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VANADIUM ALLOYS FOR STRUCTURAL APPLICATIONS IN FUSION SYSTEMS: A REVIEW OF VANADIUM ALLOY MECHANICAL AND PHYSICAL PROPERTIES*

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VANADIUM ALLOYS FOR STRUCTURAL APPLICATIONS IN FUSION SYSTEMS: A REVIEW OF VANADIUM ALLOY MECHANICAL AND PHYSICAL PROPERTIES*

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The current knowledge is reviewed on (a) the effects of neutron irradiation on tensile strength and ductility, ductile-brittle transition temperature, creep, fatigue, and swelling of vanadium-base alloys, (b) the compatibility of vanadium-base alloys with liquid lithium, water, and helium environments, and (c) the effects of hydrogen and helium on the physical and mechanical properties of vanadium alloys that are potential candidates for structural materials applications in fusion systems. Also, physical and mechanical properties issues are identified that have not been adequately investigated in order to qualify a vanadium-base alloy for the structural material in experimental fusion devices and/or in fusion reactors.

1. Introduction

Vanadium-base alloys have significant advantages over other candidate alloys, viz., austenitic and ferritic steels, for use as the structural material in experimental fusion devices, e.g., a blanket module in the International Thermonuclear Experimental Reactor (ITER), and/or for the first-wall in magnetic fusion reactors (MFR). These advantages include intrinsically lower long-term neutron activation, neutron irradiation after-heat, neutron-induced helium and hydrogen transmutation rates, biological hazard potential, and thermal stress factor [1-5]. However, in order to make use of these favorable neutronic and physical properties of vanadium-base alloys for the structural material in fusion systems, these materials (and other candidate materials) must be resistant to neutron-induced swelling, creep, and embrittlement and must be compatible with the reactor coolant and/or the reactor environment.

In this paper, we review our current knowledge on (a) the effects of neutron irradiation on tensile strength and ductility, ductile-brittle transition temperature, creep, fatigue, and swelling of vanadium-base alloys, (b) the compatibility, i.e., O, N, C, and H transfer, of vanadium-base alloys with liquid lithium, water, and helium environments, and (c) the effects of hydrogen and helium on the physical and mechanical properties of vanadium alloys. The results of this review are utilized to recommend alloys for additional experimental investigations. Also, an attempt is made to identify the major issues that have not been adequately addressed in order to qualify a vanadium-base alloy as the structural material for components in fusion systems, e.g., an ITER blanket module, and/or for the first-wall in fusion reactors.

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2. Mechanical properties

2.1. Tensile

The tensile properties of neutron-irradiated vanadium-base alloys have been investigated by Braski [6-9], Loomis, et al [10,11], van Witzenburg and de Vries [12], Carlander, et al [13], Tanaka, et al [14], Wiffen [15], Böhm, et al [16], and Grossbeck and Horak [17]. The increase of yield stress and the total elongation of vanadium-base alloys after neutron irradiation at 420, 520, and 600°C to ≈100 atom displacements per atom (dpa) reported by these investigators are summarized in Figs. 1 and 2, respectively. The computed yield stress increase of the V-15Cr-5Ti alloy on ion irradiation at 710-725°C to ≈175 dpa is also shown in Fig. 1 [18]. The yield stress, σ_0, of the unirradiated alloys reported by Loomis, et al [19,20] is shown in Fig. 1.

The tensile-test data reported in Refs. [6-17] and presented in Fig. 1 show that the alloys undergo maximum irradiation hardening, i.e., increase of yield stress, on neutron/ion irradiation at 40-50 dpa followed by a decrease of irradiation hardening on irradiation to >50 dpa. The tensile-test data also show that the total elongation (Fig. 2) of the alloys decreases with irradiation damage to ≈40 dpa and, with the exception of the V-20Ti and V-7.5Cr-15Ti alloys irradiated at 600°C, does not decrease further on irradiation to >40 dpa. With the exception of the V-15Cr-5Ti alloy, the total elongation of the alloys (420-600°C) at ≈100 dpa is >5%. The uniform elongation of the alloys is ≈75% of the total elongation [10,11].

The effect of helium (implanted before irradiation) on the tensile properties of neutron-irradiated V-3Ti-1Si, V-5Ti, V-20Ti, V-15Cr-5Ti, and Vanstar-7 (V-9Cr-3Fe-1Zr) alloys has been investigated by Braski [6-9], van Witzenburg and de Vries [12], Tanaka, et al [14], and Grossbeck and Horak [17]. The effect of helium (implanted by either cyclotron radiation or the "tritium trick") on the yield strength and total elongation of V-3Ti-1Si, V-20Ti, and V-5Ti alloys is shown in Fig. 3. Helium (100 appm) implanted by cyclotron radiation in the V-3Ti-1Si and V-5Ti alloys does not have a significant effect on the tensile properties of these alloys on irradiation at 500, 600, and 700°C to ≈6 dpa [12]; and helium (90-200 appm) implanted by cyclotron radiation in the V-20Ti alloy does not have a discernible effect on the strength properties of this alloy after irradiation to ≈17 dpa at 400, 575, and 700°C [14]. Whereas the ductility of the V-20Ti alloy is not significantly affected by implanted helium on irradiation at 400 and 575°C, the ductility of this alloy with implanted helium is significantly lower after irradiation at 700°C [14]. In the case of the V-15Cr-5Ti alloy irradiated at 400-700°C to 30 dpa, there is no significant effect of cyclotron-implanted helium (80 appm) on tensile properties, although neutron irradiation increases the ductile-brittle transition temperature (DBTT), i.e., the temperature for transition from cleavage to ductile fracture, from <25°C to ≈625°C, resulting in significant reduction of ductility of the alloy [17].

Helium (82-480 appm) implanted by the "tritium-trick" procedure in the V-3Ti-1Si alloy does not have a significant effect on the tensile properties of this alloy after irradiation at 420, 520, and 600°C to 40 dpa and at 420°C to 90 dpa [6-9]. The effect of helium (82-480 appm implanted by the "tritium-trick" procedure) on the tensile properties of V-15Cr-5Ti and Vanstar-7 alloys on irradiation at 420, 520, and 600°C to 40-90 dpa was also investigated by Braski [6-9]. Irradiation hardening, which results in substantial increase of the yield strength and reduction of total elongation, is the dominant effect that determines the post-irradiation tensile properties of these alloys.

2.2. DBTT

The DBTTs of vanadium and vanadium-base alloys with Cr, Ti, and Si additions have been determined from Charpy impact tests on these materials by Loomis and Smith [21] and Cannon, et al [22]. The DBTT dependence of dehydrogenated, hydrogenated, and neutron-irradiated vanadium and vanadium-base alloys is shown in Fig. 4. These experimental results show that vanadium alloys with Ti additions (0-20 wt.%) have a minimum DBTT (≈-250°C) in an alloy containing ≈5 wt.% Ti, that addition of up to 15 wt.% Cr to the V-5Ti alloy results in a substantial increase (90-160°C) of the DBTT, and that Si additions (0.25-1.0 wt.%) to V-3Ti alloy result in a significant increase (≈60°C) in DBTT. In addition, the results show that the presence of 400-1200 appm hydrogen in unalloyed vanadium and vanadium alloys causes a significant increase (60-250°C) in DBTT. The DBTTs of V-5Ti, V-5Cr-5Ti, V-7Cr-5Ti, and V-10Ti alloys are least affected by hydrogen. Neutron irradiation of the alloys at 420°C to 41-44 dpa results in substantial increase (210-380°C) of DBTT. It is expected that the DBTTs for irradiated V-5Ti and V-5Cr-5Ti alloys will be significantly lower than the DBTT (40°C) determined for irradiated V-3Ti-1Si alloy [21].

2.3. Creep

The creep and stress-rupture properties of unirradiated vanadium and vanadium-base alloys have been reported by Diercks and Loomis [23], Schirra [24], Böhm and Schirra [25], Bajaj and Gold [26], Kainuma, et al [27], Van Thyne [28], Carlander [29], Böhm [30], and Tesk and Burke [31]. The effect of Ti, Cr, and Si alloying additions on the stress-rupture time performance of vanadium reported by these investigators is summarized in Fig. 5. Alloying of vanadium with up to ≈3 wt.% Ti produces significant strengthening in creep, but further increases in Ti concentration result in substantial decrease in creep resistance [30]. The addition of up to 15 wt.% Cr to the V-(3-5)Ti alloy also produces significant strengthening in creep [23,24], whereas addition of 1 wt.% Si to the V-3Ti alloy causes a significant decrease in the creep strength of this alloy [23,25]. Experimental data on the effect of neutron irradiation on the creep and stress-rupture properties of vanadium-base alloys are very limited and have only been reported for V-20Ti [29], V-3Ti-1Si [30], and V-15Cr-5Ti [31] alloys. The stress-rupture data for these alloys are consistent with the susceptibility of these alloys to irradiation hardening. The V-15Cr-5Ti alloy is susceptible to significant irradiation hardening (Fig.1, 600°C) and concomitant degradation of stress-rupture time performance (Fig. 5), whereas the V-3Ti-1Si and V-20Ti alloys are less susceptible to irradiation hardening and exhibit minimal degradation of stress-rupture time performance on neutron irradiation (Fig. 5)

2.4. Fatigue

Experimental data on the response of vanadium-base alloys to fully reversed strain-controlled cyclic loading are limited to (fatigue) tests on the V-15Cr-5Ti alloy [32] and the unirradiated and irradiated Vanstar-7,8,9 alloys [33]. The dependence of cycles-to-failure under cyclic loading on total strain range for the V-15Cr-5Ti and Vanstar-7 alloys is shown in Fig. 6. The general data trends suggest that the V-15Cr-5Ti alloy has endurance limits of ≈0.7% and 0.6% on cyclic loading at 550 and 650°C, respectively [32]. The endurance limit for the Vanstar-7,8,9 alloys is ≈1.0% on cyclic loading at 400°C [33]. Neutron irradiation of the Vanstar-7,8,9 alloys to the damage levels shown in Fig. 6 have little or no effect on the fatigue behavior of these alloys [33].

3. Physical properties

3.1. Swelling

The swelling of vanadium and vanadium-base alloys on neutron irradiation has been investigated by Braski [6-9], van Witzenburg [12], Carlander, et al [13], Tanaka, et al [14], Grossbeck and Horak [17], Matsui, et al [34], Loomis, et al [35-37], Bentley and Wiffen [38], Takahashi, et al [39], and Ohnuki, et al [40,41]. The swelling data for vanadium and vanadium-base alloys irradiated at 420, 520, and 600°C reported by these investigators are summarized in Figs. 7, 8, and 9. Swelling values indicated by open symbols in Figs. 7, 8, and 9 were determined from density measurements on unirradiated and irradiated specimens.

The swelling dependence of vanadium and binary vanadium-base alloys on irradiation damage at 600°C is shown in Fig. 7. These data show that undersize solute atoms, i.e., Fe, Cr, and Ni, increase swelling of vanadium whereas oversize solute atoms, i.e., W, Mo, and Ti, decrease swelling of vanadium [12-14, 34-37, 40, 41]. Titanium alloying additions (5-20 wt.%) are the most effective in reducing the swelling of vanadium on neutron irradiation at 600°C. The swelling of V-(5-20)Ti alloys is significantly increased by a 50 min. temperature excursion of +249°C during irradiation at 600°C [35,36].

The swelling dependence of V-(0-20)Ti alloys on Ti concentration on irradiation at 420, 520, and 600°C is shown in Fig. 8. The V-3Ti-(0.25-1.0)Si alloys undergo the highest (≈2.5%) swelling of the V-Ti alloys with swelling of the V-Ti alloys generally decreasing with increase of Ti concentration >3 wt.% [35-37]. Although swelling of the V-3Ti-1Si alloy on irradiation at 420°C is increased (2X) by the presence of pre-implanted helium [6-9], the effect of helium on swelling of V-(0-20)Ti alloys is generally minimal. Temperature excursions >600°C during irradiation at 600°C increase the swelling of V-(0-20)Ti alloys whereas a temperature excursion >520°C during irradiation at 520°C decreases swelling of V-(0-20)Ti alloys. Swelling of the V-(0-20)Ti alloys on neutron irradiation to 114-124 dpa at 420°C, 50 dpa at 520°C, and 84 dpa at 600°C is <0.05% per dpa, regardless of the temperature excursions.

The swelling dependence of V-(0-15)Cr-5Ti alloys on Cr concentration on irradiation at 420, 520, and 600°C is shown in Fig. 9. Swelling of the V-5Ti alloy generally increases with increase of Cr concentration in the alloy [35-37]. Implanted helium has no significant effect on the swelling of V-(0-15)Cr-5Ti alloys [6-9, 12, 17]. Temperature excursions during irradiation of the V-(0-15)Cr-5Ti alloys at 520 and 600°C cause a significant increase in swelling of these alloys. The swelling of these alloys on irradiation at 420°C to 124 dpa, 520°C to 50 dpa, and 600°C to 84 dpa is <0.1% per dpa.

3.2. Corrosion in lithium, helium, and water

The dissolution behavior (corrosion) of vanadium-base alloys in flowing lithium (≈1 l/min) at 427-550°C has been investigated by Chopra and Smith [42], Borgstedt, et al [43], and Loomis, et al [10]. The weight losses of vanadium alloys exposed to lithium (482-550°C) containing either 20 wppm N or 12 wppm N are shown in Fig. 10a. The alloy dissolution rates in lithium (482°C) containing 20 wppm N decrease in the order: V-3Ti-1Si, V-5Ti, V-15Cr-5Ti, V-12Cr-5Ti, V-7.5Cr-15Ti, and V-20Ti [42]. A similar trend of dissolution rates is also obtained on exposure of these alloys to lithium (20 wppm N) at 427°C [42]. The dissolution rates of the V-3Ti-1Si and V-15Cr-5Ti alloys are significantly reduced on exposure to lithium containing 12 wppm N (Fig. 10a) [43]. Loomis, et al [10] have reported that the dissolution rates of vanadium alloys in lithium (482°C) containing 167 wppm N decrease in the order: V-20Ti, V-15Cr-5Ti, V-10Cr-10Ti, V-10Cr-5Ti, Vanstar-7, V-3Ti-0.5Si, and V-7.5Cr-15Ti [10].

The effect on tensile properties of vanadium alloys of exposure to static and flowing lithium has been reported by Braski [6] and Loomis, et al [10]. The tensile properties of V-15Cr-5Ti, Vanstar-7, and V-3Ti-1Si alloys are virtually unchanged after thermal aging (257 days) in static lithium (24 wppm N) at 420, 520, and 600°C. However, Loomis, et al [10] report a significant increase of yield strength (10-20%) and decrease of total elongation (1-6%) for V-15Cr-5Ti, V-10Cr-5Ti, V-7.5Cr-15Ti, V-3Ti-0.5Si, V-20Ti, and Vanstar-7 alloys on exposure (3400 hrs) to flowing lithium (167 wppm N) at 482°C.

The dissolution rates and tensile properties of vanadium alloys on exposure to lithium are strongly dependent on O, N, C, and H transfer between the alloys and lithium. Natesan [44], Loomis, et al [10], and Hull, et al [45] have reported that the O, N, C, and H distribution coefficients for vanadium and vanadium alloys in lithium (400-600°C) are $\approx 10^{-7}$, 10^{2}, 10^{7}, and 10^{-1}, respectively.

The increase in weight of V, V-5Ti, V-15Cr, and V-15Cr-5Ti alloys on exposure to helium containing hydrogen (1 vppm) and/or water vapor (1-10 vppm) at 450-650°C has been determined by Loomis and Wiggins [46]. The data obtained on exposure of the alloys to a helium (1 ppm H + 1 ppm H_2O) environment at 550°C are shown in Fig. 10b. These data clearly show that chromium in a vanadium alloy is beneficial for a minimum increase-in-weight in a helium environment.

The weight losses of V-15Cr-5Ti, V-20Ti, and Vanstar-7 alloys on exposure to flowing (1 l/min), pressurized (8.3 MPa) water containing either 0.03, 0.19, or 4 wppm dissolved oxygen have been determined by Diercks and Smith [47]. The weight-loss data for the alloys in water (288°C) containing 0.19 wppm oxygen are shown in Fig. 10c. The V-15Cr-5Ti alloy exhibits lower weight-loss rates in pressurized water at 288°C than Vanstar-7 and V-20Ti alloys, viz., 0.003-0.005 mm/yr and 0.03-0.7 mm/yr.

3.3. Precipitates

The composition and structure of precipitates in unirradiated and irradiated vanadium-base alloys with Cr, Ti, and Si additions have been reported by Schober and Braski [48], Chung, et al [49], Böhm [50], and Loomis, et al [51]. Schober and Braski [48], Chung, et al [49], and Böhm [50] report that the predominant (1 wt.%) precipitate in unirradiated V-15Cr-5Ti, V-3Ti-1Si, and V-20Ti alloys is face-centered-cubic Ti(O,N,C) with variable O, N, and C ratios, which is formed by thermal processes during casting and heat treatment. The second most frequently observed precipitate in these unirradiated alloys is face-centered-cubic $(Cr_{0.6}Fe_{0.4})_{23}C_6$ [48]. The Ti_8S_3, TiP, Ti_5S_4, Ti_2S, and TiC precipitates are occasionally detected in these unirradiated alloys [48,49]. In the case of neutron-irradiated V-15Cr-5Ti, V-3Ti-1Si, and V-20Ti alloys, hexagonal-close-pack Ti_2O and $Ti_5(Si,P)_3$ precipitates are observed [49], in addition to the intrinsic, thermally formed precipitates, i.e., primarily Ti(O,N,C) [49]. Irradiation of the V-15Cr-5Ti alloy at 650°C with 4.0-MeV $^{51}V^{++}$ ions results in formation of Ti_3O precipitates according to Loomis, et al [51]. The Ti_2O (formed on neutron irradiation) and Ti_3O precipitates are iso-structural and identical in atomic arrangement, except that oxygen vacancies in the latter are distributed orderly in a superstructure of the former [49,51].

4. UTS, 1000-h rupture stress, DBTT, and swelling for V-Ti Alloys

The dependence of ultimate tensile strength (UTS) [30], 1000 h-rupture stress [30], DBTT (Fig. 4), and swelling (Fig. 8) of V-(0-20)Ti alloys on Ti concentration is shown in Fig. 11. These mechanical and physical properties for V-Ti alloys undergo significant changes at 3-5 wt.% Ti. Böhm attributes the change of UTS and 1000 h-rupture stress at 3-5 wt.% Ti to a minimum of oxygen solubility and formation of finely dispersed, coherent precipitates of TiO [50]. The coherency of TiO precipitates in V-Ti alloys is expected to decrease with increase of Ti concentration because of an increasing disparity of lattice constants for the alloy matrix and TiO precipitates [50]. The DBTT minimum and decrease of swelling of V-Ti alloys with >3 wt.% Ti may also be attributed to a decrease of coherency of TiO precipitates.

5. Vanadium alloys for ITER and MFR

The V-5Cr-5Ti alloy is recommended for the structural material in experimental fusion systems, e.g., ITER, and magnetic fusion reactors and for additional investigation of the alloy physical and mechanical properties. This recommendation is based on a combination of (1) low DBTT (<<25°C), (2) minimal effect (<100°C) of hydrogen isotopes on DBTT, (3) low swelling (<0.05%/dpa, 420-600°C), (4) acceptable corrosion rate in lithium, helium, and water, (5) high creep strength (250 MPa, 650°C), (6) irradiated yield strength (450 MPa, 600°C), and (7) irradiated ductility (10-15%, 420-600°C). It is expected that the physical and mechanical properties of the V-5Cr-5Ti alloy can be further improved by optimal thermal-mechanical treatment and O, N, C, and Si concentration.

6. Qualification issues

On the basis of the present review of mechanical and physical properties for vanadium-base alloys, the major issues that have not been adequately addressed in order to qualify a vanadium-base alloy as the structural material for components in fusion systems are: (1) mechanical properties of components with gas-tungsten-arc (GTA) and/or electron-beam (EB) weld zones, (2) effects of credible accident scenarios, e.g., rupture of first-wall in a MFR, on alloy physical and mechanical properties, (3) fusion-system life-time effects of plasma and coolant on alloy physical and mechanical properties, and (4) susceptibility of alloy components with weld zones to fatigue, i.e., thermal cycling, failure.

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Figure Captions:

Fig. 1. Dependence of increase of yield stress of vanadium-base alloys at 420, 520, 600, and 710-725°C on neutron/ion irradiation damage; and yield stress, σ_0, of unirradiated alloys.

Fig. 2. Dependence of tensile ductility of vanadium-base alloys at 420,520,and 600°C on irradiation damage.

Fig. 3. Effect of helium on tensile yield strength and ductility of irradiated vanadium-base alloys.

Fig. 4. Effects of hydrogen and irradiation damage on the DBTT (Charpy impact loading) of vanadium and vanadium-base alloys.

Fig. 5. Dependence of rupture time on stress (creep deformation) for vanadium and vanadium-base alloys at 650°C.

Fig. 6. Dependence of cycles-to-failure on total strain range (fatigue deformation) for vanadium alloys.

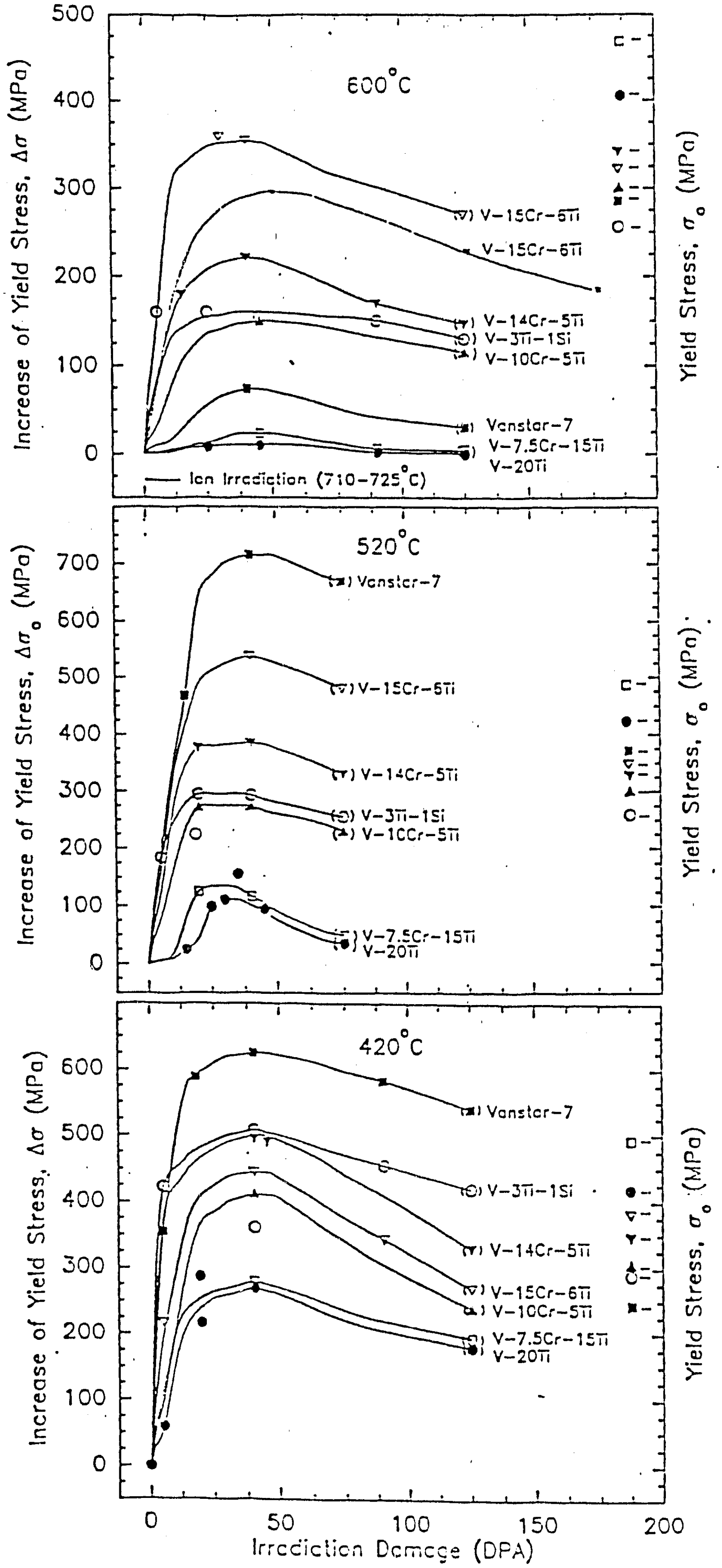
Fig. 7. Dependence of swelling of vanadium and binary vanadium-base alloys irradiated at 600°C on irradiation damage.

Fig. 8. Dependence of swelling of V-(0-20)Ti alloys irradiated at 420, 520, and 600°C on titanium concentration.

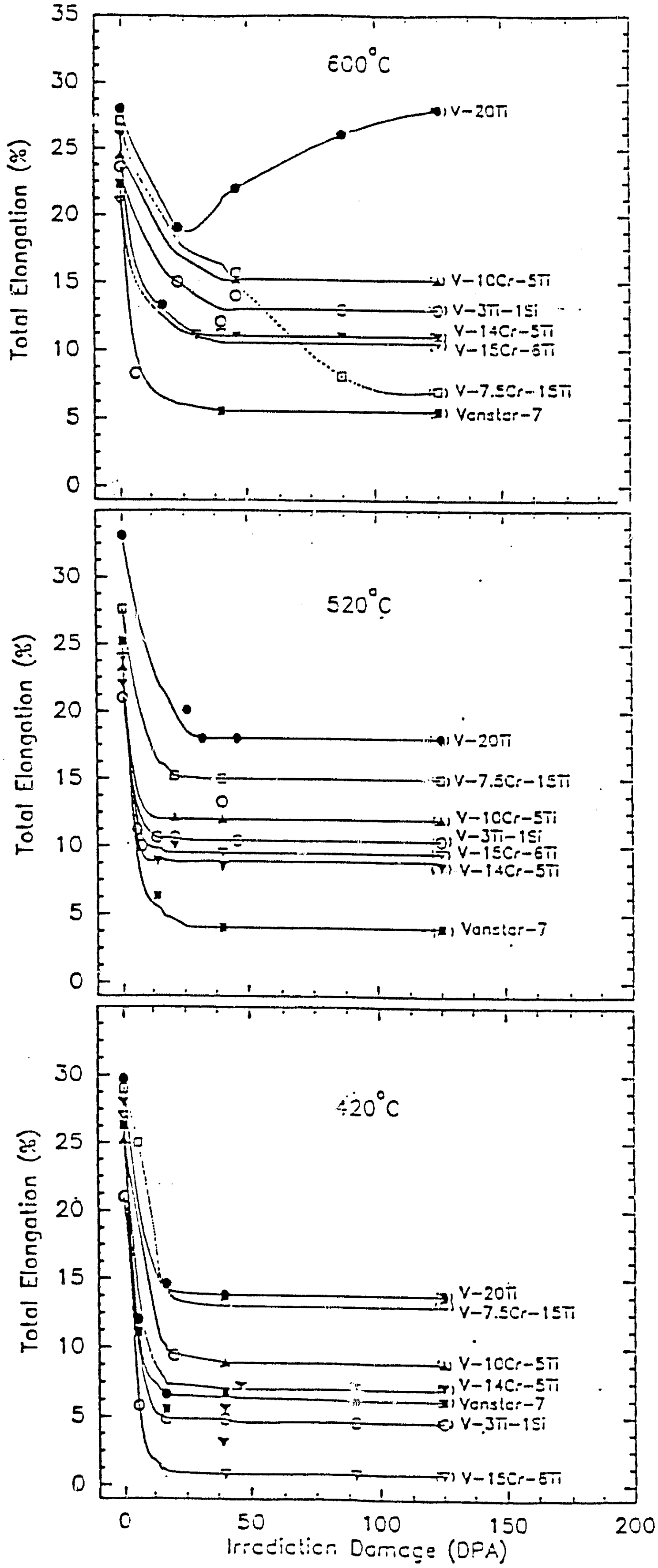
Fig. 9. Dependence of swelling of V-(0-15)Cr-5Ti alloys irradiated at 420, 520, and 600°C on chromium concentration.

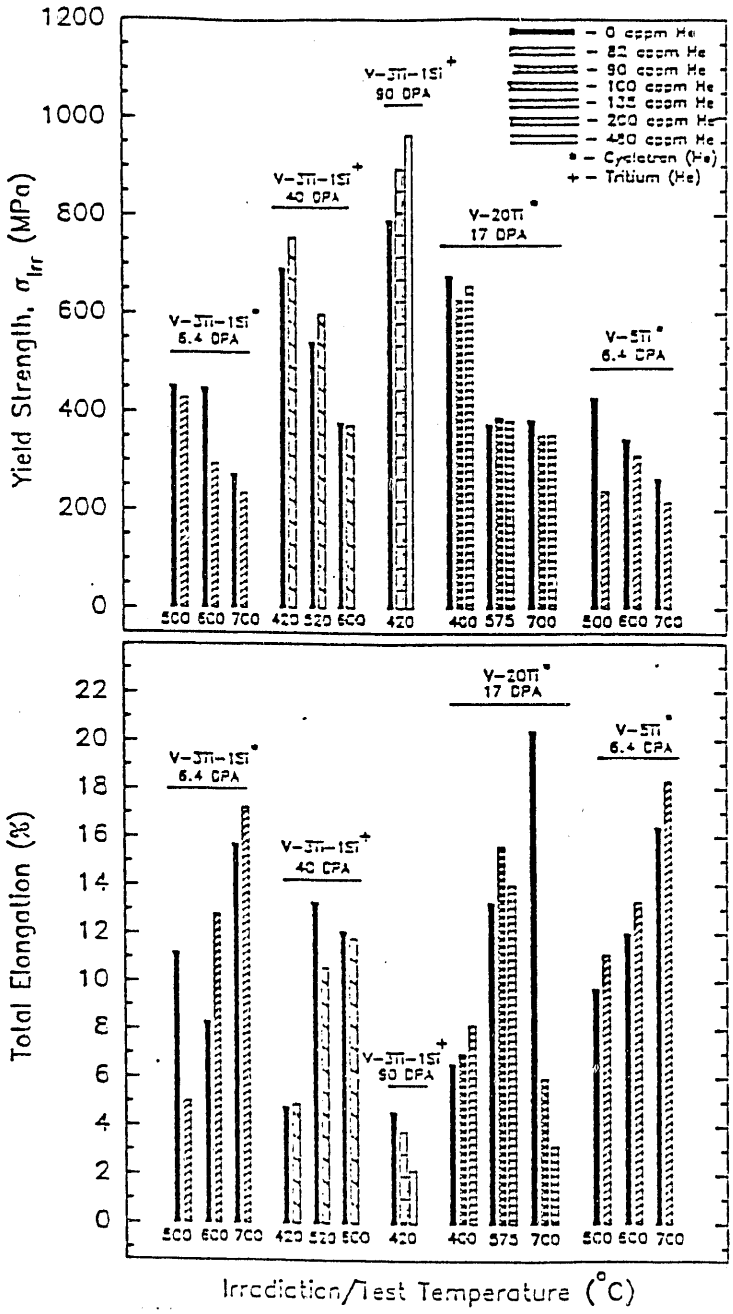
Fig. 10. Dependence of weight loss (increase) of vanadium and vanadium-base alloys on exposure time in (a) lithium, (b) water, and (c) helium environments.

Fig. 11. Dependence of UTS, stress-1000 h rupture time, DBTT, and swelling of V-(0-20)Ti alloys on Ti concentration.

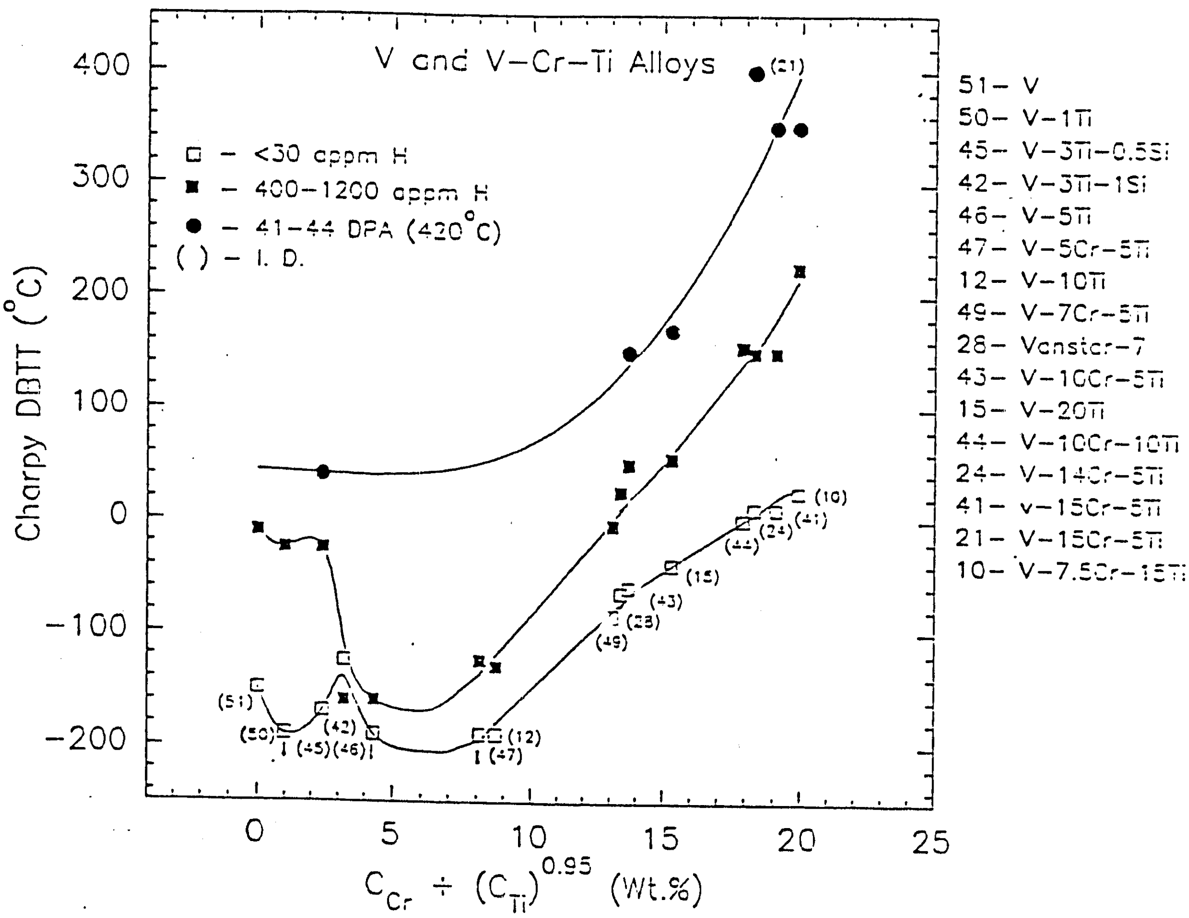


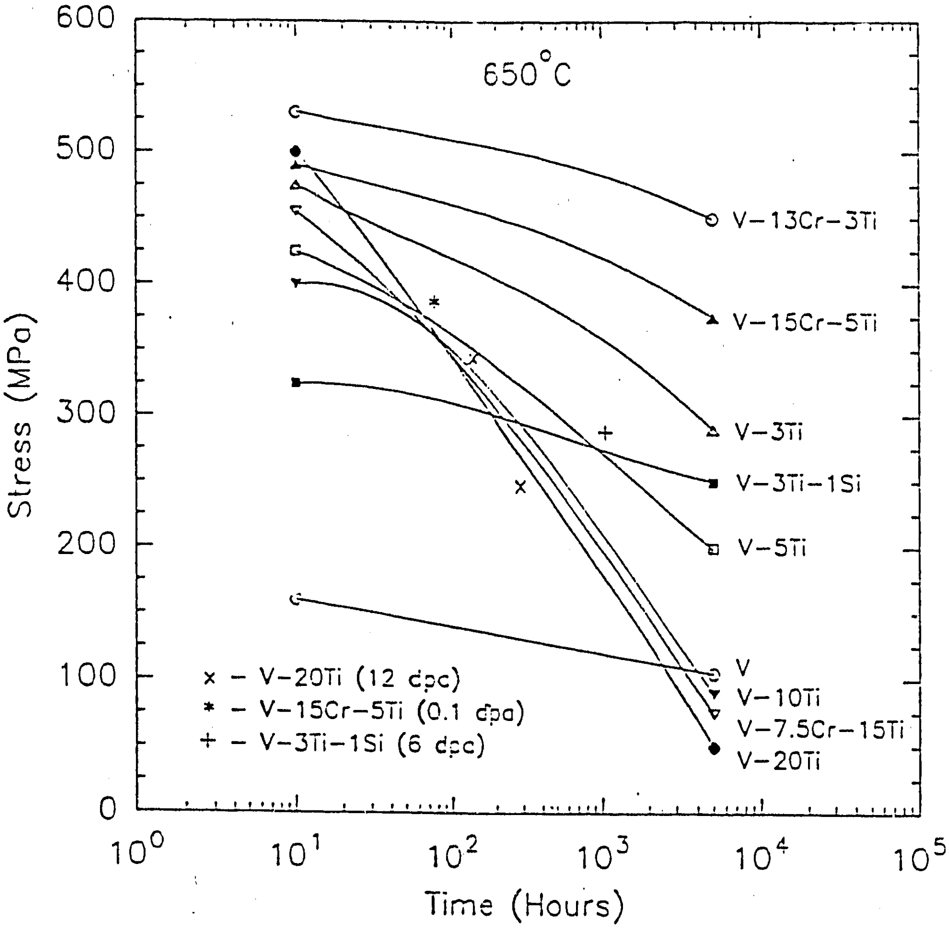
600°C
V-15Cr-5Ti
V-15Cr-6Ti
V-14Cr-5Ti
V-3Ti-1Si
V-10Cr-5Ti
Vanstar-7
V-7.5Cr-15Ti
V-20Ti
Ion Irradiation (710-725°C)
Increase of Yield Stress, Δσ (MPa)
Yield Stress, σ_o (MPa)
520°C
Vanstar-7
V-15Cr-5Ti
V-14Cr-5Ti
V-3Ti-1Si
V-10Cr-5Ti
V-7.5Cr-15Ti
V-20Ti
Increase of Yield Stress, $\Delta\sigma_o$ (MPa)
Yield Stress, σ_o (MPa)
420°C
Vanstar-7
V-3Ti-1Si
V-14Cr-5Ti
V-15Cr-6Ti
V-10Cr-5Ti
V-7.5Cr-15Ti
V-20Ti
Increase of Yield Stress, Δσ (MPa)
Yield Stress, σ_o (MPa)
Irradiation Damage (DPA)


600°C
520°C
420°C
Total Elongation (%)
Irradiation Damage (DPA)
V-20Ti
V-10Cr-5Ti
V-3Ti-1Si
V-14Cr-5Ti
V-15Cr-6Ti
V-7.5Cr-15Ti
Vanstar-7
0
5
10
15
20
25
30
35
50
100
150
200



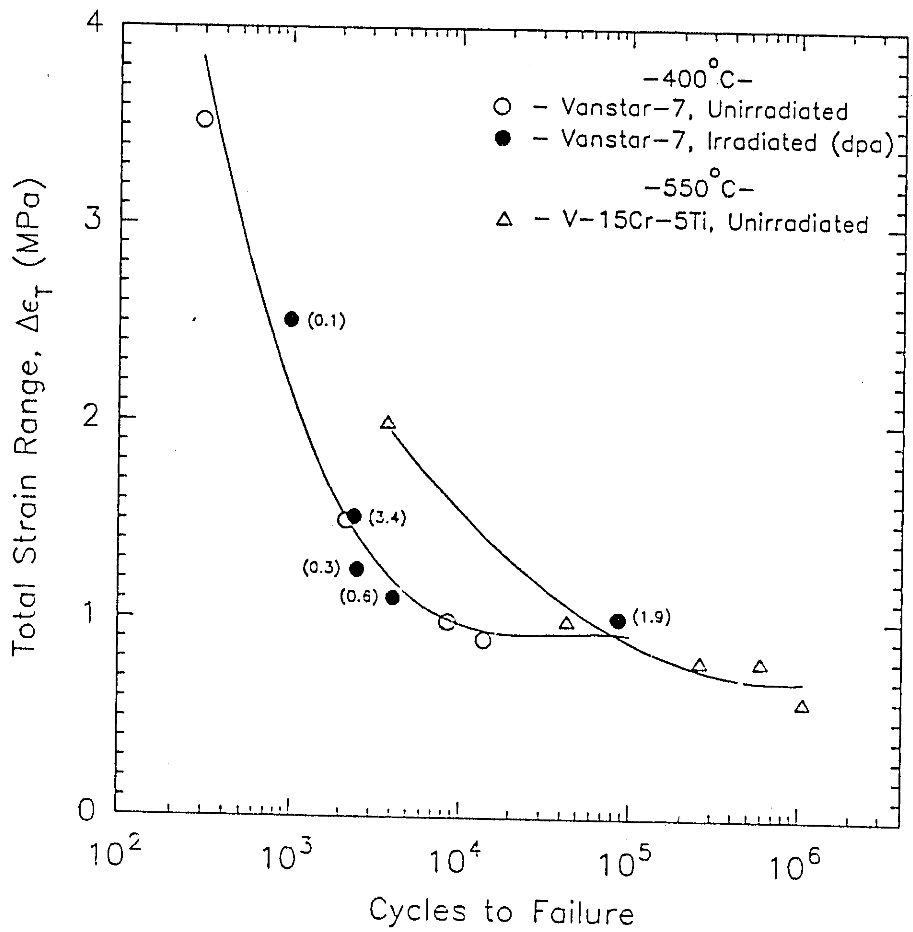
Yield Strength, σ_{Irr} (MPa)
V-3Ti-1Si* 6.4 DPA
V-3Ti-1Si+ 40 DPA
V-3Ti-1Si+ 90 DPA
V-20Ti* 17 DPA
V-5Ti* 6.4 DPA
- 0 appm He
- 82 appm He
- 90 appm He
- 100 appm He
- 135 appm He
- 200 appm He
- 480 appm He
* - Cyclotron (He)
+ - Tritium (He)
Total Elongation (%)
Irradiation/Test Temperature (°C)


V and V–Cr–Ti Alloys
□ – <30 appm H
■ – 400–1200 appm H
● – 41–44 DPA (420°C)
( ) – I. D.
Charpy DBTT (°C)
$C_{Cr} + (C_{Ti})^{0.95}$ (Wt.%)
51– V
50– V–1Ti
45– V–3Ti–0.5Si
42– V–3Ti–1Si
46– V–5Ti
47– V–5Cr–5Ti
12– V–10Ti
49– V–7Cr–5Ti
28– Vanstar–7
43– V–10Cr–5Ti
15– V–20Ti
44– V–10Cr–10Ti
24– V–14Cr–5Ti
41– v–15Cr–5Ti
21– V–15Cr–5Ti
10– V–7.5Cr–15Ti

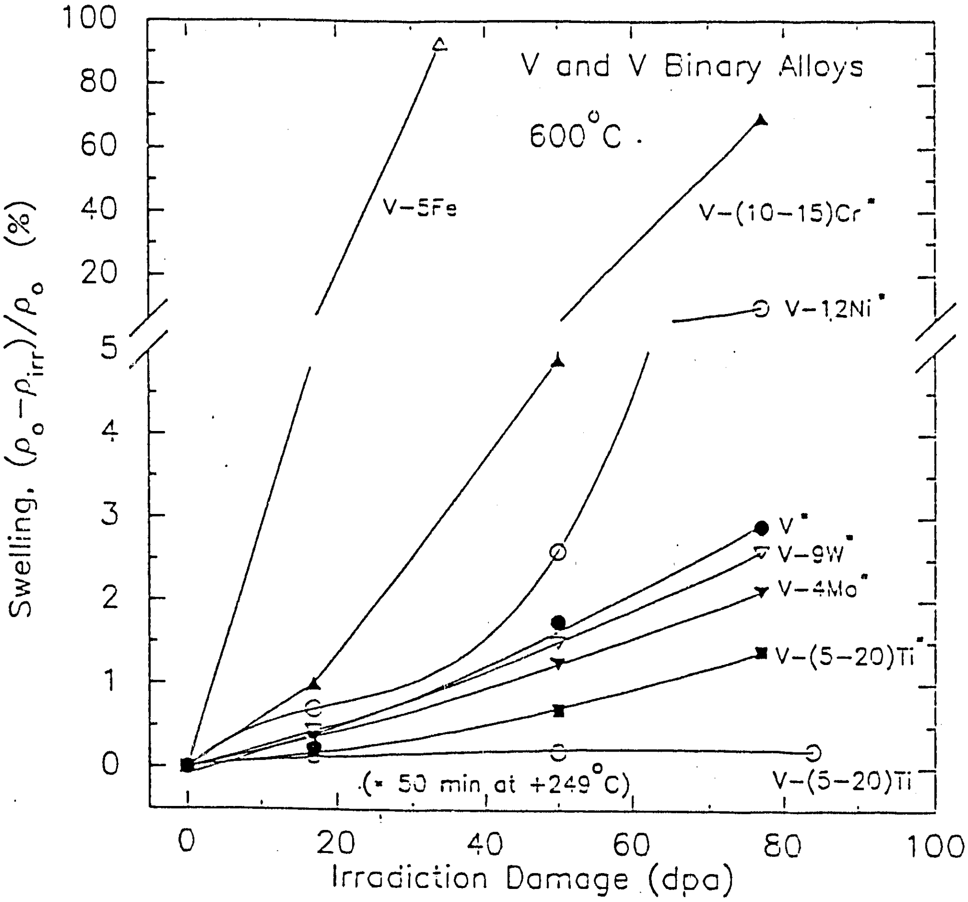


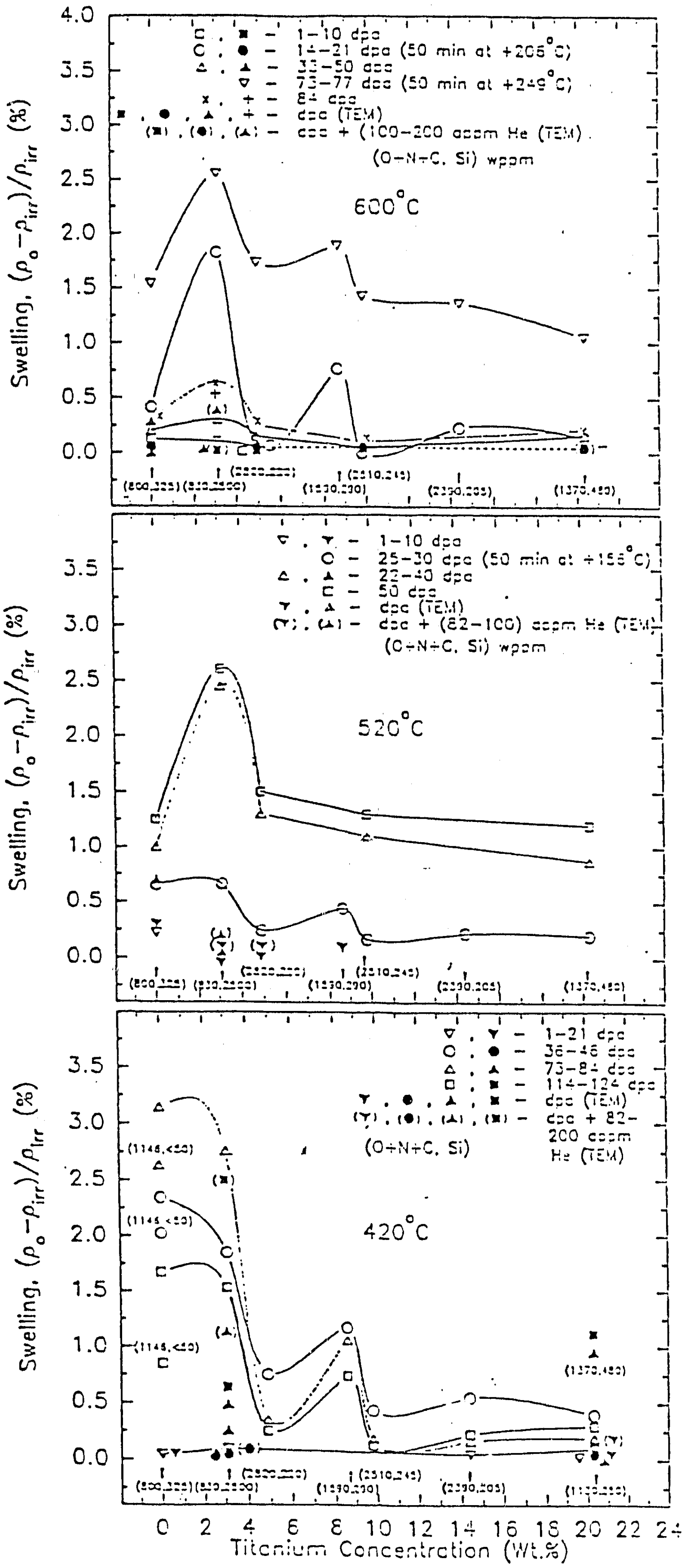
650°C
Stress (MPa)
Time (Hours)
V-13Cr-3Ti
V-15Cr-5Ti
V-3Ti
V-3Ti-1Si
V-5Ti
V
V-10Ti
V-7.5Cr-15Ti
V-20Ti
× – V-20Ti (12 dpc)
* – V-15Cr-5Ti (0.1 dpa)
+ – V-3Ti-1Si (6 dpc)

Fig. 5

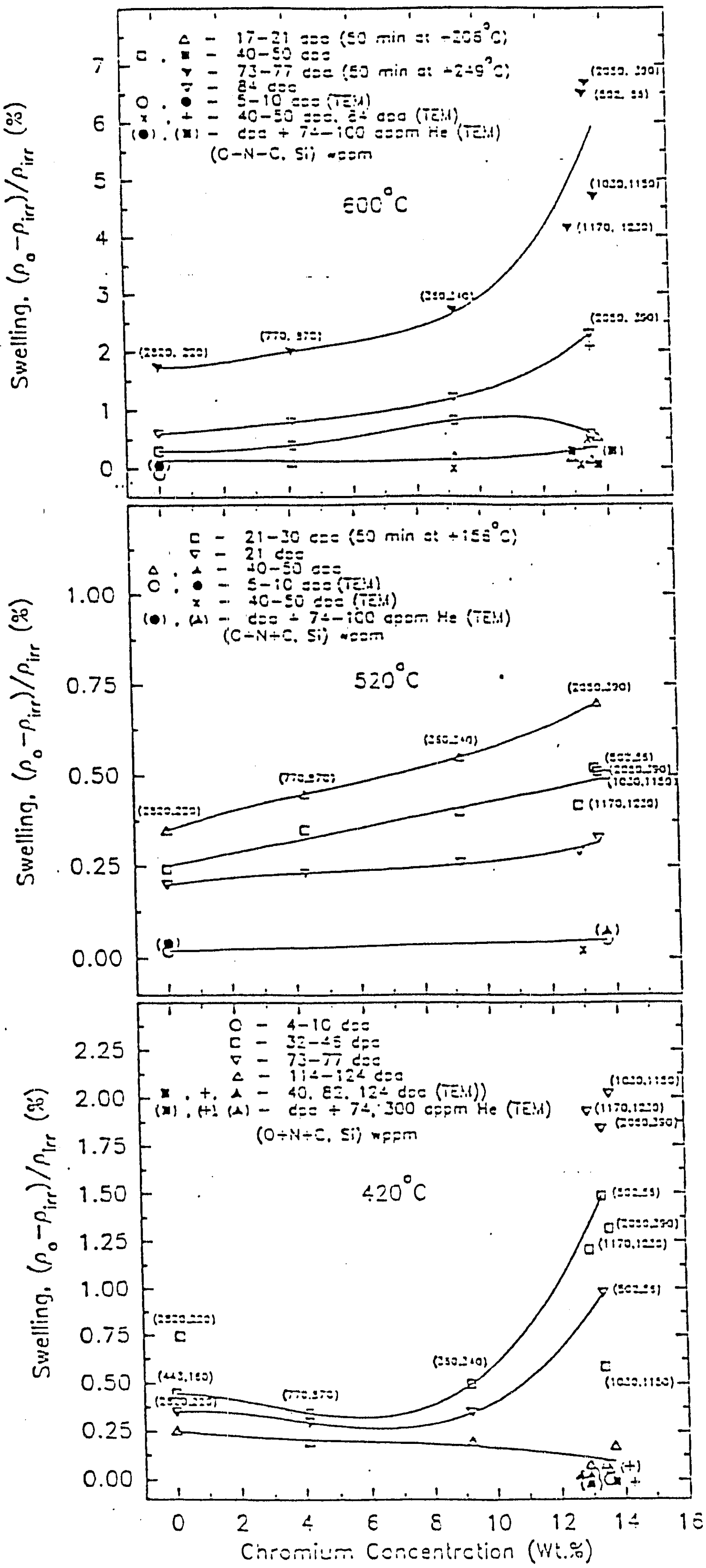


4
3
2
1
0
Total Strain Range, Δε_T (MPa)
10^2
10^3
10^4
10^5
10^6
Cycles to Failure
-400°C-
○ - Vanstar-7, Unirradiated
● - Vanstar-7, Irradiated (dpa)
-550°C-
△ - V-15Cr-5Ti, Unirradiated
(0.1)
(3.4)
(0.3)
(0.6)
(1.9)

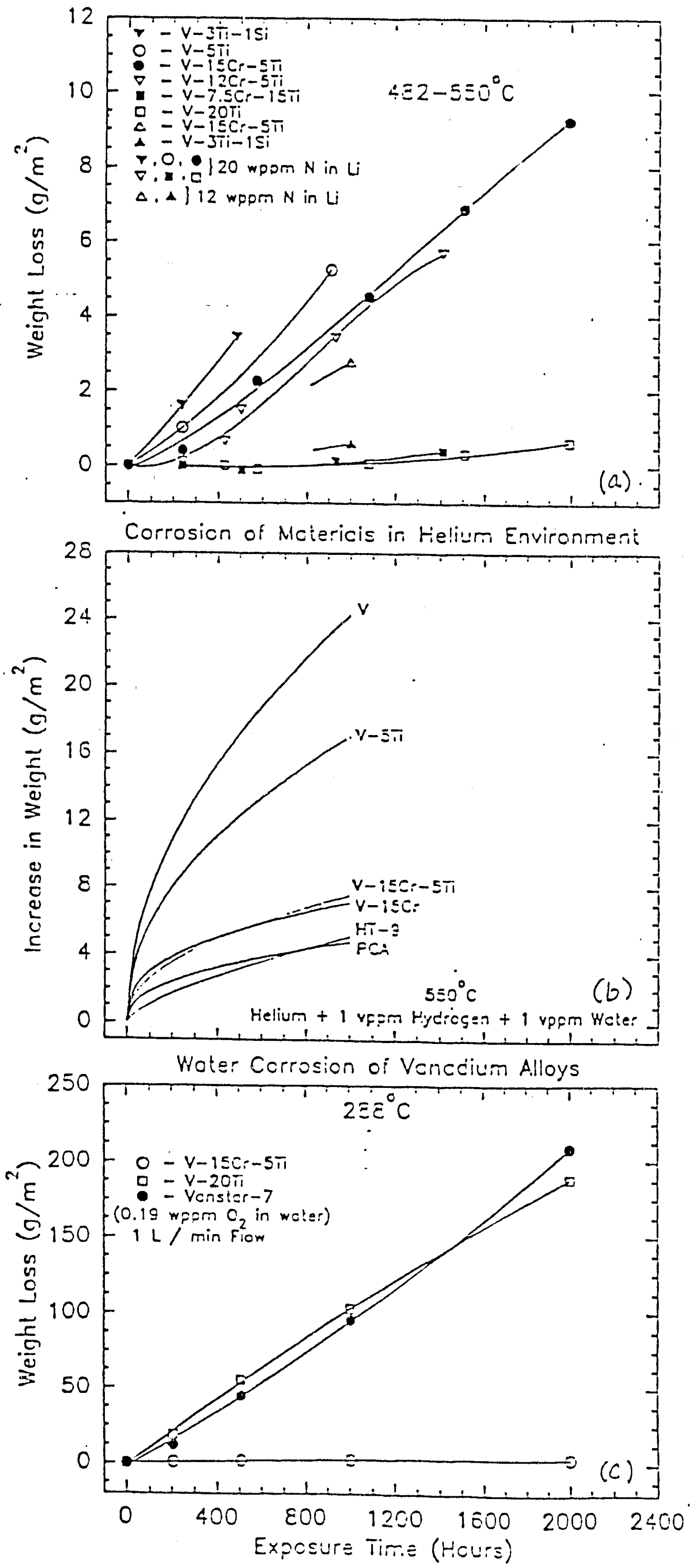

V and V Binary Alloys
600°C
V-5Fe
V-(10-15)Cr*
V-12Ni*
V*
V-9W*
V-4Mo*
V-(5-20)Ti*
V-(5-20)Ti
(* 50 min at +249°C)
Swelling, $(\rho_o-\rho_{irr})/\rho_o$ (%)
Irradiction Damage (dpa)
0
20
40
60
80
100
1
2
3
4
5

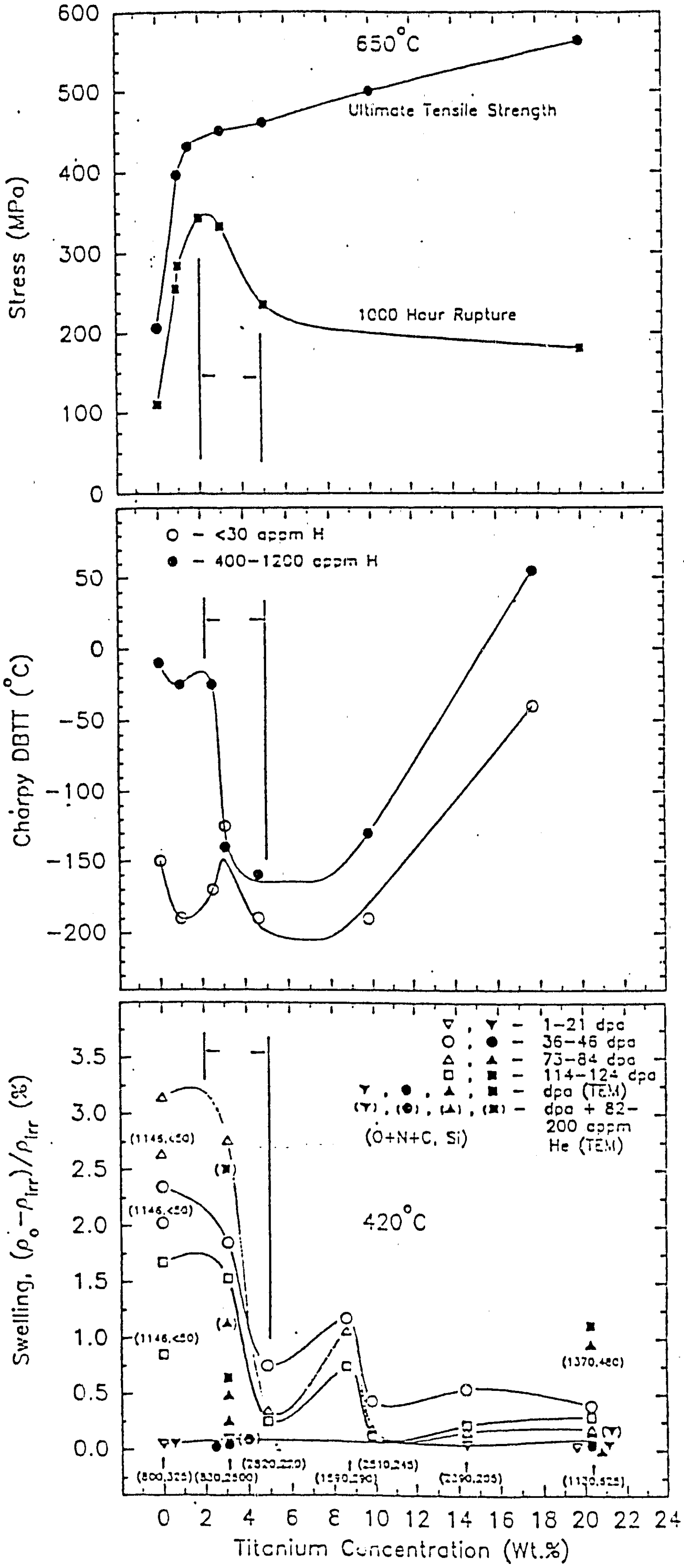


Swelling, $(\rho_o - \rho_{irr})/\rho_{irr}$ (%)
□ , ■ – 1–10 dpa
○ , ● – 14–21 dpa (50 min at +206°C)
△ , ▲ – 33–50 dpa
▽ – 73–77 dpa (50 min at +249°C)
x , + – 84 dpa
■ , ● , ▲ , + – dpa (TEM)
(■) , (●) , (▲) – dpa + (100–200 appm He (TEM)
(O+N+C, Si) wppm
600°C
▽ , ▼ – 1–10 dpa
○ – 25–30 dpa (50 min at +156°C)
△ , ▲ – 22–40 dpa
□ – 50 dpa
▼ , ▲ – dpa (TEM)
(▼) , (▲) – dpa + (82–100) appm He (TEM)
(O+N+C, Si) wppm
520°C
▽ , ▼ – 1–21 dpa
○ , ● – 36–46 dpa
△ , ▲ – 73–84 dpa
□ , ■ – 114–124 dpa
▼ , ● , ▲ , ■ – dpa (TEM)
(▼) , (●) , (▲) , (■) – dpa + 82–200 appm He (TEM)
(O+N+C, Si)
420°C
Titanium Concentration (Wt.%)



17-21 dpa (50 min at ~205°C)
40-50 dpa
73-77 dpa (50 min at ~249°C)
84 dpa
5-10 dpa (TEM)
40-50 dpa, 84 dpa (TEM)
dpa + 74-100 appm He (TEM)
(O+N+C, Si) wppm
600°C
(2050, 290)
(500, 55)
(1030, 1150)
(1170, 1220)
(250, 240)
(770, 570)
(2020, 220)
Swelling, (ρo−ρirr)/ρirr (%)
21-30 dpa (50 min at ~155°C)
21 dpa
40-50 dpa
5-10 dpa (TEM)
40-50 dpa (TEM)
dpa + 74-100 appm He (TEM)
(O+N+C, Si) wppm
520°C
(1170,1220)
4-10 dpa
32-45 dpa
73-77 dpa
114-124 dpa
40, 82, 124 dpa (TEM))
dpa + 74, 300 appm He (TEM)
(O+N+C, Si) wppm
420°C
(1030,1150)
(1170,1220)
(2050,290)
(500,55)
(250,240)
(443,160)
(770,570)
Chromium Concentration (Wt.%)


V-3Ti-1Si
V-5Ti
V-15Cr-5Ti
V-12Cr-5Ti
V-7.5Cr-15Ti
V-20Ti
V-15Cr-5Ti
V-3Ti-1Si
} 20 wppm N in Li
} 12 wppm N in Li
482-550°C
Weight Loss (g/m²)
(a)
Corrosion of Materials in Helium Environment
V
V-5Ti
V-15Cr-5Ti
V-15Cr
HT-9
PCA
550°C
Helium + 1 vppm Hydrogen + 1 vppm Water
Increase in Weight (g/m²)
(b)
Water Corrosion of Vanadium Alloys
288°C
V-15Cr-5Ti
V-20Ti
Vanstar-7
(0.19 wppm O₂ in water)
1 L / min Flow
Weight Loss (g/m²)
(c)
0
400
800
1200
1600
2000
2400
Exposure Time (Hours)



Stress (MPa)
650°C
Ultimate Tensile Strength
1000 Hour Rupture
600
500
400
300
200
100
0
Charpy DBTT (°C)
○ – <30 appm H
● – 400-1200 appm H
50
0
-50
-100
-150
-200
Swelling, $(\rho_o-\rho_{irr})/\rho_{irr}$ (%)
1-21 dpa
36-46 dpa
73-84 dpa
114-124 dpa
dpa (TEM)
dpa + 82-200 appm He (TEM)
(O+N+C, Si)
420°C
(1145,450)
(1146,450)
(1370,480)
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0 2 4 6 8 10 12 14 16 18 20 22 24
Titanium Concentration (Wt.%)

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