in fusion devices, e.g., the International Thermonuclear Experimental Reactor (ITER) and magnetic fusion reactors. These advantages include intrinsically lower levels of long-term activation, irradiation afterheat, neutron-induced helium- and hydrogen-transmutation rates, biological hazard potential, and thermal stress factor. Recent attention has focused on V-4Cr-4Ti for fusion reactor structural components because of its excellent combination of mechanical and physical properties before and after irradiation [1–6]. One of the properties of vanadium-base alloys that is not well understood is the effects of helium; no data have been reported on effects of simultaneous generation of helium and neutron displacement damage under fusion-relevant conditions (i.e., ≈ 5 appm He/dpa ratio), although helium effects on other vanadium-base alloys have been investigated by less-than-prototypic simulation techniques

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such as tritium-trick [7–11], cyclotron-injection [12–16], and boron-doping [16–19]. In the Dynamic Helium Charging Experiment (DHCE) [20–22], the fusion-relevant helium-to-dpa damage ratio is closely simulated by utilizing slow transmutation of controlled amounts of ^6Li and a tritium-doped mother alloy immersed in $^6\text{Li} + ^7\text{Li}$. This paper presents results of postirradiation examination of mechanical properties of V-4Cr-4Ti alloy which has been identified as the most promising candidate alloy on the basis of its superior baseline and irradiation properties.

MATERIALS AND PROCEDURES

The elemental composition of the V-4Cr-4Ti alloy, determined prior to irradiation, is given in Table 1. The alloy ingot, melted from low-chlorine titanium and low-impurity vanadium, was extruded at 1150°C and annealed at 1050°C several times after 8–10 passes of warm rolling between the anneals. Final forms of the product were annealed plates and sheets 3.8-, 1.0-, and 0.3-mm in thickness. Test specimens, machined from the annealed plates and sheets to investigate tensile and swelling behaviors and microstructural characteristics, were $\approx 95\%$ recrystallized and exhibited an average grain size of $\approx 14\ \mu\text{m}$. The only secondary phase present in the as-annealed specimen was Ti(O,N,C), which is normally observed in titanium-containing vanadium alloys with O+N+C > 400 wppm.

Table 1. Chemical composition of V-4Cr-4Ti (ANL ID BL-47)

ANL ID	Nominal Composition (wt.%)	Impurity Composition (wppm)							
		O	N	C	Si	S	P	Nb	Mo
BL-47	V-4.1Cr-4.3Ti	350	220	200	870	20	<40	<100	<100

The alloy specimens were irradiated in the Fast Flux Test Facility (FFTF), a fast reactor located in Richland, Washington, at 420, 520, and 600°C to neutron fluences ($E > 0.1\ \text{MeV}$) ranging from $3.7 \times 10^{22}\ \text{n/cm}^2$ (≈ 18 displacements per atom, or dpa) to $6.4 \times 10^{23}\ \text{n/cm}^2$ (≈ 31 dpa). Helium in the alloy specimens was produced by utilizing transmutation of controlled amounts of ^6Li and predetermined amount of tritium-doped vanadium mother alloy immersed in $^6\text{Li} + ^7\text{Li}$ [20–22]. Table 2 summarizes the irradiation temperature, weight of the mother alloy, fraction of ^6Li , and tritium and lithium inventory charged in each of the seven DHCE capsules before irradiation. Table 3 summarizes actual postirradiation parameters determined from tensile TEM disk specimens of the V-4Cr-4Ti alloy, i.e., fast neutron fluence, dose, and helium and tritium contents measured

shortly after the post-irradiation tests. Helium and tritium contents were determined by mass spectrometry in Rockwell International Inc., Canoga Park, California.

Table 1. Summary of Capsule-Loading Parameters of the Dynamic Helium Charging Experiment.

Capsule ID No.	Irradiation Temp. (°C)	Total Weight (g)			Fraction of ⁶ Li (%)	Initial Tritium Charged ^a	
		Vanadium ^a	Specimen ^b	Lithium		(Ci)	(mmol)
4D1	425	1.5468	5.86	0.765	5.0	99	1.70
4D2	425	1.5536	5.38	0.765	4.5	70	1.20
5E2	425	1.5657	5.38	0.670	1.0	26	0.45
5D1	500	1.5727	5.77	0.938	6.5	73.5	1.26
5E1	500	1.5651	5.82	0.952	1.0	57	0.98
5C1	600	1.5656	5.82	0.808	8.0	16.4	0.28
5C2	600	1.5466	5.95	0.955	8.0	18	0.31

^a Letter from C. E. Johnson to K. Pearce, April 23, 1991, 1 mmol = 58.3 Ci.

^b Excluding tritium-charged mother alloy.

Table 3. Summary of Irradiation Parameters of Dynamic Helium Charging Experiment and Helium and Tritium Contents Measured in V-4Cr-4Ti Specimens

Capsule ID No.	Irradiation Temp. (°C)	Fluence (E > 0.1 MeV) (10 ²² n cm ⁻²)	Total Damage (dpa)	Calculated Helium (appm) to dpa Ratio ^a at EOI ^b (Assumed k _a or k _w) ^c	Measured Helium Content ^d	Actual Helium to dpa Ratio	Measured Tritium Content ^e
				k _a =0.073 (k _w =0.01)	(appm)	(appm/dpa)	(appm)
4D1	425	6.4	31	3.8	11.2-13.3	0.39	27
4D2	425	6.4	31	2.8	22.4-22.7	0.73	39
5E2	425	3.7	18	2.1	3.3-3.7	0.11	2
5D1	500	3.7	18	4.4	14.8-15.0	0.83	4.5
5E1	500	3.7	18	3.1	6.4-6.5	0.36	1.7
5C1	600	3.7	18	1.1	8.4-11.0	0.54	20
5C2	600	3.7	18	1.1	74.9-75.3	4.17	63

^a L. R. Greenwood "Revised Calculations for the DHCE," April 30, 1993.

^b Beginning of irradiation (BOI) May 27, 1991; end of irradiation (EOI) March 19, 1992; 203.3 effective full power days (EFPD), hot standby at ≈220°C until November 1992.

^c Equilibrium ratio (k_a by atom, k_w by weight) of tritium in V alloy to that in the surrounding liquid lithium.

^d Measured June 1994.

^e Measured August 1994.

Tensile properties were measured at 23°C and at irradiation temperatures in flowing argon at a strain rate of 0.0011 s⁻¹. Fracture behavior was determined by repeated bending a TEM disk or a piece of broken tensile specimen in low-temperature baths of

liquid nitrogen or mixtures of dry ice and acetone. Temperature of the surrounding liquid was measured with a calibrated thermocouple. Approximately one-third of each side of a bend specimen was firmly held by two grips in the test bath and the middle portion of the disk was bent repeatedly until fracture. Thus, the specimen constraint was similar to that in a four-point bend test. Depending on irradiation conditions and test temperature, 2 to 62 bends were required to produce fracture in the specimens at -196 to 50°C . At a given test temperature, cold-work accumulated in the specimen with progressive number of bends. After fracture, morphology of the fracture surface was examined quantitatively by SEM. A few dozen SEM fractographs were taken at $\approx 300\times$, and a composite of the whole fracture surface was made. Four types of fracture morphology were observed: cleavage, quasicleavage, ductile-dimple, and fibrous ductile fracture. From the fracture surface composite, the percentage of ductile-fracture morphology was measured for each specimen with a planimeter.

TENSILE PROPERTIES

Yield strength, ultimate tensile strength, uniform elongation, and total elongation measured on tensile specimens irradiated at 425°C – 600°C to 18–34 dpa in the DHCE are summarized in Figs. 1A–1D, respectively. In the figure, similar properties measured on specimens irradiated in the non-DHCE (negligible helium generation) have been also plotted as function of irradiation temperature.

After irradiation to ≈ 30 dpa in either a DHCE or a non-DHCE, ductility of the alloy remained significantly high, i.e., $>8\%$ uniform elongation and $>10\%$ total elongation. Tensile properties measured at $>400^{\circ}\text{C}$ were essentially same as those measured on non-DHCE specimens, showing that effects of helium was insignificant. Room-temperature ductilities of the DHCE specimens (irradiated at 425, 500, and 600°C) were higher than those of the similar non-DHCE specimens, whereas strengths were lower. Although the mechanisms leading to the higher ductility and lower strength of the DHCE specimens are not understood at this time, the consistent observations indicate that different types of hardening centers are produced during the DHCE and non-DHCE irradiation.

The dependence of uniform and total elongation on irradiation and test temperature, shown in Figs. 1C and 1D, respectively, is in sharp contrast to similar results obtained on specimens in which helium atoms were produced by tritium-trick method. In the latter type of experiments, total elongation measured at room temperature and at 700 – 800°C

was significantly lower than that measured at 500–600°C because of strong susceptibility to intergranular cracking which was associated with extensive formation of grain boundary helium bubbles [10]. However, no intergranular fracture surface morphology was observed in any of the tensile specimens irradiated in the DHCE and tested at 25–600°C (including

Fig. 1. Yield strength (A), ultimate tensile strength (B), uniform elongation (C), and total elongation (D) of V-4Cr-4Ti after irradiation at 420–600°C to 18–34 dpa in the DHCE and in non-DHCE conventional irradiation (negligible helium generation).

the specimen irradiated in Capsule 5C2 at 600°C at a helium generation rate of 4.2 appm He/dpa), and no ductility degradation similar to that in tritium-trick experiments was observed. This is shown in Fig. 2 in which ratio of total strain in specimens with and without helium was plotted as function of irradiation and test temperature for tritium-trick and dynamic helium charging experiments.

Fig. 2.

Ratio of total strain in specimens with and without helium as function of irradiation and test temperature. Results obtained from tritium-trick experiment and DHCE are shown for comparison.

DUCTILE-BRITTLE TRANSITION BEHAVIOR

Fracture behavior of the alloy was investigated by multiple-bend tests on irradiated miniature specimens. Because no Charpy-impact specimens were irradiated in the DHCE, a TEM disk (0.3-mm thick) or a broken piece (1.0-mm thick) of a tensile specimen submerged in a low-temperature bath was bent repeatedly (typically 3–62 times) until fracture, and cleavage morphology was characterized quantitatively to determine ductile–brittle transition behavior.

As reported previously [2,5], brittle fracture of V–4Cr–4Ti did not occur at temperatures $>-196^{\circ}\text{C}$ in impact tests on one-third-size Charpy specimens either in the nonirradiated condition or after irradiation to 24–34 dpa at $425\text{--}600^{\circ}\text{C}$ in non-DHCE (i.e., negligible helium/dpa ratio). Consistent with this behavior, only ductile fracture was observed from the present multiple-bend tests in a similar temperature range on disk and broken tensile specimens of the alloy either unirradiated or irradiated in non-DHCE. This is shown in Figs. 3 and 4, respectively.

The percentage of fracture surface of disk and broken tensile specimens (irradiated at $425\text{--}600^{\circ}\text{C}$ to 18–31 dpa in the DHCE) with ductile-fracture morphology is plotted as a function of test temperature in Figs. 5A and 5B. The figures show effects of simultaneous displacement damage (18–31 dpa, T_{bale} 2), helium (4–75 appm, Table 2) generation, and tritium (2–63 appm, Table 2) uptake on ductile–brittle transition behavior. For comparison, similar results obtained for nonirradiated and irradiated non-DHCE

specimens (containing negligible amounts of helium, tritium, and hydrogen) are also shown. Despite the thickness difference, ductile-brittle transition behaviors of the disk and broken tensile specimens were similar.

Fig. 3.

Comparison of Charpy-impact energy and percentage of ductile fracture surface morphology of TEM disks (determined after multiple bend until fracture) of unirradiated V-4Cr-4Ti, plotted as a function of test temperature.

Fig. 4.

Comparison of Charpy-impact energy and percentage of ductile fracture surface morphology of TEM disks and broken pieces of tensile specimens (determined after multiple bend until fracture) of V-4Cr-4Ti irradiated in non-DHCE, plotted as a function of test temperature.

The results in Fig. 5 show that the percentage of brittle cleavage measured from fracture surfaces produced near -190°C generally was more pronounced in specimens irradiated at 425°C and retrieved from high-tritium capsules (e.g., 4D1 and 4D2) than in specimens irradiated at $500\text{--}600^{\circ}\text{C}$ and retrieved from low-tritium capsules (e.g., 5E1 and 5C2). As in irradiation during the non-DHCE, no brittle behavior was observed at temperatures $>-130^{\circ}\text{C}$ for DHCE specimens in which helium generation rate was $\approx 0.3\text{--}4.2$ appm helium/dpa (Table 2). Predominantly brittle-cleavage fracture morphologies were observed only at -196°C in some specimens that were irradiated to 31 dpa at 425°C during DHCE. The results in Figs. 5A and 5B indicate that the DBTTs for specimens irradiated at

425°C and 500–600°C are –175 and –150°C, respectively. As in case of tensile tests at 25–600°C, no intergranular fracture was observed in any specimens fractured at –196 to 50°C by multiple bending. An example of mixed ductile and cleavage fracture surface morphologies, observed in specimens irradiated at 425°C to 31 dpa and bend-tested at –196°C, is shown in Fig. 6.

Fig. 5. Percent ductile-fracture morphology vs. test temperature of V-4Cr-4Ti TEM disks and broken tensile specimens irradiated at (A) 425°C and (B) 600°C and fractured by multiple bending.

Figure 6. Example of mixed ductile and cleavage fracture surface morphologies observed in specimens irradiated at 425°C to 31 dpa and tested at -196°C

DISCUSSION

One of the important findings from the DHCE was the actual (measured) contents of helium and tritium in the V-4Cr-4Ti specimens were significantly lower than those calculated based on the assumed equilibrium ratio ($k_w = 0.01$) of tritium in the alloy to that in the liquid lithium (Table 2). Except for specimens irradiated in Capsule 5C1 and 5C2 at 600°C, actual helium/dpa ratios (i.e., 0.36–0.83) were several times lower than those calculated based on an equilibrium ratio of $k_w = 0.01$ (i.e., 2.1–4.4). This indicates that tritium level in lithium-cooled V-4Cr-4Ti first wall/blanket structure, and hence, the effect of tritium on the fracture toughness, will be significantly less than previously assumed.

As described in a separate paper [23], helium microvoids were negligible in all specimens irradiated in DHCE except for those irradiated at 425°C and retrieved from Capsule 4D1 and 4D2; only a few helium bubbles were observed at the interface between the grain matrix and some Ti(O,N,C) precipitates that are normally present in V-Ti and V-Cr-Ti alloys. Even in specimens irradiated at 600°C at the highest helium generation rate of ≈ 4.2 appm helium/dpa (Capsule 5C2), no microvoids could be detected either in grain matrix or on grain boundaries. For specimens irradiated to 31 dpa at 425°C (retrieved from Capsules 4D1, ≈ 0.4 appm helium/dpa and 4D2, ≈ 0.73 appm helium/dpa), moderate number densities of diffuse helium bubbles were observed in localized grain matrix and near limited fraction (≈ 15 –20%) of grain boundaries [23]. The number density of helium

bubbles, observed near the limited region of grain boundaries, was significantly lower than those in other alloys tested in the tritium-trick experiments, where extensive coalescence of helium bubbles occurred on all grain boundaries [7–11]. The absence of intergranular fracture morphology in any of the specimens irradiated in the present DHCE (even in the specimens irradiated at 425°C and fractured in brittle manner at -196°, Fig. 5A) seems to be consistent with the microstructural characteristics described above. However, despite the absence of intergranular fracture morphology in specimens irradiated at 600°C at a helium generation rate of ≈ 4.2 appm/dpa, a more comprehensive database for the effects of higher helium-dpa ratio (i.e., the fusion-relevant ratio of 4–5 appm helium/dpa) is needed, in particular for irradiation temperatures $< 450^\circ\text{C}$.

The uniform and total elongations determined from the room-temperature tensile tests on DHCE specimens were significantly larger than similar room-temperature elongations measured on specimens irradiated either in non-DHCE (Fig. 1) or from tritium-trick experiments (Fig. 2). This is also consistent with absence of continuous aggregation of helium bubbles on grain boundaries in the specimens irradiated in DHCE. In addition, the observation indicates also that different types of hardening centers are produced in the alloy during a DHCE (significant helium generation) and a non-DHCE irradiation (negligible helium generation) at 425–600°C. Although the nature of the hardening centers produced during DHCE is not understood at this time, helium atoms are believed to be associated with them.

From a series of studies on thermal desorption behavior of helium from unalloyed vanadium [24] and V-5Ti [25] irradiated with helium ions of various energy levels, van Veen et al. concluded that helium-oxygen-vacancy and helium-nitrogen-vacancy (and probably helium-vacancy-carbon as well) complexes formed in their irradiated material. They showed further that these complexes are stable at room temperature but dissociate into helium atoms and oxygen-vacancy and nitrogen-vacancy complexes at 270–310°C, leading to a prominent helium desorption peak at $\approx 290^\circ\text{C}$. During the degassing treatment in the present study in which DHCE specimens were heated to 400°C at a rate of $\approx 0.2^\circ\text{C/s}$, desorption peaks were observed consistently at $\approx 290^\circ\text{C}$ [23], although helium desorption was not positively identified by mass spectroscopy as in the studies of van Veen et al.

Based on these observations, it is likely that stable helium-vacancy-impurity complexes are also present at room temperature in the specimens irradiated in DHCE. In

contrast, in specimens irradiated in non-DHCE under similar conditions, vacancies and impurities (such as oxygen, nitrogen, and carbon) are not expected to form complexes because of absence of any appreciable helium atoms. Rather, the impurity atoms in solution and vacancies or vacancy clusters will be scattered more or less randomly in interstitial and vacancy sites, respectively. Dislocation motion would then be more difficult, and hence, ductility would be lower, in the latter situation (non-DHCE) than in the former (DHCE), which is in accordance with the results shown in Fig. 1.

CONCLUSIONS

1. Effects of dynamically charged helium, neutron damage, and retained tritium on DBTT of V-4Cr-4Ti alloy were determined after irradiation in the Dynamic Helium Charging Experiment (DHCE). TEM disks and broken pieces of tensile specimens, irradiated at 425–600°C to 18–31 dpa and at helium generation rate of 0.4–4.2 appm helium/dpa, were fractured by repeated bending while submerged in low-temperature baths. Ductile–brittle transition temperatures, based on quantitative SEM fractography of ductile and brittle fracture surface morphologies, were between –150 and –200°C in these specimens.
2. Tensile ductility of the alloy remained significantly high at 25–600°C, i.e., >8% uniform elongation and >10% total elongation. Tensile properties measured at >400°C were essentially same as those measured on non-DHCE specimens (negligible helium), showing that effects of helium was insignificant. Room-temperature ductilities of the DHCE specimens (irradiated at 425, 500, and 600°C) were higher than those of the similar non-DHCE specimens, whereas strengths were lower. These observations indicate that different types of hardening centers are present at room temperature in the DHCE (helium–vacancy–impurities complex, impurities being oxygen, nitrogen, and carbon) and in non-DHCE (defects and defect clusters, impurities in interstitial sites) specimens. The dependence of uniform and total elongation on irradiation and test temperature is in sharp contrast to similar results obtained on specimens in which helium atoms were produced by tritium–trick method.
3. Neither partial nor predominantly intergranular fracture was observed for tensile test at 23 to 600°C or multiple bending test at –196 to 50°C. Predominantly brittle–cleavage fracture morphologies were observed only at –196°C in some specimens that were

irradiated to 31 dpa at 425°C during DHCE.

4. One of the important findings from the DHCE was the actual (measured) contents of helium and tritium in the V-4Cr-4Ti specimens were significantly lower than those calculated based on the assumed equilibrium ratio (e.g., 0.01 by weight) of tritium in the alloy to that in the liquid lithium. This indicates that tritium level in lithium-cooled V-4Cr-4Ti first wall/blanket structure, and hence, the effect of tritium on the fracture toughness, will be significantly less than previously assumed.

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REFERENCES

- [1] B. A. Loomis, L. Nowicki, and D. L. Smith, "Effect of Neutron Irradiation on Tensile Properties of V-Cr-Ti Alloys," in Fusion Reactor Materials, Semiannual. Prog. Report, DOE/ER-0313/15, Oak Ridge National Laboratory, Oak Ridge, TN (1994), pp. 219-222.
- [2] B. A. Loomis, H. M. Chung, L. Nowicki, and D. L. Smith, "Effects of Neutron Irradiation and Hydrogen on Ductile-Brittle Transition Temperatures of V-Cr-Ti Alloys," *ibid.*, pp. 253-257.
- [3] H. M. Chung, B. A. Loomis, L. Nowicki, J. Gazda, and D. L. Smith, "Irradiation-Induced Density Change and Microstructural Evolution of Vanadium-Base Alloys," *ibid.*, pp. 223-231.
- [4] H. Matsui, M. Tanno, J. Gazda, and H. M. Chung, "Microstructural Stability of V-4Cr-4Ti During Neutron Irradiation," *ibid.*, pp. 240-246.
- [5] H. M. Chung, J. Gazda, L. Nowicki, J. E. Sanecki, and D. L. Smith, "Effects of Fabrication Variables on Impact Properties and Microstructure of V-Cr-Ti Alloys," *ibid.*, pp. 207-218.
- [6] H. M. Chung, B. A. Loomis, and D. L. Smith, "Thermal Creep Behavior of V-5Cr-5Ti and V-10Cr-5Ti Alloys," in Fusion Reactor Materials, Semiannual. Prog. Report, DOE/ER-0313/14, Oak Ridge National Laboratory, Oak Ridge, TN (1993), pp. 309-317.
- [7] D. N. Braski, in Influence of Radiation on Material Properties, ASTM-STP 956 (1986), pp. 271-290.
- [8] D. N. Braski, *J. Nucl. Mater.* 141-143 (1986) 1125.
- [9] D. N. Braski, in Reduced Activation Materials for Fusion Reactors, ASTM-STP 1047 (1988), pp. 161-178.

- [10] H. Matsui, M. Tanaka, M. Yamamoto, and M. Tada, J. Nucl. Mater. 191-194 (1992) 919.
- [11] M. Satou, K. Abe, and H. Matsui, J. Nucl. Mater. 191-194 (1992) 938.
- [12] W. van Witzenburg, A. Mastenbroek, and J. D. Ellen, J. Nucl. Mater. 103-104 (1981) 1187.
- [13] M. P. Tanaka, E. E. Bloom, and J. A. Horak, J. Nucl. Mater. 114 (1981) 895.
- [14] M. L. Grossbeck and J. A. Horak, in Influence of Radiation on Material Properties, ASTM-STP 956 (1986), p. 291.
- [15] J. M. Vitek, D. N. Braski, and J. A. Horak, J. Nucl. Mater. 141-143 (1986) 982.
- [16] W. van Witzenburg and E. de Vries, in Effects of Radiation on Materials, ASTM-STP 1125 (1990).
- [17] L. L. Horton and K. Farrell, J. Nucl. Mater. 122-123 (1984) 687.
- [18] H. Kawanishi and S. Ishino, in Reduced Activation Materials for Fusion Reactors, ASTM-STP 1047 (1988), pp. 179-189.
- [19] H. Kawanishi, Y. Arai, and S. Ishino, J. Nucl. Mater. 191-194 (1992) 933.
- [20] D. L. Smith, H. Matsui, L. R. Greenwood, and B. A. Loomis, J. Nucl. Mater. 155-157 (1988) 1359.
- [21] D. L. Smith, B. A. Loomis, H. Matsui, M. L. Hamilton, K. L. Pearce, J. P. Kopasz, C. E. Johnson, R. G. Clemmer, and L. R. Greenwood, in Fusion Reactor Materials, Semiannual Prog. Rep. DOE/ER-0313/10, Oak Ridge National Laboratory, Oak Ridge, TN (1991), p. 159.
- [22] H. Tsai, H. M. Chung, B. A. Loomis, and D. L. Smith, "Status of Dynamic Helium Charging Experiment (DHCE)," in Fusion Reactor Materials, Semiannual Prog. Report, DOE/ER-0313/15, Oak Ridge National Laboratory, Oak Ridge, TN (1994), pp. 247-252.
- [23] H. M. Chung, B. A. Loomis, and D. L. Smith, "Swelling and Structure of Vanadium-Base Alloys Irradiated in the Dynamic Helium Charging Experiment," in this proceedings.
- [24] A. van Veen, H. Eleveld, and M. Clement, "Helium Impurity Interactions in Niobium and Vanadium," in Proc. Sixth Intl. Conf. on Fusion Reactor Materials, September 27-October 1, 1993, Stresa, Italy, in press.
- [25] T. Buitenhuis, A. Fedorov, and A. van Veen, "Thermal Desorption Investigation of V-5Ti Alloy," IRI-131-94-005, Delft University of Technology, The Netherlands, 1994.

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