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REFERENCE VANADIUM ALLOY V-4Cr-4Ti FOR FUSION APPLICATION*

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Reference Vanadium Alloy V-4Cr-4Ti for Fusion Application*

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Abstract

Vanadium alloys exhibit important advantages as a candidate structural material for fusion first-wall/blanket applications. These advantages include high temperature and high wall load capability, favorable safety and environmental features, resistance to irradiation damage, and alloys of interest are readily fabricable. A substantial data base has been developed on laboratory-scale heats of V-Ti, V-Cr-Ti and V-Ti-Si alloys before and after irradiation. Investigations in recent years have focused primarily on compositions of V-(0-15)Cr-(0-20)Ti (0-1)Si. Results from these investigations have provided a basis for identifying a V-4Cr-4Ti alloy as the US reference vanadium alloy for further development. Major results obtained on one production-scale heat and three laboratory heats with compositions of V-(4-5)Cr-(4-5)Ti are presented in this paper.

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1. Introduction

Vanadium-base alloys are promising candidate materials for application in fusion reactor first-wall and blanket structures because of several important advantages, i.e., inherently low irradiation-induced activity, good mechanical properties, good compatibility with lithium, high thermal conductivity, and good resistance to irradiation-induced swelling and damage [1-3]. As part of a program to screen candidate alloys and develop an optimized vanadium-base alloy, extensive investigations of physical and mechanical properties of various V-Ti, V-Cr-Ti, and V-Ti-Si alloys have been conducted before and after irradiation in lithium environment in fast fission reactors [4-15]. From these investigations, a V-4Cr-4Ti alloy containing 500-1,000 wppm Si and <1,000 wppm O+N+C has been identified as the most promising alloy and is know as the US reference vanadium alloy. Consequently, the reference alloy has been the subject of comprehensive investigation and testing under fusion-relevant conditions, which included demonstration of production-scale fabrication, optimization of thermomechanical treatment, effects of hydrogen and other impurities, microstructural characteristics, and baseline properties (such as tensile, impact, fracture-toughness, and thermal creep properties). Also investigated was irradiation performance of the alloy after irradiation up to 35 dpa at 380°C-600°C in the fast fission reactors FFTF and EBR-II, i.e., effects of neutron irradiation and dynamically charged helium on tensile property, ductile-brittle-transition fracture behavior, impact toughness, density change, void swelling, and microstructural evolution of the alloy. Major results of this comprehensive set of investigations, obtained on one production-scale and three laboratory heats under fusion-relevant conditions, are presented in this paper.

2. Alloy Compositions

Several heats of V-(4-5)Cr-(4-5)Ti alloys have been produced and incorporated into the vanadium alloy test program. Much of the data presented previously has been on a laboratory scale heat (~30 Kg) of V-4Cr-4Ti designated BL-47. A 500 Kg production scale heat (#832665) has been produced with specifications similar to those of BL-47. Two laboratory scale heats of V-5Cr-5Ti (designated BL-63 and T87) have also been procured. The compositions of these alloys are given in Table 1. Properties measurements on these alloys are presented in the following sections. In addition, four 15 Kg laboratory scale heats with compositions of V-6Cr-6Ti, V-6Cr-3Ti, V-4Cr-4Ti and V-3Cr-3Ti have recently been procured by the US fusion program [16].

Table 1

3. Impact Properties

Impact properties were determined on the 500 Kg production scale heat and the three laboratory scale heats of V-(4-5)Cr-(4-5) Ti alloys. These alloys were given various thermal-mechanical treatments including annealing of temperatures of 950-1125°C for one hour. Charpy-impact tests were conducted on one-third-size specimens (30° and 45° angle notches) in order to evaluate their fracture behavior. Figure 1 shows the impact properties of the two V-4Cr-4Ti alloys and a recently procured heat (T87) of V-5Cr-5Ti alloy. All three alloys exhibit excellent impact properties with a ductile-brittle-transition temperature (DBTT) below -200°C. These results contrast with results previously reported for the V-5Cr-5Ti alloy heat BL-63 which exhibited much poorer impact properties [5]. The poorer impact properties of BL-63 have been [17] attributed to impurity effects and not to a much higher sensitivity to embrittlement of the V-5Cr-5Ti

Fig

compared to V-4Cr-4Ti. The effect of annealing temperature (950-1050°C for 1 hour) on the impact properties of the production scale heat (#832665) are given in Fig. 2. These results show little effect of annealing temperature on the impact properties when annealed in a high vacuum system.

Fig 2

Results on "as received" factory annealed (1050°C for 2 hours) material indicate modest reductions in the impact energies. Results obtained on Charpy specimens with a 30° notch indicated similar behavior. The impact properties of the V-5Cr-5Ti alloy (T87) as a function of annealing temperature are shown in Fig. 3. The results are similar to those for the V-4Cr-4Ti except for a modest increase in the DBTT at annealing temperatures above 1000°C. Based on these results, impact properties appear to be optimum for V-(4-5)Cr-(4-5)Ti alloys with a one hour anneal at ~1000°C. The effect of annealing temperature on the DBTT for T87 and 832665 are summarized in Fig. 4.

Fig 3

Fig 4

4. Tensile Properties

The tensile properties of several V-(0-15)Cr-(4-5)Ti alloys have been measured from room temperature to 700°C. The tensile and yield strengths and the total and uniform elongations of the three V-(4-5)Cr-(4-5)Ti alloys are given in Figure 5 (a-d). These alloys exhibit high ductility (~20% uniform elongation) and the strength properties are relatively insensitive to temperature in the range 300-700°C. The yield strength for several alloys as a function of Cr + Ti content is plotted in Figure 6. Figure 7 is a plot of the reduction in area as a function of test temperature. The reduction in areas is large (>70%) at temperatures of 600°C and below.

Fig 5

Fig 6

Fig 7

5. Creep Properties

Thermal creep properties for these reference alloys are very limited; however, Shirra [18] has compiled an extensive creep data base on a range of vanadium alloys. The Larsen-Miller plot in Fig. 8 shows that the creep strength of V-4Cr-4Ti (BL-47) is significantly higher than that of V-20 Ti binary alloy but somewhat less than that of V-(10-15)Cr-5Ti.

Fig 8

6. Irradiation Effects

The effects of irradiation, including simulated helium effects produced in the dynamic helium charging experiment are the subject of a comparison paper in this conference [19]. Hence the coverage of irradiation effects on vanadium alloys in this paper is limited to a brief summary that provides a further basis for selection of V-4Cr-4Ti as a reference alloy composition. Figure 9 is a plot showing the effect of neutron fluence on the yield strength of V-(0-15)Cr-(4-5)Ti alloys at 600°C. These results indicate increased strengthening with an increase in Cr content and a saturation of the hardening at ~40 dpa. Figure 10 is a plot of the effect on uniform elongation after irradiation at 400-600°C to fluences of 28-46 dpa. The V-4Cr-4Ti alloy exhibits a uniform elongation of greater than 8% when tested at the irradiation temperatures as well as when tested at room temperature after irradiation at 420-600°C including tests with additional He concentrations.

Fig 9

Fig 10

A critical issue in the selection of a reference composition is the effect of irradiation on the impact properties. Figure 11 is a summary plot of the DBTT of several vanadium alloys after irradiation to fluences of 24-50 dpa. Alloys with

Fig 11

Cr + Ti concentrations greater than about 10% show significantly higher DBTT's. The V-4Cr-4Ti alloy (BL-47) exhibits a very low DBTT even after irradiation to 24-30 dpa at temperatures of 420-600°C.

7. Conclusions

A V-4Cr-4Ti alloy composition has been selected as a reference alloy composition for further evaluation as a structural material for fusion first-wall/blanket applications. Highest priority in the evaluation is given to superior impact properties and high tensile ductility with less than optimum tensile and creep strength. Results obtained indicate that optimum impact properties are obtained with a one hour anneal at 1000°C, and that the impact properties are not highly sensitive to composition for alloys of V-(4-5)Cr-(4-5)Ti. The favorable properties of the V-5Cr-5Ti (T87) alloy supports the previous conclusion that the relatively poor impact properties of an earlier heat of V-5Cr-5Ti (BL-63) do not result from a high sensitivity to Cr and Ti concentration in the 4-5% range but due to impurity effects related to the fabrication process.

Further investigations including higher neutron fluences, effect of fusion relevant helium generation rates and effects of minor elements such as Si, O, N and C on properties is required.

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Figure Captions

Figure 1	Impact properties of low-Cr ternary alloys V-(4-5)Cr-(4-5)Ti.
Figure 2	Charpy energy as functon of impact temperature of production-scale heat of V-4Cr-4Ti after annealing for 1 h at 950, 1000, and 1050°C.
Figure 3	Effect of annealing on impact properties of 30°-notch Charpy specimens.
Figure 4	Effect of annealing on DBTT of 15-kg V-5Cr-5Ti and 500-kg V-4Cr-4Ti alloys.
Figure 5 (a-d)	Tensile properties of V-(4-5)Cr-(4-5)Ti alloys.
Figure 6	Yield strength of V-Ti and V-Cr-Ti alloys as a function of Cr + Ti content.
Figure 7	Reduction in area for V-(4-5)Cr-(4-5)Ti alloys as a function of temperature.
Figure 8	Thermal creep properties of V-4Cr-4Ti compared to properties of other alloys.
Figure 9	Yield strength of V-(0-15)Cr-(4-5)Ti alloys irradiated at 600°C as function of irradiation damage (dpa).

Figure 10 Effect of irradiation on uniform elongation of V-4Cr-4Ti alloy (BL-47).

Figure 11 DBTT as a function of combined Cr and Ti contents measured on one-third-size Charpy specimens of V-Ti, V-Cr-Ti, and V-Ti-Si alloys after irradiation.

Table 1

Compositions of Vanadium Base Alloys

ID No.	Nominal Composition (wt.%)	Trace Element Concentration, wppm O	N	C	Si
BL-47	4.1Cr-4.3Ti	350	220	200	870
832665	3.8Cr-3.9Ti	310	85	80	783
T87	4.9Cr-5.1Ti	380	89	109	545
BL-63	4.6Cr-5.1 Ti	440	28	73	310

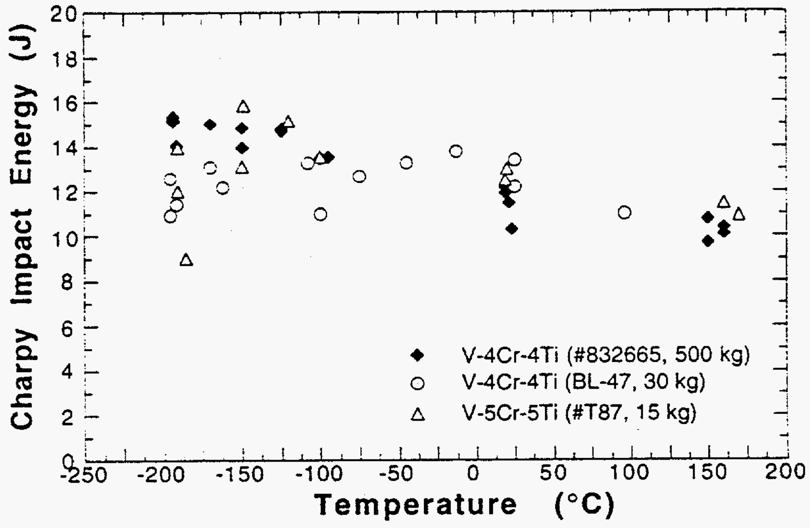

Charpy Impact Energy (J)
0
2
4
6
8
10
12
14
16
18
20
-250
-200
-150
-100
-50
0
50
100
150
200
Temperature (°C)
◆ V-4Cr-4Ti (#832665, 500 kg)
○ V-4Cr-4Ti (BL-47, 30 kg)
△ V-5Cr-5Ti (#T87, 15 kg)

Fig. 1.

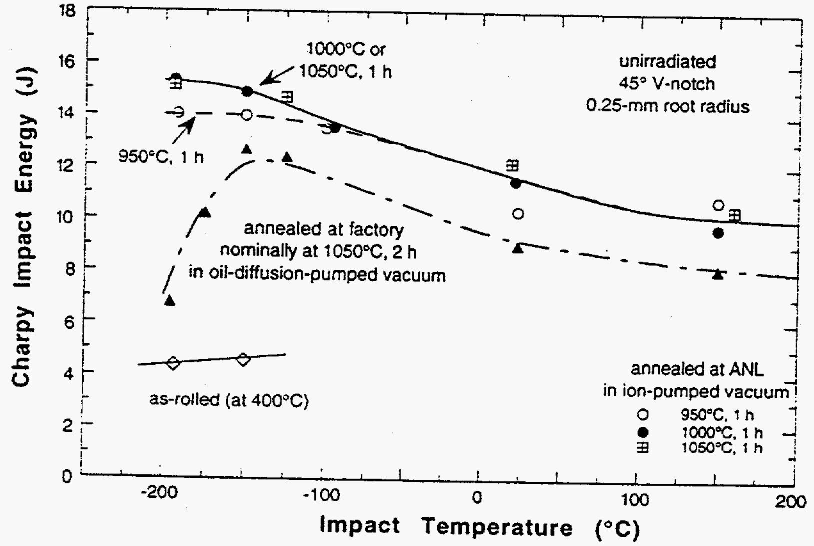

Charpy Impact Energy (J)
0
2
4
6
8
10
12
14
16
18
-200
-100
0
100
200
Impact Temperature (°C)
1000°C or 1050°C, 1 h
950°C, 1 h
unirradiated
45° V-notch
0.25-mm root radius
annealed at factory
nominally at 1050°C, 2 h
in oil-diffusion-pumped vacuum
as-rolled (at 400°C)
annealed at ANL
in ion-pumped vacuum
○ 950°C, 1 h
● 1000°C, 1 h
⊞ 1050°C, 1 h

Fig 2.

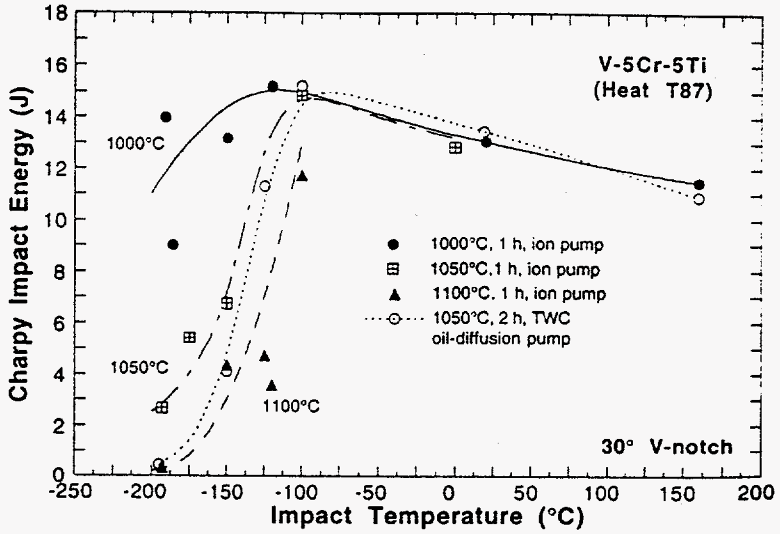

V-5Cr-5Ti
(Heat T87)
Charpy Impact Energy (J)
18
16
14
12
10
8
6
4
2
0
1000°C
1050°C
1100°C
● 1000°C, 1 h, ion pump
⊞ 1050°C,1 h, ion pump
▲ 1100°C, 1 h, ion pump
○ 1050°C, 2 h, TWC oil-diffusion pump
30° V-notch
-250
-200
-150
-100
-50
0
50
100
150
200
Impact Temperature (°C)

Fig 3

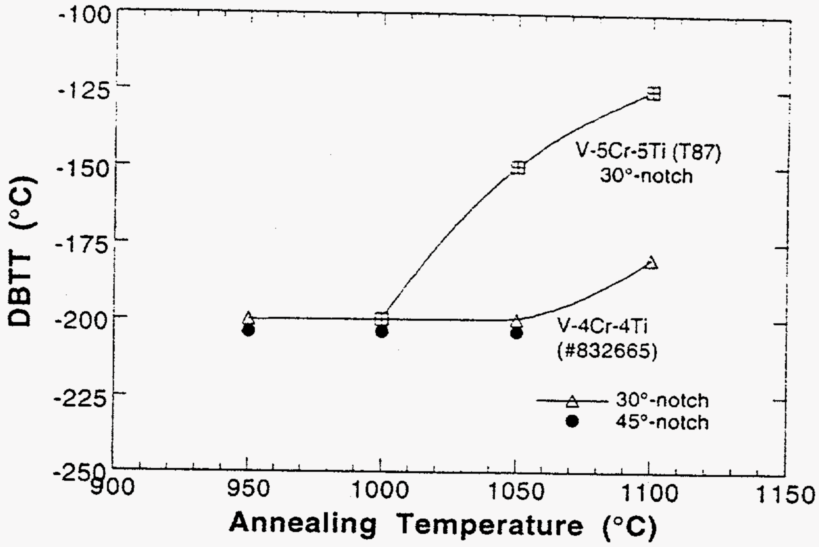

-100
-125
-150
-175
-200
-225
-250
DBTT (°C)
V-5Cr-5Ti (T87)
30°-notch
V-4Cr-4Ti
(#832665)
30°-notch
45°-notch
900
950
1000
1050
1100
1150
Annealing Temperature (°C)

Fig 4

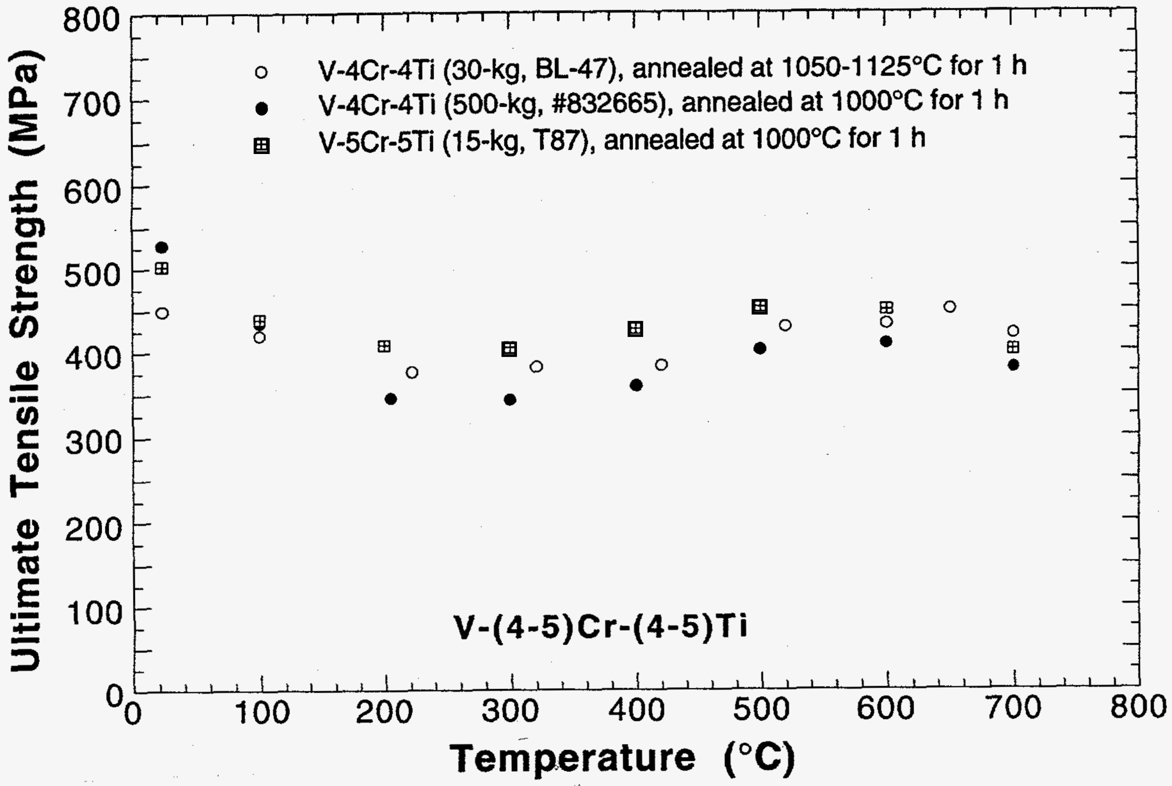

Ultimate Tensile Strength (MPa)
0
100
200
300
400
500
600
700
800
Temperature (°C)
0
100
200
300
400
500
600
700
800
○ V-4Cr-4Ti (30-kg, BL-47), annealed at 1050-1125°C for 1 h
● V-4Cr-4Ti (500-kg, #832665), annealed at 1000°C for 1 h
⊞ V-5Cr-5Ti (15-kg, T87), annealed at 1000°C for 1 h
V-(4-5)Cr-(4-5)Ti

Fig 5A

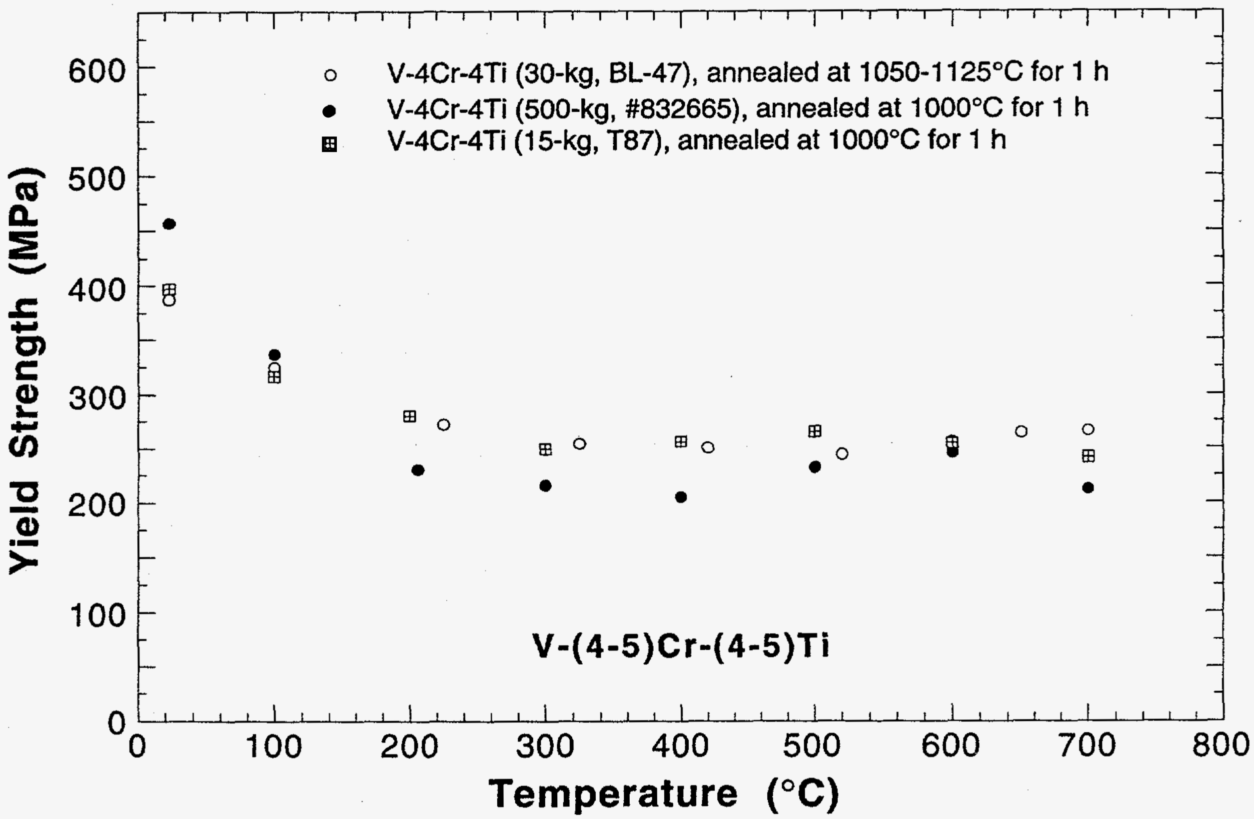

Yield Strength (MPa)
0
100
200
300
400
500
600
Temperature (°C)
0
100
200
300
400
500
600
700
800
○ V-4Cr-4Ti (30-kg, BL-47), annealed at 1050-1125°C for 1 h
● V-4Cr-4Ti (500-kg, #832665), annealed at 1000°C for 1 h
⊞ V-4Cr-4Ti (15-kg, T87), annealed at 1000°C for 1 h
V-(4-5)Cr-(4-5)Ti

Fig 5B

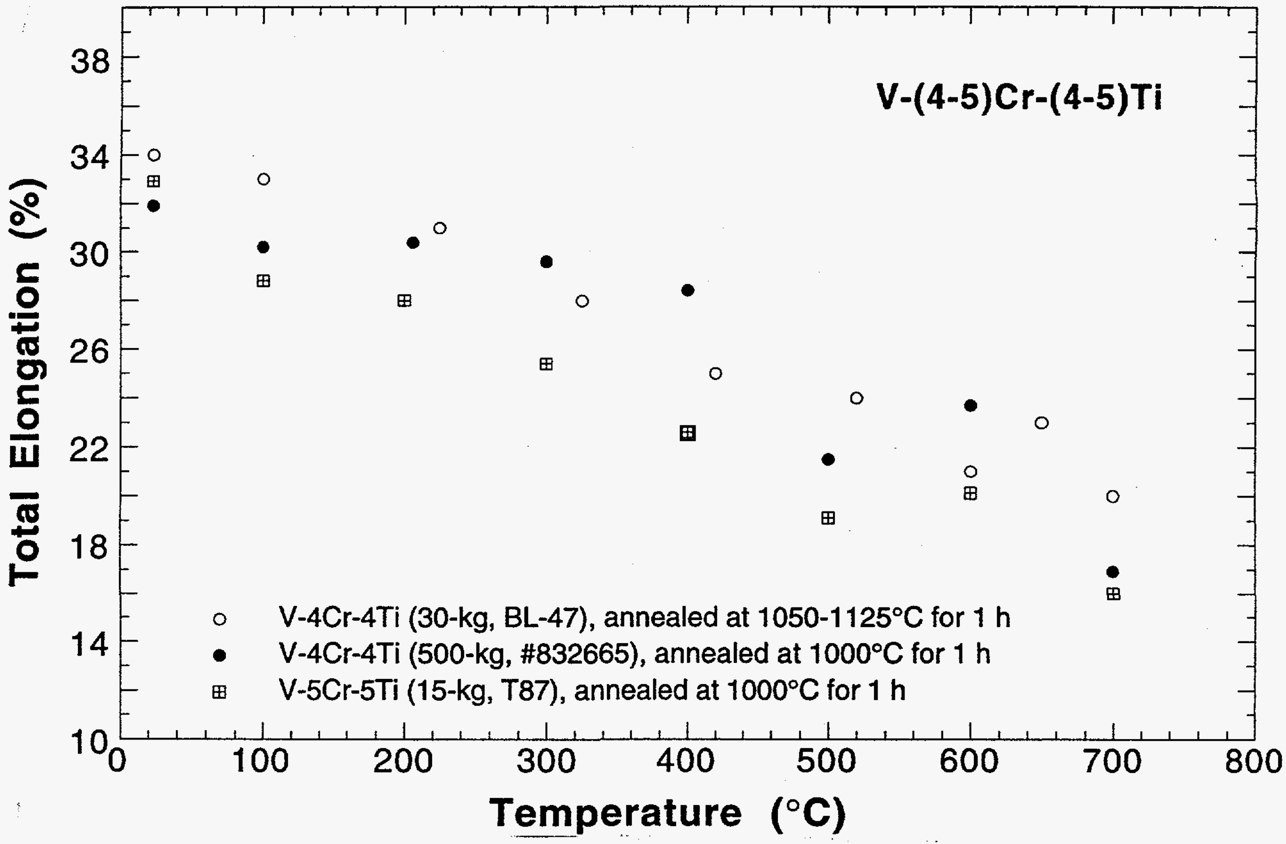

V-(4-5)Cr-(4-5)Ti
Total Elongation (%)
38
34
30
26
22
18
14
10
Temperature (°C)
0
100
200
300
400
500
600
700
800
○ V-4Cr-4Ti (30-kg, BL-47), annealed at 1050-1125°C for 1 h
● V-4Cr-4Ti (500-kg, #832665), annealed at 1000°C for 1 h
⊞ V-5Cr-5Ti (15-kg, T87), annealed at 1000°C for 1 h

FIg 5C

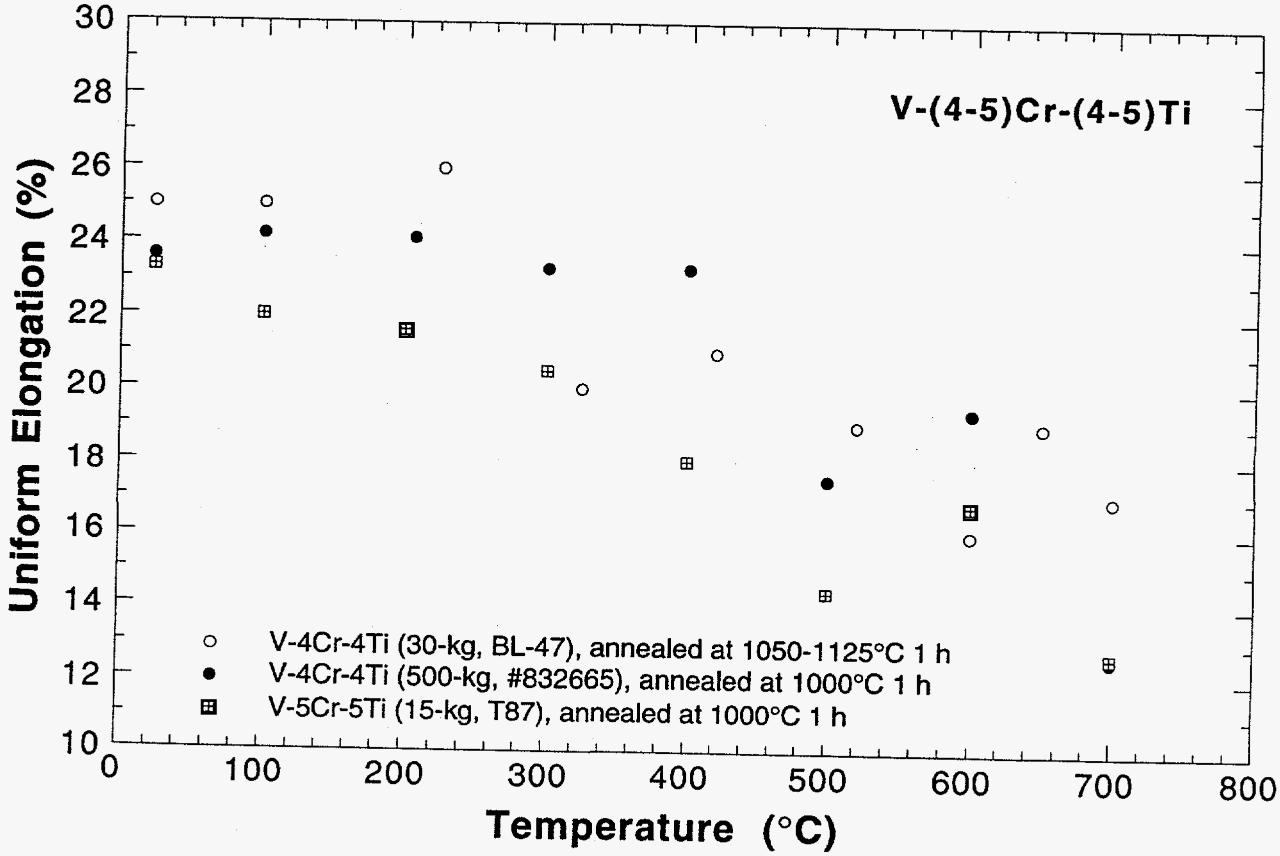
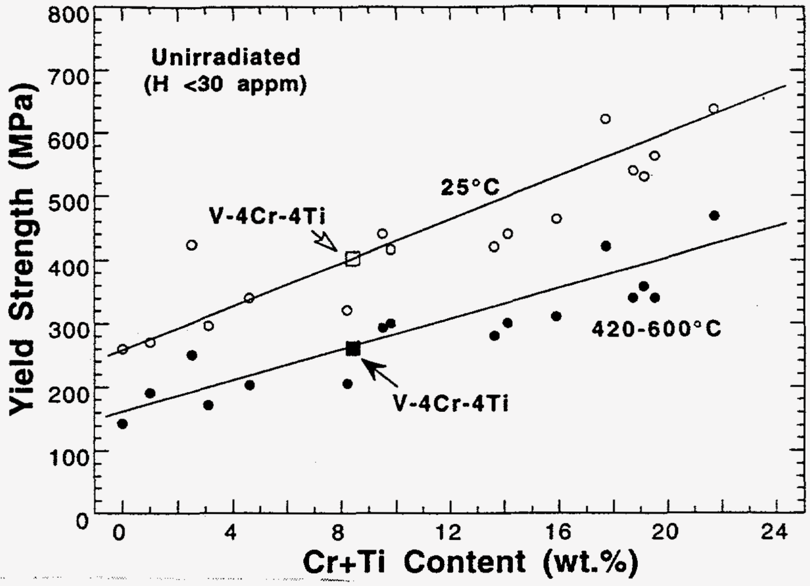

V-(4-5)Cr-(4-5)Ti
Uniform Elongation (%)
30
28
26
24
22
20
18
16
14
12
10
Temperature (°C)
0
100
200
300
400
500
600
700
800
○ V-4Cr-4Ti (30-kg, BL-47), annealed at 1050-1125°C 1 h
● V-4Cr-4Ti (500-kg, #832665), annealed at 1000°C 1 h
⊞ V-5Cr-5Ti (15-kg, T87), annealed at 1000°C 1 h

Fig 5D



Unirradiated
(H <30 appm)
Yield Strength (MPa)
800
700
600
500
400
300
200
100
0
V-4Cr-4Ti
25°C
420-600°C
V-4Cr-4Ti
0
4
8
12
16
20
24
Cr+Ti Content (wt.%)

Fig 6

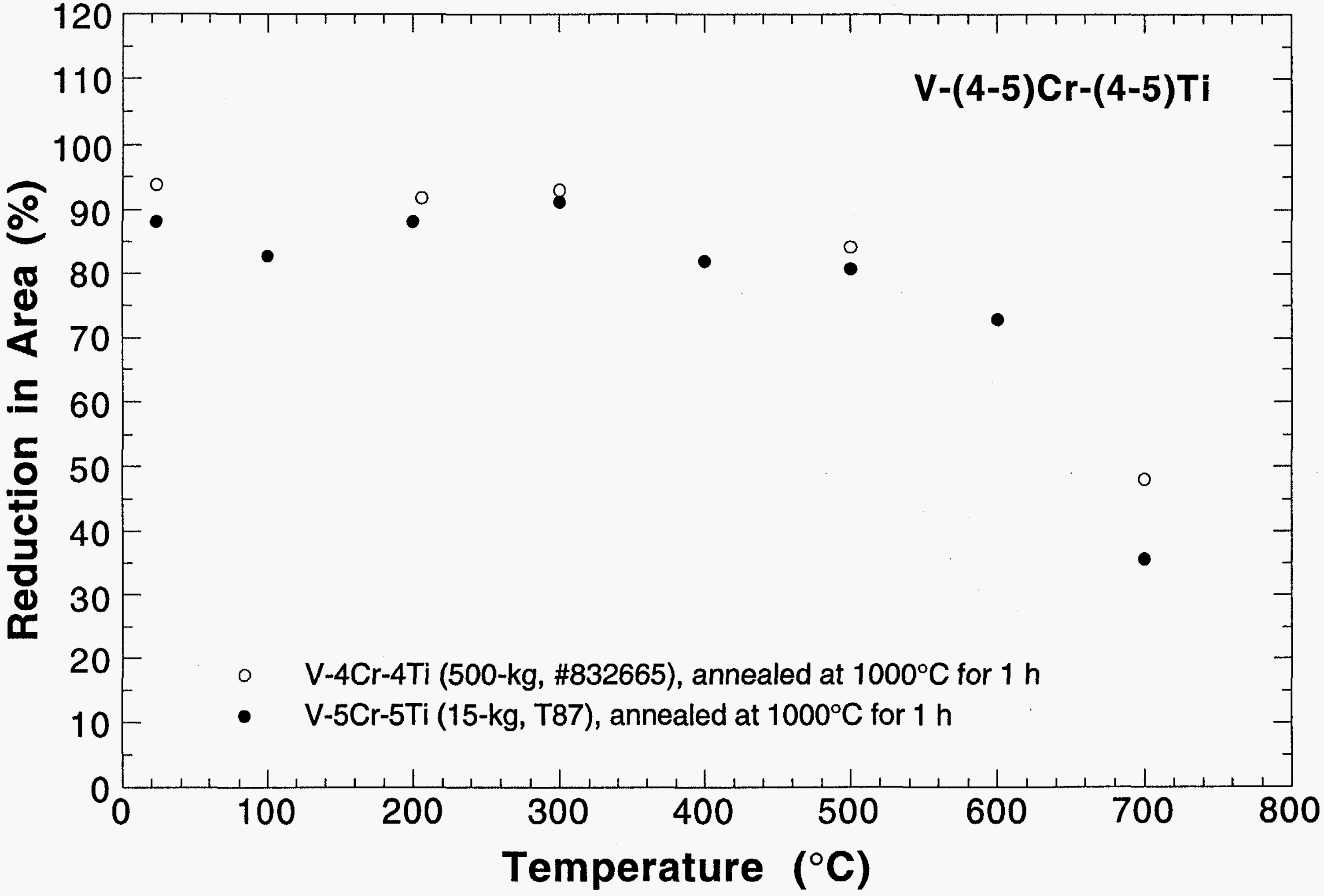
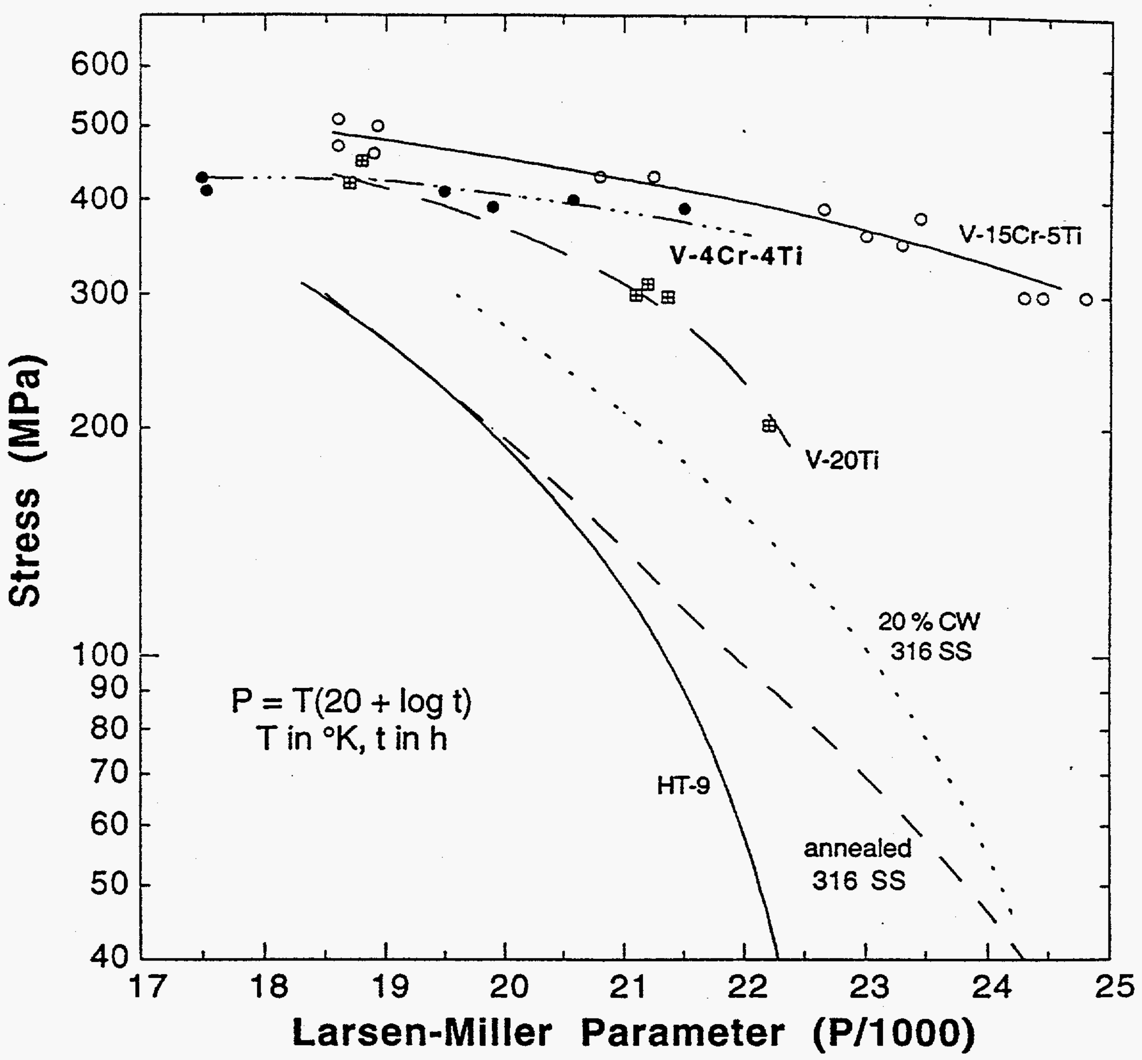

V-(4-5)Cr-(4-5)Ti
○ V-4Cr-4Ti (500-kg, #832665), annealed at 1000°C for 1 h
● V-5Cr-5Ti (15-kg, T87), annealed at 1000°C for 1 h
Reduction in Area (%)
0
10
20
30
40
50
60
70
80
90
100
110
120
Temperature (°C)
0
100
200
300
400
500
600
700
800

Fig 7.



600
500
400
300
200
100
90
80
70
60
50
40
Stress (MPa)
17
18
19
20
21
22
23
24
25
Larsen-Miller Parameter (P/1000)
V-15Cr-5Ti
V-4Cr-4Ti
V-20Ti
20 % CW
316 SS
annealed
316 SS
HT-9
P = T(20 + log t)
T in °K, t in h

Fig. 8

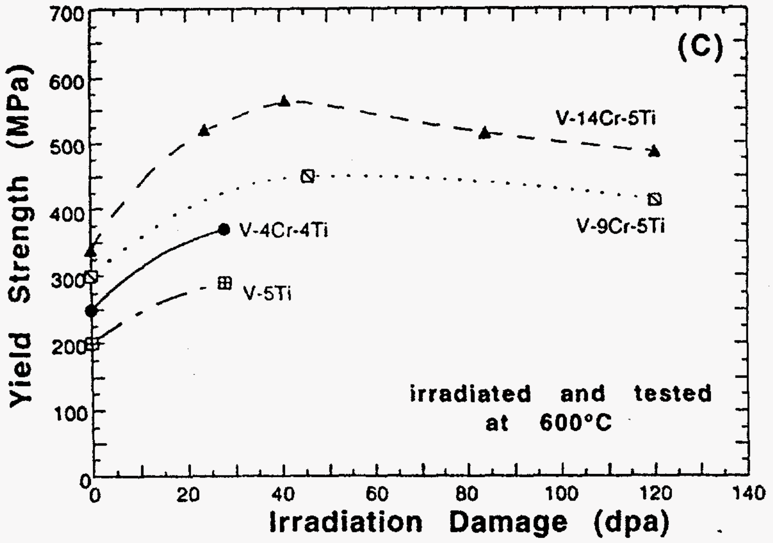

(C)
Yield Strength (MPa)
700
600
500
400
300
200
100
0
V-14Cr-5Ti
V-9Cr-5Ti
V-4Cr-4Ti
V-5Ti
irradiated and tested at 600°C
0
20
40
60
80
100
120
140
Irradiation Damage (dpa)

Fig 9

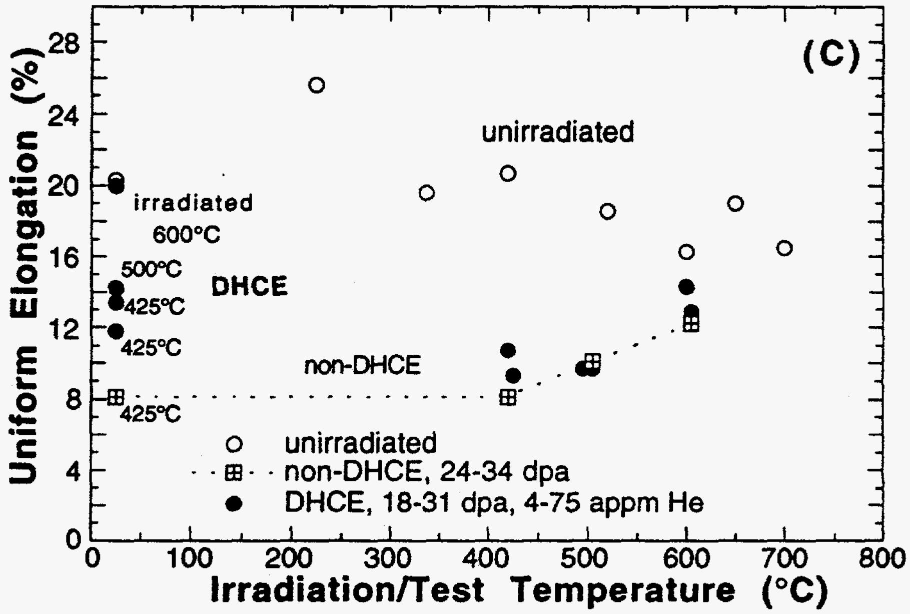

(C)
Uniform Elongation (%)
28
24
20
16
12
8
4
0
unirradiated
irradiated
600°C
500°C
425°C
425°C
DHCE
non-DHCE
425°C
unirradiated
non-DHCE, 24-34 dpa
DHCE, 18-31 dpa, 4-75 appm He
0
100
200
300
400
500
600
700
800
Irradiation/Test Temperature (°C)

Fig 10

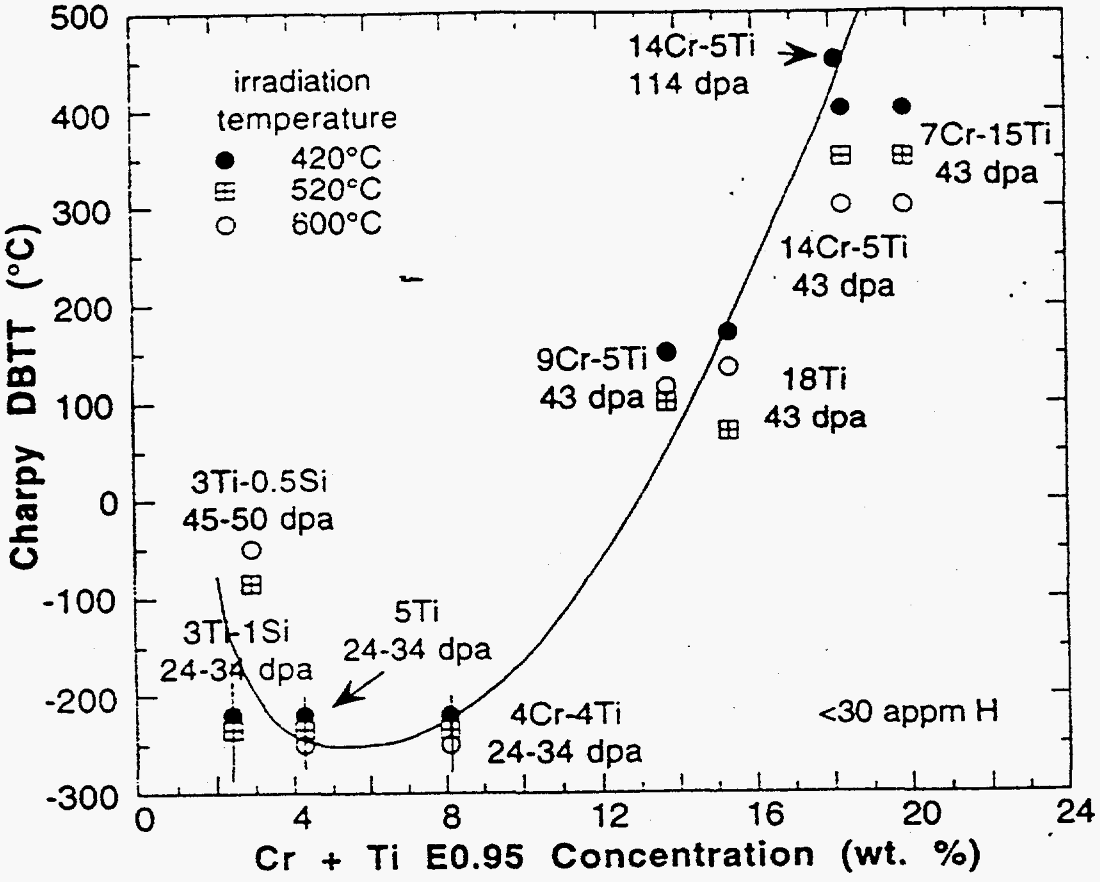

Charpy DBTT (°C)
500
400
300
200
100
0
-100
-200
-300
0
4
8
12
16
20
24
Cr + Ti E0.95 Concentration (wt. %)
irradiation temperature
● 420°C
⊞ 520°C
○ 600°C
14Cr-5Ti 114 dpa
7Cr-15Ti 43 dpa
14Cr-5Ti 43 dpa
9Cr-5Ti 43 dpa
18Ti 43 dpa
3Ti-0.5Si 45-50 dpa
3Ti-1Si 24-34 dpa
5Ti 24-34 dpa
4Cr-4Ti 24-34 dpa
<30 appm H

Fig. 11