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# SWELLING OF NEUTRON-IRRADIATED VANADIUM ALLOYS


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# SWELLING OF NEUTRON-IRRADIATED VANADIUM ALLOYS*

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## Abstract

The swelling of unalloyed vanadium and vanadium alloys containing Cr, Ti, Si, Fe, Zr, W, Mo, and Ni additions was determined after neutron irradiation at 420 and 600°C to 17-84 dpa in the FFTF-MOTA reactor facility. The swelling of these materials was obtained from a determination of the immersion density of the unirradiated and irradiated materials. The swelling of V is substantially increased by the addition of Cr, and significantly reduced by the addition of Ti. The swelling of V-Cr-Ti alloys is strongly dependent on Ti concentration for Ti concentrations <3%. For resistance to irradiation-induced swelling, the Ti concentration in a V-Cr-Ti alloy that is to be used as a structural material in a magnetic fusion reactor should be greater than 3%. For these ranges of Ti concentration in a V-Cr-Ti alloy, Cr concentrations of <15% have minimal effect on the swelling of the alloy. The Vanstar-7 alloy exhibits high (7-10%) swelling on irradiation at 600°C to 77 dpa. Swelling of V-7.2Cr-14.5Ti, V-13.5Cr-5.2Ti, V-9.2Cr-4.9Ti, V-3.1Ti-(0.3-0.5)Si, and V-17.7Ti on neutron irradiation at 600°C to 87 dpa is (in % per dpa) 0.10, 0.03, 0.03, 0.01, and 0.01, respectively.

Key words: Vanadium, vanadium alloys, neutron irradiation, swelling.

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## 1. Introduction

The swelling of V-15Cr-5Ti, Vanstar-7, V-3Ti-1Si, V-20Ti, and V-15Ti-7.5Cr on neutron irradiation at temperatures ranging from 420 to 600°C and irradiation damage levels ranging up to 40 atom displacements per atom (dpa) have been reported by several investigators [1-7]. The results obtained from these investigations have shown that V-15Cr-5Ti, V-3Ti-1Si, V-20Ti, and V-15Ti-7.5Cr are resistant to swelling caused by the presence of voids or cavities and typically exhibit swelling <0.3% (40 dpa). The results obtained from these investigations also show that Vanstar-7 can exhibit swelling of up to 6%.

Ohnuki, et al. determined the swelling of V-3Cr, V-15Ti, and V-3Mo after neutron irradiation at 500-600°C to approximately 1 dpa [8]. The swelling values reported for these neutron-irradiated alloys suggest that (1) Ti suppresses swelling of V, (2) Cr exacerbates swelling of V, and (3) Mo has a relatively minor effect on the swelling of V.

A dimensional change (swelling) of materials on neutron irradiation can occur as a result of void formation, cavity formation, thermal- and irradi-

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ation-induced precipitate formation and dissolution, thermal- and irradiation-induced phase change, and thermal- and irradiation-induced solute segregation. The swelling values that have been previously reported for neutron-irradiated V alloys were obtained from observations by transmission electron microscopy (TEM) of irradiated materials [1-8]. Therefore, these evaluations have only taken into account swelling that is attributable to the presence of voids and cavities. The TEM observations of irradiated V alloys have shown the presence of irradiation- and/or thermal-induced precipitates in addition to voids [1-10]. In this paper, swelling data for neutron-irradiated V alloys and unalloyed V are presented that were obtained from determinations of the immersion density of unirradiated and neutron-irradiated specimens.

## 2. Materials and procedure

Specimens approximately 3.0 mm in diameter and 0.3 mm thick were obtained from 50% cold-worked sheets of the materials listed in Table 1. The cold-worked specimens were annealed at 1125°C for one hour in an ion-pumped vacuum system with a typical pressure of $1.3 \times 10^{-6}$ Pa. The average recrystallized grain diameter in these annealed materials was 0.020 mm. The specimens were irradiated in the Materials Open Test Assembly (MOTA) in the Fast Flux Test Facility (FFTF) reactor. They were contained in sealed, $Li^7$-filled, TZM molybdenum capsules during irradiation to prevent contamination from oxygen, nitrogen, and carbon impurities in the FFTF sodium coolant. The specimens were irradiated at 420 and 600°C to neutron fluences (E > 0.1 MeV) ranging from $3.4 \times 10^{22}$ n/cm$^2$ (17 dpa) to $17.4 \times 10^{22}$

$n/cm^2$ (87 dpa) during Cycles 7,8,9,and 10 of the FFTF-MOTA facility. The specimens that were irradiated at 600°C during Cycles 7-8 experienced a temperature excursion of 249°C for 50 minutes during the Cycle 7 portion of the irradiation. The irradiated specimens were removed from the Li-filled TZM molybdenum capsules by immersion of the opened capsules in liquid $NH_3$ and subsequent immersion of the specimens in a mixture of 50% ethanol and 50% methanol.

The hydrogen concentration in irradiated specimens from each of the TZM capsules was determined with a quadrapole, partial-pressure gas analyzer mounted in an ion-pumped vacuum system [11]. The hydrogen concentration in specimens irradiated at 420°C during Cycles 7-8, 8, and 8-9 of the FFTF-MOTA was typically 5000-10000 appm, whereas the hydrogen concentration in specimens irradiated at 420°C during Cycles 9-10 and 10 was typically <500 appm. The hydrogen concentration in specimens irradiated at 600°C was typically <500 appm. The hydrogen concentration in specimens irradiated at 420°C was generally in the order of V-3.1Ti-0.3Si > V-13.5Cr-5.2Ti > V-7.2Cr-14.5Ti > V-17.7Ti, whereas the hydrogen concentration in specimens irradiated at 600°C was in the order of V-7.2Cr-14.5Ti > V-13.5Cr-5.2Ti > V-9.2Cr-4.9Ti > V-17.7Ti.

The specimens that were irradiated at 420°C and 600°C during Cycles 7-8, 8, and 8-9 of the FFTF-MOTA showed significant corrosion product on the surfaces. In contrast, the surfaces of specimens that were irradiated during Cycles 10 and 9-10 were conspicuously free of corrosion product. These observations, together with the results of the hydrogen analyses and the absence of a temperature excursion during irradiation, have led us to consider that the swelling data obtained for specimens irradiated during Cycles 10 and 9-10 of the FFTF-MOTA are significantly more credibile than those data obtained for specimens irradiated during Cycles 7-8, 8, and 8-9.

The swelling (S) of an irradiated specimen was obtained from a determination of the density of an unirradiated specimen ($D_{ann}$) and the density of an irradiated specimen ($D_{irr}$) by immersion in $CCl_4$, i.e., $S = (D_{ann} - D_{irr})/D_{irr}$. The reported density for a specimen was determined with a precision of 0.1% from 3-6 separate determinations on a specimen.

**3. Experimental results**

The dependence of swelling on Ti concentration for the V-Ti alloys after neutron irradiation at 420°C to 36 and 73-77 dpa is shown in Fig. 1 (data in Table 2, Ref. 12). The swelling of V on irradiation at 420°C to 36 and 77 dpa was significantly decreased by the addition of 4.9% Ti. With the exception of V-8.6Ti, the swelling of the binary V-Ti alloys on irradiation at 420°C was not strongly dependent on Ti concentration in the range of 5 to 20 wt.% Ti. The higher swelling of V-8.6Ti compared with that of V-4.9Ti, V-9.8Ti, and V-14.4Ti may be attributed to the relatively low oxygen concentration in V-8.6Ti. In general, the swelling of V-Ti alloys containing >3.1% Ti was slightly higher for those irradiated to 36 dpa than for those irradiated to 73-77 dpa.

The dependence on Ti concentration of swelling for the V-Cr-Ti and V-Ti-Si alloys on irradiation at 600°C to 77-84 dpa is shown in Fig. 2 (data from Table 2 of Ref. 12). The addition of 0.3% Ti to V-14.1Cr alloy was sufficient to reduce its swelling from 39% to 15%. An increase of the Ti concentration to 5% caused a further reduction of swelling of V-14.1Cr alloy to approximately 2% on irradiation at 600°C to 84 dpa. The swelling of the V-Ti-Si alloys on irradiation at 600°C was not strongly dependent on the Ti concentration. The lower swelling of V on irradiation at 600°C compared with swelling at 420°C (Fig. 1) may be partially attributed to the irradiation temperature of 600°C being above the peak swelling temperature, which is ~550°C [13]. The swelling data in Fig. 2 for V-14.4Ti and V-7.2Cr-14.5Ti suggest that (1) the swelling of V-Ti and V-Cr-Ti alloys may be increased for Ti concentrations in the range of 10 to 18% Ti, and (2) the swelling of V-Cr-Ti alloys containing >5% Ti is not dependent on Cr concentration for Cr concentrations of <15%.

Figure 3 shows the dependence of the swelling of V-7.2Cr-14.5Ti, V-9.2Cr-4.9Ti, V-13.5Cr-5.2Ti, V-3.1Ti-(0.3-0.5)Si, and V-17.7Ti produced by irradiation at 600°C. These specimens were irradiated during Cycles 10 and 9-10 of the FFTF-MOTA. On the basis of these data, the swelling of V-7.2Cr-14.5Ti, V-13.5Cr-5.2Ti, V-9.2Cr-4.9Ti, V-3.1Ti-(0.3-0.5) Si, and V-17.7Ti on irradiation at 600°C to 84 dpa is (in % per dpa) 0.10, 0.03, 0.03, 0.01, and 0.01, respectively. It may be noted that the swelling of these alloys (Fig. 3) at the highest damage level (84 dpa) is inversely related to the tensile ductility of the irradiated alloys (600°C, 87 dpa), i.e., highest ductility for V-17.7Ti (26.2%), intermediate ductility for V-3.1Ti-0.3Si (13.0%) and V-13.5Cr-5.2Ti (11.0%), and lowest ductility for V-7.2Cr-14.5Ti (8.1%) [14].

The addition of 8.6% W to V increased the swelling of V on irradiation at 420°C to 36 dpa, whereas the addition of 4.0% Mo and 12.3% Ni had a minor effect on the swelling of V at 420°C. However, on irradiation at

600°C to 17 dpa, such additions of either Ni, W, or Mo to V increased the swelling of V by ~0.5% [12]. The Vanstar-7 exhibited high (7-10%) swelling on irradiation at 600°C to 77 dpa [12].

## 5. Conclusions

1. The swelling of V-Ti and V-Cr-Ti alloys on neutron irradiation at 420 and 600°C is strongly dependent on Ti concentration.
2. The V-Cr-Ti alloys with greater than 3% Ti exhibit greater resistance to irradiation-induced swelling. For these ranges of Ti concentration in a V-Cr-Ti alloy, Cr concentrations of <15% have minimal effect on the swelling.
3. The swelling of V-7.2Cr-14.5Ti, V-13.5Cr-5.2Ti, V-9.2Cr-4.9Ti, V-3.1Ti-(0.3-0.5)Si, and V-17.7Ti on neutron irradiation at 600°C to 84 dpa is (in % per dpa) 0.10, 0.03, 0.03, 0.01, and 0.01, respectively.

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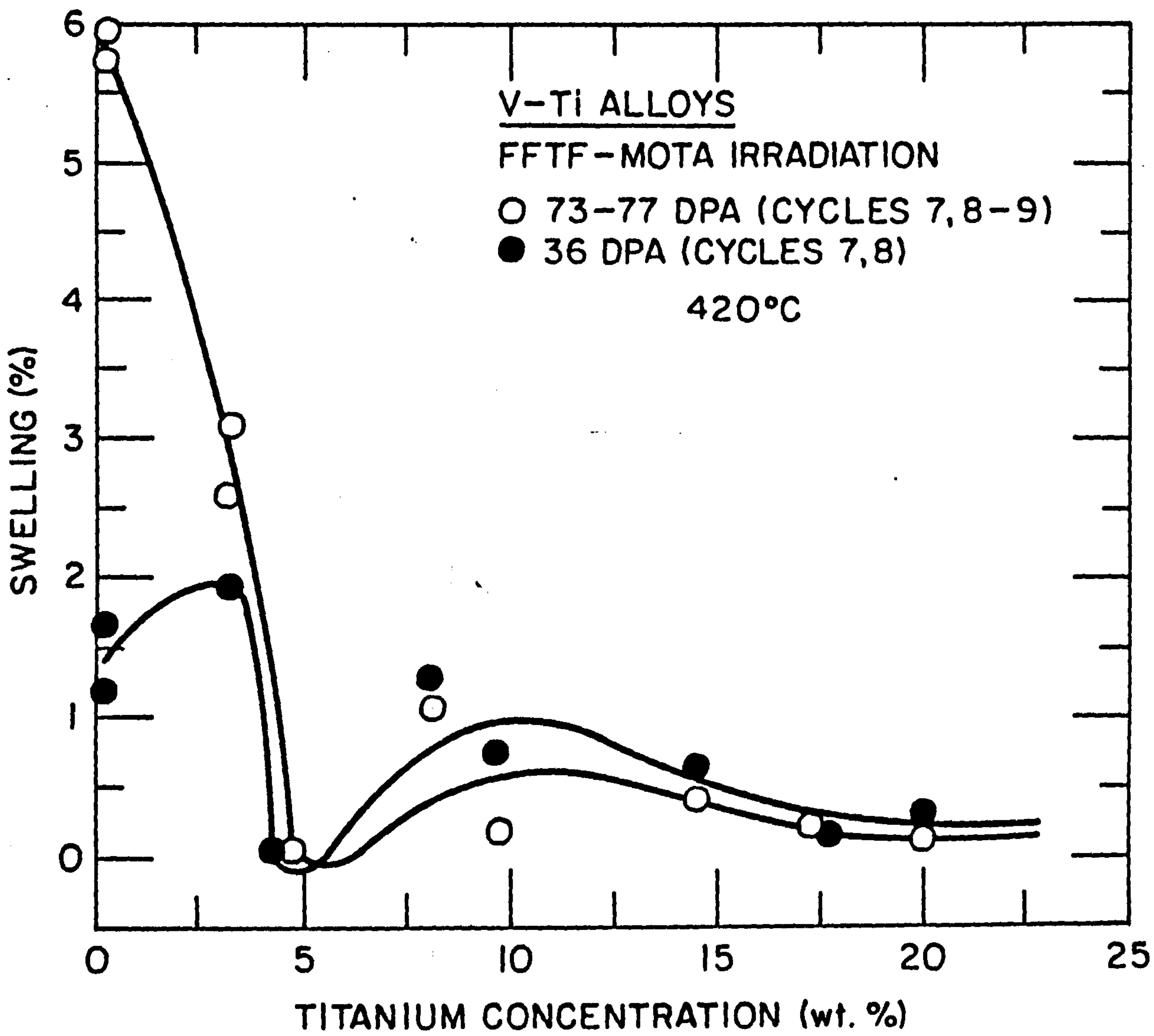
Table 1.
Vanadium and Vanadium Alloy Composition[1]

| ANL I.D. | Material (Wt.%) | Melt Number | Concentration (ppm) O | N | C | Si | Al |
|---|---|---|---|---|---|---|---|
| BL-1 | V-4.0Mo | ANL 1 | 230 | 73 | 90 | 110 | <100 |
| BL-2 | V-8.6W | ANL 2 | 300 | 150 | 120 | 59 | <100 |
| BL-3 | V-12.3Ni | ANL 3 | 490 | 280 | 500 | 405 | <100 |
| BL-4 | V-10.0Cr | ANL 4 | 530 | 76 | 240 | <50 | 1190 |
| BL-5 | V-14.1Cr | ANL 5 | 330 | 69 | 200 | <50 | 2740 |
| BL-10 | V-7.2Cr-14.5Ti | ANL 94 | 1110 | 250 | 400 | 400 | 30 |
| BL-11 | V-4.9Ti | ANL 11 | 1820 | 530 | 470 | 220 | 115 |
| BL-12 | V-9.8Ti | ANL 12 | 1670 | 390 | 450 | 245 | <100 |
| BL-13 | V-14.4Ti | ANL 13 | 1580 | 370 | 440 | 205 | <100 |
| BL-15 | V-17.7Ti | CAM 832 | 830 | 160 | 380 | 480 | 33 |
| BL-16 | V-20.0Ti | CAM 833 | 390 | 530 | 210 | 480 | - |
| BL-20 | V | ANL 20 | 570 | 110 | 120 | 325 | <100 |
| BL-24 | V-13.5Cr-5.2Ti | ANL 101 | 1190 | 360 | 500 | 390 | 40 |
| BL-25 | V-14.4Cr-0.3Ti | ANL 25 | 390 | 64 | 120 | <50 | 3270 |
| BL-26 | V-14.1Cr-1.0Ti | ANL 26 | 560 | 86 | 140 | <50 | 3090 |
| BL-27 | V-3.1Ti-0.3Si | ORNL 10837 | 210 | 310 | 310 | 2500 | 160 |
| BL-28 | Vanstar-7[2] | CAM 837 | 275 | 540 | 740 | - | - |
| BL-34 | V-8.6Ti | ANL 34 | 990 | 180 | 420 | 290 | <100 |
| BL-35 | V-9.5Cr | ANL 35 | 340 | 45 | 120 | <50 | 1450 |
| BL-36 | V | ANL 36 | 810 | 86 | 250 | <50 | <100 |
| BL-42 | V-3.1Ti-0.5Si | WI 8505 | 580 | 190 | 140 | 5400 | 290 |
| BL-43 | V-9.2Cr-4.9Ti | ANL 206 | 230 | 31 | 100 | 340 | 140 |

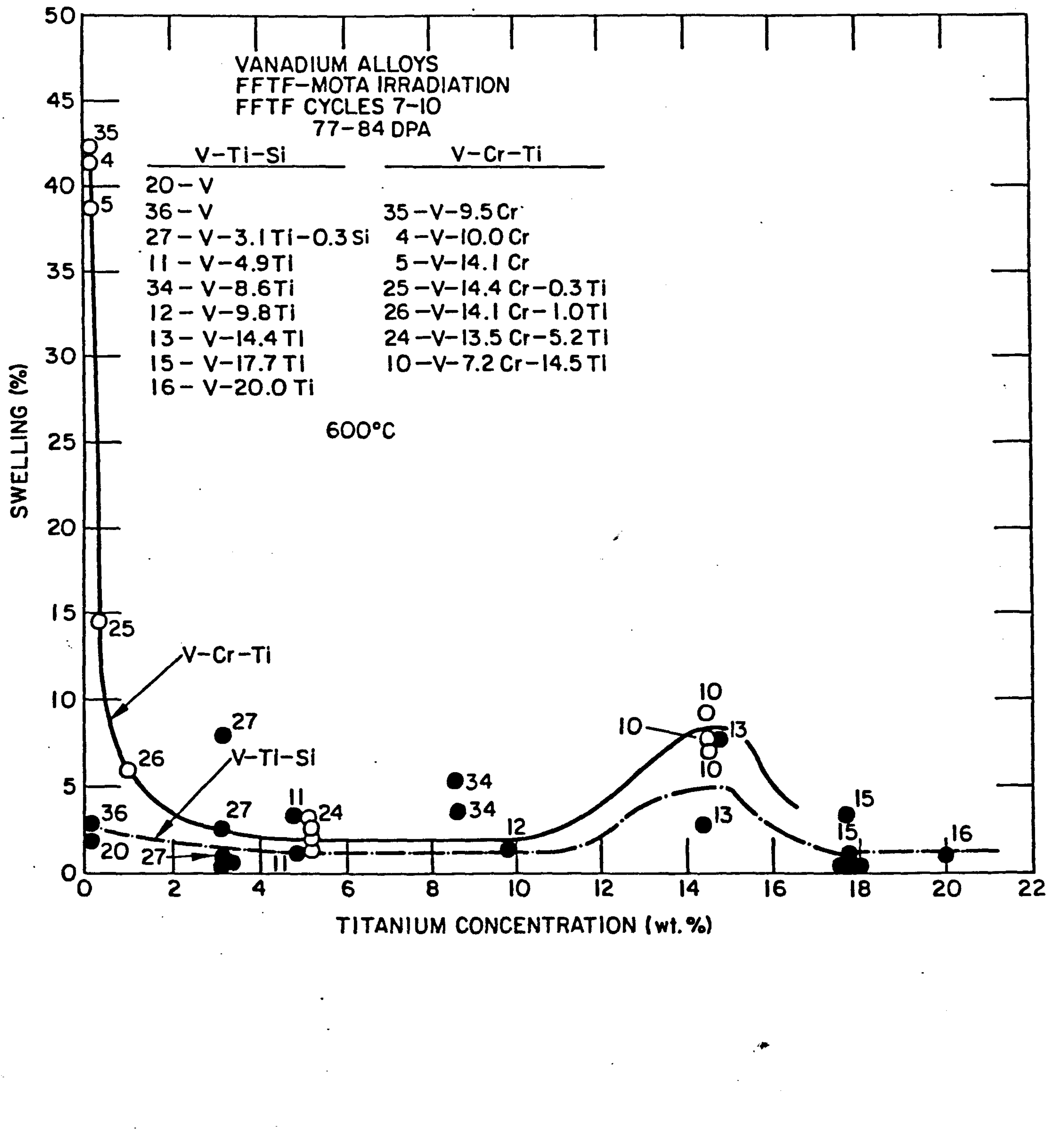
[1]The chemical analyses of these materials were performed by the Analytical Department of the Teledyne Wah Chang Albany Company.
[2]V-9.0Cr-3.2Fe-1.2Zr.

**List of Figures:**



V-Ti ALLOYS
FFTF-MOTA IRRADIATION
O 73-77 DPA (CYCLES 7,8-9)
● 36 DPA (CYCLES 7,8)
420°C
SWELLING (%)
6
5
4
3
2
1
0
0
5
10
15
20
25
TITANIUM CONCENTRATION (wt. %)


Fig. 1



VANADIUM ALLOYS
FFTF-MOTA IRRADIATION
FFTF CYCLES 7-10
77-84 DPA
V-Ti-Si
20-V
36-V
27-V-3.1Ti-0.3Si
11-V-4.9Ti
34-V-8.6Ti
12-V-9.8Ti
13-V-14.4Ti
15-V-17.7Ti
16-V-20.0Ti
V-Cr-Ti
35-V-9.5Cr
4-V-10.0Cr
5-V-14.1Cr
25-V-14.4Cr-0.3Ti
26-V-14.1Cr-1.0Ti
24-V-13.5Cr-5.2Ti
10-V-7.2Cr-14.5Ti
600°C
SWELLING (%)
TITANIUM CONCENTRATION (wt.%)


Fig. 2

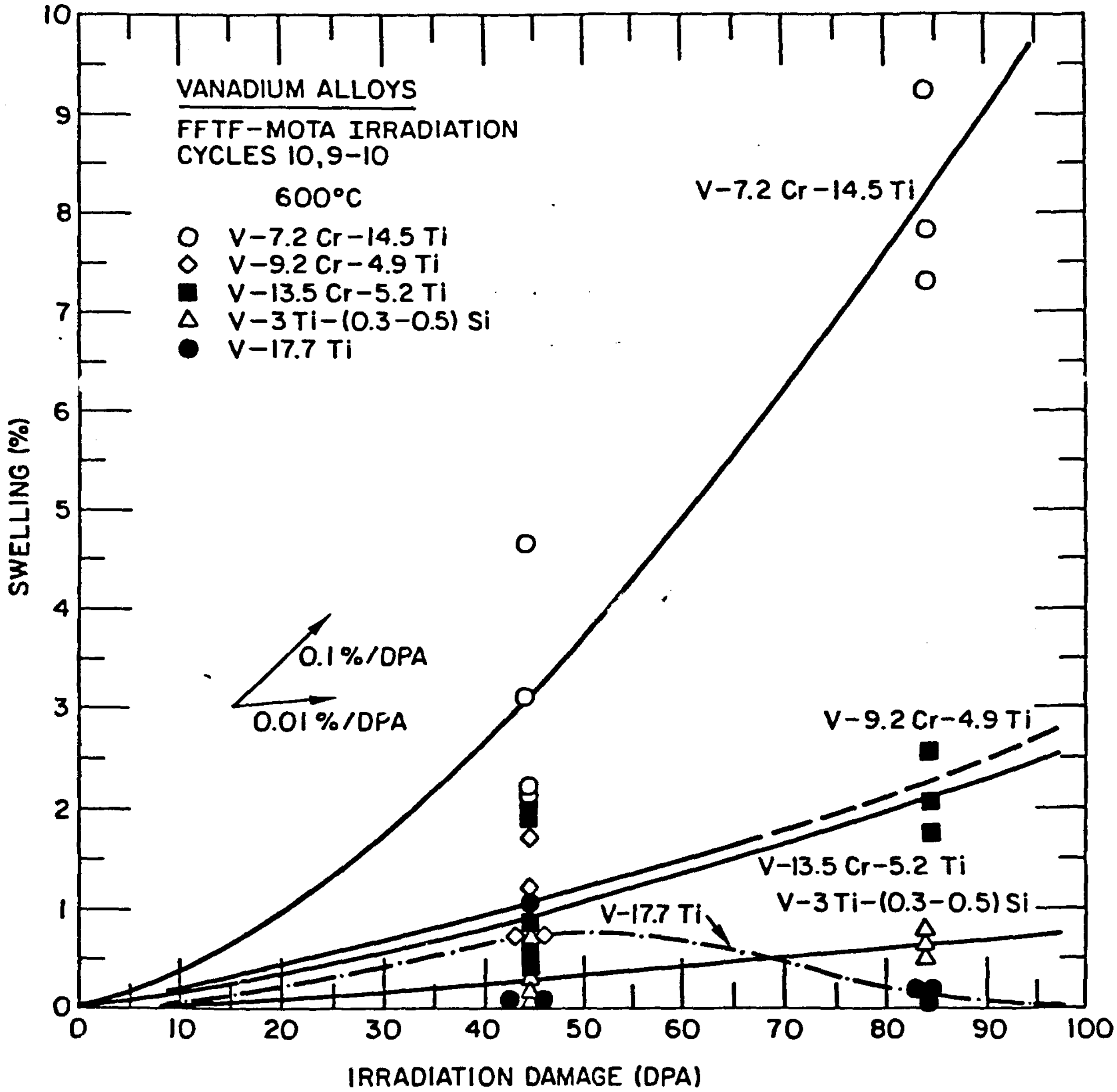

VANADIUM ALLOYS
FFTF-MOTA IRRADIATION
CYCLES 10, 9-10
600°C
V-7.2 Cr-14.5 Ti
V-9.2 Cr-4.9 Ti
V-13.5 Cr-5.2 Ti
V-3 Ti-(0.3-0.5) Si
V-17.7 Ti
0.1 %/DPA
0.01 %/DPA
V-7.2 Cr-14.5 Ti
V-9.2 Cr-4.9 Ti
V-13.5 Cr-5.2 Ti
V-3 Ti-(0.3-0.5) Si
V-17.7 Ti
SWELLING (%)
IRRADIATION DAMAGE (DPA)
0
1
2
3
4
5
6
7
8
9
10
0
10
20
30
40
50
60
70
80
90
100

Fig. 3