Received by OSTI
SEP 27 1980

Ben A. Loomis¹ and Dale L. Smith²

Relationship of Microstructure and Tensile Properties for
Neutron-Irradiated Vanadium Alloys*

CONF-900623--19

DE90 017863

¹Metallurgist, Materials and Components Technology
Division, and ²Director, Fusion Power Program, Argonne National
Laboratory, Argonne, IL 60439.

The submitted manuscript has been authored
by a contractor of the U. S. Government
under contract No. W-31-109-ENG-38.
Accordingly, the U. S. Government retains a
nonexclusive, royalty-free license to publish
or reproduce the published form of this
contribution, or allow others to do so, for
U. S. Government purposes.

* Work supported by the U. S. Department of Energy, Office of
Fusion Energy, under contract W-31-109-Eng-38.

MASTER
DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

ABSTRACT: The microstructures in V-15Cr-5Ti, V-10Cr-5Ti, V-3Ti-1Si, V-15Ti-7.5Cr, and V-20Ti alloys were examined by transmission electron microscopy after neutron irradiation at 600°C to 21-84 atom displacements per atom in the Materials Open Test Assembly of the Fast Flux Test Facility. The microstructures in these irradiated alloys were analyzed to determine the radiation-produced dislocation density, precipitate number density and size, and void number density and size. The results of these analyses were used to compute increases in yield stress and swelling of the irradiated alloys. The computed increase in yield stress was compared with the increase in yield stress determined from tensile tests on these irradiated alloys. This comparison made it possible to evaluate the influence of alloy composition on the evolution of radiation-damaged microstructures and the resulting tensile properties.

KEY WORDS: Vanadium alloys, neutron-irradiated, yield stress, microstructure, precipitates, swelling

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

The tensile properties and swelling of the V-15Cr-5Ti, V-10Cr-5Ti, V-3Ti-1Si, V-15Ti-7.5Cr, and V-20Ti alloys after neutron irradiation at 600°C to 87 atom displacements per atom (dpa) have been reported by Loomis and Smith [1-4]. The tensile-test results show that the alloys undergo maximum irradiation hardening in the range of 25 to 50 dpa and that the V-15Cr-5Ti, V-10Cr-5Ti, and V-3Ti-1Si alloys exhibit significantly greater irradiation hardening than the V-15Ti-7.5Cr and V-20Ti alloys.

The tensile-test results also show that these alloys exhibit significant total elongation (8-26%) after irradiation at 600°C to 87 dpa, with the V-20Ti alloy exhibiting greater ($\approx 2X$) total elongation than the V-15Cr-5Ti, V-3Ti-1Si, and V-15Ti-7.5Cr alloys. In this paper, we present results of analyses, based on transmission electron microscopy (TEM), of the irradiation damage in microstructures of the irradiated alloys.

These results are used to assess the influence of alloy composition on the evolution of radiation-damaged microstructures and the resulting tensile properties.

Materials and Procedure

Vanadium alloys with the compositions listed in Table 1 were obtained in the form of 50% cold-worked sheets 0.3 mm thick. Specimens for TEM were annealed at 1125°C for one h in an ion-pumped vacuum system with a typical pressure of 1.3×10^{-6} Pa. The annealed, unirradiated materials had an average grain diameter of $\approx 30 \mu\text{m}$ and contained $\approx 10^{12}$ dislocations/ m^2 .

The V-15Cr-5Ti, V-10Cr-5Ti, V-15Ti-7.5Cr, and V-20Ti alloys contained precipitates with a diameter of 60-400 nm and number density of $\approx 2 \times 10^{19}/\text{m}^3$. The V-3Ti-1Si alloy contained precipitates with a diameter of 30-100 nm and a number density of $\approx 2 \times 10^{20}/\text{m}^3$.

Specimens of the alloys for TEM were irradiated in lithium-filled TZM molybdenum capsules at 600°C to neutron fluences ($E > 0.1$ MeV) of $3.6 \times 10^{25} \text{ n/m}^2$ (21 dpa), $8.8 \times 10^{26} \text{ n/m}^2$ (44 dpa), and $14.2 \times 10^{26} \text{ n/m}^2$ (84 dpa) in the Materials Open Test Assembly during Cycles 8-10 of the Fast Flux Test Facility (FFTF-MOTA). Specimens irradiated to 21 dpa underwent a temperature excursion of +206°C for 50 min during Cycle 8 of the FFTF-MOTA.

Irradiated specimens (two or three of each alloy for each damage level) were prepared for TEM observation by electrochemical thinning of the specimens to perforation in a solution of 14% sulfuric acid-72% methanol-13% butyl cellosolve at -5°C. Microstructures were examined with a JEOL 100CX electron microscope operating at 100 KeV. The thickness of the microstructures (100-200 nm) observed by TEM was determined from stereoscopic examination of photographs of the microstructures.

Experimental Results

TEM Observations and Data for Irradiated Alloys

The microstructures in alloys after irradiation at 600°C to 21, 44, and 84 dpa are shown in Figs. 1, 2, and 3, respectively. Table 2 lists the dislocation density (ρ_d), precipitate number

density (N_p), precipitate average diameter (d_p), void number density (N_v), and void average diameter (d_v) determined from the microstructures of the irradiated alloys. The dislocation density was determined from the equation

$$\rho_d = 2NMF/Lt \quad (1)$$

where N is the number of dislocations intersecting a line of length L , M is the magnification, F (≈ 1) is a factor that allowed for those dislocations out of contrast, and t is the specimen thickness.

The density of forest dislocations in the alloys increased substantially (100-300X) on irradiation to ≈ 25 dpa but did not change significantly on additional irradiation to 84 dpa (Table 2 and Fig. 4). The dislocation density in irradiated alloys was strongly dependent on alloy composition (Fig. 4). The dislocation density in irradiated V-15Cr-5Ti and V-10Cr-5Ti alloys was $\approx 2X$ the density in irradiated V-3Ti-1Si and V-15Ti-7.5Cr alloys and $\approx 6X$ the density in irradiated V-20Ti alloy.

Voids were observed in all the irradiated alloys, with void diameter and number density increasing with irradiation damage (Table 2). The V-20Ti alloy was exceptionally resistant to void formation and growth, whereas the V-15Ti-7.5Cr alloy was least resistant to void formation and growth. Voids that formed in the V-3Ti-1Si and V-20Ti alloys were generally associated with precipitates formed during irradiation, whereas voids that formed in the V-15Cr-5Ti, V-10Cr-5Ti, and V-15Ti-7.5Cr alloys were rarely

observed to be associated with precipitates. The average diameter and number density of voids in the alloys increased as the damage level increased from 44 dpa to 84 dpa. Swelling ($\Delta V/V_0$) of these irradiated alloys due to the presence of voids was computed from the N_v and d_v data presented in Table 2. In Table 3 and Fig. 5, these swelling values are compared with those obtained from determinations of the immersion density, i.e., $(D_0 - D_{irr})/D_{irr}$, for these unirradiated and irradiated alloys [3,4]. The swelling values obtained by TEM and density measurement were generally in agreement, except for the V-15Cr-5Ti, V-10Cr-5Ti, V-3Ti-1Si, and V-20Ti specimens irradiated to 44 dpa (Table 3 and Fig. 5). On the basis of TEM, an immersion-density change of 1-2% for the V-15Cr-5Ti, V-10Cr-5Ti, V-3Ti-1Si, and V-20Ti alloys on irradiation at 600°C to 44 dpa must be attributed primarily to precipitate formation [3,4]. In the case of the V-3Ti-1Si alloy specimens irradiated to 84 dpa, regions in the microstructures contained a high density of relatively large voids, resulting in 4.3% localized swelling.

Irradiation-produced precipitates were prominent in the microstructures of all of the irradiated alloys. The irradiation-produced precipitates were categorized, primarily on the basis of diameter, into three types (Table 2) of disc-shaped precipitates. Type I precipitates were those features in the microstructures with diameters <6 nm. Type II precipitates were sited on {100} habit planes, e.g., at II in Fig. 3d, with diameter of 10-30 nm. Type III precipitates, e.g., at III in Fig. 3d, were relatively large in diameter (>30 nm) and generally

appeared to be strongly pinned or "wrapped" with dislocations (Fig. 6). The shape of the precipitates in microstructures for the irradiated V-15Ti-7.5Cr alloy (Figs. 2b and 3b) was distinctly different from that in other irradiated alloys, and it was necessary to approximate the shape of these precipitates by a disc with a diameter of equivalent cross-sectional area. Also, precipitates in the irradiated V-15Ti-7.5Cr alloy were transparent to the electron beam, which was not the case for precipitates in the other alloys. Evidence in the microstructures, e.g., strain-field contrast, led us to conclude tentatively that the Type II precipitates were coherent with the alloy matrix, whereas Type III precipitates were noncoherent.

Features of Type I precipitates were observed in all of the irradiated alloys. Type II precipitates were observed in the microstructures of the V-15Cr-5Ti, V-10Cr-5Ti, and V-3Ti-1Si alloys, but were not observed in the microstructures of the V-15Ti-7.5Cr and V-20Ti alloys. Type III precipitates were observed in the microstructures of the V-3Ti-1Si, V-20Ti, and V-15Ti-7.5Cr alloys, but were not observed in the microstructures of V-15Cr-5Ti and V-10Cr-5Ti alloys. The composition and/or crystallographic structure of the irradiation-produced precipitates in the alloys were not determined in this study.

Increase in Yield Stress

The increase in yield stress for the irradiated alloys was evaluated from the increase in shear stress ($\Delta\tau$) by use of the

equation

$$\Delta\sigma_y = \sqrt{3} \Delta\tau = \sqrt{3} (\alpha_p \mu b \sqrt{\rho_D} + \beta_p \mu b \sqrt{N_P d_P} + \gamma_v \mu b \sqrt{N_V d_V}) \quad [5-7] \quad (2)$$

where α_p , β_p , and γ_v are the interaction parameters of gliding dislocations with forest dislocations, precipitates, and voids, respectively, μ is the shear modulus and b is the Burger's vector for vanadium with values of 4.67×10^4 MPa and 0.26 nm, respectively [6]. In this paper we shall use α_p , β_p , and $\gamma_v = 0.28$ [6]. Increases in yield stress that could be attributed to voids ($\Delta\sigma_v$), dislocations ($\Delta\sigma_D$), or precipitates ($\Delta\sigma_P$) in the irradiated alloys were calculated using (2) and the data in Table 2. The results, which are tabulated in Table 4, show that forest dislocations and precipitates created in the alloys during irradiation were the major contributors ($\approx 90\%$) to the increase in yield stress. In the case of the V-15Cr-5Ti and V-20Ti alloys irradiated to 84 dpa, forest dislocations contributed $\approx 60\%$ to the increase in yield stress, whereas precipitates contributed $\approx 30\%$. Voids in the irradiated alloys contributed little ($<15\%$) to the increase in yield stress. The total increase in yield stress for irradiated alloys that was calculated by using (2), and the increase in yield stress determined by tensile testing, are also listed in Table 4 [1,2]. The computed increase in yield stress values derived from TEM observations ($\Delta\sigma_{TEM}$) and use of α_p , β_p , and $\gamma_v = 0.28$ in Eq. (2) for the V-15Cr-5Ti, V-10Cr-5Ti, and V-3Ti-1Si alloys were in good agreement with the increase in yield stress values determined from tensile tests ($\Delta\sigma_{TEN}$) (Table 4 and

Fig. 7). However, in the case of the V-15Ti-7.5Cr and V-20Ti alloys, the $\Delta\sigma_{\text{TEM}}$ values were substantially higher than the $\Delta\sigma_{\text{TEN}}$ values. Better agreement between the $\Delta\sigma_{\text{TEM}}$ and $\Delta\sigma_{\text{TEN}}$ values for these alloys was achieved by using α_p , β_p , and $\gamma_v = 0.04$ (Table 4 and Fig. 7) in Eq. 2.

Discussion of Results

TEM observations of the microstructures in V-15Cr-5Ti, V-15Ti-7.5Cr, V-20Ti, and V-3Ti-1Si alloys after neutron irradiation at 600°C to 21-84 dpa have shown features, i.e., forest dislocations, precipitates, and voids, that contributed to the increase in yield stress and swelling of the alloys. An evaluation of the dislocation density, precipitate number density and size, and void number density and size in the microstructures, together with computations of the increase in yield stress and swelling, significantly agree with the increase in yield stress determined from tensile tests and determinations of change in density for these irradiated alloys. A significant result obtained from these analyses and computations was the contribution of forest dislocations, precipitates, and voids to the increase in yield stress. In the case of the V-15Cr-5Ti and V-20Ti alloys irradiated to 84 dpa, forest dislocations contributed $\approx 60\%$ to the increase in yield stress, whereas precipitates contributed $\approx 30\%$. Voids in these irradiated alloys contributed a relatively small amount ($<15\%$) to the increase in yield stress.

It is generally recognized that production of forest dislo-

cations, precipitates, and voids in a material on irradiation are inextricably related and that an increase in yield stress (0.2% strain) for an irradiated material is determined by initiating dislocation glide and by the resistance presented to dislocation movement through these microstructural "barriers." However, it is our view that the composition of radiation-produced precipitates and the crystallographic compatibility (i.e., coherency or non-coherency) of the radiation-produced precipitates with the alloy lattice basically governs evolution of the alloy microstructures and the forest dislocation density on irradiation. On the basis of TEM observations, we have tentatively concluded that Type II radiation-produced precipitates in V-3Ti-1Si, V-15Cr-5Ti, and V-10Cr-5Ti alloys were coherent with the alloy lattice, whereas Type III precipitates in the V-3Ti-1Si, V-20Ti, and V-15Ti-7.5Cr alloys were noncoherent. The experimental results obtained by Bohm suggest that precipitates in unirradiated V-3Ti-1Si, V-15Cr-5Ti, and V-10Cr-5Ti alloys should be coherent with the alloy lattice, whereas precipitates in the V-20Ti alloy should be noncoherent with the alloy lattice [8]. Also, Loomis et al. have shown clear evidence (i.e., strain-field contrast in TEM-observed microstructures) for coherent precipitates in ion-irradiated V-5Ti and V-15Cr-5Ti alloys [9]. Type I precipitates are expected to be coherent with the alloy lattice because of their small size. In the absence of other contributing factors, it might be expected that the forest dislocation density in the irradiated alloys would be essentially equivalent because, in the present study for a given radiation damage level, the number of vacancy

and interstitial defects produced in the irradiated alloys was similar and the number density of dislocations in the alloys before irradiation can be assumed to have been nearly equal. This was not the case, however, because it was determined that the dislocation density in the V-15Cr-5Ti alloy was $\approx 2X$ the density in V-3Ti-1Si and V-15Ti-7.5Cr alloys and $\approx 6X$ the density in the V-20Ti alloy, even though the forest dislocation density in the irradiated alloys obtained a saturation level at 20-40 dpa irrespective of dislocation density. Therefore, we suggest that the difference in the observed density of forest dislocations in the alloys, and consequently their different irradiation hardening (i.e., increase of yield stress) is attributable to coherence or noncoherence of radiation-produced precipitates in the alloys.

The V-15Cr-5Ti, V-10Cr-5Ti, V-3Ti-1Si, and V-20Ti alloys were resistant to void growth during neutron irradiation ($\Delta V/V_0 < 0.1\%/dpa$). Loomis et al. attributed the inhibition of void formation in the V-Ti and V-Ti-Cr alloys on ion irradiation to the formation of Ti_3O precipitates that can incorporate vacancy defects in the precipitate structure of this titanium oxide [9]. Vacancy-O-Ti complexes are believed to form during irradiation, diffusing into and agglomerating in Ti_3O precipitates. Using TEM, Ohnuki et al. [10] may have observed experimental evidence confirming this mechanism of inhibition of void swelling in microstructures (Fig. 8) of neutron-irradiated V-10Ti alloy. It is suggested that a temperature excursion of $+206^\circ C$ (50 min duration) during irradiation at $600^\circ C$ to 14 dpa enabled visibility of vacancy clusters in the titanium oxide precipitate that

would otherwise not be visible. The exceptional resistance to void swelling during neutron irradiation of the V-20Ti alloy ($\Delta V/V_0 < 0.01\%/dpa$) in comparison to the V-3Ti-1Si and V-15Cr-5Ti alloys may be attributed to the higher solubility of oxygen in the V-20Ti alloy [11]. The extraordinarily high void swelling of the V-15Ti-7.5Cr alloy is believed due to the composition and/or crystallographic structure of the radiation-produced precipitates that did not incorporate vacancy defects.

The effect of neutron irradiation on ductility (i.e., uniform and/or total elongation) of the neutron-irradiated vanadium alloys is essentially understandable in light of the results obtained from analyses of the microstructures revealed by TEM and computations of increase in yield stress. The increase in yield stress values (Fig. 7 and Table 4) for the irradiated alloys suggests that the effect of neutron irradiation on ductility of the V-15Ti-7.5Cr and V-20Ti alloys should be less than that of the V-3Ti-1Si, V-15Cr-5Ti, and V-10Cr-5Ti alloys. If uniform elongation data for the irradiated alloys are considered, this is indeed the case, except for the V-15Ti-7.5Cr alloy irradiated to 87 dpa [1]. The low ductility in this latter case is attributed to the inability of the tensile specimen to withstand crack propagation in a matrix containing large-diameter voids ($\Delta V/V_0 = \approx 8\%$). These results suggest that vanadium alloys can undergo void swelling of $\leq 4\%$ without significant impact on the tensile properties during neutron irradiation.

Conclusions

Analyses of the microstructures revealed by TEM of the V-15Cr-5Ti, V-10Cr-5Ti, V-15Ti-7.5Cr, V-20Ti, and V-3Ti-1Si alloys after neutron irradiation at 600°C to 21-84 dpa, together with computations of the increase in yield stress from these analyses, have shown that forest dislocations and radiation-produced precipitates are major contributors to the increase in yield stress determined for these alloys on tensile testing.

Irradiation hardening of neutron-irradiated V-Ti and V-Ti-Cr alloys is dependent on Ti concentration that may be attributed to coherence or noncoherence of radiation-produced precipitates.

The inhibition of void swelling of neutron-irradiated V-Ti and V-Ti-Cr alloys by Ti may be attributed to the formation of titanium oxide precipitates that can incorporate vacancy defects.

The V-Ti and V-Ti-Cr alloys can undergo void swelling of $\leq 4\%$ without significant impact on tensile properties.

References

- [1] Loomis, B. A. and Smith, D. L., "Tensile Properties for Neutron-Irradiated Vanadium Alloys," in Fusion Reactor Materials Semiannual Progress Report for Period Ending September 30, 1989, DOE/ER-0313/7, Oak Ridge National Laboratory, Oak Ridge, TN, 1990, p. 203.
- [2] Loomis, B. A., Hull, A. B., and Smith, D. L., "Evaluation of Low-Activation Vanadium Alloys for Use as Structural Material in Fusion Reactors, "Proceedings of the Fourth International Conference on Fusion Reactor Materials",

December 4-8, 1989, Kyoto, Japan.

- [3] Loomis, B. A. and Smith, D. L., "Swelling of Neutron-Irradiated Vanadium Alloys," in Fusion Reactor Materials Semi-annual Progress Report for Period Ending March 31, 1989, DOE/ER-0313/6, Oak Ridge National Laboratory, Oak Ridge, TN, 1989, p. 339.
- [4] Loomis, B. A., Smith, D. L., and Garner, F. A., "Swelling of Neutron-Irradiated Vanadium Alloys," in Proceedings of the Fourth International Conference on Fusion Reactor Materials, December 4-8, 1989, Kyoto, Japan.
- [5] Garner, F. A., Hamilton, M. L., Panayotou, N. F., and Johnson, G. D., "The Microstructural Origins of Yield Strength Changes in AISI 316 During Fission and Fusion Irradiation," Journal of Nuclear Materials, Vols. 103 & 104, 1981, p. 803.
- [6] Moteff, J., Michel, D. J., and Sikka, V. K., "The Influence of Irradiation Temperature on the Hardening Behavior of the Refractory BCC Metals and Alloys", in Defects and Defect Clusters in BCC Metals and Alloys, Nuclear Metallurgy, Vol. 18, National Bureau of Standards, Gaithersburg, MD, 1973, p. 198.
- [7] Loomis, B. A., Kestel, B. J., and Smith, D. L., "Microstructural Evolution and Yield Stress Increase for Ion-Irradiated V-15Cr-5Ti Alloy", Journal of Nuclear Materials, Vols. 155-157, 1988, p. 1305.
- [8] H. Bohm, "Strengthening Mechanism in Vanadium-Titanium Alloys," in Proceedings of Second International Conference on the Strength of Metals and Alloys, Vol. 1, American So-

ciety of Metals, Cleveland, 1970, p. 341.

- [9] Loomis, B. A., Kestel, B. J., and Gerber, S. B., "Solute Segregation and Microstructural Evolution in Ion-Irradiated Vanadium-Base Alloys," in Proceedings of 13th International Conference on Radiation-Induced Changes in Microstructure, ASTM STP 955, Part 1, Philadelphia, 1987, p. 730.
- [10] Ohnuki, S., Gelles, D. S., Loomis, B. A., and Takahashi, H., "Microstructural Examination of Simple Vanadium Alloys Irradiated in the FFTF/MOTA," in Fusion Reactor Materials Semi-annual Progress Report for Period Ending September 30, 1989, DOE/ER-0313/7, Oak Ridge National Laboratory, Oak Ridge, TN, 1990, p. 177.
- [11] Kramer, K. H., "Ausscheidungsvorgange in Rein-Vanadin und Vanadin-Titan Legierungen", Journal of Less-Common Metals, Vol. 21, 1970, p. 365.

TABLE 1--Vanadium alloy compositions

Alloy	Concentration (wt.%)					
	Cr	Ti	O	N	C	Si
V-15Cr-5Ti	13.5	5.2	0.119	0.036	0.050	0.039
V-10Cr-5Ti	9.2	4.9	0.023	0.003	0.010	0.034
V-3Ti-1Si	...	3.1	0.021	0.031	0.031	0.800
V-15Ti-7.5Cr	7.2	14.5	0.111	0.025	0.040	0.040
V-20Ti	...	17.7	0.083	0.016	0.038	0.048

TABLE 2--Irradiation-produced defect size and concentration.

Alloy	dpa	Voids		Dislocation	Precipitates		
		d_v (nm)	N_v (m^{-3})	Density	Type	d_p (nm)	N_p (m^{-3})
				ρ_d (m^{-2})			
V-15Cr-5Ti	21	12	1.4×10^{19}	3.2×10^{14}	I	4	9×10^{20}
					II	14	8×10^{21}
"	44	29	8.5×10^{18}	4.0×10^{14}	I	4	4×10^{21}
					II	14	4×10^{21}
"	84	68	1.2×10^{20}	4.8×10^{14}	I	4	3×10^{21}
					II	17	2×10^{21}

V-10Cr-5Ti	44	57	5.1×10^{18}	3.1×10^{14}	I	5	9×10^{20}
					II	15	4×10^{21}
V-3Ti-1Si	44	25	1.1×10^{19}	1.5×10^{14}	I	5	1×10^{21}
					II	19	1×10^{21}
					III	74	3×10^{20}
"	84	46	9.8×10^{19}	1.7×10^{14}	I	5	9×10^{20}
					II	19	1×10^{21}
					III	52	5×10^{20}
"	84	77	1.8×10^{20}	1.2×10^{14}			
V-15Ti-7.5Cr	44	165	1.7×10^{19}	1.4×10^{14}	I	7	3×10^{19}
					III	91	8×10^{19}
"	87	177	2.6×10^{19}	1.4×10^{14}	I	7	3×10^{19}
					III	88	9×10^{19}
V-20Ti	21	22	8.7×10^{19}	7.6×10^{13}	I	4	1×10^{21}
					III	58	7×10^{20}
"	44	39	1.1×10^{19}	7.6×10^{13}	I	5	5×10^{20}
					III	96	2×10^{20}
"	84	46	1.2×10^{19}	6.4×10^{13}	I	5	5×10^{20}
					III	40	2×10^{20}

TABLE 3--Swelling of irradiated alloys.

Alloy	dpa	TEM	Density
		$\Delta V/V_0$ (%)	$(D_{irr}-D_0)/D_0$ (%)
V-15Cr-5Ti	21	<0.1	0.1
"	44	<0.1	0.3-1.9
"	84	2.0	1.7-2.6
V-10Cr-5Ti	44	<0.1	0.7-1.8
V-3Ti-1Si	44	<0.1	0.2-0.7
"	84	0.5	0.5-0.8
"	84	4.3	...
V-15Ti-7.5Cr	44	4.0	2.1-4.6
"	84	7.5	7.3-9.3
V-20Ti	21	<0.1	0.1
"	44	<0.1	-0.1-2.1
"	84	<0.1	-0.1-0.2

TABLE 4--Increase in yield stress for irradiated alloys.

Alloy	TEM					Tensile	
	Voids		Dislocations		Precipitates	Total	Total ^a
	$\Delta\sigma_v$		$\Delta\sigma_D$		Type	$\Delta\sigma_P$	$\Delta\sigma_{TEM}$
	dpa (MPa)		(MPa)			(MPa)	(MPa)
Dislocation Interaction Parameter = 0.28							
V-15Cr-5Ti	21	2	105		I	11	
					II	62	180
"	44	3	118		I	24	
					II	44	189
"	84	17	129		I	20	
					II	34	200
V-10Cr-5Ti	44	3	104		I	13	
					II	46	166
V-3Ti-1Si	44	3	72		I	13	
					II	26	
					III	28	142
"	84	13	77		I	12	
					II	26	
					III	30	158
V-15Ti-7.5Cr	44	10	70		I	3	
					III	17	100
"	84	13	70		I	3	
					III	17	103

23

V-20Ti	21	8	51	I	12		
				III	38	109	8
"	44	4	51	I	9		
				III	26	90	10
"	84	4	47	I	9		
				III	17	77	2
Dislocation Interaction Parameter = 0.04							
V-15Ti-7.5Cr	44	1	10	I	1		
				III	2	14	-17
"	84	2	10	I	1		
				III	2	15	23
V-20Ti	21	1	7	I	2		
				III	5	15	8
"	44	1	7	I	1		
				III	4	13	10
"	84	1	7	I	1		
				III	2	11	2

^aData in Refs. [1] and [2].

Figure Captions:

FIG. 1--Microstructures in V-15Cr-5Ti and V-20Ti alloys after irradiation at 600°C to 21 dpa in the FFTF-MOTA.

FIG. 2--Microstructures in V-15Cr-5Ti, V-15Ti-7.5Cr, V-20Ti, and V-3Ti-1Si alloys after irradiation at 600°C to 44 dpa in the FFTF-MOTA.

FIG. 3--Microstructures in V-15Cr-5Ti, V-15Ti-7.5Cr, V-20Ti, and V-3Ti-1Si alloys after irradiation at 600°C to 84 dpa in the FFTF-MOTA.

FIG. 4--Dependence of dislocation density in vanadium alloys on irradiation damage.

FIG. 5--Dependence of swelling of vanadium alloys at 600°C on irradiation damage.

FIG. 6--Precipitates pinned or "wrapped" with dislocations in V-20Ti alloy after irradiation at 600°C to 44 dpa.

FIG. 7--Dependence of increase in yield stress for vanadium alloys irradiated at 600°C on irradiation damage.

(b) V-20Ti

(a) V-15Cr-5Ti

Fig. 2

Fig-3

Fig. 4

Fig. 5

Fig. 6

Fig-7